PROBE MAGNETICS AS A RAPID, NON-DESTRUCTIVE SCREENING TOOL FOR CONSOLIDATED AND UNCONSOLIDATED CORE IN CONVENTIONAL AND UNCONVENTIONAL RESERVOIRS

[1]Toan H. To, [1,2]David K. Potter [1,2]Aminat Abiola, and [1]Vivian T. Ebufegha

[1]Department of Physics, and [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada

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ABSTRACT

A comprehensive study utilising probe magnetic susceptibility measurements has been used to characterize a wide range of slabbed core from different types of conventional and unconventional reservoirs. The probe magnetic device was small and very portable, and allowed high resolution, non-destructive screening to be undertaken very rapidly. The technique is particularly useful for unconsolidated core, where some other more conventional techniques can be destructive. The results allowed rapid acquisition of high resolution clay profiles, which correlated with other independent established methods (such as X-ray diffraction). Furthermore, the magnetic profiles also correlated with grain size variations (determined independently from laser particle size analysis) and probe permeability (where the latter was possible). Some of the key probe magnetic results in different types of reservoir are as follows:

(1) The probe magnetic technique has been particularly useful in a number of oil sands reservoirs in northern Alberta as a non-destructive screening tool for these unconsolidated samples. In particular, it has allowed the main oil sands intervals to be differentiated from the more clay rich shale and inclined heterolithic stratification (IHS) beds better than conventional gamma ray techniques.
(2) The technique has allowed one to distinguish different types of unconsolidated turbidite samples in some Middle East gas reservoirs that were difficult to differentiate visually. This included quantitatively differentiating "uniform" turbidites from "graded" turbidites, where the grain size subtly fines upwards, but which is quite difficult to identify qualitatively from mere visual inspection.
(3) The technique has been able to easily distinguish different types of shales (due to the varying amounts of clay minerals and organic matter that they contain) in some shale oil and shale gas reservoirs in western Canada. Increased paramagnetic clays, such as illite, result in higher magnetic susceptibility, whilst increased organic matter and quartz content result in lower magnetic susceptibility values.

The results suggest that probe magnetics could be used as proxy for rapidly and non-destructively estimating high resolution clay content, grain size and permeability profiles in consolidated and unconsolidated samples in several different types of conventional and unconventional reservoir.

INTRODUCTION

Previous studies have indicated the potential of using magnetic susceptibility measurements on core plugs for estimating some key petrophysical parameters such as clay content and permeability [1-5]. In many reservoirs it is not easy or practical to cut core plugs, particularly in unconsolidated samples (such as sands) or fissile samples (such as some shales) that may easily fracture. The present study focuses on the application of probe magnetic susceptibility on slabbed core to provide a rapid, non-destructive technique that can be used to characterize unconsolidated samples, as well as consolidated core, in a variety of conventional and unconventional reservoir types. A preliminary study on oil sands core in an Albertan oil well demonstrated the technique's potential in quantifying paramagnetic illite clay content, and distinguishing lithologies better than wireline gamma ray [6]. The present study extends the work not only in oil sands but also to other reservoir types.

SAMPLES AND METHODS

Sections from a number of different conventional and unconventional reservoirs were studied as follows: (i) oil sands sections from Northern Alberta, Canada, (ii) turbidite gas reservoir sections from the Nile delta, and (iii) a large shale section through the Muskwa, Otter Park and Evie formations in the Horn River Group in British Columbia, Canada. The oil sands and turbidite examples were both largely unconsolidated, and both contained sand and shale sections. This is why we present these two examples first in the results section below. The magnetic susceptibility measurements were taken using a Bartington MS2E probe sensor, which was connected to an MS2 meter that provided a digital readout of the volume magnetic susceptibility. The probe sensor applies a weak magnetic field to the sample and detects the resulting magnetization produced. The magnetic susceptibility is the magnetization divided by the applied field. The applied magnetic field of the probe sensor interrogates an area of about 3.8 x 10.5 mm and penetrates just a few mm into the core. The raw magnetic susceptibility values represent a reading on the core minus a background (in air) reading. The background and core readings at each depth take around 30 seconds in total (15 seconds per reading on the sensitive scale). The magnetic susceptibility results can be converted to mineral content assuming a simple system (e.g., quartz + illite) using equations (3) and (4) given in [1].

