SENSITIVE CARBONATE RESERVOIR ROCK CHARACTERISATION FROM MAGNETIC SUSCEPTIBILITY: MINERAL QUANTIFICATION, CORRELATION WITH PETROPHYSICAL PROPERTIES, AND ANISOTROPY

David K. Potter*, Tariq M. AlGhamdi† and Oleksandr P. Ivakhnenko*

*Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, EH14 4AS, UK

†Reservoir Description Division, Saudi Aramco, Dhahran, Saudi Arabia

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Abu Dhabi, UAE, 29 October-2 November, 2008

ABSTRACT

Recent work (Potter et al, 2004; Potter, 2005; Ivakhnenko, 2006; Ivakhnenko and Potter, 2006a,b; Potter, 2007; Ivakhnenko and Potter, 2008; Potter and Ivakhnenko, 2008) has demonstrated how rapid, non-destructive magnetic susceptibility measurements in clastic reservoir samples correlate with several key petrophysical parameters. The present paper shows how such measurements can also be a potentially important tool for characterising carbonate samples. Typical carbonate minerals such as calcite or dolomite are diamagnetic (negative magnetic susceptibility), whilst some other carbonates such as siderite (an iron carbonate) are paramagnetic (positive magnetic susceptibility). Carbonate rock typing can be achieved via high field susceptibility measurements which indicate the diamagnetic plus paramagnetic content. Small concentrations of ferrimagnetic impurities (such as magnetite) can significantly increase the low field magnetic susceptibility values, providing a further sensitive means of distinguishing between different carbonate samples and identifying samples that may give anomalous nuclear magnetic resonance (NMR) results.

Experimental magnetic susceptibility measurements demonstrated subtle differences between samples in a suite of Middle East carbonates. Low field magnetic susceptibility values from hysteresis curves indicated small concentrations of ferrimagnetic impurities in some samples. The low field values did not correlate well with key petrophysical parameters. Significantly, however, high field measurements exhibited extremely good correlations with permeability and porosity. The high field results reflected the diamagnetic and paramagnetic minerals (comprising the main rock volume and which are the main controls on the petrophysical properties), were not affected by ferrimagnetic impurities since they saturated at lower fields. Results for some North Sea carbonates were very different to the Middle East samples. Magnetic susceptibility values were substantially higher (both low field and high field), indicating increased ferrimagnetic and paramagnetic (mainly clays) concentrations in the North Sea carbonates. This generally meant that the reservoir quality of the North Sea carbonates was poorer.

The North Sea carbonates also exhibited higher values of magnetic anisotropy (which can be determined very rapidly), due mainly to their increased paramagnetic clay content.

INTRODUCTION

Recent studies (Potter et al, 2004; Potter, 2005; Ivakhnenko, 2006; Ivakhnenko and Potter, 2006a,b; Potter, 2007; Ivakhnenko and Potter, 2008; Potter and Ivakhnenko, 2008) have demonstrated the potential uses of magnetic susceptibility for reservoir characterisation, quantifying mineralogy, and for predicting important petrophysical parameters in clastic reservoirs. 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; Potter and Ivakhnenko, 2008), and subsequently predicting permeability (Potter, 2005, 2007; Potter and Ivakhnenko, 2008), 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).

In clastic reservoirs high field magnetic susceptibility measurements, derived from hysteresis curves, have shown even better correlations with permeability than low field magnetic susceptibility measurements (Potter and Ivakhnenko, 2008), since the high field behaviour reflects only the diamagnetic components (generally the matrix minerals such as quartz or calcite) plus the paramagnetic components (generally permeability controlling clays). Estimates of paramagnetic permeability controlling clays were improved since the effects of any ferro- or ferrimagnetic impurities was minimized at high fields, since they saturate at lower fields. In contrast, the low field measurements can be influenced by small amounts of these strongly magnetic ferro- or ferrimagnetic components if these are present in the sample, and in these cases the magnetic results are likely to exhibit weaker correlations with permeability. The presence of these ferro- or ferrimagnetic components can, however, easily be recognised by characteristic “kinks” or “loops” in the hysteresis curves at low fields.

