CLAY TYPING - SENSITIVE QUANTIFICATION AND ANISOTROPY IN SYNTHETIC AND NATURAL RESERVOIR SAMPLES USING MAGNETIC SUSCEPTIBILITY FOR IMPROVED PETROPHYSICAL APPRAISALS

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ABSTRACT

This paper describes a systematic theoretical and experimental magnetic analysis of different clay types for reservoir characterisation. Most clays (for example, illite, chlorite) are paramagnetic, whereas some clays (for example, kaolinite) and matrix minerals such as quartz and calcite are diamagnetic. Model magnetic susceptibility and hysteresis plots for various concentrations of different clays in a quartz matrix were first produced. Experimental measurements were then undertaken for comparison on a series of synthetic reservoir samples comprising various concentrations of dispersed clays in a quartz matrix. The experimental magnetic measurements showed substantial agreement with the model magnetic values, and with estimates of the magnetic susceptibility based on XRD derived mineral contents. Subsequent results for natural reservoir samples (turbidites) also showed a strong correspondence between the measured high field magnetic susceptibility, and that estimated from XRD derived mineral contents. The magnetic measurements potentially provide a sensitive, rapid, quantitative technique, which can be used on a routine basis, and would also be a useful complement to XRD.

Moreover, we have observed improved correlations between permeability and high field magnetic susceptibility (where the signal is dominated by paramagnetic permeability controlling clays and the influence of ferrimagnetic impurities is minimised), compared to low field magnetic susceptibility (where the signal represents the sum of all components and can be influenced by ferrimagnetic impurities). Furthermore, magnetic susceptibility measurements before and after core cleaning have suggested that some paramagnetic clay is removed (and not just the residual reservoir fluids) during hot soxhlet cleaning particularly in medium to high permeability samples. The results are consistent with permeability measurements undertaken before and after core cleaning. Magnetic measurements before and after cleaning, in conjunction with the permeability measurements after cleaning, could thus potentially be used to help estimate the permeability of the uncleaned sample with the original clay content. In addition, we show that full 3-D anisotropy of magnetic susceptibility (AMS) measurements, which can be determined very rapidly on single plugs, correlate with the total magnetically derived illite content.

INTRODUCTION

Several recent studies (Potter et al, 2004; Potter, 2005; Ivakhnenko, 2006; Ivakhnenko and Potter, 2006a; Potter, 2007) have demonstrated the potential uses of low field (initial) magnetic susceptibility for reservoir characterisation, quantifying mineralogy, and for predicting important petrophysical parameters. In particular, these measurements provide a rapid, non-destructive complement to XRD for determining the content of permeability controlling clays such as illite (Potter et al, 2004), and subsequently predicting permeability (Potter, 2005, 2007), even in cases where the relationship between porosity and permeability is very poor. The measurements also correlate with the cation exchange capacity per unit pore volume (Qv), the flow zone indicator (FZI) and the downhole gamma ray signal (Potter, 2005; 2007). Subsequently, hysteresis measurements on reservoir rocks and fluids were made so that the magnetic susceptibility at a range of both low and high fields could be determined (Ivakhnenko and Potter, 2006b). This has the advantage over a single low field measurement in allowing one to distinguish different mineral components in a sample. In particular, the presence of small amounts of strongly magnetic ferro- or ferrimagnetic components can easily be recognised by characteristic “kinks” or “loops” at low fields, whereas the high field behaviour should reflect only the diamagnetic components (generally the matrix minerals such as quartz or calcite) plus the paramagnetic components (generally permeability controlling clays). The present paper extends the work to a systematic analysis of synthetic reservoir samples comprising different clay minerals. Model hysteresis curves for different concentrations of particular clays in a quartz matrix were first produced. The results were then compared with experimental measurements for a series of selected samples. The magnetic measurements were also compared with X-ray diffraction (XRD) derived contents of the various clays. Subsequently a comparison of magnetic hysteresis and XRD was made on some turbidite reservoir samples. An important potential advantage of high field hysteresis measurements is that they ought to show even better correlations with permeability (compared to low field magnetic susceptibility measurements), because the estimates of paramagnetic permeability controlling clays should be improved since the effects of any ferro- or ferrimagnetic impurities is minimized at high fields. These strongly magnetic impurities should saturate at high fields. The present paper will demonstrate the improved correlations between high field magnetic susceptibility and permeability. Furthermore, it will be shown how magnetic measurements can quantify the effect of core cleaning, and how the results are consistent with permeability measurements both before and after core cleaning. Finally, we will show how rapid anisotropy of magnetic susceptibility (AMS) measurements correlate with the total magnetically derived illite content.

