THE USE OF CORE DERIVED QUANTITATIVE MINERALOGICAL DATA TO IMPROVE FORMATION EVALUATION

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ABSTRACT For a selected, representative North Sea well the sequence of formations comprising the Jurassic Brent Group has been evaluated using advanced core and log analysis techniques.

The mineralogy of these formations has been quantified using Fourier Transform Infra-red Spectroscopy and used, along with conventional core measured petrophysical parameters (porosity, permeability and grain density), to control, optimise and substantiate the log evaluation results. Mineral analysis results were generated in a format which enables direct incorporation into an advanced statistical log evaluation procedure. A minimum logging suite comprising acoustic, density, photo-electric, compensated neutron, gamma ray and resistivity was used as input to the evaluation procedure.

The results of this log analysis approach have proven to be more representative of core measured values than those derived through conventional deterministic log evaluation procedures.

In addition, minerals which characterise the individual formations can be recognised and used for improved in-field geological correlation and subsequent reservoir development.

INTRODUCTION

Initial identification and evaluation of reservoir intervals encountered in any well are largely based on wireline log interpretation procedures with little regard to geological information. This is mainly due to the fact that most wireline log evaluation software packages are not able to assimilate the available geological information which itself is often evaluated without regard to petrophysical properties.

In an attempt to overcome this discrepancy, two divisions of Western Atlas International (Core Laboratories and Atlas Wireline Services) have developed appropriate analysis packages. Core Laboratories' Mineralog™ analysis quantifies geological information which can be utilised within Atlas Wirelines' WDS Optima™ log analysis system. With rapidly acquired and quantified mineralogical information, petrophysical parameters can be accurately substantiated.

In order to demonstrate the benefits of having quantified mineralogical data available for incorporation into initial well evaluation routines, a typical North Sea Jurassic interval has been selected. Conventional deterministic log evaluation, (utilising assumed input variables) has been performed and compared to results obtained by incorporating Mineralog data. Additionally, the Optima statistical analysis approach has been applied using the quantified mineralogy directly to control the evaluation process.

MINERAL ANALYSIS

Common Methods

Historically, mineral analysis has only been semi-quantitative via XRD, chemical analysis, SEM and thin section point counting. These methods are relatively slow and expensive, hence this type of information was not collected in a routine manner and certainly not within the time frame required to meet with initial evaluation and completion of a well. Mineralog analysis is both quantitative and rapid thereby enabling detailed information regarding the nature of the formation to be available at a time when it can be best put to use.

Mineralog

The Mineralog technique is based on infrared (IR) spectroscopy which has been in use for qualitative mineralogical identification for at least 35 years. Recent developments allow quantitative mineralogical identification based on Fourier Transform Infrared (FTIR) Spectroscopy. The absorption energy of a rock sample is used to characterize the molecular bonds which identify the minerals present (Harville and Freeman, 1988). Mid-range infrared radiation (between wavelengths of 2.5 and 25 microns) is used to initiate chemical bond vibrations within mineral molecules. This range of radiation frequencies enables the analysis of carbon/oxygen and silicon/oxygen bonds which are of primary interest. The frequency of vibration in a molecule depends primarily on three factors: crystal structure, chemical bond strength and mass or atomic weight of the atoms. A brief review of the actual Mineralog analysis procedure follows.

A representative rock sample is ground into a very fine matrix to ensure that the particle size is less than that of the incident infrared radiation wavelength (Fridmann, 1967). The sample is then dispersed in a potassium bromide matrix. By measuring the amount of energy transmitted through a sample of known weight, it is possible to calculate the mineral abundance by using a multivariate statistical approach. It should be noted that because minerals are strong infrared absorbers, only a small quantity of material (typically around 1 g) is required for the analysis. As such, drill cuttings, core chippings (or plug end trims) and side wall samples can all be utilised although care must be taken to ensure that the sample is truly representative of the formation. Most common and many exotic minerals are currently carried in the calibration set. Ionically bonded minerals such as NaCl are not detected by this analysis method. Clay minerals in general cannot uniquely be recognised due to the nature of their bonding but the Chlorite group can be distinguished from the Illite/Smectite group of minerals. Kaolinite is an exception having a strong infrared signature enabling accurate quantification of this clay mineral.

Quality control verification of the technique using other methods shows that Mineralog mineral percentages are accurate to within $\pm 5\%$ by weight at worst and are routinely well within this tolerance (Harville and Freeman, 1988).

Speed and cost effectiveness are the primary advantages of Mineralog analysis. Rapid data aquisition enables the information to

be at hand in time for incorporation into initial well log analysis and can therefore influence the selection of test and/or completion intervals. The quantitative nature of the results are well suited to petrophysical applications and can assist with determination of reservoir characteristics. Additionally, the mineralogical profile of a reservoir interval as defined from Mineralog analysis can be of great benefit when selecting samples for further specific petrographic analysis by XRD, SEM, or thin section.

A summary comparison of Mineralog analysis with alternative techniques (presenting advantages and limitations of each) is given in Table 1. For details of the Mineralog technique, the reader is referred to references 1 and 4.

TABLE 1 Comparison of mineral analysis techniques.