The present paper extends the work to the magnetic characterisation of carbonates, building on a preliminary study by one of us (AlGhamdi, 2006). Subtle differences between carbonates can rapidly and non-destructively be recognised by the magnetic measurements. Changes in the amounts of dolomite compared to calcite, and differences in the content of any small amounts of paramagnetic clays, can easily be identified from the slope of the high field hysteresis curve (Potter and Ivakhnenko, 2008). We will show that the high field susceptibility exhibits strong correlations with porosity and permeability, which is a completely new and unexpected result for carbonates. Furthermore, the low field hysteresis behaviour identified some very small amounts of ferrimagnetic material in some samples, providing a further aid to characterisation. It is worth noting that X-ray diffraction (XRD) cannot identify such small amounts of this ferrimagnetic material.

CHARACTERISATION OF CARBONATES FROM MAGNETIC SUSCEPTIBILITY

Magnetic Susceptibility of Typical Carbonate Reservoir Minerals

The main carbonate matrix minerals, calcite and dolomite, are diamagnetic with low negative magnetic susceptibilities (Table 1). Note, however, that some carbonates (e.g., siderite and rhodochrosite) are paramagnetic with significantly higher positive magnetic susceptibilitites. Table 1 also shows values for other typical reservoir minerals. Note that kaolinite is diamagnetic, whilst illite (an important permeability controlling clay in many clastic reservoirs) is paramagnetic. Note also that ferrimagnetic minerals such as magnetite have extremely high magnetic susceptibilities, and small amounts of such impurities can on the one hand be useful in distinguishing different carbonates, and on the other hand can dominate low field measurements obscuring any correlations between the magnetics and petrophysical properties. Fortunately at high fields the influence of these ferrimagnetic minerals is negligible and the magnetic properties are dominated by the diamagnetic and paramagnetic minerals comprising the bulk of the reservoir rocks. We will show that the high field measurements correlate with key petrophysical properties.

Table 1. Mass magnetic susceptibilities of carbonate minerals and some other typical reservoir minerals. D, P and F refer to diamagnetic, paramagnetic and ferrimagnetic classes respectively. The values for the diamagnetic minerals were theoretically calculated by Ivakhnenko (2006). The values for the other minerals are from Hunt et al (1995).

Mineral	Mass Magnetic Susceptibility (10^{-8} m^3 kg^{-1})	Magnetic Class
Carbonate Minerals:		
Calcite, $CaCO_3$	-0.4839	D
Dolomite, $CaMg(CO_3)_2$	-0.4804	D
Magnesite, $MgCO_3$	-0.4762	D
Witherite, $BaCO_3$	-0.3643	D
Cerussite, $PbCO_3$	-0.2855	D
Siderite, $FeCO_3$	122.57	P
Rhodochrosite, $MnCO_3$	124.6283	P
Other Reservoir Minerals:		
Quartz, SiO_2	-0.6191	D
Anhydrite, $CaSO_4$	-0.4508	D
Gypsum, $CaSO_4 \cdot 2H_2O$	-0.5461	D
Halite, NaCl	-0.6451	D
Kaolinite, $Al_2[Si_2O_5](OH)_4$	-0.6474	D
Illite,$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH_2,(H_2O)]$	15	P
Magnetite, Fe_3O_4	20,000-110,000	F

Characterisation of some Middle East Carbonates from Hysteresis Curves

A series of hysteresis curves for some Middle East carbonate samples from the Arab-D reservoir Jurassic formation were determined (Figure 1). Note that the slope of the curves represents the magnetic susceptibility, and so hysteresis curves allow the susceptibility to be obtained over a range of low and high applied fields. 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. All samples exhibited negative high field slopes, demonstrating that the bulk of each sample comprised a diamagnetic matrix mineral or minerals (in these cases it was generally a mixture of calcite and dolomite). Some samples exhibited straight line hysteresis behaviour indicating that there were no ferrimagnetic impurities present (red curves, or light grey in b&w, in Figure 1). A number of the curves, however, showed a small "kink" at low fields, indicating the presence of a small amount of ferrimagnetic impurities (blue curves, or dark grey in b&w, in Figure 1). Note that a large "kink" at low fields would pin-point a sample that could potentially give anomalous NMR results.

