THE USE OF MAGNETIC HYSTERESIS AND REMANENCE MEASUREMENTS IN RAPIDLY AND NON-DESTRUCTIVELY CHARACTERISING RESERVOIR ROCKS AND FLUIDS

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ABSTRACT

This paper details how magnetic hysteresis and remanence measurements can be used for improved, rapid, non-destructive characterisation of multiple mineral (and fluid) components in reservoir samples. This extends previous work (Potter, 2005), which only considered low field magnetic susceptibility measurements. The advantage of the new hysteresis measurements is that they can identify ***multiple*** mineral components in the same sample, by acquiring data at a range of low and high applied fields. Plots of applied magnetic field versus magnetisation, where the slope represents the magnetic susceptibility, provide a ***universal template*** upon which any reservoir rock or fluid can be characterised. Pure diamagnetic components (matrix minerals such as quartz and calcite, or reservoir fluids such as crude oils and formation waters) are characterised by straight lines with negative slope. In contrast, the pure paramagnetic components (permeability controlling clays such as illite and chlorite) give straight lines with positive slope. Mixtures of diamagnetic and paramagnetic minerals can be theoretically modelled and compared with experimental results on the plots. The presence of characteristic "kinks" or hysteresis "loops" at relatively low fields enable very small concentrations of ferro- or ferrimagnetic minerals (such as magnetite) to be rapidly identified. The magnetic measurements provide a rapid, sensitive complement to XRD measurements. The presence of multiple components (diamagnetic, paramagnetic and ferrimagnetic) in the same sample can be recognised by distinctive changes in the slope of the hysteresis curves as a function of applied field. Furthermore, measurements of isothermal remanent magnetisation (IRM) can give independent complementary information regarding the remanence carrying ferrimagnetic particles without any influence from the diamagnetic or paramagnetic components (which do not acquire a remanence). The hysteresis and remanence measurements have allowed very sensitive characterisation of different reservoir rock and fluid types to be made. For instance, subtle variations from clean sand to slightly muddy sand in clastic reservoirs can be easily identified and quantified. The techniques have also enabled different turbidite types to be distinguished in a single well. Different types of carbonate can also be readily distinguished. In addition, different reservoir fluids (formation waters, crude oils) can be distinguished.

INTRODUCTION

Recent studies (Potter, 2004a; Potter et al, 2004; Potter, 2005; Ivakhnenko, 2006; Ivakhnenko and Potter, 2006) have shown the potential uses of low field (initial) magnetic susceptibility for reservoir characterisation, quantifying mineralogy, and in predicting important petrophysical parameters. In particular, it has been shown how these measurements provide a rapid, non-destructive complement to XRD in determining the content of permeability controlling clays such as illite (Potter et al, 2004), and how the magnetically derived illite content exhibited strong correlations with permeability (Potter, 2005), even in cases where the relationship between porosity and permeability was very poor. The magnetic measurements could also calibrate downhole wireline gamma ray data to provide useful lithological information, even in the presence of a drilling mud with a high gamma ray signal (Potter, 2005). Additionally, the magnetic measurements showed a strong correlation with the SCAL parameter Qv (the cation exchange capacity per unit pore volume). More recently we have shown how magnetic susceptibility can characterise mineral scale samples (Ivakhnenko and Potter, 2006).

This previous magnetic work primarily involved making a single, rapid susceptibility measurement per sample using a low applied magnetic field (around 700 µT). The resulting low field susceptibility value reflected the sum of all the components in the sample, and model equations were developed (Potter et al 2004) to convert the raw susceptibility signal into mineral percentages for simple systems (for example, quartz plus illite mixtures). One disadvantage of only looking at a single low field susceptibility value per sample, and using the model equations, is that the results could be influenced by other components not accounted for in the model equations (since the equations cannot simultanteously solve for several mineral components at once). In particular, the presence of a small amount of a strongly magnetic mineral (such as ferrimagnetic magnetite) could affect the estimations of the content of important permeability controlling clays. The advantage of the new hysteresis measurements on reservoir samples is that the magnetic susceptibility can be determined at a range of low and high applied fields. This allows one to distinguish different mineral components in a sample as detailed below.

