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A review of the applications of magnetic susceptibility measurements for improved reservoir characterization

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ABSTRACT

In the past, the application of magnetic susceptibility of diamagnetic and paramagnetic minerals to the study of rock magnetism was believed to be limited, due to both of their susceptibility signals being small compared to those of minerals in other magnetic. However, recent works have proved the usefulness of diamagnetic and paramagnetic susceptibility for reservoir studies. This paper summarizes results from previous studies showing the application of magnetic susceptibility measurements for characterizing different reservoir properties. Studies on the magnetic susceptibility of crude oils from different oil field regions around the world have shown good correlations of the susceptibility values with crude oil densities as well as other physical and chemical properties. In other studies, the measurements of magnetic susceptibility at the low and high fields have also been applied on rock core samples collected from different types of oil and gas reservoirs such as clastic shoreface, carbonate, shale and oil sand reservoirs. The magnetic susceptibility measurements for core samples without damaging the core by using the probe magnetic technique is probably used as a rapid, reasonable screening method for the initial estimation of core samples. The susceptibility of rock samples does not only show good correspondence with other reservoir characterizing methods, such as downhole gamma ray, spontaneous potential logs and core permeability, but it also shows some advantages over the traditional ones. The results suggested that the measurements of magnetic susceptibility could be used as an independent and improved method for distinguishing crude oil from different types of reservoirs, identifying main lithologies and predicting the permeable zone of a reservoir as well as estimating clay mineral contents.

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1. Introduction

Over the past decades, there are more and more studies that have proved the efficiency of applications of rocks magnetism in reservoir study. Among them, the applications of magnetic susceptibility measurements on reservoir minerals and fluids have shown very good results and potential future applications in different types of reservoirs. The magnetic susceptibility signals of paramagnetic and diamagnetic minerals and fluids, which were thought to have limited applications, have clearly shown their usefulness in characterizing reservoir properties. The measurements of minerals and fluids susceptibility can be used to distinguish crude oils from different oil field regions (Ivakhnenko and Potter, 2004; Ivakhnenko, 2012), estimate the mineral (illite) content of rocks samples (Potter, 2007; Potter et al., 2011), and distinguish different lithological regions (To et al., 2018; Ebufegha and Potter, 2016). The results from these studies have shown a good correlation with other traditional methods such as downhole gamma ray, X-ray diffraction (XRD), permeability measurements or geochemical measurements. Furthermore, the results from susceptibility measurements have shown some advantages of this method over other traditional methods. The method can be use as a rapid, non destructive core characterizing method. The susceptibility profile is able to identify main lithology intervals such as clean sands and mineral contents better than other traditional methods such as gamma ray. This paper will briefly introduce magnetic classes of reservoir rocks and minerals then focus on summarizing the results of the study using magnetic susceptibility measurements in reservoir characterization for different types of reservoirs.

2. Magnetic classification and magnetic susceptibility

When a material is subjected to a magnetic field, the magnetic moments of atoms are affected. The response of the material to the applied field depends on several factors, such as the atomic structure and the net magnetic field associated with the atoms. Based on this response the material can be magnetically classified into five main magnetic classes: diamagnetic, paramagnetic, ferromagnetic, ferrimagnetic, and anti-ferromagnetic, with canted anti-ferromagnetic as a subclass of the latter. However, all reservoir minerals and fluids are diamagnetic, paramagnetic and ferrimagnetic.

In order to understand the magnetic susceptibility of a material, the source of the susceptibility needs to be addressed. The magnetism in a material is associated with the motion of electrons in their orbits and, in particular, to the spin of the electrons (Figure 1).

