

How to use Infrared Spectroscopy Mineralogy Data to Calibrate Logs.

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Vienna, Austria, 27 August – 1 September 2017

ABSTRACT

Over the last decade, hyperspectral infrared spectroscopy has become recognised as a useful technique for quantifying mineral content in core, plugs and cuttings. Mineral abundance can be defined on a sub-millimetre level. These fine scale data are extremely valuable for both geologists and core analysts. This paper aims to provide methodologies to use these high resolution mineral data to help calibrate common log interpretation models.

Log interpretation models all include constant parameters that relate to some property of the rock being tested. For example, to obtain shale volumes from gamma logs requires an estimate of the gamma response in both ‘clean’ sand and high shale content rocks. The log interpreter will make an educated guess as to the value of these parameters based on all available information. Knowledge of the rocks mineralogy greatly enhances the selection of these parameters. Awareness of minerals spatial distribution allows the log interpreter to vary/zone these parameters throughout the logged section.

Examples from reservoir sections will be shown to illustrate methods to calibrate a number of log interpretation models including, shale volume from gamma logs, density log porosity models and clay bound water from NMR. The fine scale mineralogy data are also used to evaluate mineralogical controls on permeability.

INTRODUCTION

Short Wave Infrared (SWIR) Imaging Reflectance spectrometry is a semi-quantitative mineral logging technique that can rapidly analyse core, cuttings or any other material without the need for sample preparation. Detailed descriptions of infrared spectroscopy theory and measurements can be found in Clark (1999) [1] & Hunt (2014) [2].

SWIR reflectance spectroscopy is a non-destructive, molecular-vibrational analytical technique that measures the absorption and reflection of infrared light at narrow and discreet wavelengths off a sample surface, Figure 1. Many minerals have their diagnostic molecular (overtone) vibrations in the SWIR; the most common vibrations are associated with subtle changes between the hydroxyl and cation molecular bonds common to the clays and phyllosilicates [1].

Detailed mineral information about the polytype and crystallinity of clays, such as illite, smectite, chlorite, kaolin polymorphs and crystallinity, Figure 2, can be identified by this technique. Other identifiable minerals include, micas, carbonates, sulphates, borates and also hydrocarbons from core and cuttings. The only constraint is that the mineral must have a diagnostic spectral reflectance signature within the 1.3-2.5 micron spectral range that the SWIR instrument operates. So, tectosilicates, such as quartz and feldspars cannot be uniquely identified. SWIR Reflectance spectroscopy does not provide whole-rock data and is therefore a semi-quantitative technique. Increased accuracy and precision in mineral quantification can be achieved using other data to calibrate, such as XRD or point count, but these data are also considered to be semi-quantitative.

Spectra-Map's SpecCam infrared imaging spectrometer acquires automated, high-throughput mineral information from drill core, cuttings, chips, plugs or hand samples. Round, half cut and biscuit cut core can all be measured. Logging is non-contact and non-invasive so no sample preparation is required. It collects high spatial resolution scan lines at regular intervals - consisting of $140 \times 0.5\text{mm}$ square pixels – to create an infrared image over the core, Figure 3. Typically, 46,000 sample (pixel) points are acquired from a metre of core using the system.

Accurate modal percentage values can be derived from the SpecCam due to the large number of data points collected. To get a more accurate modal percentage value, the abundance of a mineral in a pixel spectrum is used to calibrate the results. Using modal counts by this method produce very accurate modal percentages, like those returned by other methods, such as XRD or petrology.

The spatially continuous data from SWIR reflectance spectroscopy allows us to determine trends that point sampling techniques, such as XRD, are unable to gauge. This makes SWIR reflectance spectroscopy of core potentially very useful for 'calibrating' log interpretation models.

Data Set

Block 21/16 is located on the Western Platform of the Central North Sea. Well 21/16-2 targeted the oil bearing Upper Jurassic Fulmar Formation. The base of the Fulmar sand and shale formation shows a deformed zone and rests unconformably on anhydrite, dolomite and halite of the Permian Zechstein Group.

