QUANTIFYING THE RELATIVE ROLES OF ILLITE AND HEMATITE ON PERMEABILITY IN RED AND WHITE SANDSTONES USING LOW AND HIGH FIELD MAGNETIC SUSCEPTIBILITY

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ABSTRACT

Recent work has demonstrated how rapid, non-destructive magnetic susceptibility measurements in clastic reservoir samples (Potter et al, 2004; Potter, 2005, 2007; Ivakhnenko, 2006; Ivakhnenko and Potter, 2004, 2006a, 2006b, 2008; Potter and Ivakhnenko 2007, 2008) and carbonate reservoir samples (AlGhamdi, 2006; Potter et al 2008) correlate with several key petrophysical parameters. The present paper details a methodology using low and high field magnetic susceptibility measurements to quantify the relative roles of illite clay and hematite (iron oxide) on the permeability of red and white reservoir sandstone samples. The motivation for the present study was the observation that for various North Sea clastic tight gas and unconventional reservoirs, containing both red and white sandstone formations, the permeability is generally lower in the red sandstones compared to adjacent white sandstones. We show how magnetic hysteresis measurements are able to quantify both the illite and hematite content in red sandstones. Hematite can be identified and quantified from its characteristic hysteresis loop behaviour over a range of low to high applied magnetic fields. The magnetic technique is very sensitive and can identify and quantify extremely small concentrations of hematite that would not be seen by X-ray diffraction (XRD). Illite can be quantified from the slope of the hysteresis curve at high fields (the high field magnetic susceptibility). The influence of each mineral on permeability in red sandstones can be estimated with the help of comparative studies in white sandstones, where the permeability correlates primarily with the magnetically derived illite content alone. Significantly, we found that permeability is systematically lower in red sandstones compared to white sandstones containing similar magnetically derived illite contents. The implication is that there is a further factor causing a reduction in permeability in red sandstones, and our work suggests that this is due to the presence of the fine-grained hematite.

We have also developed another method of deriving both illite and hematite content simultaneously in red sandstones from rapid low field magnetic susceptibility measurements alone using certain assumptions. In a series of sections of red and white sandstones in a tight gas reservoir we have seen strong correlations between the variation in hematite content with depth and the corresponding probe permeability profiles. Increases in hematite content correspond to decreases in permeability and vice versa. These exciting new results suggest that small amounts of fine-grained hematite

are playing a very important (apparently dominant) role in controlling the permeability in red sandstones, which has not previously been demonstrated.

INTRODUCTION

Recent studies have demonstrated the potential uses of magnetic susceptibility for reservoir characterisation, quantifying mineralogy, and for predicting important petrophysical parameters in both clastic (Potter et al, 2004; Potter, 2005; Ivakhnenko, 2006; Ivakhnenko and Potter, 2006a, 2006b; Potter, 2007; Ivakhnenko and Potter, 2008; Potter and Ivakhnenko, 2008) and carbonate (AlGhamdi, 2006; Potter et al, 2008) reservoirs. These measurements provide a rapid, non-destructive complement to XRD for determining the content of permeability controlling clays such as illite or chlorite (Potter et al, 2004; Potter and Ivakhnenko, 2008), and, more importantly, for predicting permeability (Potter, 2005, 2007; Potter and Ivakhnenko, 2008). The measurements have been demonstrated to give significantly improved permeability predictions even in cases where the relationship between porosity and permeability is very poor (Potter, 2007). The measurements have also been shown to 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).

High field magnetic susceptibility measurements derived from hysteresis curves in clastic reservoirs have shown even better correlations with permeability than low field magnetic susceptibility measurements (Potter and Ivakhnenko, 2008). We have also shown significantly improved correlations of petrophysical properties (permeabilty, porosity) with high field magnetic susceptibility in carbonates (Potter et al, 2008). This is because 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 the content of paramagnetic permeability controlling clays were improved because the effects of any ferro- or ferrimagnetic impurities were 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 shows how magnetic measurements can be used to identify and quantify the relative roles of illite clay and the iron oxide hematite on the permeability in some North Sea tight gas reservoirs. We will show how comparisons of magnetic hysteresis curves in white and red sandstones allow one to separate out the different roles of each of these minerals. We also describe a means of rapidly and simultaneously estimating the illite and hematite content via low field magnetic susceptibility measurements alone. We then demonstrate that the permeability in the red sandstones appears to be controlled primarily by the hematite.

