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Reservoir evaluation of 12 wells in the Devonian – Carboniferous of the Central North Sea: Petrophysical interpretations of clay volume, porosity and permeability estimations

Energy and Marine Geoscience Programme

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BRITISH GEOLOGICAL SURVEY

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Foreword

This report is a published product of the 21st Century Exploration Road Map (21CXRM) Palaeozoic project. This joint industry-Government-BGS project comprised a regional petroleum systems analysis of the offshore Devonian and Carboniferous in the North Sea and Irish Sea.

Mike Millar (BG Energy Holdings Limited), Carla Riddell (Centrica) and Mal Gall (OGA) are thanked for technical review of this report and associated digital data.

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Summary

This report details the reservoir evaluation of 12 wells across the Devonian-Carboniferous rocks of the UK Central North Sea for the 21CXRM Palaeozoic project. A companion report examines the source rock potential (total organic carbon content) of the non-reservoir intervals (for a different, but overlapping set of wells) (Gent, 2015).

This reservoir evaluation is based on the petrophysical interpretation of available digital wireline log curve data for the 12 wells and digitised core porosity and permeability data (1 to 281 measurements available for 7 of the 12 wells) across the Devonian-Carboniferous interval (according to reinterpreted stratigraphic formations defined and correlated for this project, documented Kearsey et al. (2015). Outputs of this part of the project include continuous (along borehole) interpretations of porosity, clay volume, coal presence, and include basic permeability estimations where sufficient data exists to generate these. These interpreted curves were used to calculate Net to Gross (NTG) values and average porosities and permeabilities for each formation in each well analysed.

The Yoredale and the Scremerston formations appear to have the most favourable reservoir properties in terms of porosity (up to 19% and 15% respectively), and permeability (up to 45.28 mD and 785.52 mD respectively). However, they have relatively low NTG values (0.27 & 0.18 respectively). The Fell Sandstone Formation has the greatest NTG of the intervals examined (0.61), but porosity and permeability values are lower (0.13 and 42.69mD are the greatest average values from the wells examined).

All these reservoirs show heterogeneous character in the geophysical log response, with reservoir intervals interbedded with non-reservoir.

Other reports document the stratigraphic extent of these units (e.g. Kearsey et al., 2015). Note that given the limited number of wells examined and the regional scale of the project, more detailed study of the reservoirs including mapping property trends and identifying prospective intervals was out of scope of this project. A brief examination of the distributions of net to gross and average porosities, both by formation in each well and for the total Devonian-Carboniferous interval in each well was not able to highlight any particular property trends or geographic areas with favourable properties.

1 Introduction

The 21CXRM Palaeozoic project aimed to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea - Mid North Sea High - Moray Firth - East Orkney Basin and in the Irish Sea area. The objectives of the project included regional analysis of the plays and building of consistent digital datasets, working collaboratively with the OGA, Oil and Gas UK and industry.

The project results are delivered as a series of reports and as digital datasets for each area. This report describes the methodology and results of a "quick-look" regional-scale petrophysical study of reservoir quality in the Central North Sea study area. Given this nature of the study, and the time & resources available for it, a full rigorous petrophysical interpretation of each well examined was not within scope. This is explained in the report and should be borne in mind when examining the outputs and results.

1.1 OUTPUTS OVERVIEW

1. **Continuous digital interpreted curves across the Devonian-Carboniferous intervals for 12 wells in the CNS (method Section 2.2, 5 describes the selection process). Interpreted from geophysical log responses using Interactive Petrophysics software (IP™, Version 4.2.2015.61, LR-Senergy)**

   Analysis for:

   - Volume of clay *(V_{CL})*
   - Coal intervals *(V_{COAL})*
   - Porosity *(PHIE & PHIT)*
   - Permeability estimate *(PermEst)*

2. **Summary petrophysical results (based on interpreted curves (1.)) for the Devonian-Carboniferous interval by formation in each well**

   - Gross thickness
   - Net*
   - Net to Gross
   - Average porosity (across the net intervals)
   - Thickness of coals (across the gross interval)

   *"Reservoir" definition *(i.e. Cut offs to derive "Net")*

     - Porosity greater than 5% *(PHIE>0.05)*
     - Clay volume less than 50% *(V_{CL}<0.5)*
     - No coal intervals *(V_{COAL}=0)*

3. **Digitised core-sample-derived basic porosity-permeability measurement data for the majority of wells in Quadrants 25-44 that have Devonian-Carboniferous intervals and core reports available. Available as an Excel spreadsheet.**

2 Technical details and data preparation

This section outlines the data types, sources of data and preparation required prior to the petrophysical interpretation of selected wells in the Central North Sea.

2.1 DATA TYPES AND SOURCES

A number of data types and sources were required for or contributed to the petrophysical interpretation:

- **Digital geophysical log curve data**, mainly in LAS format (or sometimes LIS or DLIS) were downloaded from CDA for the project (under licence), some BGS legacy data was also used.
- **Scanned company reports** downloaded from CDA, mainly in PDF format:
  - **Composite logs** used to check well location, depths, curves scales, spliced intervals etc
- **Tabulated core porosity and permeability data** (digitised for this project from PDFs of core reports or well completion reports on CDA). Generally the values used and referred to in this report represent helium porosity and horizontal permeability to air. Grain density was not recorded. Note that the laboratory and drying methods used were not always stated and associated data e.g. from Special Core Analysis (SCAL) reports was not generally recorded. The digitised dataset of core data (#3 listed in the outputs overview, Section 1.1) does contain some vertical permeability measurements and also instances of permeability to brine and klinkenberg corrected permeabilities (to give liquid permeability estimation) where these were listed in the core reports in addition to the horizontal air permeabilties. However these have not been included in the tabulated data in this report or used in the core-log interpretation.
- **Stratigraphy:**
  - **Well tops**, interpreted by BGS for this project (Kearsey et al., 2015). These were checked with or re-interpreted from the **digital composite log well tops** "DECC composite tops", supplied from DECC/BGS database).
- **Cored intervals** based on BGS digital core-holdings database query. This was used to indicate core locations on log plots to help to distinguish intervals where data was derived from core, or from, for example, side wall cores or cuttings (particularly for the total organic carbon (TOC) study (Gent, 2015).

2.2 DATA PREPARATION

The software used for the petrophysical interpretation was **Interactive Petrophysics** (IP^{TM}, Version 4.2.2015.61, Seneregy LR software, used under licence). Steps to select the study wells, import and prepare the data are described:

1. Digital geophysical log curve data were copied to IP^{TM} from ODM^{TM} (Senergy well manager software, used for the BGS correlation and re-interpretation of the stratigraphy).

2. The BGS-re-interpreted stratigraphy was loaded into IP for the wells it was available for (reformatted from the ODM-exported .xls file of the formation intervals)[1]
3. BGS-digitised core porosity and permeability data was loaded into IP for the wells it was available for (reformatted from the BGS-digitised tabulation of data for all wells)[1]
4. The cored intervals were loaded into IP for the wells it was available for (tops and bases, reformatted from the output of the BGS core database)
5. Wells to interpret were selected based on the length of Devonian-Carboniferous interval, stratigraphic intervals and geographic areas covered, and the availability and quality of suitable data over the interval. Figure 1 shows the location of the wells that were selected. The following list indicates the factors taken into consideration in their selection and the number of wells they apply to (listed by well in Table 8):
    - Greater than 100m of Devonian-Carboniferous section (101-1835m for the wells selected)
    - Updated stratigraphy picked (12 of the 12 selected)
    - Geophysical log curve data for reservoir evaluation, with suitable data quality (variable for each well) (see Appendix 4, Table 8)
    - Core poroperm data available (6 of the 12 selected)
    - TOC/VR data (8 of the 12 selected, to allow overlap in selection of wells between the reservoir and source rock interpretations)
    - Company log composite available for cross checking data (12 of the 12 selected)

    Note that wellbore deviation surveys were not taken into account because the data is presented against measured depth (MD). Well 43/21-2 in particular is deviated up to around 30° deviation by the bottom of the Devonian-Carboniferous section. This may affect the relative thicknesses of intervals in those wells (but not their average properties). Well 37/10-1 is also noted as deviated, but negligibly so.

[1] *Note that this data was checked and reloaded throughout the process as more data was interpreted or digitised. Given the project time-constraints, these tasks were to a large extent performed simultaneously*.

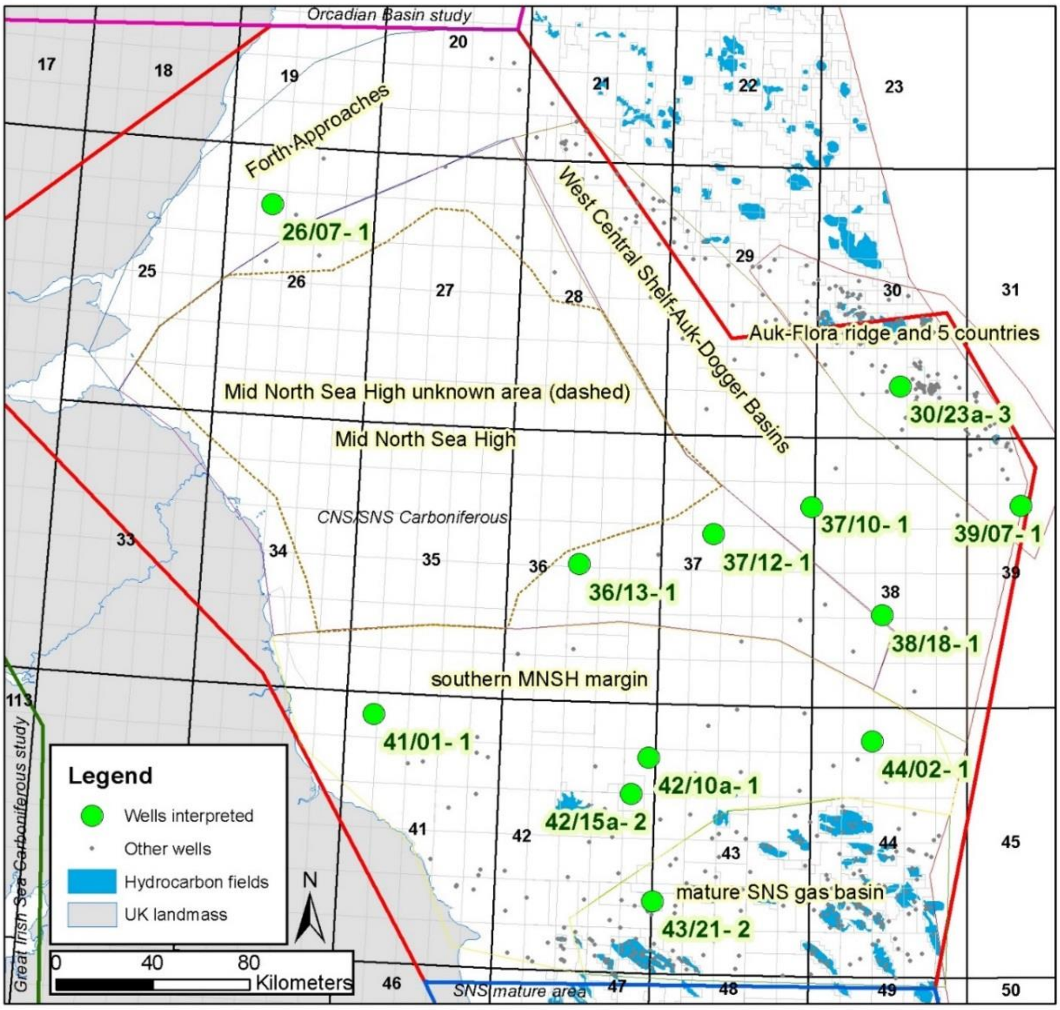


Figure 1 Map of the wells selected for the petrophysical study

3 Curve interpretation method

Continuous interpreted curves were calculated from geophysical log responses over the Devonian-Carboniferous interval using Interactive Petrophysics software (IP^{TM}, Version 4.2.2015.61, LR-Senergy). Where available, core data was used to guide parameter selection. Given the "quick-look" and regional nature of this study, some broad assumptions were necessary for the log interpretation. These include the temperature gradient (35°C/km with a surface temp of 8°C was used, based on southern North Sea trends. This is broadly in line with those in the Basin modelling report: Vincent, 2015), likely mud type (water based mud was assumed, which may affect the output porosities), and that suitable environmental corrections had already been applied to logs. Table 8, Appendix 4 includes some quality control comments and assumptions for individual wells.

3.1 INCORPORATION OF CORE POROSITY AND PERMEABILITY MEASUREMENTS

Core data was not available for all wells (see Table 8), or all reservoir intervals, but where it was available, core porosity measurements were displayed with the log porosities for comparison and to guide interpretation parameter selection (Section 3.4). Core porosity and permeability measurements were used to derive permeability estimation curves (Section 3.5). Core data is displayed on the log plots in Appendix 1.

The usual procedure for matching core and log porosities on a field - scale would be to first depth shift the core to the logs and then correct the core measurements for downhole in-situ conditions (ideally using SCAL (Special Core Analysis Laboratory) data which includes measurements with different fluid phases and different confining pressures, for example, to understand the degree of overburden stress correction to apply). The log porosities could then be robustly "calibrated" to core porosity measurements, before using them (and potentially other logs) as permeability predictors. Usually a detailed knowledge of depositional environment and reservoir heterogeneity would allow appropriate statistical methods to be selected to define permeability predictors for each identified reservoir unit. However, in the tables of core porosity measurements digitised for this regional-scale project, details about core treatment, depth shifts to apply and the measurement method(s) were not generally captured. Therefore, within this report scope, the "usual" steps to correct the core data described above are not fully implemented (Table 2 summarises the core data available for the wells studied; Table 5, Appendix 2, lists the wells for which a core-depth-shift was possible to determine). These, together with the notes below, explain the limits to the possible match between log and core porosity that could be achieved.

Other points of note for log-core matching include:

- Sample scale - the vertical resolution of geophysical logs are much larger than the few centimetres-across core samples retrieved. Thus in very heterogeneous formations, average log response over an interval may be very different to the "point" data measurements on core;
- Core treatment history - core porosity measurements (once shifted and corrected) generally fall between total and effective porosities, depending on the measurement method and also what was done to prepare it e.g. the degree of cleaning and drying processes applied prior to measurement. Permeability measurements from sidewall core samples (well 43/21-1) of sandstones are generally considered to less be valid than full cores as a result of drilling mud contamination (because of their smaller size relative to conventional core, which may have mud damage around the outsides). However, in this

case, because of the low permeabilities measured in this well, mud may have penetrated less far into the samples and so they may be valid.

Comparisons of core-measured and log-interpreted porosities are shown graphically in Appendix 2 along with graphs showing core-measured porosity against core-measured permeability. Tables 5 & 6 show the relationships derived from these graphs (where they were possible to derive).

3.2 VOLUME OF CLAY CURVE (V_{CL})

A Volume of Clay (V_{CL}) curve was interpreted for each well. This gives a continuous, geophysical log-derived volume of clay for the intervals investigated. Input curves were the Gamma Ray (GR) and a combination of the Neutron, Density and Sonic curves where available and of good quality. These curves were used to select end points representing 0% clay and 100% clay for zones of the log, subdivided based on changing log character and curve responses with depth, to create a V_{CL} log scaled from 0 (100% clean reservoir) to 1 (100% clay). Note that data on clay types (for example, evidence of tuffaceous beds) in individual wells or intervals of interest were not explored. This "quick-look", regional scale study interpretation of clay volume is based on curve responses only. The V_{CL} logs were used in combination with other curves to identify appropriate reservoir cuts off for the calculation of Net to Gross values for the main reservoir formations (section 4.2).

3.3 COAL IDENTIFICATION CURVE (V_{COAL})

A coal identification curve (V_{COAL}) curve was interpreted for each well, where "coal indicated" = 1, "no coal indicated" = 0. This gives an indication of whether coal is thought to be present at each depth, based on the log response, and certain cut off values. The cut off values selected were based on a combination of the log responses where the composite log lithology track indicated coal to be present, together with a visual evaluation of curve response with knowledge of expected responses expected in coal and other minerals. Thus slightly different cut offs were used in each well (Table 8, Appendix 3).

The V_{COAL} logs were used in combination with other curves to identify appropriate reservoir cut offs for the calculation of Net to Gross values for the main reservoir formations (section 4.2).

3.4 POROSITY CURVES

Porosity curves were interpreted for each well. Input curves included the V_{cl} curves (section 3.2), Neutron, Density and Sonic curves. (Resistivity and Photoelectric Factor curves were used as visual aids to interpretation where required and data appeared to be reading within expected ranges). Areas of poor log quality were identified using primarily the Density Correction and Caliper curves (Table 8, Appendix 4).

Effective Porosity (PHIE) and Total Porosity (PHIT) curves were computed using the Neutron – Density method*. Where Density or Neutron data was unavailable, or its quality was poor, porosity was calculated using the sonic curve. These computations take into account tool measurements and interpretations of clay, mud filtrate and rock matrix properties. Where sufficient data was available, core porosity measurements were used to guide parameter selection, see Section 3.1.

*Using IP variable matrix density logic. IP solves the tool response equations for PHIE (corrected for wet clay volume). PHIT is then back-calculated by adding back in the clay bound water. Intervals that required sonic porosity calculations utilized the Wyllie equation.

The PHIE logs were used in combination with other curves to identify appropriate reservoir cut offs for the calculation of Net to Gross values for the main reservoir formations (section 4.2).

3.5 PERMEABILITY ESTIMATION CURVE

A permeability estimation was derived for the wells for which appropriate core data was available (Section 3.1). The estimates were based on the relationships between core porosity and log porosity, and core porosity and permeability where data was available and a relationship was found to exist. The same statistical method to examine these relationships was used for each well, as follows:

- Because insufficient data often existed to depth shift the core to the logs, the RMA (reduced major axis) method of regression was chosen to describe any relationship between core and log porosity to attempt to minimise depth matching errors.
- The Robust Fit method was used to calculate the regression line in the core porosity-permeability data, because this reduces the effect of outliers in the dataset. This method minimises the sum of the errors in the Y (permeability) direction, rather than the square of the distances (as is the case with the ordinary Least Squares regression method). The resulting curve was clipped at 10,000 mD, to remove any spuriously high permeability values (applied to well 26/07-1 and 41/01-1).

As explained in Section 3.1, on a hydrocarbon field scale, the normal procedure to derive permeability curves would be more detailed than the method applied here. The permeability estimations here should therefore be regarded as a broad indicator of possible permeability fluctuations with depth and not as absolute values.

4 Outputs & results

4.1 INTERPRETED CURVES

Continuous curves for 12 wells in the CNS were interpreted using Interactive Petrophysics software (IP^{TM}, Version 4.2.2015.61, LR-Senergy) and the methods described in section 3. Curve data were clipped to the Devonian-Carboniferous interval. Any small data gaps were filled (to allow software calculation of Net to Gross and curve averages, sections 4.2 – 4.4).

Note that in many cases the base of the Devonian-Carboniferous interval was not penetrated. Continuous curves produced were:

- Volume of Clay curve (V_{CL});
- Coal Identification curve (V_{COAL});
- Effective Porosity curve (PHIE);
- Total Porosity curve (PHIT) ;
- For some wells a curve of Estimated Permeability (PermEst) exists.

Core data tables are available in Excel form.

Plots of data for each well are available as a "quick-look" output in Appendix 1. (Note that the input data is also displayed in these plots, but is not provided as an output due to data permission constraints).

4.2 NET TO GROSS

Net to Gross (NTG) in this report gives an indication of the amount of reservoir (Net) within an interval of interest (Gross). It is expressed as a fraction from 0 to 1, where a NTG of 0 means that no reservoir has been interpreted within the of interval and a NTG of 1 means that all of the rock within the interval has been interpreted to be composed of 100% reservoir. The NTG equation is shown below.

$$\text{Net to Gross (NTG)} = \frac{\text{Total thickness of reservoir'' (net)}}{\text{Total thickness of interval (gross)}}$$

The total thickness of the interval of interest is the Gross. The Net interval is the sum of the thicknesses of those parts of the reservoir that meet a set of cut-off criteria (applied to one or more curves). These parameters (the cut off criteria that define the Net) will, at the field scale, be based on operator preferences or field observations of reservoir productivity that may be refined through time. However, at this "quick-look", regional-scale, generic cut-offs have been applied to give a broad indication of the Net where:

- Clay volume is less than 50% (i.e. where $V_{CL} <0.5$);
- Porosity is more than 5% (i.e. where PHIE > 0.05);
- No coal intervals are identified (i.e. where $V_{COAL} = 0$).

Note that permeability cut offs were not applied, due to the roughly-estimated nature of the derived curves and because they were not available for every well.

NTG values were calculated for each stratigraphic unit in each well (and by stratigraphic unit (for all wells) and by well (for all stratigraphic units)).

4.3 AVERAGE POROSITY AND RANGE

Average porosities and ranges were calculated for each stratigraphic unit in each well. These are based on arithmetic average calculations and curve statistics of the interpreted effective porosity (PHIE) curve (section 3.4) over the intervals defined as net reservoir (Net: see NTG, section 4.2).

4.4 AVERAGE ESTIMATED PERMEABILITY AND RANGE

Given the nature of the permeability estimations, simple averages and ranges found over the stratigraphic units investigated for the wells studied are given, based on the estimated (PermEst) curve (Section 3.5) for the intervals defined as net reservoir (Net: see NTG, section 4.2).

4.5 SUMMARY OF PETROPHYSICAL RESULTS

Summary results (based on interpreted curves, Section 4.1) are given for the whole Carboniferous interval and by individual formation in each well. These are shown plotted on maps in Section 4.7. Main reported results are highlighted in bold type.

Table 1 Notes:

All depths and thicknesses are in metres.

- **Colours on the left side** of the table refer to the "standard " colours of the stratigraphic units used throughout this project;
- **Colours on the right side** of the table are used to help highlight the maximum and minimum values in each column or set of columns. In general the colours are scaled from the highest value shown as brightest green, shading to the lowest value shaded in darkest red, grading midway through yellow, set as the 50 percentile value. Columns for Gross, Net and NTG are scaled as individual columns. The three porosity columns are scaled together, as are the three permeability columns. The right-most column (COAL*h) is scaled in reverse (highest value is red, lowest value is green);
- No deviation logs were loaded for this study (they are presented in measured depth (MD) along the borehole) and formation dip is not taken into account. Therefore thickness of intervals in Table 1 is the interval along the borehole that they can be recognised. This is not necessarily their true stratigraphic thickness (depending on formation dip and borehole deviation). (Note that only wells 37/10/1 and 43/21-2 are recorded as deviated, the former being negligibly so).

