Magnetic Core Analysis for Improved Interpretation of Geothermal Prospects

Elena Y. Temnikova[1], *David K.* Potter[1*] and *Arfan* Ali[2]

[1]Department of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada

[2]Shell UK Limited, Aberdeen, UK

Abstract. Locating intervals where there may be radiogenic heat sources is critically important for potential geothermal prospects. This paper details use of core magnetic techniques on rock powder samples from northern Alberta to accurately determine: (i) the depth to the Precambrian crystalline basement rocks (where most of the radiogenic heat sources are expected to reside) below the Phanerozoic sedimentary cover rocks, and characterize variations in the different lithologies, (ii) the contents and domain states of certain minerals, and (iii) the temperature dependence of magnetic properties, which can potentially be used for mineral quantification from laboratory or potential borehole magnetic measurements. The results demonstrated that rapid core magnetic susceptibility measurements correlated with borehole gamma ray results, and could arguably identify certain lithologies (such as the granitic basement samples) better than the gamma ray. Whilst small rock powder samples were only available to us in this study, the same types of magnetic measurements can be made (using different sensors in some cases) on whole core, slabbed core, core plugs, drill cuttings or rock chips. The core measurements strongly suggest the potential usefulness of a high resolution borehole magnetic susceptibility tool for the above purposes. Interestingly, the magnetic susceptibility and gamma ray results with depth indicated that the Precambrian basement rocks were more complicated than initially expected, and exhibited a large range of values.

Rapid, low field magnetic susceptibility measurements using a small portable sensor were first acquired, and subsequently validated independently via magnetic hysteresis measurements using a larger, sensitive and expensive variable field translation balance (VFTB). The results demonstrated that the portable, relatively cheap sensor is potentially suitable for basic, rapid measurements. However, the VFTB had several advantages. Firstly, it enabled magnetic hysteresis and susceptibility measurements to be acquired over a range of low to high applied fields. The high field signal enables estimates of the type and contents of the diamagnetic and paramagnetic minerals to be determined. Secondly, the low field signal due to the ferrimagnetic mineral components can be extracted from the high field signal. This gives useful information on the domain state of the ferrimagnetic (generally iron oxide) carriers. Interestingly, we observed a progressive change with increasing depth from multidomain (MD) or pseudo single domain (PSD, which are essentially small MD) to stable single domain (SSD) to superparamagnetic (SP) ferrimagnetic grains. This effectively represents a change from larger to smaller ferrimagnetic grain sizes with depth, and could be a potential tool for distinguishing lithologies in future similar studies. Thirdly, the temperature dependence of the hysteresis curves and magnetic susceptibility could be measured. This information can be used to improve predictions of the contents of the diamagnetic, paramagnetic and ferrimagnetic minerals from laboratory measurements, or from in-situ borehole magnetic susceptibility data (since temperature varies with depth in a borehole).

1 Introduction

The accurate location of intervals where there may be radiogenic heat sources is critically important for the exploitation of potential geothermal prospects. Geothermal energy could become an increasingly important source of energy in the transition to greener forms of energy, not only for heating, but also for electricity and a variety of industrial applications. The area around Fort McMurray in Northern Alberta is a potential region for geothermal energy, which could in part be used for the extraction and processing of the oil sands. This would, in addition, help reduce CO_2 emissions compared to current methods of extraction and processing [1,2]. The present study aims to show how magnetic core analysis techniques can provide rapid, supplementary tools for improving the characterization of rock samples in prospective geothermal regions. The

* Corresponding author: dkpotter@ualberta.ca

methods can be performed rapidly on drill cuttings (which are available from all drilled wells) and small rock chip or powder samples even if there are no large core samples.

In northern Alberta the main radiogenic heat sources are most likely to reside in the crystalline basement rocks [2], for example in K-feldspars and heavy minerals etc, beneath the sedimentary cover rocks which include the oil sands intervals. Magnetic susceptibility measurements provide a rapid means of distinguishing high susceptibility crystalline (igneous or metamorphic) basement rocks from low susceptibility sedimentary rocks, and thus a means of pin-pointing the depths of the intervals that contain the major heat sources. Magnetic susceptibility is likely to be complementary to other techniques such as gamma ray, and can identify certain rock types better than gamma ray, due to the high magnetic susceptibility signal of small ferrimagnetic grains (e.g., iron oxides such as magnetite) contained within the rocks. We will also demonstrate that the magnetic domain state of these small ferrimagnetic grains can be potentially used to discriminate lithologies.

Temperature dependent magnetic susceptibility measurements can be used to quantify the contents of diamagnetic (e.g., quartz) and paramagnetic (e.g., illite) mineral components in a rock sample, by comparison with model mineral mixture curves that we have developed [3,4]. Temperature dependent susceptibility of minerals is also important for obtaining reliable mineral content estimates from borehole magnetic susceptibility data, since temperature and thus magnetic susceptibility varies with depth. This potentially allows a means of estimating in-situ mineral contents.

2 Samples and Methods

2.1 Rock powder samples

Small powdered rock samples were taken from whole core from various wells at different locations in northern Alberta. The samples covered a range of depths through the sedimentary cover rocks and the crystalline basement (mainly igneous) rocks. The deepest samples from 1656.5–2364.2 m were all from the same Hunt well, located close to 57º N and 111º W (see **Figure 1**). The samples at shallower depths were representative of a range of depths from 15 other wells. All the wells were close to Fort McMurray in northern Alberta.

2.2 Low field magnetic susceptibility using a small portable sensor

Part of the powdered rock samples from each location and depth was first put into small plastic vials. Magnetic susceptibility measurements per unit volume were made on the vials containing the rock powders using a small portable low field (about 250 μT) Bartington MS2B magnetic susceptibility sensor (**Figure 2 (a)**) connected to a laptop via an MS3 susceptibility meter. The magnetic susceptibility per unit volume k is given by:

$$k = J/H \quad (1)$$

where J is the magnetization per unit volume, and H is the applied external magnetic field. Each vial containing rock powders was also accurately weighed, and the magnetic susceptibility values per unit volume were converted into magnetic susceptibility per unit mass χ given by:

$$\chi = M/H = k/\rho \quad (2)$$

where M is the magnetization per unit mass, and ρ is the density of the rock powder (mass/volume). The advantage of converting to magnetic susceptibility per unit mass is that it essentially eliminates any small effects due to porosity, which can sometimes cause slight variations in magnetic susceptibility per unit volume. The mass and magnetic susceptibility values of the plastic vials themselves were subtracted from the corresponding values when the vials contained the rock powders, thus allowing values for the rock powders alone to be determined.