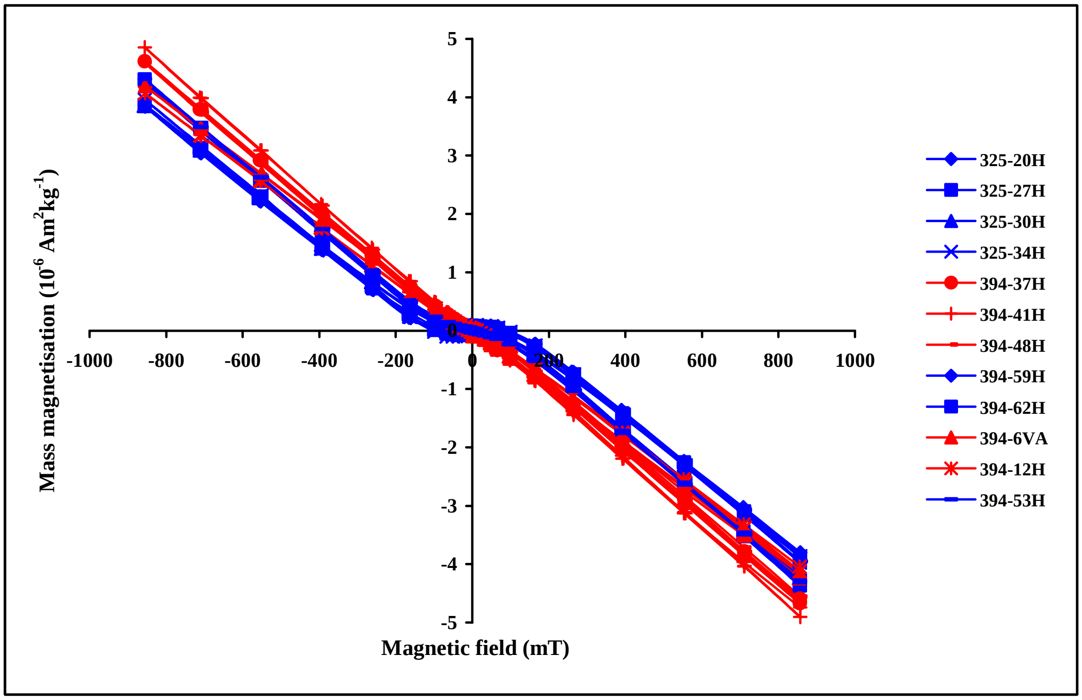


Figure 1. Magnetic hysteresis curves for a series of Middle East carbonates from the Arab-D reservoir. The red curves (light grey in b&w) indicate samples exhibiting straight line behaviour and containing no detectable ferrimagnetic impurities. The blue curves (dark grey in b&w) indicate samples exhibiting a small "kink" at low fields, indicating the presence of a small amount of ferrimagnetic impurities.

Small differences in the variability of the high field slope between samples can be the result of differences in the calcite to dolomite ratio, and also small differences in the content of any paramagnetic clays present. The high field slopes are actually slightly higher than one would expect for pure calcite or dolomite, and so it is expected that very small amounts of paramagnetic clay are also present. Around 1% of illite, for instance, could produce the observed slopes (Potter and Ivakhnenko, 2008) in most cases if the bulk matrix mineral was calcite or dolomite. Lambert et al (2006) have observed small amounts of such clay in similar Middle East carbonate formations.

