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Reservoir evaluation of 3 wells in the Palaeozoic of the Orcadian Basin (UK 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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S Hannis

Contributor

E Callaghan

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British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

The Lyell Centre, Heriot-Watt University, Riccarton, Edinburgh EH14 4AP
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Requests and enquiries should be addressed to Alison Monaghan, 21CXRM Palaeozoic Project Leader, als@bgs.ac.uk.

Foreword

This report is a published product of the 21st Century Exploration Roadmap (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.

Jonathan Pye (Premier Oil) and Tony Hewett (Eon/Premier Oil) are thanked for technical review of this report.

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Summary

This report details the reservoir evaluation of 3 wells across the Palaeozoic rocks of the Orcadian Basin of the UK North Sea for the 21CXRM Palaeozoic project.

This reservoir evaluation is based on the petrophysical interpretation of available digital wireline log curve data for 3 wells and associated digitised core porosity and permeability data (14 to 67 measurements available for each well) across the Palaeozoic interval (according to reinterpreted stratigraphic formations defined and correlated for this project, documented in Whitbread and Kearsey (2016)). Outputs of this part of the project include continuous (along borehole) interpretations of porosity, clay volume, and include basic permeability estimations. 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 3 wells were selected based on availability of core data (to allow calibration of log-derived porosities and the estimation of permeabilities) to determine reservoir quality potential in the Devonian interval. The results complement the Hannis (2015) study on Carboniferous and Devonian reservoirs of the Central North Sea.

Other reports document the stratigraphic extent of these units (e.g. Whitbread and Kearsey, 2016). 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 are not included in this report. The best reservoir properties appear to be found in the Middle Eday Sandstone Formation, which, in well 13/19-1, has a NTG of 1, an average porosity of 14% and the highest permeabilities recorded of the 3 wells (an average of 20 mD with values up to 174 mD estimated from logs calculations derived from associated core data). The Permian Rotliegend Group, and Zechstein Group also show favourable properties, slightly lower NTG and porosities than the Middle Eday Sandstone Formation (Tables 1 and 3) and although no core was available in the 3 wells examined to derive specific permeability measurements from them, log derived estimates from deeper core were up to 208 mD. The Buchan Formation also shows favourable properties, particularly in one well (13/19-1) where NTG was 1, porosity 12% and permeabilities estimated as up to 110 mD.

There may also be potential reservoir in the Upper and Lower Strath Rory Formations, as they have good NTG (0.92 and 0.56 respectively) and average porosities (16% and 10% respectively). However, from the data examined, their permeabilities appear comparatively much lower (averages estimated as less than 1 mD, with the highest values estimated (and measured on core) around 5 mD.

Over these potential formations of interest, log responses suggest that there are relatively thick intervals of clean “good” reservoir intervals, in comparison to the CNS reservoirs studied which were dominated by a heterolithic succession (Hannis, 2015).

The Eday Flagstones, Lower Eday Sandstone and Kupfershiefer formations appear to have poor reservoir properties. The Orcadia and Struie formations and the Granitic basement are not considered to have any in-matrix reservoir potential.

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 Orcadian Basin 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 Palaeozoic intervals for 3 wells in the Orcadian Basin (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})*
   - Porosity *(PHIE & PHIT)*
   - Permeability estimate *(PermEst)*

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

   - Gross thickness
   - Net*
   - Net to Gross
   - Average porosity (across the net intervals)

   *"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)*

3. **Digitised core-sample-derived basic porosity-permeability measurement data for the the 3 wells with Palaeozoic 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 Orcadian Basin, Quadrants 11, 12 and 13, UK.

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. 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 (Whitbread and Kearsey, 2016). 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.

2.2 DATA PREPARATION

The software used for the petrophysical interpretation was **Interactive Petrophysics** (IP^{TM}, Version 4.2.2015.61, LR-Senergy 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} (LR-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].

[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*.

3. BGS-digitised core porosity and permeability data was loaded into IP (reformatted from the BGS-digitised tabulation of data for all wells)[1].
4. The cored intervals were loaded into IP for the wells (tops and bases, reformatted from the output of the BGS core database).
5. Wells to interpret were selected based on the length of Palaeozoic interval, stratigraphic intervals and geographic areas covered, and the availability and quality of suitable data over the interval. The focus of this study was the Devonian interval in the Moray Firth. Carboniferous strata were examined in Hannis (2015). 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 Palaeozoic section
   - Updated stratigraphy picked
   - Geophysical log curve data for reservoir evaluation, with suitable data quality (variable for each well) (see Appendix 4, Table 8)
   - Core poroperm data available
   - Company log composite available for cross checking data

   Note that wellbore deviation surveys were not taken into account because the data is presented against measured depth (MD).

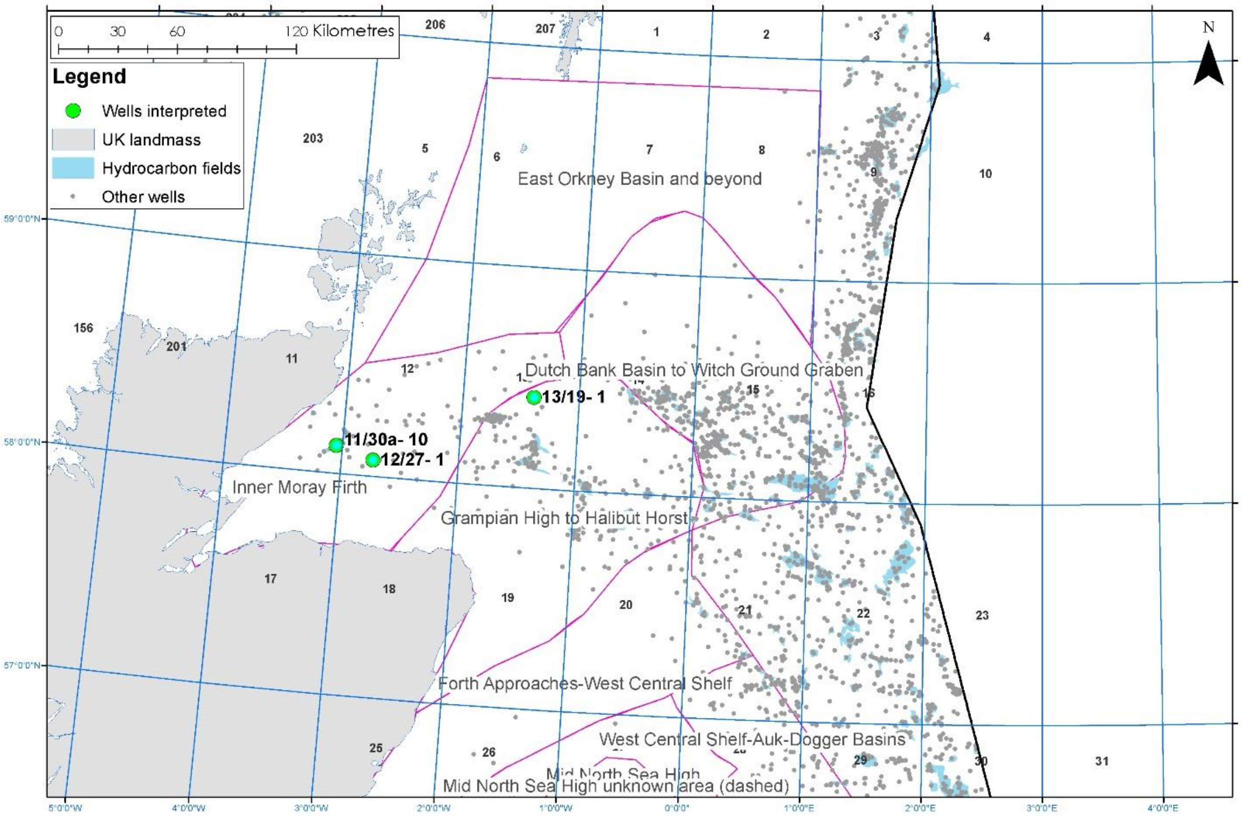


Figure 1 Map of the wells selected for the petrophysical study

3 Curve interpretation method

Continuous interpreted curves were calculated from geophysical log responses over the Palaeozoic interval using Interactive Petrophysics software (IP^{TM}, Version 4.2.2015.61, LR-Senergy). 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 (24 °C/km with a surface temp of 11 °C was used, based data derived from the 3 wells), 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 3.3). Core porosity and permeability measurements were used to derive permeability estimation curves (Section 3.4). Core data is displayed on the log plots in 5.1.