2.3 Magnetic hysteresis, variable field magnetic susceptibility, and temperature dependent measurements using a VFTB

Magnetic hysteresis measurements on small sub-samples of the rock powders were also made using a sensitive variable field translation balance, VFTB [5-7], shown in **Figure 2 (b)**. Small amounts of the rock powders were inserted in thin glass tubes, which were then placed between the poles of an electromagnet. Each hysteresis curve was produced as the sample was vibrated in applied fields from 0 mT to 1,000 mT (1 Tesla), followed by reverse fields from 1,000 mT to -1,000 mT, and finally fields from -1,000 mT to 0 mT. Thus each sample is cycled through a range of low and high applied magnetic fields. Each hysteresis curve takes around 15-20 minutes to be produced. The slope at any point on the hysteresis curve represents the magnetic susceptibility (magnetization/applied field) at that applied field strength, and thus the magnetic susceptibility at different low and high applied fields can be obtained. This information, together with the shape of each hysteresis curve, gives valuable information regarding the mineral components in the rock sample (as detailed in **section 3 Results and Discussion**). The high field portion of each hysteresis curve is generally a straight line whose slope represents the combined magnetic susceptibilities of the diamagnetic (e.g., quartz) and paramagnetic (e.g., illite) mineral components. The hysteresis loop or kink at low fields generally represents the type and domain state of the ferrimagnetic minerals (e.g., iron oxides) in the rock. These ferrimagnetic minerals generally don't contribute to the high field part of the hysteresis curve, since they usually saturate at lower fields. This is useful as it enables us to produce "extracted magnetic hysteresis curves" due solely to the ferrimagnetic mineral content of the samples, by subtracting out the high field portion of the curves due to the combined diamagnetic and paramagnetic components.

The VFTB also enables magnetic hysteresis measurements, and thus magnetic susceptibility values, to be determined as a function of temperature. This is useful as one can then simulate the temperature dependence of these magnetic properties in a borehole, where temperature varies with depth. The typical geothermal gradient in the study area is 20ºC per km [2]. The magnetic susceptibility of diamagnetic minerals is independent of temperature, but varies with temperature for paramagnetic minerals according to the Curie equation:

$$k = C_v/T \text{ or } \chi = C_m/T \qquad (3)$$

where C_v and C_m are the mineral specific Curie constants for magnetic susceptibility per unit volume or for magnetic susceptibility per unit mass respectively, and T is the temperature in Kelvin. Knowing the magnetic susceptibility per unit volume or per unit mass at room temperature **Equation (3)** allows us to construct theoretical model curves of magnetic susceptibility per unit volume or per unit mass with temperature. This can be done for a single paramagnetic mineral, or a combination of paramagnetic minerals if one knows the proportions of the minerals, or a mixture of paramagnetic and diamagnetic minerals. In **section 3.2** we will show theoretical curves of the temperature dependence of magnetic susceptibility per unit mass for a simple two component mixture comprising of a paramagnetic mineral (illite clay) and a diamagnetic mineral (quartz), compared with temperature dependent measurements of some of the rock samples. For magnetic susceptibility per unit mass the total measured signal of this mineral mixture is given by [8]:

$$\chi_T = \{(F_I)\,(\chi_I)\} + \{(1-F_I)\,(\chi_Q)\} \qquad (4)$$

where χ_T is the total mass magnetic susceptibility of the mixture, F_I is the illite fraction per unit mass, $(1\text{-}F_I)$ is the quartz fraction per unit mass, and χ_I and χ_Q are the magnetic susceptibilities per unit mass of illite (15×10^8 $m^3\ kg^{-1}$ [9]) and quartz (-0.62×10^8 $m^3\ kg^{-1}$ [10]), respectively. We can vary the fractions of illite and quartz, and the value of χ_I will be temperature dependent, but the value of χ_Q will be temperature independent. The illite fraction is given by:

$$F_I = (\chi_T - \chi_Q) / (\chi_I - \chi_Q) \qquad (5)$$

and the fraction of quartz is given by $(1\text{-}F_I)$. We could write similar types of expressions as **Equations (4)** and **(5)** for magnetic susceptibility per unit volume [11].

3 Results and Discussion

3.1 Low field magnetic susceptibility results from the rapid, portable sensor, and comparison with borehole gamma ray data

Figure 3 (a) shows the total borehole gamma ray results for the entire Hunt well, where the majority of rock powder samples were collected. The gamma ray data was acquired at a much higher resolution (readings were taken about every 1 cm) than conventional sampling every 0.5 ft. **Figure 3 (b)** gives the raw results of magnetic susceptibility per unit volume for the rock powders from the rapid Bartington MS2B sensor measurements. Note that the scale on the magnetic susceptibility axis is logarithmic. **Figures 3 (a)** and **(b)** clearly show a number of correspondences. They both exhibit low values at shallow depths from 0 m to just under 600 m, typical of clean (i.e., little clay) sedimentary rocks [11,12]). The depth of just under 600 m appears to mark the boundary between the Phanerozoic sedimentary cover and the Precambrian crystalline basement rocks, and is consistent with earlier estimates in the Fort McMurray region [2] – see **Figure 1**. Below 600 m the values of gamma ray and magnetic susceptibility are much higher, typical of igneous or metamorphic rocks [2,9]. Certain features show up on both the magnetic susceptibility and gamma ray profiles. For example, the high magnetic susceptibility and gamma ray values at a depth of around 1198 m. The results from both profiles also show that the basement rocks between depths 600 m and 1656.5 m are more heterogeneous than initially expected. There is a large range of values, suggesting some intercalations of sedimentary rocks, with low values of gamma ray and magnetic susceptibility, within the crystalline basement rocks that exhibit much higher values. Both profiles also exhibit high values at the deepest depths (2350.1–2364.2 m), which from visual inspection of the rock powders are all granitic basement samples. The highest magnetic susceptibility values are recorded for these samples, and this arguably identifies them even better than the gamma ray, which had its highest values at shallower depths. The magnetic signal is more influenced by small ferrimagnetic grains in the granitic basement rocks than the gamma ray, and seems to be a useful tool for identifying these rocks.

The overall similarities between the magnetic susceptibility and gamma ray profiles, and the correspondences observed for certain specific features, give us confidence that the rock powder samples we chose are indeed quite representative of the general lithologies with depth in this region, even though the samples between 0 and 1656.5 m were taken from a number of different wells. We were restricted in the samples available to us from the limited cored sections in these wells.

