MAGNETIC SUSCEPTIBILITY AS A RAPID, NON-DESTRUCTIVE TECHNIQUE FOR IMPROVED RCAL AND SCAL PARAMETER PREDICTION

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ABSTRACT

Magnetic measurements provide a rapid, cheap and non-destructive means of characterising high resolution mineralogical variations between core samples. Until now magnetic techniques have been a relatively unexploited tool in core analysis. One of the most useful measurements is low field (initial) susceptibility. This paper will firstly demonstrate how magnetic susceptibility measurements on core plugs, and new novel processing of the results, can be used to provide a complementary means of obtaining rapid predictions of key petrophysical parameters that would otherwise be obtained by more time consuming and expensive conventional means. The magnetic measurements can allow rapid petrophysical appraisals to be made at an early stage, long before the other RCAL or SCAL data becomes available, since all the core plugs from an entire well can potentially be magnetically screened in one day. Strong correlations have been observed between magnetically derived illite content and permeability in an oilfield where the porosity-permeability relationship is very poor. This has provided a new, rapid permeability predictor where prediction had previously been problematic. The magnetic measurements in this case also correlate with the wireline gamma ray signal. Moreover, correlations have also been observed between the magnetic measurements and a key SCAL parameter, the cation exchange capacity per unit pore volume (Q_v). Whilst the present results mainly concentrate on core plug data, the magnetic technique can also be applied at a variety of other scales, from high resolution probe measurements on slabbed core to measurements on whole core. This means that high resolution magnetic data can be obtained without the need to cut core plugs. Results have shown that this is particularly useful for unconsolidated core.

INTRODUCTION

Low field magnetic susceptibility measurements provide a rapid, cheap and non-destructive means of characterising high resolution mineralogical variations between core samples. Magnetic susceptibility is defined as the magnetization divided by the applied field, and can be expressed either in terms of the susceptibility per unit mass or per unit volume. A magnetic susceptibility measurement on a core plug can be made in under 5 seconds and requires no extra preparation of the sample. In spite of their rapidity and ease of measurement they are not commonly applied to the plugs used in an oil company's routine (RCAL) or special core analysis (SCAL) programmes. This paper will demonstrate how magnetic susceptibility measurements on routine core plugs (1 inch diameter and 1.5 inches long) can be used as a complementary technique to provide rapid predictions of key petrophysical parameters that would otherwise be obtained by more time consuming and expensive conventional means.

Table 1. Magnetic susceptibilities of some relevant reservoir minerals and fluids.

MINERAL TYPE	MINERAL	MAGNETIC SUSCEPTIBILITY PER UNIT MASS (10^{-8} m^3 kg^{-1})
Diamagnetic matrix minerals and reservoir fluids:	Quartz	-0.5 to –0.6 (-0.55 *)
	Calcite	-0.3 to -1.4
	Orthoclase feldspar	-0.49 to -0.67
	Kaolinite	-2.0
	Forties field formation water	-0.87
	Forties field crude oil	-1.02
Paramagnetic permeability controlling clays:	Illite	15.0
	BVS Chlorite	13.6 †
	CFS Chlorite	52.5 †
Ferrimagnetic minerals:	Magnetite	2^4 to 11^4

* This value, the mid-point of the range, is used in this paper for the susceptibility of quartz in Equations (1) and (2).

† From [1], who detail the localities BVS, CFS. Kaolinite value from [2], and values for fluids from [3]. All other values from [4].