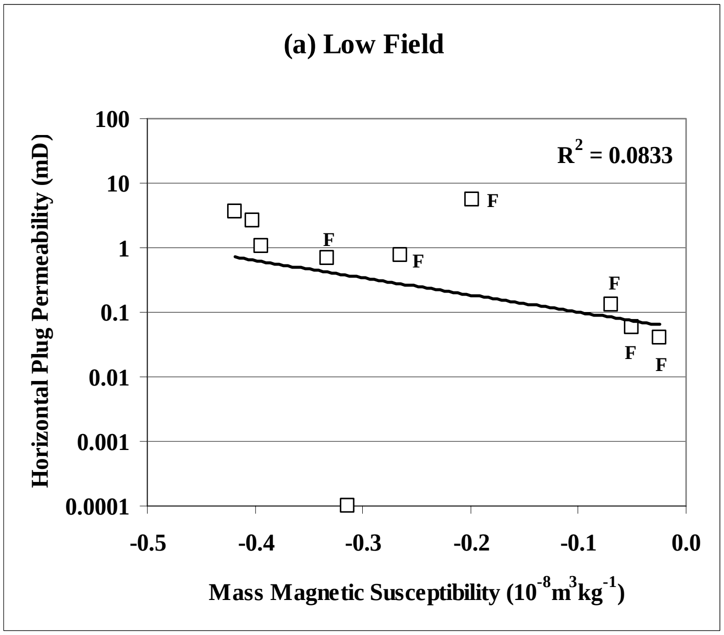
The ferrimagnetic material present in some samples (those with "kinks" at low field) is likely to be a mineral such as magnetite, since it saturates in relatively low fields. The small "kinks" also mean that the ferrimagnetic content is extremely small (much less than 1% in most cases). It is worth noting that these magnetic measurements are probably one of the few techniques that could identify such small amounts of ferrimagnetic material. X-ray diffraction (XRD) would not see such small amounts of these ferrimagnetic minerals.

CORRELATION WITH PETROPHYSICAL PROPERTIES

Correlation of Permeability with High Field Magnetic Susceptibility

The measured horizontal core permeability values were compared with the low and high field magnetic susceptibility results (Figure 2). The low field values were calculated from the slopes of the hysteresis curves in the applied field range 0-50mT, and the high field values from the straight line slopes above 750mT. The low field results did not show a good correlation with the permeability values (Figure 2(a)). This is because the low field results are influenced by small amounts of ferrimagnetic material in some samples (those marked with an "F" in Figure 2(a)). These samples exhibited a "kink" at low fields in their hysteresis curves (the blue curves, or dark grey in b&w, in Figure 1).

Significantly, however, the high field results show an extremely good correlation with permeability (Figure 2(b)). At high fields the influence of any ferrimagnetic material is negligible (the magnetization of these particles saturates at lower fields). The high field behaviour reflects the contribution of the diamagnetic and paramagnetic minerals that make up the bulk volume of the rock. Therefore, if these minerals primarily control the petrophysical properties of the rock, then one is more likely to see correlations between the high field magnetic susceptibility and petrophysical properties like permeability. Nevertheless, this is still a completely new and somewhat surprising result. In clastics the amount of permeability controlling clay can be a primary control on the permeability and so one might expect correlations between the magnetic susceptibility and permeability as reported in previous work (Potter, 2007), and in particular between high field magnetic susceptibility and permeability (Potter and Ivakhnenko, 2008). It was not necessarily expected that carbonates would also show strong correlations between high field magnetic susceptibility and permeability. The reason could be subtle differences in the amount of dolomite compared to calcite in the different samples, and / or small differences in the amount of paramagnetic clays in the samples. Very small amounts of clay can have a large effect on the permeability in clastics (Potter, 2007; Potter and Ivakhnenko, 2008), and perhaps the same is true of carbonates. Further detailed work on the mineralogy of these samples is now being undertaken to try to establish whether any particular mineralogical variable is responsible for the differences in permeability and how this relates precisely to the magnetic results.