Slabbed and resonated 'biscuit' slice core totalling 64.5m in length was available for the study. Thirty-five routine core analysis plugs were also available for testing. The previous operator included all the drilling, logging, core analysis and petrophysical reports in the data set. The core was scanned using the infrared imaging spectrometer at a resolution of one core width line scan per 3mm. The measured spectra were deconvoluted to determine core mineralogy and the modal percentage of each mineral calculated. Figure 4 shows the resulting data for part of core 3.

Shale Volume from Gamma Logs

Gamma log data can be used to estimate the volume of shale in a formation. This method assumes that the majority gamma rays are emitted from clays and fine grained sediments. The gamma log response from shales can be extremely variable. Therefore, the method relies on defining a formation specific minimum gamma value, that would be representative of a clean sand, and a maximum gamma value that defines a rock of a hundred percent shale [3]. Equation 1 defines the model:

Equation 1:

$$V_{sh}^* = \frac{GR \text{ value (log)} - GR(\min)}{GR(\max) - GR(\min)}$$

Where: V_{sh}^* = Shale/clay volume (fraction)
 $GR \text{ value (log)}$ = Log gamma value (API)
 $GR(\max)$ = 100% shale (API)
 $GR(\min)$ = 0% shale (API)

In this study, we assume that the terms clay and shale are interchangeable. This is a reasonable assumption because in most clastic formations the minerals that are gamma emitters are predominantly clays. The shale/clay volumes obtained using Equation 1 can be considered to represent an upper bound for shale/clay volumes [3]. A more realistic shale/clay volume is obtained by using the non-linear relationship defined in Equation 2:

Equation 2:

$$V_{sh} = 0.33 (2^{2V_{sh}^*} - 1)$$

Where: V_{sh} = Shale/clay volume (fraction)
 V_{sh}^* = Shale/clay volume from Equation 1 (fraction)

Equations 1 and 2 are combined and the gamma minimum and maximum values at each depth obtained. This is done by using Excel Solver (optimiser) to determine the variable values needed to match the volume of shale/clay from Equation 2 with the total clay volume measured by the core spectroscopy, Figure 5. Note that the 0.5mm resolution spectroscopy total clay volumes are averaged over a 6 inch (15.24cm) moving average to convert the spectroscopy data to a similar measurement 'window' as the gamma log. The clay content is higher in the upper half of the core, above 7115ft, this corresponds to the Fulmar Formation. The carbonate rich Zechstein Formation is below 7115ft. The optimised gamma minimum & maximum values for the gamma shale/clay model are shown in Figures 6.

The operator reported that they used a gamma minimum value of 35 API and a maximum of 115 API. From the range of values seen in Figure 6 the use of single values for gamma minimum and maximum is inadequate to model the shale/clay volume over these formations. Knowing the optimised gamma minimum and maximum at each depth allows the log interpreter to use different values for each parameter on a zone by zone basis and hence obtain a more accurate shale/clay volume than single values for the whole formation.

Porosity from Density Logs

The density log measures the bulk density of a formation. This includes all the mineral grains and fluid. If the density of the mineral grains and fluid are known an estimate of porosity can be made using Equation 3 [3].

Equation 3:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Where:

- ϕ = Total porosity
- ρ_{ma} = Grain (matrix) density (g/cc)
- ρ_b = Bulk (log) density (g/cc)
- ρ_f = Fluid density (g/cc)

Note that the porosity calculated in Equation 3 is total porosity. The grain/matrix density parameter in Equation 3 is usually estimated by plotting core plug grain density against porosity and extrapolating to porosity equals zero. Figure 7 shows these plots for the limited number of available core plugs from the Fulmar and Zechstein Formations. Grain density values of 2.74g/cc and 2.96g/cc respectively are obtained.