The magnetic susceptibility values of typical reservoir rocks and fluids have recently been detailed [3,5] and some of these are summarised in Table 1. The main matrix minerals comprising reservoir rocks, such as quartz or calcite, are diamagnetic (low, negative magnetic susceptibility), whereas the permeability controlling clays, such as illite or chlorite, are paramagnetic (positive magnetic susceptibility, significantly higher than the diamagnetic minerals). Therefore the sign of the raw magnetic susceptibility values of the routine core plugs is potentially useful information, since it can provide a rapid indication of the main lithological zonations. Clean sands should be characterised by net negative magnetic susceptibility, whereas muddy sands and shales should be characterised by net positive susceptibility. Since these broad lithological zonations are generally characterised by different fluid permeability values, then the sign of the magnetic susceptibility can also give a first pass indication of the broad permeability zonations. In general, one would expect high permeability in the clean sands (except in low permeability naturally cemented regions), and lower permeability in the muddy sands and shales, where there are increased amounts of permeability controlling clay. Moreover, it has recently been shown [5] that raw magnetic susceptibility measurements can be processed to determine mineral percentages in simple systems, and this has been applied to quantify illite and quartz content simultaneously in some North Sea shallow marine shoreface facies. Note that the presence of small amounts of ferrimagnetic minerals, which could potentially influence the results, can easily be identified using magnetic remanence measurements [5]. Ferrimagnetic particles can acquire a remanence, whereas diamagnetic and paramagnetic minerals do not.

In addition to being rapid, cheap, and non-destructive, the magnetic technique also requires no extra preparation of the sample, and the measurements can be made either before or after core cleaning. In fact, by making measurements both before and after cleaning, one could potentially quantify any anomalous effects resulting from the cleaning process. Conveniently, the measurements can be performed on the identical suite of routine core plugs (and therefore at the same volume scale) that are used for determining permeability and porosity and other petrophysical parameters. This has the added advantage that it avoids any depth shifting issues. The measurements can also be performed on equipment that is very portable. This means that measurements can even be made at the well-site. In addition, unlike acoustic measurements, good results can even be obtained from plugs that may have been accidentally fractured either during coring or at a subsequent time. This means that sidewall cores, and even drill cuttings, can potentially be used.

Many of the points mentioned above are advantages over other core analysis techniques. For instance, laboratory nuclear magnetic resonance (NMR) measurements require significant sample preparation (saturating the sample with an appropriate fluid), measurement and analysis time. Note also that there was no downhole NMR log data for the well in the present study.

Standard core gamma ray techniques are generally only applied to whole core samples, and have lower resolution than the current magnetic equipment that is available. A correlation between the magnetic susceptibility results and the gamma ray signal might be expected in this well, because illite gives a strong paramagnetic susceptibility signal and also is a significant contributor to the natural gamma ray emissions primarily in the form of radioactive potassium (K^{40}). Unfortunately there was little core gamma ray data for the well studied here, and no downhole spectral gamma ray log was run. However, downhole total gamma ray log data was available. Thus, part of this paper examines the relationship between the total downhole gamma ray signal and the depth matched magnetic measurements on core plugs.

Whilst the majority of the present results were obtained from core plugs, magnetic susceptibility measurements can also be performed at smaller probe [6,7] and larger whole core scales [6, 8-10], allowing high resolution and upscaled data to be collected on slabbed or whole core without the need to cut plugs. The results presented here on core indicate the potential usefulness of a downhole magnetic susceptibility tool for *in-situ* permeability prediction, supporting the suggestions of [11]. Currently there is no such commercially available downhole tool in the petroleum industry, although a smaller scale downhole sonde is available, and larger scale prototypes also exist.

RAW MAGNETIC SUSCEPTIBILITY SIGNAL: RELATION TO PERMEABLE ZONES

The magnetic measurements were performed using a Molspin susceptibility bridge [12], which applies a weak field of 700 μT to the core plug and measures the magnetic susceptibility along the core plug axis. Figure 1 shows a simple division of the cored section of PEGASUS Well 2 (comprising clastic shoreface reservoir intervals) into zones where the routine core plugs exhibit either net negative or net positive magnetic susceptibility, along with a comparison of the broad permeability zonations.