RECOGNITION OF DIAMAGNETIC, PARAMAGNETIC AND FERRO- OR FERRIMAGNETIC COMPONENTS FROM HYSTERESIS CURVES

Hysteresis curves are plotted on graphs of applied magnetic field versus magnetisation, and in the present experiments the applied field ranged up to 1000 mT. On such plots the magnetic susceptibility is given by the slope of the graph. Changes in the slope for a given sample can indicate the presence of multiple components in the sample. Diamagnetic minerals (quartz, calcite, kaolinite) or fluids (most crude oils and formation waters) are recognised by exhibiting straight lines with negative slope. In contrast, paramagnetic minerals (illite, chlorite) will exhibit a straight line with positive slope. A mixture of a diamagnetic matrix mineral (such as quartz) and a paramagnetic clay mineral (such as illite) will have a slope that is dependent upon the content of the two minerals. The theoretically modelled response of different quartz plus illite mixtures on a hysteresis plot is shown in Figure 1. This shows that, whilst pure quartz has a relatively steep negative slope, small increases in illite content can have a dramatic effect on the slope of the hysteresis curve. In particular, just 4-5% illite content can cause the slope of the quartz plus illite mixture to become positive. Differences in the slopes of the hysteresis curves for different reservoir samples can potentially allow very sensitive and subtle changes in the magnetic mineralogy to be readily recognised. This can be important, for instance, since small changes in illite content 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 could provide a rapid, cheap, sensitive complement to XRD, not a replacement for XRD. Whilst 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, monmorillonite etc). However, once the type of clay is known (from some representative XRD, SEM, thin section or other measurements), then the magnetics could be used to rapidly and cheaply provide high resolution quantitative data on a larger number of samples than would be possible in an equivalent time period from XRD measurements.

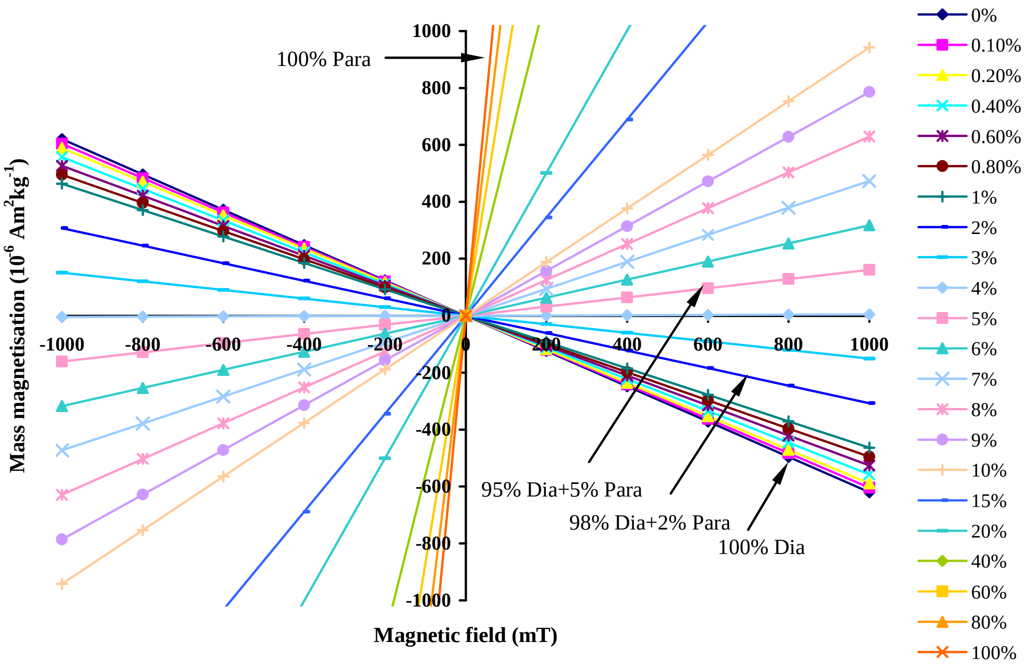

Figure 1. Theoretical models of magnetic hysteresis curves for various mixtures of illite (paramagnetic) and quartz (diamagnetic). The mass magnetic susceptibility of illite is 15 (10^{-8} m^3 kg^{-1}) and quartz is -0.62 (10^{-8} m^3 kg^{-1}) (Collinson, 1983; Dunlop and Ozdemir, 1997; Hunt et al, 1995). Percentage values in the legend indicate the content of illite.

Selected diamagnetic (Dia) and paramagnetic (Para) mixtures are shown for clarity. 100% Dia refers to pure quartz and 100% Para refers to pure illite.

