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Maturity and migration modelling of selected wells in the Central North Sea

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Foreword and acknowledgements

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Summary

This report details maturity and migration modelling of selected wells in the UK Central North Sea for the 21CXRM Palaeozoic project. The aim of the maturity and migration modelling was to predict if Carboniferous-Devonian source rock intervals are, or have been, mature for hydrocarbon generation around the Mid North Sea High (MNSH) region and to examine the timing and possible migration routes of any generated hydrocarbons.

Modelling data selection and main expected plays

Eight wells were chosen for 1D modelling based on availability of data and the location of the wells such that the models would contribute to understanding the thermal maturity of four selected Palaeozoic regions; the Forth Approaches Basin (Quadrant 26), the Mid North Sea High (Quadrant 36), an area to the south of the MNSH (Quadrants 41, 42, 43) and an area to the east of the MNSH (Quadrants 29 and 38; the North Dogger and Quadrant 29 basins). Few data were available for the latter area so this region was modelled using two ‘scenario’ wells to consider different possible burial histories and the generation potential.

For the 1D well modelling, the main play examined was generation from the late Palaeozoic mid–late Carboniferous Scremerston/Firth Coal, Yoredale and Millstone Grit formations and laterally equivalent Cleveland Group. The main caprock formation was expected to be the Zechstein Group. Other Palaeozoic rocks were also examined as potential source rocks.

Forth Approaches Basin

The modelled burial history for the Forth Approaches region supported maximum burial of the Palaeozoic source rocks during the Cenozoic Era. The main source rock, the Scremerston/Firth Coal Formation, is only proven in two wells in the depocentre so its extent is not well delineated. The Scremerston/Firth Coal Formation was present in the modelled well 26/08-01 which lay in the basin depocentre. Here it was deemed to be dominantly gas prone and the maturity modelling suggested that the gas window was not reached, thus significant generation was not expected from the Palaeozoic rocks at this location (Figure 8). Minor volumes of oil generation could be expected from the mainly gas prone kerogens as they pass through the oil maturity window. The 1D models indicated that this minor generation mainly occurred from Triassic times onwards suggesting that any expelled hydrocarbons could be trapped by the Permian Zechstein Formation. Legacy reports suggest a more optimistic picture as they describe oil and gas shows with a Carboniferous source in other wells located in the Forth Approaches depocentre (e.g. Wells 26/04-01, 26/07-01, 28/05-01) and on the basin flanks (well 26/12-01), indicative of hydrocarbon generation from more deeply buried gas- and oil-prone source rocks in the Forth Approaches Basin, than in the modelled well. Migrated hydrocarbons from a Carboniferous source are also reported in Well 26/12-01 located on the flank of the basin in one legacy report (see section 5 for more detail).

The Palaeozoic rocks deeply buried in the depocentre of the Forth Approaches Basin are believed to have potential for both oil and gas, but the potential seems variable laterally and geochemically. Oil and gas prone kerogens are likely to be present in the depocentre and there is evidence that hydrocarbons generated from a Carboniferous source have migrated into younger and shallower reservoirs.

Mid North Sea High

Deepest burial of the Palaeozoic source rocks across the Mid North Sea High (MNSH) occurred during the Carboniferous Period, prior to deposition of the main seal (Zechstein Formation) and thus trapping would have relied on intraformational seals. Though it is mapped on seismic over part of the MNSH, the Scremerston Formation has not been penetrated by wells in Quadrant 36 or 37 (the wells terminated in the Yoredale Group, see Figure 2). The maturity of the Yoredale Formation, which is penetrated by the two modelled wells, is the early – mid oil maturity window (Figure 22 and Figure 28). The organic matter in this formation is interpreted to be mainly gas prone with some oil-prone intervals so generation potential is expected to be low at the location of the modelled wells. Further south in Quadrant 36, deeper burial of the Yoredale and Scremerston formations could have pushed source rocks into the late oil maturity window. A few minor gas shows and/or UV fluorescence are reported in Wells 36/13-01 and 36/23-01 and other wells on the MNSH (36/15-01, 36/23-01, 36/26-01; see Section 6 for more detail).

At the well locations studied, the MNSH is not expected to be prospective for hydrocarbons but the Yoredale Formation could have potential if more deeply buried.

Area south of the MNSH, Quadrant 41, 42, 43

The presence of the probable kitchen area to the south of the MNSH has been suggested by previous studies (e.g. Hay et al., 2005). Four wells were modelled in this area south of the MNSH (41/14-01, 41/20-01, 43/17-02 and 42/10b-02). The geohistory models support maximum burial during the Cenozoic Era. Palaeozoic strata penetrated by wells for this study reached the late mature for oil and gas maturity windows. Organic matter contained a mix of oil and gas prone kerogens and generation potential of organic matter ranged from moderate to good. The current models suggested hydrocarbon generation from Visean-Westphalian source rocks (Coal Measures Group, Cleveland Group, Yoredale Formation and Scremerston Formation) did occur. The timescale for generation and expulsion (where it occurred) ranged from Carboniferous to

Cenozoic times. The occurrence of hydrocarbon generation is also supported by the presence of gas and oil shows described in various wells including those modelled for this study. Where the source is specified in legacy reports, for at least some wells, Palaeozoic strata are indicated (See Section 7 for more detail). In addition, the Esmond, Forbes and Gordon gasfields (blocks 43/8a, 43/13a, 43/15a and 43/20a) produce from the Bunter Sandstone Group and the source is believed to be Westphalian coals.