MAGNETIC HYSTERESIS CURVES FOR SYNTHETIC RESERVOIR SAMPLES COMPRISING DIFFERENT CLAY MINERALS

Model Hysteresis Curves

The purpose of this study was to make systematic magnetic measurements on different clay + sand mixtures in order to quantify clay content and aid interpretation of reservoir rocks. Four types of clay were studied: illite, montmorillonite, kaolinite and chlorite. Model type curves were initially produced based on previously published values (Thompson and Oldfield, 1986; Hunt et al, 1995) of the magnetic susceptibility of the individual clays and quartz matrix. These are shown in Figures 1a-d. These figures show how sensitive such hysteresis measurements are for accurately quantifying the content of each clay, especially for very low concentrations. This can be important, since small changes in illite content, for instance, can significantly affect fluid permeability. These mineralogical changes may not necessarily be readily identified by other methods, even by XRD, which is generally regarded as semi-quantitative. The magnetic measurements provide a rapid, cheap, sensitive complement to XRD, but should not be regarded as a replacement for XRD. Although the magnetic measurements alone could distinguish a diamagnetic clay (kaolinite) from a paramagnetic clay (illite), they do not unambiguously distinguish between different types of paramagnetic clay (illite, chlorite etc). However, once the type of clay is known (from some representative XRD, SEM, thin section or other measurements), then the magnetics can be used to rapidly and cheaply provide high resolution quantitative data on a much larger number of samples than would be possible in an equivalent time period from XRD measurements.