Method	*Advantages*	*Limitations*
X-Ray Diffraction	. Detailed clay mineralogy . Most inorganic compounds can be identified	. Generally only semi-quantitative on whole rock samples . Time consuming . Expensive . Unable to quantify amorphous minerals . Machine and operator dependant
Thin section Analysis	. Gives textural information . Provides distribution of components . Characterises porosity . Can recognise trace minerals	. Semi-quantitative (at best) . Sample preparation is time consuming . Expensive . Operator dependant

Chemical Analysis	. Quantitative . Can derive molucular proportions . Can differentiate atomic valencies	. Time consuming . Must have element to mineral transforms
Scanning Electron Microscopy	. Gives clay morphology and distribution . Provides pore geometry . Identifies trace minerals . Elemental composition of minerals via EDS	. Not quantitative . Expensive . Operator dependant . Too site specific
Mineralog	. Rapid . Quantitative . Cost effective . Only small sample required . Direct measurement method . Highly repeatable results (not machine or operator dependant . Can quantify amorphous minerals	. Cannot recognise ionically bonded minerals (e.g. NaCl) . Organic compound responses are swamped by mineral responses in whole rock analysis . Cannot identify specific clay minerals (excepting kaolinite)

CASE WELL STUDY

A typical Northern North Sea Jurassic reservoir section has been selected in order to demonstrate the benefits of having to hand quantitative mineralogical data to assist with initial formation evaluation.

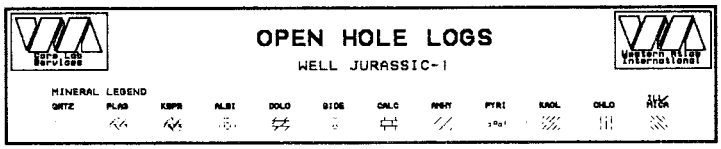
Mineralogical Effects

The available open hole logs for the interval are presented alongside the mineralogical profile, as defined from Mineralog analysis, in Figure 1. Actual core analysis results are presented alongside the mineralogical profile in Figure 2. Simple visual inspection of the Mineralog profile is sufficient to ascertain that there is significant variation in the mineral assemblages throughout the section.

Many minerals have significant impact on individual wireline log responses e.g. clay effect on the neutron device substantially increases the apparant porosity as measured by that tool. It is therefore imperative to take into account these effects in the log analysis procedures. Table 2 documents the log responses related to the mineral assemblage recognised in the Jurassic interval addressed in this paper.

TABLE 2 Effect of mineral assemblage on log responses.

Mineral	*Density g/cc*	*Neutron p.u.*	*Sonic us/ft*	*Gamma Ray*
Quartz	2.64	-2.1	51	Low
Muscovite	2.82	16.5	47	High K
K-Feldspar	2.53	-1.1	69	High K
Plagioclase	2.60	-1.3	48	Low
Calcite	2.71	0.0	46	Low
Dolomite	2.87	0.5	42	
Siderite	3.89	12.9	44	Low
Pyrite	5.00	-1.9	38	
Kaolinite	2.61	45.1	212	Low
Chlorite	2.88	22.5	51	Low - Mod
Illite	2.63	15.8	@ 190	High



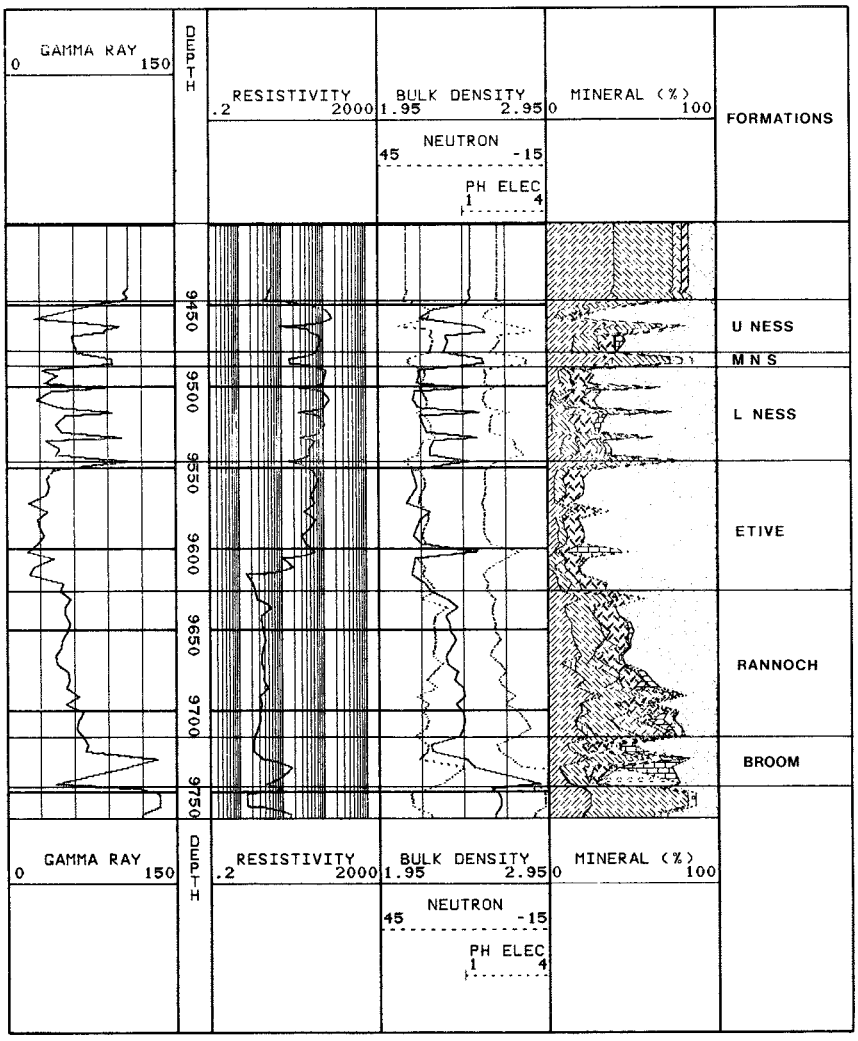


FIGURE 1 Open hole logs.