[1]Note that the base of the Devonian-Carboniferous succession is not penetrated in most wells. (i.e. a small Gross value does not necessarily mean thin Devonian-Carboniferous rocks). The stratigraphic intervals for which this applies is indicated by '[nb]'(no base) in the Gross column.

[2]Section 4.2 describes the curve cut-offs used to define "Net".

[3]Net to Gross, described in Section 4.2. See also note 1.

[4]Effective porosity (PHIE). Section 3.4 describes the method of deriving the porosities curves. Average is arithmetic average. Average, Minimum and Maximum values are over the Net intervals only, see note 2. Expressed as a fraction.

[5]Estimated permeability (PermEst) Section 3.5 describes the method of deriving the permeability curves. Average is arithmetic average. Average, Minimum and Maximum values are over the Net intervals only, see note 2. Units are milidarcies (mD).

[6]Total thickness of coal in the interval. Section 3.3 describes the coal identification method.

Stratigraphic unit name	Well	Time-equivalent name for maps	Top	Base	Gross[1]	Net[2]	NTG[3]	Average PHIE[4]	PHIE Min[4]	PHIE Max[4]	Average PermEst[5]	PermEst Min[5]	PermEst Max[5]	COAL *h[6]
Grensen Formation	39/07- 1	Grensen	2852	3020	168	98	0.58	0.12	0.05	0.26				0
Millstone Grit Formation	43/21- 2	Millstone	3138	4059	922	216	0.24	0.09	0.05	0.32	0.15	0.02	64.51	3
Yoredale Formation	36/13- 1	Yoredale	1259	1373	[nb]114	49	0.43	0.19	0.05	0.28				1
Yoredale Formation	39/07- 1	Yoredale	3020	3465	445	113	0.26	0.13	0.05	0.24				2
Yoredale Formation	41/01- 1	Yoredale	728	1505	777	184	0.24	0.11	0.05	0.32	144.45	0.03	84146.34	1
Yoredale Formation	42/10a- 1	Yoredale	2552	2995	[nb]442	138	0.31	0.12	0.05	0.30	28.15	0.20	8180.76	2
Cleveland Gp 'E'	43/21- 2	Yoredale	4059	4629	570	4	0.01	0.07	0.05	0.08	0.05	0.03	0.07	0
Upper Bowland Shale	43/21- 2	Yoredale	4629	4739	110	9	0.08	0.07	0.05	0.11	0.05	0.03	0.15	0
Cleveland Gp 'D'	43/21- 2	Yoredale	4739	4973	[nb]234	16	0.07	0.07	0.05	0.14	0.07	0.03	0.37	0
Scremerston Formation	26/07- 1	Scremerston	1285	1850	565	108	0.19	0.13	0.05	0.32	261.42	0.38	42410.28	20
Scremerston Formation	38/18- 1	Scremerston	2358	2455	97	47	0.49	0.15	0.05	0.25				8
Scremerston Formation	39/07- 1	Scremerston	3465	3605	[nb]140	27	0.19	0.14	0.05	0.30				18
Scremerston Formation	41/01- 1	Scremerston	1505	1886	380	20	0.05	0.07	0.05	0.24	16.535	0.03	810.73	1
Scremerston Formation	42/15A- 2	Scremerston	2381	2584	203	41	0.20	0.09	0.05	0.15	0.144	0.04	0.62	0
Scremerston Formation	44/02- 1	Scremerston	2778	2865	87	21	0.24	0.12	0.05	0.36				2
Fell Sandstone Formation	26/07- 1	Fell	1850	2365	515	269	0.52	0.11	0.05	0.20	15.64	0.38	283.03	0
Fell Sandstone Formation	41/01- 1	Fell	1886	2014	128	43	0.34	0.06	0.05	0.20	0.373	0.03	86.95	0
Fell Sandstone Formation	42/15A- 2	Fell	2584	2642	[nb]58	44	0.77	0.10	0.05	0.14	0.138	0.04	0.37	0
Fell Sandstone Formation	44/02- 1	Fell	2865	3200	335	274	0.82	0.13	0.05	0.19				0
Cementstone Formation	41/01- 1	Cementstone	2014	2150	[nb]136	7	0.05	0.06	0.05	0.08	0.049	0.03	0.12	0
Cementstone Formation	44/02- 1	Cementstone	3200	3383	183	27	0.15	0.10	0.05	0.18				0
Tayport Formation	37/10- 1	Devonian	1823	1959	136	96	0.70	0.13	0.05	0.26				0
Tayport Formation	44/02- 1	Devonian	3383	3499	116	27	0.23	0.10	0.05	0.15				0
Buchan Formation	30/23a- 3	Devonian	2973	3119	[nb]146	82	0.56	0.08	0.05	0.15				0
Buchan Formation	37/10- 1	Devonian	1959	2471	[nb]512	374	0.73	0.12	0.05	0.29				0
Buchan Formation	37/12- 1	Devonian	2354	2645	291	1	0.00	0.06	0.05	0.08				0
Kyle limestone	37/12- 1	Devonian	2645	2826	[nb]181	0	0.00	0.11	0.11	0.11				0

Table 1 Results of petrophysical calculations listed by formation for each well (Table notes and units are listed on previous page)

4.6 SUMMARY OF CORE POROSITY-PERMEABILITY DATA

Porosity and permeability data, measured from core samples is available as an Excel spreadsheet, contained within the digitised output dataset. Note that these measured values are against depth, and not by formation. However, for the subset of those wells that petrophysical interpretation was made, the core data has been assessed by formation. This is summarised in Table 2 and shown graphically in Figure 2, for all measurement data points (Note: the petrophysical data in Table 1 are displayed for the Net intervals only).

						Core porosity (fraction)			Permeability (Kair, mD)		
Well	**Formation**	**Number of points**	**Core type**	**Depth of top core measurement (m)**	**Depth of bottom core measurement**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**
43/21- 2	Millstone Grit	8	*Rotary side wall core*	3317.0	4057.0	0.09	0.04	0.13	0.07	0.01	0.13
	Cleveland Group E	1		4120.0	4120.0	0.02	0.02	0.02	0.01	0.01	0.01
	Upper Bowland Shale	8		4664.5	4723.0	0.02	0.01	0.02	0.01	0	0.01
	Cleveland Group D	1		4773.5	4773.5	0.01	0.01	0.01	0	0	0
41/01- 1	Yoredale	30	*Conventional core*	906.2	933.0	0.1	0.04	0.14	1.51	0.02	7.09
42/10a- 1	Yoredale	38		2566.3	2992.8	0.13	0.01	0.2	39.2	0.1	795
26/07- 1	Scremerston	65		1481.8	1557.5	0.18	0.04	0.26	295	0.12	1460
42/15a- 2	Scremerston	281		2380.0	2488.0	0.06	0	0.18	0.66	0	16
41/01- 1	Fell	37		1953.5	1979.7	0.04	0.01	0.07	0.16	0	4.11
37/12- 1	Buchan	5		2533.5	2545.7	0.06	0.05	0.06	0.02	0	0.1
	Kyle	6		2787.7	2802.9	0.03	0.03	0.05	0.01	0	0.02

Table 2 Summary of digitised core porosity-permeability measurement data by formation, for the wells studied petrophysically.

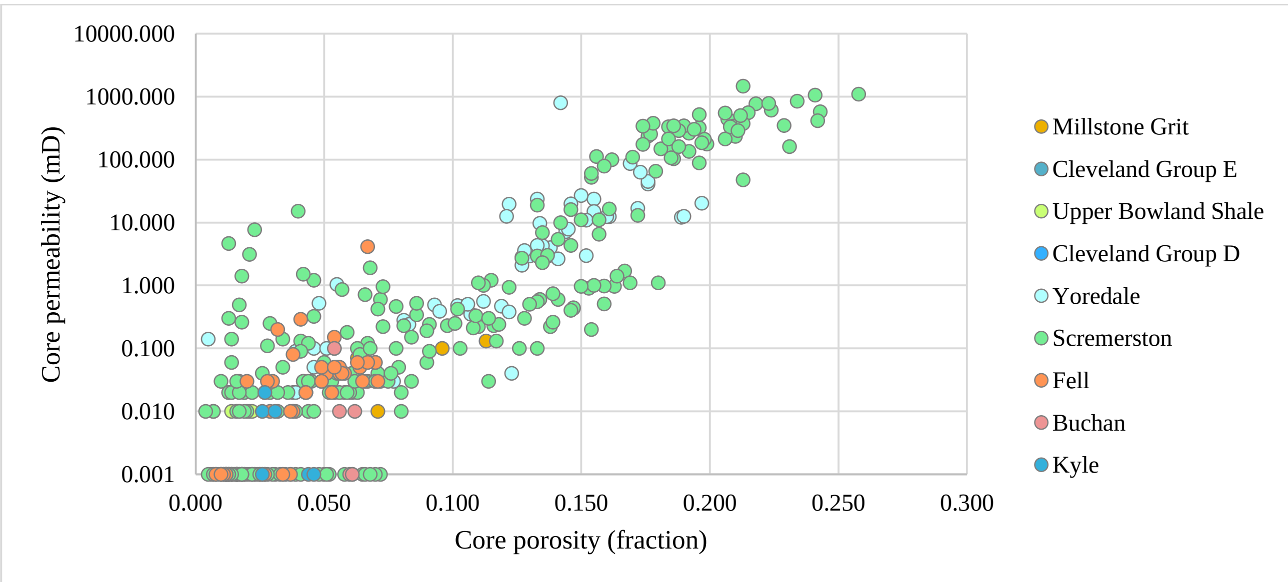
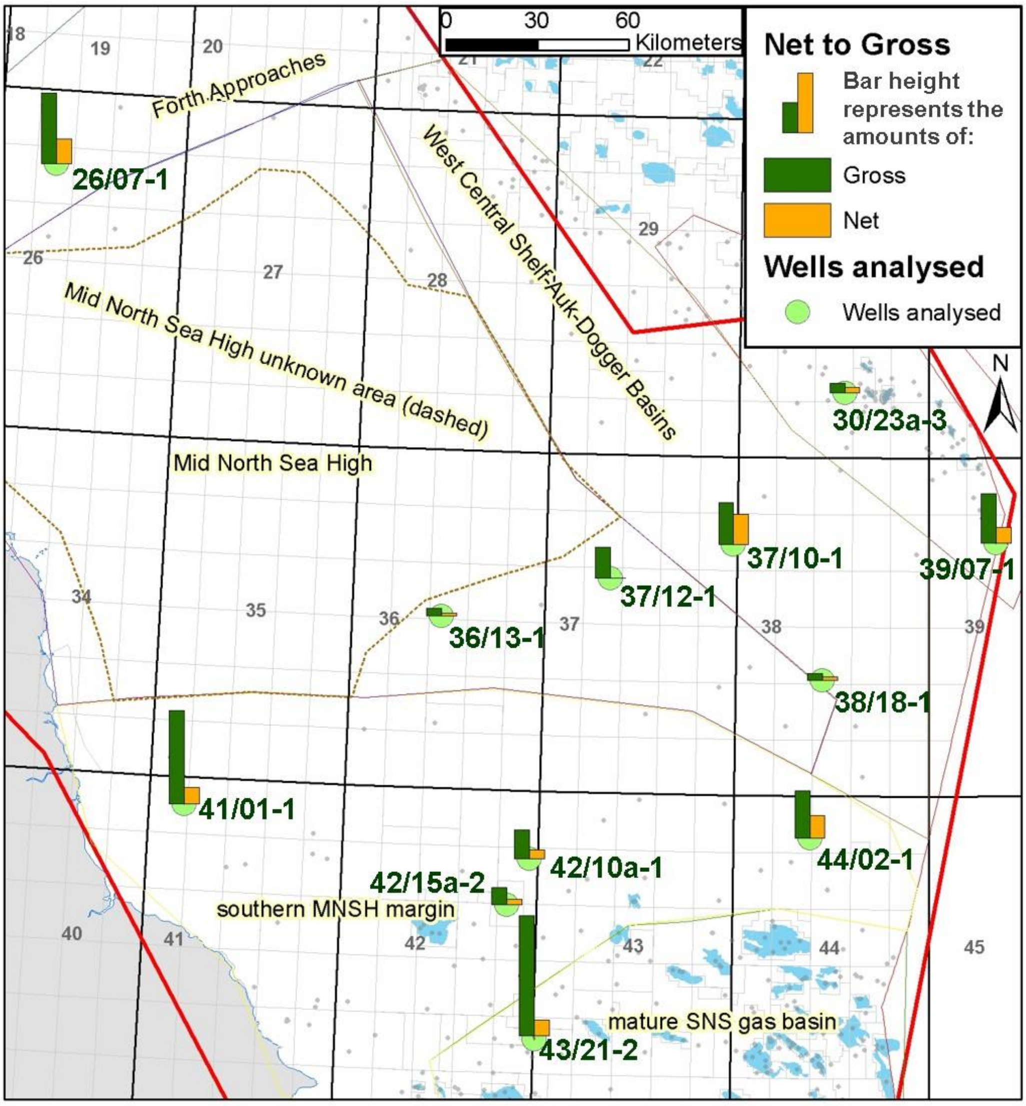


Figure 2 Cross plot of core porosity and permeability measurement data by formation for the wells examined.

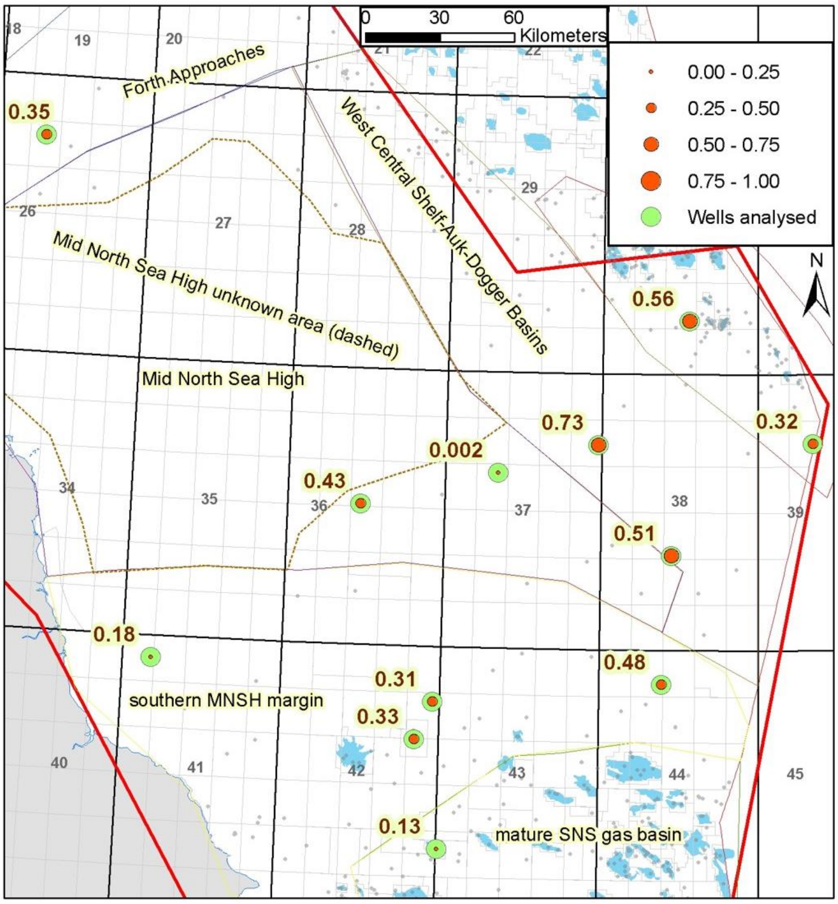
4.7 MAPS SUMMARISING PETROPHYSICAL RESULT (IN TABLE 1)

4.7.1 Indication of Gross and Net thickness for whole Devonian-Carboniferous interval for each well

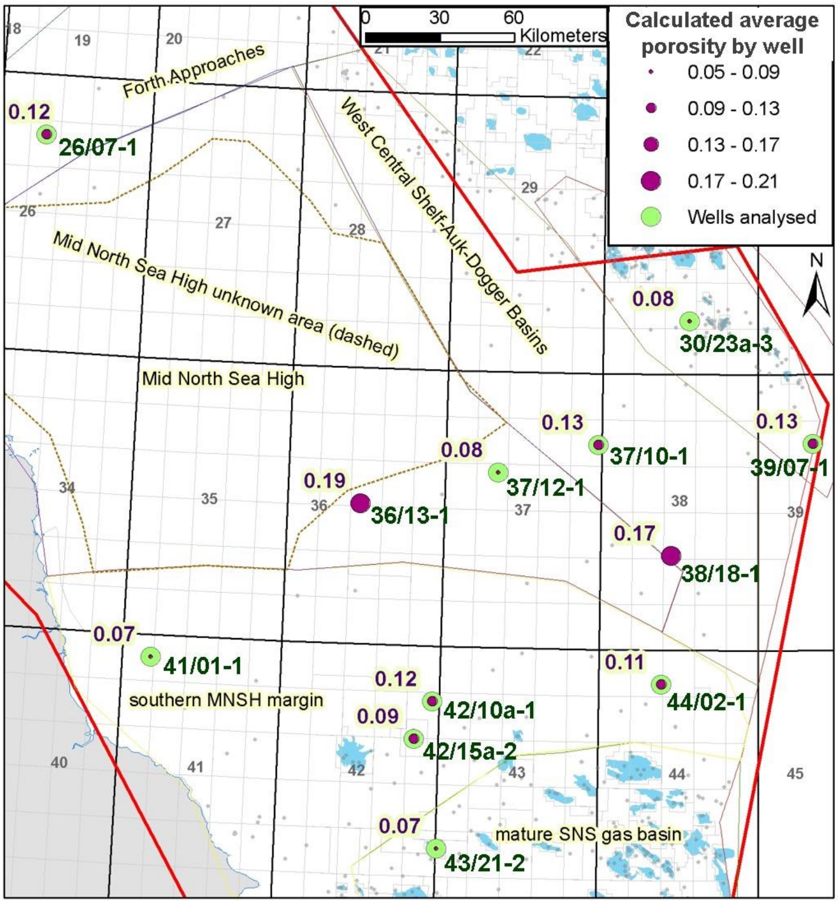
Height of bars indicate the relative thickness of Carboniferous - Devonian rocks in each well (see Table 1, Note 1 about measured depth thickness versus true stratigraphic thickness, and note 2 about how "Net" was defined).



4.7.2 Calculated Net to Gross for whole Devonian-Carboniferous by well



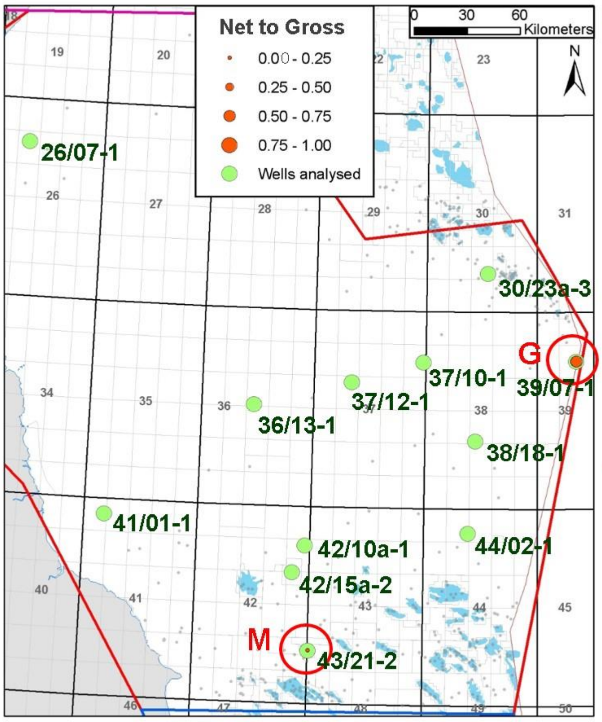
4.7.3 Calculated average porosities for whole Devonian-Carboniferous by well

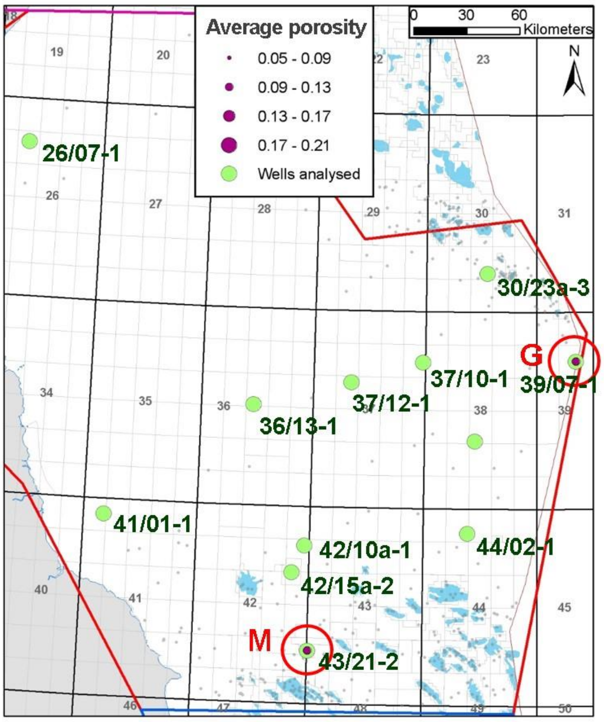


4.7.4 Grensen & Millstone Grit properties

“Time equivalent” interval referred to is shown on the stratigraphic column Appendix 5.