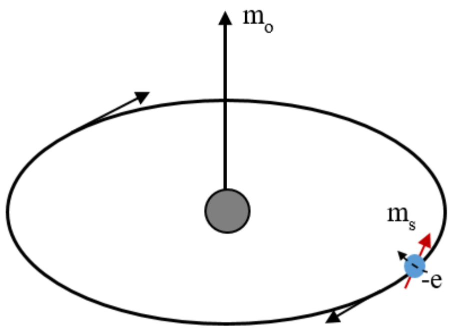

Figure 1. Schematic of the orbital magnetic moment (mo) and spin magnetic moment (ms) of an electron (To, 2020).

These two motions of electrons each generate their own magnetic dipole moments: the orbital magnetic moment (mo) and spin magnetic moment (ms). Once a material is subjected to an applied external magnetic field, the magnetic dipole moments precess in the direction of the field and generate an internal magnetic field within the sample. This internal magnetic field causes an induced magnetization, whose strength and direction depends on the electron structure of the material. Magnetization is related to the applied external magnetic field by the magnetic susceptibility of the material. Thus, magnetic susceptibility is a magnetic property of material that expresses the ability of a material to be magnetized by an applied field. Magnetic susceptibility is usually expressed in terms of magnetic susceptibility per unit volume *k* as:

$$k = \frac{J}{H} \quad (1)$$

or in terms of magnetic susceptibility per unit mass χ as:

$$\chi = \frac{M}{H} = \frac{k}{\rho} \qquad (2)$$

In which: J - the magnetization per unit volume and determined as the magnetic moment divided by the volume of the material; M - the magnetization per unit mass and determined as the magnetic moment divided by the mass of the material; H- the applied external magnetic field; ρ- the density of the material.

Magnetic susceptibility of material in diamagnetic group is small and negative. The main reservoir minerals such as quartz in clastic reservoir and calcite in carbonate reservoirs (Dunlop and Özdemir, 1997; Thompson and Oldfield, 1986), and reservoir fluids such as crude oil and formation water (Ivakhnenko and Potter, 2004). Paramagnetic minerals have positive magnetic susceptibility values compared to the negative values of diamagnetic minerals. Also, the absolute magnitudes (if one takes the moduli of the values) are generally significantly higher for paramagnetic minerals. Some typical reservoir paramagnetic minerals are the clays illite, chlorite, and the iron carbonate siderite (Hunt et al., 1995). Ferrimagnetism is observed more in compounds with complex crystal structures than in pure elements, and the magnetic susceptibility of a ferrimagnetic material is positive and much higher than diamagnetic and paramagnetic minerals, though generally slightly lower than ferromagnetic materials. Magnetite is an example of a ferrimagnetic mineral that is present in small amounts some reservoir rocks.

3. Magnetic susceptibility distinguishes crude oil from different oil field reservoir

An early study by Ergin and Yarulin (1979) presented results of susceptibility measurements on crude oil samples from different oil field provinces of the former Union of Soviet Socialist Republics. This study showed that the mass susceptibility of the crude oil was diamagnetic with low and negative magnetic susceptibility that varied from -0.942 to -1.042 x $10^{-8}m^3kg^{-1}$. The authors also analyzed components of the crude oil and found that most of the diamagnetic hydrocarbon compounds were alkanes, cyclo-pentanes, and cyclo-hexanes. They also found some correlations between susceptibility and certain physical and chemical properties. The results clearly indicated the variation of magnetic susceptibility values with different oil field regions. Therefore, the authors suggested that one could potentially use magnetic susceptibility for distinguishing crude oil from different oil field reservoirs.

An extensive study by Ivakhnenko and Potter (2004) introduced the application of magnetic susceptibility measurements to different reservoir fluids including crude oils, refined oil fractions, and formation waters. The crude oil samples were collected from worldwide oil regions such as the Middle East, North America, the Far East, and Russia, while the refined oil and formation waters came from the Forties oil field in the North Sea. The results showed that all fluid samples in this study were diamagnetic, and there was a significant difference between the mass susceptibility of crude oil and formation water. The authors also found correlations between the magnetic susceptibility of crude oils and their densities and other physical properties (such as residue content, stock tank oil gravity, and viscosity), and with chemical properties (such as the content of sulphur, vanadium, cadmium, nickel, and iron). The magnetic susceptibility of formation waters depended on their chemical composition. Based on the results, the authors suggested that magnetic susceptibility could potentially be used to characterize the physical differences between various reservoir fluids, and could distinguish crude oils from various oil provinces. A further study by Ivakhnenko (2012) has extended this work to more worldwide localities (Figure 2).