The current models and legacy reports suggest this area potentially generated hydrocarbons from a Palaeozoic source therefore this area was labelled as a 'probable' kitchen area by the current study. Model results are shown in Figure 34, Figure 42, Figure 50 and Figure 57.

East of the Mid North Sea High, Quadrants 29 and 38

Wells 29/27-01 and 38/18-01 were used to examine the two Devono-Carboniferous basins to the east of the MNSH. Although geochemical data are limited for these wells, the modelling of various potential burial history 'scenarios' suggests that deepest burial occurred during the Cenozoic Era. The Scremerston Formation was modelled as early mature for oil in both wells (note that this formation is not penetrated by Well 29/27-01 so this is a maturity scenario). The limited geochemical data available suggests this formation contains mainly gas prone kerogen with some limited oil prone organic matter so significant generation is not anticipated either modelled well location. Additional strata was added to the BasinMod models to investigate how much strata would have been required for source rocks to reach the gas window; the model results indicated an additional 3.4 – 3.5 km of additional strata would have been required (Figure 73 and Figure 87). Based on the maturity data and the geological history of this region, this is not likely and so significant generation at the location of the modelled wells is not expected.

Well 29/27-01 and Well 29/23b-02 (which lie on the same flank of the Quadrant 29 Basin) did not encounter significant hydrocarbon shows. These wells terminate in Permian strata. Although these wells do not appear prospective for hydrocarbons due to immaturity of source rocks (see model for Well 29/27-01, Figure 67), Carboniferous strata elsewhere in the Quadrant 29 Basin could have potential for hydrocarbons. This is suggested by the presence of oil and gas shows in wells around/within the basin recorded in legacy reports.

Well 38/18-01 lies on a high adjacent to the Dogger Basin. The Scremerston Formation appears to have reached the early oil maturity window (Figure 81). The Scremerston Formation is described as a good – excellent quality source rock which contains both oil and gas prone organic matter (see Section 8 for more detail). Oil staining is observed in the Scremerston Formation in Well 38/18-01, which could have been generated in-situ. Minor gas shows are reported throughout Well 38/18-01 and Well 38/16-01 which lie on the same flank of the Dogger Basin. Data is lacking from the centre of the Dogger Basin but the Scremerston Formation would be expected to be a viable mature source rock for oil assuming similar facies and TOCs to those found on its flanks.

Based on the current models, data provided by sponsors and available legacy reports the Quadrant 29 Basin and Dogger Basin were labelled as 'possible' kitchen areas. Few data are available, but the source rock potential from the limited data is good – excellent for the Dogger Basin. Oil and gas shows are recorded in legacy reports in and around the Quadrant 29 Basin so generation may have occurred. Additional data is required to confirm the potential of these two basins.

Regional 3D maturity and migration modelling

The 1D BasinMod models were used as the basis for regional 3D maturity and migration modelling across the whole CNS study area. The Scremerston Formation is one of the main source rocks for this region and has been seismically mapped over much of the CNS (Arsenikos et al., this study). This formation was used as the source rock for regional 3D flow modelling work, with the Rotliegend strata selected as the potential reservoir. The modelling suggests that generation occurred in the south of the area of interest (Quadrants 42-44 and the south part of Quadrant 36; Figure 93 and Figure 95) and migration was generally towards the north-west and to a lesser degree, towards the east of the study area. The flow model should be considered with caution due to the sparseness of included data. The regional assessment of the hydrocarbon generation carried out for this study is considered more reliable than the migration and accumulation modelling. This is because the flow modelling is more sensitive to the sparseness of data, resolution of depth grids used and the grid spacing, which will reduce the reliability of the detailed flow model results. The 1D and 3D models all suggest some generation could have occurred in the southern kitchen area which is supported by the presence of hydrocarbon accumulations in this region. However, the details of the migration/accumulation modelling, which predicts long range and multi-stage migration pathways, is not considered geologically likely due to the presence of small scale traps, intraformational seals and the lack of evidence for large scale accumulations in the regions proposed by the flow model results. The unreliability of flow model results are caused by the coarseness of the data input.

The regional maturity modelling supports the presence of a Palaeozoic kitchen area south of the MNSH across Quadrants 42-44 and the south part of Quadrant 36.

1 Introduction

The 21CXRM Palaeozoic Project aims 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 maturity and migration modelling of selected wells in the Central North Sea study area.

The aim of the modelling was to predict if Carboniferous–Devonian source rock intervals are, or have been, mature for hydrocarbon generation, and to model the timing of burial and hydrocarbon generation (if it occurred) for four regions of the Central North Sea (Figure 1). Geochemical and maturity data were extracted from CDA well reports used to supplement data generously donated by a number of Sponsor companies. A summary of the stratigraphy utilised for this report is shown in Figure 2.

