PETROPHYSICS, VOL. 48, NO. 3 (JUNE 2007); P. 191–201; 9 FIGURES, 1 TABLE

Magnetic Susceptibility as a Rapid, Nondestructive Technique for Improved Petrophysical Parameter Prediction[1]

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ABSTRACT

Magnetic measurements provide a rapid, cheap and nondestructive means of characterizing high-resolution mineralogical variations between core samples. Until now they have been a relatively unexploited tool in petrophysical core analysis. One of the most useful measurements is low-field (initial) magnetic susceptibility. This paper will demonstrate how such measurements on core plugs, both as raw values and after novel processing of the results to mineral contents, can provide rapid predictions of key petrophysical parameters. The measurements allow "quick look" petrophysical appraisals to be made long before the usual routine or special core analysis data becomes available, since all the core plugs from a well can potentially be magnetically screened in one day. In the present study the negative or positive sign of the raw magnetic susceptibility signal showed a strong correspondence with the main lithological and permeability zones. Moreover, the processed results exhibited strong correlations between magnetically derived illite content and permeability in an oilfield where the porosity-permeability relationship is very poor. This provided a new permeability predictor where prediction had previously been problematic. Furthermore, the magnetic measurements correlated with the flow zone indicator (*FZI*), the cation exchange capacity per unit pore volume (Q_v), and the wireline gamma ray signal. The relationship between magnetics and wireline gamma ray provides a quantitative means of distinguishing clean sand from muddy sand, even in the presence of a high-gamma ray-emitting (but low magnetic susceptibility) drilling mud. The results also allowed the wireline gamma ray data to be related to illite content.

Keywords: magnetic susceptibility, permeability, illite

INTRODUCTION

Low-field magnetic susceptibility measurements provide a rapid, cheap, portable and nondestructive means of characterizing high-resolution mineralogical variations between core samples at a variety of scales. Magnetic susceptibility is defined as the intensity of magnetization divided by the applied field, and can be expressed either in terms of the susceptibility per unit mass or per unit volume:

$$\text{Mass susceptibility, } \chi = J / H \qquad (1)$$

where J is the magnetization per unit mass, and H is the magnetic field strength ($H = B/\mu o$ where B is the applied field in Tesla and μo is the magnetic permeability of free space).

$$\text{Volume susceptibility, } k = M / H \qquad (2)$$

where M is the magnetization per unit volume.

The results in this paper will be expressed in terms of mass susceptibility. This requires weighing each core plug, but one advantage of obtaining mass susceptibility is that it

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

Mineral or Fluid Type	Mineral or Fluid	Magnetic Susceptibility Per Unit Mass (10^{-8} m^3 kg^{-1})
Diamagnetic matrix minerals and reservoir fluids:	Quartz	-0.5 to –0.6 (-0.55*)
	Calcite	-0.3 to -1.4
	Orthoclase feldspar	-0.49 to -0.67
	Kaolinite	-2.0
	Forties Field formation water	-0.87
	Forties Field crude oil	-1.02
Paramagnetic permeability-controlling clays:	Illite	15.0
	BVS Chlorite	13.6 †
	CFS Chlorite	52.5 †
Ferrimagnetic minerals:	Magnetite	2^4 to 11^4

*This value, the midpoint of the range, is used in this paper for the susceptibility of quartz in equations (3) and (4). † From Borradaile et al (1990), who detail the localities BVS, CFS. Kaolinite value from Thompson and Oldfield (1986), and values for fluids from Ivakhnenko and Potter (2004). All other values from Hunt et al (1995). Some minerals exhibit ranges, which may be due to measurements in different laboratories, slight compositional differences, or the presence of minute amounts of impurities. The theoretical value for calcite has recently been given as -0.48 (10^{-8} m^3 kg^{-1}) by Ivakhnenko (2006).

is not influenced by the porosity of the sample. A magnetic susceptibility measurement on a core plug (a background reading followed by a sample reading) can be made in under 5 seconds and requires no extra preparation of the sample. In spite of their rapidity and ease of measurement they are not commonly applied to the plugs used in an oil company's routine (RCAL) or special core analysis (SCAL) programs. This paper will demonstrate how magnetic susceptibility measurements on routine core plugs, which were generally 1 in (2.54 cm) diameter and 1.5 in (3.81 cm) long, can be used as a complementary technique to provide rapid predictions of key petrophysical parameters. This has the potential of providing "quick look" petrophysical appraisals well before the usual RCAL and SCAL data becomes available.

The magnetic susceptibility values of some typical reservoir minerals and fluids are given in Table 1. The main matrix minerals comprising reservoir rocks, such as quartz in clastic reservoirs or calcite in carbonate reservoirs, are diamagnetic (low, negative magnetic susceptibility). In contrast, the permeability-controlling clays such as illite and chlorite are paramagnetic (positive magnetic susceptibility, with significantly higher magnitude than the diamagnetic minerals). Therefore the negative or positive sign of the raw magnetic susceptibility values of the routine core plugs is potentially useful information, since it can provide a rapid indication of the main lithological zonations. Clean sands should be characterized by net negative values of magnetic susceptibility, whereas muddy sands and shales should be characterized by net positive values of magnetic susceptibility. Since these broad lithological zonations are generally characterized by different fluid permeability values, then the negative or positive sign of the magnetic susceptibility can also give a first pass indication of the broad permeability zonations. In general, one would expect high permeability in the clean sands (except in low permeability naturally cemented regions), and lower permeability in the muddy sands and shales where there are increased amounts of permeability-controlling clay.