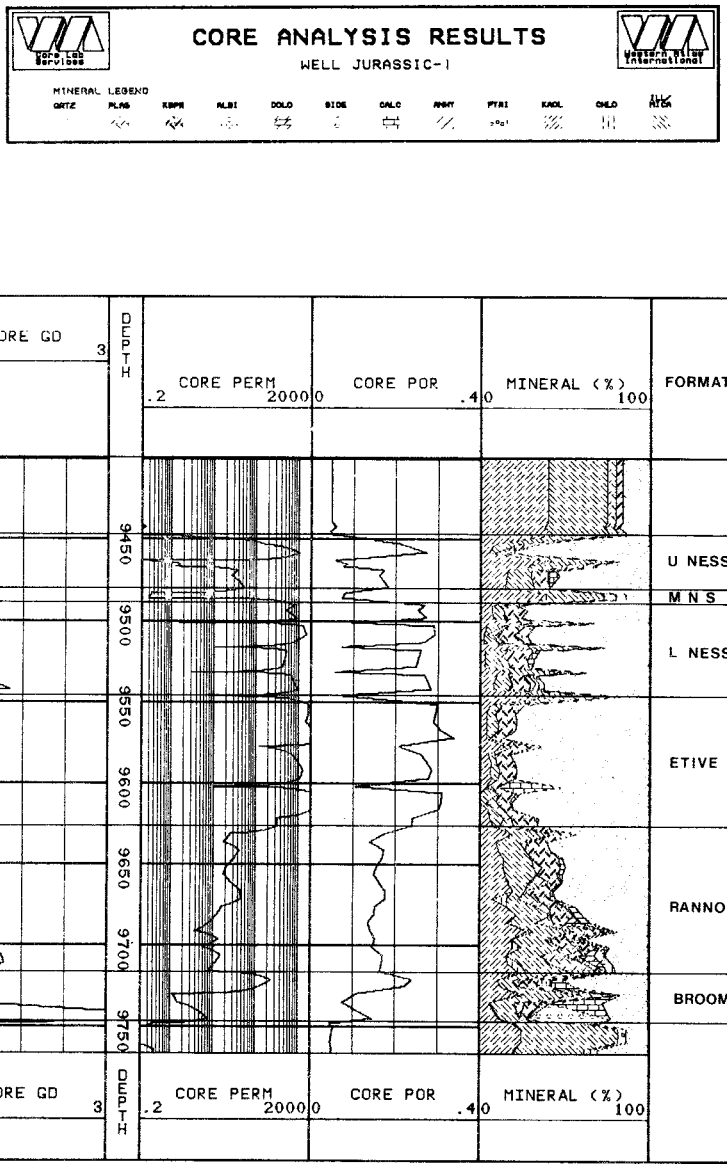


FIGURE 2 Core analysis results.

Examples of such effects observed in this type Jurassic section include:

1. A significant percentage of k-feldspar is present in most of the sands. This material is radioactive and therefore affects the gamma ray apparently increasing the shaliness of the sands.
2. In the Rannoch interval (depth range 9628 - 9718 ft) the total clay percentage is high in places. In fact the increase in apparent shale content is largely due to the presence of muscovite mica which also has a positive affect on the natural gamma ray. Note that although Mineralog is unable to clearly distinguish between illite and muscovite, it's presence can often be inferred and it's percentage estimated by observing the differences between calculated and core measured grain densities (when available).
3. Also in the Rannoch section, siderite generally increases in percentage towards the base. The grain density of siderite is 3.94 g/cc and even a very small percentage can lead to significant increases in grain density and hence errors in calculated porosity if not accounted for within the calculation procedure. Infact, for a sand having a true porosity of around 20%, each 1% increase in the proportion of siderite will lead to an error (decrease) in calculated porosity of around 0.8 of one porosity percent if not accounted for in the grain density value. At the base of this Rannoch section (depth interval 9700-9720 ft) the percentage of siderite averages around 5%. In part of the Broom sand the measured percentage of this mineral reaches almost 50%! Siderite, calcite and occasionally dolomite are present in large percentages towards the base of the interval. The calculated grain density reaches a maximum of around 3.3 g/cc, a value much higher than would normally be expected. Use of an assumed sandstone grain density for this interval would generate large errors in calculated porosity.

Deterministic Log Evaluation

A continuous grain density profile is calculated by the Mineralog software from the cummulative summation of the individual mineral component volume percentages multiplied by their relative grain densities. This curve, along with the measured total clay percentage, (summation of individual clay volumes) can be utilised in even the most basic deterministic log evaluation approach.

To better illustrate potential errors in log evaluation which can occur as a result of not accounting for the various effects of minerals

present, porosity has been calculated from the density log using a fixed (and often assumed) value for the grain density of 2.65 g/cc (i.e. that of quartz). Additionally the porosity has been calculated using the grain density profile obtained from Mineralog. Both arrays have been crossplotted against the actual in-situ corrected core porosity and are presented in Figures 3 & 4. For those sands having high grain densities (i.e. lower Rannoch) the deviation in correlation on Figure 3 is quite evident. A much improved match is achieved when using Mineralog grain densities as shown in Figure 4.