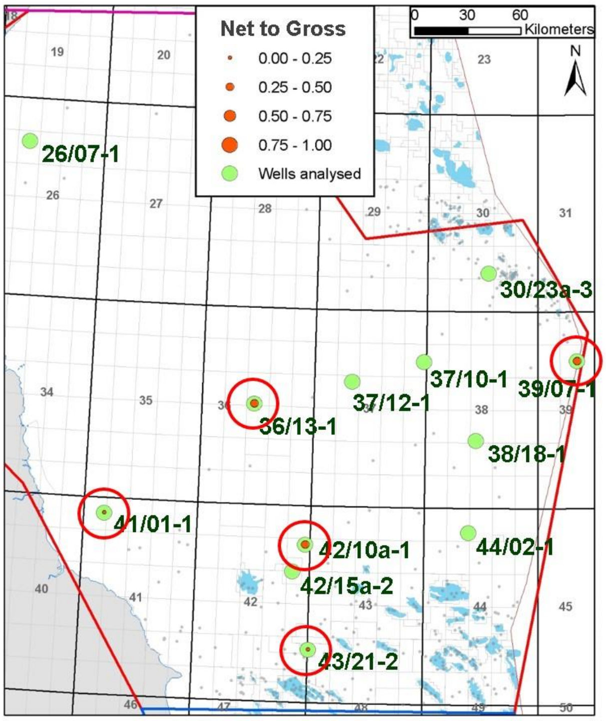
M= Millstone Grit, G = Grensen

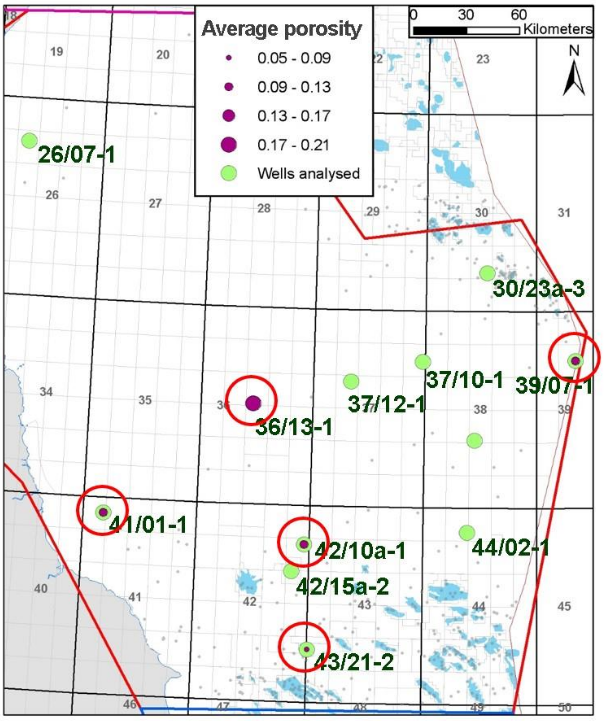




4.7.5 Yoredale properties

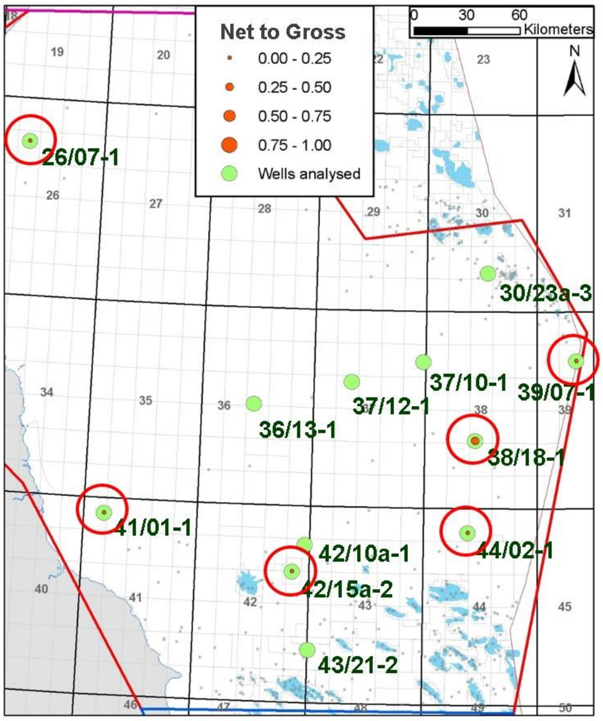
“Time equivalent” interval referred to is shown on the stratigraphic column Appendix 5.

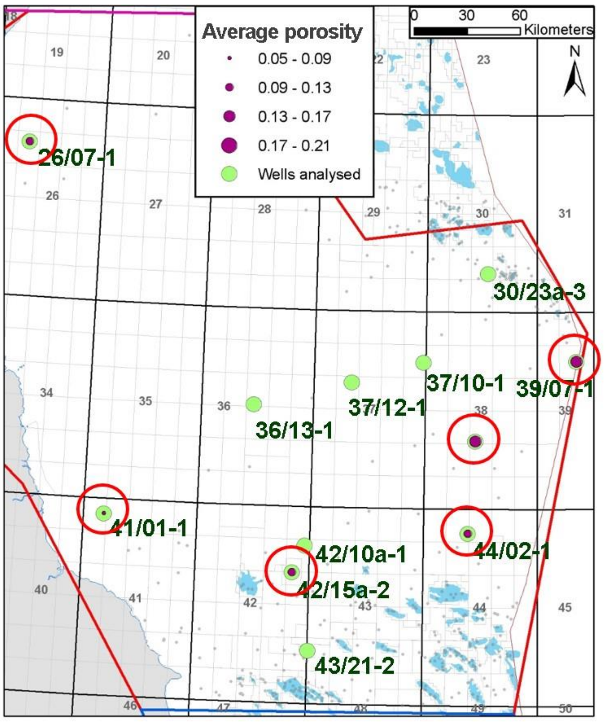




4.7.6 Scremerston properties

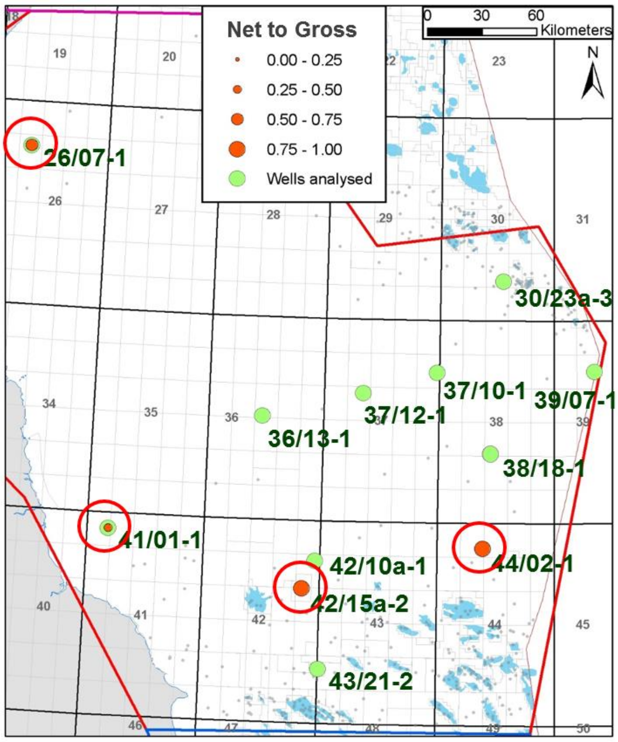
“Time equivalent” interval referred to is shown on the stratigraphic column Appendix 5.

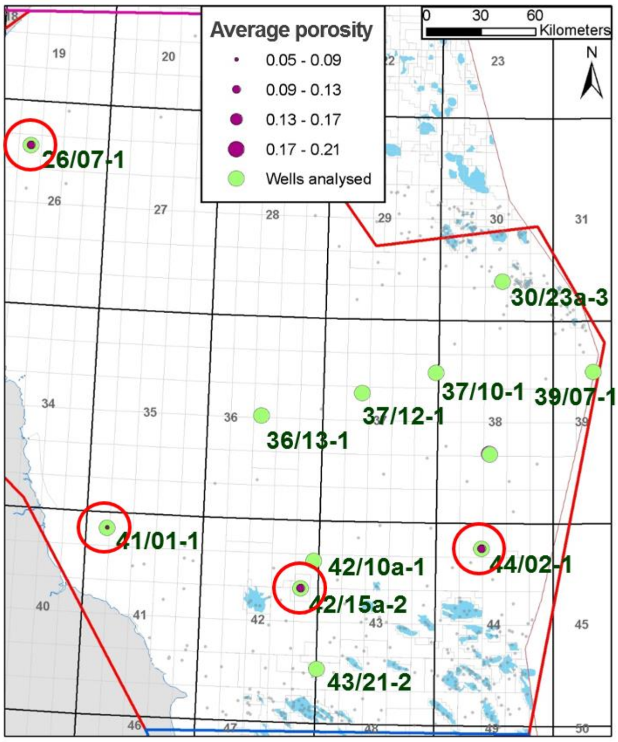




4.7.7 Fell properties

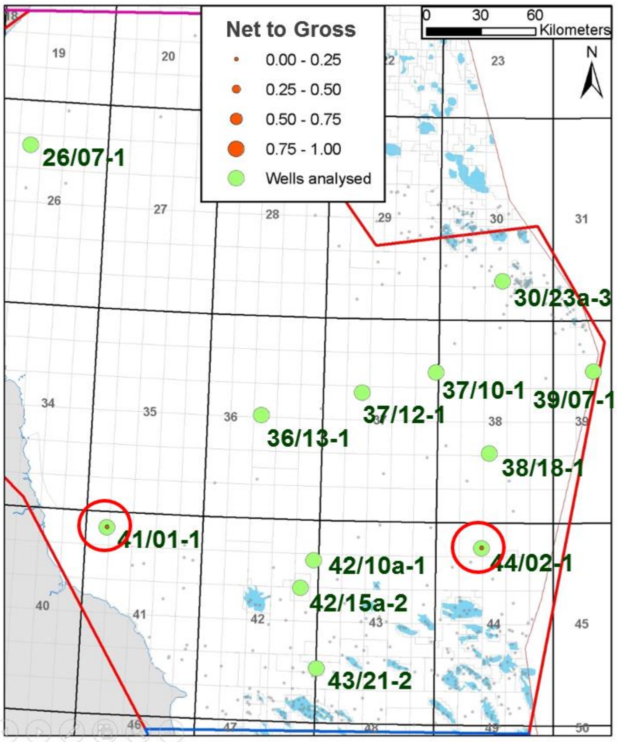
“Time equivalent” interval referred to is shown on the stratigraphic column Appendix 5.

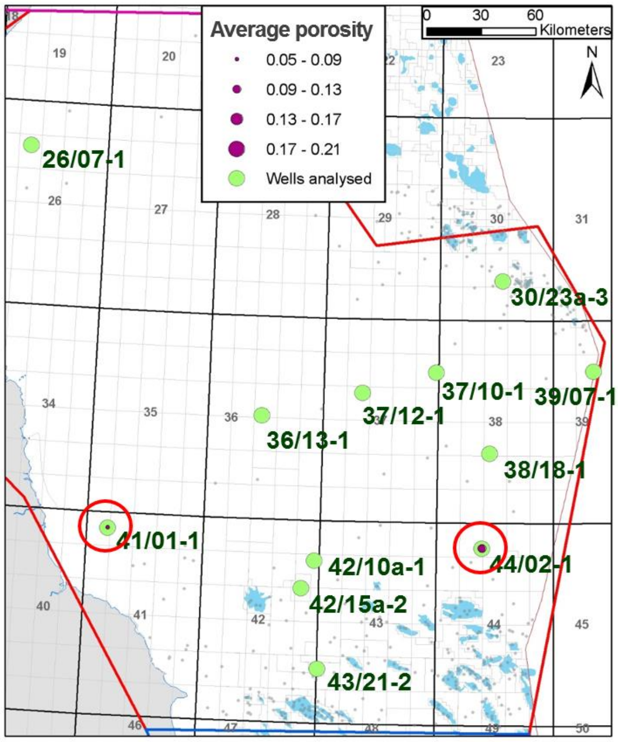




4.7.8 Cementstone properties

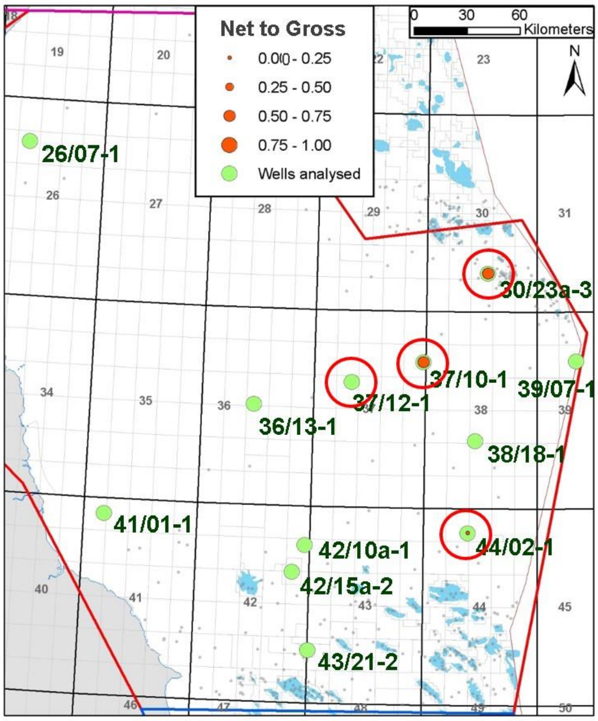
"Time equivalent" interval referred to is shown on the stratigraphic column Appendix 5.

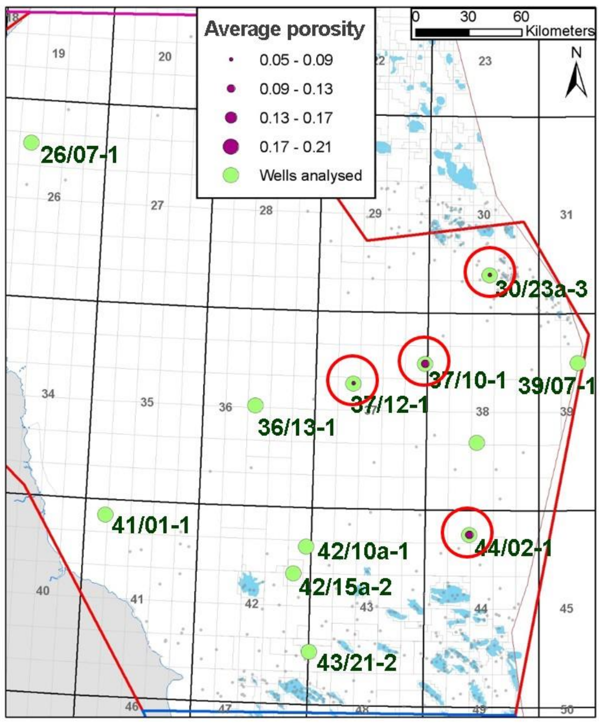




4.7.9 Devonian properties

"Time equivalent" interval referred to is shown on the stratigraphic column Appendix 5.





5 Conclusions

"Quick-look" volume of clay (V_{CL}), coal identification (V_{COAL}) and effective and total porosity curves were interpreted from geophysical log responses in each of 12 wells across the Central North Sea (Quadrants 25-44). In addition a permeability estimation curve was derived for those wells with suitable core porosity and permeability measurement data. These curves were used to calculate "quick-look" net to gross (NTG) values and average porosities for the net intervals for each formation in each well. Syntheses of the petrophysical results by formation and by well are shown in Tables 3 & 4 respectively. *Given this nature of the study, and the time & resources available for it, a full rigorous petrophysical interpretation of each well examined was not within scope. This is explained in the report and should be borne in mind when examining the outputs and results.*

The highest average porosities were found in the Yoredale Formation (19%), although it has a relatively low average NTG (0.27). Its highest average permeability estimate was 45.28 mD in one well. The Scremerston Formation had much higher average permeabilities in 1 well (up to 785 mD). Porosities were variable, but up to 15% in another well, and net to gross was generally poorer than the Yoredale Formation (Scremerston average NTG 0.18). Highest average NTG values were found in the Fell Sandstone Formation (NTG 0.61), although average porosities and average estimated permeabilities were generally smaller than for those formations previously mentioned (averages up to 13% and 42 mD respectively).

There may also be potential reservoir in the Devonian Tayport & Buchan formations, as they have moderate NTG (0.49 and 0.48 respectively) and moderate average porosities (13% and 12% respectively). However, from the data examined, little is known about their permeabilities. One well with core data over the Buchan Formation suggests that it may be very low (37/12-1), but another well (with no core data, 37/10-1) has a markedly lower resistivity signature over the Net intervals, compared to 37/12-1, which could be indicative of less cemented, more permeable reservoir.

Over these potential formations of interest, log responses suggest that clean "good" reservoir intervals are heterogeneously interbedded with non-reservoir intervals. Therefore individual reservoir units may be quite thin. Of the wells examined, the Fell Sandstone Formation appears to consistently have the most continuous reservoir intervals (i.e. thickest sand bodies, particularly in well 44/02-1), although the Buchan Formation in well 37/10-1 also appears to have relatively thick reservoir intervals compared other wells and formations.

Given the relatively few wells interpreted and the distances between them, it has not been possible to discern any regional trends within the formations (data shown geographically in Section 4.7, some of which is tabulated below, extracted from Tables 1 & 2).

	Log curve (& core) derived (Table 1)			Core measured (Table 2)		
Formation	**NTG**	**Highest Av PHI**	**Highest Av PermEst**	**Highest Av core porosity**	**Highest Av core perm**	**Concluding comments**
Grensen Formation	0.58	0.12		-	-	
Millstone Grit Formation	0.24	0.09	0.15	0.09	0.07	
Yoredale Formation	0.27	0.19	45.28			Good porosity, although quite low NTG. Slightly better permeability than Fell (in 2 wells)
Cleveland Gp 'E'	0.01	0.07	0.05	0.02	0.01	
Upper Bowland Shale	0.08	0.07	0.05	0.02	0.01	
Cleveland Gp 'D'	0.07	0.07	0.07	0.01	0.00	
Scremerston Formation	0.18	0.15	785.52	0.18	295.00	Best permeability (in 1 well, poor in 2) Low NTG, but moderate porosity
Fell Sandstone Formation	0.61	0.13	42.69	0.04	0.16	Best NTG, but porosity and permeability lower than Yoredale & Scremerston (data from 3 wells)
Cementstone Formation	0.11	0.10	0.05	-	-	
Tayport Formation	0.49	0.13		-	-	Moderate NTG and porosity, no permeability data
Buchan Formation	0.48	0.12		0.06	0.02	Moderate NTG and porosity, Core data from 1 well, suggests that permeability may be very low
Kyle limestone	0.00	0.11		0.03	0.01	

Table 3 Synthesis of petrophysical results (data in Table 1& Table 2) by formation

Well	Gross	Net	N/G	Average PHIE
26/07- 1	1080	377	0.349	0.118
30/23a- 3	146	82	0.557	0.082
36/13- 1	114	49	0.430	0.194
37/10- 1	648	470	0.726	0.128
37/12- 1	472	1	0.002	0.085
38/18- 1	97	47	0.487	0.147
39/07- 1	753	237	0.315	0.127
41/01- 1	1421	255	0.179	0.074
42/10a- 1	442	138	0.313	0.115
42/15A- 2	261	85	0.327	0.093
43/21- 2	1835	246	0.134	0.072
44/02- 1	721	349	0.484	0.112

Table 4 Synthesis of petrophysical results (data in Table 1) by well

Appendix 1 Log plots

Log plots from each well interpreted are presented. These are all shown at the same scale (1:5000) to allow some comparison of the thickness of the intervals and to summarise the data available for each well. They are not intended as a definitive output of the interpretation, the digital data is available as a project output for this purpose. Wells are shown in Quadrant block number order. Log plot tracks are explained from left to right here:

Track 1 (far left): Stratigraphic intervals, (reinterpreted for this project).

Track 2 (1 in from left): Depth in metres, measured depth

Track 3 (2 in from left): core intervals (extracted from BGS core database)

Tracks 1 to 3 are repeated in the reverse order at the far right of the plot.

Track 4: Input curves: Gamma ray (green, e.g. GR) and density correction curve (grey, e.g. DRHO). Red shading indicates where the density correction curve is out of tolerance. This can adversely affect porosity derived from the density curve and so often the sonic or other curves may be used to derive porosity instead (Table 8, Appendix 4 summarises the tolerances and quality of data in each well)

Track 5: Input curves: Resistivity curves (red, e.g. ILD, LLD etc)

Track 6: Input curves: Porosity curves, sonic (pink, e.g. DT), density (red, e.g. RHOB) and neutron (green, e.g. NPHI)

Track 7: Interpreted curves: Clay volume (V_{CL}) and coal indicator (V_{COAL}). Variable brown shading helps to highlight cleaner intervals in pale colours and clay-rich intervals in dark brown. Coal intervals are shown in black, as stripes across the full width of the track.

Track 8: Interpreted curves: Effective porosity (PHIE), Total porosity (PHIT). Also includes any discrete core porosity data from core reports, where available.

Track 9: Interpreted curves: Permeability (PermEst), estimated where sufficient core poro-perm data exists. Also includes discrete permeability data from core reports, where available.

