INTEGRATION OF LABORATORY TEMPERATURE DEPENDENT MAGNETIC PROPERTIES OF SEDIMENT AND CRYSTALLINE BASEMENT CORE SAMPLES WITH BOREHOLE DATA: APPLICATIONS TO GEOTHERMAL STUDIES IN THE OIL SANDS REGION OF NORTHERN ALBERTA, CANADA

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ABSTRACT
We describe laboratory temperature dependent magnetic (hysteresis and susceptibility) measurements on sediment and underlying crystalline basement core samples from the oil sands region of Northern Alberta, and integrate the results with available borehole log data. This is helping to provide insights into the mineralogy and main radiogenic heat source intervals at depth. These heat sources could potentially be used in the future for the extraction and processing of the oil sands. The laboratory magnetic measurements show how crystalline basement samples (where the main radiogenic heat source intervals are thought to reside) can be rapidly distinguished from sedimentary samples, thus indicating the potential usefulness of borehole magnetic susceptibility measurements for locating the different intervals. Laboratory magnetic hysteresis curves also allow characterization of the ferrimagnetic minerals, some of which may also contribute to the heat sources, and that is not possible with other techniques such as X-ray diffraction (XRD) or with the current borehole magnetic susceptibility data.

INTRODUCTION
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. The heat sources are most likely to reside in the crystalline basement rocks (for example in heavy minerals, K-feldspars etc) beneath the oil sands intervals. Magnetic susceptibility measurements provide a rapid means of distinguishing crystalline (igneous or metamorphic) basement rocks from sedimentary rocks, and thus a means of pin-pointing the depths of the intervals that contain the heat sources. Moreover, laboratory magnetic measurements at low and high applied fields can distinguish the main magnetic classes of the minerals contributing to the magnetic susceptibility signal.

METHODS

Laboratory magnetic measurements were made on small powdered samples taken from whole core at various locations and depths in and around the Fort McMurray region. These included low field magnetic susceptibility using a Bartington MS2B bridge, and magnetic hysteresis (high field magnetic susceptibility can be determined from the slope at high fields) using a variable field translation balance (VFTB) using the methodology described in Ivakhnenko and Potter (2008) and Potter and Ivakhnenko (2008). The magnetic hysteresis measurements were also performed at temperatures equivalent to the in situ temperatures relevant to the depths of the samples. This allowed us to directly compare borehole magnetic susceptibility measurements, where these were available, with the laboratory results. The geothermal gradient is around 20° C per km in this region and we had access to borehole temperature measurements for some of the samples.

RESULTS AND DISCUSSION

Table 1 shows mass magnetic susceptibility results from some available representative samples from the Hunt Well in Northern Alberta. The shallower sample HW3522 is a sedimentary rock and is clearly distinguishable from the deeper crystalline basement samples (HW3525 and HW3528) by its significantly lower low field magnetic susceptibility. The high field magnetic susceptibility of each sample is very similar, suggesting a similar proportion of paramagnetic and diamagnetic minerals (assuming a similar mineral composition). The differences in the low field magnetic susceptibility between the sediment and the crystalline basement samples are mainly due to differences in the amount and grain size of the ferrimagnetic minerals present. Figure 1 shows that the mass magnetization of the deeper crystalline basement samples is higher, suggesting a greater concentration of ferrimagnetic material than in the sediment sample. We also extracted the ferrimagnetic portion of the hysteresis curves by subtracting out the high field slope from the total signal using the methodology of Ali and Potter (2012). Figures 2 and 3 show the total and ferrimagnetic hysteresis curves for the sedimentary sample, and Figures 4 and 5 show the curves for one of the crystalline basement samples (both basement samples gave very similar shaped curves). Interestingly, Figure 3 shows that the remanent magnetization (the intercept on the vertical axis) is about half the saturation magnetization value, which is indicative of uniaxial stable single domain grains (Dunlop and Ozdemir, 1997). In contrast, Figure 5 shows that the hysteresis curve passes through the origin and the low field magnetic susceptibility (the slope of the curve) is very high, which is characteristic of superparamagnetic grains (Dunlop and Ozdemir, 1997). Some of this ferrimagnetic material may be heavy minerals that contribute to the radiogenic heat sources, such as zircon, which has been identified in trace amounts in these samples (Walsh and Chacko, personal communication), and can be ferrimagnetic (Lewis and Senftle, 1966). Curie temperature analysis is planned in order to help determine the ferrimagnetic mineralogy. The hysteresis curves also allow minute amounts (a few ppm) of ferrimagnetic material to be detected (from the saturation magnetization) that is not possible with other techniques such as XRD.