Furthermore, it has recently been shown (Potter et al., 2004) that raw magnetic susceptibility measurements can be processed to determine mineral contents in simple systems, and this was applied to quantify illite and quartz content simultaneously in some North Sea shallow marine shoreface facies. The results compared favorably with those derived from X-ray diffraction (XRD). One motivation for the present work was to investigate whether the magnetically derived illite content correlates with permeability. Vernik (2000) has used total clay volume obtained from XRD measurements to successfully predict permeability in some shallow marine and fluvial-deltaic sequences, where illite was likely to be one of the major permeability-controlling clays. The magnetic measurements described in the present work could potentially do a similar job very rapidly and nondestructively.

It is also worth noting that all the crude oils and formation waters that have recently been measured are diamagnetic (Ivakhnenko and Potter, 2004). This means that any such residual fluids that may be left in the core samples are unlikely to affect the magnetically derived estimates of the paramagnetic permeability-controlling clays.

Advantages of low-field magnetic susceptibility measurements

Low-field magnetic susceptibility measurements provide a rapid, cheap, and nondestructive screening tool for both new and old core sample sets. The measurements also require no extra preparation of the sample, and the measurements can be made either before or after core cleaning. In fact, by making measurements both before and after cleaning, one can potentially quantify any anomalous effects resulting from the cleaning process, as has been discussed in some previous preliminary experiments (Potter et al., 2004). Conveniently, the measurements can be performed on the same routine core plugs (and therefore at the same volume scale) that are used for determining permeability, porosity and other petrophysical parameters. This has the added advantage that it avoids any depth shifting issues when correlating with these other parameters. The magnetic measurements can also be performed on equipment that is very portable. This means that measurements can be made at the well site. In addition, good results can be obtained from plugs that may have been accidentally fractured either during coring or at a subsequent time. The presence of a fracture does not significantly affect the magnetic results (unlike acoustic or permeability measurements, for instance). This means that sidewall cores and drill cuttings can potentially be used for magnetic analysis.

Many of the points mentioned above are advantages over other core analysis techniques. For instance, laboratory nuclear magnetic resonance (NMR) measurements require significant sample preparation (saturating the sample with an appropriate fluid), measurement and analysis time. Furthermore, NMR measurements are essentially a measure of the pore size distribution which is not necessarily a good predicator of permeability. It will be demonstrated that magnetic susceptibility can provide an excellent permeability predictor in a case where the relationship between porosity and permeability is very poor, where the permeability is controlled by illite clay.

Low-field magnetic susceptibility measurements are potentially a very useful complement to (not a replacement for) XRD, since they can provide data on a substantially greater number of samples than would be possible in an equivalent time period using XRD. In contrast, XRD is much more time consuming, expensive, destructive to the core (powdered samples are generally required), and involves significant sample preparation compared to the magnetic technique. Magnetic susceptibility measurements can also be undertaken at much larger volume scales than traditional XRD analyses. A comparison of magnetically derived and XRD-derived illite and quartz content in some North Sea oil wells has previously been reported (Potter et al., 2004). There was a significant correlation between the results from the two techniques, and also some explainable differences.

Standard core gamma ray techniques are generally only applied to whole core samples, and have lower resolution than the current magnetic equipment that is available. A correlation between the magnetic susceptibility results and the gamma ray signal might be expected in cases where there are permeability-controlling clays such as illite. This is because illite gives a strong paramagnetic susceptibility signal, and is a significant contributor to the natural gamma ray emissions primarily in the form of radioactive potassium (K^{40}). Thus, part of this paper examines the relationship between the total downhole wireline gamma ray signal and the depth-matched magnetic susceptibility measurements on core plugs. This relationship will be shown to potentially provide improved petrophysical interpretations from downhole gamma ray data, in terms of lithology changes and illite quantification, even in the presence of a high-gamma ray-emitting drilling mud.

While the present magnetic results were obtained from core plugs, magnetic susceptibility measurements can also be performed at smaller probe (Lees et al., 1998; Lecoanet et al., 1999) and larger whole core (Weber et al., 1997; Gunn and Best, 1998; Lees et al., 1998; Vanderaveroet et al., 1999) scales, potentially allowing high-resolution and upscaled petrophysical data to be collected on slabbed or whole core without the need to cut plugs. The latter advantage is particularly useful for unconsolidated core. The results presented here on core samples also indicate the potential usefulness of a downhole magnetic susceptibility tool for in-situ prediction of permeability and other petrophysical parameters, supporting the suggestions of Potter (2004). Currently there is no commercially available large scale downhole tool in the petroleum industry, although some downhole magnetic susceptibility studies have been reported (Tabbagh et al., 1990; Barthes et al., 1999; Thibal et al., 1999).

