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Novel high resolution probe magnetic susceptibility and comparison with wireline gamma ray and grain size in an Albertan oil sand well

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Summary

High resolution probe magnetic susceptibility has been used as a novel method to characterize a 110m section of slabbed core from an oil sands well in the Athabasca region of northern Alberta. The magnetic measurements were easily able to differentiate oil sands intervals from shale and limestone intervals. The magnetics identified the main oil sands reservoir interval, a 15 m thick fluvial channel sandstone of the lower McMurray Formation, and the other lithologies much better than the wireline gamma ray. The processed magnetic susceptibility results could also be used to give estimates of paramagnetic clay (e.g., illite) and quartz simultaneously if one assumes a simple two component model mixture. The study suggests that borehole magnetic susceptibility could potentially be a very useful tool in characterizing oil sands intervals.

Introduction

High resolution low-field magnetic susceptibility provides a very rapid, cheap, and sensitive method for characterizing core samples and estimating key petrophysical parameters. The technique is non-destructive, requires no extra sample preparation, and can be conducted using very portable equipment. Most previous studies have been carried out on routine core plugs (Potter, 2007). The technique has successfully been used to estimate clay content, permeability and other petrophysical parameters in clastic and carbonate reservoirs (Potter, 2007; Potter et al., 2011). Probe magnetic susceptibility has received very little attention up to now, but is potentially very useful for unconsolidated core sections (like the oil sands), where it is not possible to cut core plugs.

In this study we use probe magnetic susceptibility to characterize a 110m slabbed core section from an oil sands well in the Athabasca region. The results are compared to the wireline gamma ray, and also a detailed grain size profile in the key reservoir interval in the McMurray formation. The processed magnetic susceptibility results are also used to estimate paramagnetic clay (illite in this case) and quartz content in the section.

General geology of the study area

The study area is located in the Athabasca area of northern Alberta, and the main target reservoir is the McMurray Formation, which contains most of the bitumen reserves. The McMurray Formation was deposited during the advancement of the Boreal Sea from north, backfilling the valley system created by earlier incision with estuarine deposits (Barson et al., 2001). The McMurray is subdivided into three informal members: a Lower, Middle and Upper member. The Lower member has been interpreted to be deposited in fluvial environments, capped with alluvial deposits consisting of pebbly to coarse sandstone, siltstone, claystone and interbedded inclined heterolithic stratification (IHS) beds (Barson et al., 2001). The Middle McMurray was deposited under more fluvio-estuarine conditions and is composed of channel fill sandstone, shale, mudstone with more shaly IHS beds (Ranger and Pemberton, 1997; Barson et al., 2001), and is thus less permeable and of lower reservoir quality than the Lower member. The Upper McMurray is composed of generally upward-coarsening successions of interbedded sandstones, siltstones and mudstones, deposited under more brackish to marine tidal flats, lagoonal and estuarine conditions (Barson et al., 2001; Wightman and Pemberton, 1997).

Methods

Magnetic susceptibility is defined as the magnitude of induced magnetization divided by the applied field strength, and can be expressed per unit mass or per unit volume (Potter, 2007):

Mass magnetic susceptibility, $\chi = J/H$ (1)

where J is the magnetization per unit mass and H is the magnetic field strength ($H = B/\mu_o$ where B is the applied field in Tesla and μ_o is the magnetic permeability of free space).

Volume magnetic susceptibility, $k = M/H$ (2)

where M is the magnetization per unit volume. The results in this paper will be expressed in volume susceptibility, since the core samples are slabs and not plugs. In order to obtain the mass magnetic susceptibility individual pieces of the slabbed core would have needed to be removed and weighed, but we needed to keep the core intact. The probe device measures the susceptibility of a small volume (about 1.5 x 0.50 cm area by 0.5 cm depth) and could easily be applied to the unconsolidated slabbed cores in this study. The use of the slabbed cores is advantageous as it provides a continuous lithological profile compared to conventional core analysis methods that use core plugs.