The Mineralog routine normally assumes illite grain density for the illite/smectite/muscovite group unless this value is over-ridden. Grain density of muscovite (2.83 g/cc) is of course significantly higher than that of illite (2.64 g/cc). This illite/muscovite recognition problem is not unique to Mineralog. Indeed the two minerals are so chemically similar that it is extremely difficult to distinguish one from the other with XRD. Ongoing detailed study of the Mineralog IR spectrum for these two minerals suggests that a slight difference does exist and it may be possible in future to infer the presence of either illite or muscovite. Meanwhile, where core measured grain densities are available, a comparison to those calculated from Mineralog can also infer the presence of muscovite. From these observed differences an approximate percentage of mica was calculated. Figure 5 illustrates the variance between core measured and Mineralog estimated grain densities in relation to this calculated muscovite percentage. The maximum discrepancy in grain density at 16% muscovite is only 0.04 g/cc.

Porosity was subsequently calculated using a grain density profile corrected for the presence of mica. Figure 6 displays the results (along with the porosity derived using both Mineralog grain density and an assumed grain density) crossplotted against the core measured porosity for the Rannoch interval. Errors are reduced in comparison to the raw Mineralog derived results which in turn show a significant improvement over values calculated from a constant assumed grain density of 2.65 g/cc.

The implications of such errors may be far reaching. For instance, in a non-cored well where the calculated porosity cannot be verified against measured values; if the assumed grain density is too low then the calculated porosity will also be too low and the interval may be interpreted to be non-reservoir material (especially as the low porosity will also lead to a low calculated value of hydrocarbon saturation in a potentially economic reservoir). For the

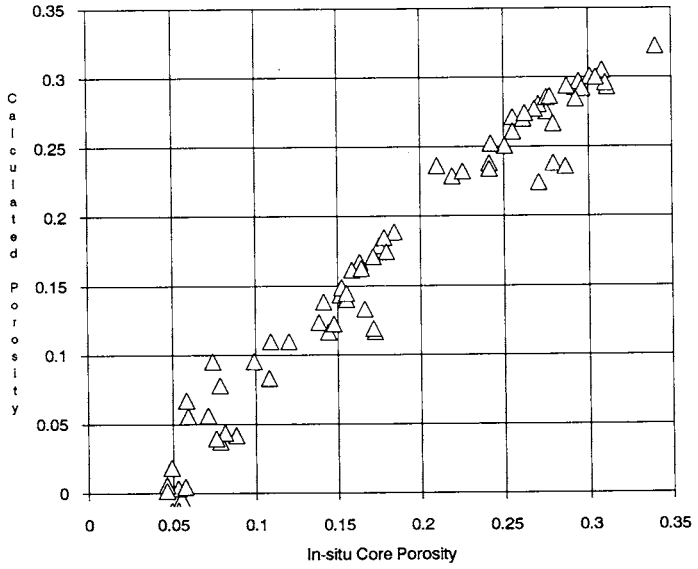


FIGURE 3 Calculated vs core porosity (assuming constant grain density of 2.65 g/cc).

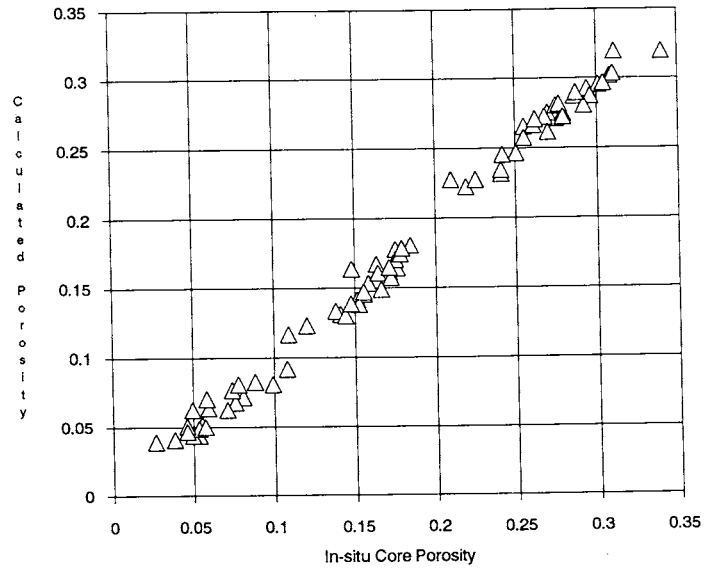


FIGURE 4 Calculated vs core porosity (Mineralog grain density).

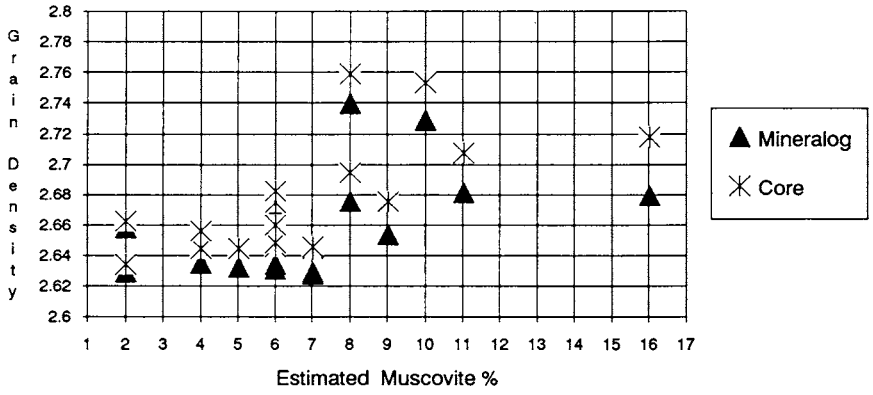


FIGURE 5 Variation in grain density for Rannoch interval viewed in relation to muscovite content.