This report is divided into a short section describing the modelling methodology and rationale for well selection (Section 2) followed by an overview of the 1D and BasinFlow modelling modelling results (Sections 3 and 4). Details of the 1D models are provided in sections 5 – 8. These sections include a geological history of each of the main areas considered, data from legacy reports for wells which lie close to the wells being studied for this report, previous maturity modelling results for the wells being studied and data and results of the new models. Details of the flow modelling are given in Section 9.

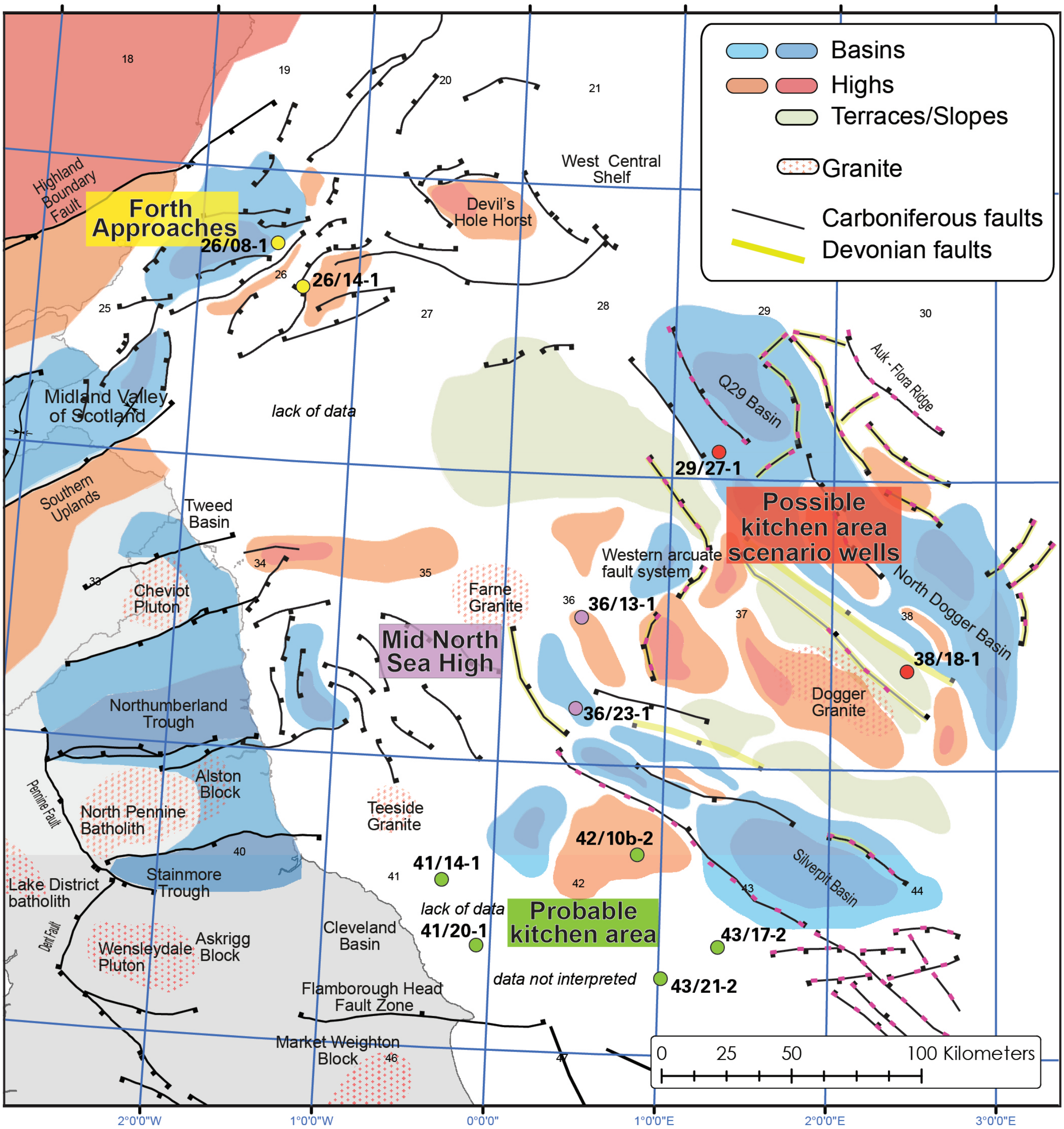


Figure 1: Summary of study areas and wells modelled in the 1D maturity study placed on the Upper Palaeozoic structural framework map from Arsenikos et al (this study). Note that Well 43/21- 2 was considered and then discarded due to poor quality data. The wells are coloured according to the study area in which they are considered to lie.