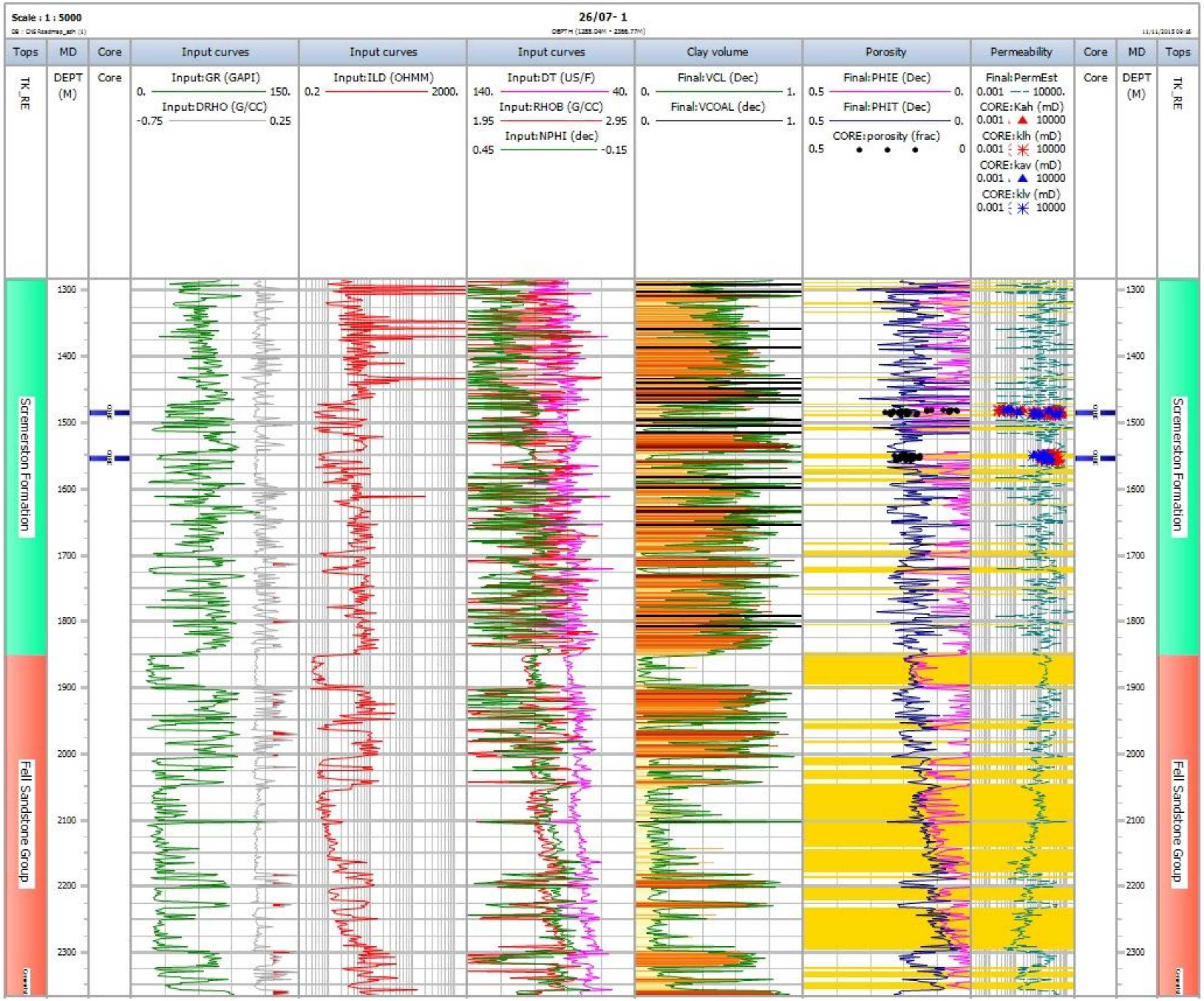
Yellow shading across the porosity – permeability tracks (8&9) indicates the reservoir intervals (but not the Net). It shows where $V_{CL}<0.5$ and $V_{COAL}=0$. Note that intervals with less than 5% porosity are still included in this shaded area, unlike the definition of Net, used in the calculations (Section 4.2).

Notes for specific wells:

For wells **37/10-1** and **44/02-1**, a cored interval is shown, but no core sample porosity or permeability measurement data is available for it.

For well **43/21-2** core poroperm data is shown, but no cored interval. This is because the measurements come from rotary sidewall cores.

In well **41/01-1** the presence of the Whin Sill is shown by purple hatched shading in track 8. It is removed from reservoir intervals shown by the yellow shading. It does not form part of the Net interval (as its porosity is too low in any case).



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Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
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Input:DRHO (G/CC)
-0.75 0.25
Input:ILD (OHMM)
0.2 2000.
Input:DT (US/F)
140. 40.
Input:RHOB (G/CC)
1.95 2.95
Input:NPHI (dec)
0.45 -0.15
Final:VCL (Dec)
0. 1.
Final:VCOAL (dec)
0. 1.
Final:PHIE (Dec)
0.5 0.
Final:PHIT (Dec)
0.5 0.
CORE:porosity (frac)
0.5 0
Final:PermEst
0.001 10000.
CORE:Kah (mD)
0.001 10000
CORE:klh (mD)
0.001 10000
CORE:kav (mD)
0.001 10000
CORE:klv (mD)
0.001 10000
Core
DEPT (M)
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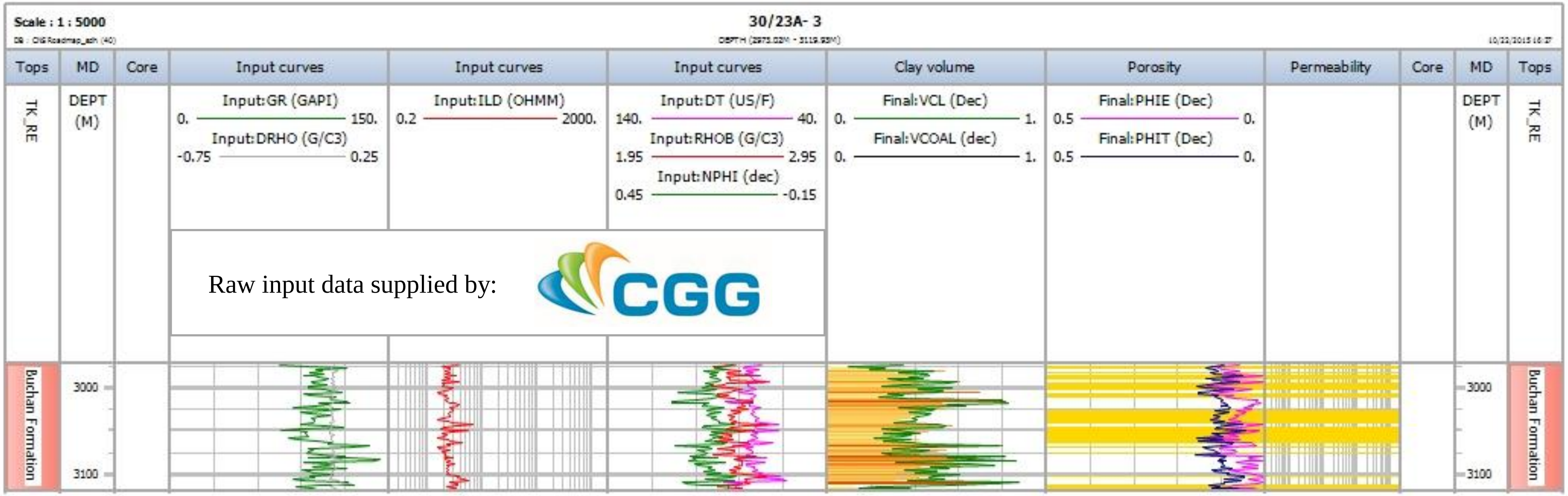
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
Scremerston Formation
Fell Sandstone Group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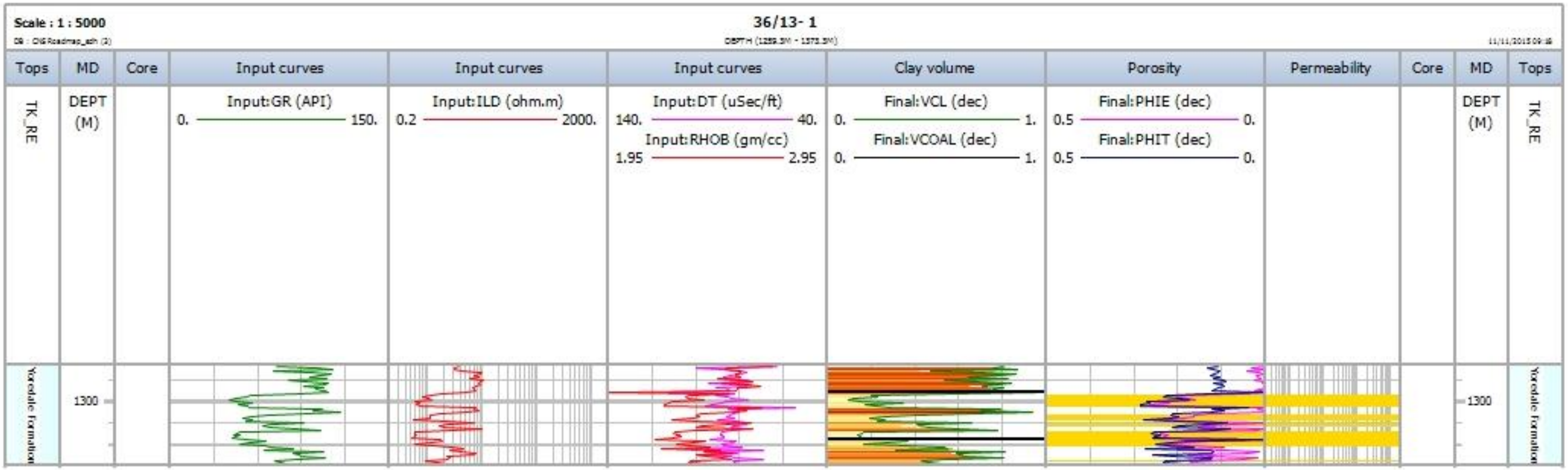
30/23A- 3
Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Input:GR (GAPI)
0. 150.
Input:DRHO (G/C3)
-0.75 0.25
Input:ILD (OHMM)
0.2 2000.
Input:DT (US/F)
140. 40.
Input:RHOB (G/C3)
1.95 2.95
Input:NPHI (dec)
0.45 -0.15
Final:VCL (Dec)
0. 1.
Final:VCOAL (dec)
0. 1.
Final:PHIE (Dec)
0.5 0.
Final:PHIT (Dec)
0.5 0.
Raw input data supplied by:
Buchan Formation
3000
3100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36/13- 1
Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
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Input:ILD (ohm.m)
0.2 2000.
Input:DT (uSec/ft)
140. 40.
Input:RHOB (gm/cc)
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Final:VCL (dec)
0. 1.
Final:VCOAL (dec)
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Final:PHIE (dec)
0.5 0.
Final:PHIT (dec)
0.5 0.
1300


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10/23/2015 14:46
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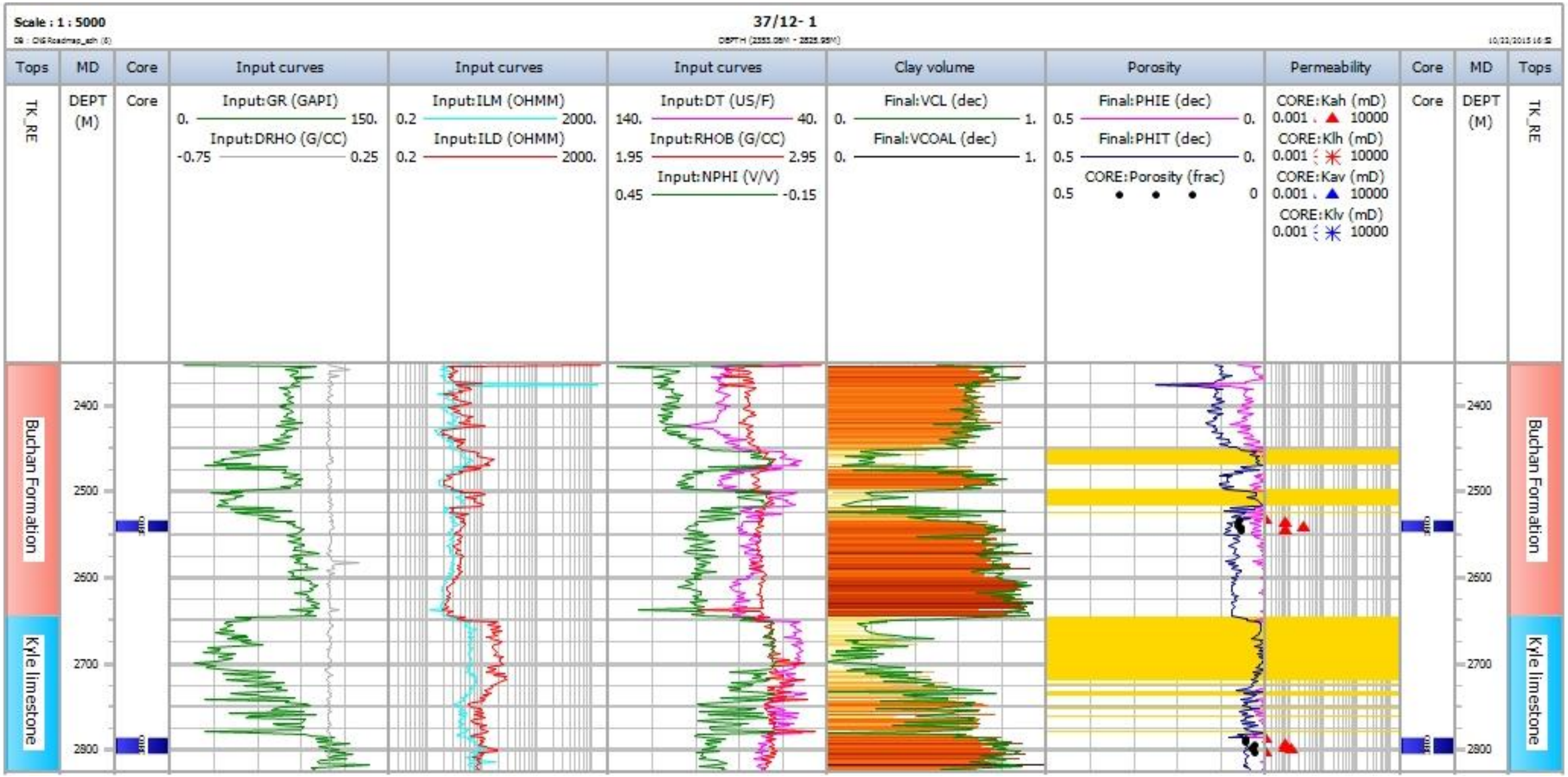
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPTH (M)
Core
Input:GR (GAPI)
Input:DRHO (gm/cc)
Input:ILD (ohm.m)
Input:DT (US/F)
Input:RHOB (gm/cc)
Input:NPHI (dec)
Final:VCL (dec)
Final:VCOAL (Dec)
Final:PHIE (dec)
Final:PHIT (dec)
Tayport Formation
Buchan Formation
1900
2000
2100
2200
2300
2400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Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Core
Input:GR (GAPI)
0. 150.
Input:DRHO (G/CC)
-0.75 0.25
Input:ILM (OHMM)
0.2 2000.
Input:ILD (OHMM)
0.2 2000.
Input:DT (US/F)
140. 40.
Input:RHOB (G/CC)
1.95 2.95
Input:NPHI (V/V)
0.45 -0.15
Final:VCL (dec)
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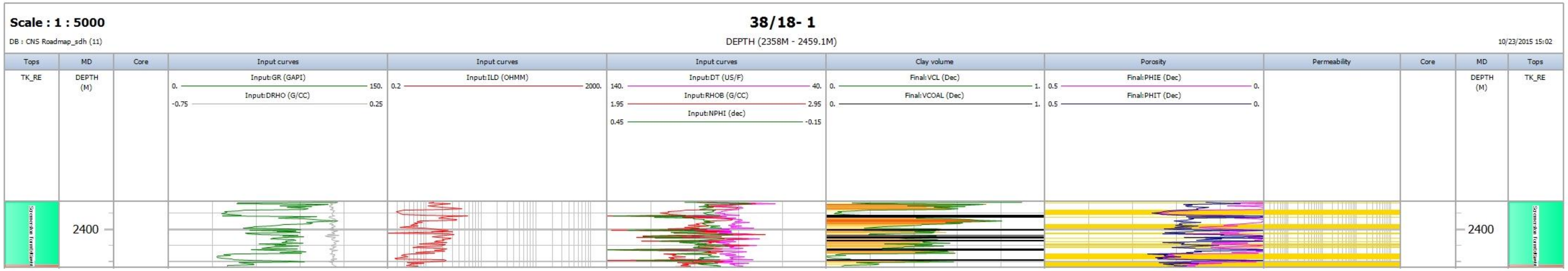
Final:VCOAL (dec)
0. 1.
Final:PHIE (dec)
0.5 0.
Final:PHIT (dec)
0.5 0.
CORE:Porosity (frac)
0.5 0
CORE:Kah (mD)
0.001 10000
CORE:Klh (mD)
0.001 10000
CORE:Kav (mD)
0.001 10000
CORE:Klv (mD)
0.001 10000
Core
DEPT (M)
TK_RE
2400
2500
2600
2700
2800
Buchan Formation
Kyle limestone