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.

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 6 & 7 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).

Note that a coal identification curve (as used in the 21CXRM Central North Sea petrophysical report (Hannis, 2015) was not deemed necessary for the wells examined in this area, as they did not display coal characteristics that would fall within the reservoir intervals (some carbonaceous matrix material is reported in the Eday Flagstone Formation in well 13/19-1, but these fall outwith the net reservoir).

3.3 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).

3.4 PERMEABILITY ESTIMATION CURVE

Permeability estimation was derived for the wells based on core data (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).

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 3 wells in the Orcadian Basin were interpreted using the methods described in section 3. Curve data were clipped to the Palaeozoic 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 only in well 11/10a-3 was the base of the Palaeozoic interval penetrated. Continuous curves produced were:

- Volume of Clay curve (V_{CL});
- Effective Porosity curve (PHIE);
- Total Porosity curve (PHIT) ;
- Estimated Permeability (PermEst).

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).

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 3.4) 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 Devonian-Permian interval and by individual formation in each well. 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.
- 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).

[1]Note that the base of the Palaeozoic succession is not penetrated in all wells. (i.e. a small Gross value does not necessarily mean thin Palaeozoic 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 3.3 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 3.4 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).

Stratigraphic unit name	Well	Top	Bottom	Gross[1]	Net[2]	N/G[3]	Average PHIE[4]	PHIE Min[4]	PHIE Max[4]	Average PermEst[5]	PermEst Min[5]	PermEst Max[5]
Zechstein Group	12/27-1	1665	1702	37	9	0.23	0.11	0.05	0.21	0.346	0.070	1.37
Zechstein Group	13/19-1	1479	1592	113	97	0.86	0.11	0.05	0.21	8.146	0.130	208.10
Kupferschiefer	13/19-1	1592	1596	3	0	0.13	0.07	0.06	0.08	0.546	0.202	0.76
Rotliegend Group	11/30A-10	2605	2689	84	63	0.75	0.09	0.05	0.23	0.726	0.094	25.12
Rotliegend Group	12/27-1	1702	1720	18	18	0.99	0.15	0.09	0.18	0.268	0.094	0.59
Rotliegend Group	13/19-1	1596	1630	35	34	0.97	0.10	0.05	0.16	3.149	0.101	28.89
Buchan Formation	11/30A-10	2689	2992	303	172	0.57	0.09	0.05	0.25	1.569	0.083	50.04
Buchan Formation	13/19-1	1630	1714	84	83	1.00	0.12	0.05	0.19	9.065	0.236	110.24
Eday Marl Formation	13/19-1	1714	1771	57	2	0.04	0.06	0.05	0.08	0.354	0.187	1.11
Middle Eday Sandstone Formation	13/19-1	1771	1832	61	61	1.00	0.14	0.06	0.20	19.992	0.258	173.58
Eday Flagstone Formation	13/19-1	1832	1949	117	21	0.18	0.09	0.05	0.14	2.084	0.145	8.93
Lower Eday Sandstone Formation	13/19-1	1949	1986	37	6	0.15	0.09	0.05	0.13	3.312	0.117	16.92
Upper Strath Rory Formation	11/30A-10	2992	3088	96	66	0.69	0.08	0.05	0.18	0.420	0.084	5.33
Upper Strath Rory Formation	12/27-1	1720	2132	412	399	0.97	0.16	0.05	0.26	0.630	0.027	3.24
Orcadia Formation	11/30A-10	3088	3190	102	18	0.18	0.07	0.05	0.11	0.195	0.081	0.62
Orcadia Formation	13/19-1	1986	2144	157	1	0.01	0.07	0.06	0.10	0.533	0.282	1.37
Lower Strath Rory Formation	11/30A-10	3190	3339	149	32	0.21	0.06	0.05	0.09	0.679	0.103	6.48
Lower Strath Rory Formation	12/27-1	2132	2346	214	171	0.80	0.10	0.05	0.20	0.195	0.038	0.94
Struie Formation	12/27-1	2346	3317	[nb]971	5	0.01	0.16	0.05	0.27	1.280	0.027	3.90
Granitic basement	11/30A-10	3339	3500	[nb]161	0	0.00	0.05	0.05	0.05	0.100	0.098	0.10

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. 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 (Khair, mD)		
Well	**Formation**	**Number of points**	**Depth of top core measurement**	**Depth of bottom core measurement**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**
11/30a-10	Upper Strath Rory	67	2992.0	3010.5	0.08	0.03	0.17	0.30	0.001	1.10
	Lower Strath Rory	27	3295.5	3303.8	0.07	0.03	0.11	5.09	0.02	44
12/27-1	Struie	14	3027.3	3314.7	0.02	0.003	0.05	0.01	0.01	0.02
13/19-1	Middle Eday	53	1775.6	1791.5	0.16	0.08	0.20	33.62	0.24	158