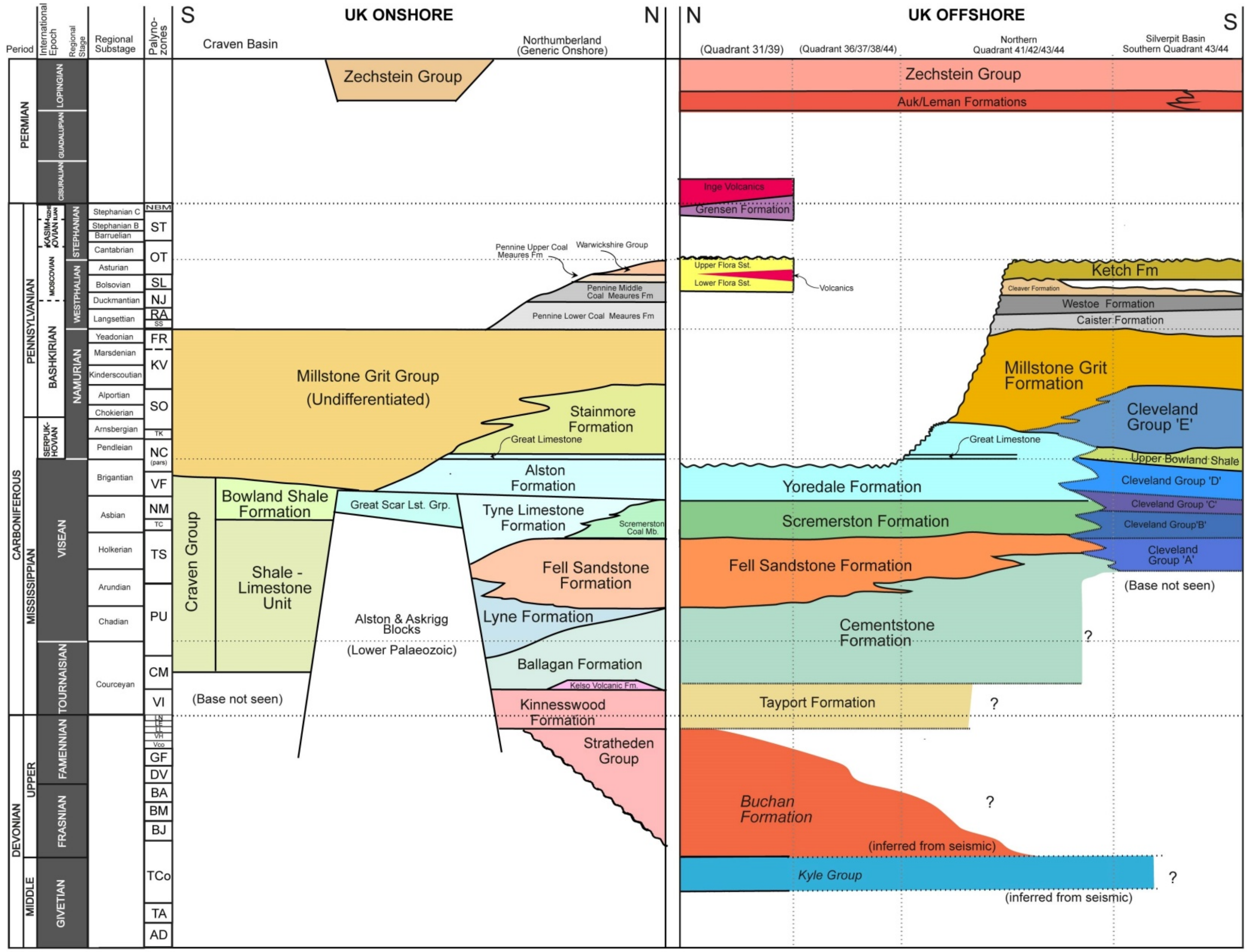


Figure 2 Sketch of Carboniferous stratigraphical successions and correlation of the onshore UK and adjacent quadrants in the Central North Sea, from Kearsey et al. (this study).

2 Modelling methodology

The aims of the thermal and burial/uplift modelling were to

- Predict if Carboniferous-Devonian source rock intervals are, or have been, mature for hydrocarbon generation (BasinMod)
- To predict when hydrocarbon generation occurred (BasinMod and BasinFlow)
- To contrast thermal histories in different areas on and around the Mid North Sea High (BasinMod)
- To predict migration routes for any generated hydrocarbon, at regional scale (BasinView and BasinFlow)

The regions of interest are the Forth Approaches Basin (Quadrant 26), the Mid North Sea High (Quadrant 36), a region to the south of the MNSH (Quadrants 41, 42, 43) and a region to the east of the MNSH (Quadrants 29 and 38, North Dogger and Quadrant 29 basins) (Figure 1).

The Forth Approaches Basin is of interest due to the adjacent productive onshore area in the Midland Valley of Scotland. The Mid North Sea High was targeted by the 21CXRM Palaeozoic Project as a possibly underexplored area which might be productive from Upper Palaeozoic source rocks. The area to the south of the MNSH was chosen to consider extension of Southern North Sea (SNS) gas field province northwards and down sequence as suggested by the Breagh Field. The area in Quadrants 29 and 38 was chosen due to the mapping of Devono-Carboniferous basins, which if generative potential is identified, could offer new underexplored plays.

The wells to be modelled were chosen based on availability of data and the location, such that the models would contribute to understanding the thermal maturity of four regions of interest.

For the Forth Approaches Basin, well 26/14-01 lies on the southern flank of the basin and penetrates to the Lower Devonian strata. Well 26/08-01 has a fair amount of maturity data and lies in the centre of the basin. These well models give an insight into the Forth Approaches Basin and northern edge of the Mid North Sea High.

