RESEARCH METHODS PAPERS

QUANTIFICATION OF ILLITE CONTENT IN SEDIMENTARY ROCKS USING MAGNETIC SUSCEPTIBILITY—A RAPID COMPLEMENT OR ALTERNATIVE TO X-RAY DIFFRACTION

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ABSTRACT: **The paramagnetic clay mineral illite can have important controls on fluid permeability and microporosity in sedimentary rocks. Increases in illite content of a few percent can reduce permeability by several orders of magnitude. Traditional X-ray diffraction (XRD) techniques for quantifying illite content can be very time consuming, requiring significant sample preparation, and generally examine only a relatively small sample volume. In contrast, a technique based on magnetic susceptibility described here is very rapid, cheap, sensitive, nondestructive, and requires no extra preparation of the sample. It is representative of a much larger sample volume, and in the present paper utilizes standard 1 inch diameter cylindrical core plugs, but it can be applied to other sample shapes and volumes.**

The magnetic-susceptibility-derived estimates of illite content from core plugs correspond well with XRD results from small powdered samples of the same material, in terms of both absolute values and overall trends with depth. However, neither the magnetic method nor XRD should be regarded as definitive. Each technique has merits and limitations, and these help to explain some observed differences in the illite determinations by each method. XRD may underestimate the illite content, particularly in muddy rocks, whereas the magnetic method theoretically provides an upper limit for the illite content. The magnetic method is also capable of simultaneously estimating the quartz content in the present samples. Changes in the concentration and distribution of illite during core cleaning or core flooding experiments can also be potentially quantified by the magnetic technique.

The development of portable field sensors potentially allows the magnetic method to provide high-resolution illite profiles on slabbed cores, outcrops, and unconsolidated samples without the need to cut core plugs. The method could also be applied to whole-core measurements and to downhole magnetic susceptibility data. The processing of the magnetic susceptibility signal can also be extended to quantify other minerals in simple systems.

INTRODUCTION

Traditional methods for quantifying illite content have generally involved whole-rock XRD followed by further XRD of the clay fraction, or have avoided separating the clay by using a method such as the SIROQUANT system (Taylor 1991). These XRD methods are generally time consuming, expensive (if one does not have the equipment and has to pay for them), and involve significant preparation of the sample. The SIROQUANT system is quicker than the whole-rock plus clay fraction XRD technique, because clay and non-clay minerals are quantified in one run, but nevertheless the sample preparation and analysis can still take around two hours per sample. In addition, XRD methods examine only a relatively small amount of the sample material. A more rapid yet equally accurate method of quantifying illite content would seem to be potentially extremely useful.

This paper describes a technique utilizing magnetic susceptibility as a rapid (a core plug can be measured in a few seconds), cheap, and nondestructive means of quantifying illite content in certain sedimentary rocks. We present results obtained on standard 1 inch diameter cylindrical core plugs, although other sample shapes and volumes can be accommodated. The measurements are representative of a much larger sample volume than for XRD analysis, and they do not require any extra preparation of the sample. We see this technique primarily as a complement to XRD, whereby an initial small number of representative samples may undergo both XRD and the magnetic technique for calibration purposes, and subsequently the magnetic method would be used to analyze a further large number of samples very rapidly. Alternatively, when there is no time for detailed XRD measurements, or it is too expensive, or a rapid analysis in the field is required, the magnetic method alone can give good results in simple systems using the rapid measurements and model mixture equations we present. The method can potentially be applied to magnetic susceptibility data at a variety of scales (probe, plug, whole core) in the laboratory, in the field, and downhole. We also detail how the magnetic method can potentially be applied more generally to quantify other minerals in simple (ideally two main magnetic susceptibility component) systems.

METHOD

Model Mineralogical Mixtures

The major constituents of many sedimentary rocks, usually quartz in sandstones or calcite in carbonates, are diamagnetic (Hunt et al. 1995) and have low negative magnetic susceptibility values (Table 1). The contribution of quartz to the magnetic susceptibility of quartzite is described by Hrouda (1986), whilst that of calcite in a carbonate is given by Owens and Rutter (1978). In contrast, important clay minerals like illite are paramagnetic with significantly higher positive magnetic susceptibilities (Table 1).

In many sedimentary sequences, such as North Sea reservoir shoreface facies, quartz and paramagnetic clays (mainly illite or chlorite) can be the dominant carriers of the magnetic susceptibility signal in the absence of a significant fraction of other paramagnetic or ferrimagnetic minerals (Potter and Corbett 2000). If we assume that the rock in these sequences is a simple mixture of quartz (diamagnetic component) and illite (paramagnetic component) then the total magnetic susceptibility signal of the rock sample per unit mass, χ_T, is the sum of the two components

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

where F_I is the fraction of illite, $(1–F_I)$ is the 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. For quartz, we used the midpoint (-0.55×10^{-8} m^3 kg^{-1}) of the narrow range of quoted values in our calculations. Note that χ_T, χ_I, and χ_Q could alternatively be expressed as volume susceptibilities. Because χ_T can be measured and χ_I and χ_Q are known then the fraction of illite, F_I, is given by

$$F_I = (\chi_Q - \chi_T)/(\chi_Q - \chi_I) \quad (2)$$

It is then a simple matter to also obtain the fraction of quartz $(1 - F_I)$.