Limitations of low-field magnetic susceptibility measurements

First, a single-reading low-field magnetic susceptibility measurement reflects the sum of all the mineral components in the sample, and depends on the fraction and intrinsic susceptibility of each component. Therefore, in terms of quantifying mineral contents, magnetic susceptibility works best for a simple two component mixture (such as a diamagnetic matrix mineral and a paramagnetic clay) where one can estimate simultaneously the fraction of each mineral (Potter et al., 2004). If more than one paramagnetic clay is present in a sample, such as a combination of illite and chlorite, the

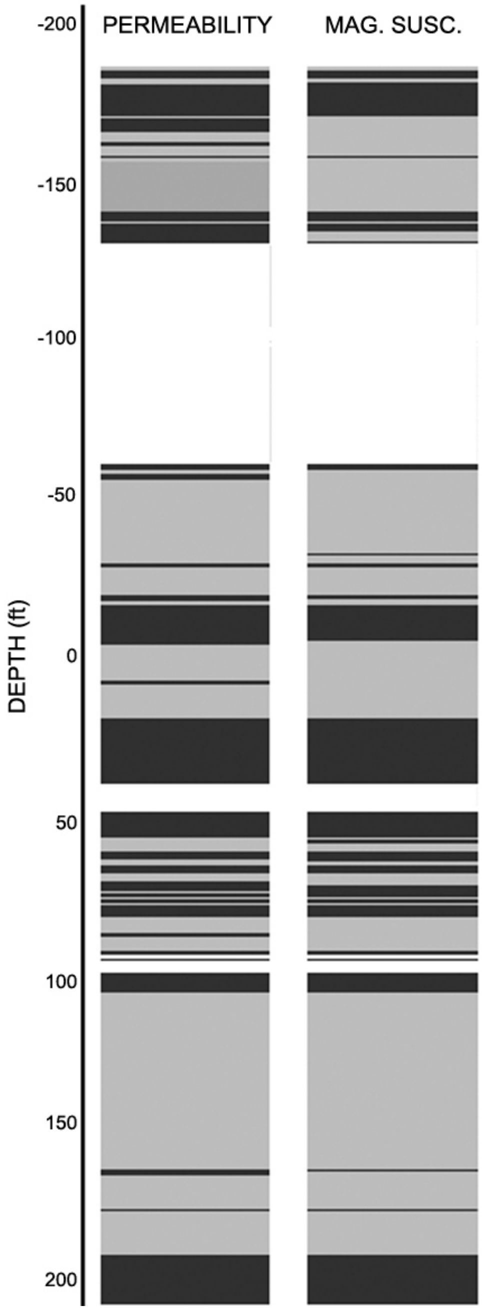

FIG. 1 A comparison of the negative or positive sign of the raw magnetic susceptibility signal and the main permeability zones with depth in a North Sea oil well (PEGASUS Well 2). Net negative magnetic susceptibility due to clean sand comprising diamagnetic quartz (grey shaded areas in right hand column) correspond to the high permeability, >100 mD, reservoir intervals (grey shaded areas in left hand column). Likewise net positive magnetic susceptibility due to increased amounts of paramagnetic illite clay correspond to the lower permeability, <100 mD, muddy sand and shale intervals (black shaded areas in both columns). The white areas represent intervals where no core was taken. Depths are confidential and are shown arbitrarily from the top of one genetic unit.

low-field magnetic measurements will see the combined signal from both of these components and unfortunately cannot distinguish between them. The extension of the method to quantify more than two main components has been discussed in Potter et al. (2004). Ideally some initial XRD, scanning electron microscopy (SEM), thin section or other mineralogical information can be used to constrain the model magnetic mixture equations, and extend the analysis to more than two components.

Second, the presence of small amounts of ferro- or ferrimagnetic minerals (such as magnetite, see Table 1), which have high positive values of magnetic susceptibility, could potentially influence the estimates of paramagnetic clays if they are not accounted for in the model equations. Fortunately such minerals can easily be identified using magnetic remanence measurements, such as isothermal remanent magnetization (IRM) produced by a pulse magnetizer in the laboratory. Ferro- or ferrimagnetic particles can acquire a remanence, whereas diamagnetic and paramagnetic minerals do not.

Third, some naturally cemented zones (for example, quartz overgrowths or barite cements) with low permeabilities will not necessarily be identified by magnetic techniques, since their susceptibility values will be close to the surrounding matrix values. However, these zones are generally readily picked out by other measurements, either from wireline log data such as bulk density, or by weighing the core plugs (naturally cemented zones generally have higher bulk density). Note, however, that some natural cemented zones, such as calcite cemented regions in the North Sea, can be pinpointed by their magnetic susceptibility signatures since they often contain small amounts of other magnetic minerals with higher positive susceptibility (paramagnetic clays or ferrimagnetic minerals).

METHODS AND RESULTS

Raw magnetic susceptibility signal: Relation to permeable zones

Low-field magnetic susceptibility measurements were undertaken using a Molspin susceptibility bridge (Collinson, 1983), which applies a weak field of 700 μT to the core plug and measures the magnetic susceptibility along the cylinder axis (the z axis). Figure 1 shows a simple division of the cored section of a North Sea oil well (PEGASUS Well 2 comprising clastic shoreface reservoir intervals) into zones where the routine core plugs exhibit either net negative or net positive magnetic susceptibility, along with a comparison of the broad permeability zonations. There is an extremely good correspondence between the two parameters. Intervals containing plugs exhibiting high permeability (>100 mD) correspond almost exactly to those exhibiting net negative magnetic susceptibility, while intervals containing plugs with lower permeability (<100 mD) correspond to those exhibiting net positive susceptibility. This strong correspondence is directly related to the mineralogy comprising the different zones. The high permeability intervals are the clean sand units containing primarily diamagnetic (negative susceptibility) quartz and feldspars, as indicated by XRD, scanning electron microscopy (SEM), thin section, and wireline gamma ray data. The quartz content, which is generally around 95-98% in these samples, dominates the magnetic susceptibility signal over the small amounts of paramagnetic and ferrimagnetic minerals present. Conversely, the lower permeability intervals are generally associated with muddy sands and shales which contain an increased proportion of paramagnetic clays (mainly illite) and possibly some minute amounts of ferrimagnetic minerals (such as magnetite). The results show that a rapid, simple division of the main permeability zonations can be obtained directly from the negative or positive sign of the raw magnetic susceptibility values without any processing of the data. A downhole magnetic susceptibility tool that was capable of doing the same would therefore appear to be extremely useful.