3.2 Variable field, temperature dependent, magnetic susceptibility and magnetic hysteresis curves from the variable field translation balance (VFTB)

Figure 3 (c) shows values of temperature dependent magnetic susceptibility per unit mass for 3 sedimentary cover rock samples (M0034, N04b and M12351) and 1 basement crystalline rock (M4017) derived from the linear high field portions of the VFTB hysteresis curve at the different temperatures. The initial magnetic hysteresis curve for one of these samples (M12351) is shown in **Figure 4 (a)**. **Figure 3 (c)** also shows theoretical model temperature dependence of magnetic susceptibility curves for simple illite + quartz mixtures, using **Equations (3)**, **(4)**, and **(5)**, and the methodology in **section 2.3**. The model curves allow the contents of the two minerals in each rock sample to be quantified from the figure, assuming these two minerals are the major components in each sample. This example is merely shown to illustrate one possible combination of minerals in the samples. We chose this combination since these minerals are often two of the key components in the sedimentary cover rocks. Model curves for these, and other mineral combinations, can also be used to quantify mineral contents from in-situ borehole magnetic susceptibility measurements, where temperature and magnetic susceptibility (especially for paramagnetic minerals) varies with depth. The temperature axis can be converted to a depth axis using the local geothermal gradient (around 20ºC per km in this case).

In order to help verify the room temperature magnetic susceptibility values from the portable Bartington MS2B sensor we also independently determined the magnetic susceptibility from the magnetic hysteresis curves from the VFTB. Examples of some of the initial magnetic hysteresis curves are shown in **Figures 4 (a)**, **5 (a)** and **6 (a)**. These examples are representative of the 3 main differing types of behavior exhibited by the samples (discussed in more detail below). Each hysteresis curve exhibits a linear portion at high fields, which is due to the combined effects of the diamagnetic and paramagnetic mineral components in the sample. At low field the kinks or loops in the curves represent the response of the ferrimagnetic components, which will be discussed in more detail in **section 3.3**. The magnetic susceptibility at any point on the hysteresis curves is given by the slope (mass magnetization/applied field) at that point, and thus magnetic susceptibility values for a range of low to high applied fields can be obtained. In order to directly compare magnetic susceptibility values from the hysteresis curves with those from the portable Bartington MS2B sensor we needed to (i) determine the values at a comparable low applied field strength, (ii) use the room temperature hysteresis curves (the same temperature as the Bartington sensor measurements), and (iii) convert the Bartington sensor values per unit volume to values per unit mass (using **equation (2)**) as also used by the VFTB. We accurately determined the magnetic susceptibility values from the slope of the initial room temperature hysteresis curves at a suitable low field. The raw initial hysteresis curves (such as those in **Figures 4 (a)**, **5 (a)** and **6(a)**) are used because they reflect the contributions of all the mineral components in each sample, just as the Bartington sensor measures the combined magnetic susceptibility of all the mineral components in a sample. (Note that we distinguish these raw initial hysteresis curves from the corresponding hysteresis curves of **Figures 4 (b)**, **5 (b)** and **6 (b)** where we extract the response of just the ferrimagnetic components of the samples, as discussed later).

Figure 7 shows the Bartington sensor magnetic susceptibility results in values per unit mass, together with the VFTB hysteresis curve derived values. Whilst there are some small differences in the results between the two methods (which would be expected given the different techniques and slightly different amounts of rock powder required for each sample container), there is an overall correspondence between the two sets of values. This gives us confidence in the initial, rapid Bartington sensor results. The agreement between the two sets of results also confirms the large range of values in the heterogeneous crystalline basement between depths 600 m and 1656.5 m. We also show in **Figure 7** our interpretation of the main lithological divisions based on the magnetic susceptibility results and the gamma ray data of **Figure 3 (a)**.

3.3 Extracted ferrimagnetic hysteresis curves and the variation of ferrimagnetic domain state with depth

By subtracting out the linear high field portions of the initial hysteresis curves of **Figures 4 (a)**, **5 (a)** and **6 (a)**, which are due solely to the diamagnetic plus paramagnetic mineral components of the rock samples, we produced corresponding extracted hysteresis curves for just the small amounts of ferrimagnetic mineral components in the samples (**Figures 4 (b)**, **5 (b)** and **6 (b)**). Some supplementary magnetic measurements suggest these components may be magnetite or titanomagnetite. The rock powders exhibited 3 different types of behaviour, which were related to the domain state of the ferrimagnetic minerals in the samples. The sample in **Figure 4 (b)** exhibits multidomain (MD) ferrimagnetic behavior, which is characterized by a hysteresis loop where the maximum value (the saturation magnetization, M_s) is relatively low, and the intercept on the mass magnetization axis (the remanent magnetization, M_{rs}) is also significantly lower than the value of M_s. The sample in Figure **5 (b)** exhibits stable single domain (SSD) ferrimagnetic behavior, which is characterized by a hysteresis loop where the maximum value M_s is quite high and the intercept on the mass magnetization axis magnetization M_{rs} is about 0.5 times the value of M_s (significantly higher than that for MD grains in **Figure 4 (b)**). Some other samples exhibited behavior intermediate between MD and SSD grains (characteristic of small MD grains), and are termed pseudo-single domain (PSD) grains. The sample in **Figure 6 (b)** exhibits superparamagnetic (SP) ferrimagnetic behavior, which is characterized by an 'S' shaped curve with a steep slope (high magnetic susceptibility) at low applied field going through the origin.

The ferrimagnetic extracted curves were determined for all samples, and interestingly we observed a clear trend of MD/PSD to SSD to SP with increasing depth. This essentially represents a decrease in the ferrimagnetic grain size with increasing depth. The depth ranges of the different domain states are labelled on **Figure 7**. These observations of different domain states may provide an important tool for distingushing the various lithologies in future similar studies.

4 Conclusions

The following overall conclusions can be drawn:

1. Low field magnetic susceptibility measurements using a small portable sensor on powdered rock samples from a series of wells in northern Alberta were able to rapidly distinguish samples of the crystalline basement rocks from the sedimentary cover rocks. The crystalline basement samples (where the main radiogenic heat sources are expected to reside) exhibited significantly higher magnetic susceptibility values than the sedimentary cover samples.

2. Independent low field magnetic susceptibility measurements derived from accurate, sensitive magnetic hysteresis curves on the same samples using a vibrating sample translation balance (VFTB) were consistent with the rapid portable sensor results. This confirmed that the portable, cheap sensor is suitable for basic, rapid measurements for identifying crystalline basement samples from sedimentary cover samples, and can thus pin-point the depth to the crystalline basement and thus the location of the main radiogenic heat sources.

3. There were correspondences between the core magnetic susceptibility results and the borehole gamma ray data, both in terms of the overall similarities in the profiles with depth, and the location of certain high signal features.