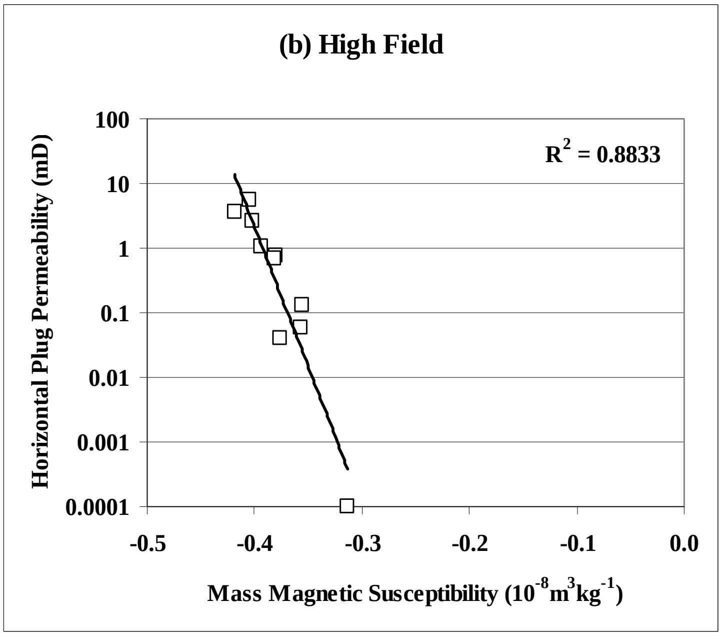
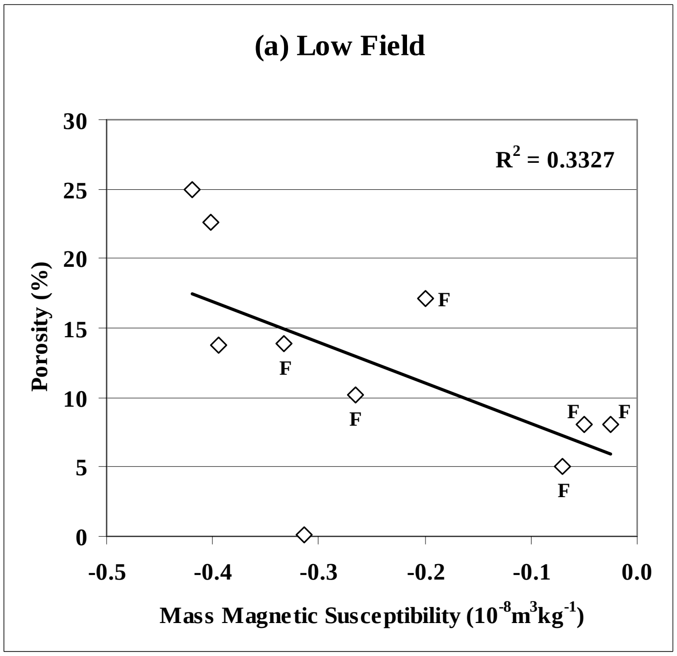


Figure 2. (a) Low field magnetic susceptibility versus plug permeability. The magnetic results are influenced by small amounts of ferrimagnetic material in some samples (those marked “F”). (b) High field magnetic susceptibility versus plug permeability showing a strong correlation (the ferrimagnetic material does not affect the high field results).