Processed magnetic susceptibility data: Quantification of mineral content

Each raw magnetic susceptibility value can be converted to an estimate of mineral content, since each value represents the combined signal from all the diamagnetic, paramagnetic and ferrimagnetic etc mineral components in the sample. This means that samples can have a net positive or negative magnetic susceptibility dependent upon their composition. Model mixture equations can be used, ideally with some mineralogical input from XRD or other measurements on a few representative samples, to estimate mineral contents directly from the low-field magnetic susceptibility signal. As mentioned above, thin-section petrography, SEM and XRD analysis of representative core samples from the oil well shown in Figure 1 showed that the mineralogy can be approximated as a simple mixture of quartz and illite (Potter et al., 2004). Other minerals are present in minor amounts. Following Potter et al. (2004), and assuming a two component system of quartz and illite, the magnetic susceptibility results allow both the illite and quartz content to be estimated simultaneously. The total magnetic susceptibility signal of the rock sample per unit mass, $_T$, is the sum of the illite (paramagnetic) and quartz (diamagnetic) components:

$$\chi_T = \{(F_I)(\chi_I)\} + \{(1 - F_I)(\chi_Q)\} \quad (3)$$

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

$$F_I = (\chi_Q - \chi_T) / (\chi_Q - \chi_I) . \quad (4)$$

It is then a simple matter to also obtain the mass fraction of quartz $(1 - F_I)$. Theoretically, by putting $\chi_T = 0$ in equation (4), the transition from a net negative to a net positive magnetic susceptibility signal occurs at a critical illite content of about 3.5% for a rock sample consisting of a simple model mixture of quartz and illite.

The method can also be applied to other simple mineral mixtures in sediments. For example, in clastics one might have mixtures of quartz (diamagnetic component) and chlorite (paramagnetic component), and in carbonates one might have calcite (diamagnetic component) and magnetite (ferrimagnetic component). The relevant components would merely replace the respective ones in equations (3) and (4). The components for these model mixture equations can be obtained from some preliminary XRD, thin section analysis, SEM, drill cuttings or from downhole data using standard crossplot charts of different wireline parameters. Even without any supplementary information, an educated guess of the mineralogy for the model equations could be made; calculations of mineral contents greater than 100% would be indicative that the educated guess was wrong. Note that while the present study has been undertaken on a clastic reservoir, we have also undertaken some initial magnetic measurements on carbonates. Variations in the presence of magnetic impurities seem to distinguish different carbonates on the basis of their magnetic signature.

Converting the raw magnetic susceptibility signal into a mineral percentage (that is, processing it to a positive number) has certain key advantages. First, correlations can be readily identified by plotting the magnetically derived mineral contents against petrophysical parameters on *logarithmic* scales on crossplots. This would not be possible if one used the raw magnetic susceptibility values, since these can be negative or positive depending upon the mineralogy and one cannot take the logarithm of a negative number. Second, intervals containing anomalous mineralogy can rapidly be pinpointed. For instance, if estimates of the content of a particular mineral (such as a paramagnetic clay) from the model equations (3) and (4) were greater than 100% then it would clearly indicate that the assumed mineralogy was not entirely correct and that other minerals were present. This potentially allows a rapid screening tool for identifying zones where further detailed study (using XRD, etc.) may be of benefit.

Correlation with permeability

The raw magnetic susceptibility results from PEGASUS Well 2 were processed using equations (3) and (4) to obtain an estimate of the illite content. Figure 2 shows a crossplot of the magnetically derived illite content versus the horizontal plug air permeabilities measured on the same suite of cleaned core plugs. The results show that very small increases in the magnetically derived illite content, of the order of 1-2%, correspond to dramatic decreases in permeability of about 2-3 orders of magnitude. There is a very strong correlation between the two parameters with the power regression coefficient of determination $r^2 = 0.73$ for the 297 plugs measured. If one omits only two anomalous points from the dataset (the low permeability barite plug and the vuggy high permeability plug as shown in Figure 2) then the correlation is even better with $r^2 = 0.80$. Note that there are also some anomalously high "illite" content values (two points greater than 100% and another slightly under 100%). These plugs clearly also contain another mineral or minerals with positive susceptibility, and have been readily pinpointed by the magnetic technique. If these three plugs are omitted from the analysis then the correlation coefficient is only marginally reduced with $r^2 = 0.70$ (and if one excludes the barite plug and the vuggy plug $r^2 = 0.78$). Since the magnetic signal of the three anomalously high "illite" plugs is clearly influenced by other minerals, these plugs have been excluded from the later comparisons with flow zone indicator and gamma ray.