4. The core magnetic susceptibility and borehole gamma ray results with depth within the crystalline basement exhibited a wide range of values, indicating that the crystalline basement rocks were more heterogeneous than initially expected.

5. The extracted ferrimagnetic hysteresis curves from the VFTB results exhibited a distinct variation of the ferrimagnetic domain state with depth, which appeared to be directly related to different lithogical zonations. Multidomain (MD) and pseudo-single domain (PSD) ferrimagnetic grains were dominant in the Phanerozoic sedimentary cover samples and uppermost Precambrian basement samples, whilst stable single domain (SSD) ferrimagnetic particles were dominant in a deeper zone of the Precambrian basement samples, and superparamagnetic (SP) ferrimagnetic particles were dominant in the deepest Precambrian granitic basement samples. The observed trend represents a decrease in ferrimagnetic domain state with increasing depth. Whilst we don't fully understand the reasons behind these distinctive differences at present, they may have important practical implications for identifying particular lithologies and improving estimates of the depths to potential radiogenic heat sources in studies of other potential geothermal prospects.

6. The magnetic techniques described here have certain advantages over some other rock powder analysis techniques. For example, X-ray diffraction (XRD) would be unlikely to detect the small amounts of ferrimagnetic particles present in the samples, let alone determine their domain state.

7. The core measurement results reported here strongly suggest the potential usefulness of a high resolution borehole magnetic susceptibility tool for in-situ determination of the depths to the crystalline basement and thus the main radiogenic heat sources. In the absence of such a borehole tool, low field magnetic susceptibility measurements can rapidly do the same on powdered core samples (as in the present study) or drill cuttings [13] using either the small, portable, rapid sensor or the more sensitive VFTB. Note that there are also portable, rapid, low field magnetic susceptibility sensors for analysis of whole core, slabbed core [11], and core plug samples [8].

8. The temperature dependence of the magnetic hysteresis curves and magnetic susceptibility from the VFTB, along with model curves for different mineral combinations, can be used to improve estimates of the contents of the diamagnetic, paramagnetic and ferrimagnetic mineral components in the rock. The model curves can also help to provide estimates of the contents of minerals from borehole magnetic susceptibility data, by converting the temperature axis to a depth axis using the local geothermal gradient, since temperature varies with depth in a borehole.

9. The high field portion of the VFTB's magnetic hysteresis curves specifically allows potential quantitative estimates of the type and content of the diamagnetic and paramagnetic mineral components in the samples to be determined. These components are generally not influenced by the ferrimagnetic components at high fields, since most ferrimagnetic minerals saturate at lower applied magnetic fields.

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5 List of abbreviations

MD	Multidomain
PSD	Pseudo-single domain
SP	Superparamagnetic
SSD	Stable single domain
VFTB	Variable field translation balance
XRD	X-ray diffraction

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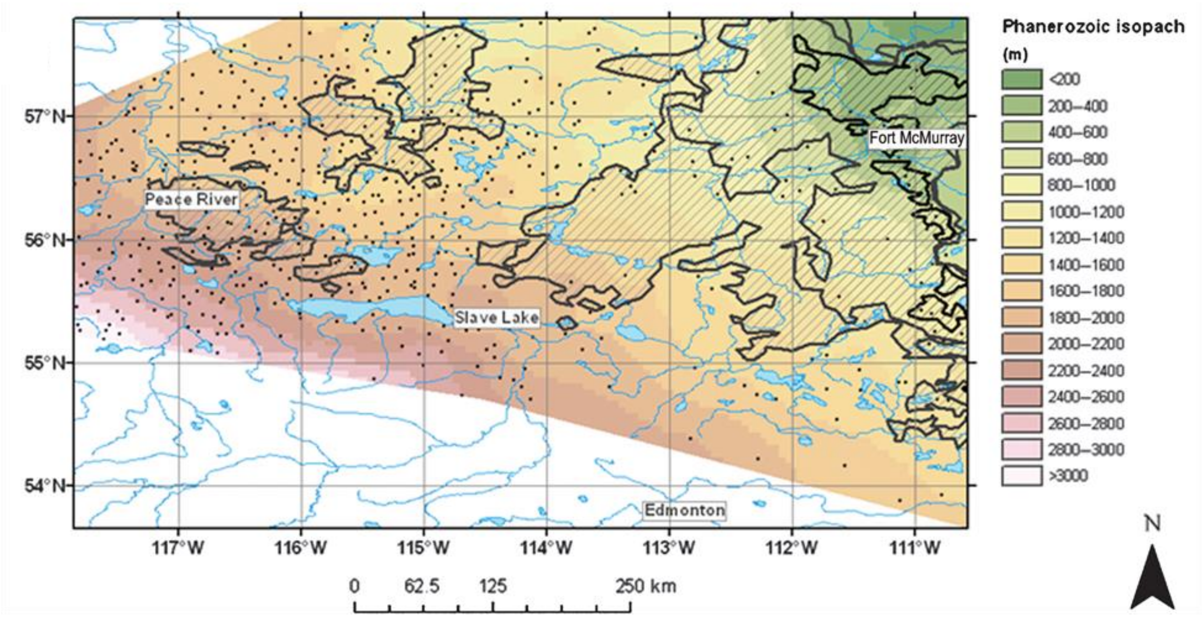
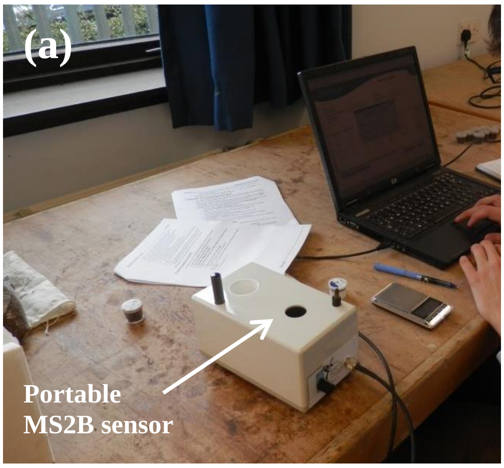


Fig. 1. Location map in northern Alberta, showing the depth to the Precambrian basement in metres (after [2]), which also essentially represents the thickness of the Phanerozoic sedimentary cover rocks. Most of the rock powder samples were taken near the Fort McMurray area. The Hunt well, where several of the deeper samples were taken, is located close to 57º N and 111º W.



