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Magnetic measurements for assessing mineral contents in areas of potential geothermal prospects in Northern Alberta

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Summary

This study focuses on the investigation of mineral composition variations in areas of potential geothermal prospects in Northern Alberta, utilizing powdered rock samples from diverse wells. Low field and high field magnetic susceptibility measurements, together with their temperature dependence, allows mineral components to be quantified which helps aid the distinction of different lithologies. The Curie law was used to estimate the paramagnetic and diamagnetic mineral components from the temperature dependence of the high field magnetic susceptibility. By subtracting the high field magnetic susceptibility from the low field signal extracted ferrimagnetic hysteresis curves were also obtained, which allowed estimates of the content of the ferrimagnetic mineral magnetite. Clear increases in magnetite content with increasing depth were observed, which appear to relate to rock types with increasing radiogenic heat sources with depth.

Introduction

Geothermal energy is crucial for transitioning to sustainable sources [1]. The region around Fort McMurray in Northern Alberta has been considered a potential area for geothermal energy, showcasing a geothermal gradient of 20ºC per km and temperatures exceeding 80°C in the Precambrian crystalline basement rocks beneath the sedimentary cover [2,3]. Despite the thermal gradient limitations for conventional geothermal electricity in Northern Alberta, Engineered Geothermal Systems (EGS) may still allow heating applications, such as crucial hot water for oil sands extraction, addressing environmental concerns usually associated with this process [1,4]. Comprehensive geothermal exploration demands detailed geological information, including variations in rock mineral composition with depth, crucial for accurate drilling cost estimates associated with EGS reservoir stimulation [5].

In this context, magnetic susceptibility measurements offer a rapid tool for deciphering lithological changes and assessing rock homogeneity [6,7,8]. Our research delves into the application of magnetic measurements to refine the mineralogical characterization of rock samples in potential geothermal zones, utilizing advanced magnetic core techniques on powdered samples from Northern Alberta. The primary objective is a precise determination of the mineral content variations with depth by analyzing the change in magnetic susceptibility. Additionally, we seek to illustrate the potential utility of the magnetic domain state of ferrimagnetic grains, such as the iron oxide magnetite, to discern patterns with depth.

Laboratory Measurements

We used powdered rock samples as analogues for our proposed magnetic methods for drill cuttings, which are universally available in wells, while core samples may be limited to specific wells. The samples were obtained from diverse well locations across Northern Alberta, spanning depths from 239 to 2364.2 meters. Exclusive to the Hunt well near 57º N and 111º W were the deepest samples, ranging from 1656.5 to 2364.2 meters. Magnetic measurements were conducted using both a simple low field magnetic susceptibility sensor (Bartington MS2B), and a high sensitivity Variable Field Translation Balance (VFTB). The latter produces magnetic hysteresis loops over a broad applied magnetic field range (-1000 to 1000 mT) at a frequency of 2.4 Hz, and allows the hysteresis measurements to be obtained at different temperatures to simulate temperatures in boreholes. Saturation magnetization, remanent magnetization, coercivity, and magnetic susceptibility were derived from the hysteresis loops and precisely analyzed. Magnetic susceptibility was particularly employed, along with its temperature dependence, to quantify the presence of certain minerals in the rock powders.

Estimation of diamagnetic and paramagnetic mineral components

Low and high field magnetic susceptibility measurements can help to quantify different mineral components of a rock sample [9,10,11]. The major minerals in rocks are typically paramagnetic and diamagnetic. The magnetic susceptibility of these minerals can be obtained from the high-field segment of a magnetic hysteresis curve, since the ferrimagnetic components (such as magnetite) generally saturate at lower applied fields and don't contribute to the high field signal. In the modeling we assume the major rock components consist of a mixture of diamagnetic (exhibiting weak negative magnetic susceptibility, e.g. quartz and feldspar) and paramagnetic minerals (exhibiting weak positive magnetic susceptibility, e.g. biotite, chlorite, and pyroxene) [12].

Minerals possessing exclusively diamagnetic properties are anticipated to display magnetic susceptibility values that remain unaffected by temperature variations, ensuring consistency with depth. Conversely, paramagnetic minerals are expected to exhibit a reduction in magnetic susceptibility with increasing depth (assuming temperature increases with depth), as governed by the Curie law [13]:

$$\chi = \frac{Cm}{T} \tag{1}$$

where, χ denotes mass magnetic susceptibility, C_m represents mineral-specific Curie constants for magnetic susceptibility per unit mass, and T stands for temperature in Kelvin. The Curie law equation can also be written in terms of volume magnetic susceptibility k.