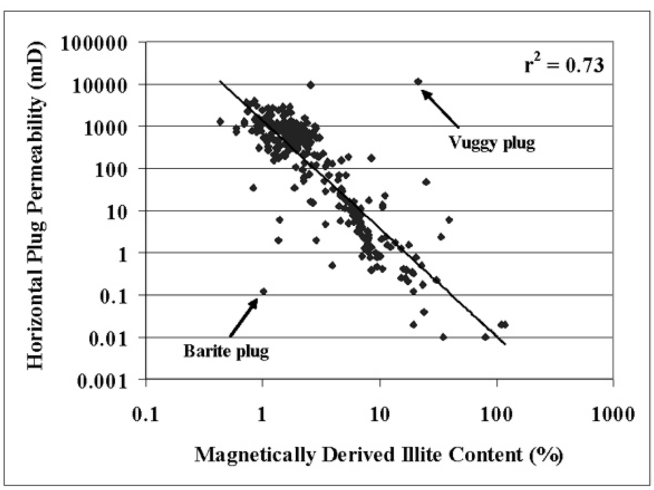

FIG. 2 Crossplot of magnetically derived illite content versus horizontal plug air permeability in PEGASUS Well 2.

The correlation between the magnetic results and permeability is a significant improvement over the corresponding poor relationship between porosity and permeability, where $r^2 = 0.25$ (Figure 3), for the same suite of horizontal plugs. The main reason for this poor porosity-permeability relationship appears to be the presence of microporous rims of fibrous illite grains surrounding the quartz matrix grains, as seen in a typical SEM image of one of the samples from this well (Figure 4). Small increases in illite content can dramatically affect the permeability of a sample (Hurst and Nadeau, 1994) by bridging pore space and creating these microporous rims. The rims can significantly lower the permeability, but may have little effect on the porosity. This is clearly shown in Figure 3 where the porosity is similar over much of the crossplot, whilst the permeability changes over several orders of magnitude. This is consistent with the effect of illite in a quartz matrix as theoretically modeled by Cade et al. (1994).

The processed magnetic susceptibility results can be used as a rapid improved permeability predictor. Figure 5 shows the predicted horizontal plug air permeabilities derived from the magnetics (using the equation of the regression line in Figure 2), along with the measured horizontal plug permeabilities, plotted versus depth. It is apparent that the two trends follow each other very closely. The stacked shoreface coarsening-upwards parasequences are

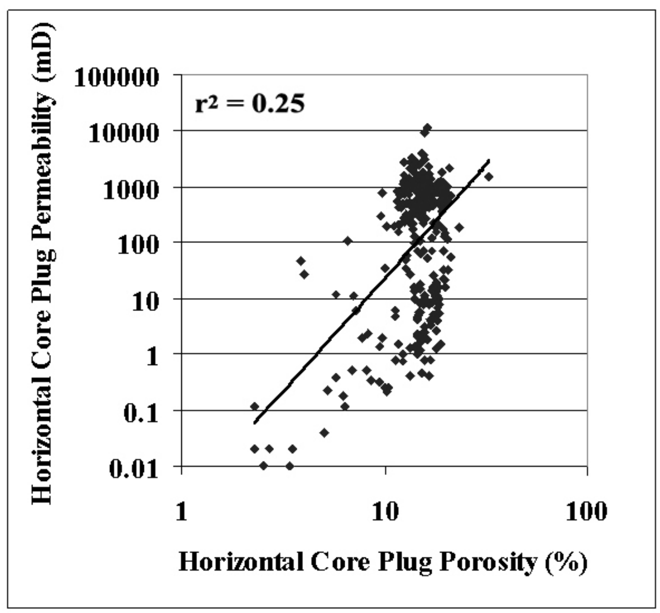

FIG. 3 Crossplot showing the poor relationship between porosity and permeability for the same horizontal core plugs as in Figure 2. The results are given on a log-log plot (rather than the usual log-linear plot) for direct comparison with the log-log plot of Figure 2.

clearly picked out by the magnetically derived predictions. Some of the minor differences between the predicted and measured permeabilities (for example, at about 6-9 ft below the arbitrary zero depth) are due to low permeability barite-cemented intervals that are not picked out by the magnetics (barite is diamagnetic like the quartz matrix). This is a limitation of the magnetic technique, as mentioned earlier, but was not a major problem in this well since the naturally cemented zones could be easily picked out by higher density spikes on the bulk density log. The core plugs in the barite-cemented zones also had higher weights.

Note that in the present examples the permeability-controlling illite clay can be readily quantified by the magnetics even in the presence of kaolinite. This is because kaolinite is diamagnetic (Table 1) and has negligible effect on the determination of the paramagnetic illite clay in this case. The kaolinite also does not appear to be a major permeability-controlling clay in this case. In fact, XRD analysis indicated that there was a higher content of kaolinite (up to about 2%) in the high permeability clean sands, and a much lower content in the lower permeability muddy sands.

Correlation with the flow zone indicator

Amaefule et al. (1993) laid the foundations for improved permeability prediction by characterizing reservoirs in terms of hydraulic flow units. All samples in a particular hydraulic flow unit have similar values of the flow zone indicator (*FZI*), which is related to porosity and permeability as follows:

$$FZI = RQI \,/\, \Phi_z \qquad (5)$$

where *RQI* is the reservoir quality index (= 0.0314 $\sqrt{K/\Phi_e}$ where *K* is the permeability and Φ_e is the effective porosity), and Φ_z is the pore volume to grain volume ratio (= $\Phi_e/1 - \Phi_e$). Since it was shown earlier that the magnetic susceptibility is related to permeability in the present study, where the permeability is controlled by paramagnetic clays, then there ought to be a correlation between magnetically derived illite content and *FZI*. The results for PEGASUS Well 2 are shown in Figure 6 where a log-log crossplot of the two parameters shows a good correlation (the power correlation coefficient is relatively high with $r^2 = 0.67$), with the illite content decreasing as the *FZI* value increases as expected. Svirsky et al. (2004) reported a similar general trend for illite content derived from SEM images plotted against *FZI* (their Figure 17) for some samples in a Siberian oilfield. The present magnetic results suggest the potential usefulness of such measurements for rapidly characterizing hydraulic flow units in core or outcrop samples when porosity and permeability measurements are unavailable or impractical.