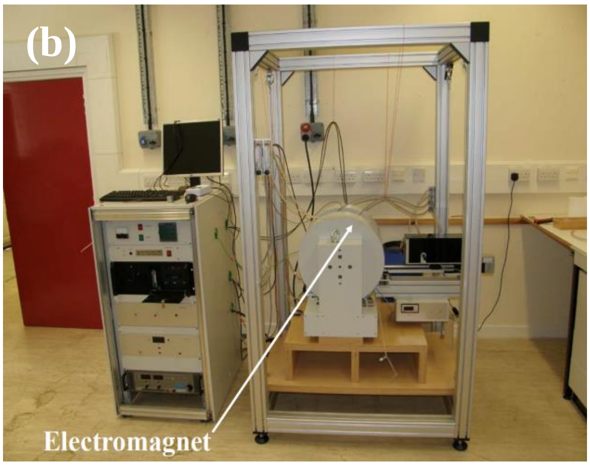


Fig. 2. (a) Image of the small portable Bartington MS2B sensor that was used to measure the low field magnetic susceptibility of the rock powders. Each sample was placed in a cylindrical plastic vial and inserted into the sensor at the point indicated by the arrow. **(b)** Image of the large variable field translation balance (VFTB). Each sample is put in a small glass tube and vibrated between the poles of the electromagnet which cycles through a range of low and high applied fields. The resulting magnetic hysteresis curve takes around 15-20 minutes to be produced. Hysteresis curves can be measured at different temperatures to (i) simulate magnetic properties (magnetization, susceptibility) at borehole conditions where the temperature varies with depth, and (ii) determine the magnetic properties and contents of different mineral components.

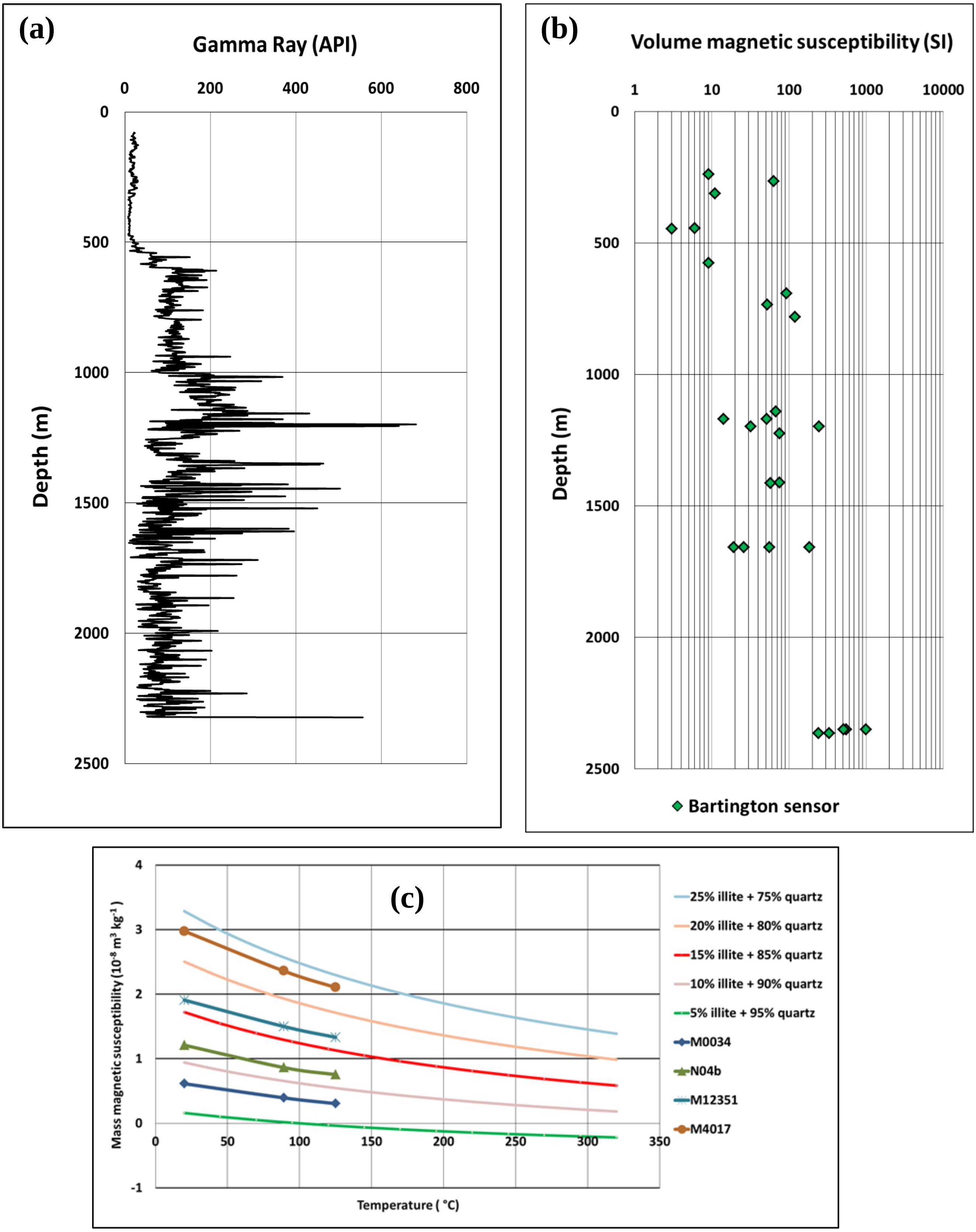
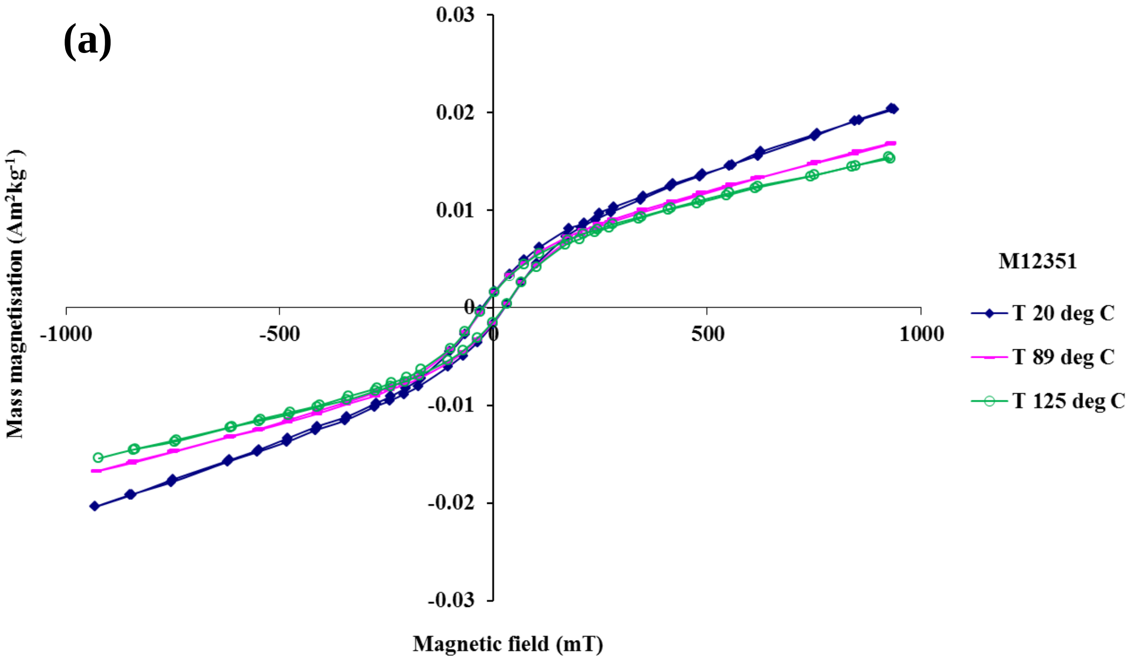