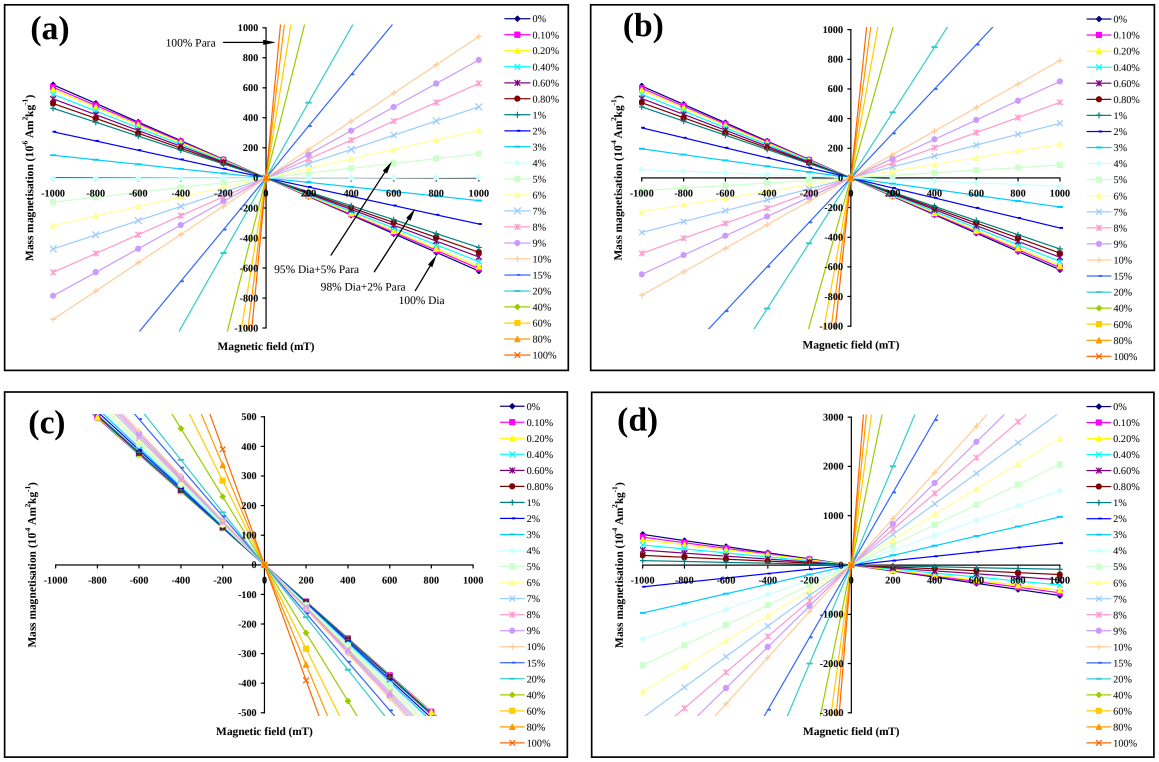

Figure 1. Model magnetic hysteresis curves for various concentrations of different clay types in a quartz matrix. (a) Illite + quartz. (b) Montmorillonite + quartz. (c) Kaolinite + quartz. (d) Chlorite + quartz.

Experimental Hysteresis Curves

For each clay type different concentrations were dispersed with quartz sand (using the methodology described by Orr et al, 2005) to provide a set of test synthetic reservoir samples (supplied to us by Imperial College). Figure 2 shows the magnetic hysteresis curves for samples containing 10% of each of the individual clay types dispersed in quartz matrix. Figure 2a shows the expected model curves and Figure 2b the corresponding experimental results. The experimental curves were obtained by a Variable Field Translation Balance (VFTB) in the rock magnetic laboratory of the Ludwig-Maximilians University in Munich, Germany. For each clay type the experimental curves were quite close to those expected from the models. However, the values were slightly lower in all cases than the expected values based on the clay concentrations given by Imperial College. A similar picture emerged from the experimental results of other concentrations of the clays. In order to reconcile these slight differences between the experimental values and the expected model values it was then decided to check the experimental magnetic results against XRD derived values, in order to test the validity of the magnetic data, and check whether the given concentrations were indeed accurate.

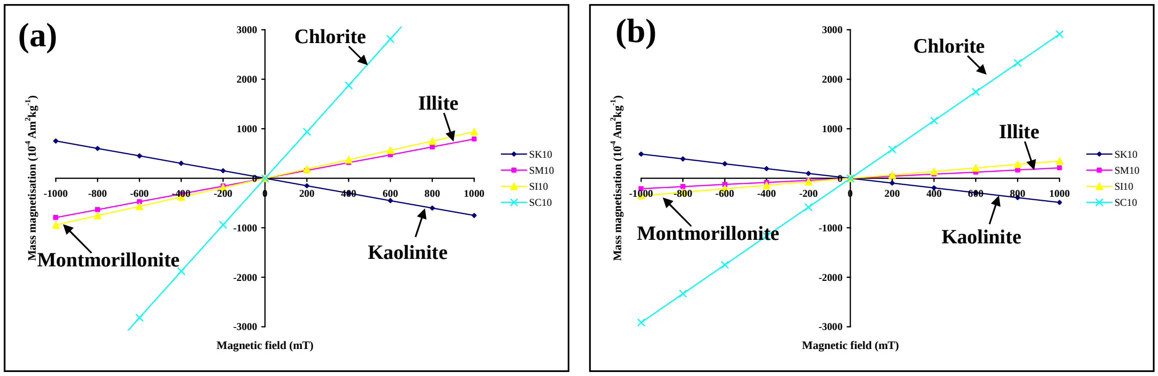

Figure 2. (a) Model magnetic hysteresis curves for 4 types of clay (each with 10 % clay concentration in a quartz matrix). (b) Corresponding experimental results on synthetic samples with nominal clay concentrations of 10 %.