QUANTIFYING THE RELATIVE ROLES OF ILLITE AND HEMATITE ON PERMEABILITY IN WHITE AND RED SANDSTONES VIA MAGNETIC HYSTERESIS MEASUREMENTS

We have noticed that in some tight gas reservoirs in the North Sea the permeability in white sandstones is almost always higher (and therefore the reservoir quality slightly better) than in adjacent red sandstones. In an attempt to identify and quantify the reasons for this we undertook magnetic hysteresis measurements using a Variable Field Translation Balance (VFTB) to get some idea of the different mineral components present, and compared the permeability values of the different samples.

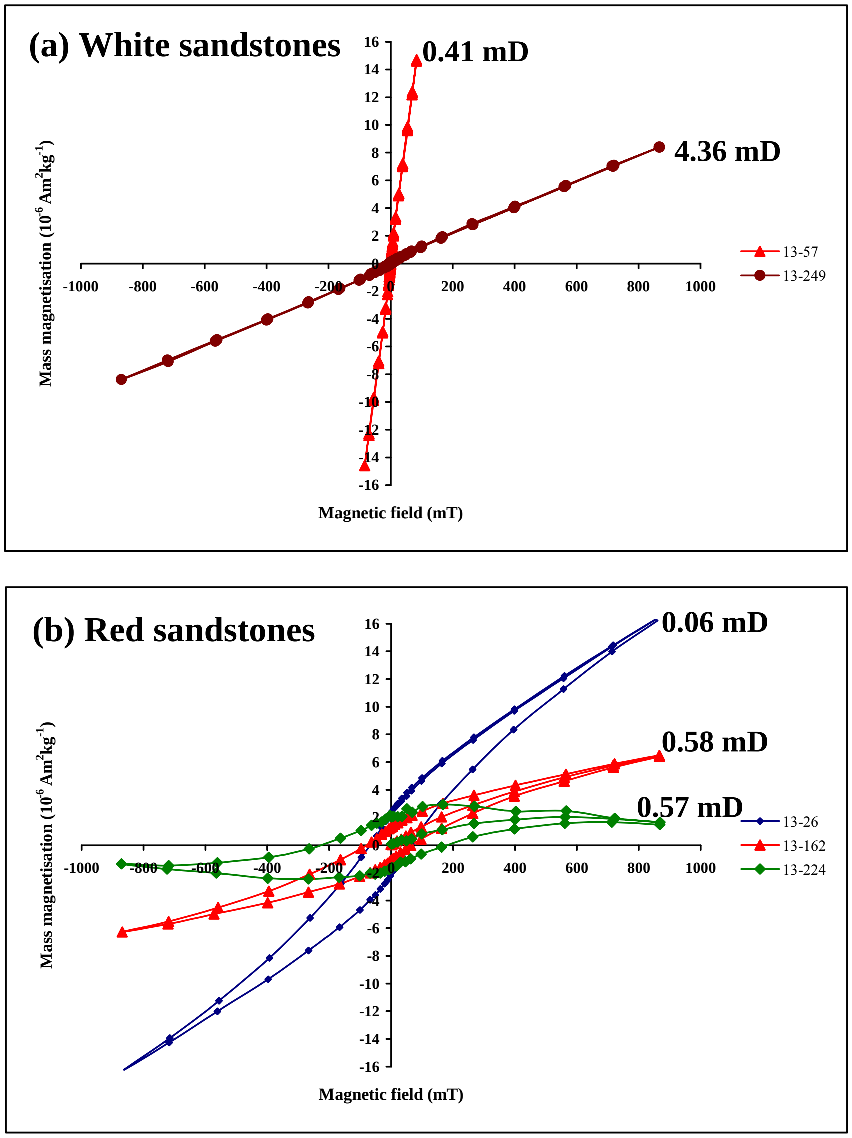

Figure 1. Magnetic hysteresis measurements from a N. Sea reservoir. (a) For white sandstones the mineralogy is dominated by quartz and illite. The higher the high field slope, the higher the illite content and the lower the permeability. (b) For red sandstones the wide hysteresis loops indicate hematite. Sample 13-224 has a slightly lower permeability than sample 13-162 most likely because it's hematite content is higher (wider hysteresis loop) even though the illite content is lower (lower high field slope).