Wells 36/13-01 and 36/23-01 both have a reasonable amount of maturity data and are representative of wells of the central-southern region of the Mid North Sea High, with a relatively thin Permo-Triassic strata overlying Carboniferous strata.

The wells in the area south of the MNSH have a good amount of maturity data and penetrate a good section of Palaeozoic strata. Well 41/20-01 has a large dataset, well 42/10b-02 penetrates a gas discovery, well 41/14-01 and 43/17-02 have a fair amount of maturity data and penetrate a good thickness of Palaeozoic strata. These wells were used together to give an idea of the generative potential of this region and are representative of this area. However, given that this region looks promising, additional modelling would be recommended to refine the understanding of the generative potential of this region.

In the Devono-Carboniferous basins of Quadrants 29 and 38, as maturity data were so sparse, selection of the wells was mainly constrained by the presence of data and the section of strata penetrated. Most wells had fewer than 5 maturity data which is insufficient to reliably calibrate a model. Well 29/27-01 was chosen to investigate the Quadrant 29 Basin since it lies within the depression, some maturity data were available for the upper part of the section and the well penetrates to the Rotliegend Group. (No wells penetrate any deeper than the Rotliegend Group in this basin). Well 38/18-01 was chosen to constrain the North Dogger Basin. Well 38/18-01 has few maturity data, but does penetrate the Carboniferous section.

Commonly used (e.g. Kubala et al., 2003) vitrinite reflectance values (VR) for oil and gas windows were used (Table 1). Some gas will be generated by gas-prone kerogens in the oil maturity windows, but main gas generation is expected in the main gas maturity window.

Table 1: maturity windows used for modelling

Maturity window	Vitrinite reflectance (VR, %)
Early Oil	0.5 – 0.7
Mid Oil	0.7 - 1
Late Oil	1 - 1.3
Main Gas	1.3 - 3

The VR data, 1-D and BasinFlow models give an understanding of the maturity of the basin and indicate which strata have reached sufficient maturity for any organic material which is present to generate oil or gas.

2.1 1D MODELLING METHODOLOGY

The 1D models were initially prepared in BasinMod™ v7.61 (Platte River Associates software) (v. 7.61). The software was then upgraded to BasinMod™ (v. October 2014) The 1D models allowed entry of detailed lithology and modelling of the heat flow to achieve the best fit to the vitrinite reflectance (VR) data.

Well stratigraphy and rock properties were used to model compaction and temperature through burial over geological time. The modelled maturity and vitrinite reflectance maturity data were then compared graphically and used to refine the model until the best fit to the available data was achieved. Where measured VR data were not available, VRcalc was generated by conversion of T_{max} from the RockEval and legacy datasets (see Vane et al. (this study) for limitations of this technique).

Kerogen typing and pyrolysis data (including Total Organic Content, TOC) were used to model the generative potential of the formations penetrated by the wells. Cumulative hydrocarbon plots (with cumulative mg/gTOC on the y axis) can be generated using BasinMod 1D. At any given time, the cumulative hydrocarbon curve is inversely proportional to the hydrogen index (HI) and TOC model results. The TOC (%) and HI (mg/gTOC) indicate the generative potential of the strata penetrated by the well. The cumulative hydrocarbon volume on the time plot shows generative potential being realised through time during thermal maturation. Examples of values for this parameter from other hydrocarbon basins are given to allow comparison: published BasinMod studies which show this factor include cumulative generation of hydrocarbons ranging from 600 mg/gTOC for the oil-prone source rocks of Beetaloo Basin, Australia (Silverman et al., 2007), to 160 mg/gTOC in the gas prone Gyeongsang Basin (unconventional reserves) and South Korea (Kang et al., 2014).

Plots of the maturity, temperature vs. depth and vs. time were produced. All depths used are measured depths below rotary table as given in the well logs and reports (here the abbreviation BRT is used to indicate measured depth below rotary table). The Rotary Table height and water depth are entered into the BasinMod model so these factors are corrected for in the model. None of the wells are significantly deviated.

BasinMod 1-D calculates heat flow curves based on the finite rifting model of Jarvis & McKenzie (1980). This assumes that in an extensional environment there is rapid initial subsidence due to crustal thinning associated with a thermal anomaly i.e. high heat flow. When crustal stretching ceases, heat is lost by vertical conduction and the slow decay of the heat flow leads to further subsidence due to thermal contraction.

In order to match the model to the recorded vitrinite data, estimates of the palaeo-heat flow and eroded sediments thicknesses are required. The thickness of sediment removed is estimated based on surrounding sediments and the VR data. The palaeo-heat flow is estimated based on a model of palaeo-rifting, subsidence and uplift events, to fit the scattered VR point data. Boreholes with more complete VR data were used to supplement understanding where there were fewer VR data available.