In reality other minerals may also contribute to the total magnetic susceptibility signal, and the presence of other paramagnetic or ferrimagnetic mineral components in the rock would mean that the illite content is overestimated, unless these components are taken into account. Our method thus provides a rapid upper limit to the amount of illite present, because we assume that the positive component of the total magnetic susceptibility signal is due entirely to illite. The method, however, does not distinguish between authigenic and detrital illite.

In cases where the rock consists of two or more diamagnetic minerals (such as quartz and orthoclase feldspar) plus paramagnetic illite, then the magnetic estimates of the illite will not generally be significantly affected by the assumption in Equations 1 and 2 that the total diamagnetic signal in the rock is due to entirely to quartz, because orthoclase feldspar (Table 1) and many other diamagnetic minerals have magnetic susceptibility values very similar to that of quartz. In the case of calcite, which can exhibit a range of diamagnetic values (Table 1), the illite content could be overestimated slightly if the intrinsic susceptibility of the calcite was close to -1.4×10^{-8} m^3 kg^{-1}. For instance, if 10% of the bulk rock is calcite cement of this susceptibility, then the illite content would be overestimated by around 0.5% for the majority of samples in the present study. This, however, is not the case in the present study, because XRD analysis has shown that calcite comprises less than 1% for most samples analyzed here.

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TABLE 1.—*Magnetic susceptibilities of some relevant minerals.*

Mineral Type	Mineral	Magnetic Susceptibility per Unit Mass (10^{-8} m^3 kg^{-1})
Diamagnetic minerals:	Quartz	−0.5 to −0.6 (−0.55*)
	Calcite	−0.3 to −1.4
	Orthoclase feldspar	−0.49 to −0.67
	Kaolinite	−2.0
Paramagnetic minerals:	Illite	15.0
	BVS Chlorite	13.6†
	CFS Chlorite	52.5†
	Pyrite	2.0‡
Ferrimagnetic minerals:	Magnetite	2[4] to 11[4]

* This value, the mid-point of the range, is used in this paper for the susceptibility of quartz in Equations 1 and 2.
† From Borradaile et al. (1990), who detail the localities BVS, CFS.
‡ Upper limit for pure pyrite given by Parasnis (1986).
Kaolinite from Thompson and Oldfield (1986), and other values from Hunt et al. (1995).

The magnetic method detailed in the present paper could also potentially be applied to other rock types (part of a patent pending; see Acknowledgments) consisting of simple mineral mixtures, such as sandstones comprising a dominant diamagnetic mineral (e.g., quartz) and a paramagnetic mineral (e.g., chlorite), or carbonates comprising a diamagnetic mineral (e.g., calcite) and a ferrimagnetic mineral (e.g., magnetite). In the generalized case where a rock sample consists of a simple two-component mixture comprising mineral A with intrinsic positive magnetic susceptibility (paramagnetic, or ferrimagnetic, or ferromagnetic behavior, etc.) together with mineral B with intrinsic negative magnetic susceptibility (diamagnetic behavior), then the total magnetic susceptibility signal of the rock sample per unit mass, χ_T, is given by

$$\chi_T = \{(F_A)(\chi_A)\} + \{(F_B)(\chi_B)\} \quad (3)$$

or alternatively, because we are considering just two components, this can be rewritten, like Equation 1, as

$$\chi_T = \{(F_A)(\chi_A)\} + \{(1-F_A)(\chi_B)\} \quad (4)$$

where F_A is the fraction of mineral A, F_B (or $1-F_A$) is the fraction of mineral B, and χ_A and χ_B are the known magnetic susceptibilities per unit mass of minerals A and B. The fraction of mineral A is then given by

$$F_A = (\chi_B - \chi_T)/(\chi_B - \chi_A) \quad (5)$$

and the fraction of mineral B can now be calculated simply as $1-F_A$.

The most appropriate choice of minerals A and B for a given situation can be made by initial characterization of field hand specimens, drill cuttings, thin sections, or limited preliminary XRD analysis, etc. Even if no other initial information is available, then the magnetic method can usefully be employed using an educated guess of the components. This would at least pinpoint any definite anomalies where one's guess was wrong (for instance, if the calculated fraction of one of your presumed minerals was greater than 1).

If the rock is known to contain more than two mineral components that contribute significantly to the magnetic susceptibility signal, then extra terms of the form $\{(F_X)(\chi_X)\}$ would appear in Equation 3 for each component X. For instance, if the rock comprises three principal components, A (a mineral with positive susceptibility), B (a mineral with negative susceptibility) and C (a mineral with positive or negative susceptibility), then Equation 3 becomes

$$\chi_T = \{(F_A)(\chi_A)\} + \{(F_B)(\chi_B)\} + \{(F_C)(\chi_C)\} \quad (6)$$

The magnetic method cannot provide quantitative estimates simultaneously for three or more components, because Equation 6 cannot be uniquely solved for the three unknown quantities. However, if some quantitative information is available, for instance whole-rock XRD that identifies component C as a main matrix mineral, then the magnetic method can be used to quantify components A and B. These components could be paramagnetic and diamagnetic clay minerals, thus avoiding the need to separate the clay fraction and perform further XRD on the clays.