The mineralogy data from the core spectroscopy scanner can be used to calculate grain/matrix density at each 3mm interval. A grain density for each mineral is defined and the relative proportion of each used to calculate average grain density at each depth. Because the spectroscopy core scanner does not detect quartz or feldspar we assume a grain density (2.65g/cc) for these ‘undetected’ minerals and include these minerals in the density calculation. The calculated and core plug grain density is plotted in Figure 8A. The calculated grain density match the plug values well in the Fulmar Formation (7087-7115ft) and Upper Zechstein (7115-7138ft). Below 7138ft the Zechstein is thought to contain high density anhydrite. Anhydrite was not one of the minerals included in the library of mineral spectra during deconvolution, hence it was not detected. The resulting calculated grain density below 7138ft is too low.

The spectrometer derived grain density has been used to calculate porosity using the density log and Equation 3. The operator quoted a fluid density of 0.64g/cc over the zone of interest. The resulting porosity is compared with the plug porosity in Figure 8B. The ‘standard’ density log porosity is also calculated using the grain density values from Figure 7. The spectrometer based density log porosity matches the plug porosity much better than the ‘standard’ density log porosity in most zones apart from between 7125-7135ft. Three QEMSCAN mineralogy data points from this zone are available, they contain more plagioclase feldspar than any other part of the core. The grain density of plagioclase ranges from 2.61 to 2.765g/cc. Plagioclase is one of the minerals not detected by this spectroscopy core scanner. Therefore, the assumed grain density of 2.65g/cc for the undetected minerals may need to be revised for this zone. Increasing the grain density of the undetected minerals in this zone would increase the calculated density log porosity closer to the measured plug values. More investigation into the mineralogy of this zone is required.

Clay Bound Water Volume from NMR

Definition of clay bound water volumes is vital to know when defining total and effective porosity. Clay bound water (CBW) volumes can be obtained from NMR data by applying a clay bound water T_2 cut-off. The standard clay bound water T_2 cut-off for clastic rocks is 3ms [4]. The clay bound water T_2 cut-off can be obtained for individual core plugs by inspection of the humidity oven dried sample T_2 distributions. These data are available for three Zechstein Formation plugs, Figure 9. These three plugs were also scanned in the infrared imaging spectrometer and mineralogy content obtained. The basic properties and clay volumes for the plugs are listed in Table 1. We can calculate a clay bound water volume if we know both the clay volume and the clay porosity. For the purposes of this workflow illustration we assumed a clay porosity of 20%. The calculated clay bound water volumes are reported in Table 1. These values are then used to estimate the clay bound water T_2 cut-off using the ‘sum of amplitudes’ method detailed in Moss & Jing (2001) [5], Table 1. The clay bound water T_2 cut-off are also plotted on Figure 9. The estimated clay bound water T_2 cut-off values define the clay bound water for these plugs reasonably well.

Plug	Depth (ft)	Helium Porosity (pu)	NMR Porosity (pu)	Klinkenberg Permeability (mD)	Humidity Oven Dried Water Saturation (%)	Spectroscopy Clay Volume (%)	Clay Bound Water Estimate (assume clay porosity = 20%) (%)	Clay Bound Water (CBW) T_2 Cut-off (ms)
46	7121.0	7.87	7.78	0.36	13.95	2.59	6.654	4.47
50	7124.9	21.74	22.09	31.00	2.78	8.08	7.314	2.28
74	7149.1	4.45	3.58	0.01	15.17	12.39	69.265	5.62

Table 1: NMR plug data

Linking Mineralogy and Permeability

In many clastic formations clay and cement type and volume have a large effect on permeability. High resolution mineralogy data such as that produced by the infrared imaging spectrometer can be used to evaluate the mineralogical controls on permeability. A 21.5ft section of core had plug calibrated mini-permeability measurements made at 1cm intervals. A comparison of the calibrated mini-permeability data and the spectrometer derived mineralogy can be seen in Figure 10. An increase in total clay content corresponds to a reduction in permeability between 7099ft and 7108ft, Figure 10A. Between 7108ft and 7115ft permeability increases by four orders of magnitude with very little variation in clay content. In this zone, no mineralogical controls on permeability could be found. The permeability increase is probably due to grain size/textural variation. The Zechstein Formation begins at 7115ft, below this depth dolomite controls permeability, Figure 10B.