The majority of ferro- or ferrimagnetic minerals saturate in fields much lower than the maximum field used in the present experiments (1000 mT). The presence of such minerals therefore causes “kinks” or characteristic hysteresis “loops” in the low field region of the graphs (see Figures 2-7). In many cases the magnetic measurements allow these minerals to be quickly and non-destructively detected even when they occur in such small quantities that they may not be seen by destructive XRD.

CHARACTERISATION OF FERRO- AND FERRIMAGNETIC COMPONENTS FROM REMANENCE MEASUREMENTS

An additional independent means of rapidly identifying ferro- or ferrimagnetic mineral components is by undertaking remanence measurements. These strongly magnetic minerals acquire a remanence on application of a magnetic field, whereas diamagnetic and paramagnetic minerals do not. Therefore remanence measurements can be used to detect small concentrations of these minerals even in the presence of large concentrations of diamagnetic matrix minerals and paramagnetic clays. One of the most convenient forms of remanence to give is isothermal remanent magnetisation (IRM), because it can be acquired rapidly and gives the highest signal of any form of remanence (Potter, 2004b) allowing minute amounts of these minerals to be detected. The shape of the normalised IRM curves can also be diagnostic. For instance, if the normalised IRM curve does not saturate well before 1000 mT then it is likely that the sample contains hematite (which is strictly termed a canted antiferromagnetic mineral). In the present experiments hysteresis and IRM measurements could be made on the same piece of equipment.

EQUIPMENT

The magnetic hysteresis and IRM curves were obtained by a Variable Field Translation Balance (VFTB) in the rock magnetic laboratory of the Ludwig-Maximilians University in Munich, Germany. The VFTB is a horizontal translation balance in which the magnetisation of the sample is measured in applied fields up to 1000 mT. The main advantage of the VFTB is that all the apparatus is computer controlled so that once the sample is in the measuring position, many experiments (hysteresis, IRM) can be applied to the same sample. The studied reservoir rock samples consisted of sediment chips or powdered material (in the case of unconsolidated sands) of known mass (normally about 0.5 g), and were compacted into a non-magnetic container at the end of the sample holder. The sample was very tightly packed into the sample cup container with quartz wool in order to fix the material. Reservoir fluid samples could also be analysed. The sample holder slides into the sleeve at the end of the balance assembly. A full hysteresis curve for each sample takes around 10-15 minutes.

RESULTS FOR SOME REPRESENTATIVE RESERVOIR SAMPLES

Reservoir rock samples were tested from shoreface, turbidite and carbonate reservoirs. Additionally, some reservoir fluids (crude oil and formation water) were measured.

Shoreface and Shallow Marine Samples

Two shoreface reservoir rock samples from the North Sea were represented by a clean sandstone (P21.0) and a muddy sandstone (P28.6) from the same oil well genetic unit. Sample P28.6 was situated around 7 m below sample P21.0. Hysteresis curves for the two samples (Figure 2) reveal clear differences, that can be explained by the relative amounts of the different mineral components they contain. Sample P21.0 exhibits an almost straight line with a steep negative slope. This demonstrates that the sample consists primarily of a diamagnetic mineral. This is consistent with the fact that this sample is a clean sand (essentially diamagnetic quartz). The slight "kink" in the curve at low applied field indicated the presence of a very minute amount of a ferrimagnetic mineral. Sample P28.6 also exhibits a negative slope at high fields, indicating a predominant diamagnetic component (again quartz in this case), but the slope is less negative than for sample P21.0.