Fig. 3. (a) High resolution borehole gamma ray in the Hunt well. **(b)** Magnetic susceptibility per unit volume from rock powders in the same area. All samples below 1500 m were from the Hunt well, whilst the shallower samples were from a few different wells. **(c)** Temperature dependent magnetic susceptibility per unit mass for 3 sedimentary cover rocks (M0034, N04b and M12351) and 1 basement crystalline rock (M4017) along with model curves indicating possible mineral contents.



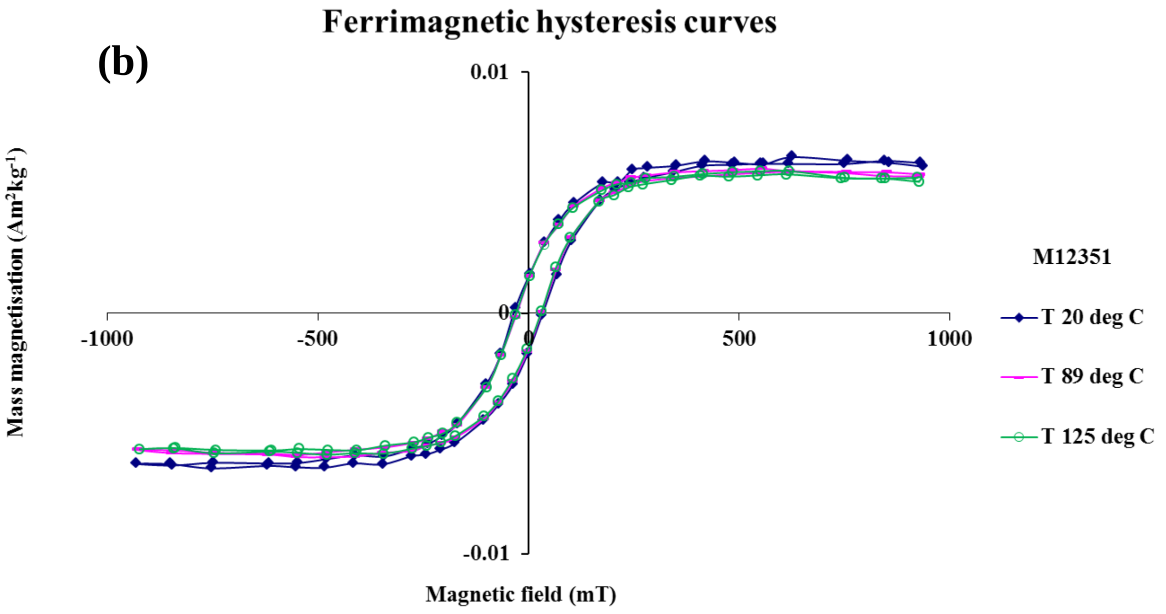


Fig. 4. Magnetic hysteresis curves of a Phanerozoic sedimentary cover rock powder sample at 576 m depth. **(a)** Initial raw magnetic hysteresis curves at different temperatures due to all the mineral components in the rock. The linear regions at high applied field can be used to quantify the diamagnetic and paramagnetic mineral contents. The slope at any point on the curves is the magnetic susceptibility (magnetization/applied field). **(b)** Extracted magnetic hysteresis curves at different temperatures due only to the ferrimagnetic mineral components in the rock. For this sample the ferrimagnetic hysteresis curves indicate that the domain state is multidomain (MD), characterized by a hysteresis loop where the maximum value (the saturation magnetization, M_s) is lower than for stable single-domain (SSD) grains shown in **Figure 5 (b)**, and the intercept on the mass magnetization axis (the remanent magnetization, M_{rs}) is much lower than the value of M_s compared to SSD grains in **Figure 5 (b)**.