The infrared imaging spectrometer can also detect solid and liquid hydrocarbon. Figure 10C shows the percentage of pixels that produced a hydrocarbon spectra versus depth. The hydrocarbon parameter appears to relate to permeability, although the link is weak. This effect could be due to increased hydrocarbon saturation in high permeability zones and or increased oil based mud filtrate in higher permeability rocks. Regardless of the cause the hydrocarbon parameter could be used as a useful proxy for permeability. This is an area of ongoing research.

CONCLUSIONS

Infrared imaging spectrometer measurements on core produce spatially continuous mineral data. Workflows have been developed to use these data to help calibrate log interpretation models and evaluate mineralogical controls on permeability. Spatially continuous mineral data of this type are invaluable to both geologist and petrophysicist.

ACKNOWLEDGEMENTS

The authors would like to thank Weatherford Laboratories (UK) Ltd for the core mini-permeability and core plug NMR measurements and Jenny Omma from Rocktype Ltd for useful discussions and geological information.

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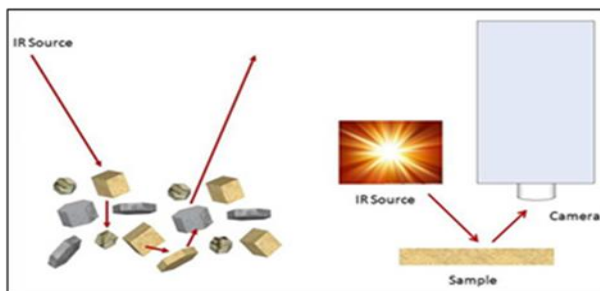


Figure 1: Reflectance spectroscopy light pathway

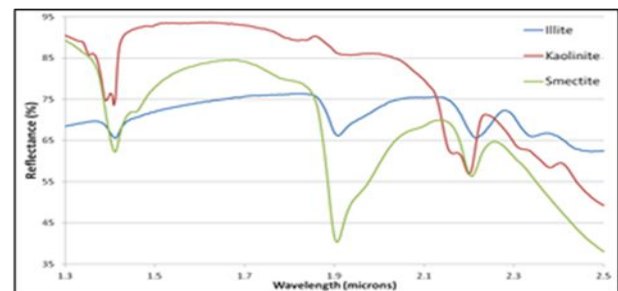


Figure 2: Example mineral reflectance spectra

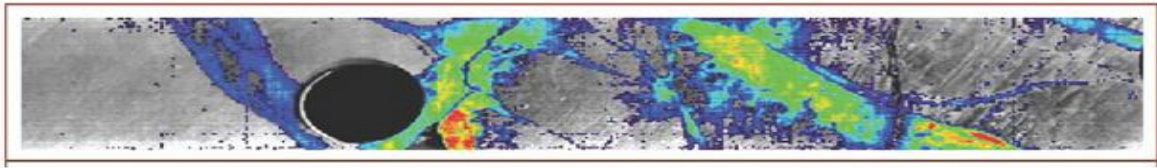


Figure 3: A section of core colour coded to show the presence and amount of chlorite infill in sandstone, against a greyscale IR background image.

