Magnetic SCAL Techniques for Rapidly Improving Estimates of Mineral Contents, Elemental Contents and Permeability in Oil Sands Core

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Abstract. We have previously demonstrated correlations between rapid probe magnetic susceptibility measurements on slabbed core with clay mineral content, permeability, and X-ray fluorescence (XRF) derived elemental contents in cores from oil sands. However, low field probe magnetic susceptibility values reflect the total signal from all the mineral components at each measurement point and are unable to distinguish between the permeability controlling paramagnetic clays (such as illite) and small amounts of ferrimagnetic particles (such as magnetite). This means the clay content can be overestimated if the small ferrimagnetic fraction is not accounted for. Whilst the paramagnetic clay versus ferrimagnetic mineral contents can be quantified from low and high field behaviour using a large, laboratory based, expensive variable field translation balance (VFTB), it would be useful to have a cheap, rapid, portable method of quantifying the ferrimagnetic fraction. The present study shows how rapid, cheap measurements of isothermal remanent magnetization (IRM) on core samples using a portable pulse magnetizer can quantify the ferrimagnetic mineral content, allowing one to correct the estimation of the paramagnetic illite clay content, and potentially then the permeability. Also, our previous probe magnetic susceptibility results on intact slabbed cores gave values per unit volume, which meant the results could potentially change slightly if the porosity varies even in the same rock type. Therefore, in the present study, we examined a selection of individual extracted core samples taken from the slabbed cores of 3 oil sands wells (from similar depths to the initial probe measurements), and converted the magnetic susceptibility per unit volume results to per unit mass (which theoretically is less dependent upon porosity) by dividing by the density. The results gave even better correlation coefficients (which were already quite high in the previous work) in most cases with XRF derived elemental contents, paramagnetic clay contents, and permeability compared to our earlier work. The results also demonstrated that the relatively small effect of variable porosity did not affect the overall conclusions of our previous work or the usefulness of the initial probe method. Furthermore, the temperature dependence of magnetic susceptibility of individual extracted samples was also measured to provide a further technique to quantify and verify the paramagnetic clay content (paramagnetic susceptibility decreases with increasing temperature). Importantly, this also allows accurate *in situ* predictions of paramagnetic mineral content (such as illite), and subsequently permeability, from borehole magnetic susceptibility data. The techniques described here can also be applied to other reservoir cores.

1 Introduction

Magnetic characterization of oil sands cores has received almost no attention, but has the potential to provide rapid, less destructive petrophysical appraisals. We previously demonstrated that low field, high resolution probe magnetic susceptibility on the intact slabbed cores of one oil sands well (Well 03) correlated with elemental contents derived from X-ray fluorescence (XRF) measurements [1], and illite contents derived from the magnetic results correlated with permeability. The current paper presents new special core analysis (SCAL) results on small representative core samples collected from the slabbed cores of three oil sands wells (Well 01, Well 02, as well as Well 03 from our earlier study) from northern Alberta, Canada. The samples were representative of the 3 main lithologies present: (i) clean sand (where most of the bitumen and heavy oil resides), (ii) inclined heterolithic stratification (IHS) beds (which comprise alternating thin sand rich and clay rich layers), and (iii) shale. The new laboratory SCAL measurements include low field magnetic susceptibility per unit volume and per unit mass, high field magnetic susceptibility per unit mass, isothermal remanent magnetization (IRM), temperature dependent magnetic susceptibility, and XRF measurements. The main objectives were as follows:

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1. IRM measurements can readily identify the presence of remanence carrying particles (such as ferrimagnetic magnetite, or canted anti-ferromagnetic hematite) in the core samples. We will show how rapid IRM measurements using a pulse magnetizer can: (i) identify the type of remanence carrying particles and their content, and (ii) use the results to provide an improved estimate of the content of illite clay in the samples.

2. The new measurements on the small extracted core samples were used to evaluate the possible effects of variable porosity and fluid type/content in the pore space on the probe magnetic susceptibility per unit volume results obtained on the intact slabbed core in our earlier study [1]. Each former probe reading examined a similar sized volume, and if the porosity or fluid type changed then the magnetic susceptibility per unit volume could theoretically vary slightly, even if the mineralogy stayed the same. Although variations in porosity and fluid content may be expected to have little effect on the magnetic susceptibility per unit volume of sediments, since most fluids are diamagnetic [2], to minimize these effects it is useful to convert the magnetic susceptibility per unit volume to values per unit mass. This is because as magnetic susceptibility per unit volume changes then the mass also tends to change accordingly, so that magnetic susceptibility per unit mass should not change significantly with changes in porosity (unless porosity is exceptionally large). The present study on small core samples allowed us to obtain mass values to do the conversions to magnetic susceptibility per unit mass.

3. The further comparisons of the magnetic results with XRF measurements on the small extracted core samples also enabled key elemental contents to be obtained on the same samples used for all the other SCAL measurements, and help to constrain the mineralogical compositions.

4. Temperature dependent magnetic susceptibility measurements were performed to positively identify the presence of paramagnetic minerals (e.g., illite) and to quantify their content. Paramagnetic minerals exhibit temperature dependent magnetic susceptibility in accordance with the Curie equation (see **section 2.3**), whereas diamagnetic minerals (e.g., quartz, calcite) do not. This is important for borehole applications of magnetic susceptibility. Temperature varies with depth in boreholes, and so modelling the temperature dependent magnetic susceptibility behaviour of paramagnetic minerals is necessary to accurately estimate paramagnetic mineral contents from *in situ* borehole magnetic susceptibility data.