RESULTS AND DISCUSSION

Oil Sands Reservoirs (Northern Alberta)

High resolution low field probe volume magnetic susceptibility measurements were taken at one inch intervals on the slabbed core from 3 wells in the Athabasca oil sands in northern Alberta, Canada. **Figure 1** shows a comparison of the profiles with depth of the magnetic susceptibility on the slabbed core and the depth matched wireline gamma ray for Well 02. The left hand profile of **Figure 1** shows the 1 foot vertical running average of the magnetic susceptibility values. This was plotted in order to compare the magnetic data more closely with the wireline gamma ray data, shown in the right hand profile, which averages over about 1 foot vertically. There is some correspondence between the magnetic and gamma ray profiles. Certainly both profiles pick out the more clay rich shale and inclined heterolithic stratification (IHS) intervals at the top of the section (light green shaded region from approximately 349-379 m in **Figure 1**). Despite the fact that the gamma ray log data is good quality, the magnetic data seems capable of distinguishing the lithological boundaries better than the gamma ray. In particular, the main clean sand interval (i.e., the best reservoir interval with low clay content) is clearly delineated as a zone of mainly negative magnetic susceptibility due to diamagnetic quartz (pink shaded region from 390-425 m in **Figure 1**). In this interval the gamma ray is much more variable, and it is more difficult to tell from the gamma ray alone whether the lithology is clean sand or more muddy sand (i.e., sand + clay). Other components (such as small amounts of uranium due to organic matter) can contribute to the gamma ray but not the magnetic susceptibility. The probe magnetic technique was also particularly useful in identifying and quantifying variations that were not obvious from mere visual observations in black bitumen saturated intervals. Moreover, the magnetic results pin-pointed small intervals of anomalous mineralogy as indicated in **Figure 1** (often thin layers of siderite) that the gamma ray did not detect.

Figure 2 shows a comparison of the profiles with depth of the illite content derived from the magnetic susceptibility results using equation (4) from reference [1] on the slabbed core, and the wireline spontaneous potential (SP) log for Well 03. The two profiles show quite a close correspondence. The low permeability shale interval at the top of the section is clearly picked out by both profiles (light green shaded region in **Figure 2**). Furthermore, the values of lowest illite content (pink shaded region in **Figure 2**), which should indicate the cleanest sand and therefore potentially best reservoir intervals, also correspond to the largest deflection to the left of the SP log at around 90 mV from the shale base line at about 160 mV. The low illite content and large SP deflection are both consistent with potentially good permeable zones.

Turbidite Gas Reservoirs (Nile Delta)

Figure 3 shows some examples of the use of probe magnetic susceptibility in a turbidite gas reservoir in the Nile delta. The probe technique was able to clearly distinguish "uniform" sand sections from "graded" sand sections that were not easy to differentiate from mere visual observations. In the top left profile of **Figure 3** the lighter sand intervals are "uniform" and the magnetic susceptibility values are all quite similar and low. Note that these values are positive, which is actually due to the presence of some paramagnetic clay minerals in the sand (pure quartz sand would give a small negative, diamagnetic, signal). In contrast, in the top right hand profile of **Figure 3** the sand rich interval in the bottom half of the section is "graded" and shows increasing magnetic susceptibility as one goes upwards in the section. The increases in magnetic susceptibility are in large part due to increasing paramagnetic clay content. This trend in clay content was supported by some limited X-ray diffraction results, where for example the content of the paramagnetic clay illite increased by a factor of about 3.8 from depth 1763.70 m to 1763.40 m.

The top right hand “graded” sand section of **Figure 3** is a typical fining upwards turbidite genetic unit. The quartz grain size decreases from the bottom to the top of the section. The crossplot in **Figure 3** shows a strong correlation between the quartz grain size of some samples of the core from the “graded” turbidite section and the corresponding probe volume magnetic susceptibility values. The quartz grain size was determined from laser particle size analysis.