Table 1. Low and high field mass magnetic susceptibility measurements three powdered rock samples from the Hunt Well in Northern Alberta. The low field measurements were taken with a Bartington MS2B bridge. The high field measurements were taken from magnetic hysteresis data using a VFTB, and were determined at both room temperature and the in situ temperatures relevant to the depths of the samples. A combination of electron microprobe data and whole rock geochemistry (Walsh and Chacko, personal communication) gave the following major mineral components: HW3522: 52% quartz, 4% K-feldspar, 32% plagioclase, 6% biotite, 6% garnet; HW3525: 25% quartz, 13% K-feldspar, 53% plagioclase, 6% orthopyroxene; HW3528: 28% quartz, 13% K-feldspar, 50% plagioclase, 6% orthopyroxene.

Sample name	**Sample depth (m)**	**Low field mass magnetic susceptibility at room temperature (10^{-8} m^3 kg^{-1})**	**High field mass magnetic susceptibility (10^{-8} m^3 kg^{-1})**	
			At room temperature	**At in situ temperature**
HW3522	1657	12.6 ± 0.1	4.20 ± 0.01 (at 20 ^{0}C)	3.80 ± 0.01 (at 34.0 ^{0}C)
HW3525	2350.4	311.8 ± 0.1	3.40 ± 0.01 (at 20 ^{0}C)	2. 67 ± 0.01 (at 47.9 ^{0}C)
HW3528	2364.2	207.6 ± 0.1	3.06 ± 0.01 (at 20 ^{0}C)	2.86 ± 0.01 (at 48.1 ^{0}C)

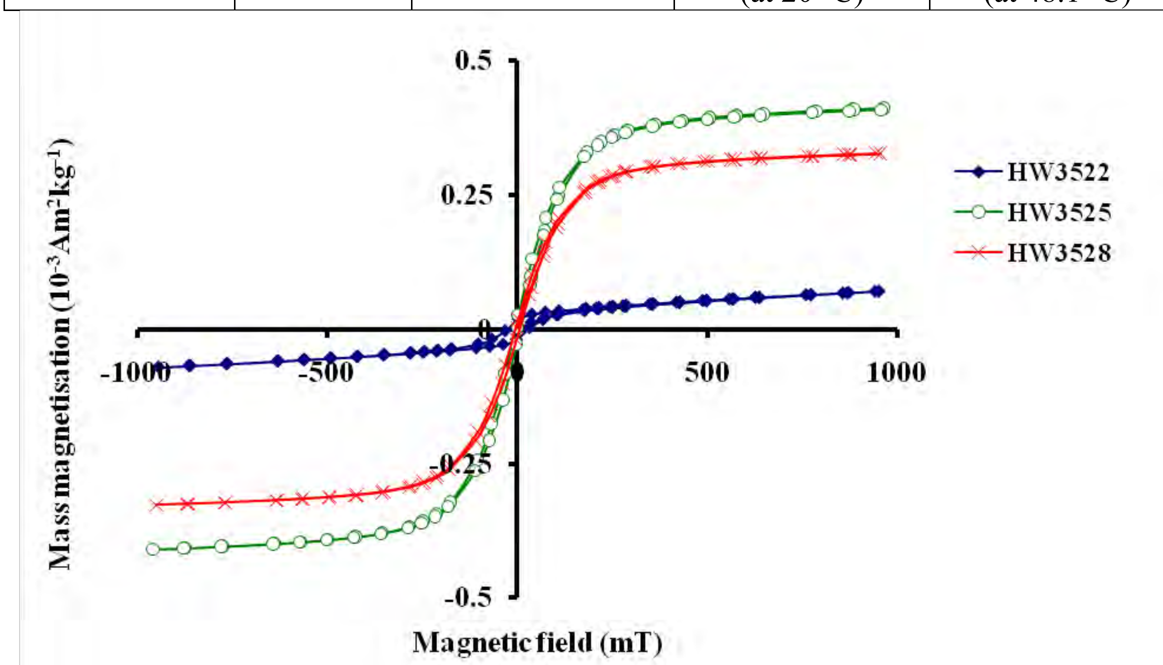

Figure 1. Ambient (room temperature) magnetic hysteresis curves for three powdered rock samples from the Hunt Well in northern Alberta.