2 Methods and Samples

2.1 Low field magnetic susceptibility per unit volume and per unit mass, and X-ray fluorescence measurements on core samples

A total of 24 core samples were collected from the slabbed cores of the three oil sands wells in this study for the magnetic and XRF analyses (**Table 1**). No core cleaning with solvents was required or done. Any residual fluids are likely to be diamagnetic [2], very low and negative magnetic susceptibility, and so are unlikely to have any significant effect on the magnetic results. Each sample was ground into powdered form, and placed into a cylindrical plastic holder about 1 inch in diameter and 1 inch in height for the magnetic susceptibility and XRF elemental contents measurements. The grinding helps to improve the XRF results by effectively increasing the mineral content to porosity ratio of each sample (finer particles produce less pore space). The collected samples were representative of the 3 main lithologies in the wells: clean sand, IHS beds, and shale. The magnetic susceptibility per unit volume was measured by using a probe MS2E sensor connected to an MS2 meter, identical to the probe measurements conducted on the intact slabbed core in our earlier study [1]**.** The mass magnetic susceptibility was measured using a Bartington MS2W sensor connected to an MS2 susceptibility meter. Both the MS2E and MS2W sensors involve taking a background reading in air followed by a sample reading (each reading takes just 12 seconds on the sensitive setting). The elemental contents of the samples were measured using the same Niton XL3t XRF analyzer as for our earlier study [1], but for this new study it was connected to a portable stand specifically for laboratory measurements on small samples (**Figure 1 (A)**). The stand was attached to a shielded box in which the sample was placed on top of a window during the measurement (**Figure 1 (B)**). The shielded box is made of lead, which can stop scattered X-rays, thus avoiding any radiation exposure to the operator.

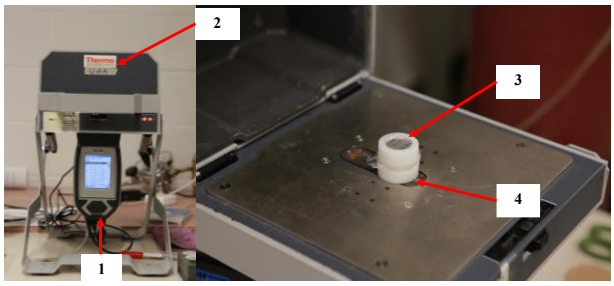

Fig. 1. (A) shows the system for laboratory elemental contents measurements that includes (1) a Niton XL3t XRF analyzer connected to (2) a portable stand with a shielded box. (B) shows the interior of the shielded box with (3) an example of a sample placed on top of (4) the measurement window.

2.2 Isothermal remanent magnetization (IRM) measurements

Representative samples were collected from the slabbed cores for IRM measurements. The samples again covered representatives of the 3 main lithologies: clean sand, IHS beds, and shale. Each sample was placed in a cylindrical plastic cup 1 inch in diameter and about 1 inch in height. The material comprising the cup did not affect the IRM results. Each sample was subjected to a series of direct field (DF) applications up to 130 mT generated by a Molspin pulse magnetizer (**Figure 2**).

Each DF application consisted of a pulse lasting about 100 ms along the z (vertical) axis. The acquired IRM magnitude after each DF application was then measured on a Molspin magnetometer. Since the samples were ground into powders the grains were essentially isotropically distributed, and so the IRM measurements could have been performed along any of the x, y or z axes and would be expected to give similar results.

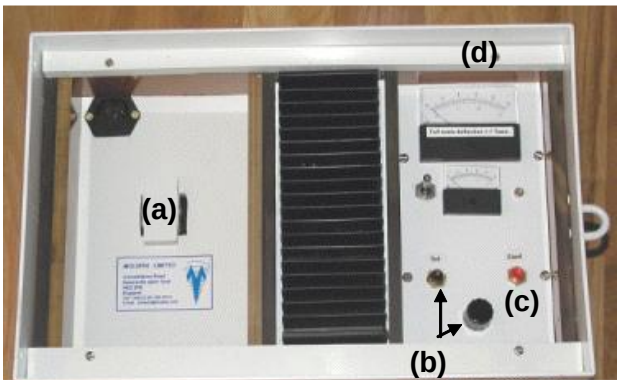

Fig. 2. Top view of the Molspin pulse magnetizer. **(a)** Sample holder. (b) Pulse applied direct field (DF) setting controls. (c) Pulse trigger. (d) Pulse DF indicator.

2.3 Temperature dependent magnetic susceptibility measurements

Paramagnetic minerals such as illite exhibit temperature dependent magnetic susceptibility according to the Curie equation below:

$$M/H = C/T \qquad (1)$$

where M is the mass magnetization, H is the applied field, M/H is the magnetic susceptibility per unit mass, C is a mineral-specific Curie constant, and T is the absolute temperature in Kelvin. Note that a similar equation can be written in terms of the magnetization per unit volume, J, which would replace M, and J/H would be the magnetic susceptibility per unit volume.

Measuring the variation of magnetic susceptibility with temperature potentially allows for more accurate determinations of the paramagnetic versus diamagnetic mineral contents in a sample, compared to a single room temperature magnetic susceptibility measurement. For example, a single room temperature negative magnetic susceptibility measurement could either mean one or more diamagnetic components, or one or more diamagnetic components plus a small quantity of one or more paramagnetic components. However, any changes of magnetic susceptibility with temperature consistent with **Equation (1)** would identify the presence of any paramagnetic minerals.

Measurements of temperature dependent magnetic susceptibility per unit mass were undertaken using a Bartington system (**Figure 3**) that included an MS2 susceptibility meter, a MS2WF furnace, and an MS2W sensor, which was cooled by a water jacket to avoid damage to the sensor from the furnace coils surrounding the sample. The sensor has a 30 mm internal diameter sample cavity. Each sample was put into a 24 mm (1 inch) diameter and 1-inch-long ceramic holder, which was then placed into the sample cavity. The furnace coils were comprised of non-inductively wound platinum wire, and the furnace was specially designed for use with the water jacketed MS2W sensor to facilitate temperature dependent magnetic susceptibility measurements up to 850 °C. A MS2WFP power supply unit was connected to the MS2WF furnace via an 8-way cable for the transmission of data and power. The unit supplies power to the furnace and provides either direct control of the temperature, or a slowly varying linear increase or decrease of temperature. During operation of the furnace, the flow of water needed to be steady to avoid any thermal damage to the sensor. A submersible water pump was used to circulate the water around the sensor during the measurements, and a flowmeter was connected to the water pipe to ensure the water was flowing at the required rate.