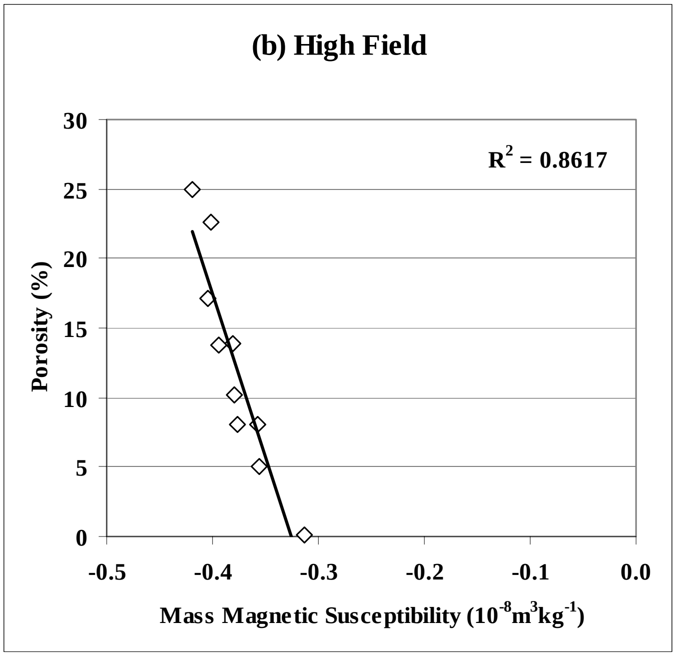


Figure 3. (a) Low field magnetic susceptibility versus plug porosity. The magnetic results are influenced by small amounts of ferrimagnetic material in some samples (those marked “F”). (b) High field magnetic susceptibility versus plug porosity showing a strong correlation (the ferrimagnetic material does not affect the high field results).

Correlation of Porosity with High Field Magnetic Susceptibility

The core plug porosity (helium) values were also compared with the low and high field magnetic susceptibility results (Figure 3). The low field results again did not show a good correlation with the porosity values (Figure 3(a)), due to the influence of small amounts of ferrimagnetic material in some of the samples (those marked with an “F” in Figure 3(a)). Significantly, the high field results again showed an extremely good correlation with porosity (Figure 3(b)). Since the high field behaviour reflects the contribution of the diamagnetic and paramagnetic minerals making up the bulk rock volume (with negligible influence from ferrimagnetic minerals), then one is more likely to see correlations between the high field magnetic susceptibility and other petrophysical properties like porosity. The reason for the good correlation could be due to the relative amounts of calcite, dolomite and other minerals in the samples, and further work is underway to establish this.

COMPARISON OF MAGNETIC RESULTS FOR DIFFERENT CARBONATE RESERVOIRS

Magnetic hysteresis curves for samples from carbonate reservoirs in the USA and the UK are compared with the Middle East carbonates in Figure 4. The USA and UK carbonates studied generally have slightly more ferrimagnetic material, as shown by slightly larger “kinks” at low field. They also have slightly more positive slopes at high field than the Middle East carbonates, indicating small increases in their paramagnetic mineral content. The North Sea calcite dogger sample is very different to all the other samples. The high field slope is positive, indicating a significant amount of paramagnetic minerals (in this case paramagnetic clays) compared to the other samples. This increased clay content appears to have been responsible for the low permeability of this sample (0.01 mD) compared to most of the Middle East samples. Only one of the Middle East samples has a lower permeability, and that is because it contains a significant amount of anhydrite.

Anisotropy

The low field anisotropy of magnetic susceptibility (AMS) of the North Sea calcite dogger sample is around 5%, and is significantly higher than the AMS of most of the Middle East samples (which are generally around 1%). The increased anisotropy of the dogger sample appears to be due mainly to the paramagnetic clay. Previous studies on mudstones have suggested that the degree of anisotropy is directly related to the amount of paramagnetic clay (Charpentier et al, 2003), and it seems likely that the same is true for carbonates. Further work is planned on high field anisotropy in order to get a better estimate of clay orientation without the effect of any ferrimagnetic components.

Effect of Temperature

Samples containing pure diamagnetic carbonate minerals (calcite, dolomite etc) experimentally showed virtually no dependence of the magnetic results on temperature from ambient to beyond typical reservoir temperatures (245 ºC) as expected. Samples containing any significant paramagnetic material should show a decrease with temperature (Curie-Weiss law), and experimentally the N. Sea dogger sample shows a systematic decrease in the high field magnetic susceptibility with increasing temperature (Figure 5).