The probe magnetic susceptibility profiles shown in **Figure 3** would also be expected to reflect the permeability profiles. The sand rich intervals that show low magnetic susceptibility would be expected to have higher permeability than the more clay rich muddy sand and shale intervals that show higher magnetic susceptibility. Support for this was provided by a few probe permeability measurements where these were possible (using a portable TinyPerm II air probe permeameter). The permeability in the “graded” sand section decreased from 6,500 mD at depth 1763.80 m to 2,300 mD at depth 1763.34 m, consistent with the upward trend of increasing paramagnetic clay content and fining upwards trend of quartz grain size. The number of probe permeability measurements was limited, however, due to the unconsolidated nature of the core and the need for the probe tip to have a good seal with the rock surface. Note that the probe magnetic technique does not require any such seal.

Horn River Shale (British Columbia)

Figure 4 shows a depth profile of the probe volume magnetic susceptibility signal from slabbed core from the Imperial Komie well in British Columbia, Canada. The profile goes through the Muskwa, Otter Park and Evie formations. The probe magnetics show large variations in the shale, which are due to differences in clay type, clay content and organic content. **Figure 4** shows both the bedding parallel (blue profile) and bedding perpendicular (black profile) probe volume magnetic susceptibilities. It is clear that there are significant differences between the bedding parallel and bedding perpendicular values, with the bedding parallel (blue profile) values being higher than the bedding perpendicular (black profile) values at each depth. Magnified versions of certain intervals are given on the right of the plot to show the differences more clearly. These differences would suggest that the probe technique is able to pick out variations in magnetic anisotropy. Some of the variations, however, could be due to heterogeneity if there are laminae thinner than the longest dimension (10.5 mm) of the sensing coil in the probe.

CONCLUSIONS

1. Probe magnetic susceptibility was able to clearly pick out different lithologies in oil sands intervals. In particular, it was able to identify clean sand intervals better than wireline gamma ray. It was also able to pick out some anomalous mineralogies that the gamma ray did not. The profile of illite content derived from the probe magnetic

susceptibility also correlated with the profile of the wireline SP log, suggesting that the probe magnetic results could also potentially be used as an indicator of permeable zones.
2. The probe magnetic technique was able to distinguish "uniform" from "graded" sand in different turbidites from gas reservoirs in the Nile delta. The magnetic susceptibility profiles reflected the clay content, quartz grain size and permeability profiles of the core sections and suggested that probe magnetics could be used as a proxy for rapidly determining high resolution profiles of such parameters in these turbidite samples.
3. The probe technique identified variations in shale sections in the Horn River Group, which primarily reflect differences in the clay type and content, and the organic content. A comparison of bedding parallel and bedding perpendicular probe magnetic measurements indicated variations in the magnetic anisotropy of the shales, though some of the variations could be due to heterogeneity if there were laminae thinner than the long dimension of the sensing coil in the probe.
4. The probe technique appears to be particularly useful in unconsolidated sections (oil sands, turbidites) and fissile shale sections, where it is difficult or impossible to cut consolidated core plugs. The technique can also show quantitative variations in situations where such variations are not obvious from visual observations (for example, in black bitumen saturated oil sands core, and in different types of turbidite).