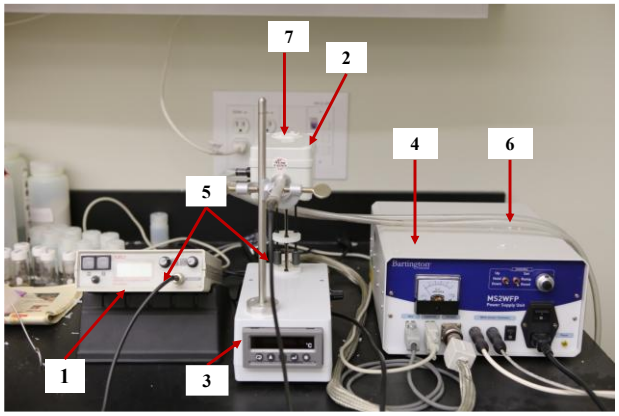

Fig. 3. Bartington MS2W temperature dependent magnetic susceptibility measurement system. **1** is the MS2 magnetic susceptibility meter, **2** is the MS2W sensor (water cooled and surrounds the furnace coils), **3** is the MS2WF furnace and heating coils that surround the sample, **4** is the MS2WFP power supply unit for the furnace, **5** is the cable connecting the meter and sensor, **6** is a water pipe circulating water between the supply tank and the sensor, and **7** is the sample cavity.

3 Results and Discussion

3.1 Results of low field magnetic susceptibility per unit volume and per unit mass, and X-ray fluorescence measurements on core samples

Table 1 shows the results of the magnetic susceptibility values per unit volume and per unit mass, as well as the XRF derived elemental contents for Fe, K and Al measured on the 24 selected powdered samples. Also shown in brackets are the probe magnetic susceptibility per unit volume and XRF values from our previous work [1] on the intact slabbed cores at the same respective depths. The clean sand samples generally give negative magnetic susceptibiity values (due to predominantly diamagnetic quartz), whereas the IHS and shale samples give positive values (due to increased amounts of paramagnetic illite clay plus ferrimagnetic magnetite, as detailed later). The probe magnetic susceptibilities per

unit volume from the new measurements on the extracted samples are generally comparable to those from the original probe magnetic susceptibilities per unit volume on the original intact slabbed cores in our earlier study [1] at the same depths (**Table 1**, column 3 shows both the new and previous results). The XRF derived contents of the elements Fe, K and Al from the extracted samples are also generally comparable to the original XRF values determined previously on the intact slabbed cores (**Table 1**, columns 5-7). Since the extracted samples were ground into powders to improve the XRF results, by effectively increasing the mineral content to porosity ratio of each sample, one might expect the elemental contents to be slightly higher in the extracted samples, which is the case for several samples.

Figure 4 shows example crossplots of magnetic susceptibility against key elemental contents of iron (Fe, **Figures 4 (a)**, **(b)**, **(c)**), potassium (K, **Figures 4 (d)**, **(e)**, **(f)**) and aluminium (Al, **Figures 4 (g)**, **(h)**, **(i)**) from XRF measurements for Well 03 (the well that was the subject of our previous published study [1]). **Figures 4 (a), (d), (g)** give the probe magnetic susceptibility per unit volume results for the extracted core samples against the elemental contents, **Figures 4 (b), (e), (h)** give the magnetic susceptibility per unit mass results for the extracted core samples against the elemental contents, and **Figures 4 (c), (f), (i)** give our previous [1] probe magnetic susceptibility per unit volume results from the original intact slabbed core samples against the elemental contents (at the same depths as for the extracted core samples). The correlation coefficients (R^2 values) for each element are quite high in all cases, and not strongly dependent upon whether the magnetic susceptibility is per unit volume or per unit mass, nor on whether the measurements were made on the extracted core samples or the original intact slabbed cores. The R^2 values are generally marginally higher for the extracted core samples (which might be expected since these powdered samples will have a lower porosity). Nevertheless, the results demonstrate that any effect due to variable porosity and/or fluid type or content in the original intact slabbed cores is minimal. The rapid probe magnetic susceptibility per unit volume measurements (24 seconds for a background and sample measurement) undertaken in our earlier study [1] appear to be adequate for quick, non-destructive appraisals. For the new study that generated magnetic susceptibility per unit mass measurements, additional time was required to extract the core samples and measure their masses.

3.2 Results of isothermal remanent magnetization (IRM) measurements, quantification of magnetite, and application for correcting illite clay content

Figure 5 shows the IRM acquisition curves for selected samples from each of Wells 01, 02 and 03 plotted on a normalized scale, and indicates that all the curves are quite similar. This suggests that the mineralogy and particle size is fairly similar for these core samples, with only minor differences. Most curves are starting to saturate at the maximum applied field of 130 mT. This provides some insights into the type of remanence carrying particle. It cannot be hematite, since hematite needs much higher fields before saturating. The curves are, however, similar to the types of curves acquired by magnetite [3]. Two particle size curves for similar magnetite from [3], which we recently experimentally extended to higher fields up to 130 mT, are also plotted on **Figure 5** for comparison. The normalized curves for core samples W01.11, W02.03, W02.04 and W03.04 show a close correspondence to the 4.4–7.6 μm magnetite sample, whereas core samples W01.01, W02.01, W02.06 and W02.07 are closer to the 7.6-13.1 μm magnetite sample. These sizes of magnetite are regarded as small multidomain. Using this information, and assuming the IRM results for the core samples are due to magnetite, one can estimate the mass of magnetite in the core samples. The two particle size fractions of magnetite each had 10 mg of magnetite, and the mass of magnetite in the core samples could be estimated from the following equation:

$$\textit{Mass of magnetite in mg} = [(\textit{IRM of core sample}) / (\textit{IRM of 10 mg magnetite})] \times \textit{10} \quad (2)$$

where the *IRM of the core samples* was taken from the IRM per unit volume values at 130 mT (**Table 2**), and the *IRM per unit volume of the 10 mg magnetite* samples was 6,802 mA m^{-1} for the 4.4-7.6 μm magnetite and 3,857 mA m^{-1} at 130 mT for the 7.6–13.1 μm magnetite. The IRM per unit volume values (i.e., volume magnetization) were used since these compared similarly derived raw IRM values for the core samples and magnetite particle size fractions. The most relevant magnetite particle size fraction for each core sample, as indicated above, was used in **Equation (2)**. The multiplier of *10* in **Equation (2)** relates to the 10 mg mass of the magnetite particle size samples.