The results in Figure 2 clearly show the differences in magnetic susceptibility of crude oil samples collected from various oil field regions. However, most of the crude oil samples shown in this figure were from the North Sea oil field while there is only one sample from each other region. The results of these sample cannot represent all crude oil in those areas. In the future, the measurement of magnetic susceptibility should be made for more crude oil samples that are collected from various oil field regions around the world. The results from magnetic susceptibility measurements can be compared

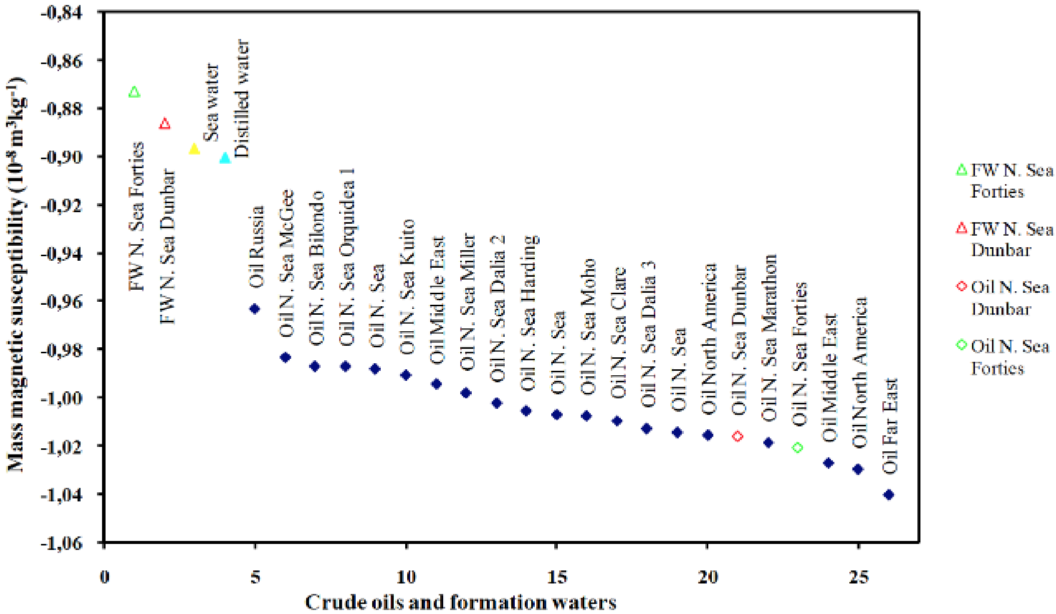

Figure 2. Mass magnetic susceptibility of crude oil from worldwide oil fields. The measurement errors are +/- 0.0035 ($10^{-8}m^3kg^{-1}$), close to the symbols (Ivakhnenko, 2012)

with each other and with their chemical and physical components or American Petrolem Institute density to distinguish crude oils.

4. Magnetic susceptibility quantifies clay content in clastic shoreface reservoir

Magnetic susceptibility measurements were first applied for characterizing rock core plug samples from a vertical North Sea oil well, and the results showed the potential use of magnetic susceptibility for quantifying mineral contents (Potter et al., 2004). In this study, core plugs of 1 inch in diameter and 1.5 inches long were cut from selected depths from two wells (a 24 foot long interval in PEGASUS Well 2, and a 120 ft interval in PEGASUS Well 2a). Core plugs were then hot soxhlet cleaned before measuring their mass magnetic susceptibility, and X-ray diffraction (XRD) measurements were made on small powder samples from the cleaned cores. The illite content in PEGASUS Well 2 shows a good correlation with the gamma ray log (Figure 3). The higher illite content indicates that there are more clay in the sample at lower profile where the gamma ray signal also increases. The mineral contents of illite (Figure 4) and quartz (Figure 5) quantified by magnetic susceptibility and XRD had generally similar trends with depth, and the absolute values were close within the uncertainties of each technique. There were some differences due to the limitations of each technique, for example XRD did not identify fine amorphous illite.