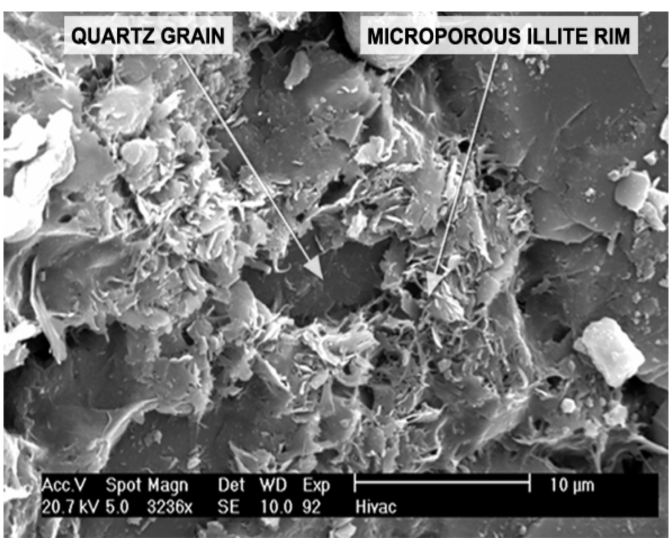

FIG. 4 SEM image from PEGASUS Well 2 showing a microporous illite rim around a quartz grain. The scale bar is 10 μm.

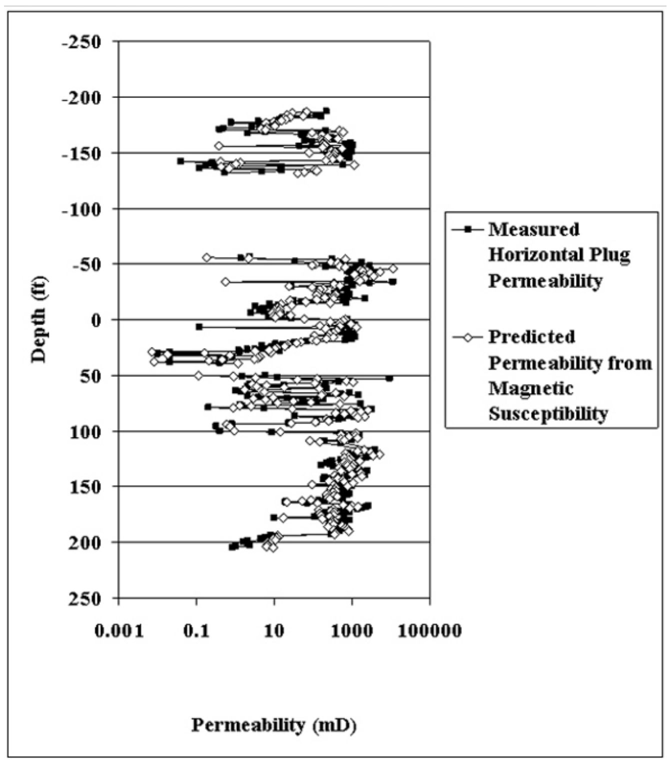

FIG. 5 The variation with depth of the magnetically derived predicted permeability (using the regression line of Figure 2) and the measured horizontal plug air permeability values in PEGASUS Well 2.

Correlation with wireline gamma ray

A total-count gamma ray wireline log was run in PEGASUS Well 2. Unfortunately there was no core gamma ray or downhole spectral gamma ray data for this well. Figure 7 shows a correlation between the raw (unprocessed) core plug magnetic susceptibility measurements and the depth-matched total wireline gamma ray signal. The intercept of the regression line on the gamma ray axis gives the critical gamma ray value below which the formation rock in this well has a net negative susceptibility (clean sand) and above which it has a positive susceptibility (more muddy sand). As detailed earlier, this represents a critical illite content of about 3.5% in a simple system of quartz and illite model system. In this case it indicates that the intercept of the regression line occurs at about 20 API. This approach using magnetics may provide more quantitative and less arbitrary means of estimating wireline log gamma-ray cutoff for distinguishing clean sands from low-permeability muddy sands and for establishing net pay cutoffs. Moreover, the approach could be particularly useful when one uses drilling muds that themselves give a high gamma ray signal (such as potassium chloride, KCl), yet have low values of magnetic susceptibility. Potassium chloride is diamagnetic with low, negative magnetic susceptibility (Gupta, 1986), and therefore does not exhibit a significant magnetic susceptibility compared to the paramagnetic permeability-controlling clays. Where potassium chloride has been used in a drilling mud, this will merely produce a higher intercept on the crossplot of raw magnetic susceptibility versus wireline gamma ray (schematically shown in Figure 7). This type of plot could therefore be used to accurately distinguish changes in lithology even in the presence of a high-gamma ray-emitting mud.