Table 2 shows the IRM values at 130 mT given both in terms of IRM per unit mass and IRM per unit volume for the core samples, together with the calculated masses of magnetite using **Equation (2)**, and the percentage magnetite mass in the sample. The results show that the masses of magnetite are extremely small, particularly as a percentage of the total mass of the samples (the sample masses ranged from 12.60–16.38 g). Nevertheless, the high magnetic susceptibility of magnetite means that the contribution of this magnetite to the total magnetic susceptibility of the sample may still be significant.

The magnetic susceptibility per unit mass, χ_m, of each magnetite amount given in **Table 2** for the core samples can be determined from the following equation:

$$\chi_m = [(\textit{mass of magnetite in mg}/\textit{10}) \times k_{sm} \times \textit{4}\pi \textit{ x } \textit{10}^{-9} \textit{ x } \textit{12.8}] / \textit{mass of core sample in g} \quad (3)$$

where k_{sm} is the magnetic susceptibility per unit volume of the most relevant magnetite particle size fraction for each core sample (4.4–7.6 μm or 7.6-13.1 μm), and $4\pi \times 10^{-9} \times 12.8$ is a conversion factor from magnetic susceptibility per unit volume to magnetic susceptibility per unit mass (and also accounts for the 1 inch cylindrical sample volume to SI units), and the number *10* relates to the 10 mg mass of the magnetite samples. **Table 3** shows the magnetic susceptibility per unit mass values of magnetite for the samples calculated via **Equation (3)**.

In our previous study [1] the illite content was determined from a simple model that merely assumed a mixture of quartz + illite. This simple model assumed illite was the only positive component of the magnetic susceptibility, and will overestimate the illite content if there are other positive magnetic susceptibility minerals (such as magnetite) in the sample. The range of magnetic susceptibility values for some paramagnetic clays can overlap, so distinguishing between some paramagnetic clays is one of the limitations. However, we can differentiate between clays of different magnetic classes, for example between paramagnetic clays such as illite and diamagnetic clays such as kaolinite.

Knowing the contribution of the magnetite to the total magnetic susceptibility signal as shown in **Table 3** one can calculate more accurate estimates of the illite contents. **Table 3** shows the initial estimated illite contents for the samples from the simple quartz + illite model, as well as the corresponding improved illite estimates considering the magnetic susceptibility of the magnetite. The fraction of illite, F_I, from the initial simple quartz + illite model is given by the following equation from [4]:

$$F_I = (\chi_T - \chi_Q) / (\chi_I - \chi_Q) \qquad (4)$$

where χ_T is the total magnetic susceptibility per unit mass of the sample, and χ_I and χ_Q are the magnetic susceptibilities per unit mass of illite (15 x 10^{-8} m^3kg^{-1} from [5]) and quartz (-0.62 x 10^{-8} m^3kg^{-1} from [6]), respectively. The improved estimation of the fraction of illite, ${}^*F_I$, that takes into account the magnetic susceptibility per unit mass of the magnetite (and assumes a mixture of quartz + illite + magnetite) is given by the following equation:

$${}^*F_I = [(\chi_T - \chi_m) - \chi_Q] / (\chi_I - \chi_Q) \qquad (5)$$

where χ_m is the magnetic susceptibility per unit mass of the magnetite in the sample as given in **Table 3**. The results in **Table 3** show that the corrected illite contents are lower than those from the simple quartz + illite model, and improve the interpretations of the lithologies. For example, 0% illite is now indicated in all the clean sand samples W01.01, W02.01 and W02.03 as would be expected. Our previous study [1] showed a good correlation between the magnetically derived illite contents from **Equation (4)** and permeability in Well 03. Recent work comparing corrected illite contents using **Equation (5)** on the same samples exhibit even better correlations with permeability (results in preparation to be published elsewhere).

We also undertook an independent method to support the presence of magnetite by comparing the low field and high field magnetic susceptibility signals. All minerals will contribute to the low field magnetic susceptibility signal, but magnetite saturates in high fields (generally by about 300 mT), and so will generally not contribute to the high field magnetic susceptibility. Thus, the difference between the low field and high field magnetic susceptibility values will represent the magnetic susceptibility signal of the magnetite. **Table 4** shows values of low field (0.1 mT from a Bartington MS2W sensor) and high field (450 mT from a Sherwood AUTO balance) magnetic susceptibility per unit mass for sample W02.04. The difference in the two values (0.43 x 10^{-8} m^3 kg^{-1}) is close to the expected value for magnetite for this sample (0.50 10^{-8} m^3 kg^{-1}) given in **Table 3** that was determined via the IRM technique.

3.3 Results of temperature dependent magnetic susceptibility measurements

The temperature dependences of magnetic susceptibility per unit mass for two IHS samples (W01.12 and W03.03) and three shale samples (W01.15, W02.05 and W03.06) are shown in **Figure 6**. The susceptibilities of all these samples decrease with increasing temperature, indicating that they contain one or more paramagnetic minerals.

For samples W01.12, W02.05 and W03.03 the curves largely follow the trend of theoretical template curves for a quartz + illite mixture developed by Ali and Potter [7, 8], especially for W01.12, strongly suggesting that illite is the main paramagnetic mineral in these samples. In contrast, the curves of samples W01.15 and W03.06 are slightly steeper than the trends of the illite + quartz curves. These samples could contain small amounts of another paramagnetic mineral (with or without illite). To account for the slightly steeper trends this other paramagnetic mineral would need to have a larger variation of magnetic susceptibility with temperature than illite. One possibility is the iron carbonate siderite.

The magnetic susceptibilities per unit mass of samples W01.01, W02.01 and W03.01 do not show any variation with increasing temperature up to 190 °C (**Figure 7**). These samples are clean sands saturated with heavy oil (for samples W01.01 and W02.01) or with bitumen (for sample W03.01). This means there are no paramagnetic minerals in these samples, otherwise there would have been decreases in magnetic susceptibility with increasing temperature. The results are consistent with the values of 0% illite for all the clean sand samples corrected for the magnetite content given in **Table 3** (note that samples W01.01 and W02.01 in **Figure 7** are the same samples as in **Table 3**).