Comparison between Magnetic and X-Ray Diffraction Results

The clay + sand samples were sent for XRD analysis. The compositions of all the samples derived from XRD were then used to give an expected high field magnetic susceptibility for each sample. These were then compared to the actual values from hysteresis measurements. The results are summarised in Table 1 (note SI5 means 5 % illite, SM3 means 3 % montomorillonite, SK5 means 5 % kaolinite and SC8 means 8 % chlorite etc). The values correspond very well, in particular for the illite, montmorillonite, and kaolinite samples. This shows that the original magnetic estimates of clay content for these samples were very close to those obtained from XRD. This meant that the magnetics correctly predicted slightly lower clay contents than labelled on the samples. One reason for the lower clay contents, compared to the labelled values, could be that some clay was removed during flow experiments by Corex before we obtained the samples (future studies could quantify this by making magnetic measurements before and after the flow experiments). For the sand + chlorite mixtures, however, the XRD derived values of chlorite content appeared to be too high compared to the labeled values. The magnetic measurements gave values that were much closer to those expected. This is being investigated further, but might be due to the assumptions regarding chlorite composition in the XRD program.

Table 1. Clay + quartz matrix mixtures: expected magnetic susceptibilities based on XRD derived mineral contents and measured susceptibilities from hysteresis results.

Sample	Expected theoretical mass magnetic susceptibility derived from XRD (10^{-8} m^3 kg^{-1})	Measured experimental mass magnetic susceptibility (10^{-8} m^3 kg^{-1})
Illite		
SI5	-0.406	-0.425
SI10	0.350	0.351
Montmorillonite		
SM3	-0.174	-0.147
SM8	-0.023	-0.020
SM10	0.211	0.209
SM15	0.679	0.888
Kaolinite		
SK5	-0.636	-0.579
SK10	-0.509	-0.488
Chlorite		
SC8	7.826	2.337
SC10	6.498	2.915

A COMPARISON OF MAGNETICS AND XRD IN TURBIDITES

Hysteresis curves were determined for various samples of “uniform” and “graded” turbidite. All the samples exhibited “kinks” at low field indicating the presence of ferrimagnetic minerals. At high field all the hysteresis curves exhibited straight lines with differing slopes for each sample, indicating different amounts of paramagnetic minerals. To demonstrate that the magnetics are picking out genuine meaningful differences we compared the measured high field magnetic susceptibility from the hysteresis curves with the expected high field susceptibility based on XRD derived mineral contents (Table 2). The results show a good correspondence, demonstrating that the magnetic measurements are capable of pin-pointing subtle real differences in these reservoir samples.

Table 2. Turbidite samples: a comparison of XRD derived and measured high field magnetic susceptibilities.

Sample	XRD derived high field magnetic susceptibility (10^{-8} m^3 kg^{-1})	Measured high field magnetic susceptibility (10^{-8} m^3 kg^{-1})
"Uniform" Turbidite		
50.24	1.018	1.034
S3	9.363	9.406
"Graded" Turbidite		
60.16	1.545	2.379
60.50	4.651	3.764
60.61	4.355	4.355
60.82	2.371	3.093