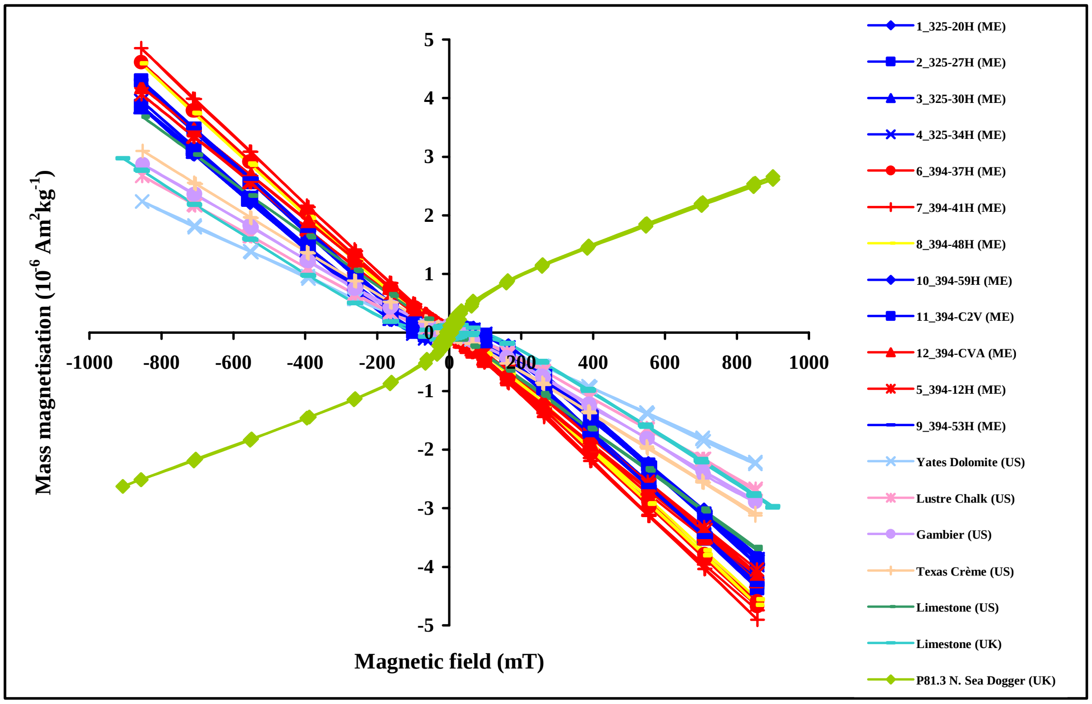


Figure 4. A comparison of magnetic hysteresis curves from some Middle East (ME), United States (US) and United Kingdom (UK) carbonate samples.