4 Conclusions

The main objectives of this study were to (i) quantify the content of ferrimagnetic magnetite in core samples from 3 oil sands wells from IRM measurements, (ii) use the results to improve estimates of illite content, and (iii) test if variable porosity or fluid type/content affected our previous work [1]. The conclusions are as follows:

1. The IRM measurements allowed small amounts of magnetite to be detected and quantified. The IRM acquisition curves suggested that these particles were magnetite of particular size ranges. The effect of magnetite on the low field magnetic susceptibility signal enabled corrected estimates of illite content to be made, which in turn can potentially lead to improved estimates of permeability. For practical use in industry our original probe magnetic susceptibility measurements on the intact slabbed core [1], without correcting for magnetite, still gave good, rapid estimates of the illite content.

2. Independent support for magnetite being the remanence carrying mineral in the samples came from comparing low and high field magnetic susceptibilities, where the difference in magnitude of the two susceptibilities for one sample tested was consistent with the magnitude of the mass magnetic susceptibility of magnetite as determined by the IRM method.

3. Crossplots of the magnetic susceptibilities per unit volume or per unit mass versus the elemental contents of Fe, K and Al from XRF on the small extracted samples showed high correlation coefficients (R^2 values), and were generally slightly higher than the R^2 values for the respective plots from our previous probe magnetic susceptibility per unit volume results [1] on the original intact slabbed cores. However, since the R^2 values for the magnetic susceptibility per unit mass plots on the extracted samples were not substantially different from our previous [1] probe magnetic susceptibility per unit volume results on the original intact slabbed cores, this suggested that variations in porosity or fluid type/content in the pore space of the slabbed cores had minimal effects on the previous results.

4. The strong correlations between the magnetic and XRF elemental results on the extracted core samples further supported illite as the major paramagnetic clay in these samples, since the elements Fe, K and Al are key components of illite.

5. Temperature dependent magnetic susceptibility measurements on the extracted core samples enabled us to identify and quantify any paramagnetic mineral(s) present, such as illite, whose magnetic susceptibility decreases with increasing temperature according to the Curie equation. In contrast, the magnetic susceptibility of diamagnetic minerals, such as quartz comprising the clean sand samples, is temperature independent. Comparisons between the temperature dependent magnetic susceptibility measurements and theoretical template curves for mixtures of quartz + illite provided an independent method to estimate the illite content in the IHS and shale samples, and also to identify samples potentially containing other paramagnetic minerals.

6. The temperature axis of the theoretical template curves of magnetic susceptibility for mineral mixtures (quartz + illite in the studied case) can be converted to depth using an appropriate geothermal gradient in the Albertan oil sands. This would allow one to provide rapid interpretations of mineralogy from *in situ* borehole magnetic susceptibility per unit volume measurements.

D. K. P. thanks the Natural Sciences and Engineering Research Council of Canada (NSERC) for a Discovery Grant. Ryan Armstrong and Hassan Mahani are thanked for their thorough reviews which helped to improve the manuscript.

5 List of Abbreviations

DF	Direct Field
IHS	Inclined Heterolithic Stratification
IRM	Isotherml Remanent Magnetization
XRF	X-Ray Fluorescence

6 References

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Table 1. Results of magnetic susceptibility per unit volume and per unit mass and key XRF derived elemental contents (Fe, K and Al) measured on powdered core samples that were collected from the slabbed cores of the three oil sands wells. The values in brackets in the magnetic susceptibility per unit volume and XRF elements contents columns are our previous probe results [1] measured on the original intact slabbed cores at the same depths. The lithologies of the samples are given in the footnote.

Well	Samples	Volume Susceptibility (10^{-5} SI)	Mass Susceptibility (10^{-8} m^3kg^{-1})	Fe (%)	K (%)	Al (%)
Well 01	*W01.01	-1.6 (-1.6)	-0.53	0.056 (0.064)	0.162 (0.260)	0.275 (0.571)
	*W01.03	-1.2 (-1.3)	-0.84	0.069 (0.167)	0.273 (0.324)	0.432 (0.819)
	*W01.04	-0.4 (-1.0)	-0.67	0.046 (0.187)	0.230 (0.317)	0.388 (0.882)
	*W01.05	-0.1 (-0.9)	-0.96	0.042 (0.087)	0.098 (0.293)	0.241 (0.942)
	*W01.06	-0.2 (-0.6)	-0.58	0.094 (0.555)	0.193 (0.564)	0.417 (0.144)
	*W01.07	0.7 (0.6)	-0.62	0.153 (0.413)	0.381 (0.531)	0.772 (1.702)
	*W01.08	0.5 (2.8)	0.61	0.444 (0.432)	0.556 (0.640)	0.819 (1.806)
	+W01.09	1.9 (3.5)	1.03	0.781 (0.678)	0.713 (0.423)	2.148 (1.691)
	+W01.10	3.3 (3.6)	2.22	0.623 (0.325)	0.724 (0.589)	2.927 (1.129)
	+W01.11	4.6 (5.9)	3.00	1.905 (1.662)	0.863 (0.633)	3.135 (1.892)
	+W01.12	4.9 (7.8)	2.96	1.196 (1.365)	1.592 (1.156)	6.656 (3.698)
Well 02	*W02.01	-0.3 (-1.4)	-0.92	0.036 (0.043)	0.267 (0.518)	0.347 (0.596)
	+W02.02	2.6 (2.3)	1.16	1.218 (0.569)	0.215 (0.152)	1.142 (1.443)
	+W02.03	2.9 (2.9)	1.22	0.264 (0.284)	0.416 (0.456)	0.775 (1.020)
	+W02.04	9.1 (10.5)	5.79	2.31 (2.461)	1.608 (1.144)	4.065 (6.042)
	#W02.05	15.0 (20.4)	8.61	4.265 (3.279)	1.338 (1.653)	5.896 (5.437)
	#W02.06	20.9 (25.5)	11.89	3.257 (5.943)	1.450 (1.097)	3.914 (6.337)
	#W02.07	25.1 (28.2)	14.56	6.193 (6.598)	3.121 (1.715)	4.779 (4.138)
Well 03	*W03.01	0.0 (-0.5)	-0.28	0.384 (0.379)	0.136 (0.494)	1.083 (1.083)
	*W03.02	-0.1 (-0.1)	-0.81	0.246 (0.333)	0.280 (0.672)	0.786 (1.268)
	+W03.03	2.8 (4.7)	1.79	0.838 (1.067)	1.089 (1.191)	3.292 (3.317)
	#W03.04	8.3 (12.4)	4.53	2.310 (3.251)	1.608 (1.398)	5.533 (6.624)
	#W03.05	10.2 (16.3)	7.61	3.474 (3.520)	1.836 (1.787)	5.967 (6.72)
	#W03.06	10.5 (18.4)	7.97	3.684 (2.982)	1.888 (1.515)	5.932 (6.711)

* Clean sand.
+ Inclined heterolithic stratification (IHS) comprising alternating clay rich and sand rich layers.
# Shale.