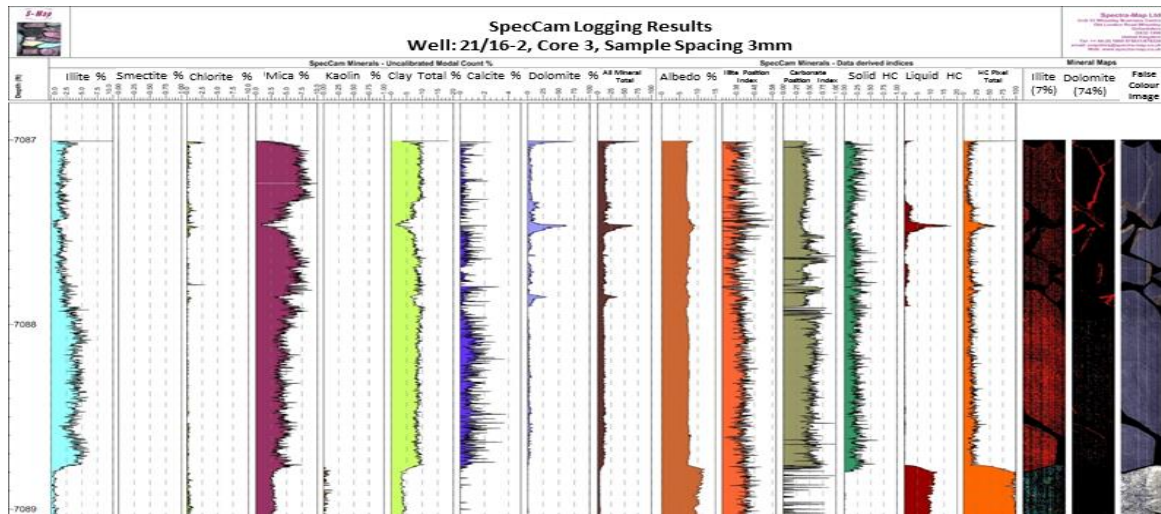


Figure 4: SpecCam infrared core logging results for well 21/16-2, core 3

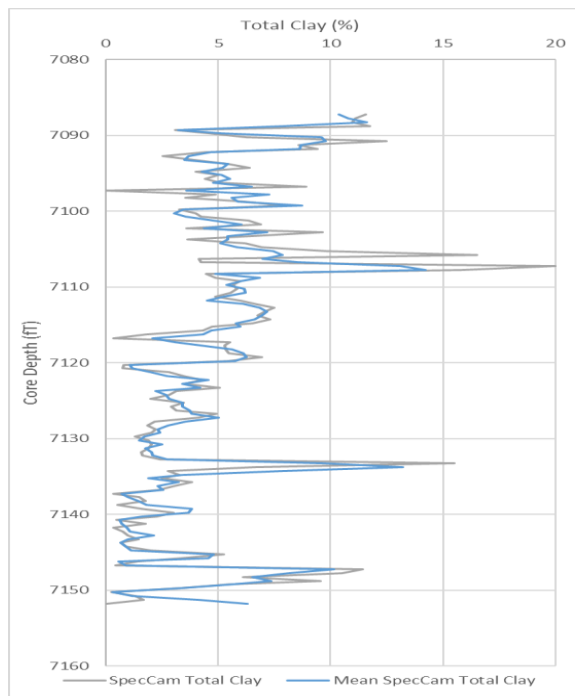


Figure 5: Spectrometer total clay volume versus depth

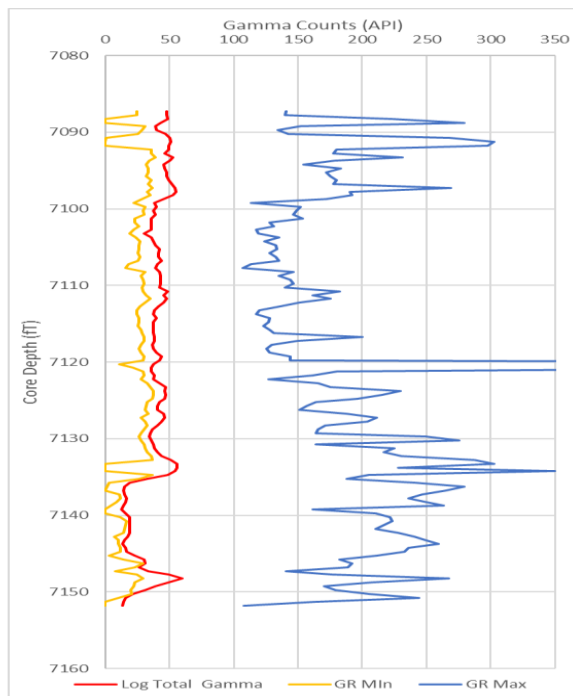


Figure 6: Total gamma log & optimised gamma min & max values versus depth for the non-linear gamma