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

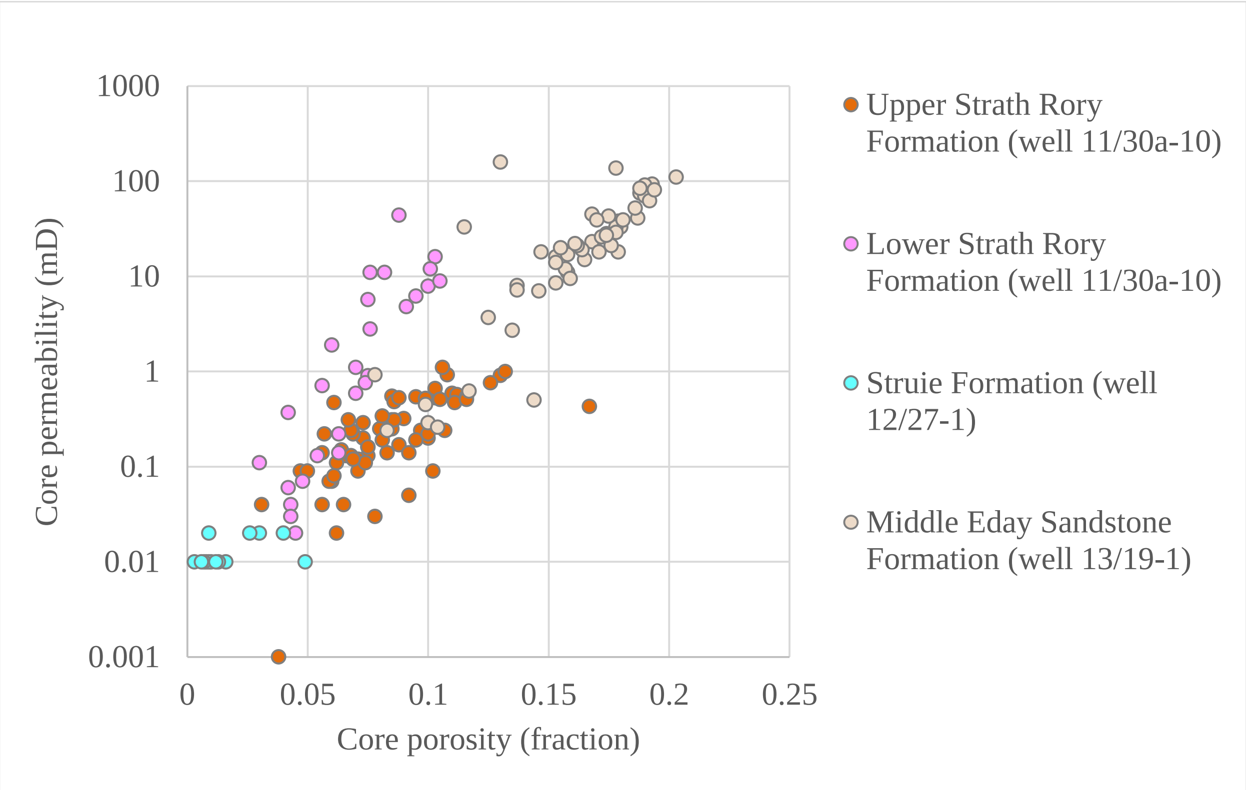


Figure 2 Cross plot of core porosity and permeability measurement data by formation for the wells examined.

5 Conclusions

"Quick-look" volume of clay (V_{CL}) and effective and total porosity curves were interpreted from geophysical log responses in each of 3 wells across the Orcadian Basin (Quads 11, 12 & 13). In addition a permeability estimation curve was derived from core porosity and permeability measurement data. These curves were used to calculate "quick-look" net to gross (NTG) values and average porosities and permeabilities 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 best reservoir properties appear to be found in the Middle Eday Sandstone Formation, which, in well 13/19-1, has a NTG of 1, an average porosity of 14% and the highest permeabilities recorded of the 3 wells (an average of 20 mD with values up to 174 mD estimated from logs calculations derived from associated core data). The Permian Rotliegend Group, and Zechstein Group also show favourable properties, slightly lower NTG and porosities than the Middle Eday Sandstone (Tables 1 and 3) and although no core was available in the 3 wells examined to derive specific permeability measurements from them, log derived estimates deeper core were up to 208 mD. The Buchan Formation also shows favourable properties, particularly in one well (13/19-1) where NTG was 1, porosity 12% and permeabilities estimated as up to 110 mD.

There may also be potential reservoir in the Upper and Lower Strath Rory formations, as they have good NTG (0.92 and 0.56 respectively) and average porosities (16% and 10% respectively). However, from the data examined, their permeabilities appear comparatively much lower (averages estimated as less than 1 mD, with the highest values estimated (and measured on core) around 5 mD.

Over these potential formations of interest, log responses suggest that there are relatively thick intervals of clean "good" reservoir intervals, in comparison to the CNS reservoirs studied which were dominated by a heterolithic succession (Hannis, 2015).

The Eday Flagstones, Lower Eday Sandstone and Kupfershiefer formations appear to have poor reservoir properties. The Orcadia and Struie formations and the Granitic basement are not considered to have any in-matrix reservoir potential.

Given the relatively few wells interpreted and the distances between them, no attempts to discern any regional trends within the formations has been made (some data is shown geographically in Section 5.1. Average properties by formation and well are tabulated below, with data extracted from Tables 1 & 2).

Formation	Av NTG	Log calculated (for 'net intervals') Highest Av PHI	Highest Av PermEst	*Measured on core (from parts of the formation)* ***Highest Av PHI***	***Highest Av PermEst***	**Concluding comments**
Zechstein Group	0.7	0.11	8.15			*Reasonable reservoir potential*
Kupferschiefer	0.13	0.07	0.55			
Rotliegend Group	0.83	0.15	3.15			*Good reservoir potential*
Buchan Formation	0.66	0.12	9.07			
Eday Marl Formation	0.04	0.06	0.35			*Mostly non-reservoir*
Middle Eday Sandstone Formation	1.00	0.14	19.99	*0.16*	*33.62*	*Best net to gross and highest permeability*
Eday Flagstone Formation	0.18	0.09	2.08			
Lower Eday Sandstone Formation	0.15	0.09	3.31			
Upper Strath Rory Formation	0.92	0.16	0.63	*0.08*	*0.30*	*High NTG and porosity, although permeability is low*
Orcadia Formation	0.07	0.07	0.53			*Mostly non-reservoir*
Lower Strath Rory Formation	0.56	0.10	0.68	*0.07*	*5.09*	
Struie Formation	0.01	0.16	1.28	*0.02*	*0.01*	*Lowest net to gross values; not considered to be a reservoir units*
Granitic basement	0.00	0.05	0.10			

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

Well	Gross	Net	N/G	Average PHIE	Average PermEst
11/30A-10	895	351	0.39	0.09	1.05
12/27-1	1652	602	0.36	0.14	0.50
13/19-1	665	305	0.46	0.12	9.62

Table 4 Synthesis of petrophysical results (data in Table 1) by well for the Palaeozoic section

5.1 MAPS SUMMARISING PETROPHYSICAL RESULT (IN TABLE 1)

Height of bars indicate the relative thickness of Palaeozoic 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).