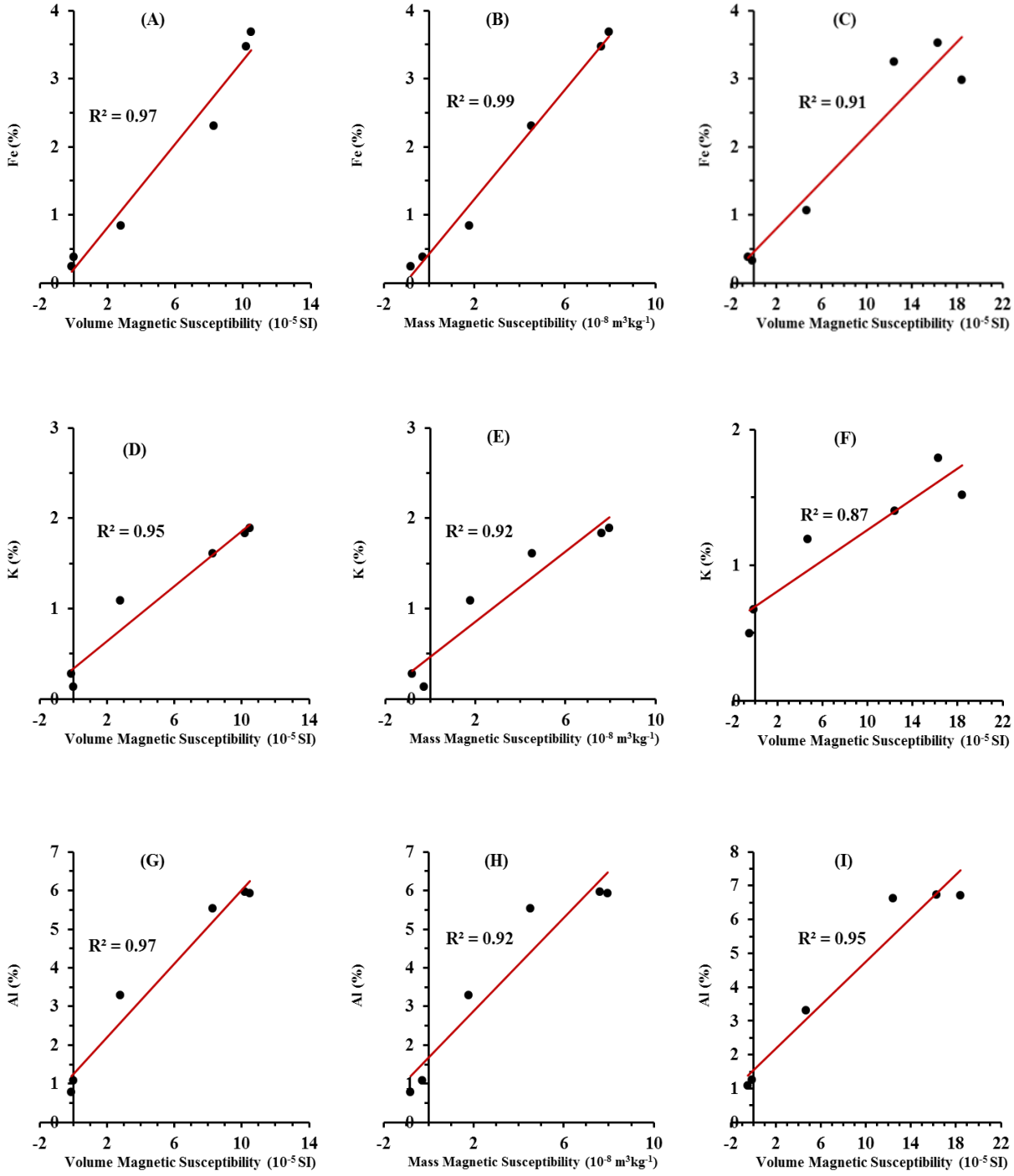

Fig. 4. Well 03 crossplots. **(A), (D), (G)** show Fe, K and Al contents from XRF versus probe magnetic susceptibility per unit volume of the extracted core samples. **(B), (E), (H)** show Fe, K and Al contents from XRF versus magnetic susceptibility per unit mass of the extracted core samples. **(C), (F), (I)** show Fe, K, and Al contents from XRF versus probe magnetic susceptibility per unit volume measured in our previous study [1] on the original intact slabbed cores.