ACKNOWLEDGEMENTS

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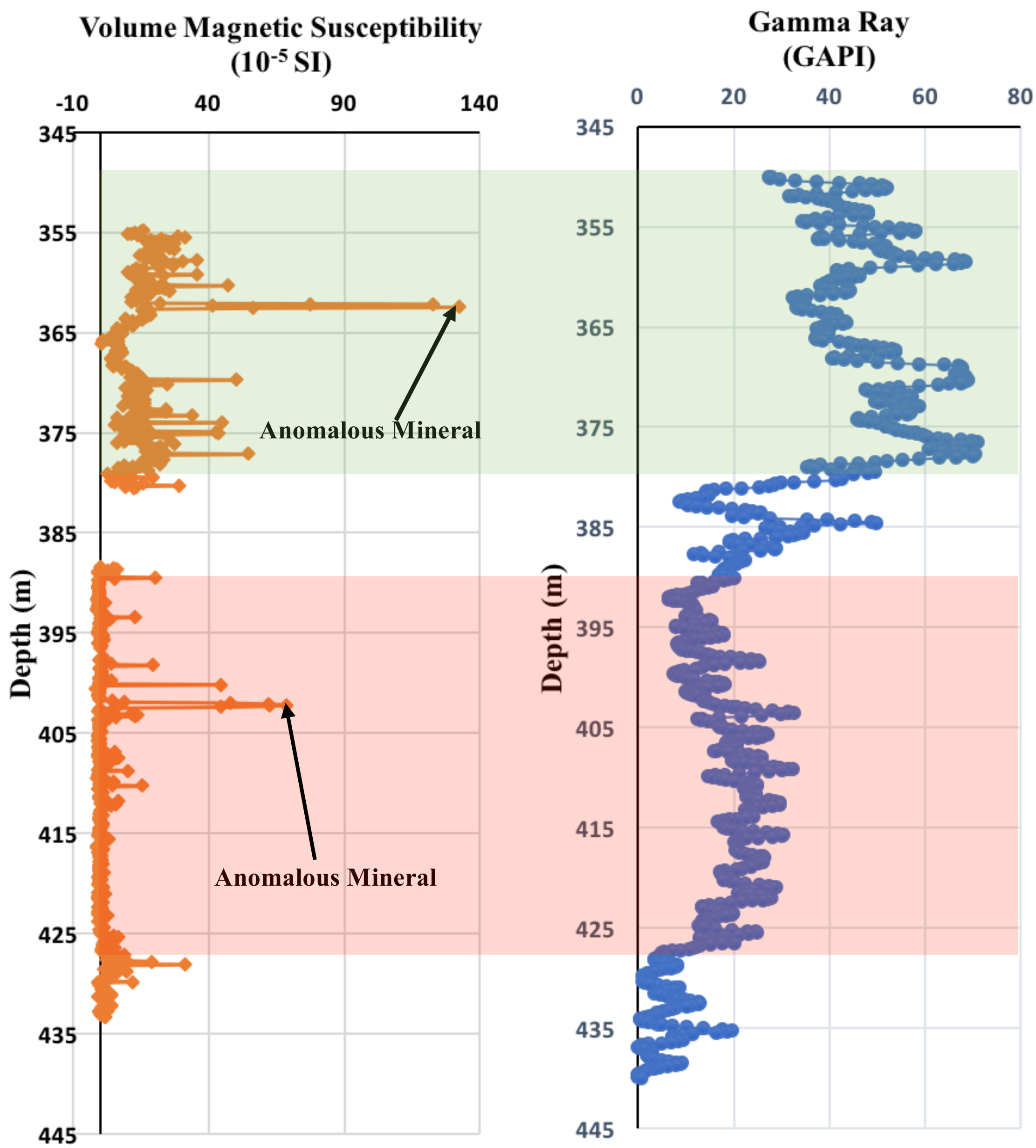

Figure 1. Oil sands Well 02. **Left:** Probe volume magnetic susceptibility profile on slabbed core depth matched to the wireline gamma ray in the right hand profile. Each magnetic susceptibility value shown is an average over the same vertical interval that each gamma ray reading averages over. Note that the magnetic susceptibility identifies the clean sand interval (pink shading) better than the gamma ray which is more variable in that interval. Light green shading indicates the more clay rich shale and inclined heterolithic stratification (IHS) intervals. Note also that the magnetic susceptibility identifies some anomalous minerals that the gamma ray does not. **Right:** Wireline gamma ray in the same well.