THE USE OF HIGH FIELD MAGNETIC SUSCEPTIBILITY FOR IMPROVED CORRELATION WITH PERMEABILITY

High field magnetic susceptibility (the slope of the hysteresis curve at high fields) should be a better reflection of the paramagnetic clay content than low field measurements, since any strongly magnetic ferro- or ferrimagnetic material is likely to have saturated in the high fields. If the permeability is controlled primarily by paramagnetic clays (rather than natural cements) then the high field slope should show a correspondence with permeability. The steeper (more positive) the slope the greater amount of paramagnetic clay and the lower the permeability. Figure 3 shows some typical examples of hysteresis curves that clearly demonstrate this trend from samples from a low permeability zone in a North Sea oil well. In this example most of the "curves" are straight lines, which means that the low field values are similar to the high field values and are not affected by any ferrimagnetic material. One of the samples (5-67.1) exhibits a small kink at low fields indicating some small amounts of ferrimagnetic material. The susceptibility is actually slightly positive at low fields, but negative at high fields. Therefore the low field value would slightly overestimate the actual content of paramagnetic clay in the sample, if one didn't correct for the ferrimagnetic material present (which increases the low field magnetic susceptibility). In such cases one might therefore expect high field magnetic susceptibility to show better correlations with permeability than low field susceptibility, since the high field measurements are a better indication of the true paramagnetic clay content. We tested this in another well, where the hysteresis curves were not straight lines, and where there were clear differences between the low field and high field measurements. Figure 4(a) shows a plot of illite content derived from low field measurements versus permeability. The power correlation coefficient of determination is already very good with $R^2 = 0.89$, however there is some scatter about the regression line. Figure 4(b) shows a corresponding plot where the illite content was derived from high field measurements. In this case there is less scatter and the correlation coefficient has improved where $R^2 = 0.95$.

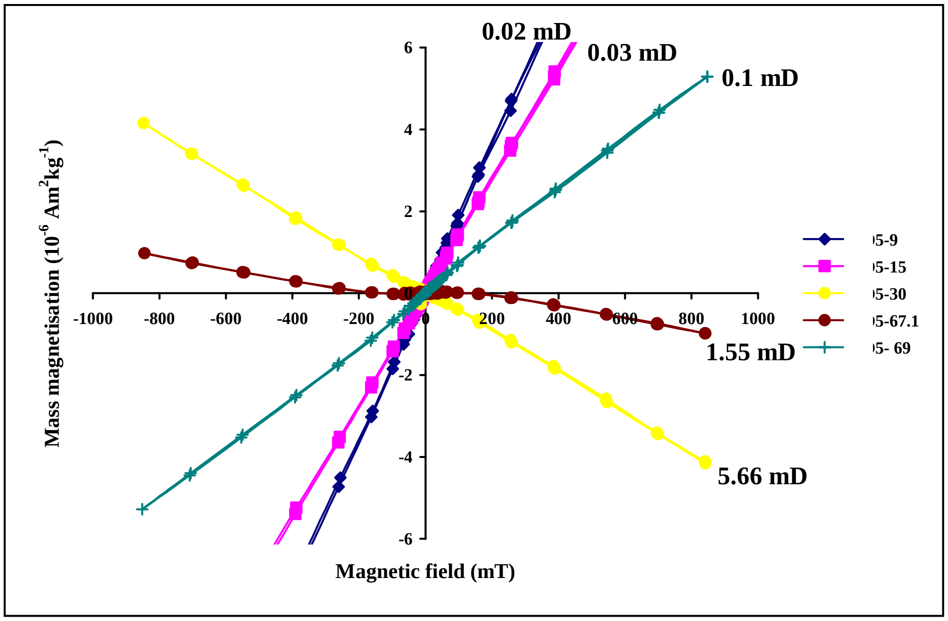

Figure 3. Examples from a North Sea oil well showing the correspondence between high field magnetic susceptibility (the hysteresis curve slope at high fields) and permeability.