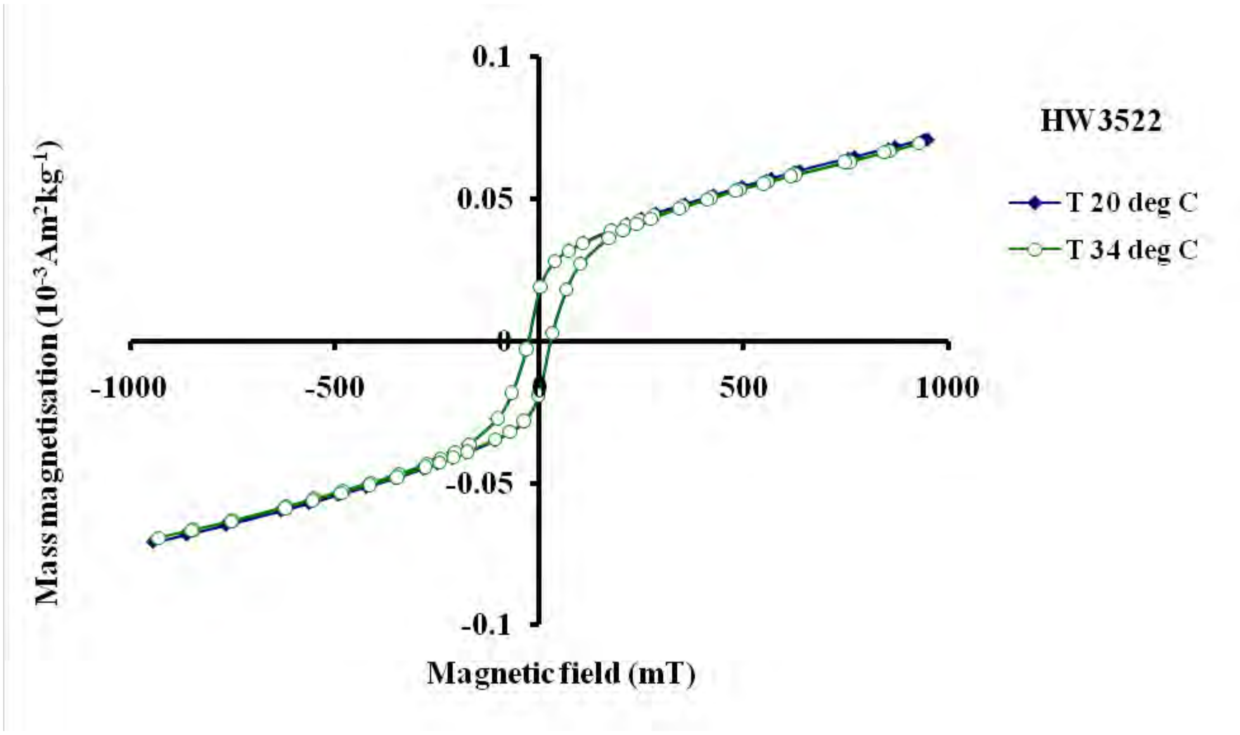

Figure 2. Magnetic hysteresis curves at two different temperatures for sample HW3522 (a sediment).