White sandstones

Examples of magnetic hysteresis results from white sandstones in a tight gas reservoir in the North Sea are shown in Figure 1(a). These white sandstones exhibited almost straight lines with no “hysteresis loop” and only a very slight “kink” at low fields. This means that they do not contain any significant ferrimagnetic minerals (the slight kink at low field indicates that only extremely small amounts are present). These samples are comprised mainly of quartz, with small amounts of illite which are controlling the permeability. The steeper the straight line hysteresis “curve” (particularly at high fields) for one of the samples means that it has a higher illite content (Potter and Ivakhnenko, 2008). This is consistent with it having a lower permeability. In these samples, where illite is the dominant control on permeability, the higher the high field slope the higher the illite content and the lower the permeability.

Red sandstones

In contrast, red sandstones in the same tight gas reservoir exhibited distinctive “hysteresis loops” at lower fields rather than straight lines (Figure 1(b)). The fact that these “loops” remain open to quite high fields indicates that they are due to the presence of hematite. In general the wider the “loop” the more hematite is present; however the loop dimensions will also depend on the hematite grain size.

The high field slope (approximating to a straight line) is due only to the combined effect of the diamagnetic matrix (quartz) and any paramagnetic minerals present (illite in this case). The higher the high field slope the higher the amount of paramagnetic illite present. The advantage of the high field hysteresis measurements is that they can provide this information without the influence of the hematite (which is close to saturation at these high fields). It can be seen from Figure 1(b) that the high field slopes are different for the three samples shown. Again the higher the high field slope the higher the illite content and, one would expect, the lower the permeability. The key point to notice is that in these red sandstones the permeability is lower compared to equivalent white sandstones with similar high field slopes (i.e., similar illite contents). This suggests that there is another factor controlling the permeability, causing it to be lower in these red sandstones compared to the equivalent white sandstones. It would seem that the hematite in the red sandstones is having a significant impact in reducing the permeability. Red hematite is very fine-grained (compared to the specularite variety which is more grey in colour) and it would seem logical that this fine-grained hematite might be blocking pores and causing the reduction in permeability.

RAPID SIMULTANEOUS QUANTIFICATION OF ILLITE AND HEMATITE IN WHITE AND RED SANDSTONES FROM LOW FIELD MAGNETIC SUSCEPTIBILITY MEASUREMENTS

We wanted to look at a large number of samples to see whether hematite was indeed having a significant influence on the permeability. Since magnetic hysteresis measurements typically take around 10-15 minutes to complete, it can be quite time consuming if one is studying several hundred samples. The hysteresis equipment is also bulky, not portable, and requires small samples to be cut from the core. We therefore devised a method of estimating illite and hematite simultaneously in red sandstones from rapid low field measurements (which take a few seconds), and which can be done on slabbed core using a portable surface scanning probe which does not require any samples to be cut. This built on previous work (Potter, 2007) applicable to quantifying illite in white sandstones. These methods are described below.

Methodology in White Sandstones

XRD analysis of representative white sandstone core sections in this study showed they comprised primarily of quartz and illite. There are small amounts of other minerals present, but they do not significantly influence the results. Assuming a simple two component mineral mixture comprising quartz and illite, we can derive the fraction of illite using the following equation (which is a re-written form of Equation (4) in Potter, 2007):

$$F_I = \frac{\chi_T - F_Q \chi_Q}{\chi_I} \qquad (1)$$

where F_Q is the fraction of quartz, χ_Q and χ_I are the magnetic susceptibilities of quartz and illite (-1.5×10^{-5} SI and 41×10^{-5} SI respectively if we consider volume magnetic susceptibilities, Hunt et al, 1995), and χ_T is the total magnetic susceptibility of the sample (which can be obtained using a small probe on slabbed core, or by using a magnetic susceptibility bridge for core plugs).