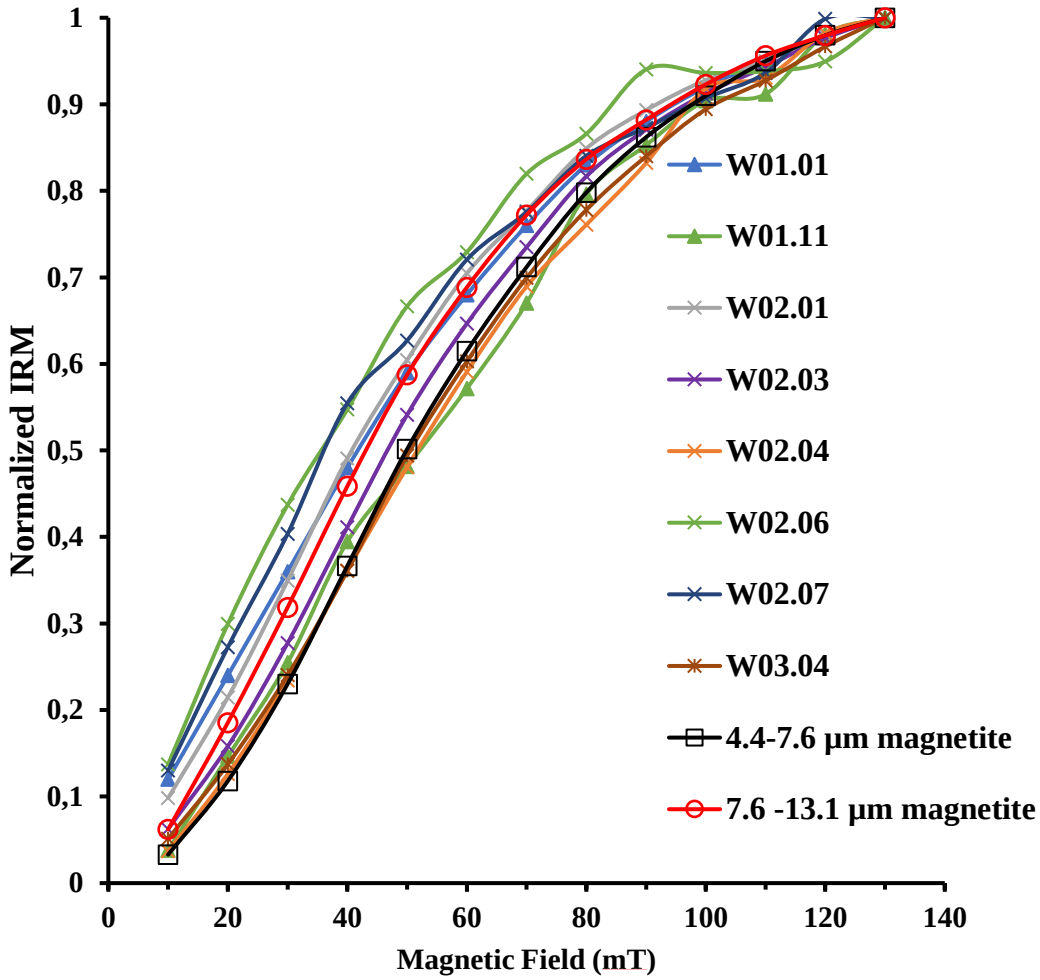

Figure 5. IRM acquisition curves for selected core samples plotted on a normalized scale. Most of the curves follow a closely related trend. Also plotted for comparison are curves for two magnetite particle size fractions which extended the results for magnetite shown in [3] up to an applied direct field (DF) of 130 mT. Some of the normalized core sample results follow the trend of the 4.4-7.6 µm magnetite sample, whilst others follow the trend of the 7.6-13.1 µm magnetite sample. The maximum appplied DF for the IRM acquisition was 130 mT so that the samples could subsequently be alternating field (AF) demagnetized for other magnetic measurements (since the AF demagnetizer has a maximum field of 130 mT).

Table 2. IRM results for the maximum applied field of 130 mT for various samples and the corresponding masses of magnetite in those samples calculated using **Equation (2)**. Also shown is the magnetite mass as a percentage of the total sample mass.

Well	Sample and lithology	IRM per unit mass at 130 mT (10^{-6} Am^2 kg^{-1})	IRM per unit volume at 130 mT (mA m^{-1})	Magnetite mass (mg)	Percent magnetite mass in sample (%)
Well 01	W01.01 (clean sand + heavy oil)	489.4	626.0	1.62	0.0099
	W01.11 (muddy sand, IHS)	222.2	217.0	0.32	0.0025
Well 02	W02.01 (clean sand + heavy oil)	92.2	100.5	0.26	0.0018
	W02.03 (clean sand)	433.4	427.8	0.63	0.0049
	W02.04 (muddy sand, IHS)	78.9	95.3	0.14	0.0009
	W02.06 (clay/shale)	199.6	205.4	0.53	0.0040
	W02.07 (clay/shale)	307.8	331.6	0.86	0.0062
Well 03	W03.04 (muddy sand, IHS)	56.1	65.4	0.10	0.0007

Table 3. Magnetic susceptibility per unit mass of magnetite in the core samples from **Table 2** using **Equation (3)**. Also shown are the illite contents estimated from the simple quartz + illite model using **Equation (4),** and the corrected illite estimates accounting for the magnetic susceptibility per unit mass values of magnetite in the samples using **Equation (5)**. *For these results the equations gave small negative values, but since that's not realistic the values have been given as zero. This can happen if the samples contain small amounts of other components, whereas the models assume simple mixtures.

Well	Sample and lithology	Magnetic susceptibility per unit mass of magnetite in sample (10^{-8} m^3kg^{-1})	Illite estimated from simple quartz + illite model (%)	Illite estimate corrected for magnetite content (%)
Well 01	W01.01 (clean sand + heavy oil)	6.17	0.58	0.00*
	W01.11 (muddy sand, IHS)	1.40	23.18	14.21
Well 02	W02.01 (clean sand + heavy oil)	1.13	0.00*	0.00*
	W02.03 (clean sand + heavy oil)	2.72	11.78	0.00*
	W02.04 (muddy sand, IHS)	0.50	41.04	37.84
	W02.06 (clay/shale)	2.51	80.09	64.02
	W02.07 (clay/shale)	3.89	97.18	72.30
Well 03	W03.04 (muddy sand, IHS)	0.36	32.97	30.67

Table 4. Low field (using a Bartington MS2W sensor) and high field (using a Sherwood AUTO balance) magnetic susceptibility per unit mass values for an IHS sample. The difference between the low and high field values (column 4) is consistent with the mass magnetic susceptibility of magnetite in the sample that was independently determined from the IRM results (column 5) given in **Table 3**.