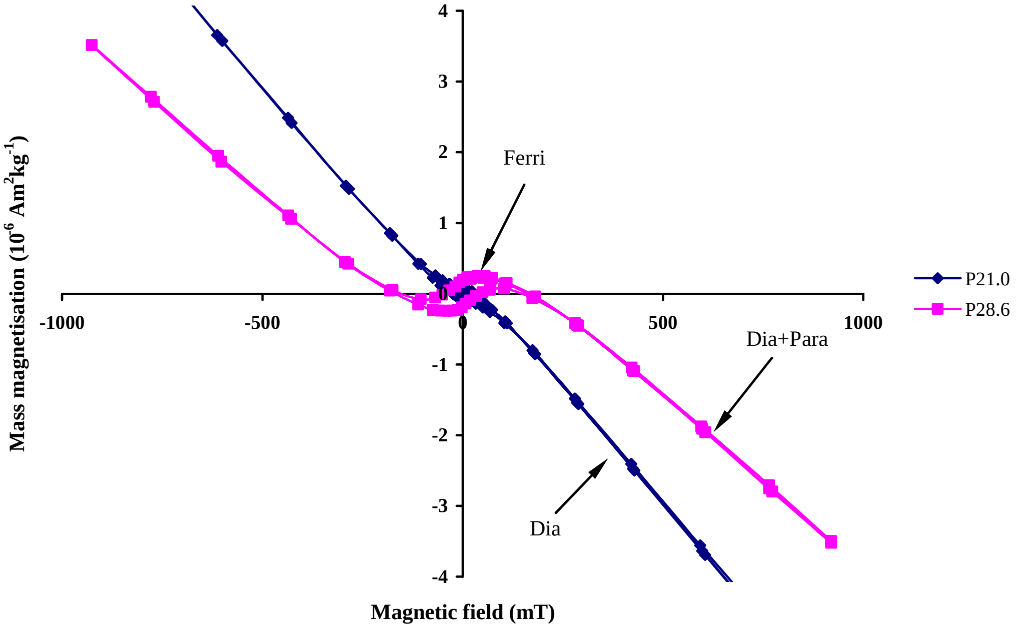

Figure 2. Magnetic hysteresis curves of representative samples from a shoreface reservoir. Diamagnetic (Dia), paramagnetic (Para) and ferrimagnetic (Ferri) components are indicated.

This suggested a higher content of paramagnetic component(s) in sample P28.6. This is consistent with this sample being a muddy sandstone, with a slightly higher content of paramagnetic illite clay (Potter et al, 2004). Also the more pronounced hysteresis "loop" at low applied fields demonstrated an increased ferrimagnetic component in sample P28.6 compared to sample P21.0. If one had merely measured the low field susceptibility, which is positive for sample P28.6 from the slope of the hysteresis curve, then one might have overestimated the amount of illite in the sample if one had assumed a simple mixture of quartz and illite and applied Equation (2) of Potter et al (2004). This demonstrates the usefulness of high field measurements, in that they better represent the actual diamagnetic matrix and paramagnetic clay contents, without the influence of strongly magnetic ferro- or ferrimagnetic components which have generally saturated at much lower fields.

Another example is provided by some shallow marine samples in another part of the N. Sea. Sample M68 (Figure 3) exhibits a straight line with negative slope (diamagnetic component) at high fields, with a slight "kink" at low fields (small ferrimagnetic component). Interestingly, this sample had a counterpart that contained an enriched ferrimagnetic component (M68FC). The results are also shown in Figure 3. Sample M68FC exhibits exactly the same high-field slope as sample M68 (similar high-field magnetic susceptibility), indicating a similar diamagnetic component, but at low fields reveals a significantly higher ferrimagnetic mineral content. Again if one had only measured the low field magnetic susceptibility one would not have been able to demonstrate that the diamagnetic matrix for both samples was the same.