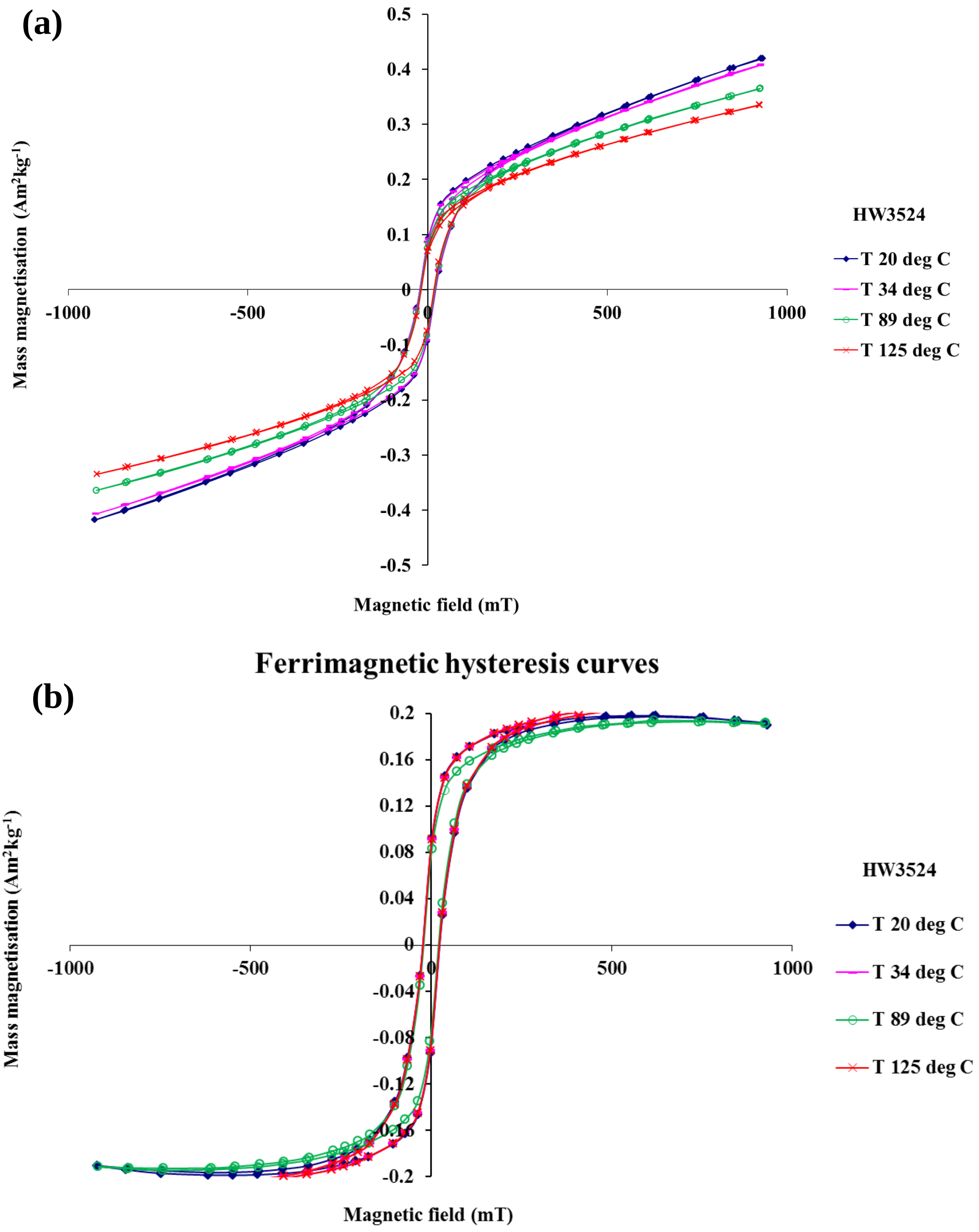
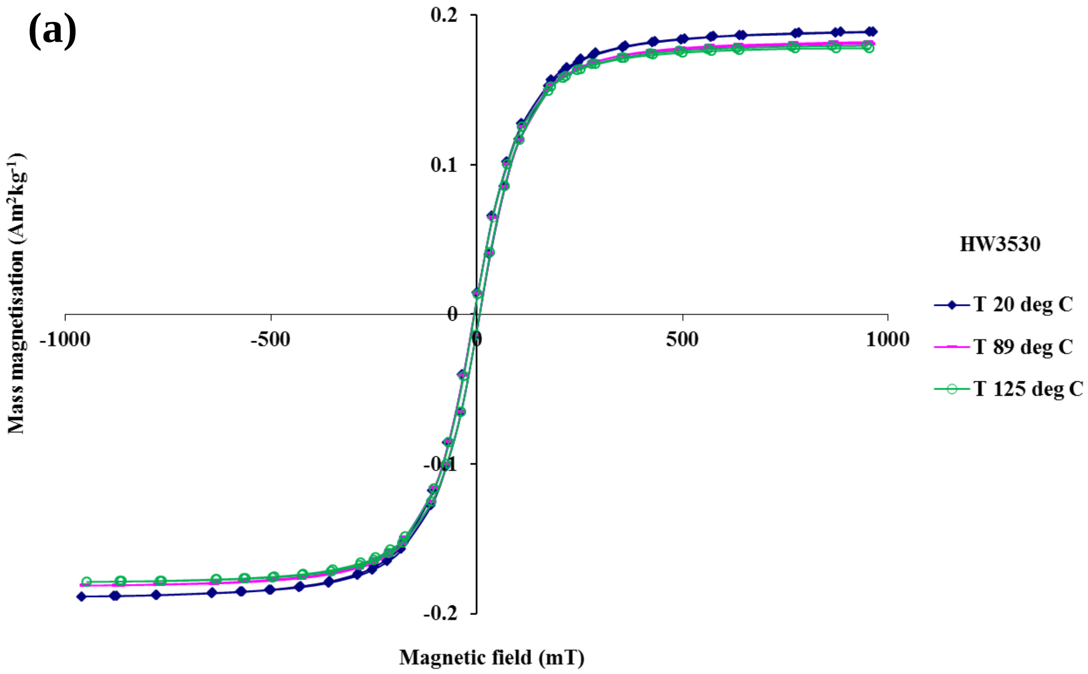


Fig. 5. (a) Magnetic hysteresis curves of a Precambrian basement rock powder sample at 1657 m depth. **(a)** Initial raw magnetic hysteresis curves at different temperatures due to all the mineral components in the rock. **(b)** Extracted magnetic hysteresis curves at different temperatures due only to the ferrimagnetic mineral components in the rock. For this sample the ferrimagnetic hysteresis curves indicate that the domain state is stable single-domain (SSD), characterized by a hysteresis loop where the maximum value (the saturation magnetization, M_s) is quite high and the intercept on the mass magnetization axis (the remanent magnetization, M_{rs}) is about 0.5 times the value of M_s (significantly higher than that for MD grains in **Figure 4 (b)**).