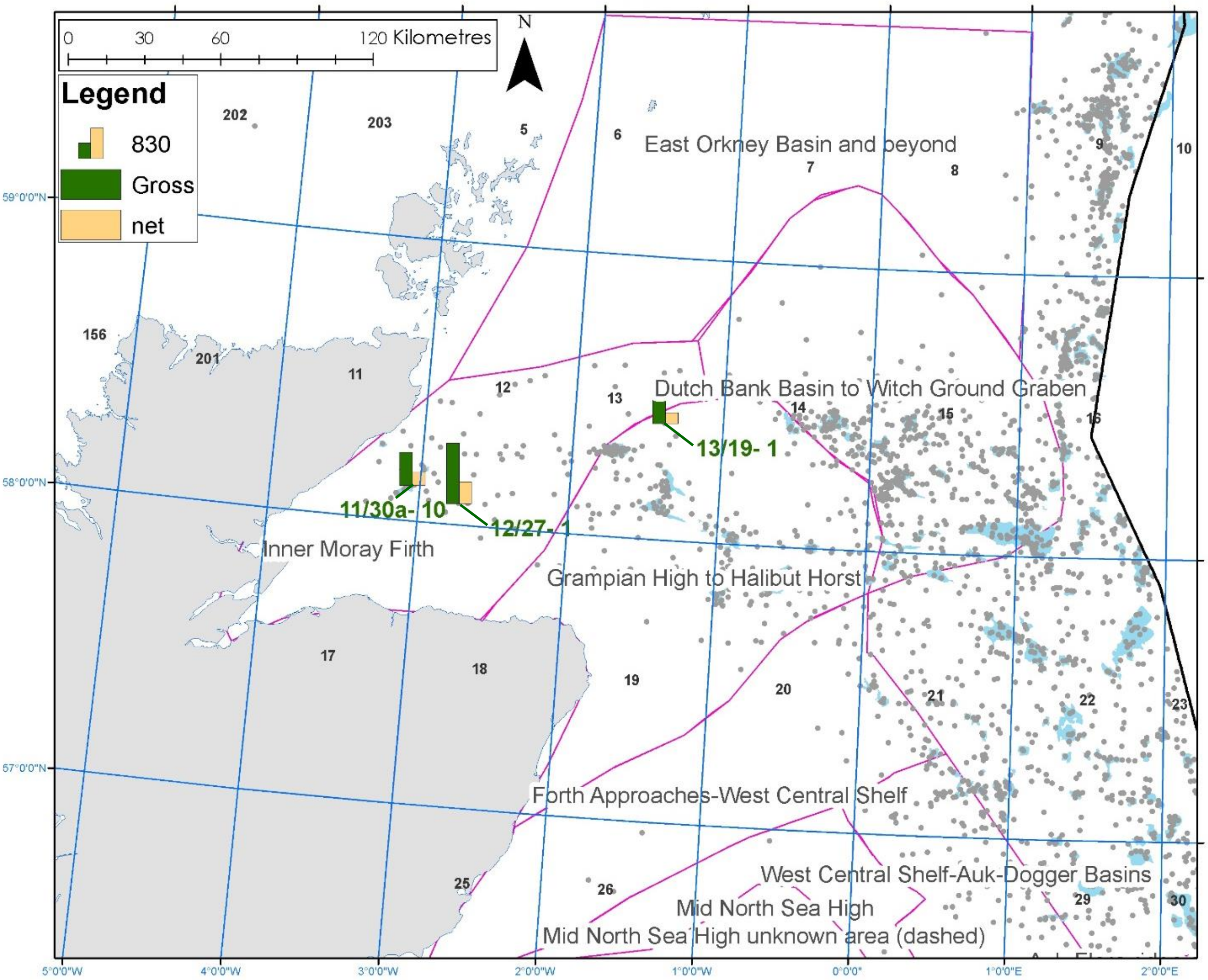


Figure 3 Indication of Gross and Net thickness for whole Palaeozoic interval for each well

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 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)

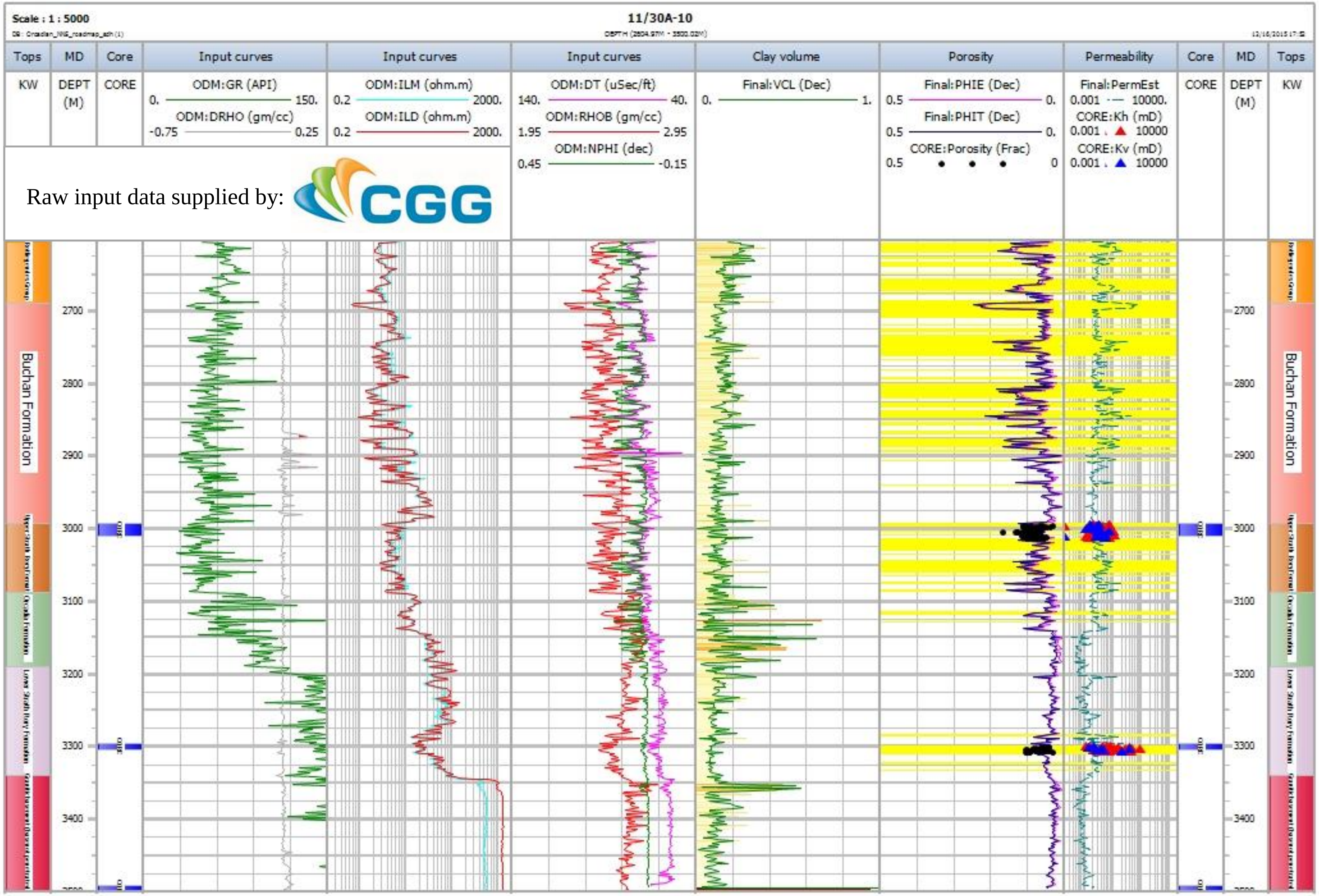
Track 6: Input curves: Porosity curves, sonic (pink, e.g. DT), density (red, e.g. RHOB) and neutron (green, e.g. NPHI)