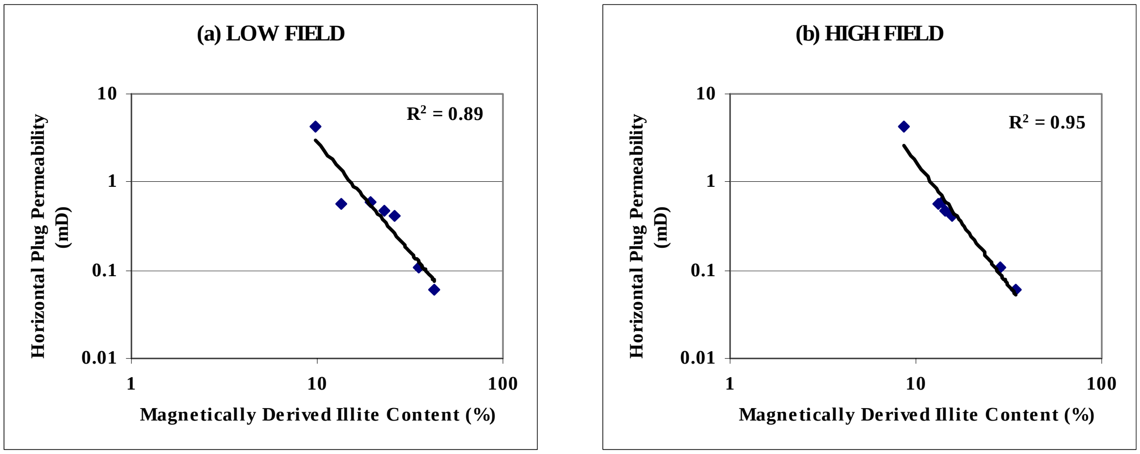

Figure 4. Correlations between the magnetically derived illite content and permeability in a North Sea oil reservoir. In (a) the illite content was derived from low field magnetic susceptibility measurements, whilst the improved correlations in (b) were derived from high field magnetic susceptibility measurements.

QUANTIFYING THE EFFECT OF CORE CLEANING USING MAGNETICS

Some previous preliminary work on core plugs (Potter et al, 2004) suggested that hot soxhlet core cleaning may remove some paramagnetic clay in intrinsically high permeability samples. In the present paper we undertake a more detailed analysis of a sample of a heterogeneous slabbed core by measuring the low field probe magnetic susceptibility before and after core cleaning. We also compared the results with probe permeability before and after cleaning. Figure 5a shows values of magnetically derived illite content from low field probe magnetic susceptibility measurements, before and after hot soxhlet cleaning. Significantly, the illite values are slightly lower or the same in all cases after core cleaning (the raw magnetic susceptibility values were always lower or identical after core cleaning). This demonstrated that a mineral (or minerals) with positive susceptibility had to have been removed during the cleaning process. If only the residual reservoir fluids had been removed during cleaning then the magnetic susceptibility would have actually increased after cleaning, since all the crude oils and formation waters that have been measured (Ivakhnenko and Potter, 2004) are diamagnetic (low, negative susceptibility).