Relationships between raw magnetic susceptibility and gamma ray data have been reported previously by Lovlie and Van Veen (1995). However, they also reported intervals where the two parameters did not show a correspondence. The present work also shows that some samples exhibit relatively high paramagnetic susceptibility where the gamma ray signal is comparatively low (Figure 7). This supports Lovlie and Van Veen's (1995) suggestion that magnetic susceptibility could provide an added independent lithostratigraphic correlation tool complementing the other more conventional parameters such as gamma ray.

In the present study, by plotting the magnetically derived illite content against the wireline gamma ray one can also obtain the gamma ray cutoff for any chosen illite content. This is shown in Figure 8 for the same set of plugs as for Figure 7, with both parameters plotted on logarithmic scales. The power correlation coefficient of determination is high with $r^2 = 0.70$. This relationship could be potentially useful for improved interpretation of the downhole gamma ray log in other wells in the same oilfield where there may be no core data.

Correlation with the cation exchange capacity per unit pore volume

The cation exchange capacity per unit pore volume (Q_v) is related to the clay content as follows

$$Q_v = [V_{cl(\mathrm{dry})}\, \rho_{cl(\mathrm{dry})}\, CEC_{cl}] / \Phi_t \tag{6}$$

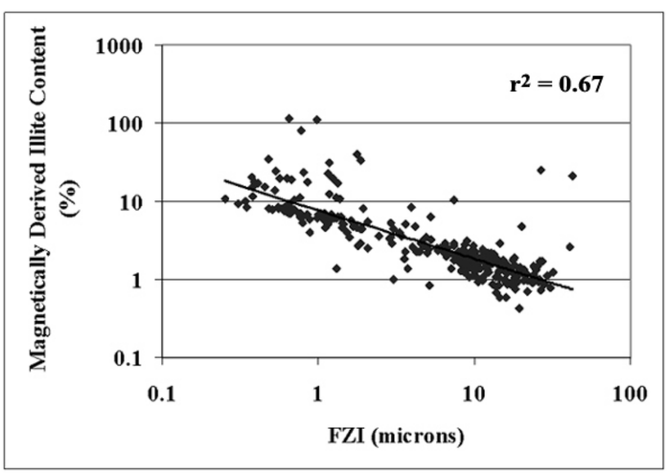

FIG. 6 Crossplot of values of the flow zone indicator (*FZI*) versus magnetically derived illite content for the horizontal core plugs (PEGASUS Well 2).

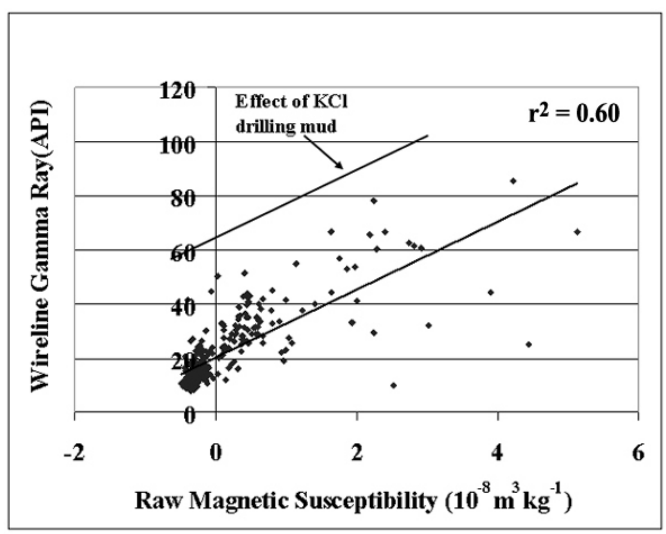

FIG. 7 Crossplot of the raw mass magnetic susceptibility of the horizontal core plugs versus the wireline gamma ray (PEGASUS Well 2).

(adapted from Juhasz, 1979), where $V_{cl\ (dry)}$ is the volume of clay, $\rho_{cl\ (dry)}$ is the density of the clay, CEC_{cl} is the cation exchange capacity of the clay, and Φ_t is the total fractional porosity. Since we have already seen a relationship between clay (illite) content and magnetic susceptibility, one might expect a relationship between Q_v and magnetic susceptibility. This was tested in some core plugs from another North Sea oil well. Figure 9 shows a strong correlation between the raw magnetic susceptibility and Q_v for the few plugs where Q_v data was available. (Note that a similar result would be obtained from a plot of the processed magnetic susceptibility against Q_v). The relationship is in the theoretically expected direction, in that the higher the Q_v the higher the magnetic susceptibility. The magnetic measurements potentially allow rapid estimates of Q_v to be obtained over large intervals, complementing the (often scarce) actual Q_v SCAL measurements. Q_v is normally determined from costly and time consuming wet chemistry measurements. Determination of Q_v measurements from a few representative samples could be calibrated against magnetic measurements, and subsequently further magnetic measurements on a large number of other samples could be made rapidly to predict Q_v throughout a well.

CONCLUSIONS

This work demonstrates that low-field magnetic susceptibility measurements have the potential to be a useful complementary RCAL and SCAL analysis technique, allowing rapid, cheap, sensitive, and high-resolution petrophysical appraisals (for predicting clay content, permeability, etc.) to be made long before the other RCAL and SCAL data becomes available.

The negative or positive sign of the raw magnetic susceptibility values of routine core plugs in a North Sea oil well (shoreface facies) strongly correlated with the main permeability zonations. Net negative susceptibility values corresponded to high permeability clean sand units, containing predominantly diamagnetic quartz and feldspars. Net positive susceptibility values corresponded to lower permeability muddy sand and shale units, containing an increased proportion of paramagnetic illite clay.