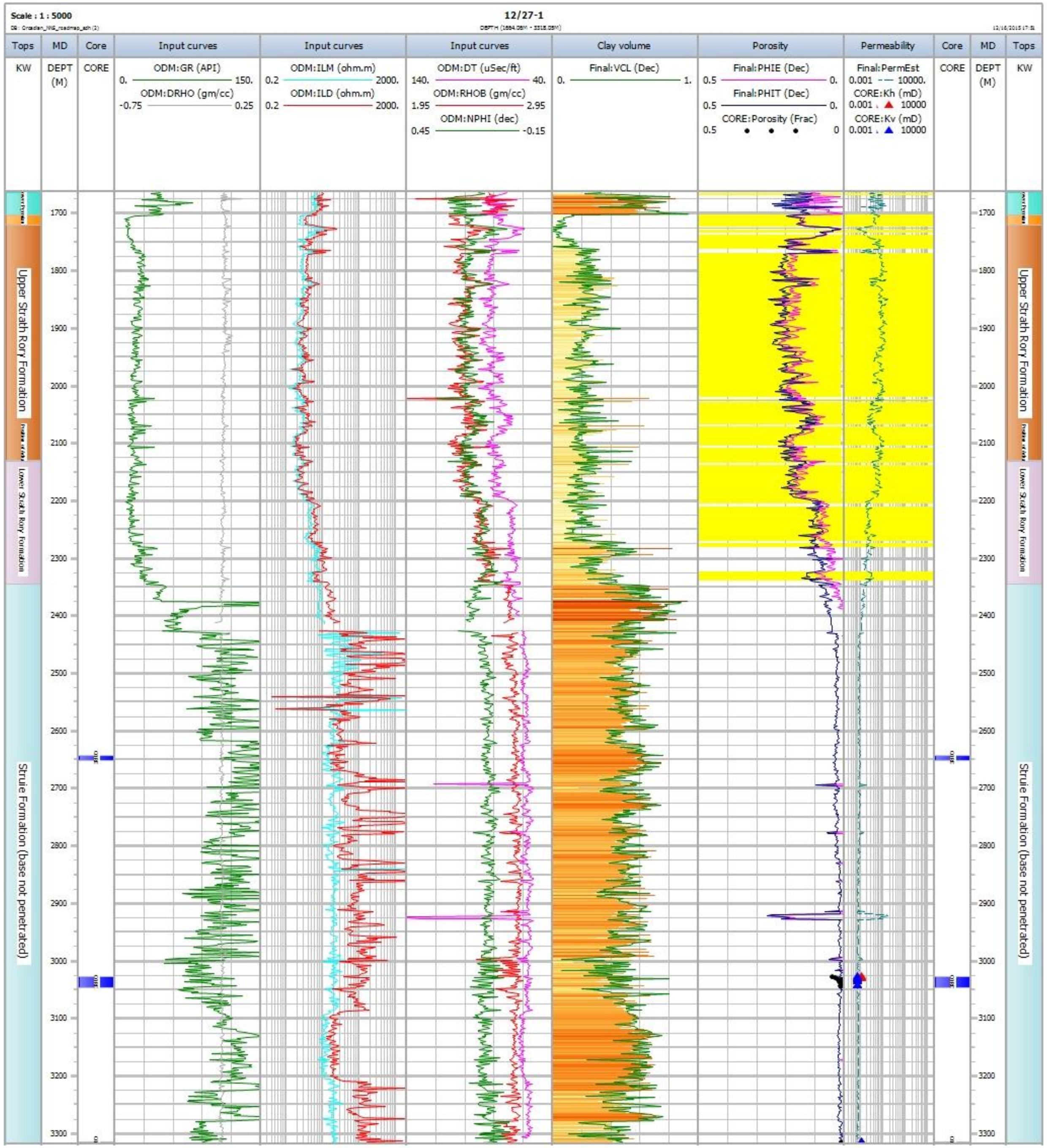
Track 7: Interpreted curves: Clay volume (V_{CL}). Variable brown shading helps to highlight cleaner intervals in pale colours and clay-rich intervals in dark brown.

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

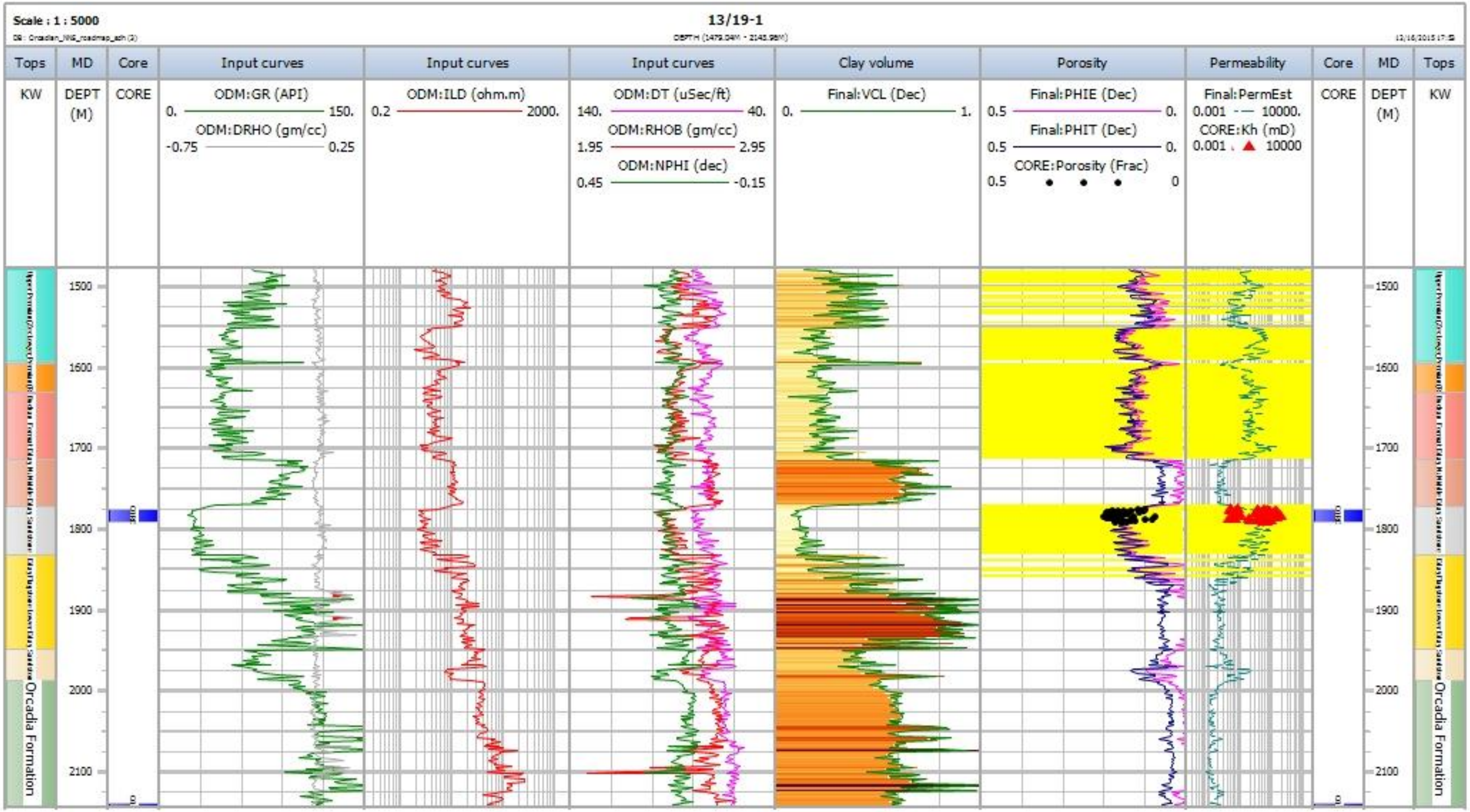
Track 9: Interpreted curves: Permeability (PermEst). Also includes discrete permeability data from core reports, where available.

Yellow shading across the porosity – permeability tracks (8&9) indicates the Net reservoir intervals. It shows where V_{CL}<0.5 and PHIE>0.05. Note that intervals with less than 5% porosity are not included in this shaded area, unlike for the CNS area report (Hannis, 2015).


Scale : 1 : 5000
11/30A-10
Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
KW
DEPT (M)
CORE
ODM:GR (API)
0. 150.
ODM:DRHO (gm/cc)
-0.75 0.25
ODM:ILM (ohm.m)
0.2 2000.
ODM:ILD (ohm.m)
0.2 2000.
ODM:DT (uSec/ft)
140. 40.
ODM:RHOB (gm/cc)
1.95 2.95
ODM:NPHI (dec)
0.45 -0.15
Final:VCL (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:Kh (mD)
0.001 10000
CORE:Kv (mD)
0.001 10000
CORE
DEPT (M)
KW
Raw input data supplied by:
CGG
2700
2800
2900
3000
3100
3200
3300
3400
Buchan Formation



Raw input data supplied by:



Scale : 1 : 5000
13/19-1
Tops
MD
Core
Input curves
Input curves
Input curves
Clay volume
Porosity
Permeability
Core
MD
Tops
KW
DEPT (M)
CORE
ODM:GR (API)
0. 150.
ODM:DRHO (gm/cc)
-0.75 0.25
ODM:ILD (ohm.m)
0.2 2000.
ODM:DT (uSec/ft)
140. 40.
ODM:RHOB (gm/cc)
1.95 2.95
ODM:NPHI (dec)
0.45 -0.15
Final:VCL (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:Kh (mD)
0.001 10000
DEPT (M)
KW
1500
1600
1700
1800
1900
2000
2100
Orcadia Formation

Appendix 2 Core and curve data used for permeability estimations

See section 3.4 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 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 purely on comparison between the log and core porosity, rather than using e.g. 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.