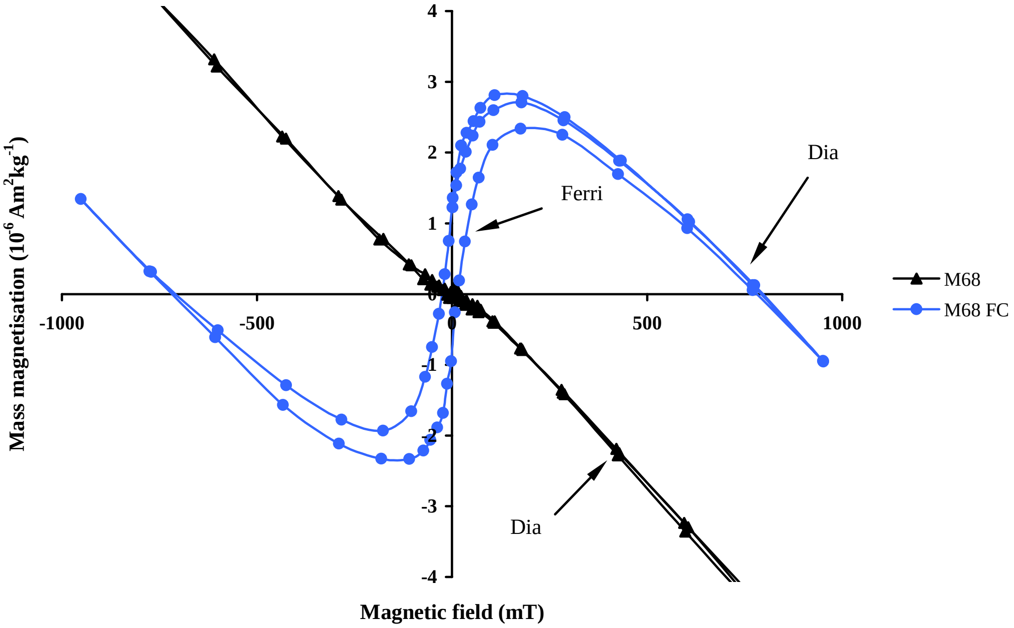

Figure 3. Magnetic hysteresis curves of sample M68 and its enriched ferri-concentrate analogue (M68FC). The high field diamagnetic component (Dia) and ferrimagnetic component (Ferri) are shown.

Turbidite Samples: Hysteresis and Remanence Measurements

Figure 4 shows the hysteresis curves (right) and corresponding IRM acquisition curves (left) for three turbidite reservoir samples, comprising two unconsolidated sands (50.24 and 60.61), and a shale sample (S3) from the same well. From the hysteresis curves all these samples exhibit straight lines with positive slope at high fields (positive high-field magnetic susceptibility), indicating the presence of at least one paramagnetic mineral. Visual observation of the core suggests it is due to paramagnetic clays. The steeper positive high field slopes of samples 60.61 and S3 indicate a higher paramagnetic (clay) content than the cleaner sand sample 50.24. All these reservoir rock samples exhibit a “kink” in the hysteresis curve at low fields indicating the presence of ferrimagnetic components. The larger “kinks” for samples 60.61 and S3 show that they contain a higher ferrimagnetic content than sample 50.24. This is also consistent with the IRM curves, where samples 60.61 and S3 exhibit higher values of IRM than sample 50.24. The fact that all the IRM curves saturate in relatively low fields indicates that the magnetic carrier in each case is likely to be a mineral such as magnetite (but no significant hematite).