Methodology in Red Sandstones

For red sandstone core sections hematite is present along with illite and quartz. This has been confirmed by XRD analysis in the cores we have examined. Hematite can exhibit a range of magnetic susceptibility values depending upon its grain size. The red colour usually means it is very fine-grained sub micron hematite. We can get a good estimate of the magnetic susceptibility of the hematite in our core samples by using the following methodology. Assuming a three component system consisting of hematite, illite and quartz the total magnetic susceptibility is given by the following equation:

$$\chi_T = X\,(\chi_{hem}) + Y\,(\chi_I) + Z\,(\chi_Q) \qquad (2)$$

where X, Y and Z are the percentages of hematite, illite and quartz (which can be obtained for a selection of representative samples via XRD measurements), and χ_{hem}, χ_I, and χ_Q are the magnetic susceptibilities of hematite, illite and quartz. Since χ_T can be measured using a magnetic susceptibility probe on slabbed core, χ_I and χ_Q are known constants (and do not depend on grain size), and X, Y and Z can be obtained from XRD measurements, then the only unknown is χ_{hem}. Experiments on the core samples we investigated suggested that the volume magnetic susceptibility of the hematite was close to 400×10^{-5} SI.

For a red sandstone containing this three component system the fraction of illite can be obtained by rewriting Equation (1) as follows:

$$F_I = \frac{\chi_T - F_Q(\chi_Q - \chi_{hem}) - \chi_{hem}}{\chi_I - \chi_{hem}} \qquad (3)$$

In the core samples we examined we have assumed that F_Q is 0.9 in all cases, since the selected representative samples that were measured by XRD gave values for the total diamagnetic fraction close to this (actually 0.92 average from 15 samples). For simplicity we assumed that F_Q was the sum of all the diamagnetic components in the rock (which was dominantly quartz). The fraction of hematite is then simply obtained by the following equation:

$$F_{hem} = 0.1 - F_I \qquad (4)$$

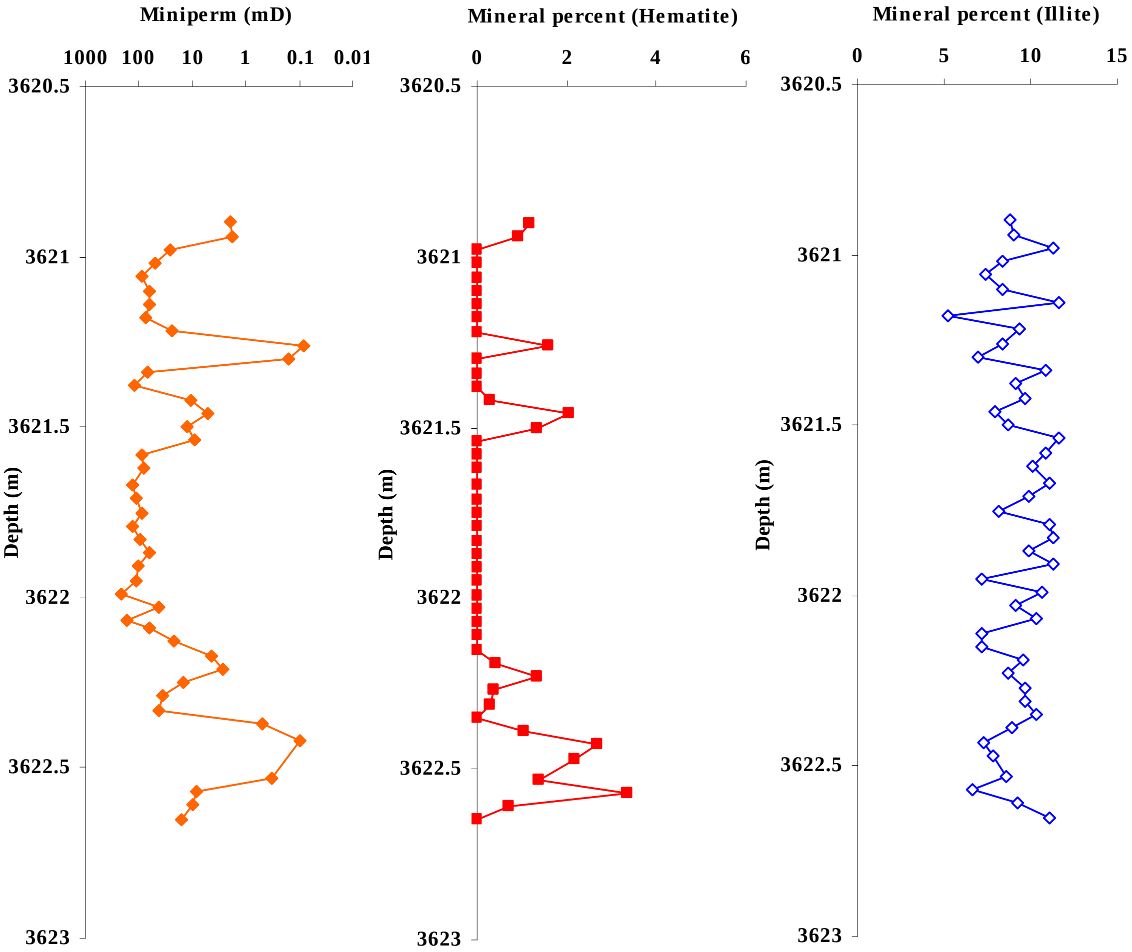

Figure 2. Probe permeability and magnetically derived hematite and illite contents (using Equations (1), (3) and (4)) for a section of slabbed core from a North Sea tight gas reservoir. Note that the hematite content closely follows the probe permeability profile with depth, but that the illite content does not.

Experimental Variation of Hematite and Illite Content from Low Field Magnetic Susceptibility in Red and White Sandstones and Comparison with Permeability

We have experimentally determined the volume magnetic susceptibility on several red and white sandstone sections of slabbed core from a tight gas reservoir in the North Sea using a small probe device. We then estimated the contents of illite and hematite using Equations (1), (3) and (4). XRD showed that there were small amounts of other minerals present in most cases, but these do not significantly affect the magnetic results. We then compared the magnetically derived mineral contents with the probe permeability profile on the same sections of slabbed core. Figure 2 shows an example from a 2.5 metre section of the core. It is clear that the variation of hematite content with depth closely matches the variation in probe permeability. Low hematite content corresponds to high permeability values and vice versa. In contrast the variation in illite content does not correspond with the permeability profile.