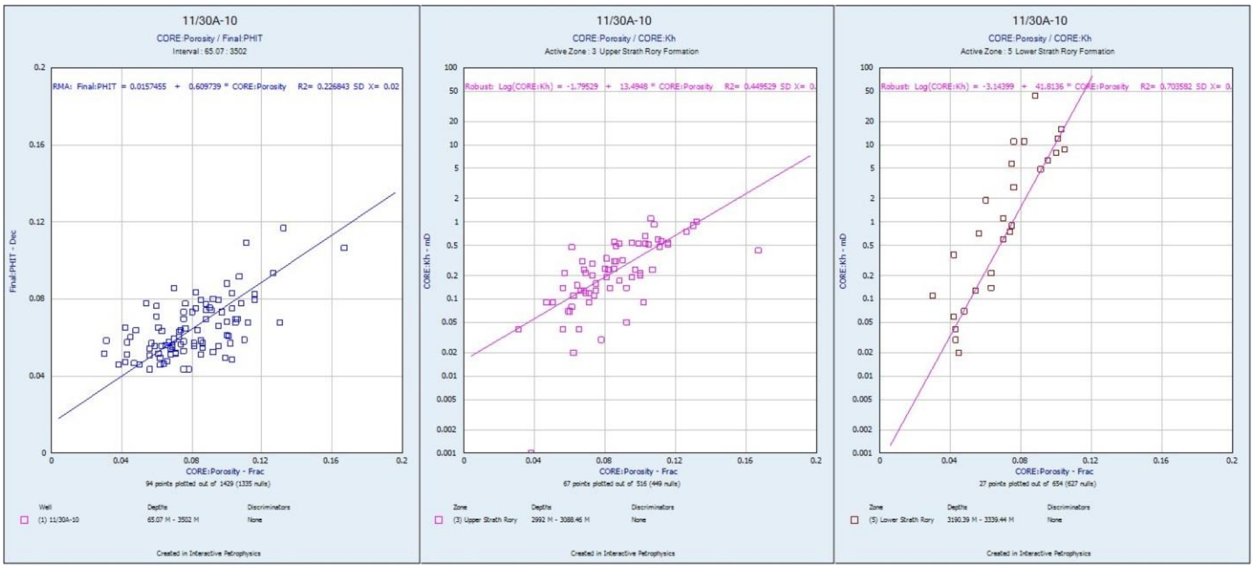
Well	Top depth (m)	Bottom depth (m)	Core depth shift (m)	Comments
11/30a-10	2987.2	3016.9	3.6	-
	3292.0	3309.1	4.8	-
12/27-1	3027.3	3314.7	0	Not possible, too few data points and not enough difference in values
13/19-1	1775.6	1791.5	0	Data appears to be on depth already

Table 5 Depths shifts applied to core porosity and permeability data

CROSS PLOTS AND SUMMARY STATISTICS OF RELATIONSHIPS USED FOR PERMEABILITY ESTIMATIONS

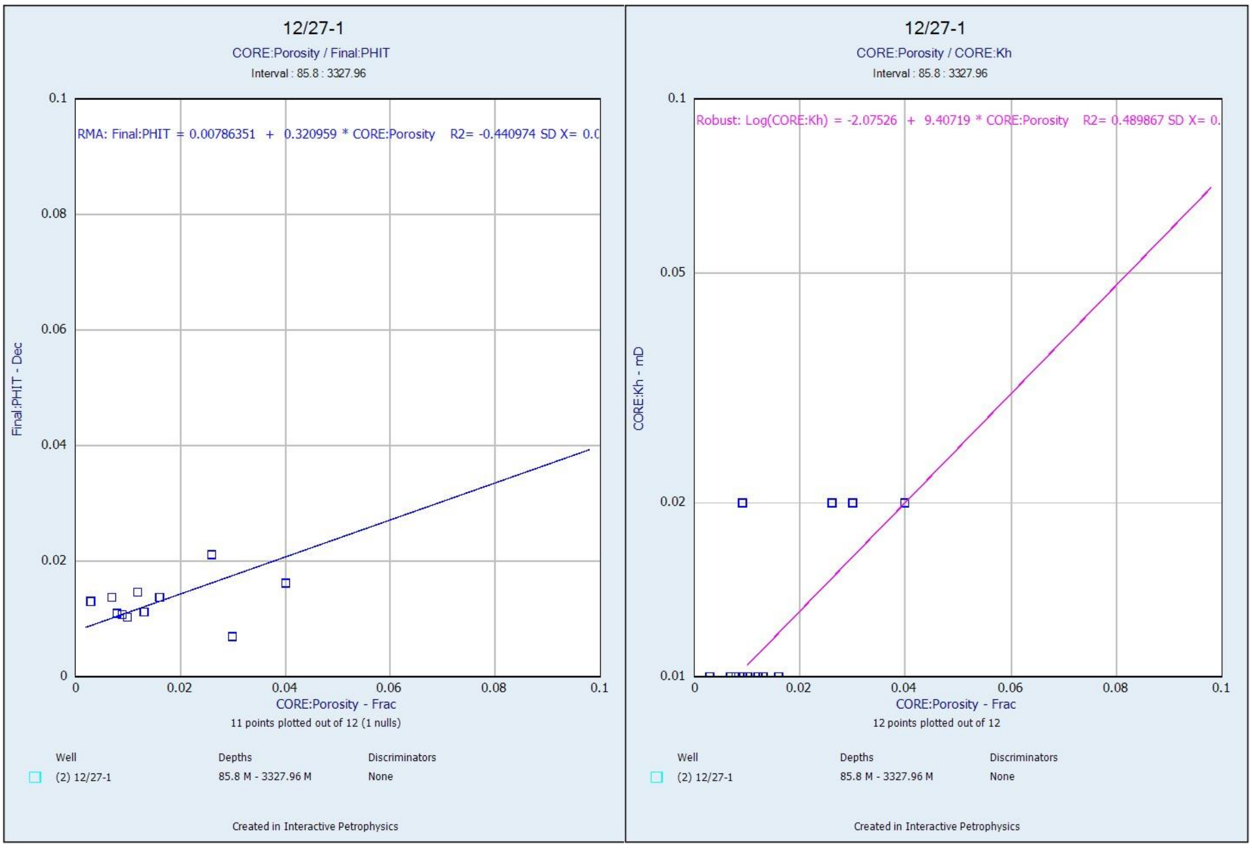
For each well that data was available for, core porosity is plotted against log porosity (left) and core porosity is plotted against permeability (right). The equations of the lines (where a relationship was found to exist) are summarised in Table 6 and Table 7. In general PHIT was found to give the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