Available Instrumentation

Single-Axis Magnetic Susceptibility Measurements.—The method described in this paper is generally intended to be applied to single-axis, usually called ''bulk,'' magnetic susceptibility measurements on core plugs. These measurements can be made very rapidly using a variety of relatively cheap commercially available magnetic susceptibility bridges (for a review see Collinson 1983). Generally cylindrical core plugs about 1 inch (2.54 cm) in diameter are used, and the magnetic susceptibility along the cylinder axis (the z axis) is measured. In this study we report measurements made on routine oil company core plugs (1 inch diameter and 1.5 inches long) using a Molspin susceptibility bridge. A typical measurement consisting of a background reading followed by a sample reading takes under five seconds. This means that several hundred core plugs can be analyzed in one day. The measurement is extremely sensitive, allowing illite content to be estimated with an uncertainty of about ± 0.25%, in part because of repeatability in the measurement (very small uncertainty) and also because of the possible range of magnetic susceptibility values for quartz (Table 1). In contrast, the XRD techniques we used have measurement uncertainties of between about ± 0.5% to 1.5% (uncertainties in the XRD can partly depend on the intrinsic amounts of the clay, because more amorphous material, not seen by XRD, can sometimes be generated in more clay-rich samples during sample preparation). Other susceptibility bridges, such as the Kappa bridge (Jelinek 1973), are slightly more sensitive, but the measurement time is a bit longer. Other shapes (for example cubes) and sizes of sample can be accommodated in all these standard susceptibility bridges. The single-axis measurements represent a mean susceptibility value (i.e., χ_T) if the sample is isotropic or has only a weak intrinsic anisotropy.

Anisotropic Measurements.—Whilst anisotropy may not be important in relatively isotropic sandstones with low clay content, it could be significant in shales and clay-rich sandstones with pronounced fabrics parallel to bedding. An estimate of illite content in strongly anisotropic samples would require an average susceptibility value from the three orthogonal principal susceptibility axes (χ_{max}, χ_{int}, and χ_{min}), instead of the single-axis bulk susceptibility reading. This could be achieved from three single-axis measurements, two taken from plugs cut in orthogonal directions within the bedding plane and one taken from a plug cut perpendicular to the bedding plane. However, a more accurate determination of the orientation and magnitude of the anisotropy of magnetic susceptibility (AMS) ellipsoid, particularly when the bedding plane is not obvious, can be made on a single core plug in about a minute using a spinner AMS meter (Tarling and Hrouda 1993) in conjunction with a single-axis bulk reading on the same plug using a susceptibility bridge. AMS measurements are generally undertaken on plugs 1 inch in diameter and about 0.8 inches in height. These dimensions represent the nearest cylindrical approximation to a sphere, which is the ideal shape to eliminate anisotropies induced by sample shape. Magnetic anisotropy measurements have additional advantages in that they allow an extremely rapid means of quantifying the average *in situ* 3-D anisotropic distribution of the illite particles in a simple quartz-plus-illite system. AMS measurements could complement another recent innovative, although more time consuming, method which uses X-ray transmission diffractometry (Inigo et al. 2000) to quantify illite and other clay particle orientations in much smaller sample volumes.

Scaled-Up Measurements.—The magnetic method could potentially be used to quantify illite content at a variety of scales. The magnetic method using core plugs measures a significantly greater sample volume than that used for XRD work. At a smaller scale there are several types of field magnetic susceptibility probe (Lecoanet et al. 1999) potentially allowing *in situ* high-resolution determinations of illite and quartz concentration in outcrop, slabbed core, or unconsolidated samples without the need to cut plug samples. At a larger scale there are systems capable of measuring magnetic susceptibility in whole cores up to about 6 inches in diameter in the laboratory (Weber et al. 1997; Gunn and Best 1998; Lees et al. 1998), and these measurements could also be used for mineral quantification. Potentially the technique could also be applied to downhole magnetic susceptibility data, such as that obtained from the geological high-sensitivity magnetic tool, GHMT (Barthes et al. 1999; Thibal et al. 1999). Thus magnetic measurements might provide important insights into how illite quantities might be up-scaled to much larger sample volumes than those used for XRD. In all these magnetic susceptibility measurements, no extra preparation of the sample is needed.

Testing for the Presence of Ferromagnetic or Ferrimagnetic Minerals

It is important to ensure that the observed magnetic susceptibility signal is not significantly influenced by small amounts of ferromagnetic or ferrimagnetic grains, which have high positive susceptibility (Table 1). These would cause an overestimate in the illite content if their effect is not accounted for. Fortunately, their presence can easily be checked by determining if the sample acquires a significant laboratory remanence. Paramagnetic minerals like illite do not acquire a remanence, but ferromagnetic and ferrimagnetic particles do, unless they are superparamagnetic (very small particles with relaxation times less than 100 s). The most convenient remanence to give is isothermal remanent magnetization, IRM (Robertson and France 1994). This is because it can be given rapidly using a pulse magnetizer (Stephenson et al. 1986), and it induces the largest signal of any laboratory remanence, thus ensuring that minute amounts of ferromagnetic or ferrimagnetic minerals can be detected. The possible presence of high-susceptibility superparamagnetic particles can also be inferred by looking at the distribution of the time-dependent decay of the IRM (Worm 1999).