The magnetic susceptibility values for some typical reservoir minerals and fluids have been established by Ivakhnenko and Potter (2004) and Potter (2007). The major reservoir matrix minerals (e.g., quartz or calcite) are diamagnetic and exhibit negative magnetic susceptibility values, whereas key permeability controlling clay minerals (e.g., illite or chlorite) are paramagnetic and exhibit weakly positive magnetic susceptibility. The raw magnetic susceptibility values can thus provide a rapid indication of the main lithological and mineralogical zonations. Clean sands should be characterised by net negative susceptibility values, while muddy and shale units should be characterised by net positive susceptibility values. Since the lithological zonations are related to permeability, the clean sand zones should correspond to higher permeability intervals (except where they contain low permeability naturally cemented zones), and muddy and shale units should generally correspond to low permeability intervals.

The low-field volume magnetic susceptibility measurements were undertaken using a Bartington MS2E probe sensor that makes measurements while in contact with the slabbed core surface. The probe sensor records the magnetic susceptibility at a high resolution of a few mm, much higher than the conventional wireline gamma ray that averages its signal per foot. The magnetic measurements were taken at 3 cm intervals down the core. The measurements first involve taking a background (air) reading followed by the sample reading at each measurement point. The background reading is subtracted from the actual reading to obtain the raw magnetic susceptibility value.

Each raw magnetic susceptibility value is a reflection of the total signal from all the diamagnetic, paramagnetic and ferrimagnetic mineral components in the sample (Potter, 2007). If one assumes a simple two component mineral mixture, such as illite and quartz, then the magnetic results can be used to estimate the illite and quartz content simultaneously (Potter et al., 2004; Potter, 2007). This previous work used core plugs and mass magnetic susceptibility. In the present study using volume magnetic susceptibility similar equations can be used (just substituting volume for mass magnetic susceptibility). For a two component system of illite and quartz (a reasonable assumption for sections of the oil sands core) the total magnetic susceptibility signal of the core sample per unit volume, k_T, is the sum of the illite (paramagnetic) and quartz (diamagnetic) components:

$$k_T = \{(F_I)\ (k_I\} + ((1-F_I)\ (k_Q)\} \qquad (3)$$

where k_T is the measured raw magnetic susceptibility, F_I is the volume fraction of illite, $(1-F_I)$ is the volume fraction of quartz, k_I is the magnetic susceptibility per unit volume of illite and k_Q is the magnetic susceptibility per unit volume of quartz. Since k_T, k_I and k_Q are known, the volume fraction of illite, F_I, is given by:

$$F_I = (k_Q - k_T) / (k_Q - k_I) \qquad (4)$$

The volume fraction of quartz is obtained from $(1-F_I)$.

The magnetic results were compared with the wireline gamma ray data. In the McMurray formation the results were also compared with a detailed grain size profile.

Results

Analysis of the raw magnetic susceptibility signal

The high resolution magnetic susceptibility measurements provided a quick appraisal of the lithological and mineralogical variations. The negative (diamagnetic) signal (Figure 1a) corresponds to the clean sand zones, which are often fully saturated with. The bitumen did not affect the magnetic susceptibility readings as most reservoir fluids are diamagnetic (Ivakhnenko and Potter, 2004). Shaly sand zones showed either negative or positive susceptibility depending on the percentage of clay within the interval. Shale zones had the highest paramagnetic clay content and exhibited moderate positive magnetic susceptibility values. The limestone units exhibited negative values in calcite rich intervals, and larger positive values in siderite rich intervals. High spikes in the raw magnetic susceptibility plots (Figure 1a) were due to small amounts of ferromagnetic material in some of the shale rich zones.

The raw magnetic susceptibility readings were also averaged over one-foot intervals (Figure 1b), so see the variations more clearly and also to compare with the downhole gamma ray log, which averages over about 1 foot depth intervals. Averaging to one foot was also useful as it picked out the IHS intervals of the McMurray section, which were more difficult to see from raw data.

Mineral content estimation

Equation (4) was used to estimate the illite and quartz contents from the raw magnetic susceptibility, assuming a simple two component mixture. The results clearly showed that the sand intervals (the main reservoir zones containing bitumen) contain a small fraction of illite, whereas the shale rich intervals correspond to higher illite contents. One such example from a short interval is shown in Figure 2. The raw magnetic susceptibility is the blue curve on the left, and the corresponding magnetically derived illite content is the red curve on the right. In the middle is an image of the core. The dark section at the top is the oil sand (bitumen saturated), and the lighter section at the bottom is shale.