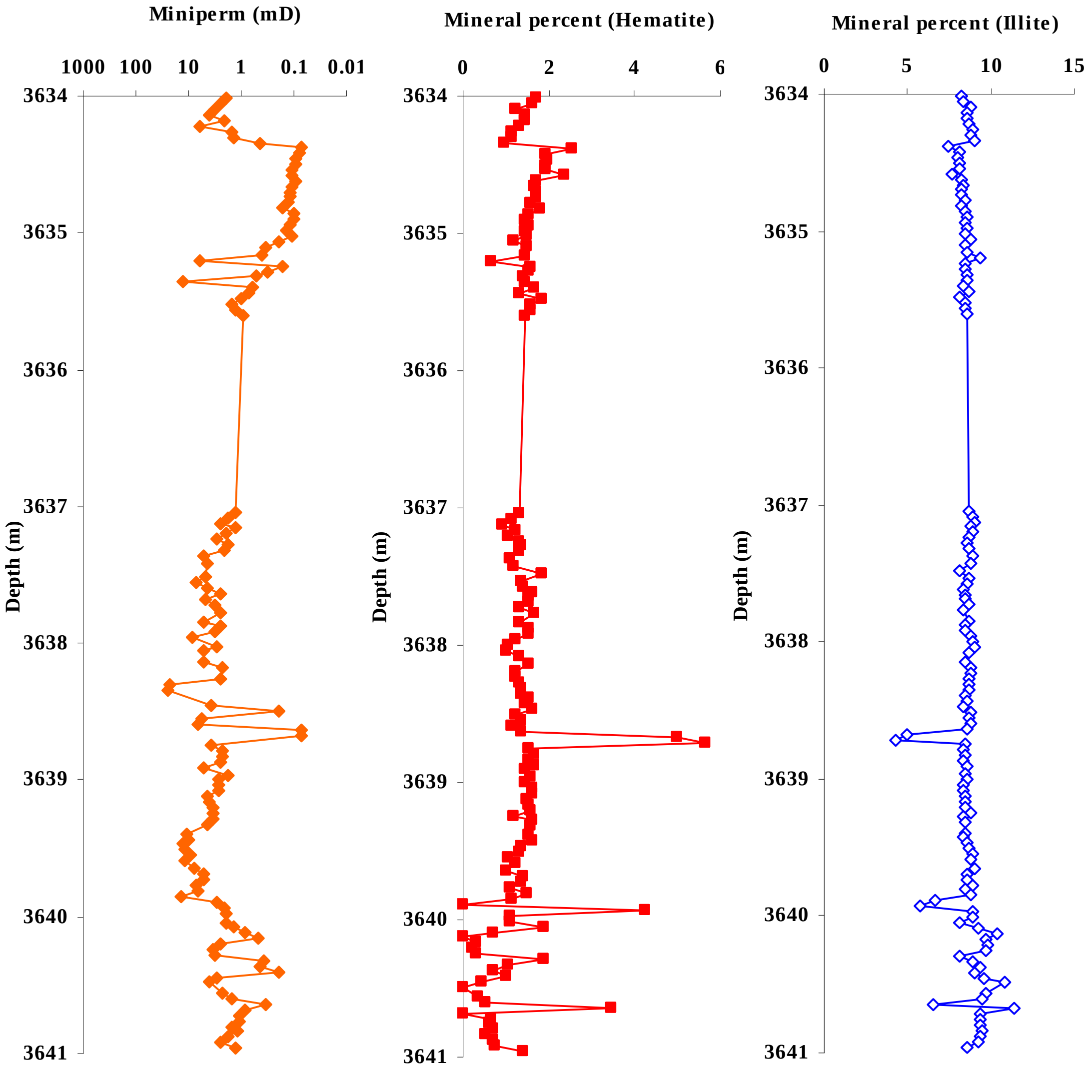

Figure 3. Probe permeability and magnetically derived hematite and illite contents (using Equations (1), (3) and (4)) for a section of slabbed core from a North Sea tight gas reservoir. Note that peaks in the hematite content correspond to minima in the permeability values. XRD on small samples gave 4.3% hematite and 6.7% illite at 3634.3m, and negligible hematite and 5.3% illite at 3640.7m.

This result was completely unexpected as it had previously been assumed that illite was still the dominant control on permeability in these sandstones. It appears, however, that hematite is in fact the major factor controlling permeability. We then tested this on several other sections in the same reservoir. Figure 3 shows results from a 6 metre section of slabbed core. Note in particular that peaks in the hematite content occur at exactly the same depths (for example, at 3638.6m) as minima in the permeability values. At these depths the content of illite goes down. If illite was controlling the permeability and causing the minima in permeability one would expect that the illite content would have increased at these depths.