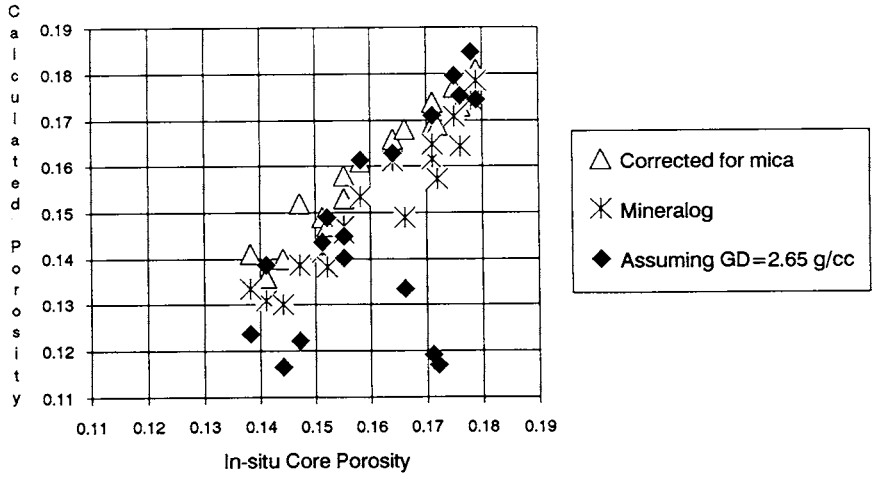


FIGURE 6 Calculated vs core-derived porosity mica-bearing Rannoch sands.

case of a development well this may lead to the interval being excluded from the completion thereby reducing production potential. For the case of an exploration or appraisal well the interval may not be tested and hence the full potential of a new prospect could be seriously under-estimated.

Equally important to the grain density profile is the Mineralog measured total clay curve. For example, work spanning the past twenty years on shaly sand conductivity has shown that, regardless of which model one chooses to apply, knowledge of the amount and type of clay material is important for proper log evaluation. Porosity, and more so permeability, can vary significantly with subtle changes in clay content and lithology.

The clay volume index (Vcl) used in shaly sand analysis is often calculated from the gamma ray log response viz;

$$Vcl = \frac{GR - GRmin}{GRmax - GRmin}$$

Where: GR is the actual Gamma log response in the interval of interest.
GRmin is the Gamma log response in clean beds.
GRmax is the Gamma log response in shale beds.

One major limitation of this technique is that non-clay radioactive minerals such as certain feldspars and other uranium and thorium bearing minerals can make sandstones appear 'shaly' on the gamma log when they are infact 'clean'. We observe this effect in the subject Jurassic sand sections as already commented upon in 1) and 2) under Mineralogical Effects above. Conversely, certain clay minerals such as kaolinite and chlorite are essentially non-radioactive and can therefore lead to the assumption that a sand is 'clean' whereas infact it contains a significant percentage of clay. Mineralog analysis detects kaolinite and chlorite discretely and thus the Mineralog measured total clay can be used to calibrate the gamma ray log to provide a valid calculated Vcl.

In the subject Jurassic interval kaolinite is present throughout. Infact the 'clean' sands contain on average 10-15% total clay around half of which is kaolinite. Figure 7 presents a crossplot of measured total clay versus gamma ray. Three data groups are identified; the Ness and Etive sand/shale sequences (depth range 9450 - 9620 ft), the Rannoch sands (depth range 9620 - 9715 ft) where the increased

gamma reponse is largely attributable to increases in the mica percentage, and the third group (depths 9715 - 9750 ft) which relates to the basal Broom sand where there is no clear correlation between total clay or feldspar content and the gamma response. It is believed that a trace percentage of a highly radioactive material (e.g. uranium) in the sand has led to an erratic gamma response for this interval.

Clays (and micas) can also have significant effects on the neutron log. The subject Rannoch interval appears, from density and neutron values, to be extremely poor reservoir quality. Infact core permeability values in the Upper and Middle Rannoch average around 20-30 mD making this section undoubtedly reservoir quality.

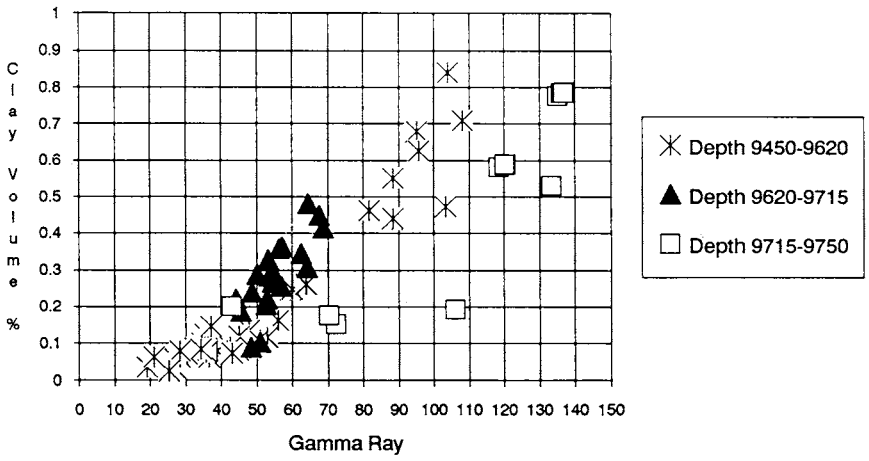


FIGURE 7 Gamma ray vs measured Vcl (Mineralog) illustrating 3 distinct data groups.

Optima Statistical Log Analysis

The Optima software package consists of a flexible set of advanced programmes developed by Atlas Wireline Services for the interpretation of well log and core data using their Well Data System (WDS). The Optima software supports solving for a maximum of six different minerals (per horizon), plus porosity, shale and fluid saturations provided that the minimum necessary log input data is

available. The package will also generate synthetic curve data based on the formation parameters chosen plus the uncertainties associated with the actual log data.