Good correspondences between magnetic susceptibility and other traditional results, such as gamma ray and XRD, suggested that the magnetic technique is able to be used as an independent method for quantifying and estimating mineral contents in rock samples. In the other way, it also can be used as an additional method for improved mineral contents quantification from other methods.

5. Magnetic susceptibility characterize permeability of reservoir rock

The above studies examined the low field mass magnetic susceptibility of fluids or core plug samples. In these studies, the total magnetic susceptibility signal represents the sum of all the mineral or fluid susceptibility components in the sample, including any ferrimagnetic mineral components. Since the magnetic susceptibility of ferrimagnetic minerals is extremely high compared to the main diamagnetic and paramagnetic minerals comprising a rock, the presence of any ferrimagnetic components can

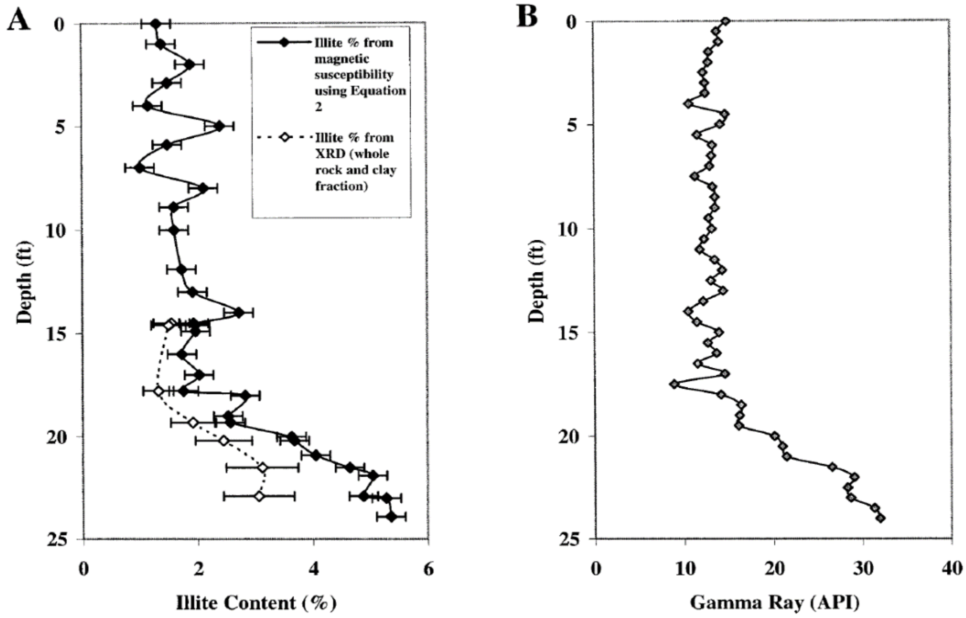

Figure 3. A) Illite percentage with depth in an interval of PEGASUS Well 02 estimated from magnetic susceptibility measured on cleaned core plugs and from XRD measurements. B) Wireline gamma log from the same interval (Potter et al., 2004).