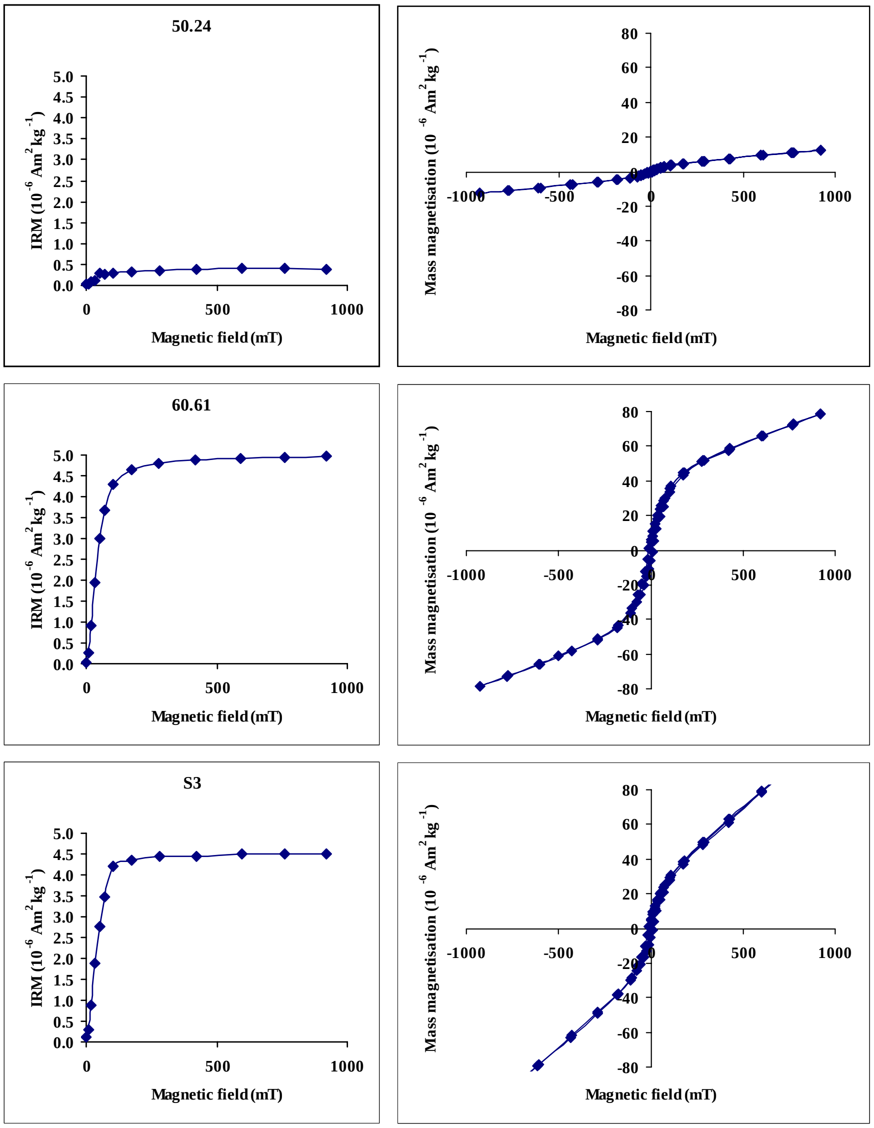

Figure 4. IRM curves (left) and corresponding hysteresis curves (right) for two types of turbidite sand, samples 50.24 and 60.61, and a turbidite shale sample S3.

Interestingly, the cleaner sand sample 50.24 and the shale sample S3, which are both from the same type of turbidite genetic unit, show very similar normalised hysteresis curves (Figure 5) even though the absolute magnitudes of the magnetisation (Figure 4) are very different. This suggests a direct link between the amount of paramagnetic and the amount of ferrimagnetic material in each sample from the same turbidite unit, since the ratio of paramagnetic to ferromagnetic material was similar. This in turn could provide a new way of characterising samples from the same type of turbidite genetic unit.

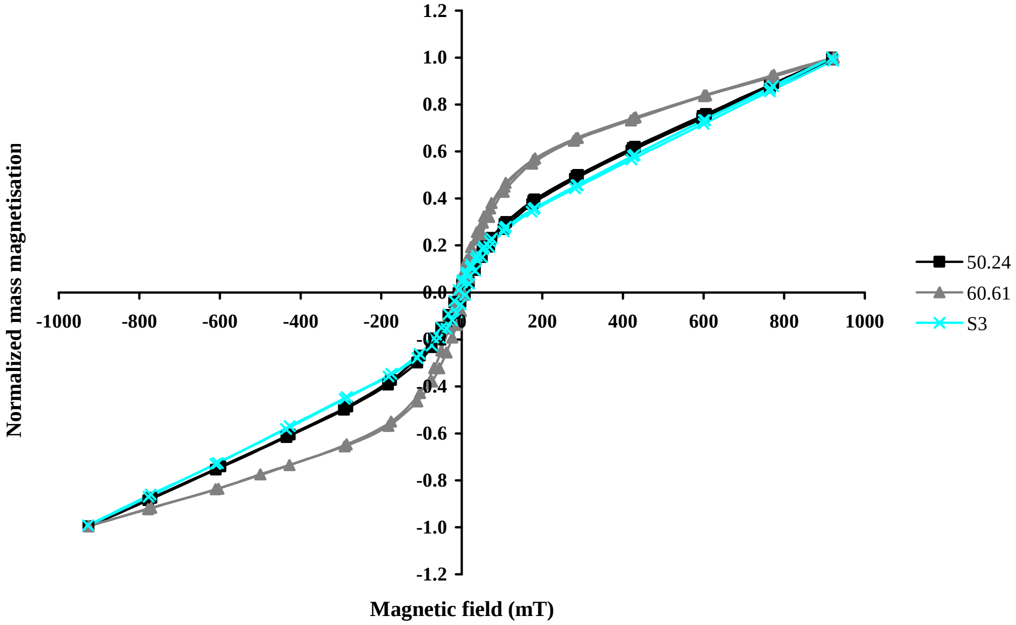

Figure 5. Normalized magnetic hysteresis curves for the three turbidite reservoir samples shown in Figure 4.

Carbonate Samples

Figure 6 shows hysteresis results for two carbonate samples. The limestone shows an expected diamagnetic curve typical of calcite. A slight "kink" at low fields indicates the presence of a small amount of a ferrimagnetic mineral, and it is known that limestones often contain small concentrations of magnetite (Jackson and Worm, 2001). The other sample is a "calcite dogger" from a reservoir in the N. Sea. Whilst calcite is clearly apparent from visual inspection of the core, the magnetic measurements were dominated by a paramagnetic component (likely to be clay) at high fields. Pyrite, observed in the core material, is also a contributing paramagnetic component. The dogger sample also exhibits a "kink" in the low field portion of the curve, again indicating the presence of a ferrimagnetic mineral. Subtle variations in different carbonate samples might thus be characterised by these magnetic measurements.