The magnetic susceptibility signal can be processed to provide quantitative mineralogical information. Significantly, the magnetically derived illite content exhibited a strong correlation with the core plug permeability. This generated an excellent rapid new permeability predictor from core magnetic measurements in an oilfield where the relationship between core porosity and permeability is very poor. The magnetic measurements are essentially a proxy for the permeability-controlling illite clay in this case.

The magnetic susceptibility measurements on core plugs correlated with the downhole wireline gamma ray. The relationship (using the raw or processed magnetic susceptibility values) can be used to quantify net pay cutoffs from the wireline gamma ray log by introducing a means of distinguishing between clean and muddy sands. This approach could be particularly useful when employing drilling muds which themselves generate a high gamma ray signal, such as potassium chloride, and which have a low magnetic susceptibility. Crossplotting the magnetic susceptibility and wireline gamma ray data allows subtle changes in the for-

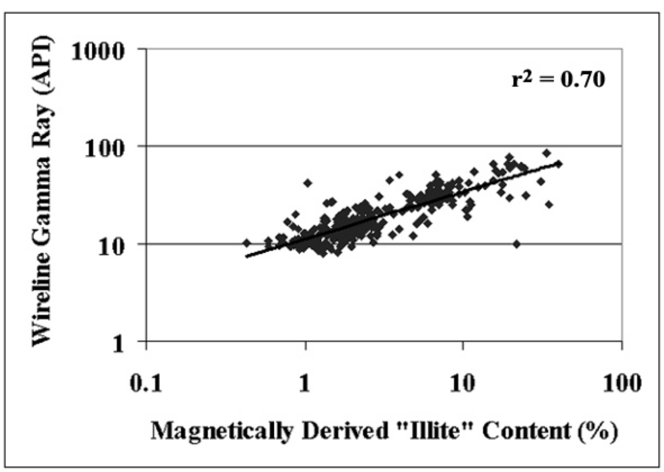

FIG. 8 Crossplot of the magnetically derived illite content versus wireline gamma ray (PEGASUS Well 2).

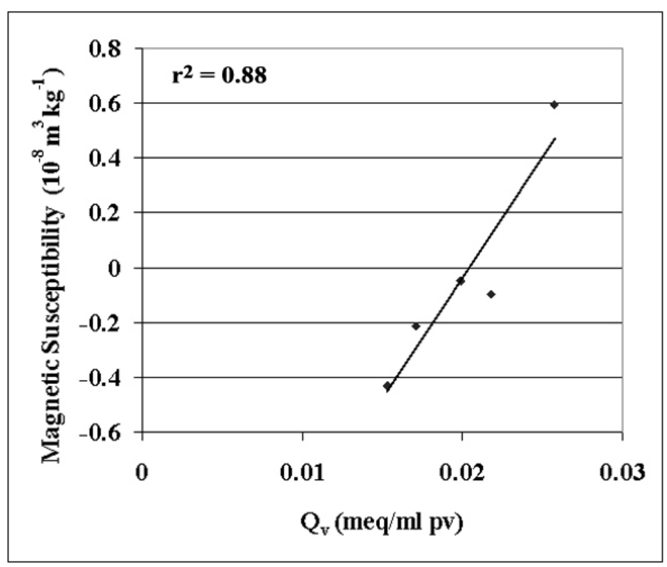

FIG. 9 The cation exchange capacity per unit pore volume (Q_v) versus raw mass magnetic susceptibility for SCAL plugs in a North Sea oil well.

mation from clean to muddy sand to be identified even in the presence of such a drilling mud. The relationship between magnetic susceptibility and wireline gamma ray can in this case also be exploited to allow quantification of illite content directly from the wireline gamma ray, thereby providing additional information from this routine downhole tool.

The magnetic results correlated with the flow zone indicator (*FZI*). Magnetic measurements therefore potentially allow rapid hydraulic flow unit determination on core or outcrop samples even when core porosity and permeability measurements are unavailable or impractical.

The magnetic measurements correlated with the cation exchange capacity per unit pore volume (Q_v). The magnetic measurements could therefore potentially be used to rapidly generate predictions of this important SCAL parameter over large intervals.

While the results in the present study were obtained from core samples they strongly suggest the potential usefulness of a downhole magnetic susceptibility tool for *in-situ* petrophysical parameter prediction.

NOMENCLATURE

B	Applied field in Tesla
CEC_{cl}	Cation exchange capacity of the clay
F_I	Fraction of illite
FZI	Flow zone indicator
H	Magnetic field strength
IRM	Isothermal remanent magnetization
J	Magnetization per unit mass
k	Volume susceptibility
K	Permeability
M	Magnetization per unit volume.
Q_v	Cation exchange capacity per unit pore volume
RCAL	Routine core analysis
RQI	Reservoir quality index
r^2	Coefficient of determination
SCAL	Special core analysis
SEM	Scanning electron microscopy
$V_{cl\,(dry)}$	Clay volume
XRD	X-ray diffraction
μ_o	Magnetic permeability of free space
$\rho_{cl\,(dry)}$	Clay density
χ	Mass susceptibility
χ_I	Magnetic susceptibility signal of illite per unit mass
$_Q$	Magnetic susceptibility signal of quartz per unit mass
$_T$	Total magnetic susceptibility signal per unit mass
Φ_z	Pore volume to grain volume ratio
Φ_e	Effective porosity
Φ_t	Total fractional porosity

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