WELL 11/30a-10



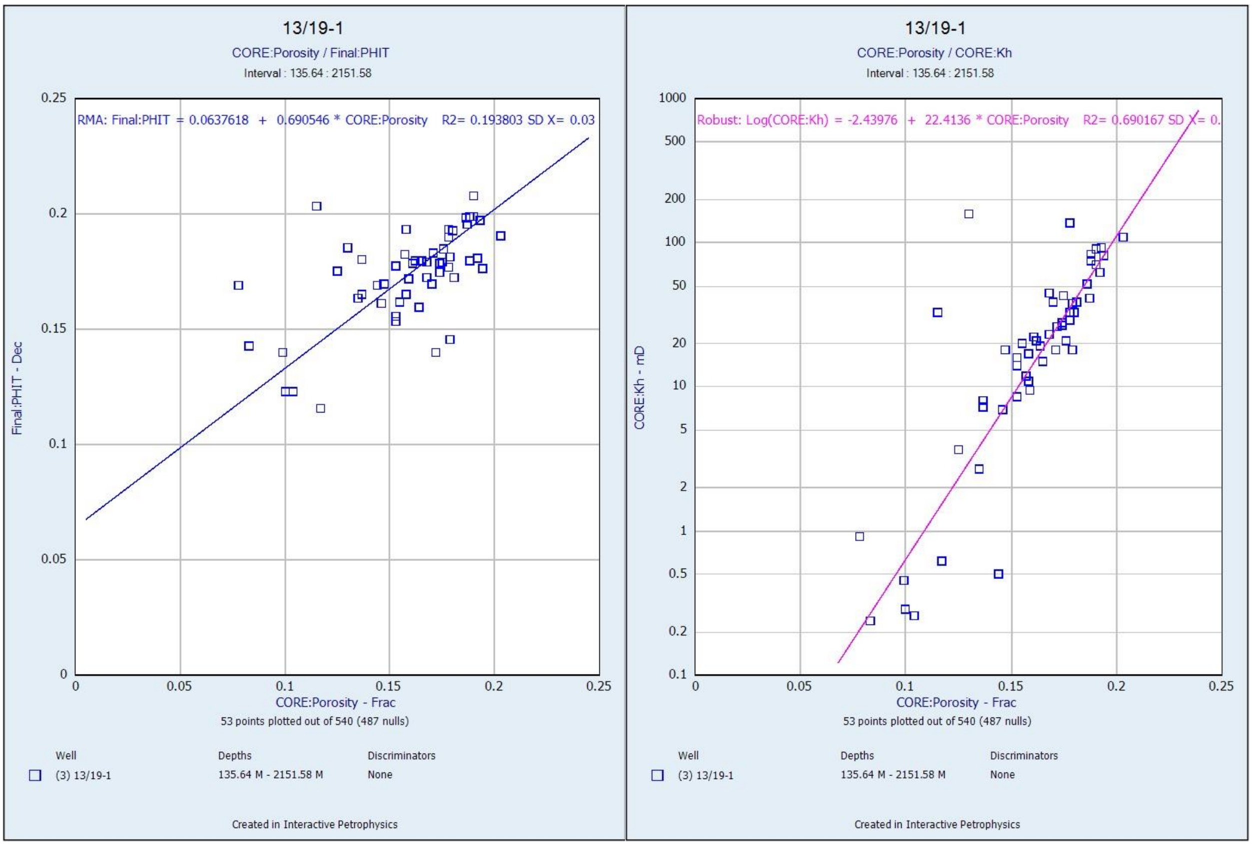
The core data over the Upper and Lower Strath Rory formations had quite different porosity-permeability relationships, so these were separated and the Upper Strath Rory relationship (above, middle) was used above the depths of 3140.2m and the Lower Strath Rory relationship (above right), was used below that depth. The split is midway through the Orcadia Formation and corresponds to an observed change in the porosity styles between the Upper and Lower Palaeozoic log section. It is not clear whether this is a lithological or diagenetic effect.

WELL 12/27-1



There are relatively few data points from which to define relationships in this well and the points sampled show very low porosity and permeability values. The propagation of this relationship into the upper parts of the Palaeozoic log section (above the Lower Strath Rory Formation) should be treated with extreme caution.

WELL 13/19-1



The core data from this well is from the Middle Eday sandstone. Although there is a reasonably good relationship in the core porosity – permeability data across this interval, the projections of this relationship to estimate permeabilities into the other Palaeozoic formations, should naturally be treated more cautiously.

				Relationship			Core porosity statistics				PHI curve statistics			
Well	**Top depth**	**Base depth**	# of points	Porosity Curve (Final:PHI) =	Core porosity points (Core:porosity) =	R2	SD	Mean	Max	Min	SD	Mean	Max	Min
11/30A-10	2992	3303	94	Final:PHIT = 0.015745505 + 0.609739049 * CORE:Porosity	CORE:Porosity = -0.025823351 + 1.640045856 * Final:PHIT	0.23	0.02	0.08	0.17	0.03	0.01	0.06	0.12	0.04
12/27-1	3027	3314	11	Final:PHIT = 0.007863511 + 0.320959498 * CORE:Porosity	CORE:Porosity = -0.024500011 + 3.115657914 * Final:PHIT	-0.44	0.01	0.02	0.04	0.00	0.00	0.01	0.02	0.01
13/19-1	1775	1791	53	Final:PHIT = 0.063761785 + 0.690546019 * CORE:Porosity	CORE:Porosity = -0.092335315 + 1.448129411 * Final:PHIT	0.19	0.03	0.16	0.20	0.08	0.02	0.17	0.21	0.12

Table 6 Summary statistics of core porosity – curve porosity relationships

			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
11/30A-10 Upper	2992	3140	67	**10^(-1.795291305 + 13.49483332 * Final:PHIT)**	-1.795291305 + 13.49483332 * CORE:Porosity	0.133035456 + 0.074102434 * Log(CORE:Kh)	0.45	0.02	0.08	0.17	0.03	0.48	-0.71	0.04	-3.00
11/30A-10 Lower	3140	3303	27	**10^(-3.143994808 + 41.813571268 * Final:PHIT)**	-3.143994808 + 41.813571268 * CORE:Porosity	0.075190774 + 0.02391568 * Log(CORE:Kh)	0.70	0.02	0.07	0.11	0.03	0.97	-0.02	1.64	-1.70
12/27-1	3027	3314	12	**10^(-2.075258017 + 9.407189938 * Final:PHIT)**	-2.075258017 + 9.407189938 * CORE:Porosity	0.220603393 + 0.10630167 * Log(CORE:Kh)	0.49	0.01	0.02	0.04	0.00	0.15	-1.90	-1.70	-2.00
13/19-1	1775	1791	53	**10^(-2.439762115 + 22.41359902 * Final:PHIT)**	-2.439762115 + 22.41359902 * CORE:Porosity	0.108851868 + 0.044615771 * Log(CORE:Kh)	0.69	0.03	0.16	0.20	0.08	0.72	1.18	2.20	-0.62