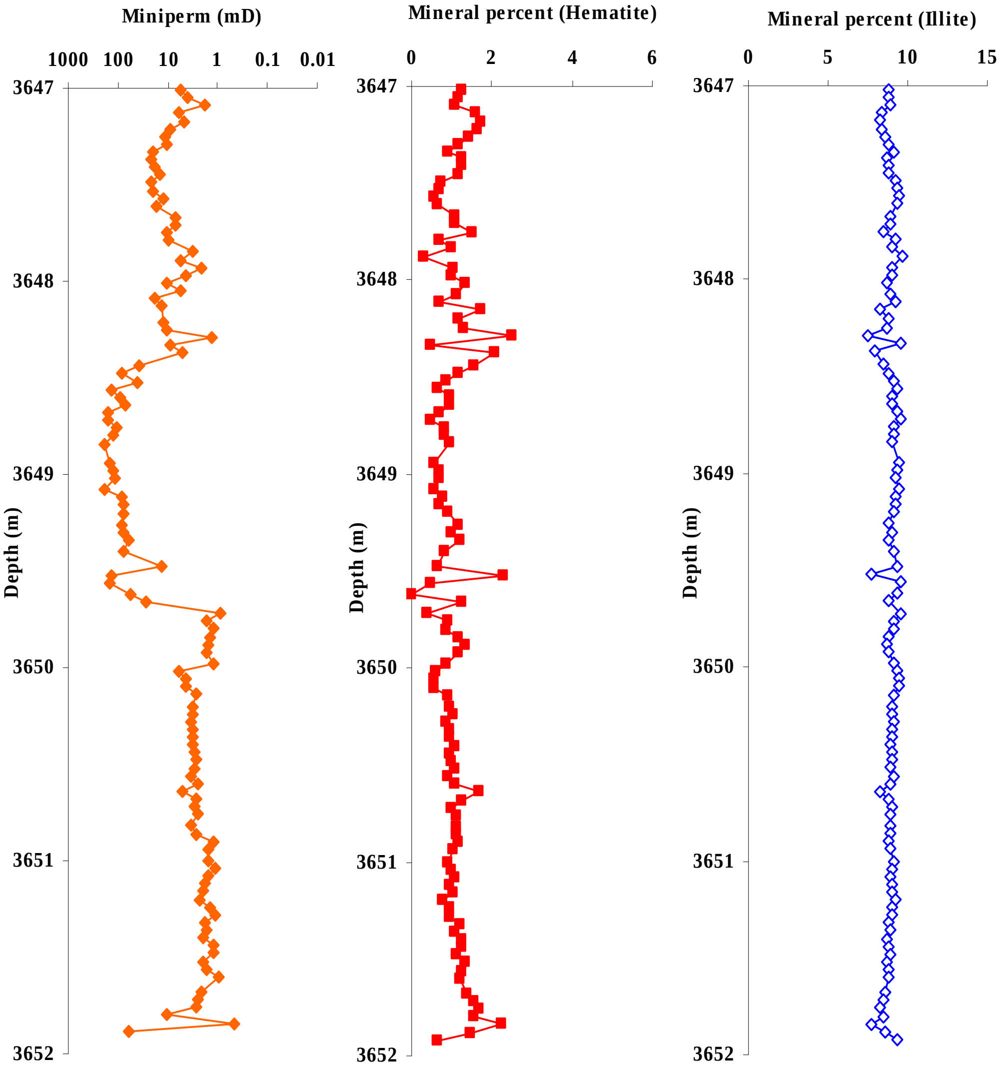

Figure 4. Probe permeability and magnetically derived hematite and illite contents (using Equations (1), (3) and (4)) for a section of slabbed core from a North Sea tight gas reservoir. Note again that the hematite content closely follows the probe permeability profile with depth. XRD on small samples gave negligible hematite at 3648.3m, and 1.2% hematite at 3648.6m, though direct comparisons with the magnetic results are difficult because the XRD sample volumes are smaller and the XRD samples were taken by the operating company before the magnetic measurements were done (and so the XRD and magnetic results were obtained from slightly different parts of the core).

The results are strong evidence that hematite is the dominant control on permeability in these sandstones. Figure 4 shows another example of a 5 metre section of slabbed core where the profile of hematite content with depth closely matches the probe permeability profile. Note that relatively small amounts of hematite are having a very significant effect on the permeability. The illite variation in the red sandstone sections of Figures 2-4 is of course the mirror image of the hematite variation (by virtue of Equation (4)). However, the key point in all these plots is that the hematite content peaks where permeability is lowest. If illite was the dominant control on permeability it would be peaking (not troughing) where permeability was lowest.

Figure 5 shows results from a 0.8 metre section of slabbed core. It is evident that the most significant decreases in permeability occur precisely at the points where the hematite content increases towards the base of this section (the darker, redder, intervals shown in the core photo).