In general, the Optima routine is a non-linear, weighted least squares method of analysis used to combine the actual logging tool measurements with their associated theoretical values and uncertainties into an objective function (WSSE) which is minimized to yield the most reliable set of results (Atlas Wireline Services, 1989). The Optima programme is structured such that the produced results are constrained to a user-defined range of validity based on user input of geological and field knowledge constraints.

The normal mode of the Optima package is initiated by determining the uncertainties in each of the log data measurements. These uncertainties vary between tools but generally encompass environmental effects i.e. borehole conditions, principle of measurement and activity of the measurements. Log data measurements and petrophysical parameters (for each of the input devices defining each of the minerals to be identified) are manipulated by the programme. Formation mineralogy, volume of shale, porosity and water saturations are output along with their confidence intervals to indicate the accuracy of the data. As mentioned earlier, the programme also generates theoretical tool responses as defined by the petrophysical parameters of all the curve data. This in itself is an excellent check to determine if the computed results are within the acceptable range as determined by the initially calculated uncertainties.

To demonstrate how Mineralog analysis complements Optima processing, a simplified analysis using just two of the input devices (density and neutron) can be carried out to determine volume of shale and porosity. The petrophysical parameters required in this case are the density log and neutron log responses for fluid, shale and the matrix.

The total volume of a mass of rock is the sum of porosity, volume of shale and the matrix minerals which in this case is simply assumed to be quartz. The set of theoretical tool response equations and the associated error can be expressed as:

$$bi_{th} = fi(X_i, Z_i), 2, \ldots\ldots\ldots n \quad (1)$$

$$ei = bi - bi_{th}\ 1,2, \ldots\ldots\ldots n \quad (2)$$

Where:

bi_{th} = i-th theoretical tool response
bi = i-th actual tool response
ei = i-th error
fi = i-th tool response equation
Zi = i-th set of user defined parameters
X = set of unknown parameters (mineral volumes, porosity, fluid saturation etc)
n = number of tool responses included in the analysis

These equations are then minimized to obtain the desired output as defined by the objective function (WSSE) with constraints:

$$WSSE(X) = \sum_{i=1}^{n_t} \frac{[b_i - b_{i\,th}]^2}{W_i} + \sum_{j=1}^{n_c} \frac{g_j^2(X)}{Qj} \qquad (3)$$

Where:

W_i = total uncertainty associated with the error ei
g_j = represents the j th constraint
Q_j = represents the weight applied to the j-th constraint

The validity of the results obtained are compared with the data from available mineralogical studies (e.g. Mineralog) on that particular well. Figure 8 shows the results of this Optima two-component model. Porosity errors occur where significant percentages of additional minerals are present in the formation; particularly in the basal Lower Ness sand (depth 9535-9542 ft) which contains both pyrite and siderite and in the Lower Rannoch and Broom sands where siderite and dolomite are abundant.

This method of analysis does not guarantee that the parameters used to define the unknowns are individually correct. It does, however, indicate that the combined input parameter selection produces results which give an answer consistent with the geology for that particular well. This can be a concern when applying the input parameters on a field-wide basis. Using Mineralog data however, allows the analyst to circumvent this problem. The Optima family has an optional programme entitled Amitpo which allows for

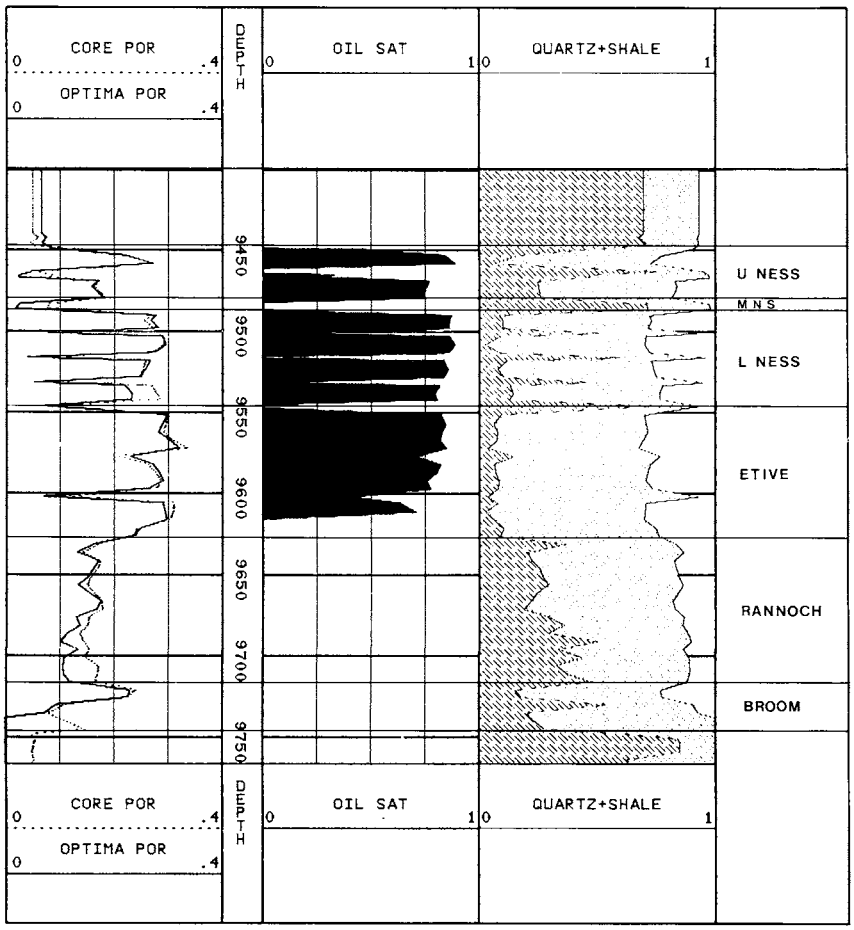


FIGURE 8 Optima two component model.