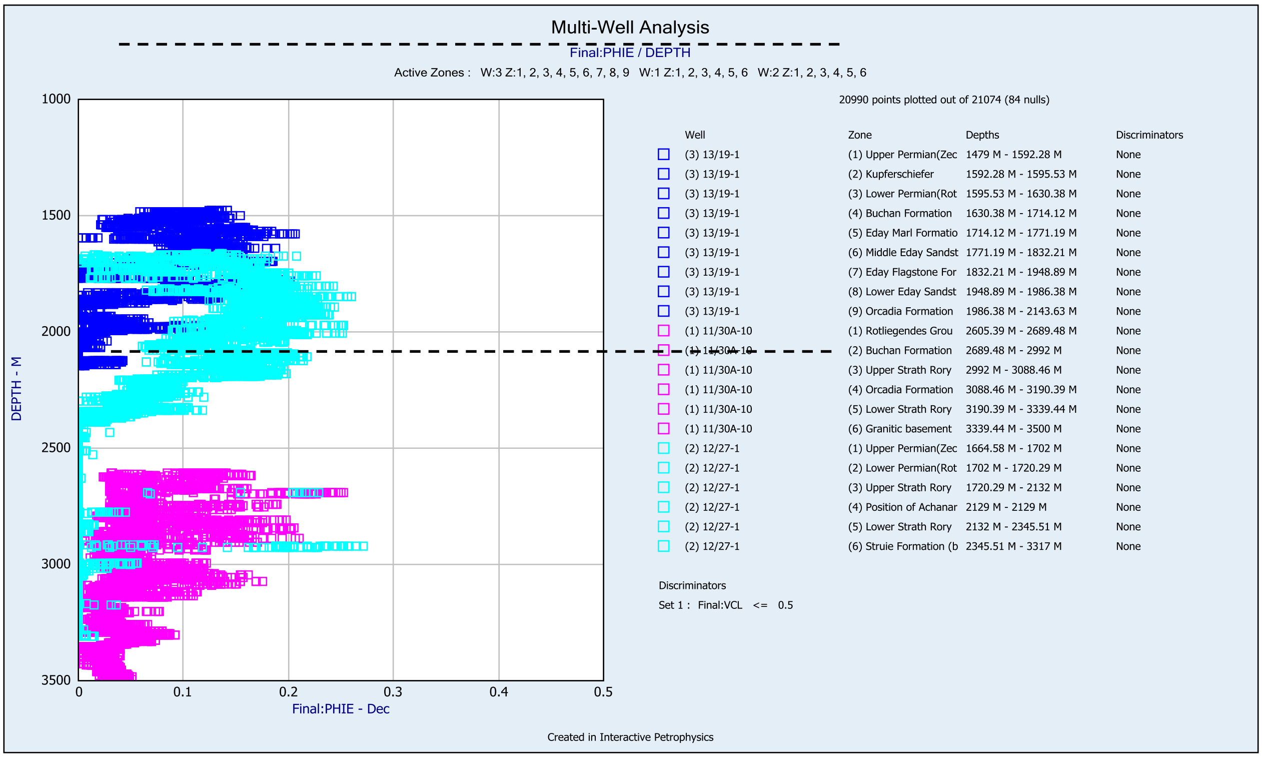
Table 7 Summary statistics of core porosity – permeability relationships

(11/30A-10 boundary between relationships defined by change in porosity style at 3140 m)

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 (3 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 c**ore porosities versus depth** plot is coloured by formation and shows all core points.

PHIE VERSUS DEPTH FOR ALL WELLS, ALL FORMATIONS



CORE POROSITIES VS DEPTH FOR ALL WELLS, ALL FORMAIONS

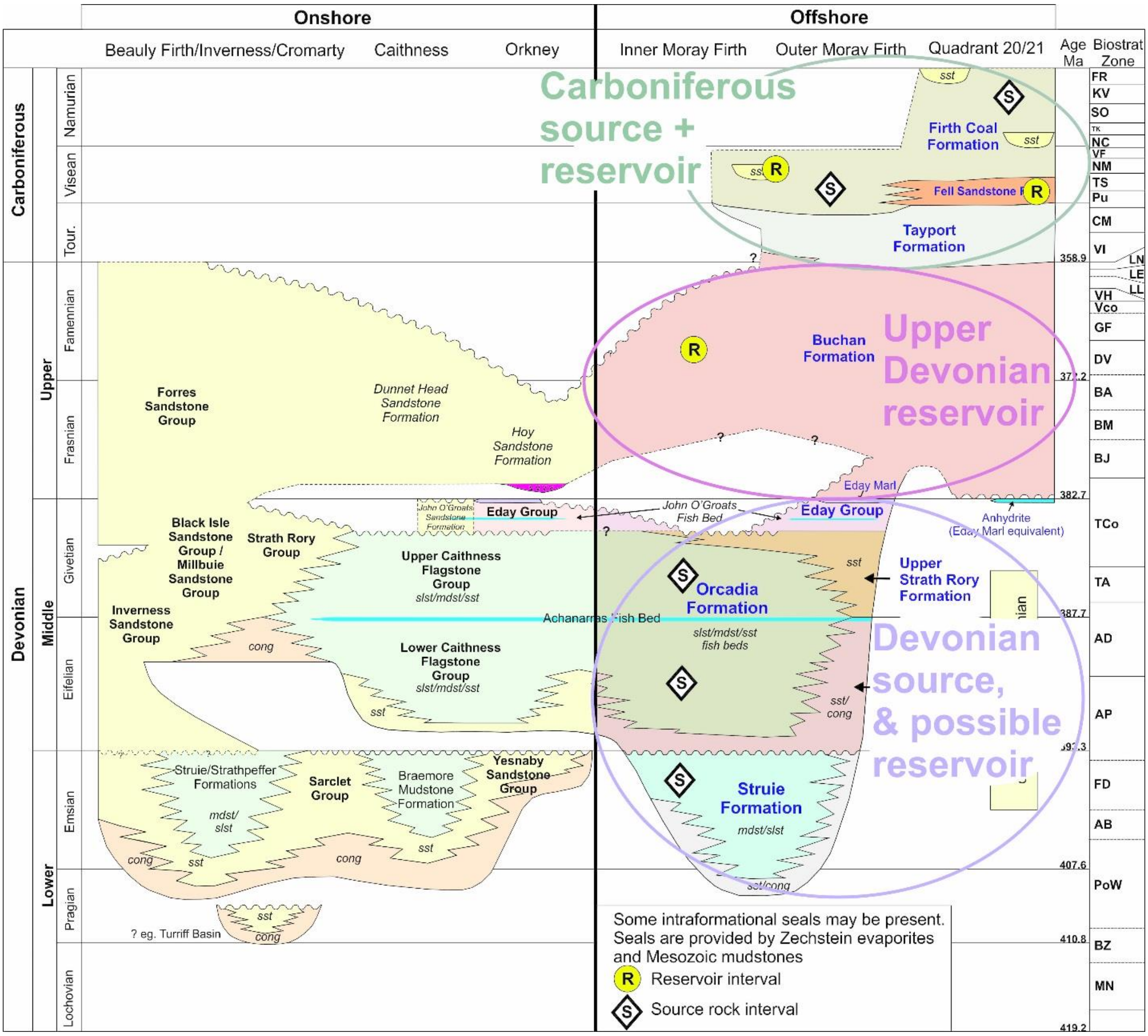
Appendix 4 Table of log quality and interpretation comments

Well	Interpretation/data quality comments for report
11/10a-30	Few points where DRHO is out of tolerance
12/27-1	DRHO in tolerance for full Perm-Dev-Carb section, suggests density data is good. Data gap from 2400.5 to 2427.3. filled with straight line value.
13/19-1	Coaly or organic matter eday flagstones. Some DRHO out of tolerance. Used sonic porosity calculation over those zones Good match to core data.

Table 8 Table of log quality and interpretation comments

Appendix 5 Copy of stratigraphic chart

A summary of the stratigraphic report is shown below, from Whitbread and Kearsey (2016).



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.

HANNIS, S. 2015. Reservoir evaluation of 12 wells in the Devonian – Carboniferous of the Central North Sea: Petrophysical interpretations of clay volume, porosity and permeability estimations. *British Geological Survey Commissioned Report*, CR/15/120. 55pp

SCHLUMBERGER, 2009. Log Interpretation Charts. 2009 Edition. Available from http://www.slb.com

SERRA, O. 2007. Well logging and reservoir evaluation (Paris: Editions Technip) ISBN 978 2 7108 0881 7

WHITBREAD, K AND KEARSEY, T 2016. Devonian and Carboniferous stratigraphical correlation and interpretation in the Orcadian area, Central North Sea, Quadrants 7 – 22. *British Geological Survey, Commissioned Report* CR/16/032, 74pp