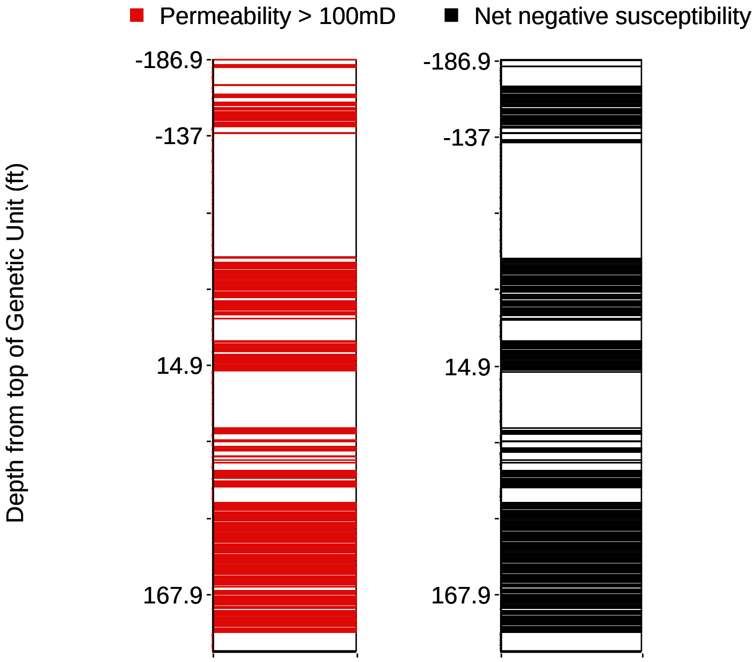

Figure 1. A comparison of the sign of the raw magnetic susceptibility signal and the main permeability zones with depth in a North Sea oil well. Net negative magnetic susceptibility correlates with high permeability clean sand reservoir intervals (containing predominantly diamagnetic quartz), and net positive magnetic susceptibility (white areas) correlates with the lower permeability muddy sand and shale intervals (containing

increased amounts of paramagnetic illite clay). Depths are confidential and are shown arbitrarily from the top of one genetic unit.

There is an extremely good correspondence between the two parameters. Intervals containing plugs exhibiting high permeability (> 100 mD) correspond almost exactly to those exhibiting net negative magnetic susceptibility, whilst intervals containing plugs with lower permeability (< 100 mD) correspond to those exhibiting net positive susceptibility. The reason for this strong correspondence is directly related to the mineralogy comprising the different zones. The high permeability intervals are the clean sand units containing primarily diamagnetic (negative susceptibility) quartz and feldspars (indicated by a combination of XRD, SEM, thin section, and wireline gamma ray data). The quartz content, which is generally at least 95 % in these samples, dominates the magnetic susceptibility signal over the small amounts of paramagnetic or ferrimagnetic (positive susceptibility) minerals present. Conversely, the lower permeability intervals are generally muddy sands and shales containing an increased proportion of paramagnetic clays (mainly illite) and possibly some ferrimagnetic minerals (such as magnetite). The results show that a rapid, simple classification of the main permeability zonations can be obtained directly from the sign of the raw magnetic susceptibility values without any processing of the data.

Some of the minor differences between the magnetic and permeability zonations are due to low permeability naturally cemented regions that are not picked out by the magnetics. This is a limitation of the magnetic technique, but was not a major problem in this well where the magnetic measurements were essentially a proxy for clay (illite) content. In any case the cemented zones can be easily picked out by the bulk density log. In some cases natural cements (such as calcite cemented regions in the North Sea) can often contain small amounts of other magnetic minerals with high susceptibility (such as magnetite), and so the magnetic technique is capable of pin-pointing these particular cemented zones also.