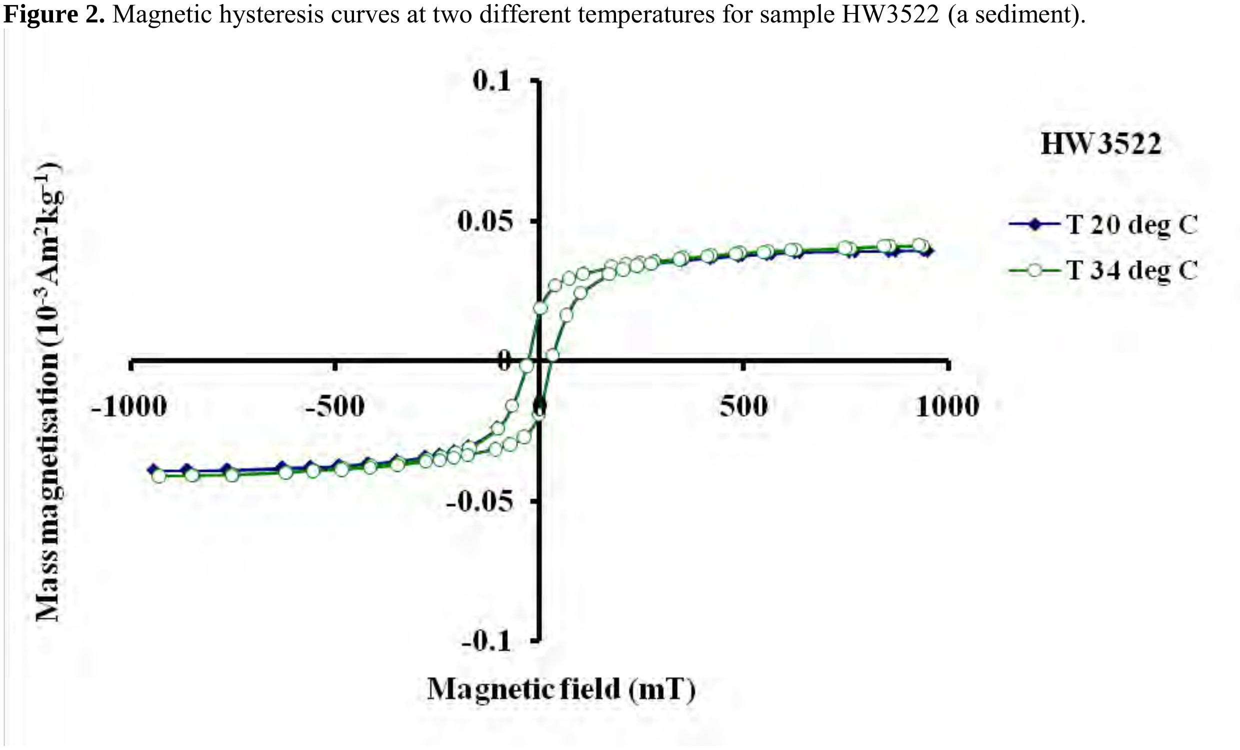

Figure 3. The extracted ferrimagnetic hysteresis curves at various temperatures for sample HW3522.

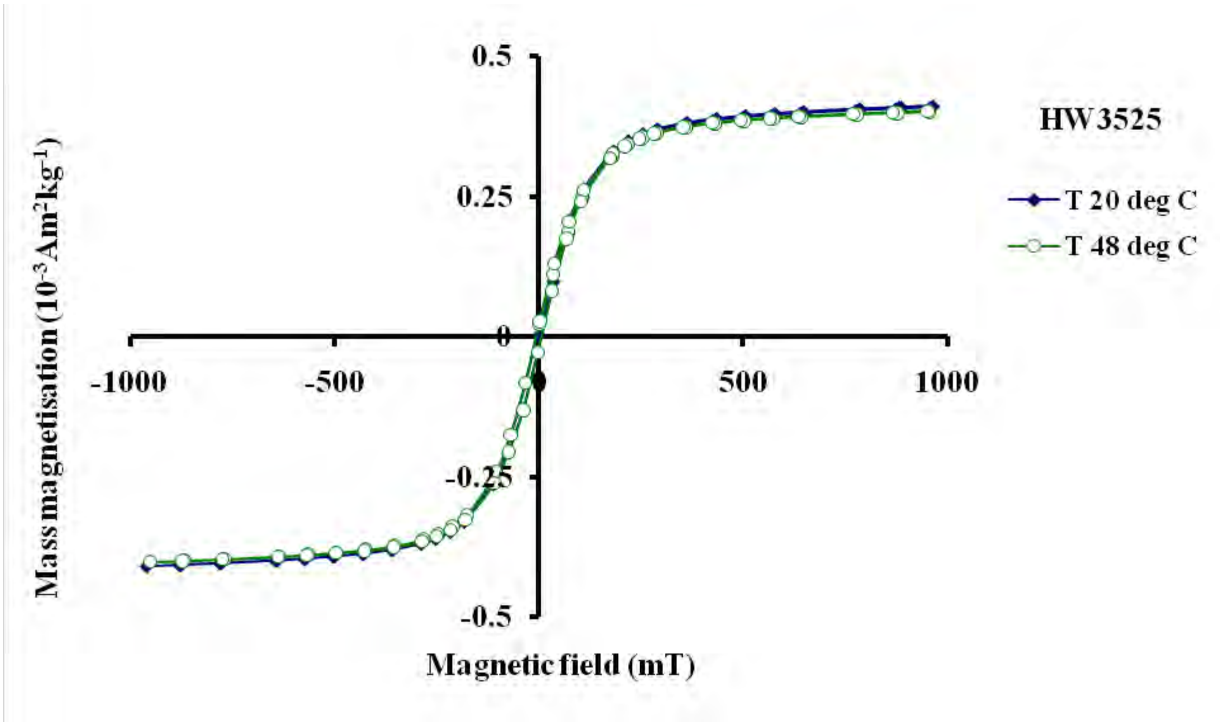

Figure 4. Magnetic hysteresis curves at two different temperatures for sample HW3525 (a crystalline basement sample).