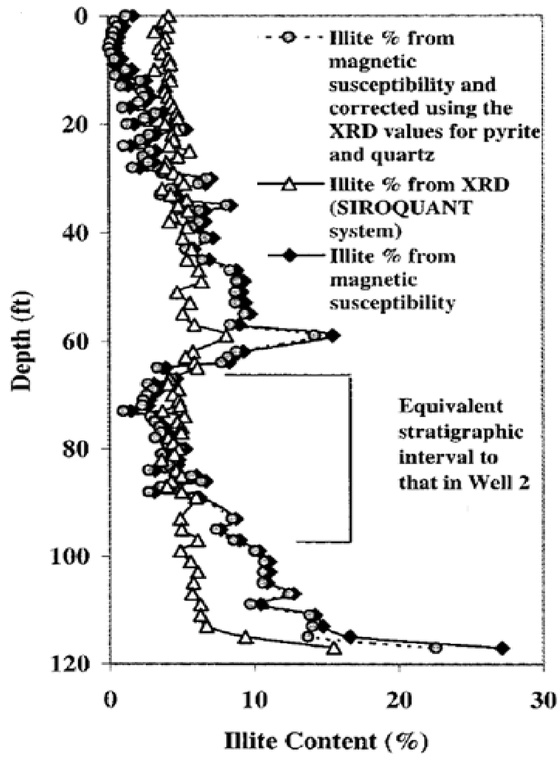

Figure 4. Illite percentage with depth in PEGASUS Well 2a from magnetic susceptibility measured on cleaned core plugs and illite percentage from XRD using the SIROQUANT system measured on powdered uncleaned core (Potter et al., 2004).

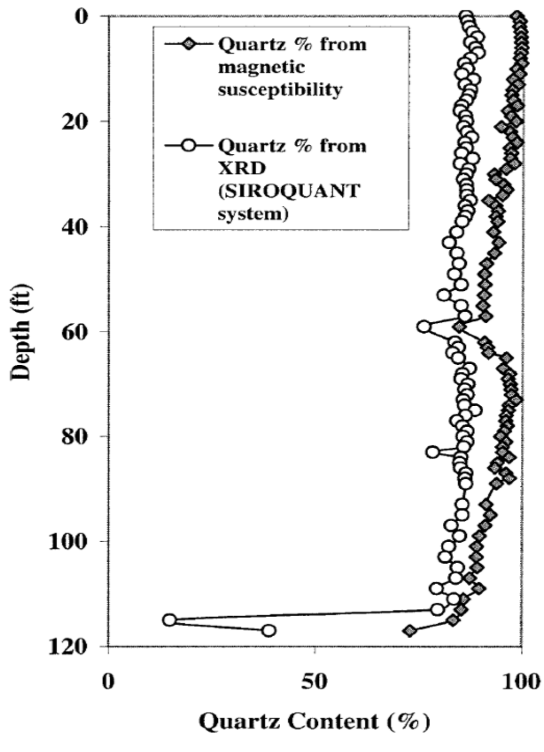

Figure 5. Quart percentage with depth in PEGASUS Well 2a from magnetic susceptibility measured on cleaned core plugs and quart percentage from XRF using SIROQUANT system measured on powerded uncleaned core (Potter et al., 2004).

potentially affect reservoir properties predicted from low field magnetic susceptibility measurements (such as clay content and fluid permeability). Fortunately, the susceptibility signal of a ferrimagnetic mineral can be eliminated by the application of high field magnetic susceptibility measurements. Studies comparing the low and high field magnetic susceptibilities of some core plugs showed that the high field susceptibility had a slightly higher correlation with permeability in a shoreface North Sea oil reservoir (Potter and Ivakhnenko, 2008), and a much higher correlation with permeability and porosity in an Arab-D carbonate reservoir (Potter et al., 2011) compared to low field susceptibility. The high field measurements effectively removed the contribution of the ferrimagnetic components to the magnetic susceptibility signal (since the ferrimagnetic signal saturates in high fields) and allowed the strong relationships between the magnetic susceptibility and the core permeability to be observed (Figure 6).