PROCESSED MAGNETIC SUSCEPTIBILITY

The measured raw magnetic susceptibility value represents the combined signal from all the diamagnetic, paramagnetic and ferrimagnetic etc mineral components in the formation, which means that samples can have a net positive or negative magnetic susceptibility dependent upon their composition. From thin section petrography, scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis the composition of the present samples can be approximated as a simple mixture of quartz and illite [5]. Other minerals are present in minor amounts. The magnetic susceptibility results allow both the illite and quartz content to be estimated simultaneously. Following [5] the total magnetic susceptibility signal of the rock sample per unit mass, χ_T, is the sum of the illite (paramagnetic) and quartz (diamagnetic) components:

$$\chi_T = \{(F_I)\ (\chi_I)\} + \{(1 - F_I)\ (\chi_Q)\} \tag{1}$$

where F_I is the fraction of illite, $(1- F_I)$ is the fraction of quartz, and χ_I and χ_Q are the magnetic susceptibilities per unit mass of illite and quartz as shown in Table 1. Note that χ_T, χ_I, and χ_Q could alternatively be expressed as volume susceptibilities (k_T, k_I and k_Q). Since χ_T can be measured (rapidly using a magnetic susceptibility bridge as described earlier), and χ_I and χ_Q are known, then the fraction of illite, F_I, is given by:

$$F_I = (\chi_Q - \chi_T) / (\chi_Q - \chi_I) \qquad (2)$$

It is then a simple matter to also obtain the fraction of quartz $(1- F_I)$. Theoretically, by putting $\chi_T = 0$ in Equation (2), the transition from a net negative to a net positive magnetic susceptibility signal occurs at a critical illite content of about 3.54 % for a rock consisting of a simple model mixture of quartz and illite.

The method can also be applied to other simple mineral mixtures in sediments of different composition. For example, in clastics one could have simple mixtures of quartz (diamagnetic component) and chlorite (paramagnetic component), and in carbonates one might have calcite (diamagnetic component) and magnetite (ferrimagnetic component). The relevant components would merely replace the respective ones in the above equations. The relevant components for the model mixture equations can be obtained from some preliminary XRD, thin section analysis, SEM or from downhole data using standard crossplot charts of different wireline parameters. If more than one paramagnetic clay is present in a sample, such as a combination of illite and chlorite, the magnetic measurements will see the combined signal from both these components and cannot unfortunately distinguish between them. The extension of the method to quantify more than two main components has been discussed in [5]. Note that whilst the present study has been undertaken on a clastic reservoir, we have also undertaken some initial magnetic measurements on carbonates. Different carbonates appear to be distinguishable based on their magnetic signature, and further work is in progress to compare carbonate magnetic properties with petrophysical parameters.

Correlation with Permeability

The raw magnetic susceptibility results from the clastic reservoir were processed using Equations (1) and (2) to obtain an estimate of the illite content. Figure 2 shows a crossplot of the magnetically derived illite content versus the horizontal plug air permeabilities on the same suite of core plugs from PEGASUS Well 2.

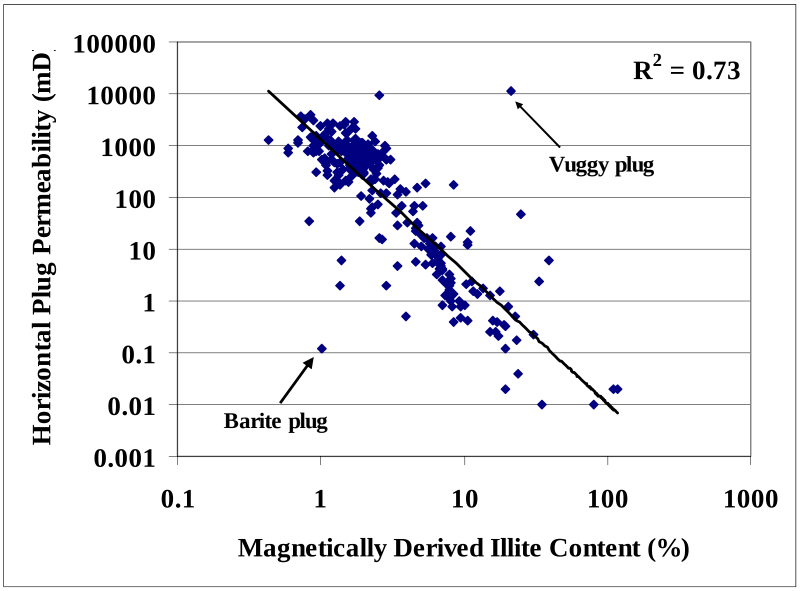

Figure 2. Crossplot of magnetically derived illite content versus horizontal plug air permeability in PEGASUS Well 2.