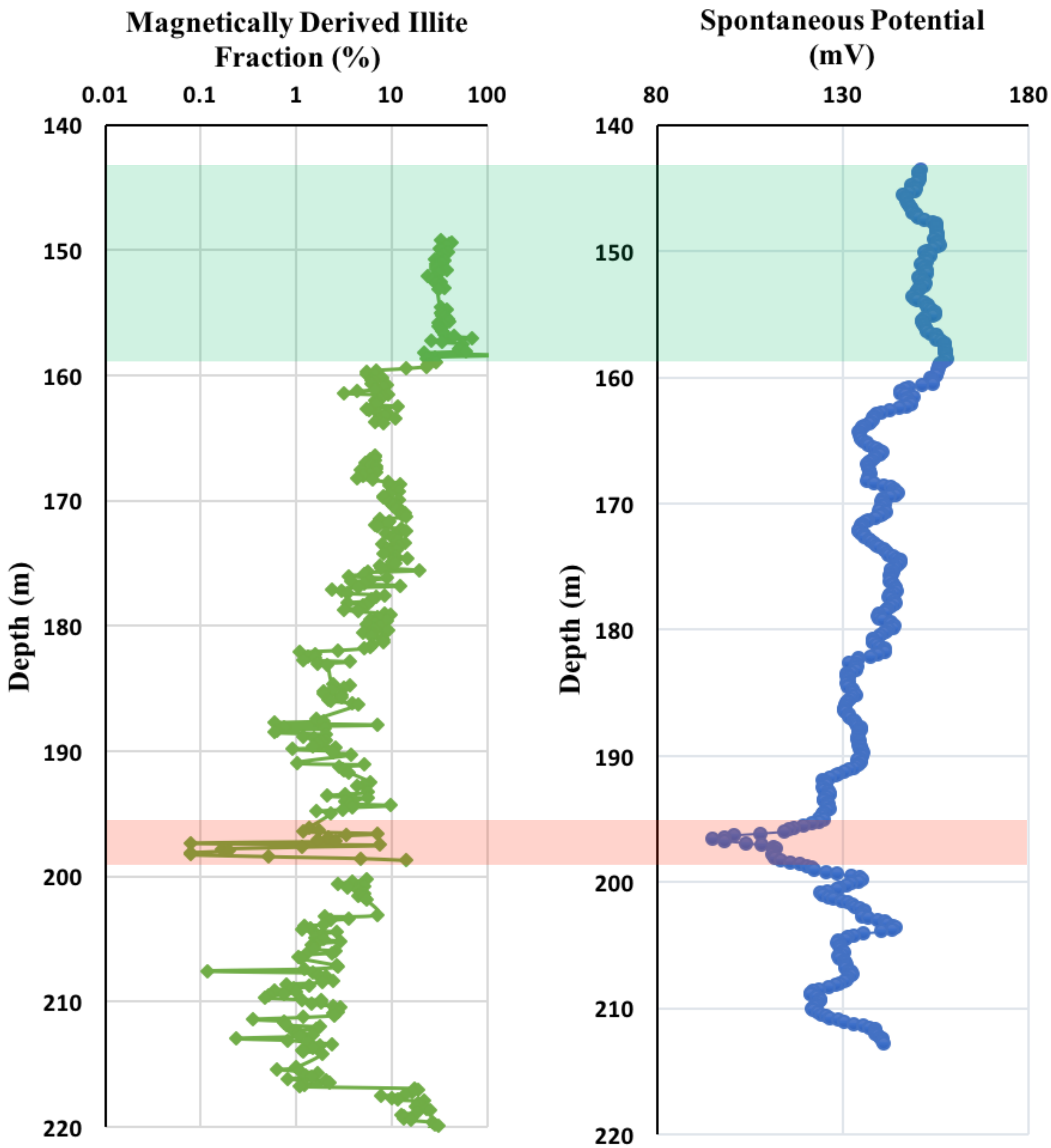

Figure 2. Oil sands Well 03. L**eft:** Profile of illite content derived from probe magnetic susceptibility on slabbed core using equation (4) of reference [1]. R**ight:** Depth matched wireline SP log profile. Note that both profiles pick out the low permeability shale interval at the top (light green shaded region), and the potentially most permeable interval (pink shaded region) where the lowest illite content corresponds to the largest negative deflection of the SP log from the shale baseline.