Permeability is known as one of the key reservoir parameters; therefore, the relationship between magnetic susceptibility and core permeability should be very useful in estimating the value of permeability from magnetic susceptibility measurement. Furthermore, one can also use the magnetic results for identifying permeable zone or zones of a well if there is a good correlation between magnetic susceptibility and permeability. However, the study about the relationship between magnetic susceptibility and permeability is still limited with results measured on core samples from North Sea shoreface and Arab-D carbonate reservoir as discussed above. There are many different types of reservoirs that should be studied to evaluate the application of magnetic susceptibility as a method for estimating core permeability.

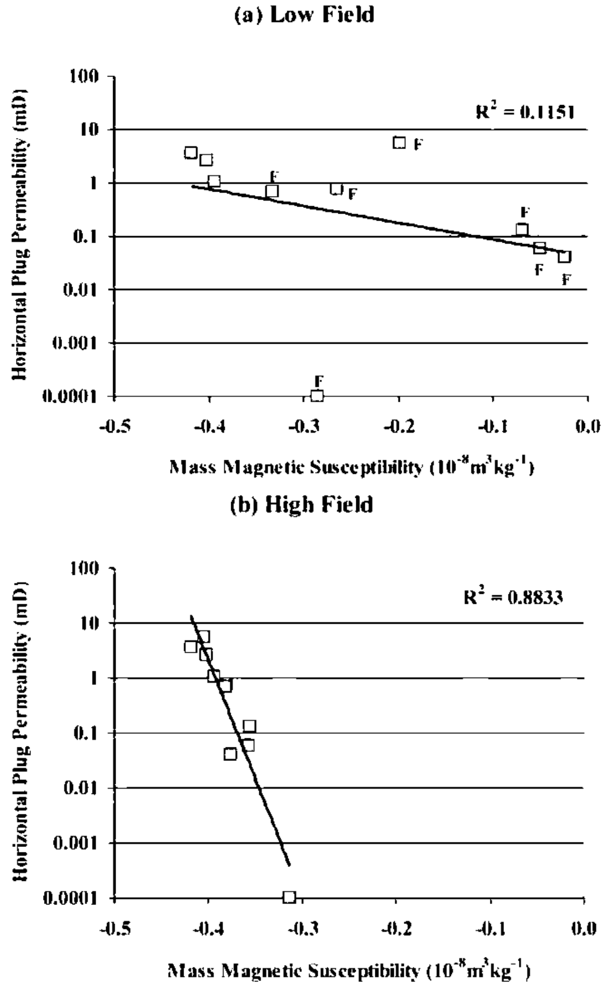

Figure 6. Correlation between horizontal plug permeability and mass magnetic susceptibility measured at (a) low field and (b) high field in carbonate reservoir in Arab-D (Potter et al., 2011).

6. Magnetic susceptibility quantifies mineralogy in shale reservoir

Magnetic susceptibility of paramagnetic minerals increases with the decrease of temperature while magnetic susceptibility of diamagnetic minerals is independent of temperature, the measurements of magnetic susceptibility in the variation of temperature is potentially used for quantifying the contents of paramagnetic and diamagnetic minerals in a sample. A study by Ebufegha and Potter (2016) showed how the mineralogy of Horn River shale samples (from British Columbia, Canada) was quantified by cooling the samples with liquid nitrogen (-100^{0}C) and measured the susceptibility as a function of temperature while it was warmed to room temperature (21^{0}C). The results were then compared with a model template for estimating the percentage of illite content in the samples. The results of illite content was also then compared with aluminium oxide (Al_2O_3) for the evaluation since most of Al_2O_3 in shales is found in clays (Figure 7).