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Input curves
Input curves
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Porosity
Permeability
Core
MD
Tops
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Input:DRHO (G/CC)
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DEPTH (M)
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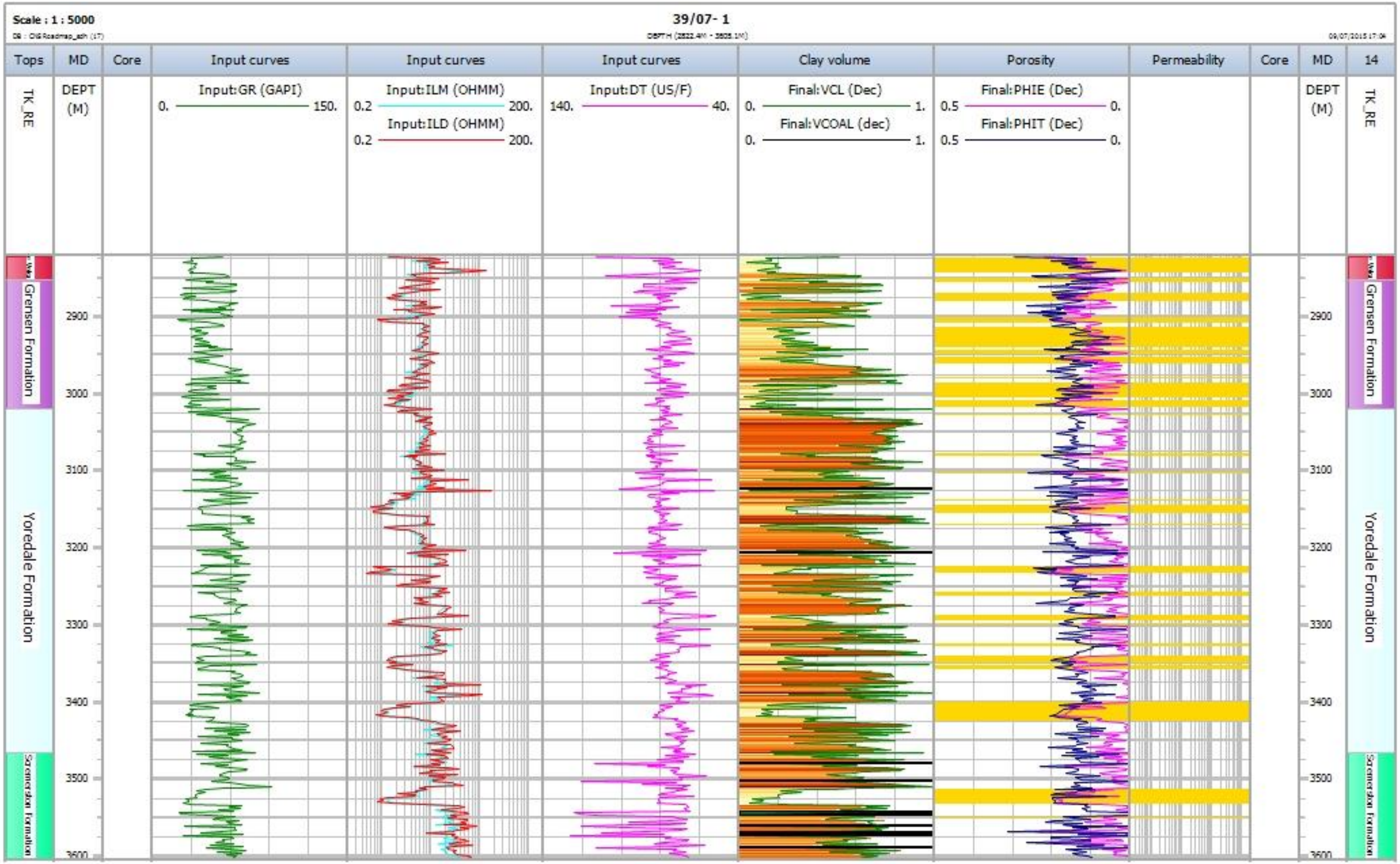
2400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Input curves
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Clay volume
Porosity
Permeability
Core
MD
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200.
Input:ILD (OHMM)
0.2
200.
Input:DT (US/F)
140.
40.
Final:VCL (Dec)
0.
1.
Final:VCOAL (dec)
0.
1.
Final:PHIE (Dec)
0.5
0.
Final:PHIT (Dec)
0.5
0.
DEPT (M)
TK_RE
Grensen Formation
Yoredale Formation
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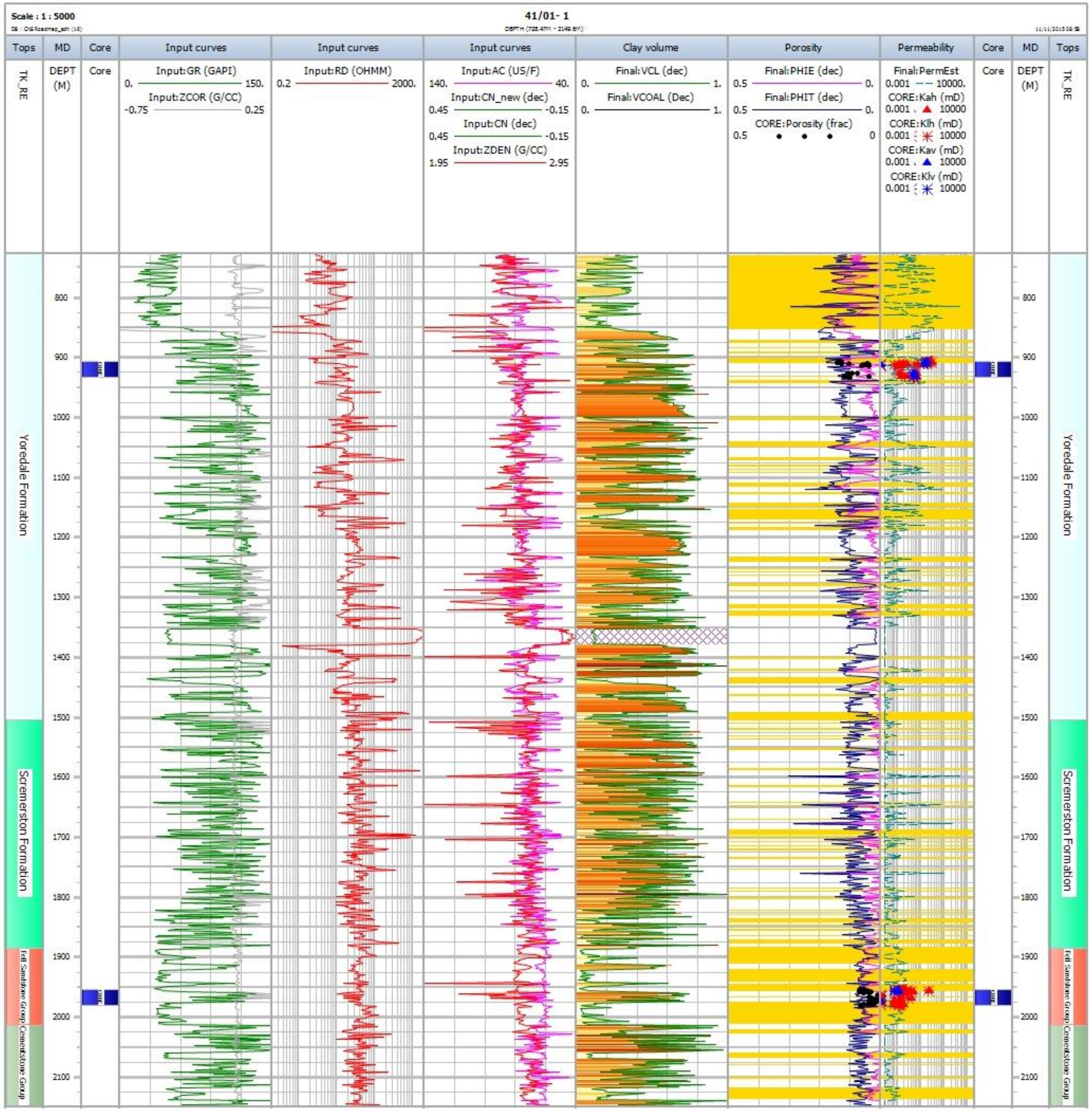
3000
3100
3200
3300
3400
3500
3600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41/01- 1
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MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Core
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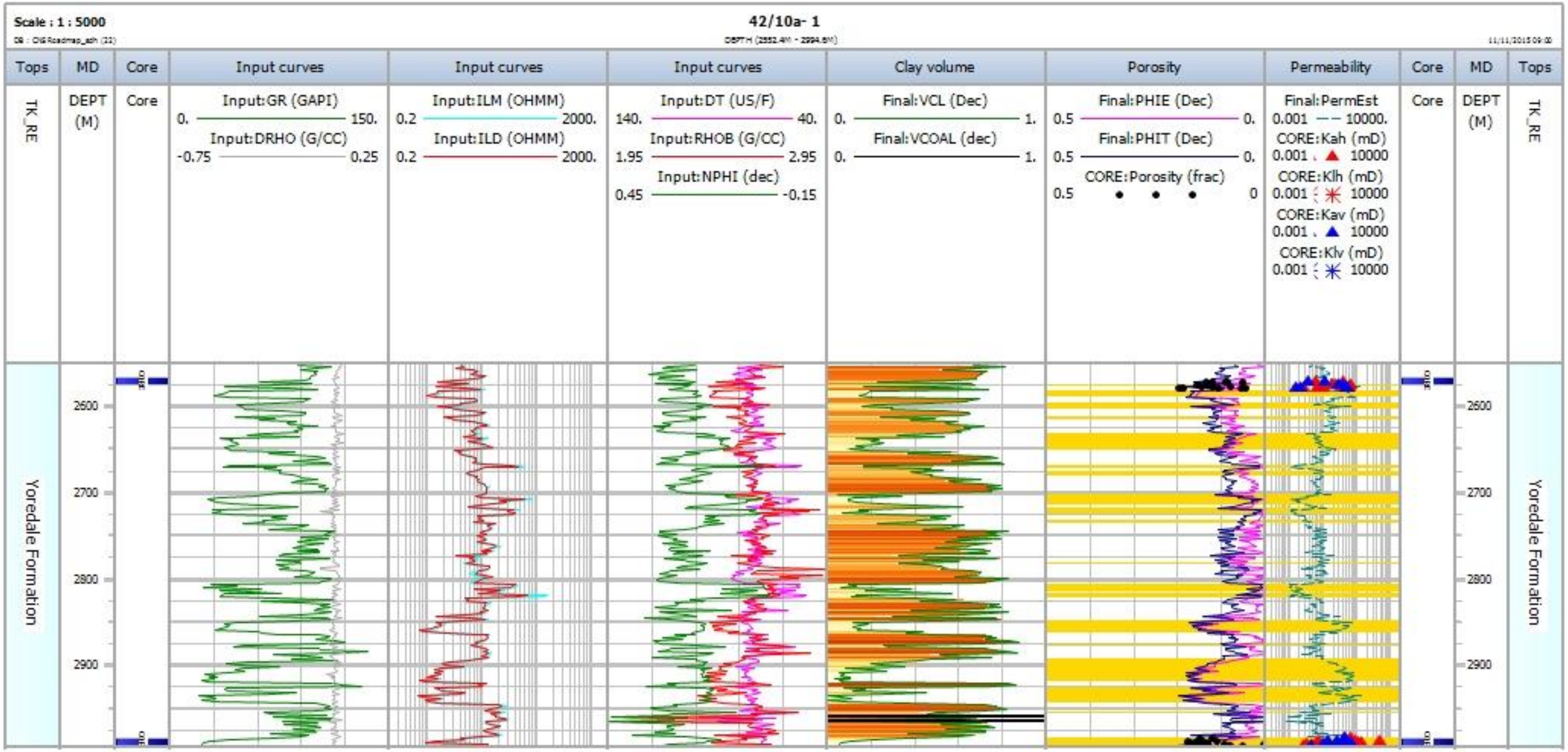
Input:ZCOR (G/CC)
-0.75 0.25
Input:RD (OHMM)
0.2 2000.
Input:AC (US/F)
140. 40.
Input:CN_new (dec)
0.45 -0.15
Input:CN (dec)
0.45 -0.15
Input:ZDEN (G/CC)
1.95 2.95
Final:VCL (dec)
0. 1.
Final:VCOAL (Dec)
0. 1.
Final:PHIE (dec)
0.5 0.
Final:PHIT (dec)
0.5 0.
CORE:Porosity (frac)
0.5 0
Final:PermEst
0.001 10000.
CORE:Kah (mD)
0.001 10000
CORE:Klh (mD)
0.001 10000
CORE:Kav (mD)
0.001 10000
CORE:Klv (mD)
0.001 10000
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Yoredale Formation
Scremerston Formation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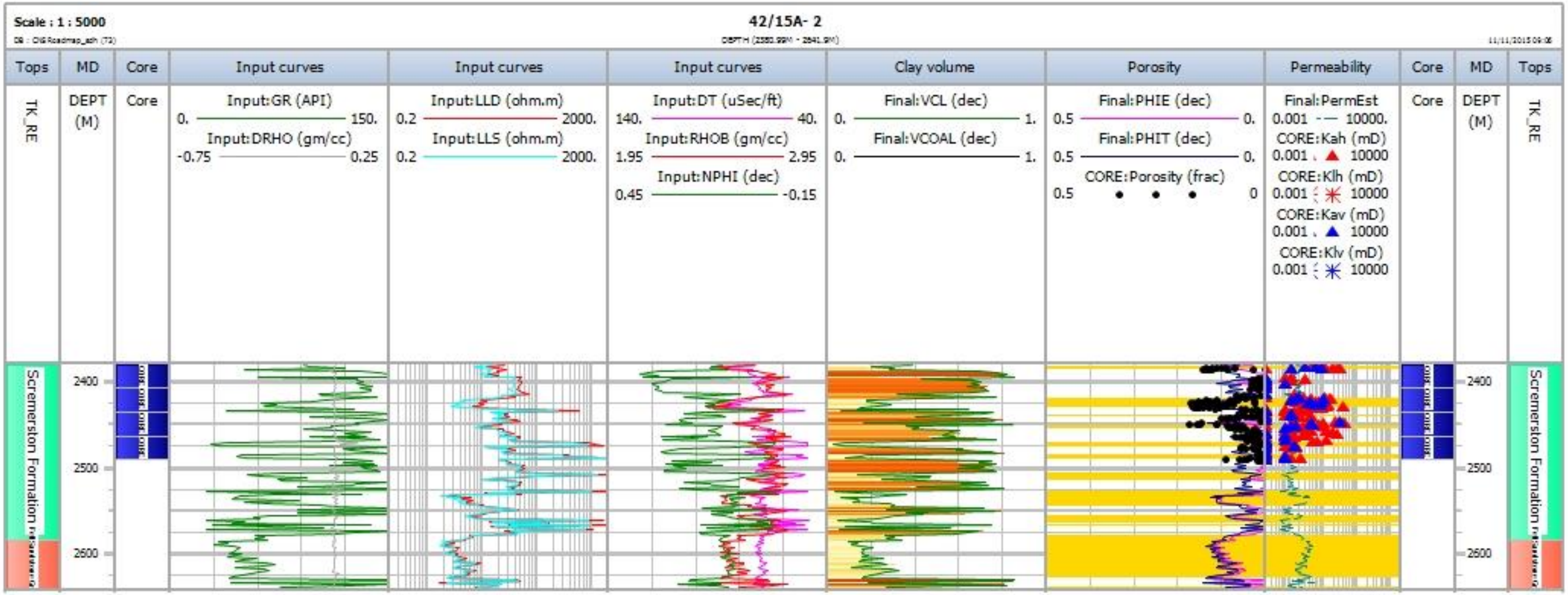
42/10a- 1
Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Core
Input:GR (GAPI)
0. 150.
Input:DRHO (G/CC)
-0.75 0.25
Input:ILM (OHMM)
0.2 2000.
Input:ILD (OHMM)
0.2 2000.
Input:DT (US/F)
140. 40.
Input:RHOB (G/CC)
1.95 2.95
Input:NPHI (dec)
0.45 -0.15
Final:VCL (Dec)
0. 1.
Final:VCOAL (dec)
0. 1.
Final:PHIE (Dec)
0.5 0.
Final:PHIT (Dec)
0.5 0.
CORE:Porosity (frac)
0.5 0
Final:PermEst
0.001 10000.
CORE:Kah (mD)
0.001 10000
CORE:Klh (mD)
0.001 10000
CORE:Kav (mD)
0.001 10000
CORE:Klv (mD)
0.001 10000
Core
DEPT (M)
TK_RE
Yoredale Formation
2600
2700
2800
2900
Yoredale Formation



Scale : 1 : 5000
42/15A- 2
Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Input:GR (API)
0. 150.
Input:DRHO (gm/cc)
-0.75 0.25
Input:LLD (ohm.m)
0.2 2000.
Input:LLS (ohm.m)
0.2 2000.
Input:DT (uSec/ft)
140. 40.
Input:RHOB (gm/cc)
1.95 2.95
Input:NPHI (dec)
0.45 -0.15
Final:VCL (dec)
0. 1.
Final:VCOAL (dec)
0. 1.
Final:PHIE (dec)
0.5 0.
Final:PHIT (dec)
0.5 0.
CORE:Porosity (frac)
0.5 0
Final:PermEst
0.001 10000.
CORE:Kah (mD)
0.001 10000
CORE:Klh (mD)
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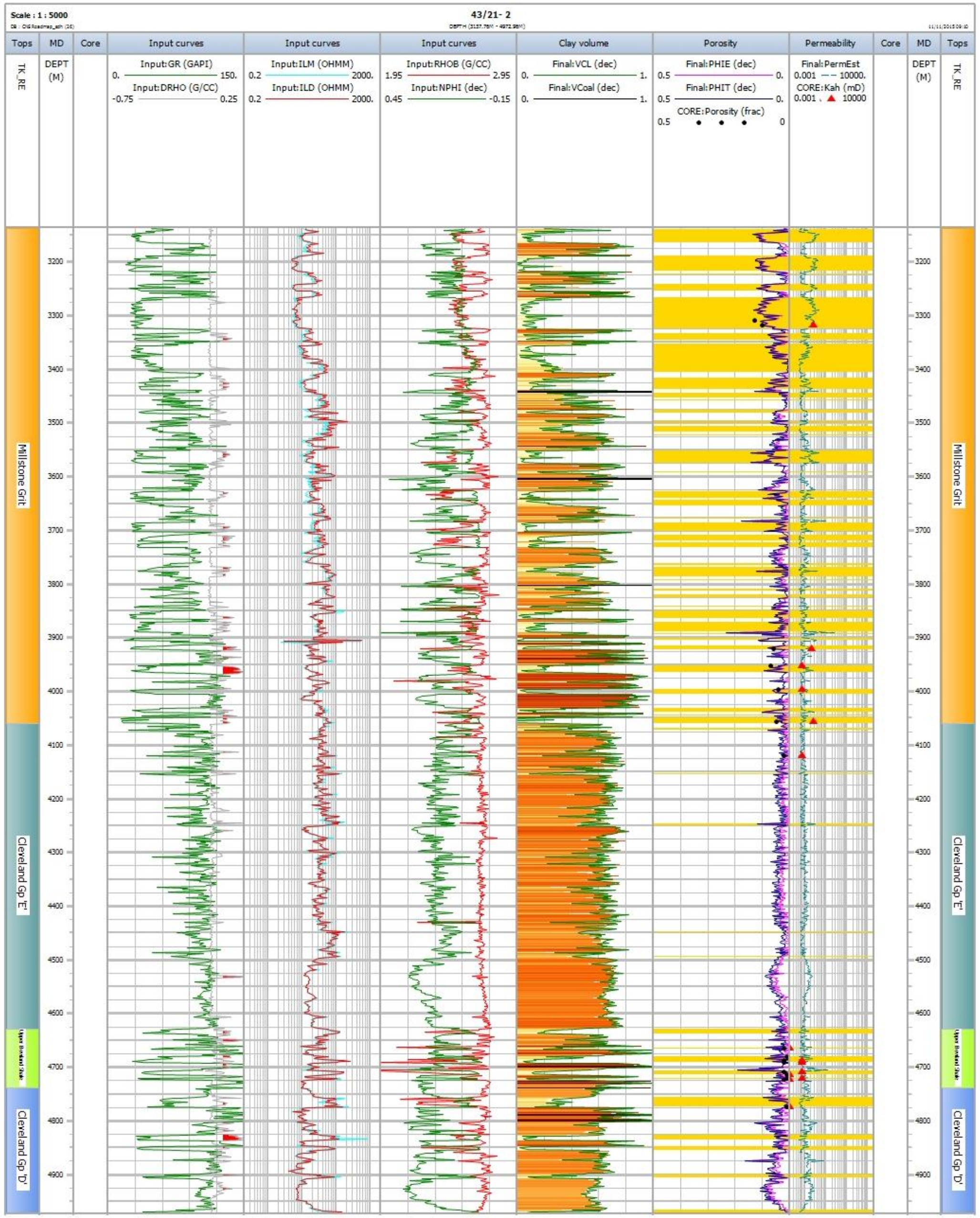
Scremerston Formation
2400
2500
2600



Scale : 1 : 5000
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Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Input:GR (GAPI)
0. 150.
Input:DRHO (G/CC)
-0.75 0.25
Input:ILM (OHMM)
0.2 2000.
Input:ILD (OHMM)
0.2 2000.
Input:RHOB (G/CC)
1.95 2.95
Input:NPHI (dec)
0.45 -0.15
Final:VCL (dec)
0. 1.
Final:VCoal (dec)
0. 1.
Final:PHIE (dec)
0.5 0.
Final:PHIT (dec)
0.5 0.
CORE:Porosity (frac)
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CORE:Kah (mD)
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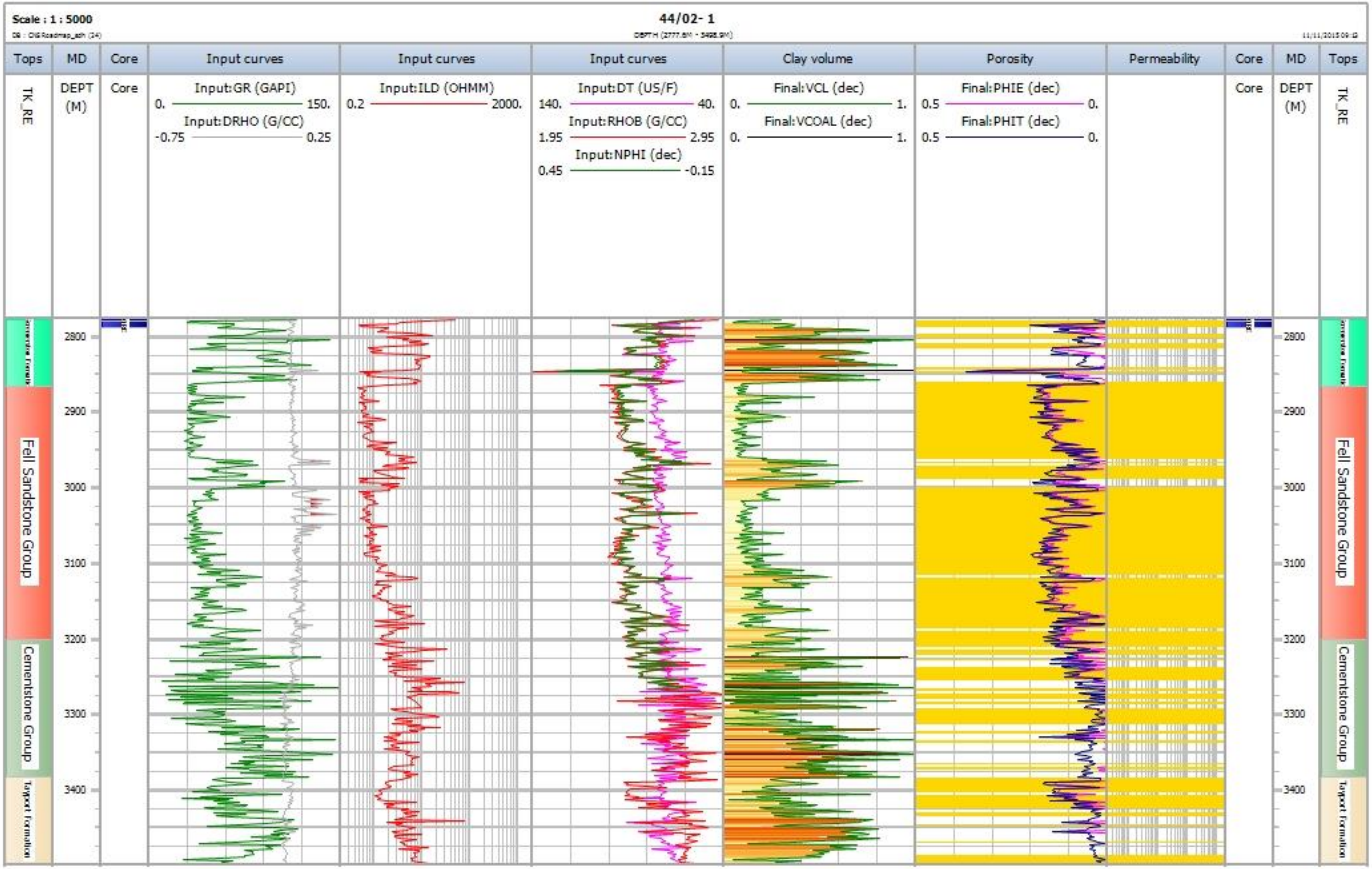
Millstone Grit
Cleveland Gp 'E'
Cleveland Gp 'D'



Scale : 1 : 5000
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Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
TK_RE
DEPT (M)
Core
Input:GR (GAPI)
0. 150.
Input:DRHO (G/CC)
-0.75 0.25
Input:ILD (OHMM)
0.2 2000.
Input:DT (US/F)
140. 40.
Input:RHOB (G/CC)
1.95 2.95
Input:NPHI (dec)
0.45 -0.15
Final:VCL (dec)
0. 1.
Final:VCOAL (dec)
0. 1.
Final:PHIE (dec)
0.5 0.
Final:PHIT (dec)
0.5 0.
Core
DEPT (M)
TK_RE
2800
2900
3000
3100
3200
3300
3400
Fell Sandstone Group
Cementstone Group

Appendix 2 Core and curve data used for permeability estimations

See section 3.5 for explanations. For some wells, where possible, the core data has been depth shifted to improve the relationship with the log porosity (Table 5). For each well that data was available for, the relationship between core porosity and log porosity, and core porosity core permeability is shown in cross plots. Relationship equations derived from the cross plots and used for the permeability estimation curve (PermEst) are shown together with their statistics (Table 6 and Table 7).

DEPTH SHIFTS APPLIED TO CORE DATA

Note that these depth shifts were based on comparison between the log and core porosity, rather than using a gamma ray log of the core stick as would be normal hydrocarbon-field-scale procedure. Therefore it was only possible where there was a sufficient density of core data to be able to correlate the two.