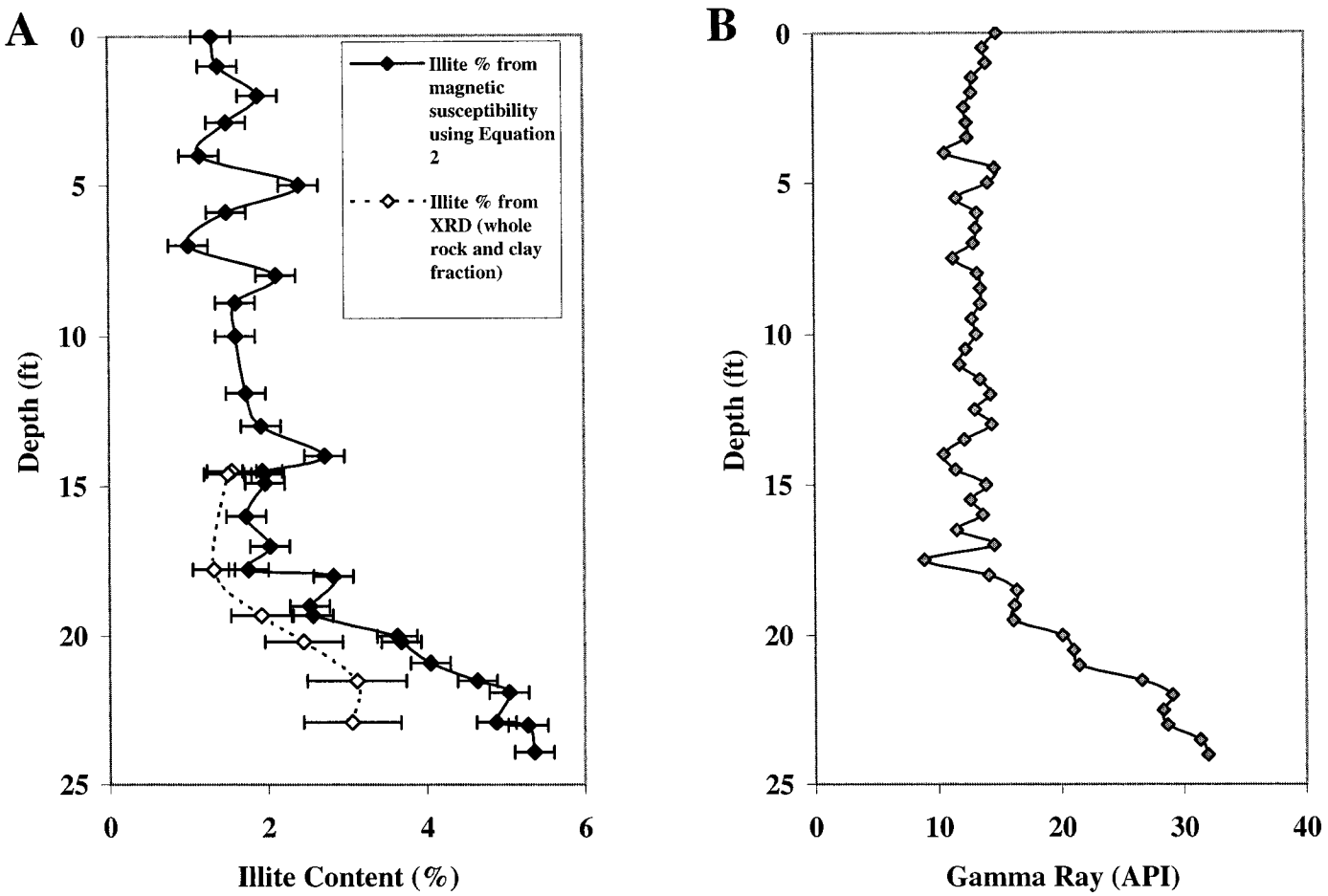

FIG. 1.—**A)** Illite percentages with depth in an interval from a vertical North Sea oil well (PEGASUS Well 2), as estimated from magnetic susceptibility on horizontal core plugs and from XRD measurements (whole rock XRD followed by XRD of the clay fraction) on small samples of powdered core. All measurements were performed on cleaned core. Depths are shown from the top of the interval. **B)** Wireline gamma ray log from the same interval.

TEST CASE

Illite Quantification

Magnetic and XRD derived estimates of illite content were initially determined in a short 24 foot (7.3 m) interval (Fig. 1A) from a vertical North Sea oil well (PEGASUS Well 2). This genetic unit, a parasequence, has been described in detail elsewhere (Potter et al. 1999; Potter 2000; Potter and Corbett 2000). The upper part of the interval consists of about 19 feet (5.8 m) of clean sand and the basal 5 feet (1.5 m) of the interval represents a transition to a more muddy sandstone exhibiting a pronounced coarsening-upwards sequence. The two-component quartz plus illite (in this case mainly authigenic illite) formulaic model is a valid assumption for these sandstones, because thin section analyses, scanning electron microscopy (SEM), and XRD analysis indicate that these are the two dominant phases present.