Model magnetic susceptibility curves of certain mineral mixtures allow the prediction of the magnetic susceptibility behaviour with temperature as per **Equation (1)**. An example of the use of the Curie law equation for some samples containing a mixture of quartz, feldspar and biotite is given in **Figure 1**. The theoretical template curves show the percentage of biotite and the remaining content represents the combined percentage of quartz + feldspar, since these latter two minerals have very similar magnetic susceptibility characteristics. The choice of mineral combinations is intentional, drawing upon insights from prior studies conducted on these samples [14]. The results for four of the rock sample powders are also shown, and they follow the trend of the theoretical template curves, allowing the mineral contents to be determined.

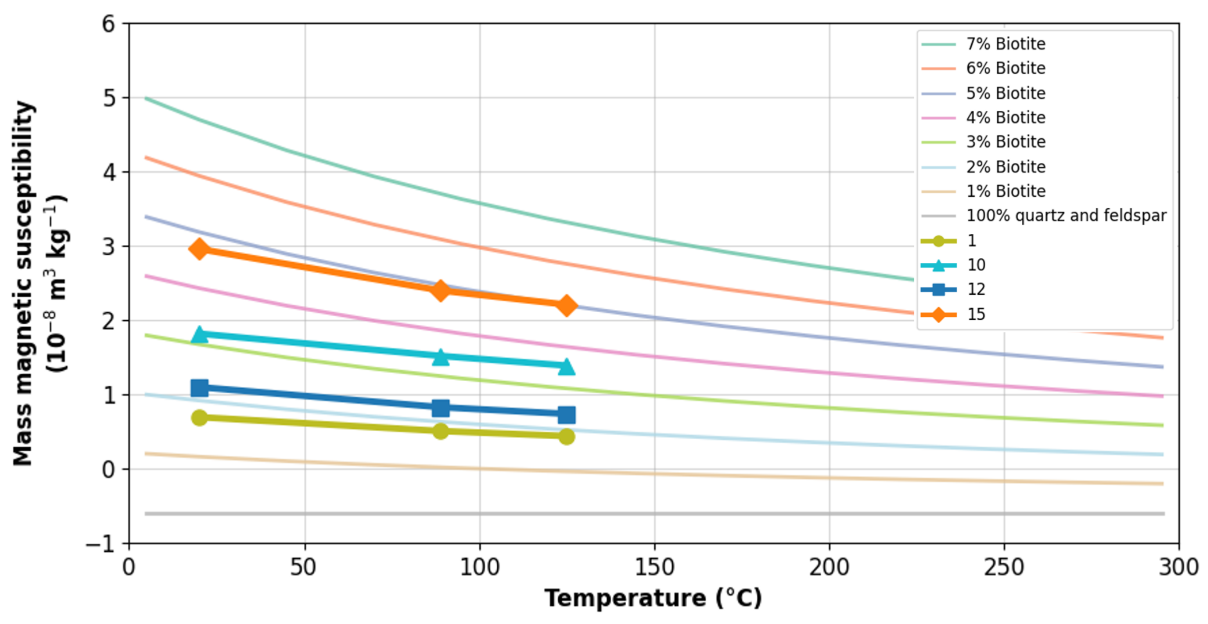

Figure 1. Model and experimental compositional mixture curves using Curie's law for four samples (1, 10, 12, 15). Notably, the experimental data closely aligns with the trends exhibited by the theoretical template curves, indicating the accuracy and reliability of the Curie Law for these mixtures.

Observed gradual reductions in magnetic susceptibility with increasing temperature can assist in the detection of these paramagnetic minerals in situ [3,8,12]. The geothermal gradient in the study area, 20ºC per kilometer, allows one to track the true changes of rock mineral composition with depth (since temperature varies with depth in a borehole). Applied to borehole magnetic susceptibility data, and knowing the local geothermal gradient, these models can provide depth-related mineral content estimates. However, current borehole magnetic susceptibility tools use low fields, and so the use of templates such as **Figure 1** will give better results for diamagnetic and paramagnetic mineral content from borehole data if samples don't have any significant ferrimagnetic mineral components in the rock.

Quantifying magnetite abundance

The most abundant minerals in common rock types are paramagnetic or diamagnetic, whilst the magnetic susceptibility can sometimes be dominated by small amounts of ferrimagnetic minerals [13]. A key mineral in the iron-titanium system is magnetite (Fe_3O_4), recognized as the most abundant ferrimagnetic mineral on Earth and is anticipated to be present in varying amounts in the studied samples. By subtracting the high-field susceptibility from the low-field susceptibility, we generate extracted magnetic hysteresis curves which are solely attributed to the ferrimagnetic mineral content in the samples.