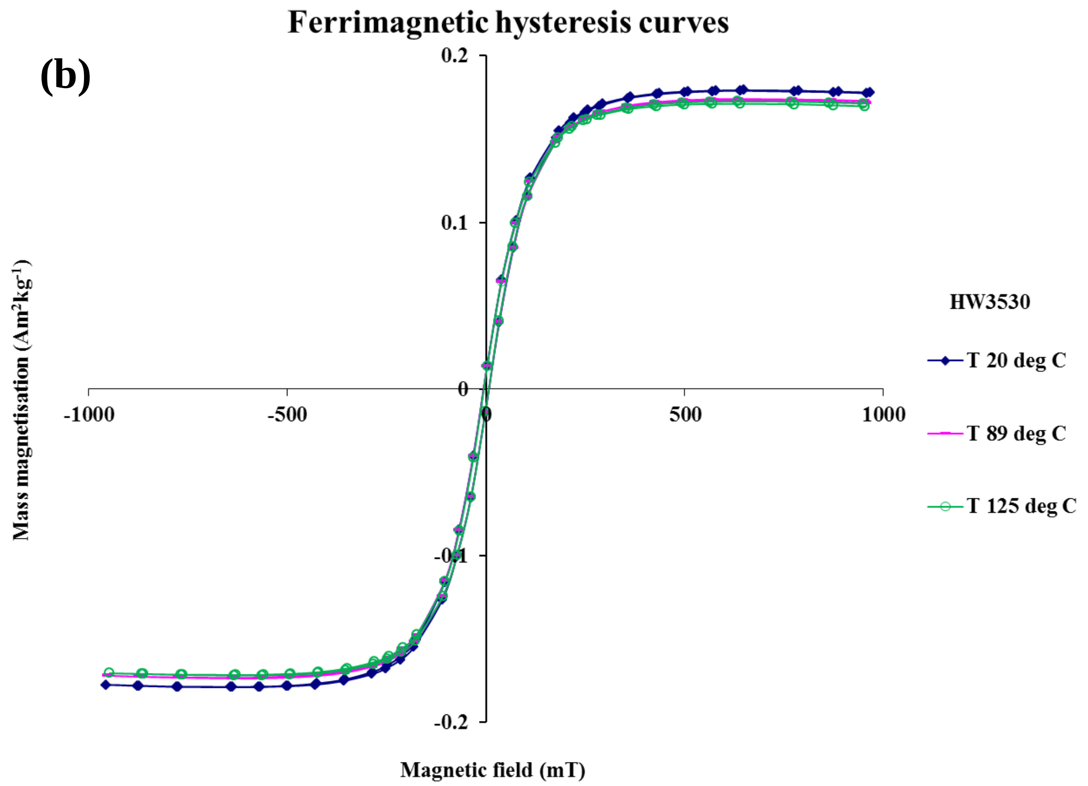


Fig. 6. (a) Magnetic hysteresis curves of a Precambrian granitic basement rock powder sample at 2364.2 m depth. **(a)** Initial raw magnetic hysteresis curves at different temperatures due to all the mineral components in the rock. **(b)** Extracted magnetic hysteresis curves at different temperatures due only to the ferrimagnetic mineral components in the rock. For this sample the ferrimagnetic hysteresis curves indicate that the domain state is superparamagnetic (SP), characterized by an 'S' shaped curve with a steep slope (high magnetic susceptibility) at low applied field going through the origin.

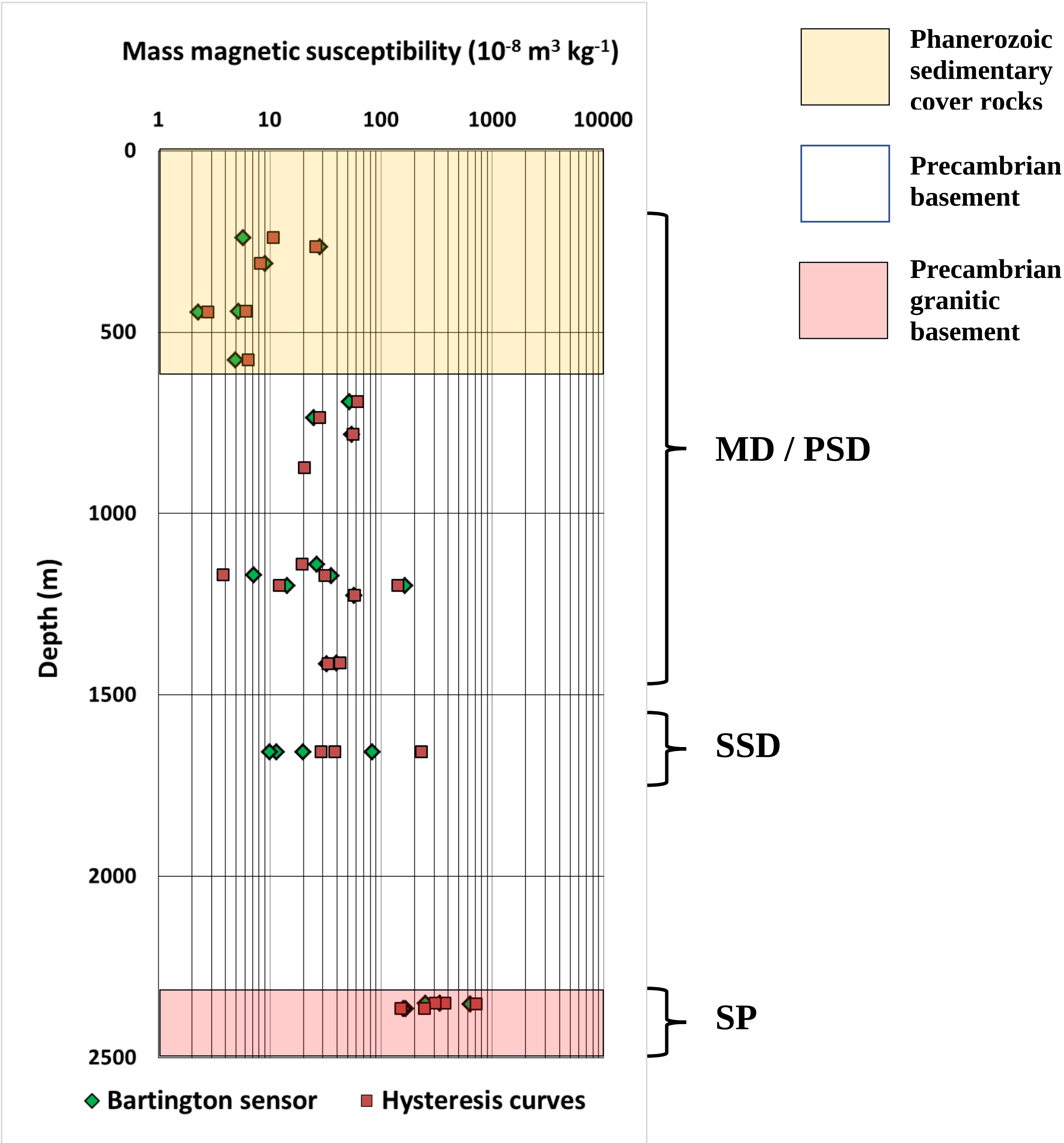


Fig. 7. Values of the magnetic susceptibility per unit mass with depth for the rock powder samples as determined by two independent methods: the Bartington MS2B sensor and the magnetic hysteresis curves from the VFTB. The main lithological intervals are shown, as determined from the magnetic susceptibility results in conjunction with the borehole gamma ray log data. Domain state determinations from the extracted ferrimagnetic hysteresis curves are indicated, and significantly show a clear trend of ferrimagnetic domain state with depth going from multidomain (MD) or pseudo single-domain (PSD, which are effectively small MD grains) to stable single-domain (SSD) to superparamagnetic (SP) with increasing depth. This represents a decrease in the ferrimagnetic grain size with increasing depth, and the distinctive domain states may provide a potential tool for identifying different key lithologies in future studies of similar prospective geothermal regions.