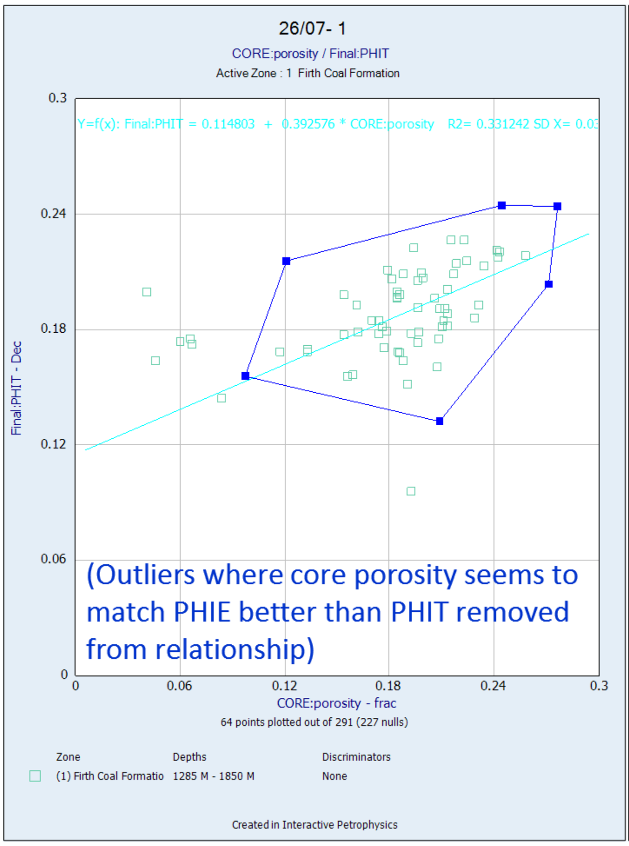
Well	Top depth (m)	Bottom depth (m)	Core depth shift (m)
26/07- 1	1481.80	1490.05	-1.77
	1549.00	1557.50	-1.16
42/10a- 1	2566.30	2992.80	4.89
42/15A- 2	2380.00	2488.00	4.04

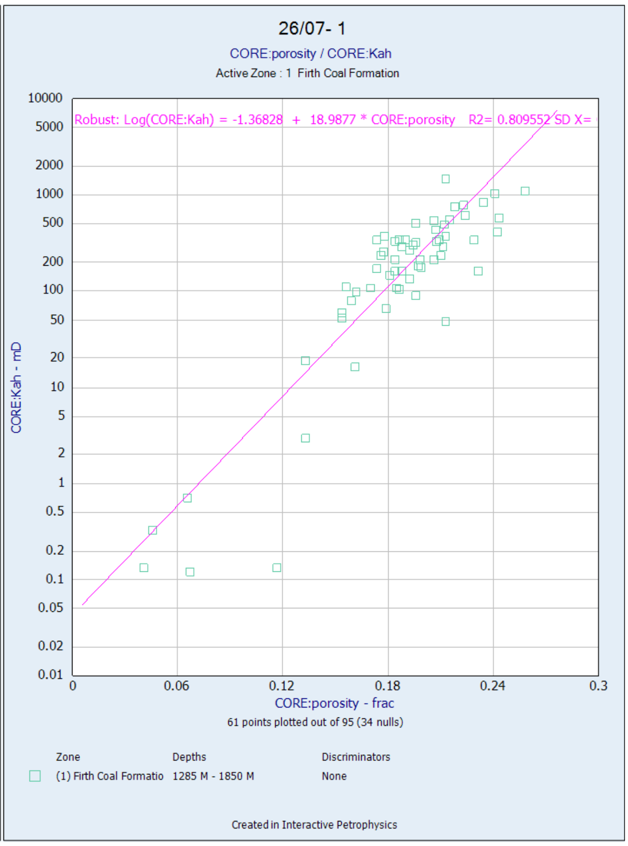
Table 5 Depths shifts applied to core porosity and permeability data

CROSS PLOTS AND SUMMARY STATISTICS OF RELATIONSHIPS USED FOR PERMEABILITY ESTIMATIONS

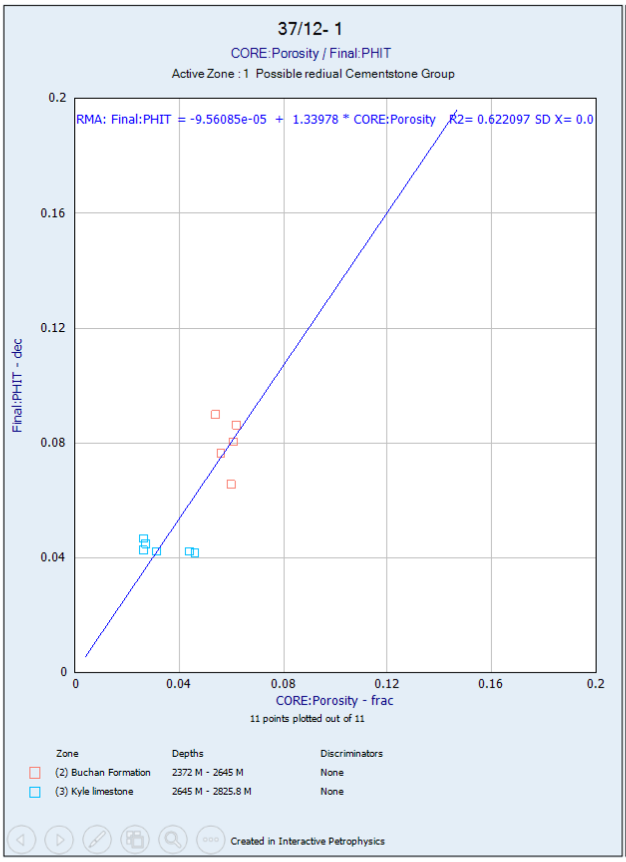
For each well that data was available for, core porosity is plotted against log porosity (left) and core porosity is plotted against permeability (right). The equations of the lines (where a relationship was found to exists) are summarised in Table 6 and Table 7. In general PHIT was found to give the best match to core porosity (except for 41/01- 1). Usually core porosity falls between PHIT and PHIE. Further explanations of potential mismatches can be found in Section 3.1

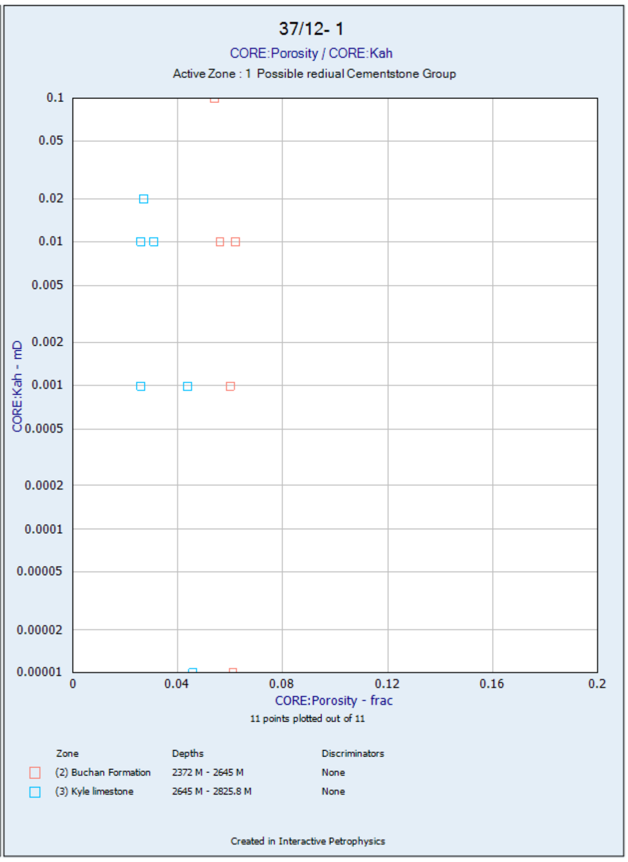
WELL 26/07-1



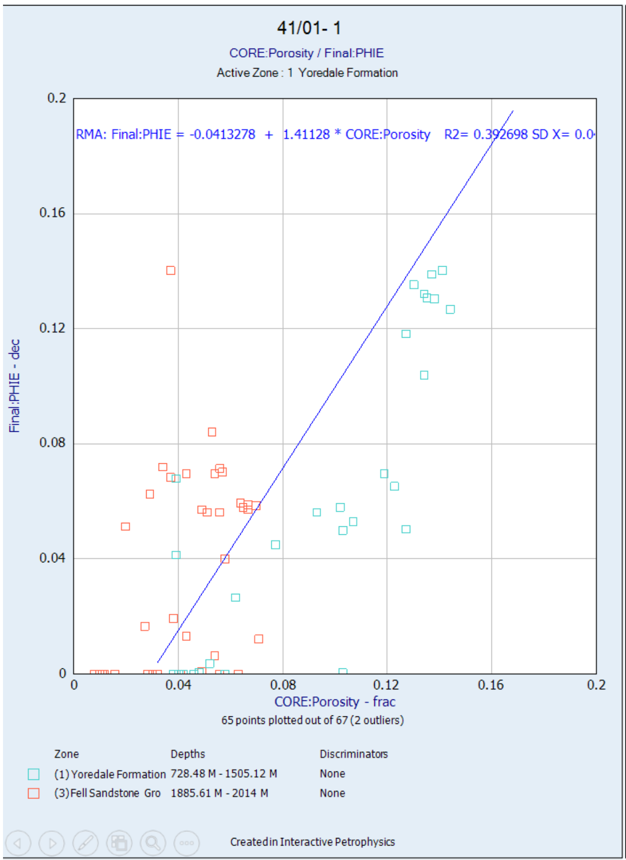


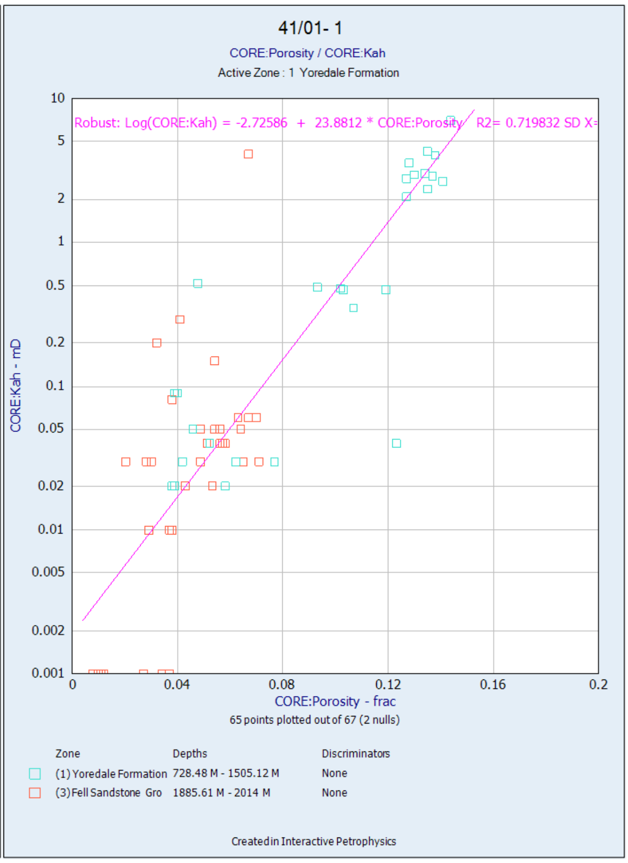
WELL 37/12- 1



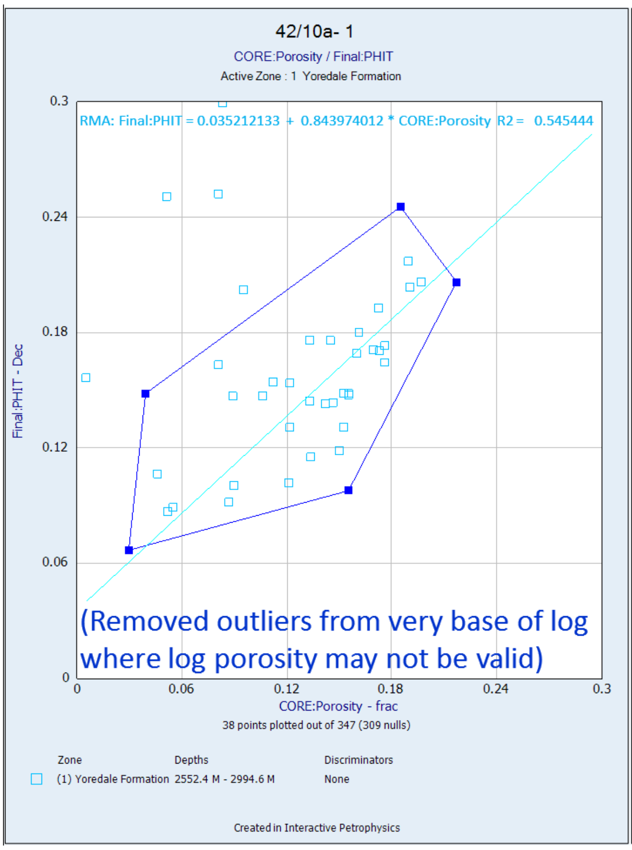


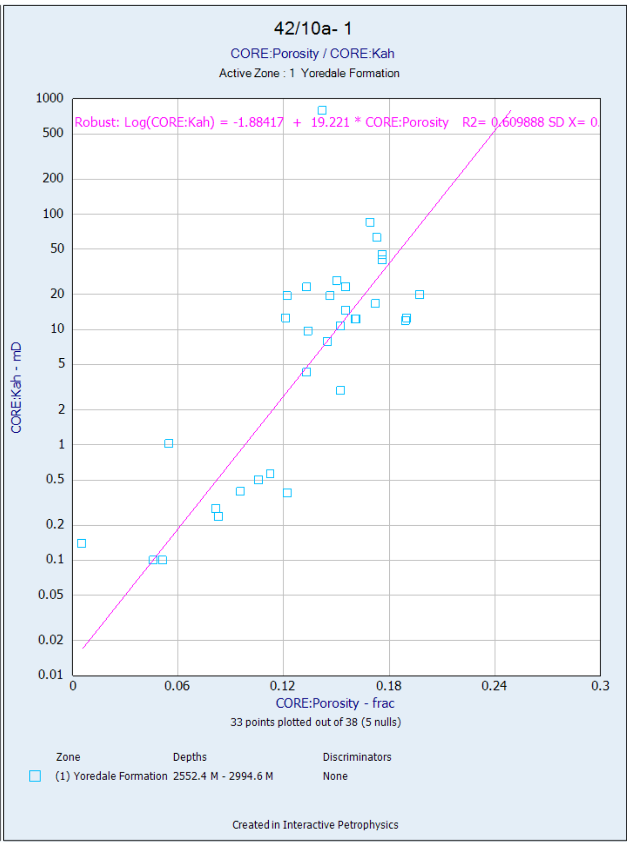
WELL 41/01- 1



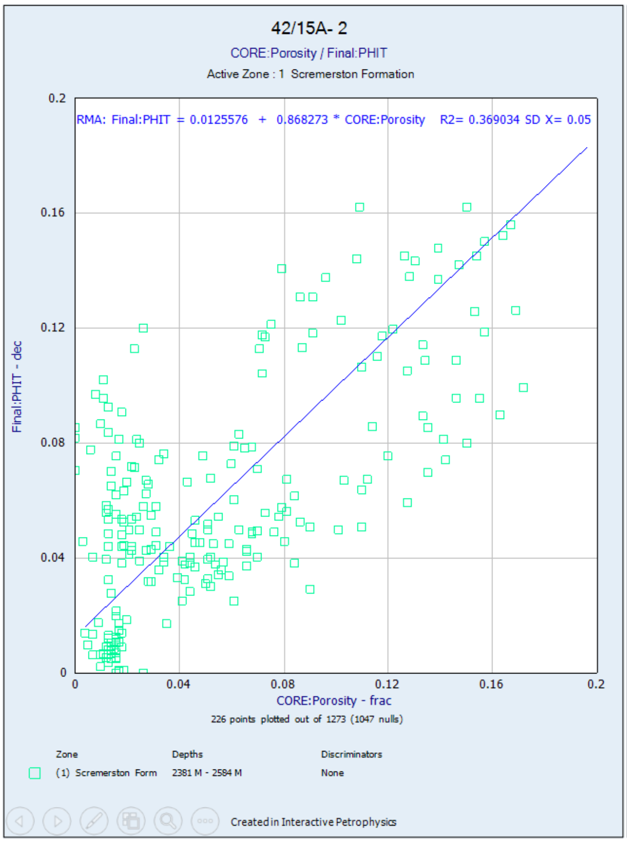


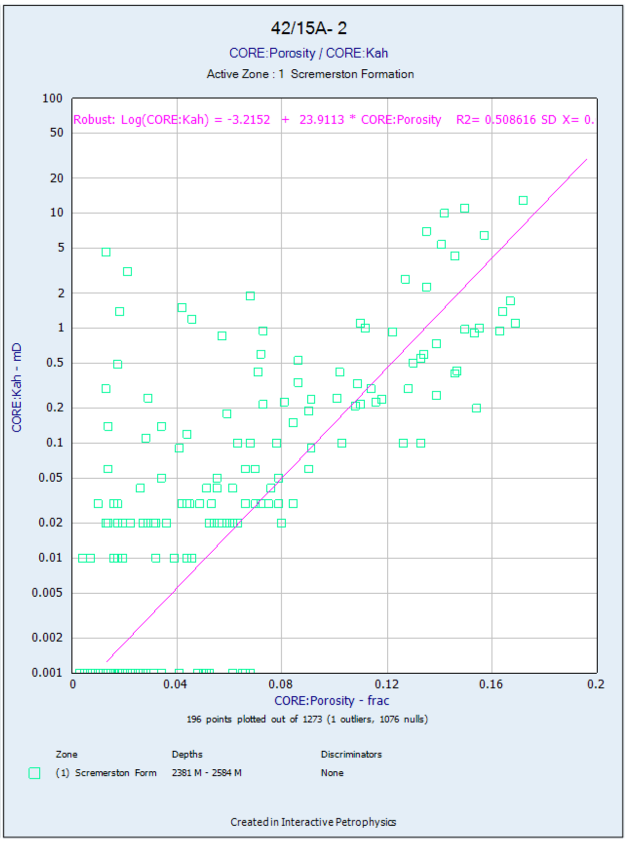
WELL 42/10A- 1



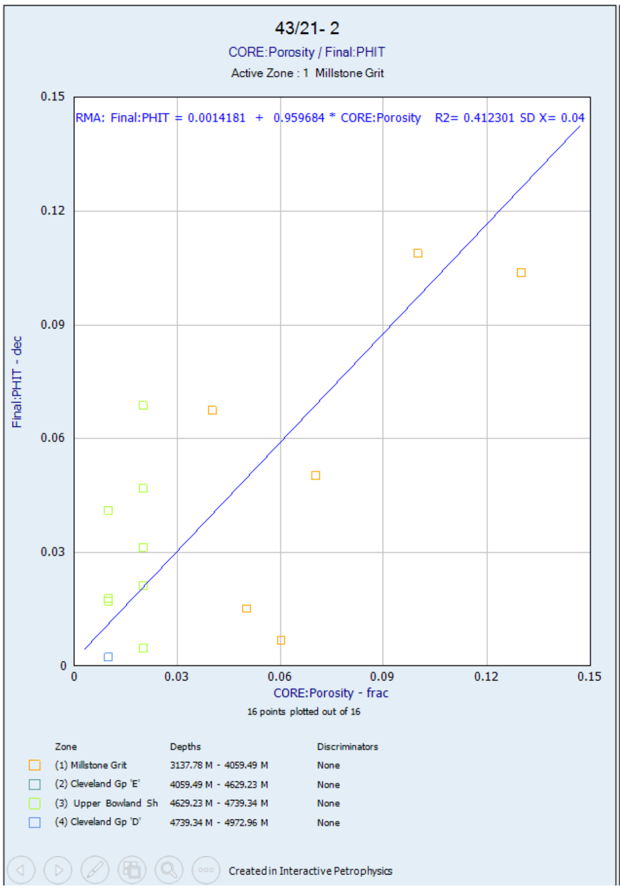


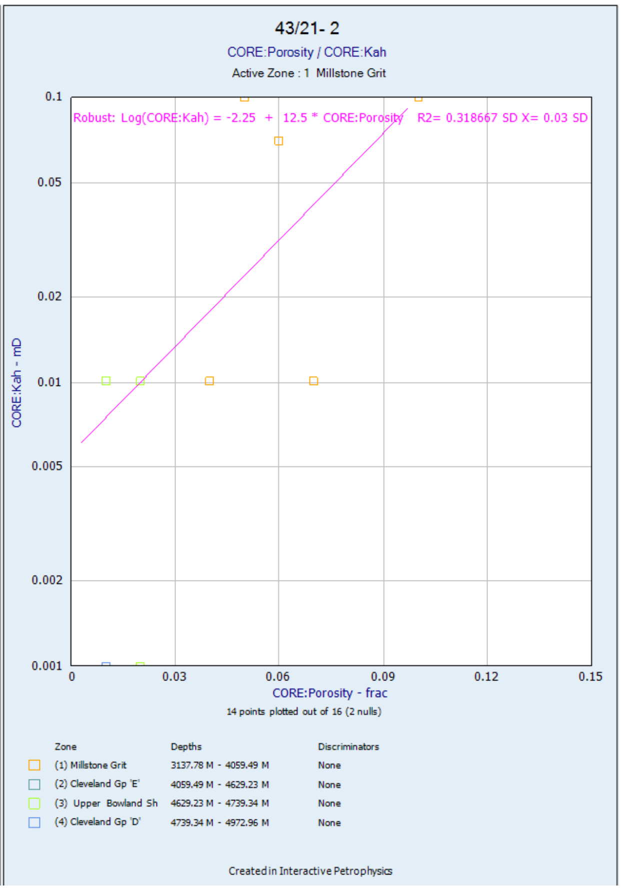
WELL 42/15A- 2





WELL 43/21- 2





			Core porosity - Curve porosity (PHI) relationship: RMA method												
					Relationship			Core porosity statistics				PHI curve statistics			
Well	**Top depth**	**Base depth**	# of points	Comments on core porosity - curve porosity relationship	Porosity Curve (Final:PHI) =	Core porosity points (Core:porosity) =	R2	SD	Mean	Max	Min	SD	Mean	Max	Min
26/07- 1	1285	1850	57	A few points in top core omitted as they match PHIE better than PHIT.	Final:PHIT=0.114803263 +0.392576017*CORE:porosity	CORE:porosity=-0.292435752+2.547277363*Final:PHIT	0.33	0.03	0.19	0.26	0.12	0.02	0.19	0.23	0.15
37/12- 1	2372	2826	11		Final:PHIT=-9.56084766E-5+1.339775991*CORE:Porosity	CORE:Porosity=7.1361539E-5+0.746393432*Final:PHIT	0.62	0.01	0.04	0.06	0.03	0.02	0.06	0.09	0.04
41/01- 1	728	2014	67	PHIE used, because of improved fit to PHIE over PHIT	Final:PHIE = -0.041327789 + 1.41127904 * CORE:Porosity	CORE:Porosity = 0.029283925 + 0.708577093 * Final:PHIE	0.39	0.04	0.07	0.14	0.01	0.06	0.05	0.25	0.00
42/10a- 1	2552	2995	33	Basal points below 2991m omitted (base of log curves, no core-log match, log data probably spurious	Final:PHIT=0.035212133 +0.843974012*CORE:Porosity	CORE:Porosity=-0.041721821+1.184870607*Final:PHIT	0.55	0.04	0.13	0.20	0.05	0.03	0.15	0.22	0.09
42/15A- 2	2381	2584	226		Final:PHIT=0.012557561 +0.868273387*CORE:Porosity	CORE:Porosity=-0.014462681+1.151710988*Final:PHIT	0.37	0.05	0.05	0.17	0.00	0.04	0.06	0.16	0.00
43/21- 2	3138	4973	16		Final:PHIT=0.001418095 +0.959683877*CORE:Porosity	CORE:Porosity=-0.001477669+1.042009795*Final:PHIT	0.41	0.04	0.04	0.13	0.01	0.03	0.04	0.11	0.00