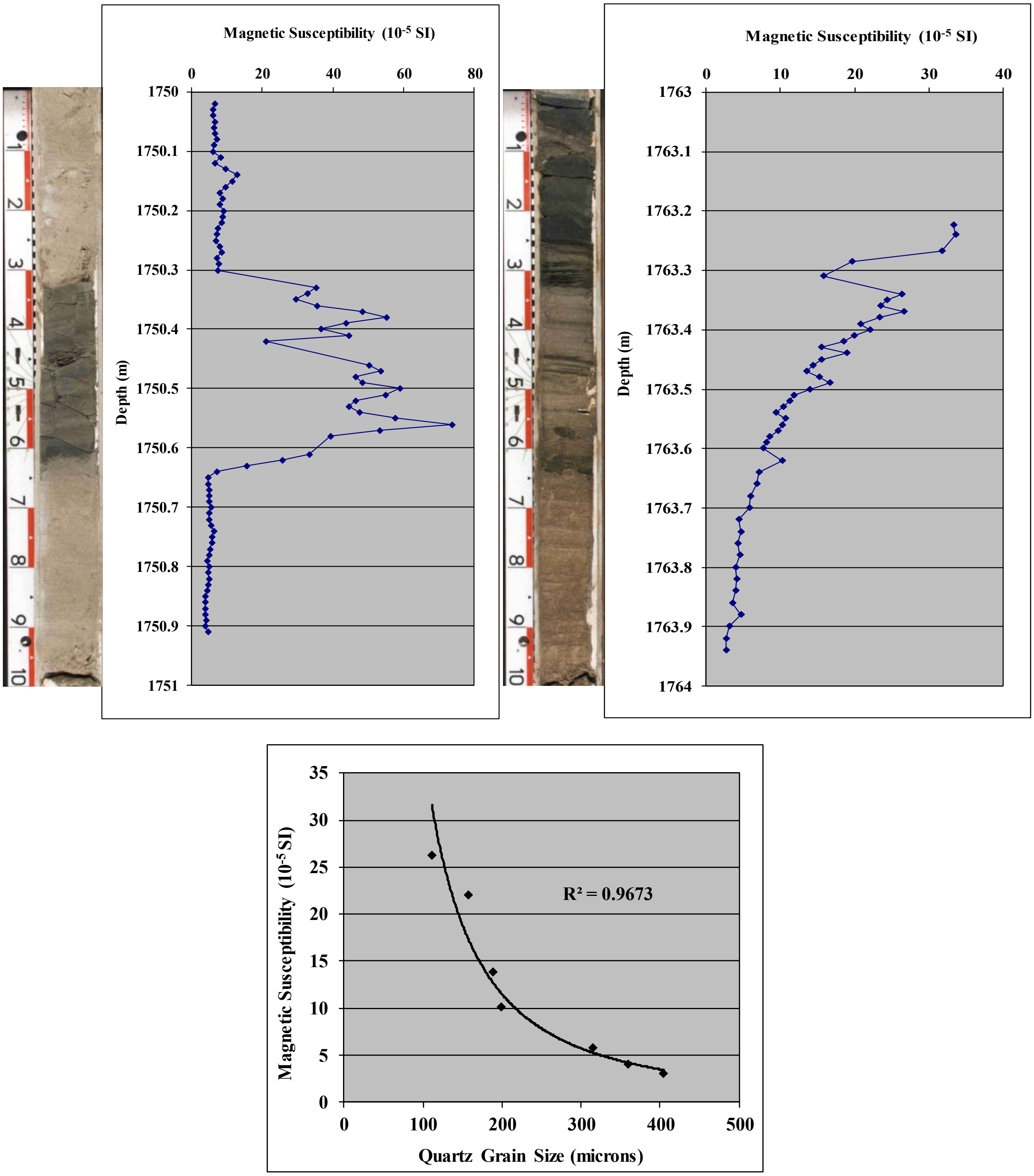

Figure 3. Results from some turbidite gas reservoir sections. **Top:** Probe volume magnetic susceptibility of two "uniform" sand sections with shale in between (**top left image and profile**), and a "graded" sand overlain by shale (**top right image and profile**). **Bottom:** Crossplot of quartz grain size (from laser particle size analysis) and probe magnetic susceptibility for the "graded" sand section at top right.