the entry of mineral volumes obtained from Mineralog analysis and other known results such as porosity and Vsh. Applying the recorded well logging tool responses to these volumes predicts, in a linear fashion, what the petrophysical parameters must be for each of the requested minerals. Further statistical analysis is performed on the fit of these parameters and a value of the confidence fit is output. This procedure in itself gives the operator confidence in the analysis performed and ensures that the petrophysical parameters determined will apply to a given area (i.e. a field) and not just to an individual well.

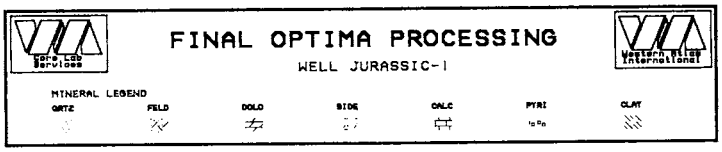
In this case study the Mineralog curve data were used to define components for input to the Optima routine. As Optima is restricted to six minerals per horizon plus shale, the feldspars were grouped together as were the clays. The available log curves; density, photo-electric, neutron, gamma ray, acoustic and resistivity curves were all utilized in the evaluation. The output values for porosity and fluid saturation are presented on Figure 9 alongside the re-confirmed mineral volumes which confidently reflect the measured mineral percentages as displayed on Figure 1. The agreement between calculated and core-derived porosity is excellent. Control parameters from this well evaluation could now be applied with confidence to a nearby well where no Mineralog analysis is available provided that the same log reference set is recorded.

RESERVOIR MONITORING

Applications of quantitative mineralogy outlined above relate to open hole log evaluation. However, the data is equally valid when interpreting cased hole logs used for reservoir monitoring.

Quantitative pulsed neutron log interpretation requires input sigma matrix values which are controlled by the formation mineralogy. A continuous sigma matrix curve could be modelled if the continuous mineralogy profile is known.

Similarly for gamma spectroscopy devices such as GST and Carbon/Oxygen logs and other geochemical logging tools which measure elemental contributions, detailed knowledge of the formation mineralogy is necessary in order to perform accurate quantitative evaluation of fluid saturations.



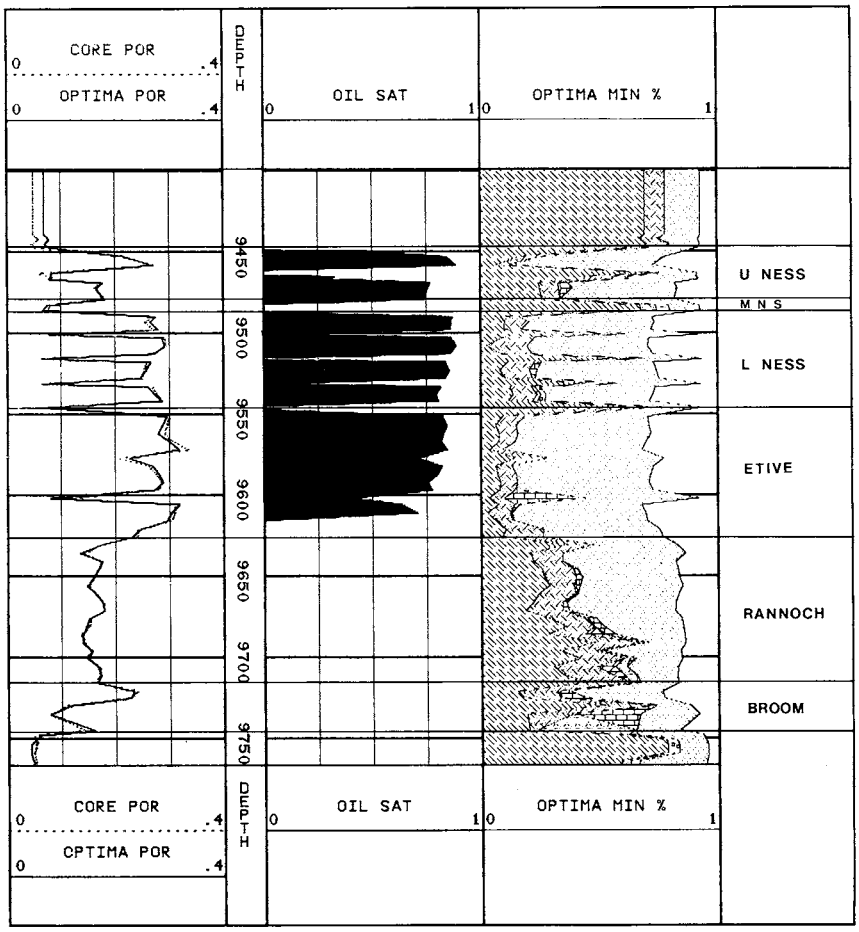


FIGURE 9 Final Optima processing.

IN-FIELD CORRELATION

Wireline logs are routinely used by geologists to correlate horizons from one well to another. This often proves difficult when adjacent sands of similar log character are present within a formation.

Within the Lower Ness interval of this example case well (9485 - 9550 ft) there are four individual sand members. The log responses for these sands (ref. Figure 1) are very similar and it would therefore be most optimistic to presume that these individual members would be correlatable to those of the same interval in any nearby well.