Regional memoirs, reports donated by sponsors and papers were used for the initial models of burial history (see references in the relevant sections). Additional input was received from the 21CXRM Palaeozoic project team:

- Updated Devonian-Carboniferous well picks (see Kearsey et al., this study). Younger picks from are taken from composite logs and well reports
- Eroded thickness compared to overburden thickness calculated from density logs (see Kimbell and Williamson, this study)
- Timing of deposition for Carboniferous formations was provided by expert stratigrapher (C. Waters, *pers. comm.*)
- Seismic interpretations of unconformity surfaces in/near wells to assess if estimated thicknesses of eroded strata are reasonable (Arsenikos et al., this study and S. Arsenikos *pers. comm.*)
- Average TOC for shaly intervals was calculated from log data by the project team (Gent, this study). The average TOC for each formation included in the 1D models was used. These average TOC values were used in preference to averages of TOC data from legacy reports as the average across all the shaly intervals is more likely to avoid an overoptimistic TOC since samples for RockEval analysis will generally be chosen from the most promising looking parts of the interval. An average of the TOC values from legacy reports for each formation was used where a value was not available from Gent (this study). Using the wireline log average does have the disadvantage that coals are excluded from that analysis (due to their wireline character) and so these are too low on average for the coal bearing horizons
- Source rock organic geochemistry results and kerogen typing (Vane et al., this study and A. Kim, *pers. comm.*)

2.2 FLOW (MIGRATION) MODELLING

The 3D models were prepared in BasinView™ (v. October 2012) and BasinFlow® (v. October 2012) Platte River Associates Inc. software. The 1D well models were simplified for input to BasinView/BasinFlow.

In BasinView, maturity, porosity and other basic geological and thermal properties were gridded across the whole area of interest. Initially, a relatively coarse grid was chosen to test the flow modelling process. The 5 km resolution depth converted grids from the project seismic interpretation team were then included in the BasinView model for the chosen source and reservoir horizons. The possible generation area and migration routes and accumulation were then plotted. After the process had been tested, refinements were made to the time steps saved in the model and the BasinView and BasinFlow models were produced with a finer grid resolution. The maximum number of grid nodes which could be run was about 3000, otherwise the modelling process failed.

BasinFlow was used to assess possible generation scenarios and possible gross migration routes in pseudo-3D.

3 Overview of observations from 1D BasinMod wells

Four regions of interest were examined through 1D thermal modelling utilising BasinMod. Table 2 provides a summary of generation potential for the most promising formations based on model results.

3.1 THE FORTH APPROACHES BASIN

The current model suggests that main phase of hydrocarbon generation within the depocentre of the Forth Approaches Basin occurred from Triassic times onwards (based on Well 26/08-01 which lies in the depocentre; Figure 1). The kerogens in the Scremerston Formation in this well are dominantly gas prone and burial was insufficient to reach gas maturity, thus generation potential at this well location is expected to be low. Some mixed oil/gas prone kerogens are present in the Scremerston and Boulton formations which could have generated oil when the strata reached the oil window, but no oil staining is reported in the Boulton Formation and only poor oil shows are reported in the Scremerston Formation so the well report does not support generation in the Boulton Formation and suggests very minor oil generation in the Scremerston Formation.

Well 26/14-01 lies on the flank of the Forth Approaches Basin. Carboniferous strata have been eroded and Permian strata rest directly on Lower Devonian strata. Confidence in the model for Well 26/14-01 is low due to issues with contamination of VR data noted in legacy reports and a mismatch between VR and VRcalc data. The Lower Devonian strata appear to have good potential for oil here but this is based on a single datapoint. The current model for Well 26/14-01 implies that main generation for southern flank of the Forth Approaches Basin occurred during deep Cenozoic burial. The deepest parts of the basin are predicted to have generated hydrocarbons from Triassic times onwards, with generation on the flanks continuing into the Cenozoic Era, however, as the kerogens are mainly gas prone and gas maturity is only expected to have been reached in the deepest parts of the basin, significant generation is only anticipated in the basin centre.

3.2 MID NORTH SEA HIGH

The 1D models for 36/13-01 and 36/23-01 suggest that maximum burial and main generation occurred during Carboniferous times. Palaeozoic strata only reached the early – mid mature for oil maturity window as the MNSH has been an area of non-deposition or erosion for considerable periods of time. The only Carboniferous interval penetrated is the Yoredale Formation which appears to contain mainly gas prone kerogens (Yoredale Formation in Well 36/13-01 is gas prone, and in Well 36/23-01 contains mainly gas prone with some oil prone kerogens). The Yoredale Formation is early-mid mature for oil based on the current models, therefore limited hydrocarbon generation is expected at these well locations. The model for Well 36/23-01 is not well constrained by data and maturity data did not all suggest the same degree of maturity had been reached (VRcalc and VR are quite different, UV fluorescence suggests that greater maturity was achieved than is supported by the VR data). However, a satisfactory match between the data and model was achieved with a similar burial history to Well 36/13-01, increasing confidence in this model as a similar burial history would be expected based on the relative location of the wells.

3.3 SOUTH OF THE MID NORTH SEA HIGH

The current BasinMod models suggest that hydrocarbon generation started during the Carboniferous Period for Upper Palaeozoic strata in the modelled wells in this region which don’t lie on local highs (Wells 41/14-01, 41/20-01 and 43/17-01) and continued until

Triassic/Jurassic times with significant generation during maximum burial through the Cenozoic Era for some Carboniferous strata.