The shape of hysteresis curves is highly dependent on the domain state of magnetite [8]. High magnetite content generally leads to increased magnetic susceptibility, but the specific domain state distribution within the magnetite population significantly influences the overall magnetic behavior. Rocks dominated by small superparamagnetic magnetite can exhibit very high low field magnetic susceptibility, whist slightly larger stable single domain particles have somewhat lower low field magnetic susceptibility (but still much higher than paramagnetic minerals). Rocks with larger multi-domain magnetite may have a range of magnetic susceptibility values (depending upon particle size) that is lower than superparamagnetic particles but may be higher than stable single domain particles. We observed variations of ferrimagnetic domain states with depth for the studied rock powder samples. Combining domain state and magnetic susceptibility information, we quantified magnetite abundance (**Figure 2**).

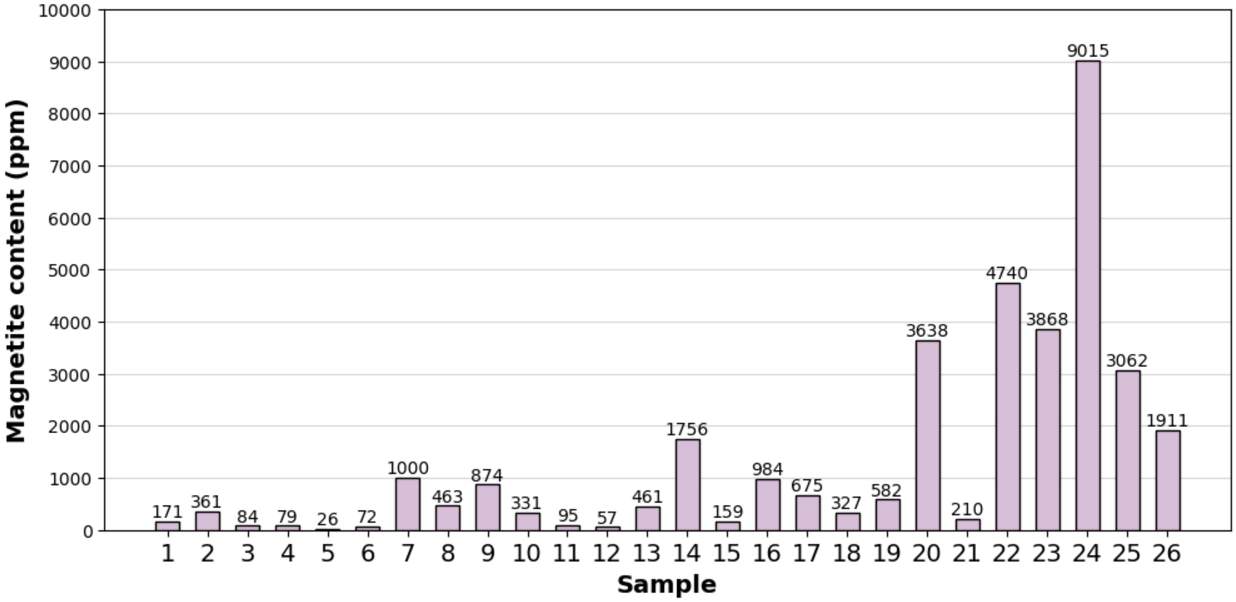

Figure 2. Magnetite content estimation using magnetic susceptibility data and predicted ferrimagnetic domain states of the magnetite particles. The samples are arranged in ascending order of depth, progressing from left to right.

The distribution of magnetite values exhibits a pronounced rightward skew, indicating that the majority of shallower samples do not surpass 1000 parts per million (ppm), with the exception of sample 14. A noteworthy trend is observed in the last eight samples extracted from the Hunt well. In contrast to the shallower samples, these latter specimens display a substantial increase in magnetite content, reaching levels of up to 9015 ppm. The average value for this subset is around 3370 ppm, indicating a significant rise in magnetite. The increase in magnetite content (from sample 7 onwards) suggests crystalline basement rocks, which serve as primary radiogenic heat sources for geothermal purposes. The shallower samples with very low magnetite values are likely to be mainly sedimentary rocks with lower amounts of radiogenic heat sources.

Conclusion

Magnetic susceptibility measurements have the potential to characterize the mineralogy of drill cuttings that are widely available from wells drilled in the potential geothermal areas of Northern Alberta. High field temperature dependent magnetic susceptibility allows quantitative determination of diamagnetic (quartz and feldspar) and paramagnetic (biotite, chlorite, and pyroxene) mineral components unaffected by ferrimagnetic components. Low field temperature dependent magnetic susceptibility can also quantify diamagnetic and paramagnetic components if the ferrimagnetic content is not significant. The latter can be applied to borehole magnetic susceptibility data (which currently is acquired using low applied fields), along with the local geothermal gradient, to provide depth-related mineral content estimates using mineral mixture templates as detailed in this study. Furthermore, low field magnetic susceptibility can estimate the amount of magnetite. The distribution of magnetite values reveals a significant increase in magnetite content with depth. The results likely reflect the increase in radiogenic heat sources within the crystalline basement rocks.

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