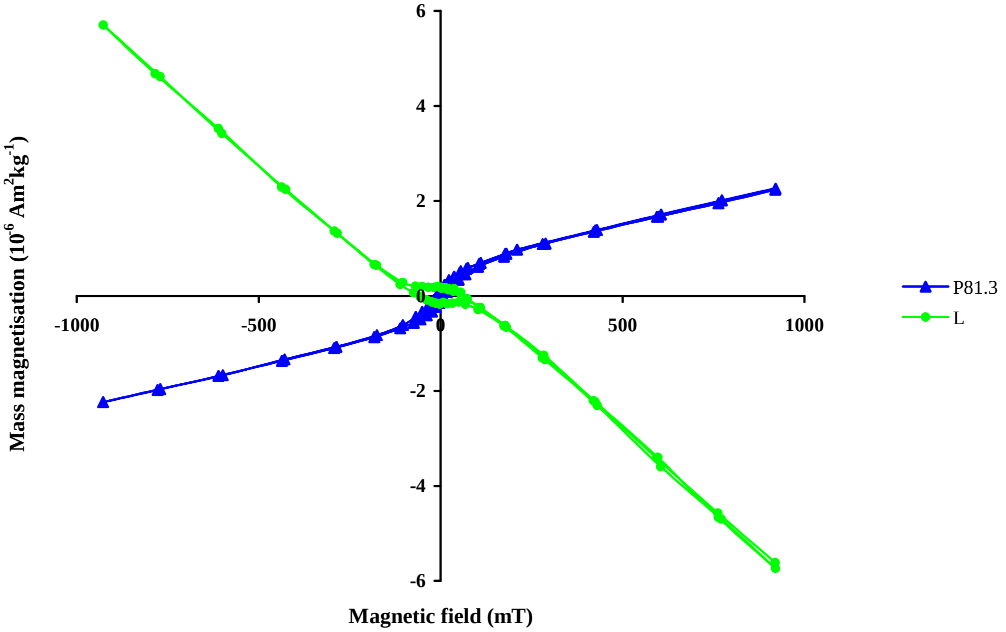

Figure 6. Magnetic hysteresis curves for two carbonate samples: a limestone (L), and a “calcite dogger” (P81.3).

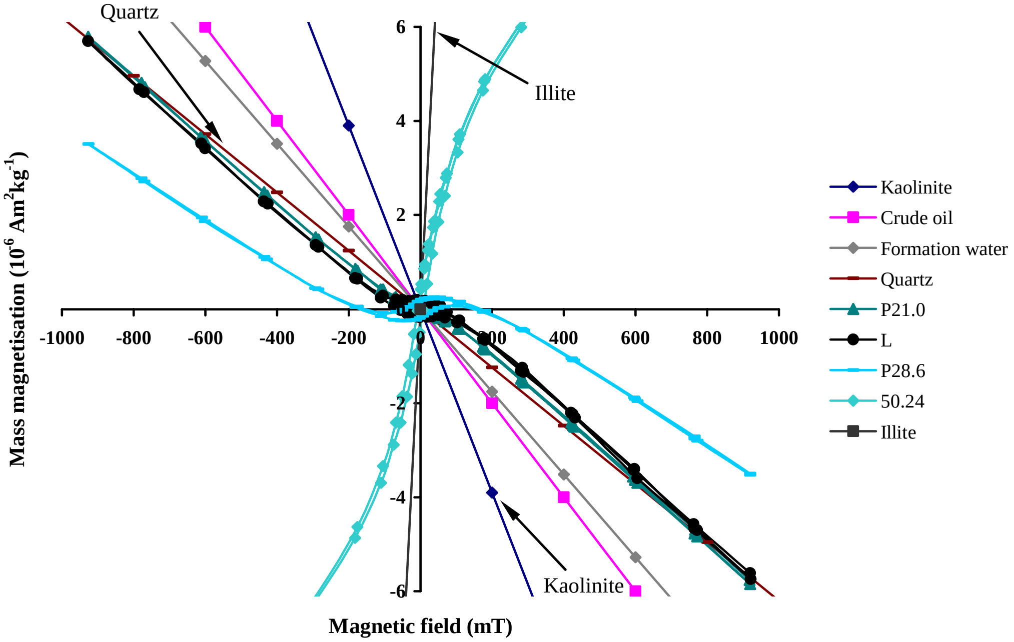

Figure 7. Composite showing hysteresis curves for some minerals, reservoir fluids (fluids from Dunbar Field, N. Sea), shoreface (P21.0), turbidite (50.24) and carbonate (L) samples. In the legend the samples shown are ordered in terms of high field susceptibility from most diamagnetic (kaolinite) to most paramagnetic (illite).