Well 42/10b-02 lies on a local high and current models suggest main generation occurred during the Cenozoic Era. Deepest burial occurred during the Cenozoic Era.

Wells 41/14-01, 41/20-01, 42/10b-07 and 43/17-02 contain a mixture of kerogens so oil and gas generation would be expected. Any hydrocarbons expelled before deposition of the Upper Permian could potentially have migrated out of the system as the main regional seal is the Zechstein Group. However, this does not preclude trapping due to intraformational seals where low permeability argillaceous Upper Palaeozoic rocks could have trapped hydrocarbons.

Based on the current models, the majority of Palaeozoic strata reached the gas maturity window thus, with the exception of areas where local highs have resulted in shallower burial of source rocks, the area south of the MNSH seems worth further investigation. This area is considered to be a Lower-Mid Carboniferous ‘probable’ kitchen area.

3.4 NORTH DOGGER AND QUADRANT 29 BASINS

3.4.1 Quadrant 29 Basin

Well 29/27-01 did not penetrate to the Palaeozoic succession, so the depth to the relevant horizons was inferred from the 5 km depth grids (Arsenikos et al., this study) for the current model. The preferred model (Scenario 2) suggests that Carboniferous strata reached early - mid maturity for oil and that the main gas maturity window was only reached by Devonian and older strata from Jurassic times onwards. Although no kerogen information was available for Well 29/27-01, a theoretical kerogen mix was entered into the model to examine if oil or gas would be generated by the burial history scenarios. Based on this kerogen mix and the burial history for scenario 2, main generation occurred during deep Jurassic and Cenozoic burial, however, generated volumes are expected to be low as the Scremerston Formation tends to be gas prone and the gas window was not reached. Scenario modelling suggested an additional 3.4 km of burial would be required for the Scremerston Formation to reach the gas window (Scenario 3), but based on the current understanding of the geological history of this well and maturity data, this does not seem likely. No significant hydrocarbon shows were observed in this well, but minor gas shows and weak fluorescence are reported.

Based on the presence of hydrocarbon shows in and around the Quadrant 29 Basin, the deeper parts of the Quadrant 29 Basin were considered a ‘possible’ kitchen area.

3.4.2 Dogger Basin

Further south in the Dogger Basin, Well 38/18-01 was modelled using three burial history scenarios to examine the generation potential of Palaeozoic strata. The model suggested that the Scremerston Formation is early mature for oil and some generation of hydrocarbons would be expected during deep Carboniferous burial (Scenario 2). The Scremerston Formation is considered to have excellent source rock quality and to contain a mixture of gas and oil prone organic matter (Vane et al., this study). An additional 4 km of burial would be required for the Scremerston Formation to reach the gas window (Scenario 3) but based on the modelled geological history of this well and maturity data, this does not seem likely to have occurred at this location.

Based on the presence of hydrocarbon shows in and around the Dogger Basin, the deeper parts of the Dogger Basin were considered a ‘possible’ kitchen area.