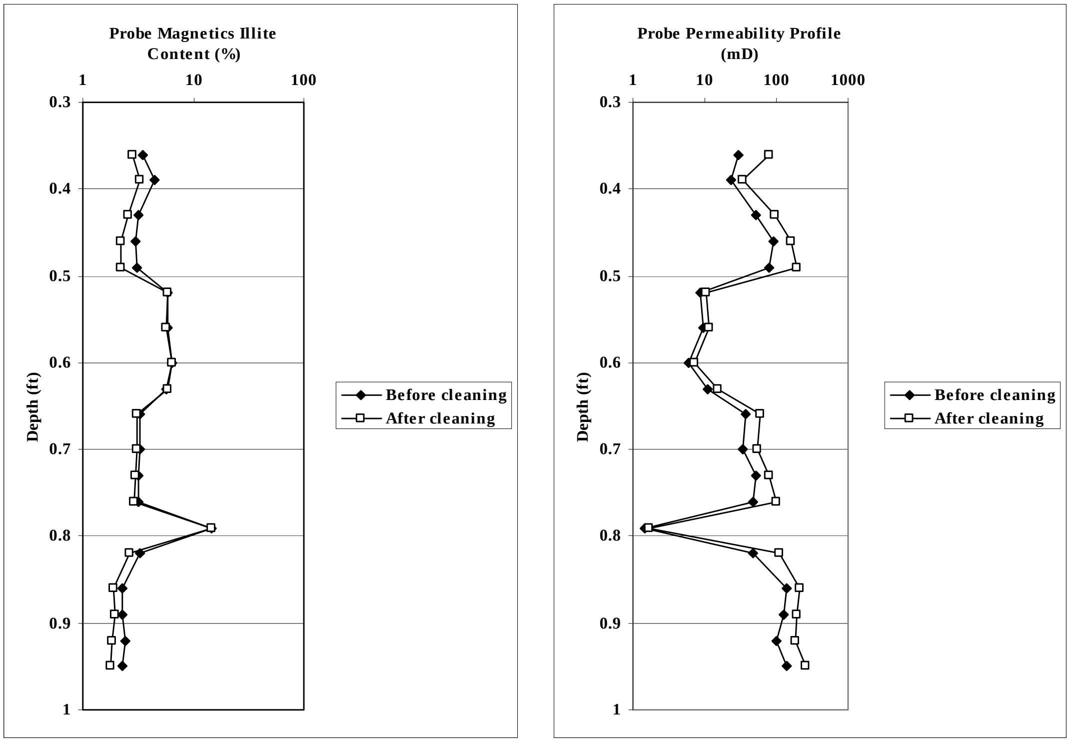

Figure 5. (a) Illite content derived from low field probe magnetic susceptibility both before and after hot soxhlet cleaning on a section of slabbed core from a North Sea oil reservoir. (b) The corresponding probe permeability results.

The magnetic results suggested that permeability measurements undertaken after hot soxhlet cleaning of core samples (particularly intrinsically higher permeability samples), might overestimate the actual permeability of the uncleaned samples. This is consistent with probe permeability measurements taken before and after the hot soxhlet cleaning (Figure 5b). The permeability increases in most cases after the core cleaning. The greatest increases in permeability after core cleaning occur in the highest initial (uncleaned) permeable samples, and in exactly the same intervals where there was the greatest decrease in magnetically derived illite content. This further suggests that it is the removal of illite clay through cleaning that causes the corresponding increase in permeability. The variation in illite content down the slabbed core (Figure 5a) also shows an inverse correspondence with permeability (Figure 5b) in the results both before and after core cleaning. This would strongly suggest that magnetic measurements before and after cleaning, in conjunction with the permeability measurements after cleaning, could potentially be used to help estimate the permeability of uncleaned samples with the original clay content.

RAPID 3-D ANISOTROPY USING MAGNETICS

Full 3-D anisotropy of magnetic susceptibility (AMS) measurements can be determined very rapidly on single plugs, unlike anisotropic measurements of many other parameters (permeability, acoustics etc) where several plugs have to be cut in different directions to derive the full anisotropy ellipsoid. Measurements at low field can be made in around one minute using a Molspin anisotropy meter (Collinson, 1983), and are extremely sensitive, allowing very small anisotropies to be detected. We undertook such measurements on samples from a North Sea shoreface reservoir, and compared the results with the total illite content derived from low field magnetic susceptibility (Figure 6). Interestingly, although the values of anisotropy are very small in all the samples (low anisotropy is perhaps surprising in the more muddy sands), they correlate with the total magnetically derived illite clay content. It appears therefore that small quantities of illite are capable of producing low but measurable anisotropies in these samples. The results are consistent with backscattered electron microscope image analysis data of mudstones from the Gulf of Mexico (Charpentier et al, 2003), which suggested that fabric development was the result of the illitization of smectite. In other words the fabric development was directly related to the amount of illite, and was not merely related to compaction. Potentially, magnetic measurements provide a rapid means of estimating anisotropic distributions of clay (and other minerals), that are likely to influence the anisotropic behaviour of key petrophysical parameters, such as permeability. Relating these rapid, non-destructive anisotropic magnetic measurements to the anisotropic properties of key petrophysical parameters might lead to improved anisotropic predictors of these parameters. Furthermore, extending the anisotropic magnetic measurements to high fields is likely to be extremely fruitful.