The results show that very small increases in the magnetically derived illite content, of the order of 1-2 %, correspond to dramatic decreases in permeability of about 2-3 orders of magnitude. There is a very strong correlation between the two parameters with the power regression coefficient of determination $r^2 = 0.73$ for the 297 plugs measured. If one omits only two anomalous points from the dataset (the low permeability barite plug and the vuggy high permeability plug as shown in Figure 2) then the correlation is even better with $r^2 = 0.80$. This is a significant improvement over the poor relationship between porosity and permeability, where $r^2 = 0.25$ (Figure 3) for the same suite of horizontal plugs.

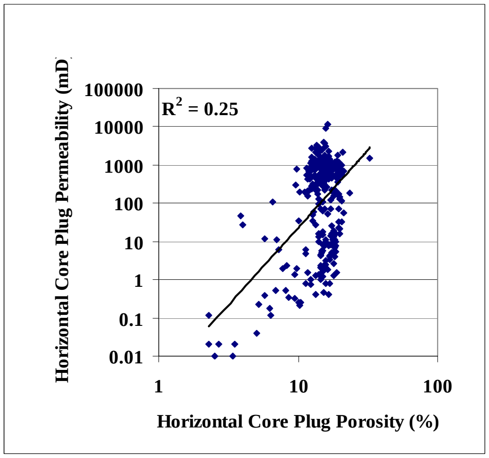

Figure 3. Crossplot showing the poor relationship between porosity and permeability for the same horizontal core plugs as in Figure 2.

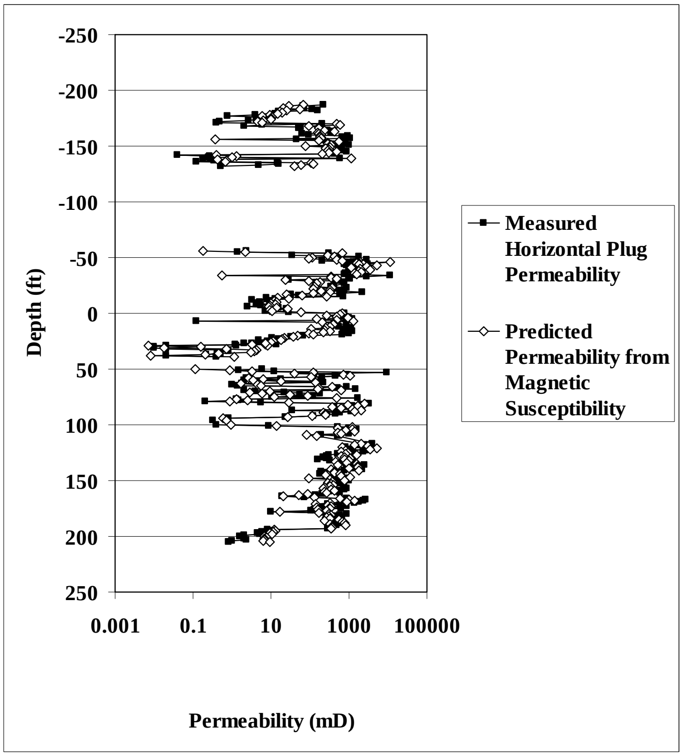

Figure 4. The variation with depth of the magnetically derived predicted permeability (using the regression line of Figure 2) and the horizontal plug air permeability values in PEGASUS Well 2.

Figure 4 shows the predicted horizontal plug air permeabilities derived from the magnetics with depth (using the equation of the regression line in Figure 2), along with the measured horizontal plug permeabilities. It is apparent that the two trends follow each other very closely. The stacked shoreface coarsening upwards parasequences are clearly picked out by the magnetically derived predictions.