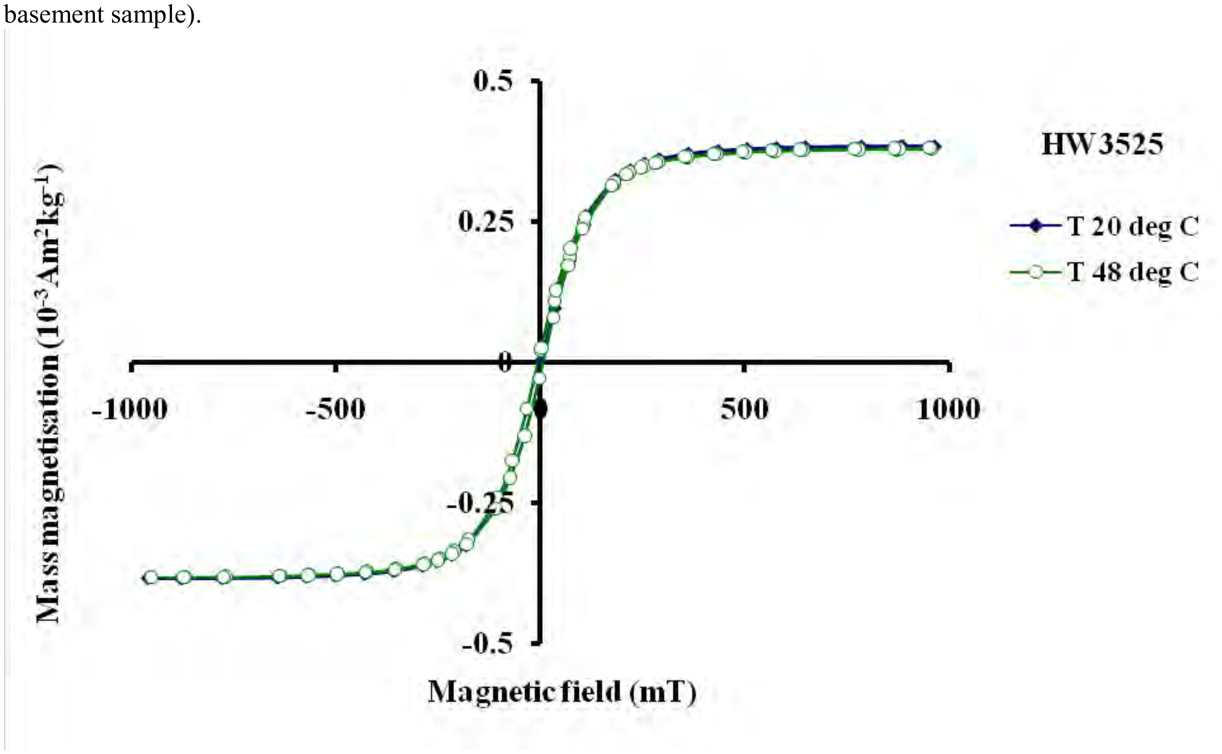

Figure 5. The extracted ferrimagnetic hysteresis curves at various temperatures for sample HW3525.

The magnetic differences between the sediment and the crystalline basement samples are even more pronounced (12.6 $\times 10^{-8}$ m^3 kg^{-1} for sample HW3522 and 311.8 $\times 10^{-8}$ m^3 kg^{-1} for sample HW3525 at low field) than the differences in the gamma ray log (34 and 169 API respectively), showing the potential usefulness of borehole magnetic susceptibility data. A low field borehole volume magnetic susceptibility log at the depth of the sediment sample HW3522 gave a value of 39.92 x 10^{-5} SI compared to a laboratory value of 30.22 x 10^{-5} SI at the relevant temperature of 34 ^{0}C. These values are close considering the different scales of measurement. We do not currently have borehole magnetic susceptibility measurements at the depths of the two crystalline basement samples. Borehole magnetic susceptibility measurements can readily identify extremely small amounts of (some heat producing) ferrimagnetic minerals, potentially better than a temperature log which would only exhibit very small changes. The small decreases in high field magnetic susceptibility with increasing temperature of all samples (Table 1, and derived from Figures 2 and 4) are due to the Curie law temperature dependence of magnetic susceptibility of the paramagnetic mineral fraction (Ali and Potter, 2012), and are significantly greater than the experimental measurement uncertainties.

CONCLUSIONS

Laboratory magnetic characterization at low and high applied fields can rapidly distinguish sedimentary from crystalline basement samples, and thus show the potential of borehole magnetic susceptibility measurements for locating the depth to basement (where the main radiogenic heat sources are likely to reside). The laboratory magnetic techniques can characterize the ferrimagnetic mineral fraction, unlike other methods.

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