The modelled mineral estimates also enabled one to pin-pointed zones with anomalous mineralogies, most likely containing ferrimagnetic minerals. Since the simple two component mixture model doesn't take account of these ferrimagnetic minerals, these zones are readily indicated when the calculated "illite" per cent was greater than 100%.

Correlation of magnetic susceptibility with wireline gamma ray and grain size

Figure 3 is a plot of the one foot averaged magnetic susceptibility, the lithological grain size profile, and the wireline gamma ray log. Good correlations exist between the magnetic and gamma ray data. Net negative magnetic susceptibility corresponds to low gamma ray, whereas net positive magnetic susceptibility corresponds to high gamma ray. Note, however, that the high resolution low-field magnetic susceptibility clearly picks out the clean sands and HIS beds much better than the gamma ray. This is particularly evident by the smooth signal of the magnetics in the permeable clean sand interval (~80.0–95.0 m), compared to the more variable (zig-zag) signal of the gamma ray. The magnetic measurements may provide a more quantitative and less arbitrary means of establishing net pay cut offs. This is because the net negative susceptibility values are a clear indication of clean sands, while net positive magnetic susceptibility values indicate more muddy sand and/or shale etc. Note also that the magnetic susceptibility clearly picked out the thin siderite zone, whilst the gamma ray showed a high signal over a much larger interval.

Conclusions

This study has demonstrated that non-destructive, high resolution probe magnetic susceptibility is a very useful tool in characterizing the lithological and mineralogical variations in an oil sands core interval. The different lithologies were distinguished better by the one foot averaged magnetic susceptibility results than the wireline gamma ray log data.

This study suggests that borehole magnetic susceptibility measurements would be potentially very useful for charactersing oil sands intervals in situ.

Acknowledgments

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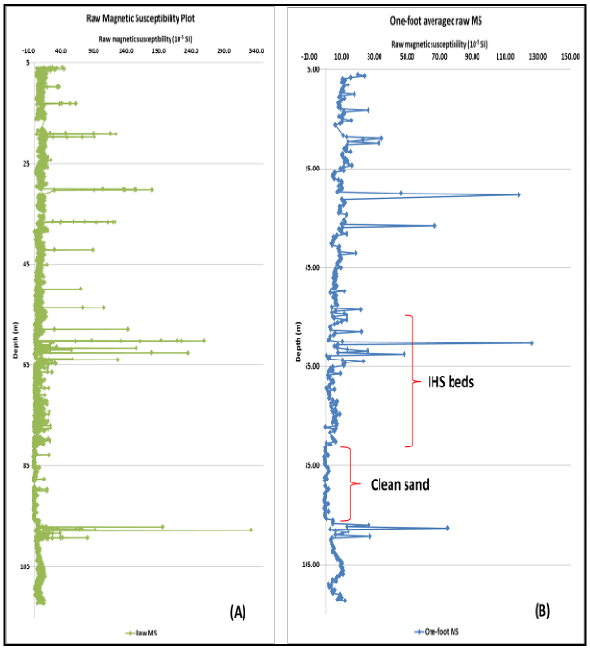

Figure 1: A comparison of (a) the entire raw magnetic susceptibility signal and (b) the one foot averaged magnetic susceptibility.

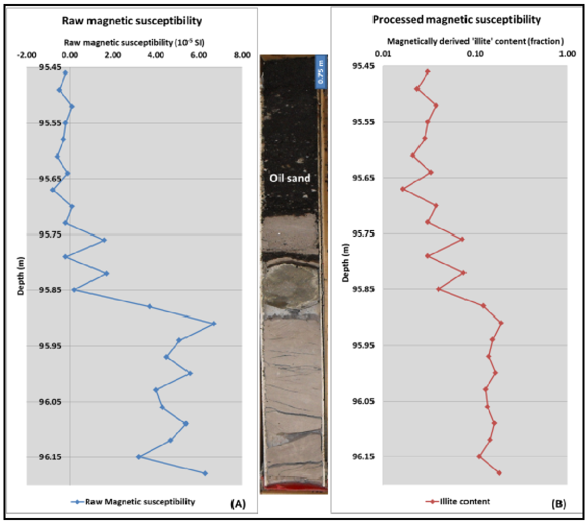

Figure 2: A comparison of (a) raw volume magnetic susceptibility and (b) corresponding magnetically derived illite content of shale and sandstone section.