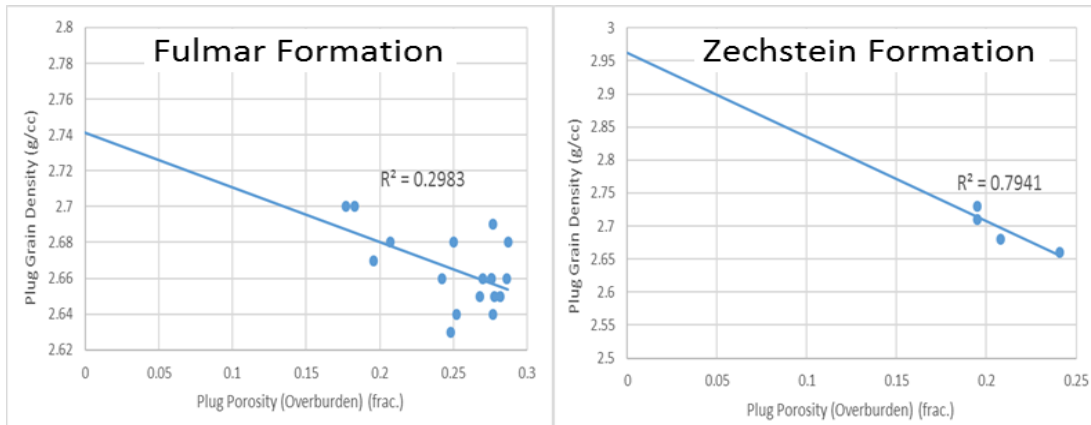


Figure 7: Plug grain density versus porosity for the Fulmar and Zechstein formations