Correlation with Wireline Gamma Ray

Figure 5 shows a reasonably strong correlation between the raw (unprocessed) magnetic susceptibility measurements and the total wireline gamma ray signal. The intercept of the regression line on the gamma ray axis conveniently gives the critical gamma ray value below which the rock in this well has a net negative susceptibility (clean sand) and above which it has a positive susceptibility (more muddy sand) and, as detailed earlier, also represents a critical illite content of about 3.54 % in a simple quartz plus illite model system. In this case it indicates that the intercept of the regression line occurs at about 20 API.

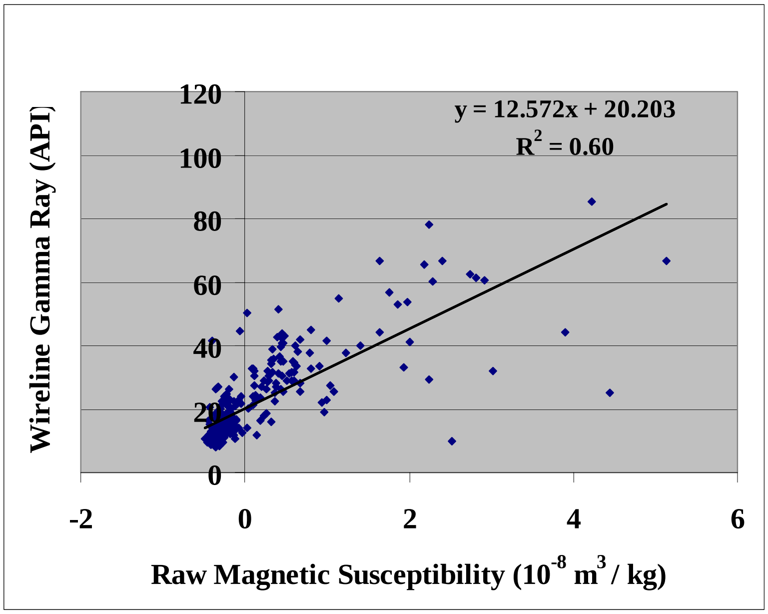

Figure 5. Crossplot of the raw mass magnetic susceptibility of the horizontal core plugs versus the wireline gamma ray.

This approach using magnetics may provide a more accurate and less arbitrary means of estimating the wireline log gamma ray cut-off for identifying clean sand units from low permeability muddy sands in transitional zones above true shales. Moreover, the approach could be particularly useful when one uses drilling muds that themselves give a high gamma ray signal (such as potassium chloride), yet have low values of magnetic susceptibility. Potassium chloride is diamagnetic (low, negative magnetic susceptibility), and therefore does not exhibit a significant magnetic susceptibility compared to the paramagnetic permeability controlling clays. Where potassium chloride has been used as a drilling mud, this will merely produce a higher intercept on the crossplot of raw magnetic susceptibility versus wireline gamma ray. This type of plot could therefore be used to accurately distinguish changes in lithology even in the presence of a high gamma ray mud. Furthermore, by plotting the magnetically derived illite content against the wireline gamma ray one can obtain the gamma ray cut-off for any chosen illite content. This is shown in Figure 6, for the same points as in Figure 5, with both parameters plotted on logarithmic scales. The power correlation coefficient of determination is high with $r^2 = 0.70$.