The single-axis magnetic susceptibility measurements were made using a Molspin susceptibility bridge on routine horizontal oil industry core plugs, 1 inch in diameter and 1.5 inches long, that had been hot soxhlet cleaned (at around 110° C firstly with toluene and then methanol). The illite content was then calculated using Equation 2. Whole-rock XRD measurements were determined on powdered samples of the cleaned core, followed by further XRD of the separated clay fraction. The latter separation was done by gently disaggregating the rock by crushing and use of an ultrasonic bath. The material was then sieved with a 20 μm sieve, and the less than 20 μm fraction was sedimented onto the mount for the XRD analysis. The XRD was then run ''as is'' for the clay proportions. The size fraction was chosen to be less than 20 μm so that we were not biased by only the smallest clays.

Magnetic and XRD estimates of the illite percentage have a similar trend with depth (Fig. 1A), and the absolute values are close within the uncertainties of each technique. Data at identical depths from both methods gave a high linear regression correlation coefficient r^2 of 0.99 (Fig. 2). The slope of the regression line, however, is not unity. This is partly due to the fact that theoretically the magnetic method should provide an upper estimate of the illite content, as explained earlier. Also, XRD may underestimate the amount of illite, because the presence of some amorphous material, produced during the crushing of the samples for the analysis, may not be detected via XRD. For these reasons the magnetic results should theoretically give higher values than the XRD ones, and indeed this is the case for every point in Figure 1A, resulting in the slope of the regression line not being unity. The deviations between the magnetic and XRD results appear to be more pronounced in the lower muddy sandstone interval at the base of the sequence (Fig. 1A).

A more comprehensive test of the magnetic method was subsequently undertaken on a 117 foot (35.7 m) section (Fig. 3A) consisting of two stacked coarsening-upwards parasequences from another vertical North Sea oil well (PEGASUS Well 2a), which is just over 2 km from PEGASUS Well 2. The single-axis magnetic susceptibility measurements were again performed on cleaned routine oil industry horizontal core plugs (1 inch diameter and 1.5 inches long) using a Molspin susceptibility bridge. The XRD results were this time performed at a different laboratory using the SIROQUANT system on samples of the powdered uncleaned core pressed into a disc 2.5 cm in diameter and 0.2 cm in thickness. Figure 3A shows that both methods again have reasonably similar trends of illite concentration with depth, and both exhibit increases in illite content towards the base of each parasequence. The absolute values are also in general agreement, particularly in portions of the upper clean sand intervals of each parasequence. The linear regression correlation coefficient r^2 is 0.73 for the increased number of PEGASUS Well 2a data points (Fig. 2). There are, however, some significant differences between the magnetic and XRD estimates in certain intervals, as explained below.

Quartz Quantification

The magnetic technique also allows rapid estimates of the approximate quartz percentage to be made simultaneously. Quartz percentages are simply 100 minus the uncorrected magnetically derived illite percentages. The results for PEGASUS Well

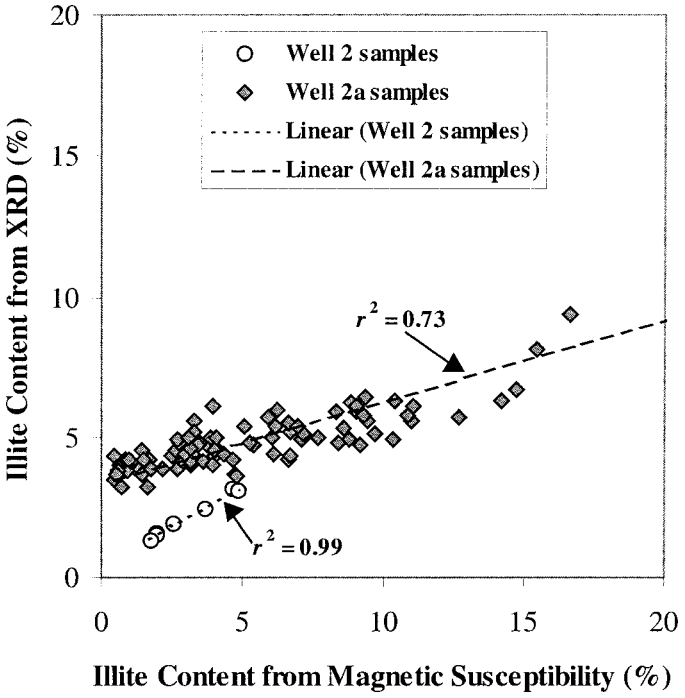

FIG. 2.—Crossplot of the illite percentages from magnetic susceptibility utilizing Equation 2 versus those from XRD measurements for the PEGASUS Well 2 and 2a samples. As explained in the text, the slopes of the regression lines are unlikely to have values of unity. We would expect that the slope of the line for the Well 2a samples would be steeper if the XRD measurements had been performed on cleaned core. A single Well 2a point at coordinates of 27.1% (magnetically-derived) and 15.5% (XRD-derived) is not shown but is included in the regression.