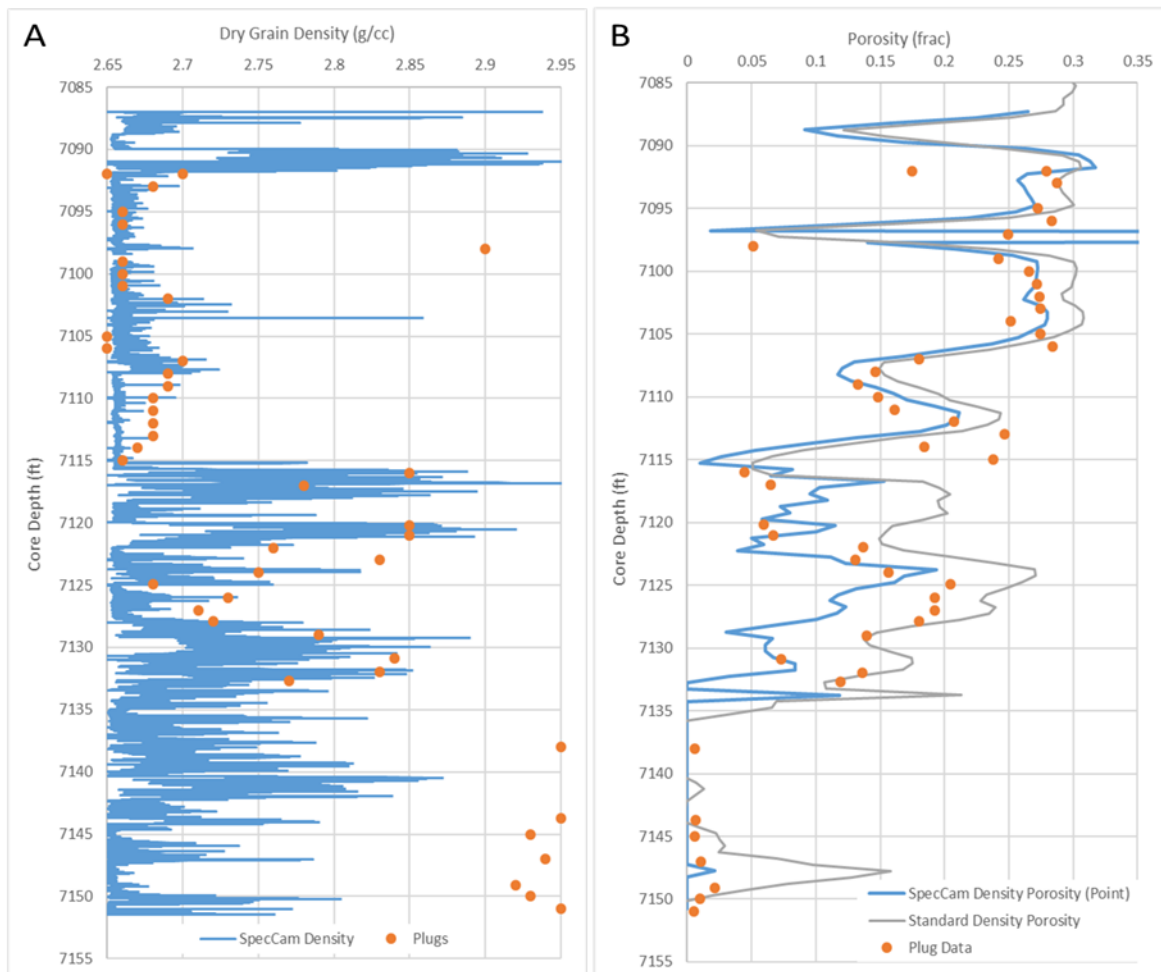


Figure 8A: Spectrometer mineralogy modelled and core plug grain density versus depth

Figure 8B: Density log and core plug porosity versus depth

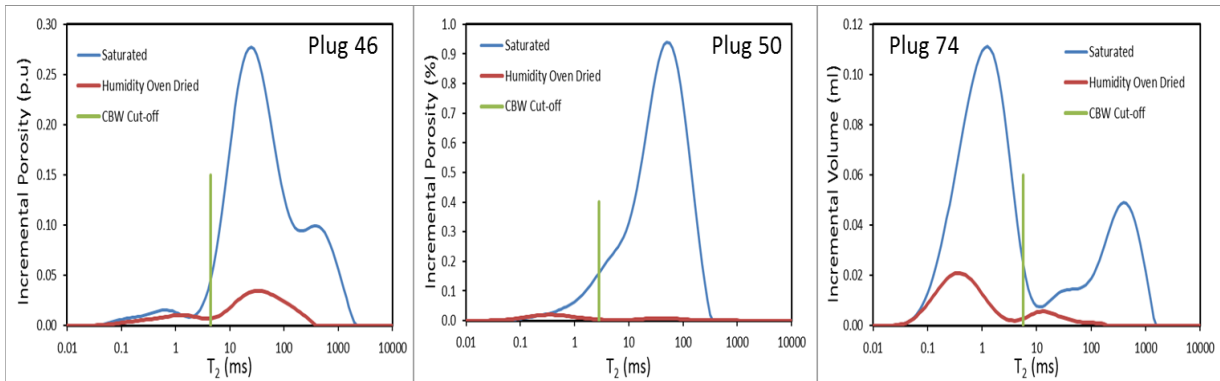


Figure 9: NMR T_2 distribution plots for three Zechstein Formation core plugs.