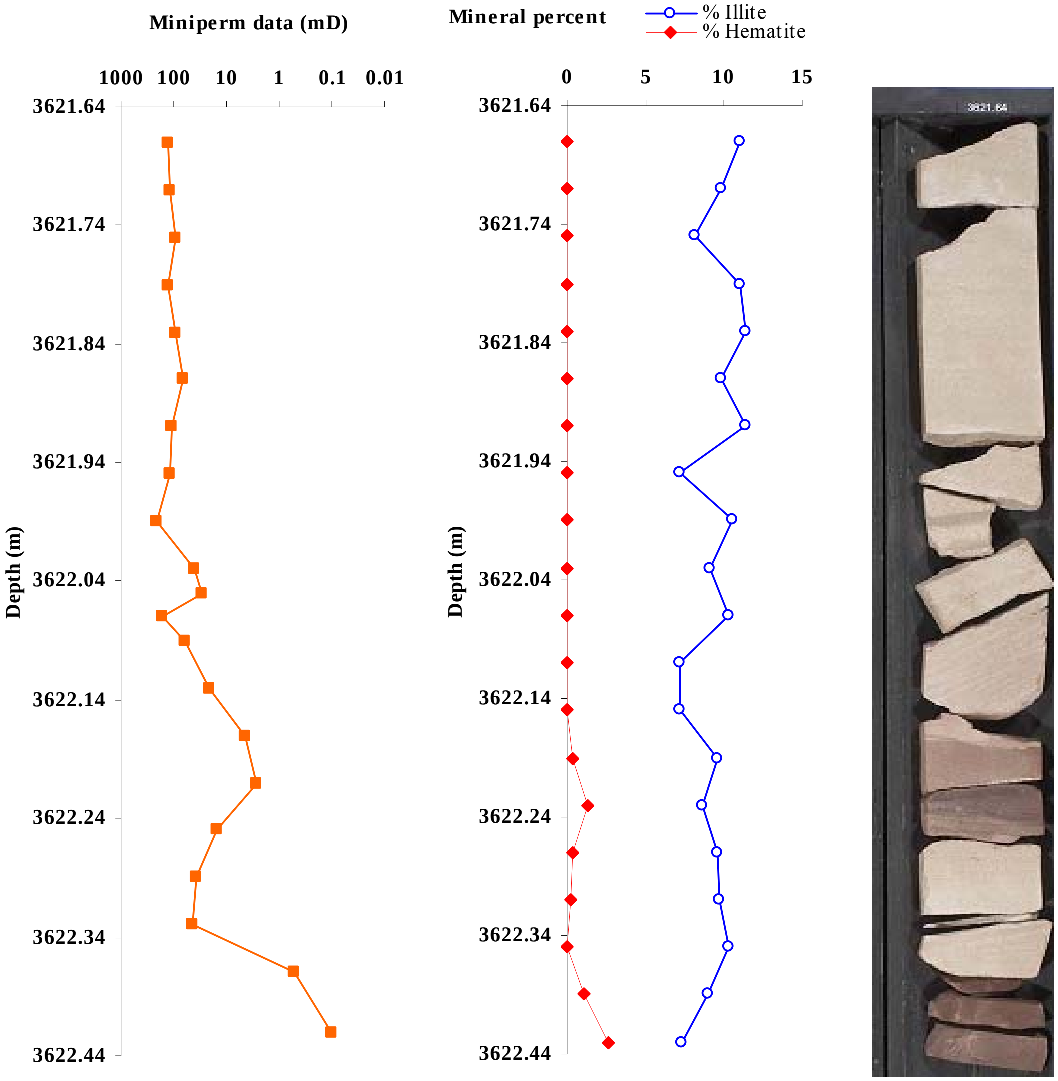

Figure 5. Probe permeability and magnetically derived hematite and illite contents (using Equations (1), (3) and (4)) for a section of slabbed core from a North Sea tight gas reservoir. Note that the most significant decreases in permeability occur precisely at the points where the hematite content increases towards the base of this section (darker, red, sections of the core).

CONCLUSIONS

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

- In the North Sea tight gas sandstones that we have studied we found that permeability is systematically lower in red sandstones compared to white sandstones containing similar magnetically derived illite contents. A comparison of magnetic hysteresis curves from red and white sandstones indicated that a paramagnetic mineral (illite) was controlling the permeability in the white sandstones, whilst the presence of hematite (shown by wide hysteresis loops) was a further factor controlling the permeability in the red sandstones. It would appear that the presence of the fine-grained red hematite is having a significant effect, by decreasing the permeability (and therefore the reservoir quality) in the red sandstones compared to the white sandstone sections.
- A new rapid method of simultaneously obtaining hematite and illite content in red sandstones from low field magnetic susceptibility measurements, along with a previous comparable method of obtaining illite content in white sandstones, has helped to further demonstrate the relative importance of each mineral on the reservoir rock quality. In a series of red and white sandstone slabbed core sections from a North Sea tight gas reservoir the variation of hematite content with depth closely followed that of the probe permeability. High hematite content corresponded to low permeability and vice versa. Moreover, where the permeability decreased (especially in the red sandstone sections) the illite content often also decreased. If illite was the primary control of permeability in these sections then one would have expected the illite content to increase as the permeability decreased. We now need to perform low and high field magnetic susceptibility measurements (via a new VFTB that has recently been installed at Heriot-Watt) to validate the results obtained using low field measurements alone and Equation (4) for estimating the contents of hematite and illite.
- The above observations strongly suggest that hematite is having a dominant control on the permeability of red sandstones, and is degrading the reservoir quality compared to the equivalent white sandstones (i.e., white sandstones with a similar illite content).
- The methodology for obtaining rapid simultaneous hematite and illite contents could potentially be applied to downhole low field magnetic susceptibility measurements.

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