Reservoir Fluids

The vast majority of reservoir fluids are diamagnetic. Ivakhnenko and Potter (2004) identified clear differences between crude oils and formation waters mainly on the basis of single reading measurements from a Sherwood Scientific magnetic susceptibility balance (MSB) Mark I. Hysteresis measurements have confirmed these differences. An example is given in Figure 7, where a crude oil sample from the Dunbar Field in the N. Sea exhibits a steeper negative slope (more diamagnetic susceptibility) than a formation water sample from the same field. Lines for kaolinite, quartz and illite using quoted values of susceptibility (Hunt et al, 1995; Thompson and Oldfield, 1986), and some reservoir samples, are also plotted for comparison.

CONCLUSIONS

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

- Plots of applied field versus magnetisation from rapid, non-destructive hysteresis measurements can be used as a ***universal template*** for identifying ***multiple*** mineral components in any reservoir rock sample, and therefore provide another means of reservoir rock typing. Different reservoir fluids can also be distinguished. Changes in the slope (the magnetic susceptibility) of the hysteresis curves reflect the different components. At low fields characteristic “kinks” or hysteresis “loops” indicate the presence of ferro- or ferrimagnetic minerals. Straight line sections with negative slope are due to diamagnetic components (such as the matrix minerals quartz and calcite, as well as reservoir fluids), whilst straight line sections with positive slope are due to paramagnetic components (such as the clay illite). Such straight line sections are generally apparent at high applied fields, where there is no influence from the ferrimagnetic components that generally saturate in lower fields. The relative amounts of paramagnetic and diamagnetic minerals in a rock (such as paramagnetic clays in a quartz matrix) can potentially be quantified from the slope of the straight line at high fields, and compared with model curves for varying concentrations of the different minerals involved.
- Hysteresis measurements provide more information regarding reservoir samples than conventional single reading low-field (initial) magnetic susceptibility measurements. This is because they can identify multiple components through the application of a range of low and high fields, whereas a single low field reading merely represents the sum of all the components (including the ferro- or ferrimagnetic minerals) present in the sample. The high field hysteresis measurements are particularly useful because they enable better estimates of the true diamagnetic or paramagnetic content to be obtained, without the influence of ferro- or ferrimagnetic components that may mask a single low field measurement. Subtle variations in the amount of paramagnetic clay in different samples, which can significantly affect fluid permeability, can easily be identified on the hysteresis plots from differences in the slope at high fields. This should enable better estimates of the permeability controlling clays (such as illite) to be obtained, and thus provide better predictors of permeability.

- Low-field hysteresis measurements, or IRM acquisition curves, can detect minute amounts of ferrimagnetic minerals that may not necessarily be readily identified by XRD. The samples with the largest low-field hysteresis "kinks" or "loops" have the largest ferrimagnetic content, and this was consistent with them exhibiting the highest values of IRM from independent measurements.
- The results suggest that a single low field together with a single high field magnetic susceptibility measurement should be adequate to identify and provide some idea of the relative amounts of ferri-, dia- and paramagnetic components in a sample. The potential development of a high field magnetic susceptibility probe for laboratory or downhole applications would appear to be very useful.
- The magnetic measurements may provide a rapid, cheap, sensitive, non-destructive complement to XRD measurements, and enable mineralogical information to be gained from significantly more samples than would be possible in an equivalent time period from XRD measurements. The magnetic measurements, however, should not be regarded as a replacement for XRD, since they cannot unambiguously distinguish between different types of paramagnetic clays for instance.
- In the turbidite samples studied, sand and shale from the same type of turbidite genetic unit gave almost identical normalised hysteresis curves, even though the absolute magnitudes of the mass magnetisation for the two samples were very different. This demonstrated that the ratio of the ferrimagnetic to paramagnetic components were similar, and suggested a diagenetic link between these two components. It also suggested a new way of identifying sands and the corresponding shale samples from the same turbidite type.

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