2a are given in Figure 4. The magnetic method certainly picks out the lower quartz content at the base of each of the two parasequences. For most samples the magnetic estimates of quartz content (generally 80–95%) were within 5–10% of those determined by XRD. The XRD quartz values were generally slightly less than the magnetic estimates. This is mainly because some of the diamagnetic signal in these samples is actually due to small amounts of other diamagnetic minerals, whereas the magnetic method assumes that all the diamagnetic signal is due to quartz and thus slightly overestimates its abundance. These other minerals include the feldspar albite (about 3–4%), kaolinite (about 1–2%) and calcite (about 0.5–1%). Albite has a diamagnetic susceptibility similar to that of orthoclase feldspar (Rosenblum and Brownfield 1999). Note that Rosenblum and Brownfield (1999) give relative susceptibilities, based on magnetic separator measurements, and do not quote mass or volume susceptibility units, and so we have not included a mass susceptibility value for albite in Table 1, whereas there are accurate published values of the mass susceptibility of orthoclase.

Differences between the Magnetic and XRD Estimates of Illite Content

Towards the base of each parasequence in Figures 1A and 3A, the magnetic estimates of illite content are significantly greater than those from XRD. In both wells the results from the two techniques start to deviate precisely at the transition to finer quartz grained and more clay-rich muddy sandstone lithologies. The magnetic illite estimates appear to highlight the lithological boundaries much clearer than the XRD estimates, particularly for Well 2a (Fig. 3A). Some support for this is provided by the gamma ray logs for each section (Figs. 1B and 3B). For Well 2 the correlation between the illite content and the gamma ray is high (r^2 is 0.93 for the XRD derived values and 0.99 for the magnetically derived values for the small number of points which have data from both methods). In the case of Well 2a, the trends of the gamma ray and magnetically derived illite content are strikingly similar, particularly for the lower parasequence (Figs. 3A, B). The correlation coefficient r^2 is 0.89 for the lower parasequence between the magnetically derived illite content and gamma ray values at the same depths, with the regression line passing close to the origin. For XRD-derived illite and gamma ray r^2 is 0.86, but the regression line is shifted and does not pass through the origin. For the entire Well 2a interval, the correlations are worse, 0.46 for the magnetic method and 0.39 for XRD, which may be partly due to small inaccuracies in depth shifting in the upper parasequence (we have used the company's depth shifts). Accurate depth shifting may improve these correlations. It should be remembered that the correlations will also be influenced