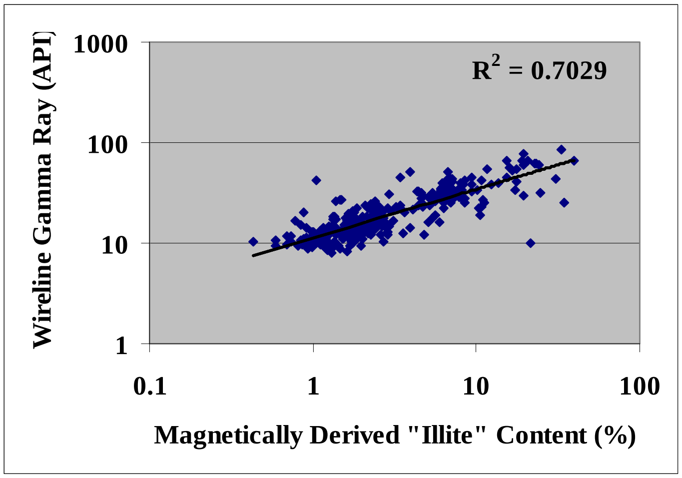

Figure 6. Crossplot of the magnetically derived illite content versus wireline gamma ray.

Correlation with the SCAL parameter Q_v

Since the cation exchange capacity per unit pore volume (Q_v) is related to the clay content, then one might expect a relationship between Q_v and magnetic susceptibility. This was tested in some core plugs from another North Sea oil well. Figure 7 shows a strong correlation for the few plugs where Q_v data was available. The relationship is in the theoretically expected direction, in that the higher the Q_v the higher the magnetic susceptibility.

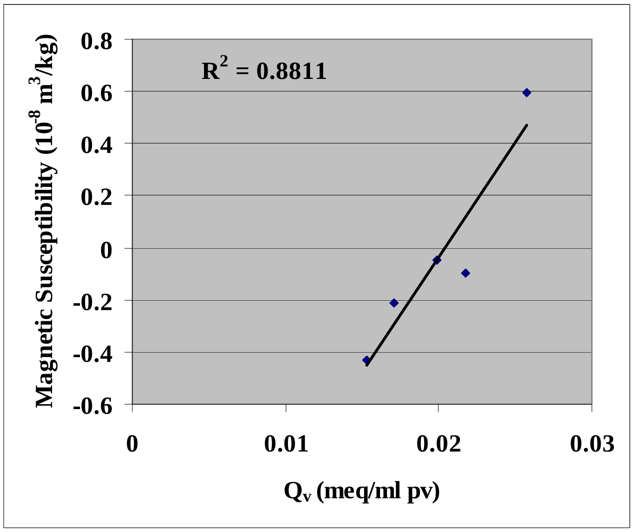

Figure 7. The cation exchange capacity per unit pore volume (Q_v) versus mass magnetic susceptibility for SCAL plugs in a North Sea oil well.

The magnetic measurements potentially allow rapid estimates of Q_v to be obtained over large intervals, complementing the (often scarce) actual Q_v SCAL measurements. Q_v is normally determined from costly and time consuming wet chemistry measurements.

Determination of Q_v measurements from a few representative samples could be calibrated against magnetic measurements, and subsequently further magnetic measurements on a large number of other samples could be made rapidly to predict Q_v throughout a well.

PROBE MAGNETIC SUSCEPTIBILITY: APPLICATION TO UNCONSOLIDATED CORES

We have a probe (Bartington MS2E) that can measure volume magnetic susceptibility at high resolution on slabbed core. This allows very high resolution at the lamina scale, but the sensitivity is slightly lower than the equipment for the plug measurements. The probe is also particularly useful in cases where you don't want to cut plugs, or for unconsolidated core where core plug cutting can be problematic. A typical measurement time for 100 measurements at 1 cm intervals on a metre length of core would be about 1 hour. Figure 8 shows a typical volume magnetic susceptibility profile in a 1m section of a thinly bedded turbidite reservoir. The lower values of magnetic susceptibility in the sandy intervals is clearly evident. None of the values are negative in this case, because there is some clay even in the cleanest sand. Note also that the magnetic results show that there is grading within the individual thin sand packages. Whilst there is not room in this paper to detail all the correlations between the magnetics and other petrophysical parameters, it is worth noting that these magnetic profiles can be related to clay content, grain size and permeability.