Sample	Low field magnetic susceptibility per unit mass (10^{-8} m^3kg^{-1})	High field magnetic susceptibility per unit mass (10^{-8} m^3 kg^{-1})	Difference between the low and high field mass magnetic susceptibilities (10^{-8} m^3 kg^{-1})	Mass magnetic susceptibility of magnetite in the sample from Table 3 (10^{-8} m^3 kg^{-1})
W02.04 (muddy sand, IHS)	5.79	5.36	0.43	0.50

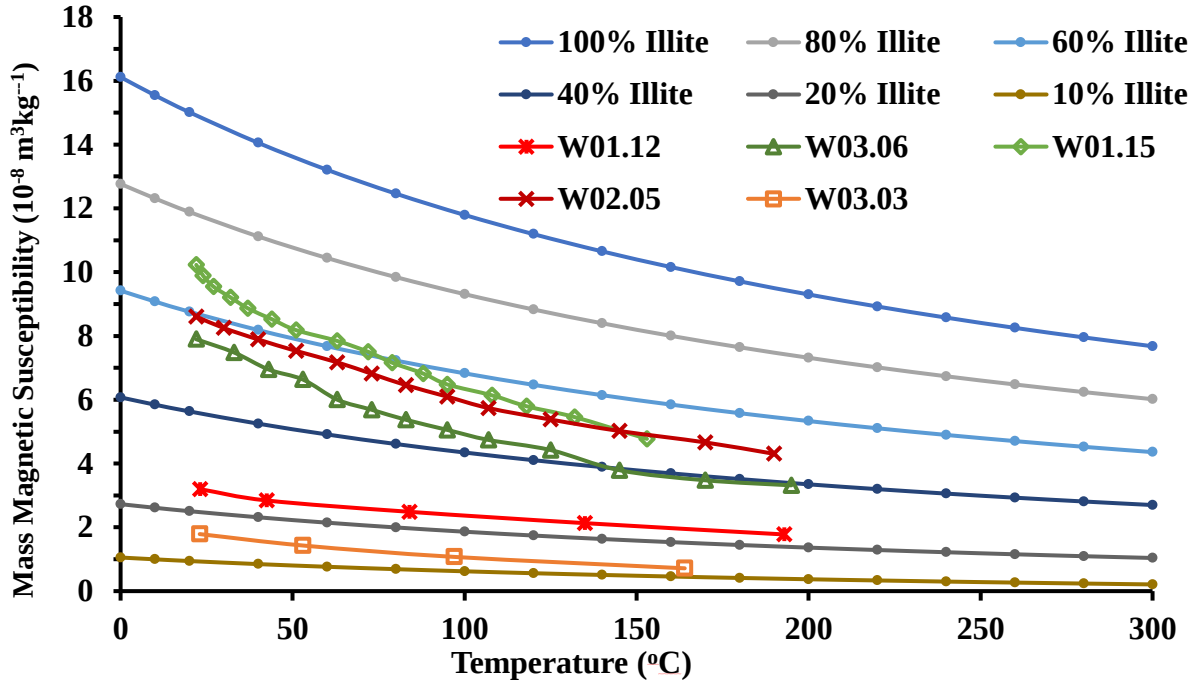

Figure 6. Results of temperature dependent magnetic susceptibility measured on two IHS samples (W01.12 and W03.03) and three shale samples (W01.15, W02.05 and W03.06). The results are plotted on model template curves of Ali and Potter [7, 8] for various mixtures of illite + quartz. The susceptibilities of all these samples decrease with increasing temperature, indicating that they contain a paramagnetic mineral or minerals.

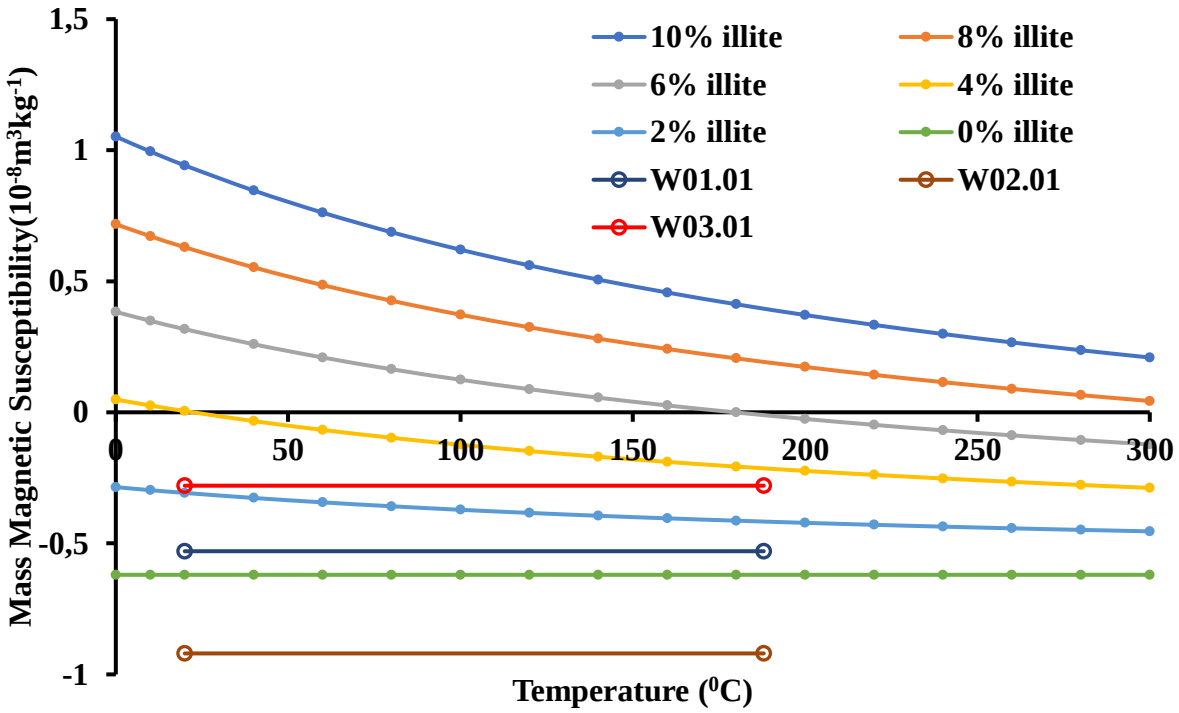

Figure 7. Results of temperature dependent magnetic susceptibility measurements on three selected clean sand samples (W01.01, W02.01 and W03.01). The results show no dependence on temperature up to 190 ºC, consistent with clean sand comprising diamagnetic quartz. The differing sample values are due to minute variations in magnetite content (**Table 2**).