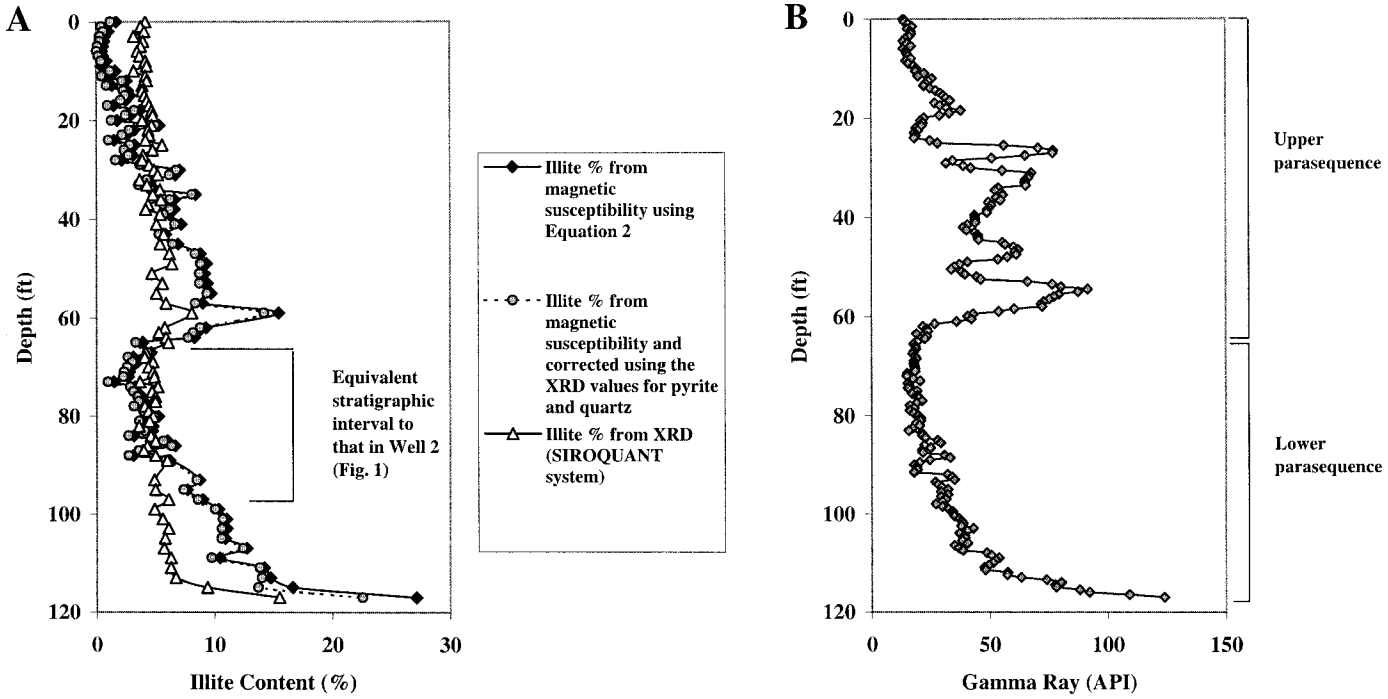

FIG. 3.—**A)** Illite percentages with depth in two coarsening-upwards parasequences in PEGASUS Well 2a from magnetic susceptibility on cleaned horizontal core plugs and XRD measurements using the SIROQUANT system on powdered uncleaned core. Magnetic estimates corrected for the XRD measured pyrite and quartz percentages are also shown. Measurement uncertainties result in the estimated illite percentages having errors of about ± 0.25% from the magnetics and about ± 0.5 to 1.5% from XRD. Depths are from the top of the interval. **B)** Wireline gamma ray log from the same interval.

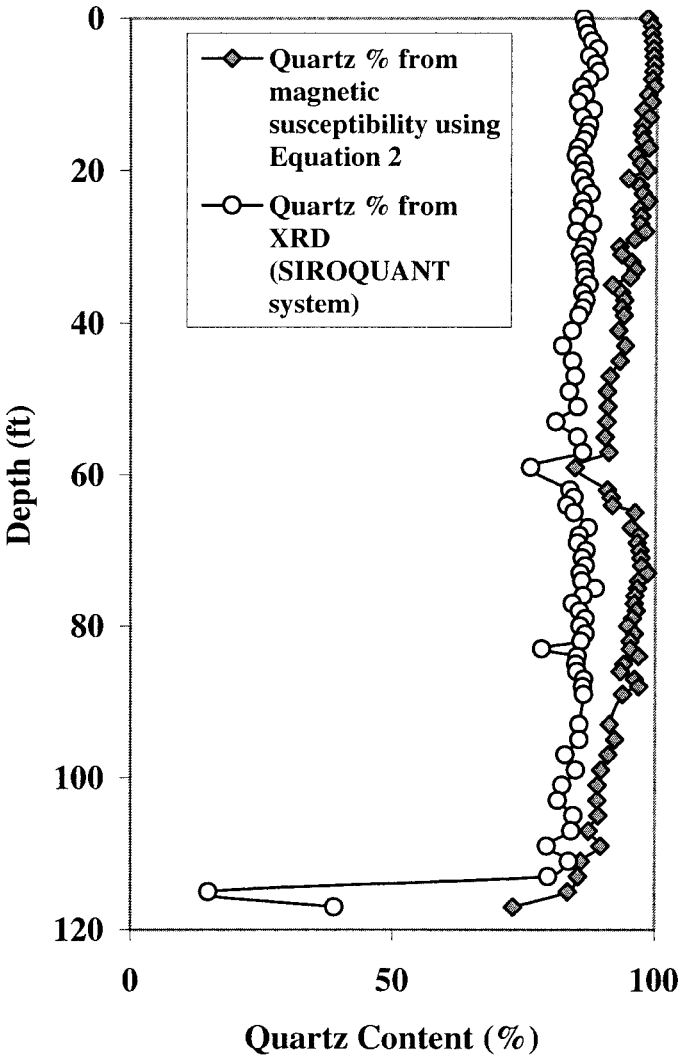

FIG. 4.—Quartz percentages with depth in the two parasequences in PEGASUS Well 2a from magnetic susceptibility on cleaned horizontal core plugs and XRD measurements using the SIROQUANT system on powdered uncleaned core.

by the different scales of measurement: XRD is measured on relatively small disaggregated samples, the magnetic method is here performed at the core plug scale, and the gamma ray tool averages over a much larger volume scale.

There are a number of possible reasons for the differences between the magnetic and XRD illite results in these basal units. Firstly, the XRD measurements may underestimate the amount of illite, particularly if a greater proportion of amorphous material is produced during the crushing of these more clay-rich samples. In fact, in two samples (one from a distinct shaley interval) XRD gave zero percent illite. These readings were clearly wrong, from analysis of thin sections, and were excluded from the plotted points. Note that the presence of kaolinite, which occurs in XRD-derived concentrations of about 1–2% in the present samples, does not affect the calculated illite percentages significantly because the magnetic susceptibility of kaolinite is low and diamagnetic (Table 1). Also, the XRD results indicated that kaolinite content actually decreases in the basal muddy units, whereas XRD illite content increases.

Secondly, because we have assumed that the total susceptibility signal is a simple mixture of quartz and illite, then the presence of other paramagnetic or ferrimagnetic minerals will cause an overestimate in the illite concentration. Indeed, paramagnetic pyrite is present in minor amounts, particularly in the PEGASUS Well 2a samples, and is slightly more abundant in the basal units. This, however, does not seriously affect the results. Illite estimates corrected for pyrite and quartz were calculated by subtracting the magnetic susceptibility contributions of the pyrite and quartz, using the measured XRD percentages for these minerals in conjunction with their quoted susceptibility values (Table 1), from the total measured susceptibility of each sample. Figure 3A shows that the initial magnetic estimates of illite are not significantly affected in the vast majority of samples after applying the corrections. Note that the initial (uncorrected) illite estimates from magnetic susceptibility in Figures 1A and 3A utilize Equation 2, and do not use the XRD derived quartz values, highlighting the usefulness of the magnetic technique.