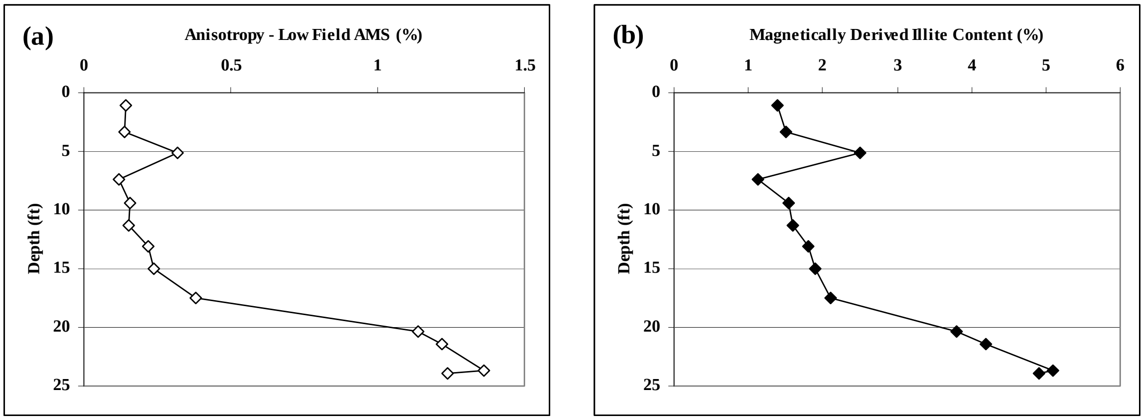

Figure 6. (a) Low field anisotropy of magnetic susceptibility (AMS) for a shoreface reservoir from a North Sea oil well. (b) The corresponding plot of total magnetically derived illite content.

CONCLUSIONS

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

- It has been shown that magnetic hysteresis measurements can complement XRD data by potentially providing a very sensitive means of quantifying clay content if the clay type is known. The high field magnetic susceptibility of clay + quartz samples agreed well with estimates based on XRD derived mineral contents. The rapid, non-destructive magnetic measurements enable significantly more samples to be screened than could possibly be measured by XRD in an equivalent time period. Whilst magnetic measurements alone can distinguish paramagnetic clays (e.g., illite) from diamagnetic clays (e.g., kaolinite) they cannot distinguish different paramagnetic clays (e.g., illite from chlorite) on the basis of the magnetic measurements alone.
- For some real reservoir turbidite samples the high field magnetic susceptibility again agreed well with estimates based on XRD derived mineral contents.
- Improved correlations were observed between high field magnetic estimates of illite content and permeability, than between low field magnetic estimates of illite content and permeability. This is because the high field hysteresis measurements enable better estimates of the true diamagnetic plus paramagnetic components to be obtained, without the influence of ferro- or ferrimagnetic components that can mask low field measurements.
- Probe magnetic measurements before and after core cleaning have shown that hot soxhlet cleaning can remove small amounts of illite clay, particularly in intrinsically higher permeability samples. This means that some permeability measurements, undertaken after hot soxhlet cleaning of core samples, might overestimate the actual permeability of the uncleaned samples. The results were also consistent with probe permeability measurements undertaken both before and after core cleaning. Magnetic susceptibility screening provides a way of quantifying any clay removal during cleaning. Magnetic measurements before and after cleaning, in conjunction with the

permeability measurements after cleaning, could therefore potentially be used to help estimate the permeability of the uncleaned sample with the original clay content.

- Results from rapid, low field anisotropy of magnetic susceptibility (AMS) measurements correlated with the magnetically derived illite content. Potentially, AMS measurements provide a rapid means of estimating anisotropic distributions of clay in reservoir samples (if there is minimal influence from ferrimagnetic components), that is likely to reflect the anisotropic behaviour of key petrophysical parameters, such as permeability.

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