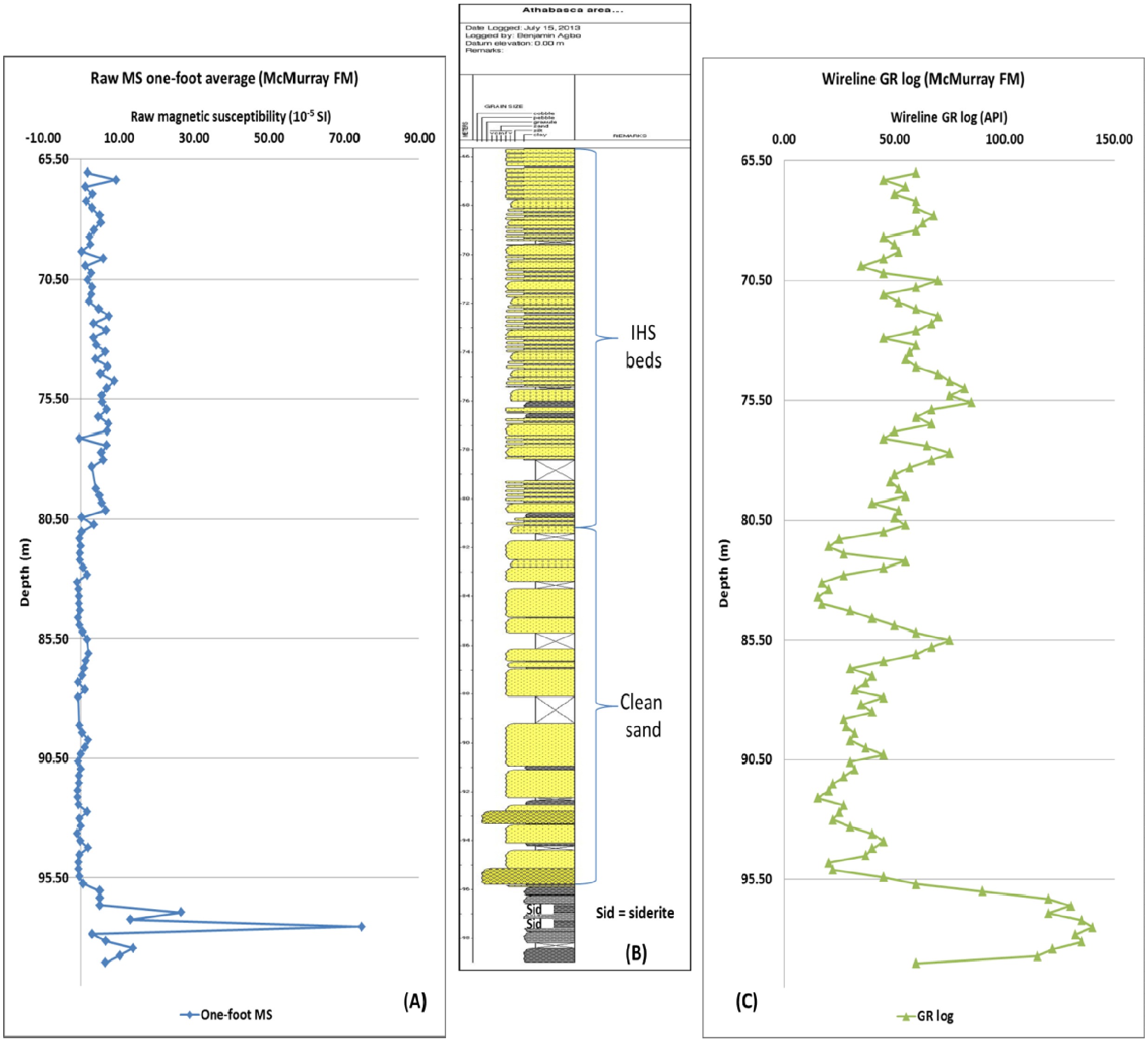

Figure 3: A comparison of (a) the raw magnetic susceptibility, (b) grain size distribution and (c) wireline gamma ray log of a section of the Cretaceous McMurray Formation. Note how the magnetic susceptibility clearly picks out the high permeability pebbly-coarse clean sand interval (~80-95m) and the interbedded IHS beds compared to the gamma ray log.

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