Table 6 Summary statistics of core porosity – curve porosity relationships (Section 3.5 summarises the method)

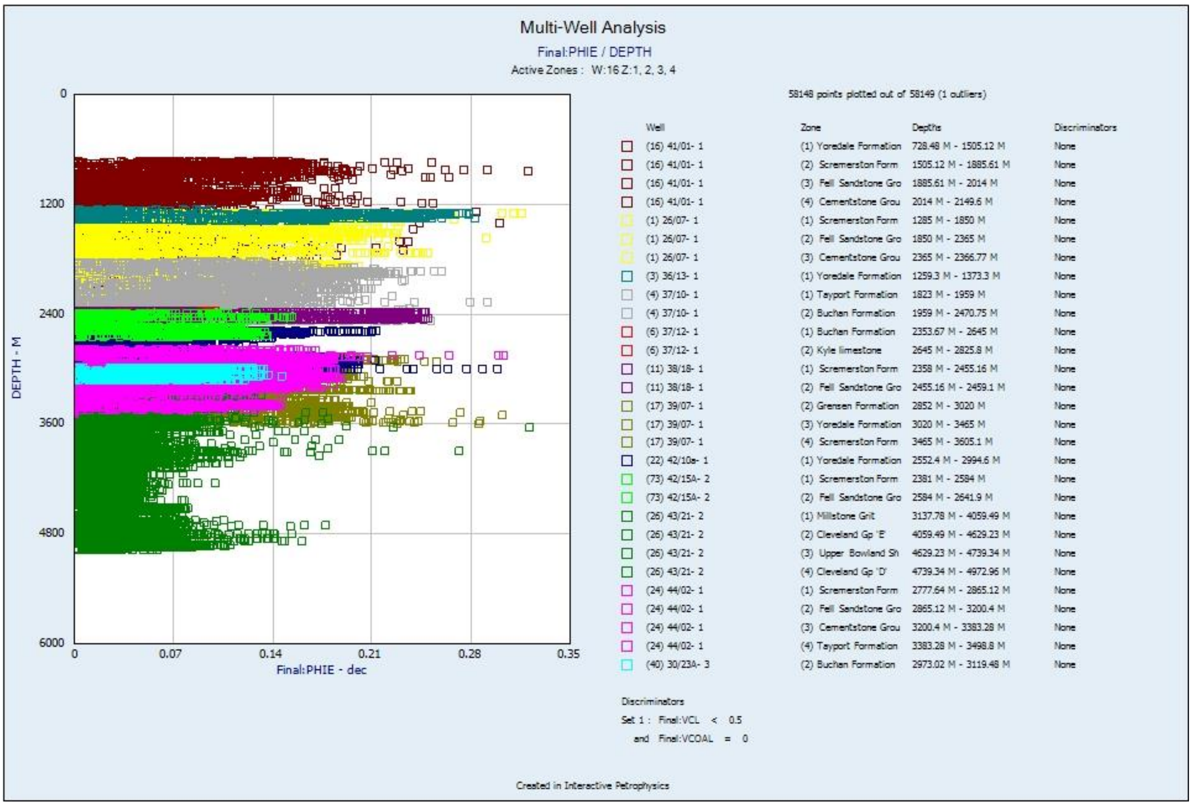
			Core porosity - log of Core permeability relationship: Robust fit method												
			#of points	**Equation applied to porosity curve to derive permeability estimator (PermEst) curve**	Relationship			Core porosity statistics				Log of core permeability stats			
Well	**Top depth**	**Base depth**			Log of core permeability points (Log (Core:Kah)) =	Core porosity points (Core:porosity) =	R2	SD	Mean	Max	Min	SD	Mean	Max	Min
26/07- 1	1285	1850	61	**10^(-1.36828351+18.987654366*Final:PHIT)**	Log(CORE:Kah)=-1.36828351+18.987654366*CORE:porosity	Log(CORE:Kah)=-1.36828351+18.987654366*CORE:porosity	0.81	0.04	0.18	0.26	0.04	0.95	2.08	3.16	-0.92
37/12- 1	2372	2826		**No poro-perm relationship seen.**											
41/01- 1	728	2014	65	**10^(-2.725862026+23.881167178*Final:PHIE)**	Log(CORE:Kah)=-2.725862026+23.881167178*CORE:Porosity	CORE:Porosity=0.114142747+0.041874*Log(CORE:Kah)	0.72	0.04	0.07	0.14	0.01	1.05	-1.10	0.85	-3.00
42/10a- 1	2552	2995	33	**10^(-1.884171247+19.221004347*Final:PHIT)**	Log(CORE:Kah)=-1.884171247+19.221004347*CORE:Porosity	CORE:Porosity=0.09802668+0.052026418*Log(CORE:Kah)	0.61	0.05	0.13	0.20	0.01	0.96	0.74	2.90	-1.00
42/15A- 2	2381	2584	197	**10^(-3.215202808+23.911343439*Final:PHIT)**	Log(CORE:Kah)=-3.215202808+23.911343439*CORE:Porosity	CORE:Porosity=0.134463495+0.041821155*Log(CORE:Kah)	0.51	0.05	0.06	0.17	0.00	1.23	-1.65	1.11	-4.00
43/21- 2	3138	4973	14	**10^(-2.250004292+12.500001611*Final:PHIT)**	Log(CORE:Kah)=-2.250004292+12.500001611*CORE:Porosity	CORE:Porosity=0.18000032+0.07999999*Log(CORE:Kah	0.32	0.03	0.03	0.10	0.01	0.71	-2.08	-1.00	-3.00

Table 7 Summary statistics of core porosity – permeability relationships (Section 3.5 summarises the method)

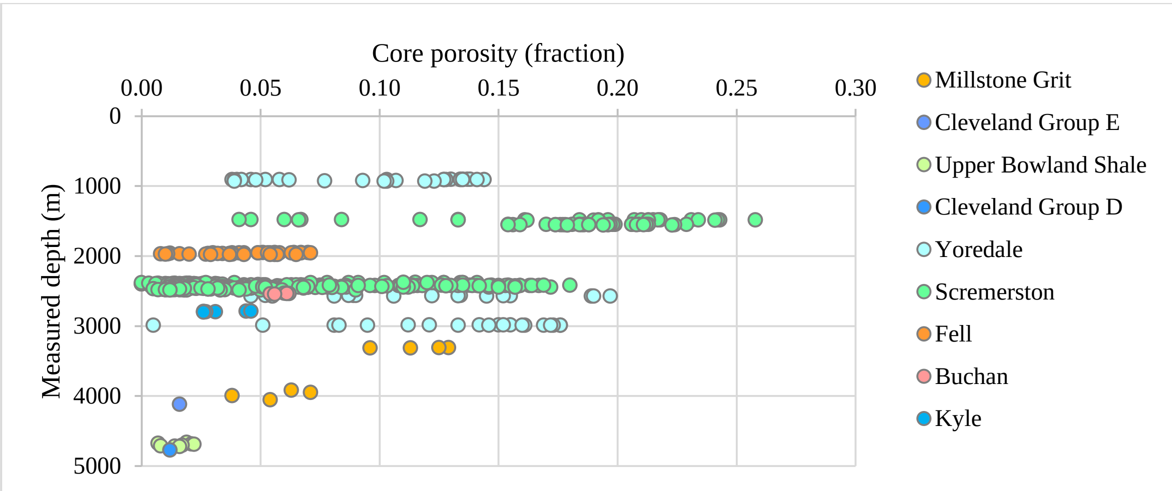
Appendix 3 Porosity versus depth plots

These are included to show the data spread versus measured depth (m). The **Log interpreted porosity (PHIE) versus depth** (m) plots are coloured by well (12 wells, see section 4.5). Data points are filtered to show only those points for which clay volume is less than 50% (V_{CL}<0.5) and there are no coals present (V_{COAL} = 0), i.e. similar to the net reservoir definition (but without the removal of porosities less than 5%). The **core porosities versus depth** plot is coloured by formation and shows all core points (for the 7 wells, see section 4.6). (For information on the structure of the area and basin history, please refer to the relevant project reports Arsenikos et al., 2015, report CR/15/118; Kimbell & Williamson, 2015, report CR15/119; Vincent, 2015, report CR/15/122).

PHIE VERSUS DEPTH FOR ALL WELLS, ALL FORMATIONS

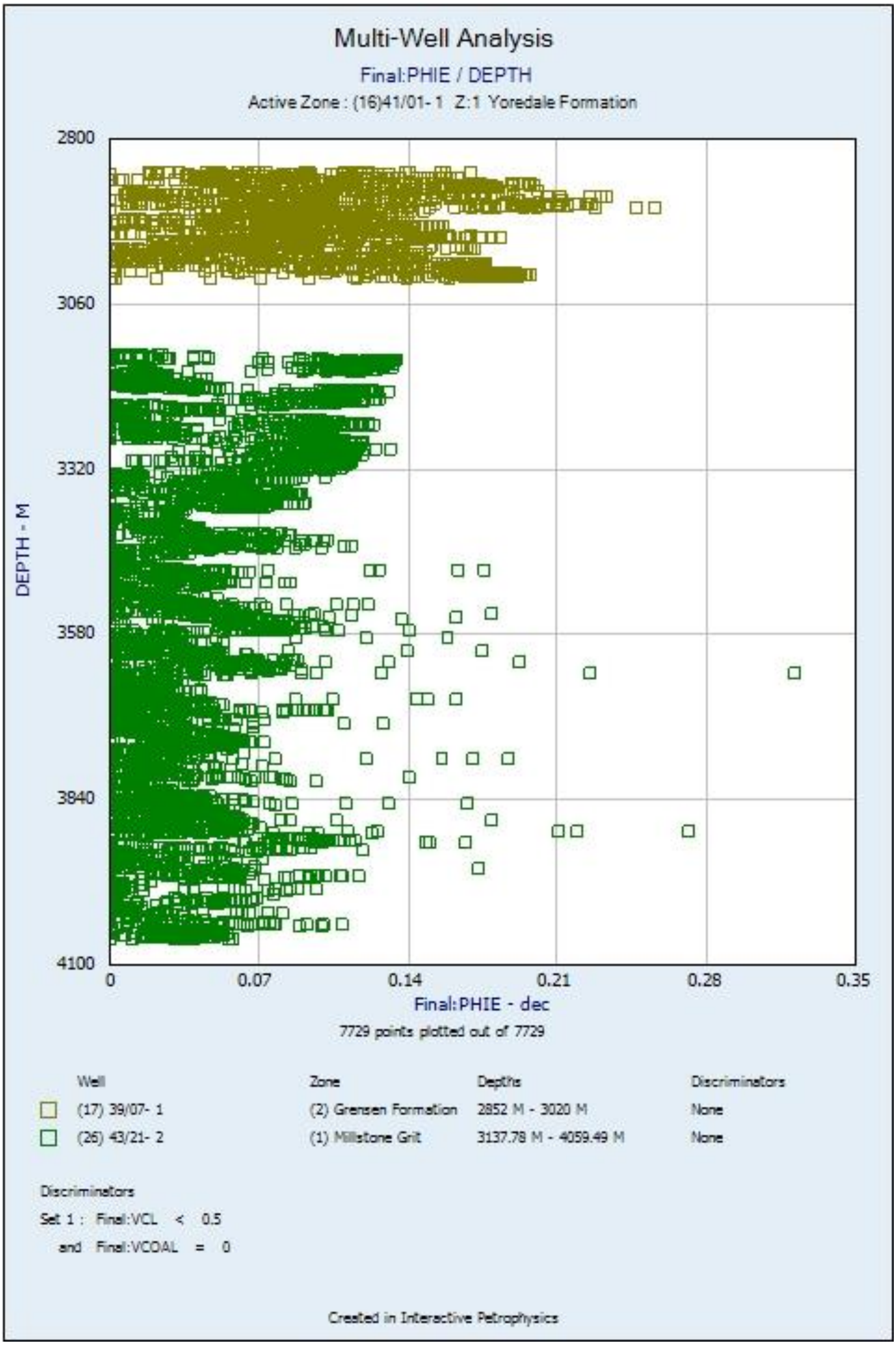


CORE POROSITIES VS DEPTH FOR ALL WELLS, ALL FORMATIONS

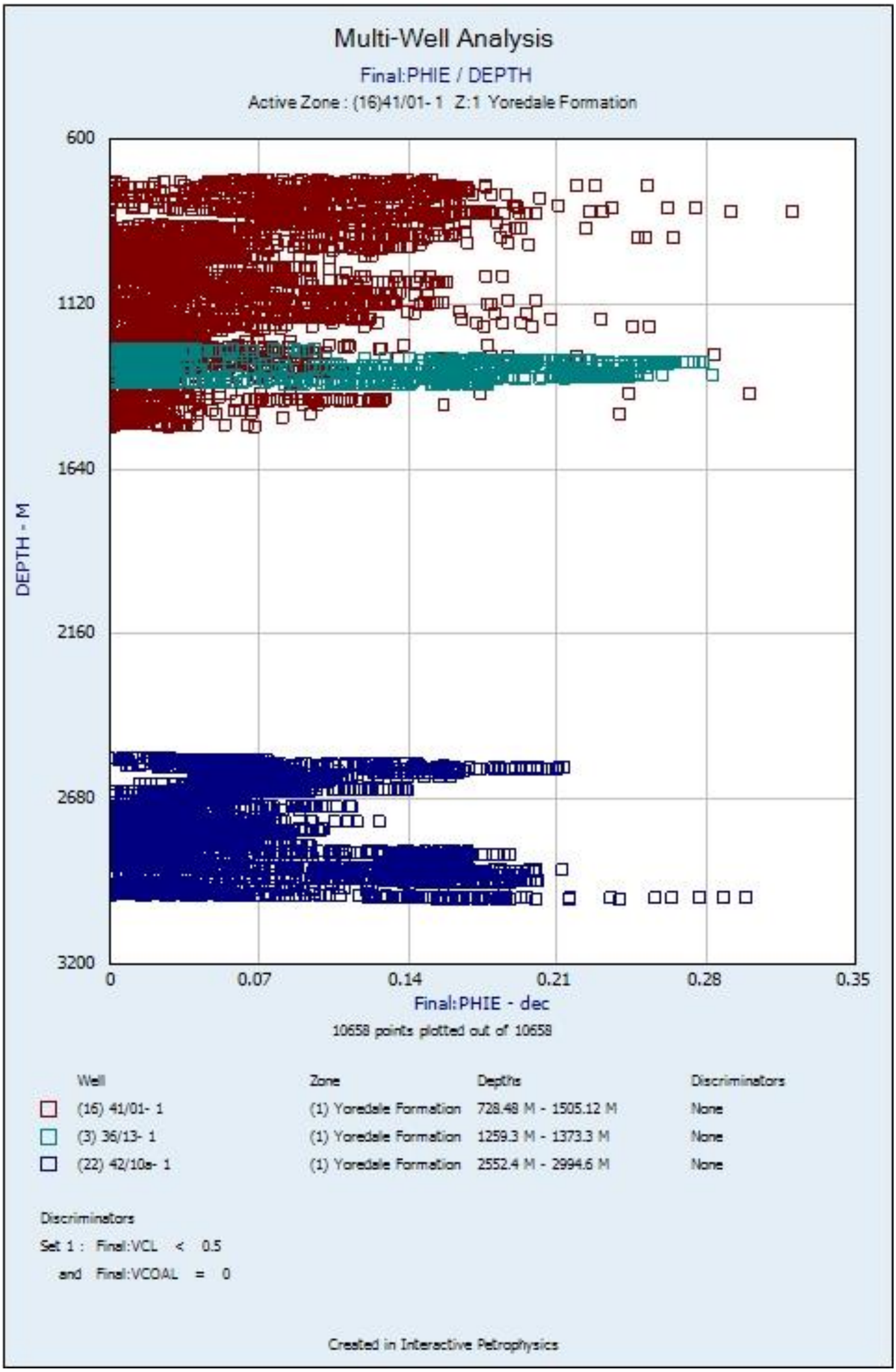


PHIE VS DEPTH BY FORMATION:

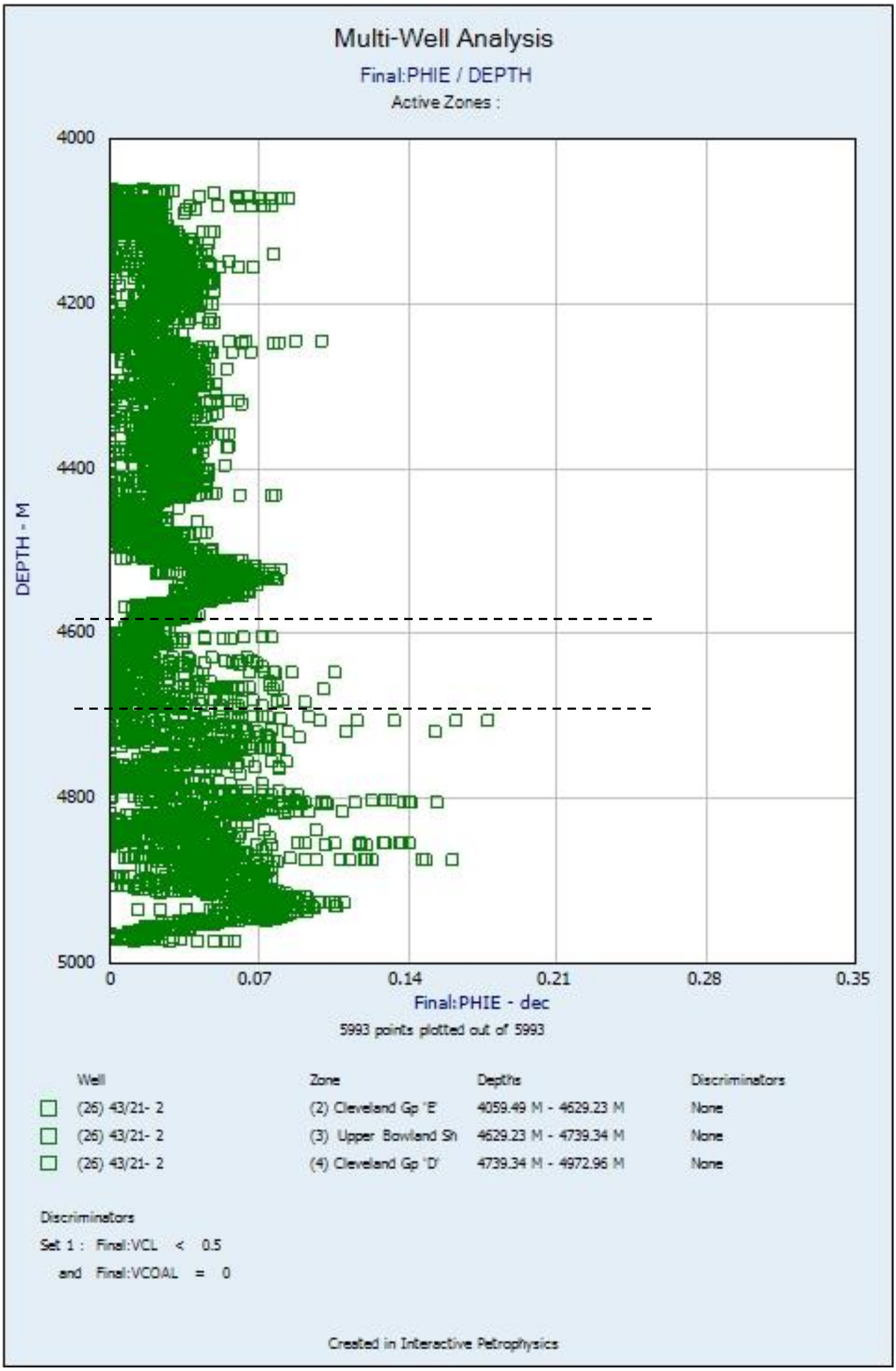
GRENSEN & MILLSTONE GRIT



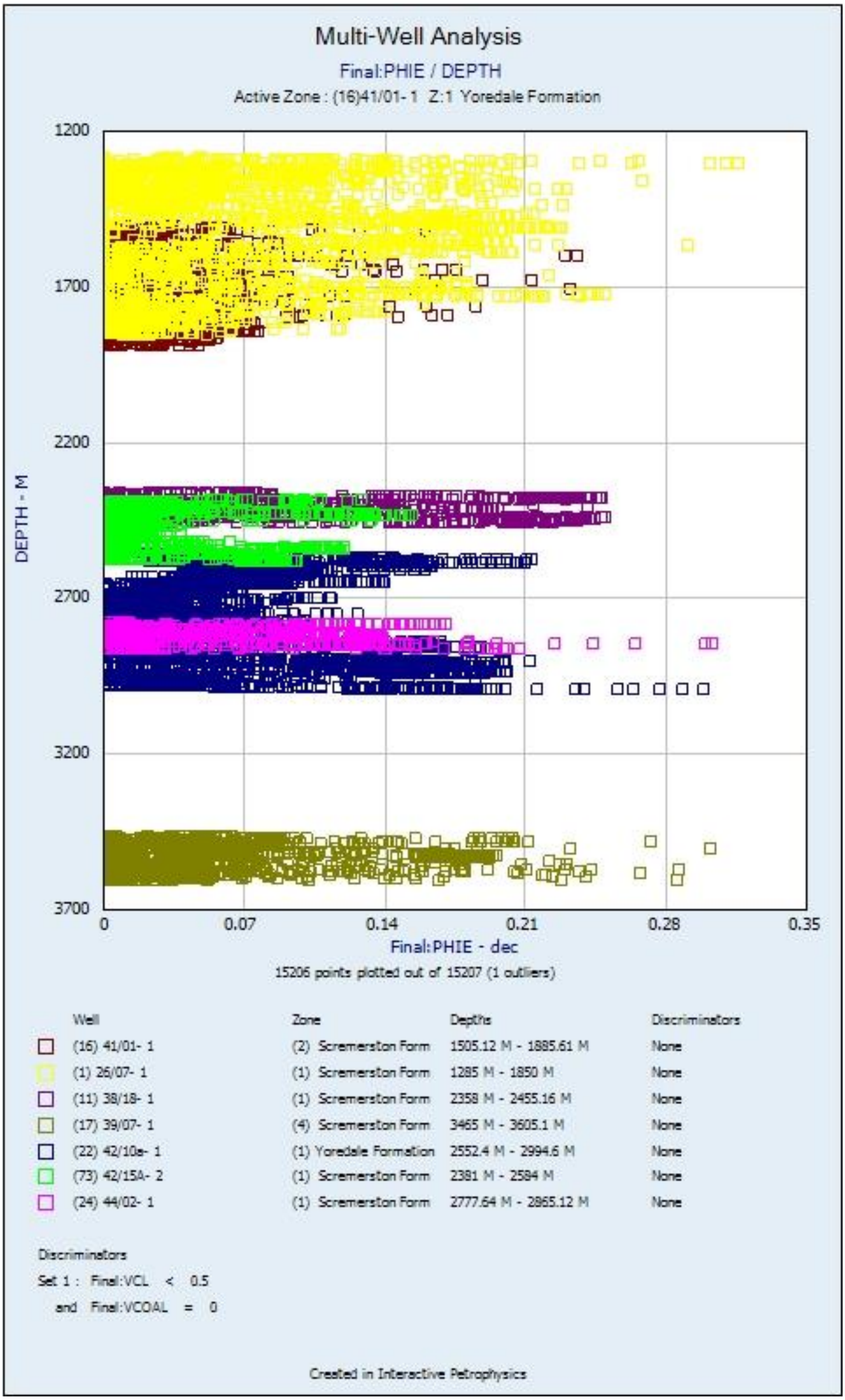
PHIE vs DEPTH: YOREDALE



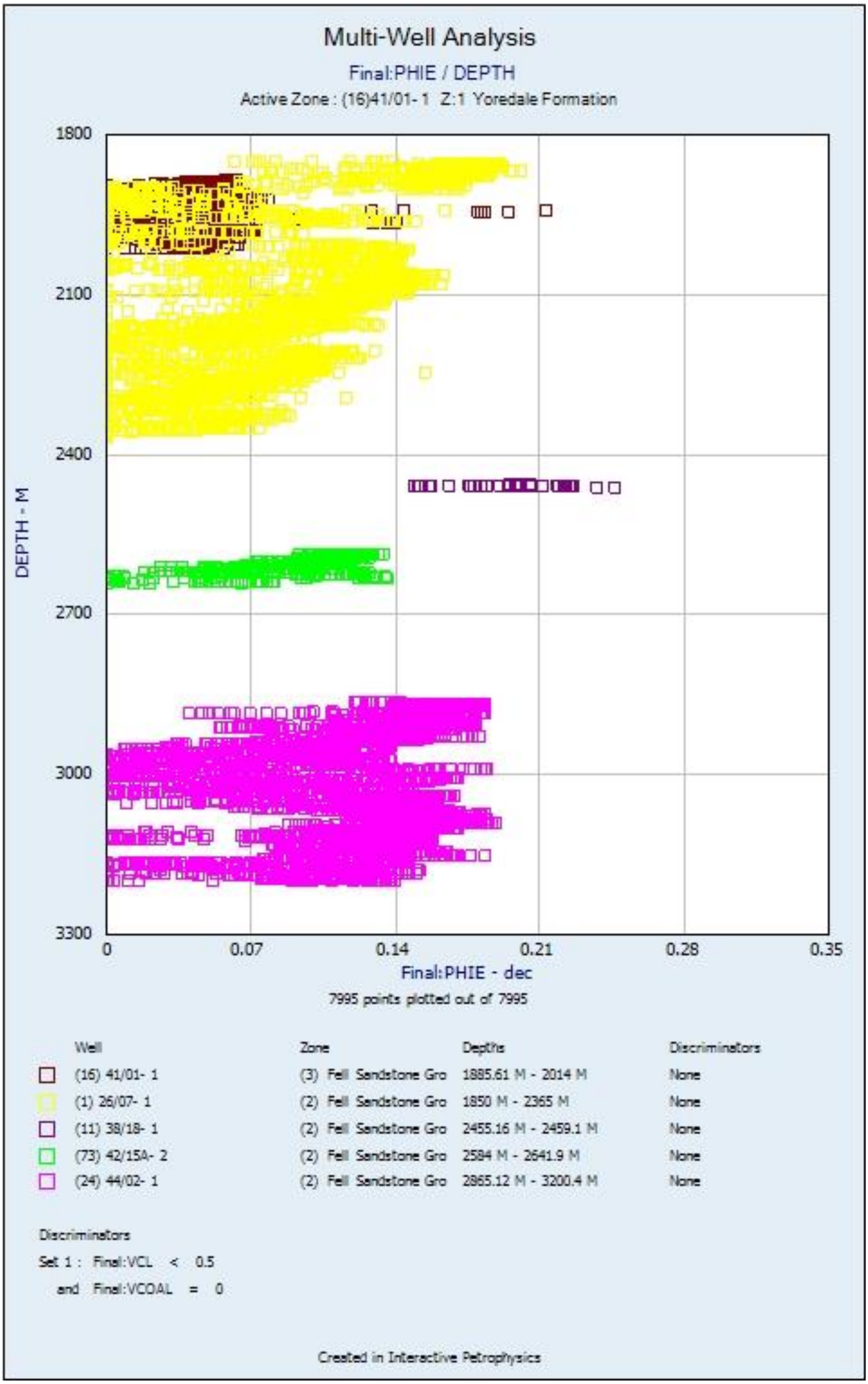
PHIE vs DEPTH: CLEVELAND GROUP E, UPPER BOWLAND SHALE, CLEVELAND GROUP D



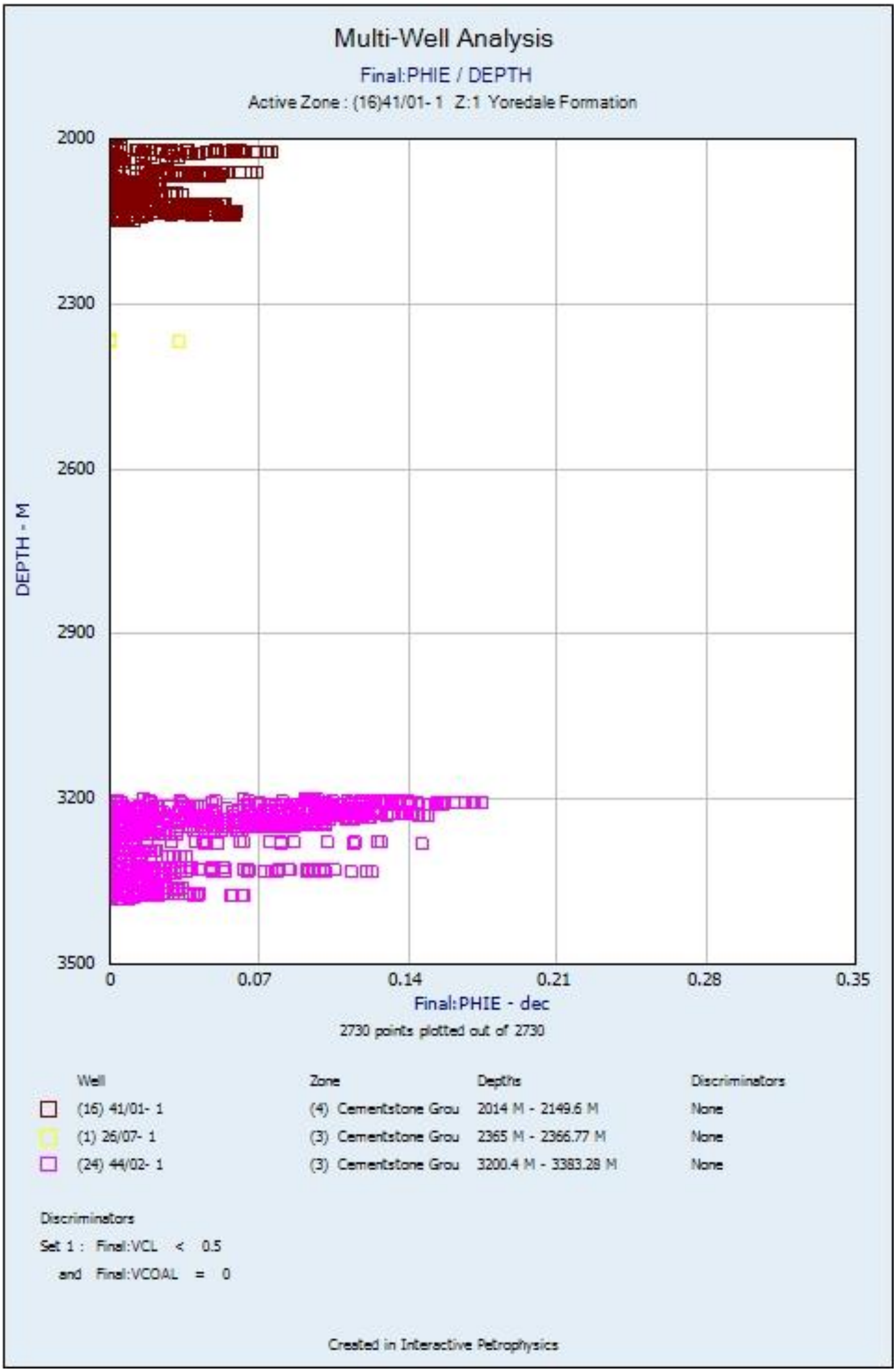
PHIE vs DEPTH: SCREMERSTON



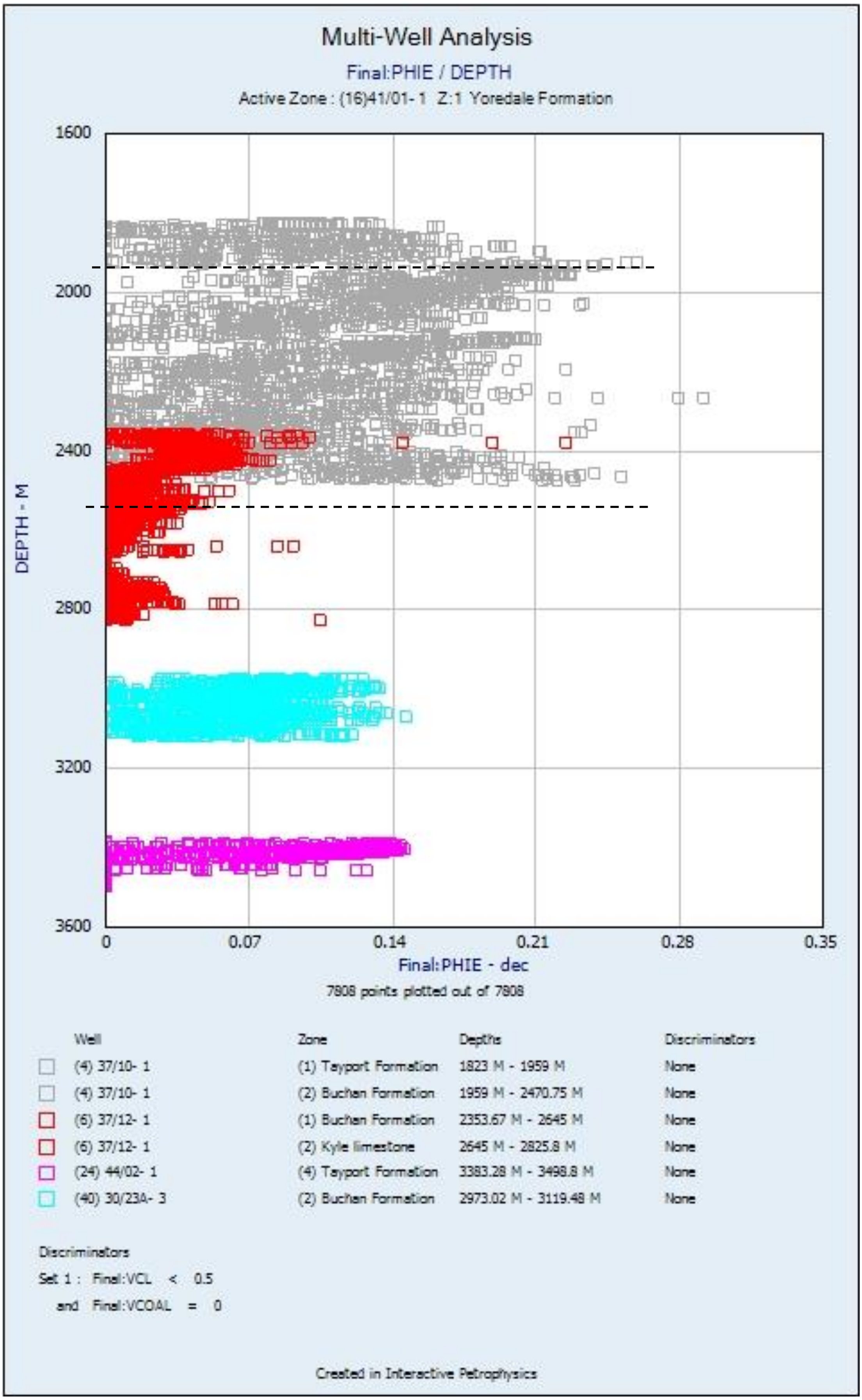
PHIE vs DEPTH: FELL



PHIE vs DEPTH: CEMENTSTONE



PHIE vs DEPTH: TAYPORT, BUCHAN, KYLE



Appendix 4 Table of well information and log quality and interpretation comments

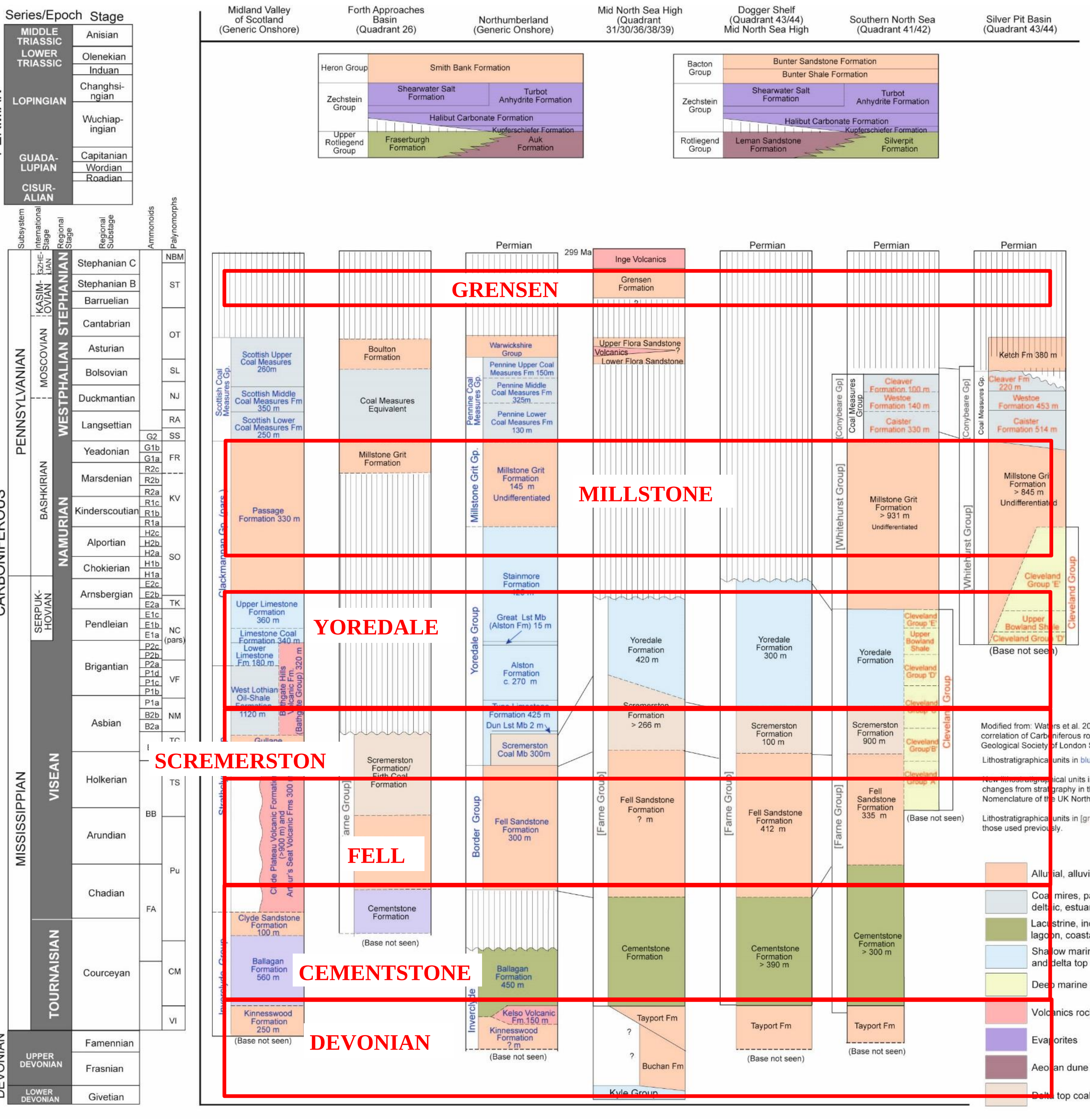
Well	Selection process						Curves available					Curves used for V_{cl} and poro						Cut off values for V_{COAL}			Interpretation/data quality comments for report. *Notes:*
	New strat	**Core data**	**Composite**	**Rock Eval**	**TOC points**	**Vr Points**	**Gamma Ray (GR)**	**Resistivity**	**Sonic, DT (S)**	**Density (D)**	**Neutron (N)**	**Clay vol:GR**	**Clay vol:ND**	**Clay vol:DS**	**Poro: ND**	**Poro: D**	**Poro: S**	**D**	**N**	**S**	• ***Tension curves were generally not available (because the files were composites).*** • ***It was assumed that appropriate borehole corrections had already been applied to all curves.*** • ***DRHO in tolerance was assumed to be -0.1 to 0.1*** • ***Calliper logs were compared to bit size to identify washouts or zones of potential poor pad-tool contact.*** • ***All curves were compared to their expected responses and to the company composite pdf logs where available.***
26/07- 1	x	x	x	x			x	x	x	x	x	x					x	1.85	0.45	90	Poor density data quality: DHRO indicates that D is frequently out of tolerance, probably due to hole rugosity (CALI shows frequent washouts). N-D used to help select GR Clay volume parameters, but not used for calculation. S used for poro because D poor quality.
30/23a-3	x		x				x	x	x	x	x	x	x		x			2.00	0.31	90	Data quality appears good: DHRO indicates that D is in tolerance. No other indicators suggest poor data quality.
36/13- 1	x		x		11	7	x	x	x	x		x				x		2.10	-	90	Data quality appears OK, but only CALI available for assessment and D poro mostly agrees well in comparison to S poro.
37/10- 1	x		x				x	x	x	x	x	x	x		x		x	2.25	0.37	90	Potentially spurious Neutron data (source/processing). A few intervals of poor D quality (DRHO out of tolerance). N-D used to help select GR Clay volume parameters, but not used for calculation. N-D used for poro except where DRHO indicates poor D, then S used for poro. S poro across whole interval compares well to N-D poro.
37/12- 1	x	x	x				x	x	x	x	x	x			x		x	2.30	0.3	90	Data quality appears good: DHRO indicates that D is in tolerance. No other indicators suggest poor data quality. A few spikes (not within Net intervals) appear to be a lithological response.
38/18- 1	x		x		17	8	x	x	x	x	x	x			x			2.25	0.28	88	Potentially spurious Neutron data (source/processing). Density data quality appears good (DRHO in tolerance). GR-S curves depth shifted to match Res, D, N to ensure N,D,S peaks were on depth with each other for Coal ID calculation. N-D used to help select GR Clay volume parameters, but not used for calculation. N-D used for poro (compares well to S poro).
39/07- 1	x		x		20	8	x	x	x			x					x	-	-	100	Only Sonic available for poro calc. S spikes > 100 over Yoredale & Scremerston inferred to be coals from composite pdf. Only GR used for Clay volume calculation. No other curves available for verification of parameters.

Well	Selection process						Curves available					Curves used for V_{cl} and poro						Cut off values for V_{COAL}			Interpretation/data quality comments for report. *Notes:* • ***Tension curves were generally not available (because the files were composites).***
41/01- 1	x	x	x	x	26		x	x	x	x		x				x	x	2.10	-	90	A few intervals of poor density data quality (DHRO out of tolerance, appears to be due to hole rugosity (CALI). May correspond to coaly/carbonaceous intervals, but unable to verify. Coal ID therefore a compromise. May correspond simply to areas of poor data quality, but either way are excluded from Net calculations. This has led to some sharp changes in porosity curve). D used to help select GR Clay volume parameters, but not used for calculation. D used for poro except where DRHO indicates poor D, then S used for poro. S poro across whole interval compares reasonably well to D poro.
42/10a- 1	x	x	x	x	123	16	x	x	x	x	x	x	x		x			2.38	0.31	78	Data quality appears good: DHRO indicates that D is in tolerance apart from at a couple of points. No other indicators suggest poor data quality. N-D and D-S used to help select GR Clay volume parameters, N-D and GR used for calculation. Appear to be thin carbonaceous intervals in base of Yoredale creating high poro spikes. Edited coal ID parameters to exclude them.
42/15a- 2	x	x	x	x	10		x	x	x	x	x	x	x		x			1.85	0.45	90	Data quality appears good despite multiple washouts 2-5" from bit size. : DHRO indicates that D is in tolerance apart from at a couple of points. No other indicators suggest poor data quality. N-D and D-S used to help select GR Clay volume parameters, N-D and GR used for calculation.
43/21- 2	x	x	x		71	111	x	x	x	x	x	x			x			2.35	0.31	78	Poor density data quality: DHRO indicates that D is frequently out of tolerance, probably due to hole rugosity (CALI shows corresponding washouts). N-D & D-S used to help select GR Clay volume parameters, but not used for calculation. N-D used for poro as it corresponded reasonably well to S poro over the net reservoir intervals.
44/02- 1	x		x	x	19	12	x	x	x	x		x				x	x	1.90	0.3	88	Data quality appears mostly OK apart from interval where DRHO is out of tolerance. No CALI available over that interval. D poro mostly agrees in comparison to S poro.

Table 8 Table of well information and log quality and interpretation comments

Appendix 5 Copy of stratigraphic chart

Generalised time-equivalent slices shown in the maps (Section 4.7) are highlighted in red. The stratigraphic report is from (Kearsey et al., 2015, report CR/15/117)



References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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