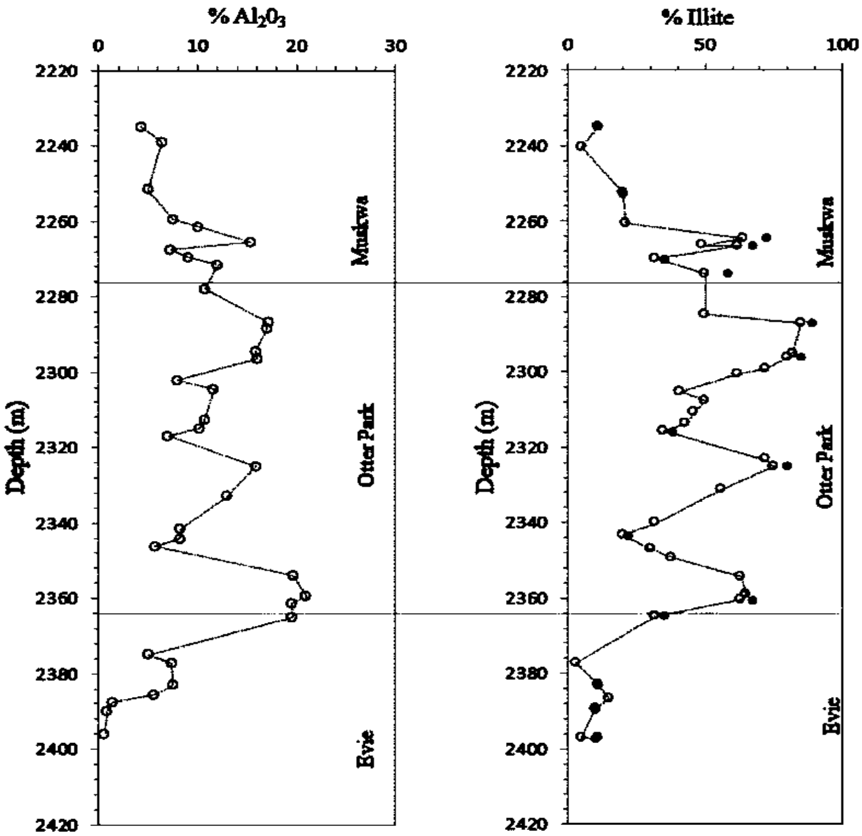

Figure 7. Comparison between the profile of illite percentage quantified from low field magnetic susceptibility measurement technique and the profile of aluminium percentage from geochemical measurements (Ebufegha and Potter, 2016).

The two profiles clearly show a good correlation between magnetically derived illite content and the percentage of aluminimum oxide from geochemical measurements.

This study gave an improved method for quantifying clay mineral contents in rock samples collected from shale reservoirs. The percentage of illite content was identified from a number of susceptibility measurements on a rock sample, therefore it gave a more accurate result than from a single susceptibility measurement as in the above study at the North Sea shoreface reservoir. The variation of magnetic susceptibility with temperature can also be used to identify types of minerals contributing to a sample when it is compared with different model templates of variation of magnetic susceptibility. This is so far the only research measuring the variation of magnetic susceptibility with temperature and it was applied to a shale reservoir in Canada. Therefore, the application of this method should be done for other types of reservoirs from different locations over the world to evaluate the efficiency of the method.

7. Magnetic susceptibility identify main lithology intervals in oil sands reservoir

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 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