The presence of ferrimagnetic minerals was tested by imparting an IRM to some representative plugs (1 inch in diameter and 1 inch long), which we specifically cut from slabbed core in the studied intervals (depths 3.4, 13.1, 19.9, 22.1 and 23.7 ft. in Well 2, and depths 10.1, 38.2, 57.5, 81.3, 105.2 and 115.5 ft in Well 2a; note 1 ft = 0.3048 m). It would have been ideal to do these tests on all the original plugs used for the susceptibility measurements, but this was not possible since the latter were too long at 1.5 inches to fit into the magnetometer holder, and we did not wish to destroy them for other purposes by cutting them down to size. The plugs we did test all exhibited extremely low values of IRM. If this signal was due to magnetite it would have contributed only about 5% at most to the total susceptibility signal (there would be a small range dependent on the grain size, due to the variation of magnetic susceptibility with magnetite grain size; see fig. 4 of Potter and Stephenson 1990).

Thirdly, any significant anisotropy in the core plugs would cause a slight overestimate in illite content. This is because we made single-axis measurements on horizontal core plugs and in anisotropic material the magnetic susceptibility (measured along the axis of the core plug cylinder) will generally be higher for horizontal (usually bedding-parallel) plugs than for vertical (bedding-perpendicular) plugs. Measurements of the anisotropy of magnetic susceptibility (AMS) using a Molspin anisotropy delineator, as well as CT (computer tomography) imaging, NMR (nuclear magnetic resonance) imaging, and linear X-ray imaging, showed that most of the samples in this study are close to being isotropic, but some high illite samples towards the base of each parasequence are weakly anisotropic. Even in these latter cases the illite percentages corrected for magnetic anisotropy was only about 1–2% lower than the values shown. To correct for anisotropy, the average susceptibility value from the three principal susceptibility axes (derived from the AMS measurement in conjunction with the bulk reading) was used in Equation 2 instead of the single-axis bulk reading.

Influence of Core Cleaning

In PEGASUS Well 2a, the magnetic illite estimates in the upper sand intervals of both parasequences in Figure 3A are actually slightly lower than the XRD values, particularly in the upper parasequence. Unless there is some calibration error in the XRD values, we believe that this is a real difference between the cleaned samples used for the magnetic analyses and the uncleaned core used for the XRD measurements in PEGASUS Well 2a. The top 17 foot (5.2 m) interval of the upper parasequence has by far the highest values of permeability (up to about 1000–2000 mD), and it is possible that some illite was removed during hot soxhlet cleaning of the core plugs. As part of another study, we noticed a difference in illite content between cleaned and uncleaned core material in some intrinsically high permeability samples. Three cleaned samples from a different North Sea oil well with permeabilitites ranging from 475 to 736 mD had XRD derived illite contents averaging 2.1%, whereas adjacent uncleaned samples at the same depth all had higher XRD illite percentages averaging 3.9%. In contrast, three cleaned samples with permeabilities ranging from 3.7 to 4.8 mD had XRD derived illite contents averaging 6.1%, compared to their cleaned counterparts which still averaged 5.9%. In PEGASUS Well 2, the magnetic and XRD measurements were both performed on cleaned core, and the results from the two techniques gave almost identical low values of illite in the upper 19 foot (5.8 m) high permeability sand unit (Fig. 1A). The regression line goes almost through the origin (Fig. 2), as one would expect theoretically. We might expect that the slope of the regression line for the PEGASUS Well 2a samples would be steeper and pass nearer to the origin if the XRD analyses had been performed on cleaned samples. The cleaning issue is expected to be less of a problem below the top 17 ft (5.2 m) high permeability zone. Below this zone the permeability values are typically < 1 mD and range from 0.1 to 56 mD, and significant illite removal is less likely to occur during core cleaning.

If cleaning is an issue in intrinsically high permeability samples, then further potential applications of the magnetic technique may include rapid quantification of illite (or other components) before and after cleaning, and tracking the migration of ''fines'' in core flooding experiments. An additional possibility is a rapid means of estimating permeability in uncleaned core (where the illite is undisturbed) using the measured permeability in the cleaned core plugs and the magnetic measurements in both cleaned and uncleaned samples.

Application to Paleoclimate Studies

It is worth mentioning that the magnetic susceptibility variations seen here, which are dominantly due to variations in clay mineralogy, may have consequences for

some climate cyclicity studies. These studies typically interpret magnetic susceptibility variations as due to variations in heavy-mineral content, particularly magnetite, and indeed many results are due to this ferrimagnetic mineralogy. Some studies, however, may need reevaluating in the light of our present results, if the susceptibility variations were interpreted without supplementary remanence measurements such as IRM.

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