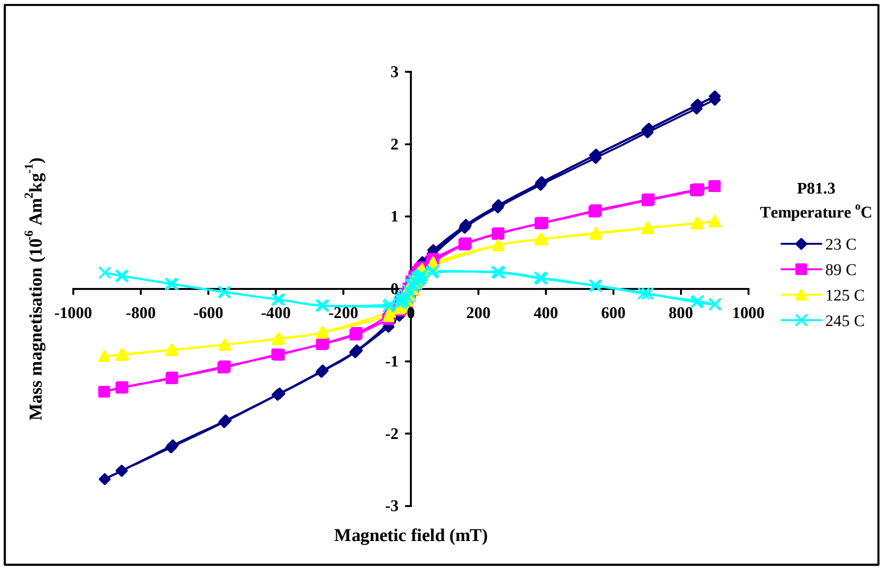


Figure 5. Effect of temperature on the hysteresis behaviour of the N. Sea dogger sample.

CONCLUSIONS

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

- Subtle mineralogical differences in carbonates can be characterised by their magnetic hysteresis curves. The slope of the hysteresis curve (the magnetic susceptibility) at high fields indicates the combined contribution of the diamagnetic plus paramagnetic minerals in the carbonate. Most major carbonate minerals (such as calcite, dolomite, magnesite) are diamagnetic, however come carbonates are paramagnetic (such as siderite and rhodochrosite). The low field hysteresis behaviour can indicate the presence of any ferrimagnetic material (via “kinks” or “loops” at low field), and can be a further means of characterising subtle differences between different carbonate samples. The magnetic measurements can identify extremely small amounts of these ferrimagnetic particles (parts per million), which cannot be done by techniques such as XRD.
- The high field magnetic susceptibility exhibited very strong correlations with both permeability and porosity in a series of Middle East carbonates from the Arab-D reservoir Jurassic formation. This appears to be a significant breakthrough in the characterisation of carbonates via rapid magnetic techniques. This is the first time, as far as we are aware, that *high field magnetic susceptibility* has been compared with petrophysical properties in carbonates. The precise reasons for the strong correlations are presently unclear, however it seems likely that differences in the calcite to dolomite ratio, and / or differences in paramagnetic clay content between the samples is responsible for the variability in permeability and porosity, and that these mineralogical differences are reflected in the magnetic susceptibility values. In clastics we have previously established strong links between the paramagnetic clay content, high field magnetic susceptibility and permeability (Potter, 2007; Potter and Ivakhnenko, 2008). If links between the mineralogy, high field magnetic susceptibility and petrophysical properties can be established in this and other carbonates, then it could potentially allow rapid petrophysical characterisation of carbonates to be achieved by these magnetic techniques.
- The low field magnetic susceptibility did not exhibit good correlations with permeability and porosity, and this can be explained entirely by the influence of small amounts of ferrimagnetic material in some of the samples. This ferrimagnetic material does not influence the high field results, since it saturates in the lower fields, and is also not expected to affect the petrophysical properties.
- Carbonates that contained a greater amount of paramagnetic clay also exhibited a greater low field anisotropy of magnetic susceptibility (AMS). Future anisotropy measurements should determine the high field anisotropy of magnetic susceptibility to better characterise the diamagnetic and paramagnetic components in the samples without the influence of any ferrimagnetic material.
- The effects of temperature on the high field magnetic susceptibility (the slope of the hysteresis curve at high field) are only noticeable if the carbonate sample contains a significant amount of paramagnetic material. In these cases a downhole measurement at *in-situ* reservoir temperatures would give a lower high field magnetic susceptibility

value than a corresponding ambient measurement. For the main diamagnetic matrix minerals (pure calcite or dolomite) the effect of temperature is insignificant.

ACKNOWLEDGEMENTS

The Industry Technology Facilitator (ITF) “Low Permeability Reservoir” programme, funded by BP, Chevron, Shell, Total, and Scottish Enterprise is gratefully acknowledged. We thank Nicolai Petersen and Valerian Bachtadse for the use of the VFTB at the Ludwig Maximilians University, Munich. We thank Jim Somerville and Sally Hamilton for the Middle East carbonate samples, and Norman Morrow for the US carbonate samples.

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