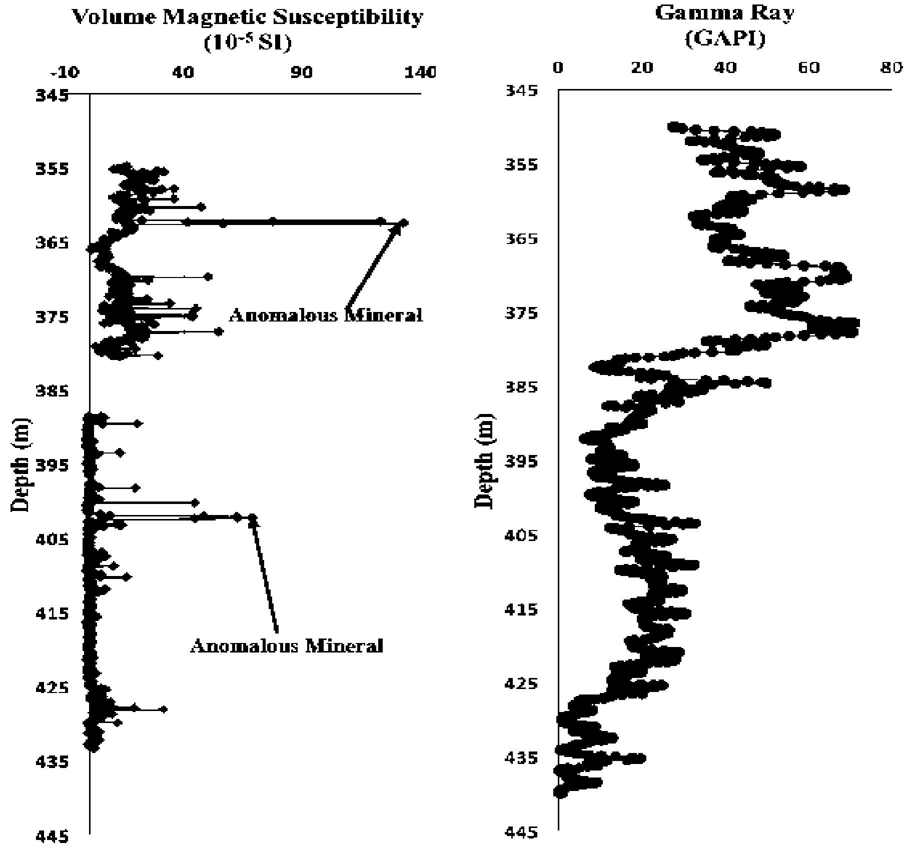

Figure 8. Comparison between volume magnetic susceptibility measured on slabbed cores and downhole gamma ray log of an oil sands well in the Northern Alberta, Canada (To et al., 2018).

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 (To et al., 2018).

Figure 8 shows a comparison between volume magnetic susceptibility and the total downhole gamma ray log of an oil sands well in the Northern of Alberta, Canada. The left hand profile of Figure 8 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 (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 (390÷425 m in Figure 7). 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 pinpointed small intervals of anomalous mineralogy as indicated in Figure 8 (often thin layers of siderite) that the gamma ray did not detect.

8. Conclusion

The results from all above studies prove that the measurement of magnetic susceptibility on reservoir rocks has a wide range of application. The magnetic susceptibility can be used to distinguish lithology from different worldwide oil fields, identifying clay mineral content in rock samples of shoreface clastic reservoir. The high field magnetic susceptibility was useful to identify clay mineral content in a carbonate rock samples. A magnetic susceptibility profile is able to distinguish main lithological interval such as shale, IHS beds and clean sands. The results shown that magnetic susceptibility pick out anomalous mineral and boundary layers better than the traditional gamma ray logs. Low temperature magnetic susceptibility measurement technique can be used for quantifying clay minerals contents in a shale reservoir by using a model template of magnetic susceptibility and temperature of a mixture containing a paramagnetic clay mineral and a diamagnetic mineral. It is clear that magnetic susceptibility has potential applications in reservoir study. The measurement of magnetic susceptibility can be used either as an independent method or an additional method to improved reservoir characterization from traditional methods.

There is also an improvement in magnetic susceptibility measurement techniques. The measurements are now able to measure the core samples without damaging the core by using the probe magnetic technique, therefore it is potentially used as a rapid, inexpensive screening tool for the initial evaluation of core samples. In the future, the measurements of magnetic susceptibility can be developed as an in situ technique as other downhole logging tools.

Author contributions

Toan Huu To - methodology, writing, review & editing; Thanh Van Nguyen and Huy Duc Dinh - writing, review & editing, supervision; Long Khac Nguyen - writing review & editing.

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