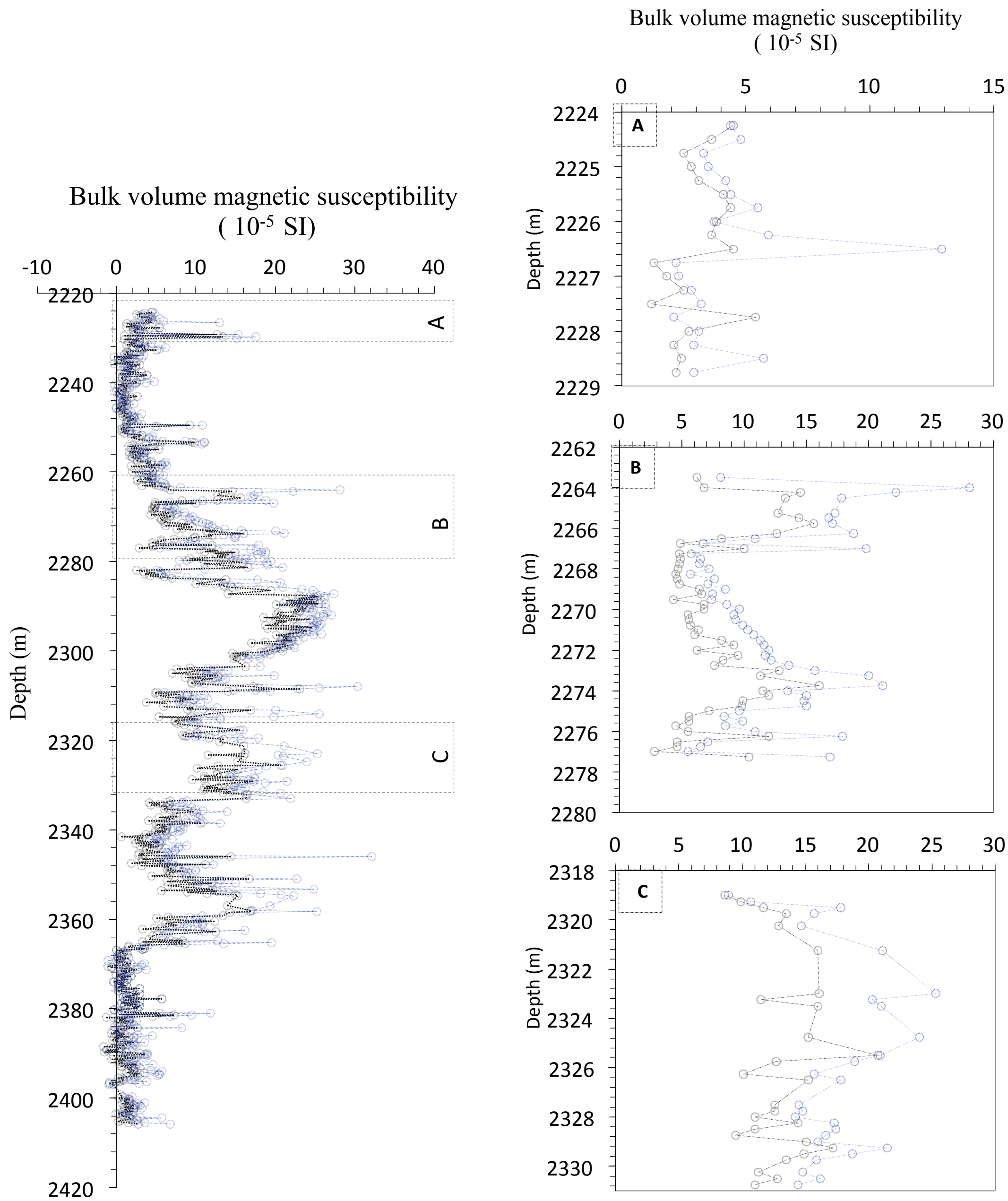

Figure 4. Probe volume magnetic susceptibility profile in the Imperial Komie well, which cuts through a section of the Horn River shales. The bedding parallel (blue profile) and bedding perpendicular (black profile) values are shown, with the bedding parallel values being higher than the bedding perpendicular values at each depth. Magnified versions of certain intervals are shown on the right side of the figure.