However, close observation of the Mineralog profile as displayed in Figure 10 and detailed in Table 2 below reveals some interesting factors in relation to actual mineral percentages.

TABLE 3 Mineralogical composition of Lower Ness sands.

DEPTH		QRTZ	PLAG	K-FELD	ALBI	CALC	SIDE	PYR	KAOL	ILLI
9487.0	SHALE	14	7	0	0	0	6	0	39	34
9491.0	SAND 1	78	0	10	0	0	0	0	7	5
9494.1	.	72	0	14	0	0	0	0	7	7
9499.0	.	76	0	10	0	0	0	0	8	6
9502.0	SHALE	28	7	5	0	0	0	0	33	27
9504.0	SAND 2	68	3	10	6	0	0	0	4	9
9509.0	.	72	5	11	8	0	0	0	2	2
9514.1	.	70	3	12	3	0	0	0	2	10
9517.0	SHALE	22	5	3	0	0	3	0	36	31
9519.0	SAND 3	65	4	11	0	4	0	0	3	13
9524.1	.	68	5	12	0	4	0	0	3	8
9529.0	.	69	4	11	0	2	0	0	3	11
9532.5	SHALE	34	7	6	0	0	2	0	20	31
9534.2	SAND 4	66	0	9	3	0	2	3	8	11
9539.0	.	62	0	11	3	0	2	3	8	11
9543.0	.	62	0	12	2	0	3	4	8	9
9547.0	SHALE	17	0	6	0	0	0	0	44	33

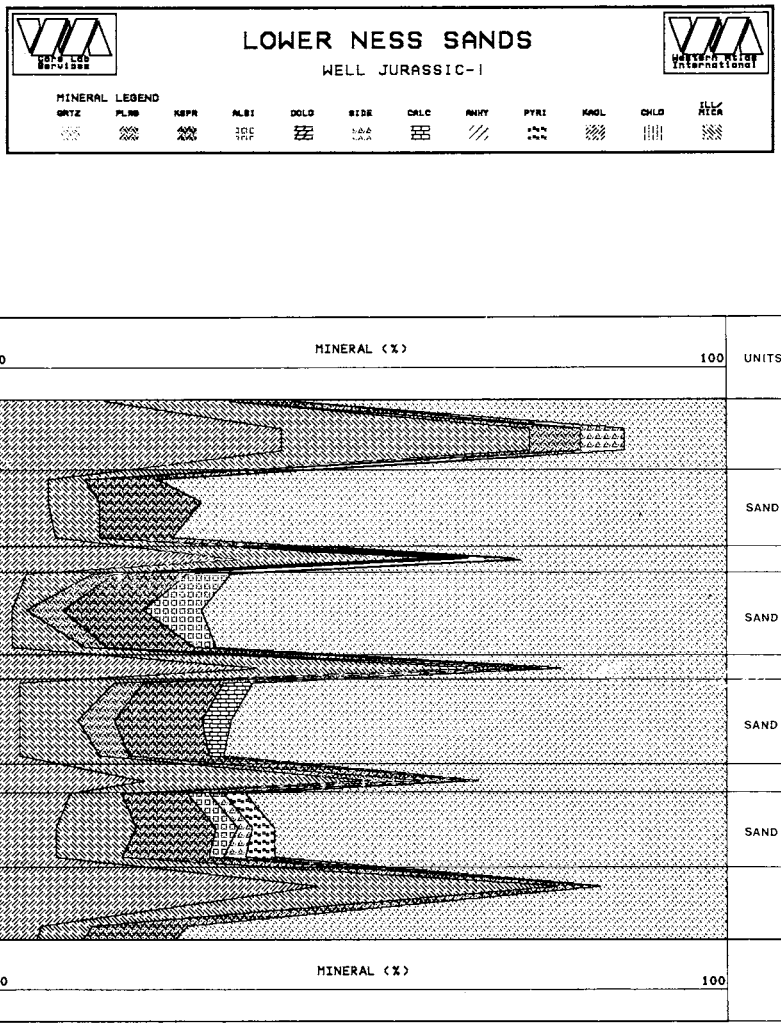


FIGURE 10 Lower Ness sands.

The uppermost sand comprises quartz, k-feldspar and shale (50-50 kaolinite and illite). The underlying (second) sand contains these same four minerals and in addition albite and plagioclase (oligoclase) feldspar are also present in small percentages. Sand 3 contains plagioclase but no albite. The basal sand contains albite, plagioclase is absent but small percentages of pyrite and siderite.

These variations in the mineral assemblages could be used to 'fingerprint' each sand. Correlation to nearby wells may reveal like assemblages in sands within the same formation thus assisting with a more detailed correlation than would be possible using wireline logs alone.

CONCLUSIONS

Results from the Jurassic interval analized demonstrate that use of quantitative core-derived mineralogical (Mineralog) data can significantly improve formation evaluation even when using the most basic deterministic log evaluation approach. Furthermore, combination of Mineralog and Optima statistical processing leads to accurate determination of petrophysical properties and therefore the petrophysical parameters used in the final log analysis can be more accurately substantiated. These petrophysical parameters can then be applied in other wells within the field with a high degree of confidence.

In reservoir monitoring/cased hole interpretation, detailed knowledge of formation mineralogy is a pre-requisite for accurate determination of fluid saturations.

When quantitative mineralogical data is available for a number of wells on a field, then mineralogical fingerprints of individual sand bodies may be used as an additional correlation tool where log responses alone are unable to clearly distinguish these horizons.

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