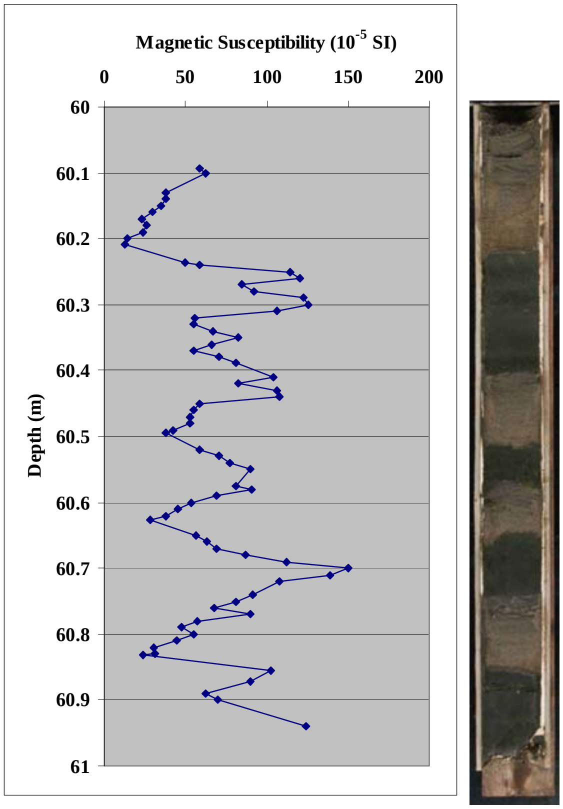

Figure 8. Probe volume magnetic susceptibility in a thin interbedded sand and shale turbidite reservoir.

CONCLUSIONS

The main conclusions from this work can be summarised as follows:

- The results demonstrate that magnetic susceptibility measurements have the potential to be an extremely useful complementary RCAL analysis technique, allowing rapid, cheap, sensitive, and high resolution petrophysical appraisals (of clay content and permeability) to be made long before the RCAL and SCAL data becomes available. The entire suite of core plugs from a well can easily be magnetically screened in one day, without requiring any extra sample preparation.
- The sign of the raw magnetic susceptibility values of routine core plugs in a North Sea oil well (shoreface facies) strongly correlated with the main permeability zonations. Net negative susceptibility values corresponded to high permeability clean sand units, containing predominantly diamagnetic quartz and feldspars. Net positive susceptibility values corresponded to lower permeability muddy sand and shale units, containing an increased proportion of paramagnetic illite clay.
- The magnetic susceptibility signal can be processed to provide quantitative mineralogical information. Significantly, the magnetically derived illite content exhibited a strong correlation with the core plug permeability. This has generated an excellent rapid new permeability predictor from core magnetic measurements in this oil well where the relationship between core porosity and permeability is very poor. The magnetic measurements are essentially a proxy for the permeability controlling illite clay in this case.
- The magnetic susceptibility measurements on core plugs correlated with the downhole wireline gamma ray. The relationship (using the raw or the processed magnetic susceptibility values) can be used to quantify the wireline gamma ray cut-off for distinguishing between clean and muddy sand in transition zones. This approach could be particularly useful when employing drilling muds which themselves generate a high gamma ray signal, but a low magnetic susceptibility, such as potassium chloride. Crossplotting the magnetic susceptibility and wireline gamma ray data would potentially allow the changes in the formation to be identified even in the presence of the high drilling mud gamma ray signal. The relationship between magnetic susceptibility and wireline gamma ray can in this case also be exploited to allow quantification of illite content directly from the wireline gamma ray, thereby providing additional information from this routine downhole tool.
- The magnetic measurements correlate with the cation exchange capacity per unit pore volume (Q_v). The magnetic measurements could therefore potentially be used to rapidly generate predictions of this important SCAL parameter over large intervals.
- Probe magnetic measurements can provide rapid high resolution profiles on slabbed core without the need to cut plugs. This is particularly useful for unconsolidated core.
- Whilst the results in the present study were obtained from core samples they suggest the potential usefulness of a downhole magnetic susceptibility tool for *in-situ* parameter prediction.

ACKNOWLEDGEMENTS

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