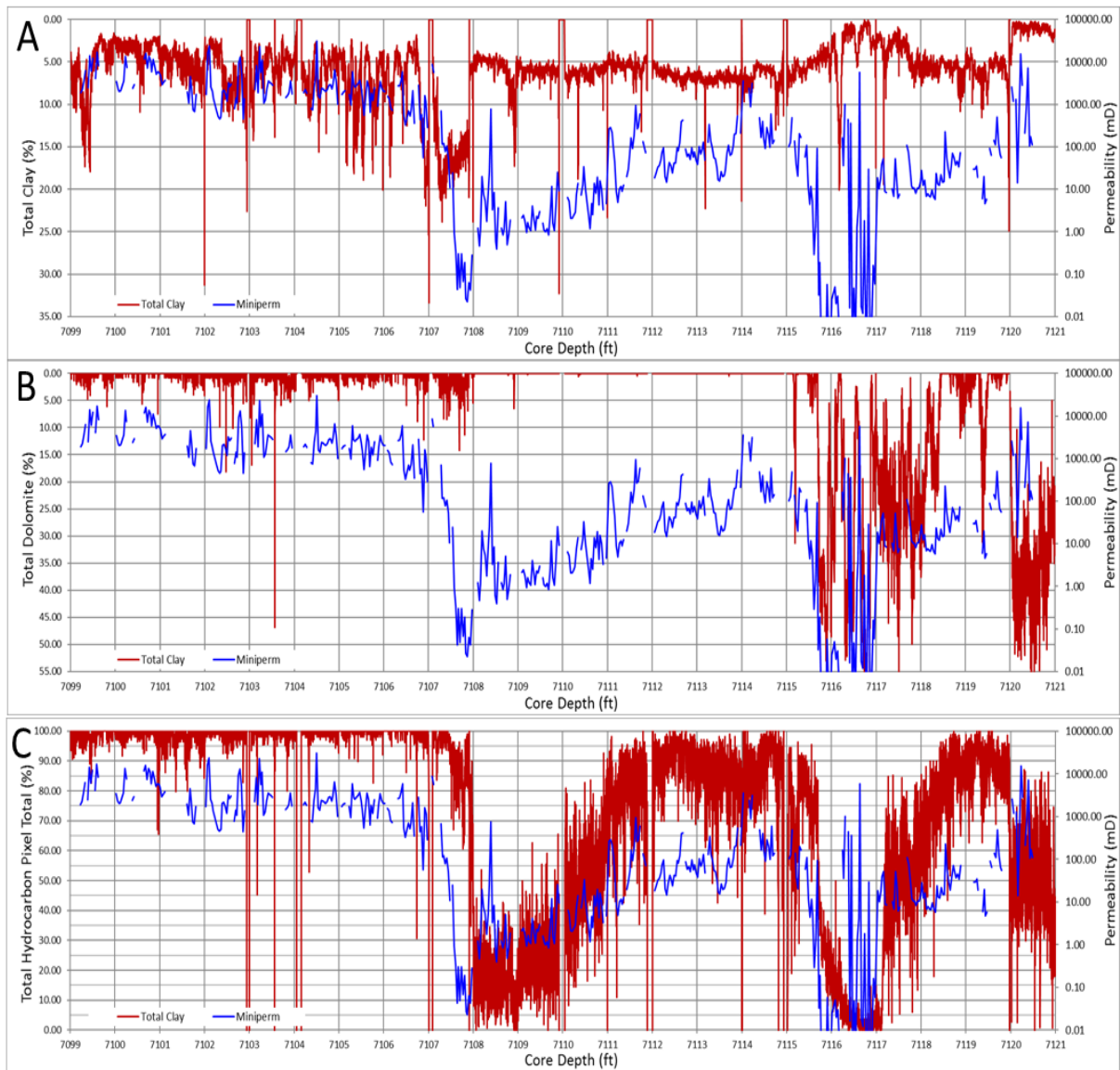


Figure 10: Permeability, mineralogy and hydrocarbon total versus depth.