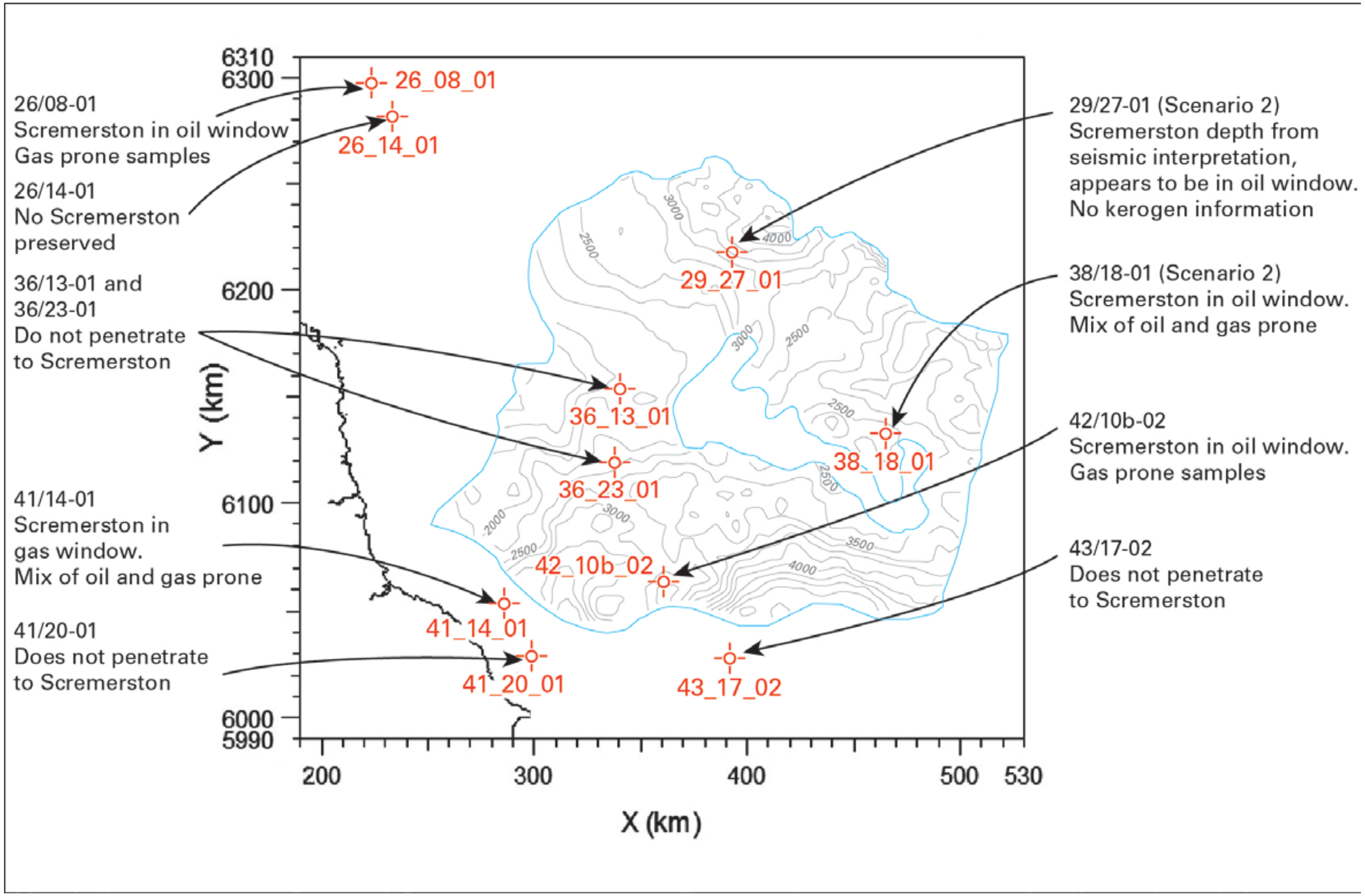


Figure 3: Summary of maturity and gas/oil prone tendencies of organic matter for Scremerston Formation based on 1D basin models (contours show depth to Scremerston Formation, 5km grid; see Arsenikos et al., this study). The blue polygon shows extent of Scremerston Formation interpreted on seismic data (Arsenikos et al., this study). The Scremerston Formation is present in some regions outside this polygon which delineates the interpretation extent for this project. The Scremerston Formation is proven in wells to the south and the north-west (see comments in Arsenikos et al., this study). The maturity of the Scremerston Formation interpolated from this well data and the 5km depth grid is given in Figure 91.

Table 2: Summary of BasinMod 1D results for most promising Devonian and Carboniferous formations/model layers

Region	**Well**	**Most promising formation (and Scremerston Formation as this expected to be a major source rock)**	**Gas or oil prone based on project team assessment and legacy reports?**	**Maturity window reached in model**	**Average TOC from log analysis (Gent , this study)**	**Approximate cumulative hydrocarbon from depth plot (mg/g TOC) (please note this is very approximate and only intended for comparison purposes)**	**Gas/oil generated and expelled?**	**Comments**
Forth Approaches	26/08-01	Scremerston	Type III, Gas prone and some oil prone	Late mature oil during deep Cenozoic burial	3	95	Minor amounts of oil and gas generated from Triassic to Cenozoic times. Very small amount of expulsion during Cenozoic burial.	Only reached oil maturity window but kerogen is mainly gas prone
Forth Approaches	26/14-01	*Scremerston (eroded layer)*		*Lower part of deposit could have reached early oil maturity window during Carboniferous burial*				*Confidence in this model is low*
		Lower Devonian	Oil prone	Mid mature oil during deep Cretaceous – Cenozoic burial	0.7	530 (low confidence)	Main oil and small amount of gas generation during deep Cenozoic Burial. No expulsion.	Confidence in data entered into model is low, data quality noted as low by Vane et al (this study) so this generative potential estimate is considered low confidence
MNSH	36/13-01	Yoredale	Gas prone	Early mature oil during deep Carboniferous burial	2.0	1	Oil and minor gas generated during Carboniferous burial but not expelled	Only reached oil maturity window
		Scremerston not penetrated		*Mid – late mature for oil during deep Carboniferous burial (model only)*				*Depth inferred from 5km grids*

MNSH	36/23-01	Yoredale	Gas prone	Mid mature oil during deep Carboniferous burial	9.91*	60	Oil and gas generated during Carboniferous burial. Minor expulsion from lower part of formation.	Gas prone but only reached oil maturity window
		Scremerston not penetrated		*Main gas maturity window (based model only) during deep Carboniferous burial*				*Depth inferred from 5km grids*
Probable kitchen area	41/14-01	Cleveland E,	Mixture of oil/gas prone or inert	Mid mature oil during Carboniferous burial and main gas maturity window during deep Cenozoic burial	3.2	190	Main oil and gas generation during Carboniferous Period. Only minor amount of gas generated. Expulsion from lower part of formation during Carboniferous and Cenozoic times. Expulsion from upper part during deep Cenozoic burial.	Broad scatter of maturity data
		Bowland Shale	Mixture of oil/gas prone or inert assumed	Mid mature oil during Carboniferous burial and main gas maturity window during deep Cenozoic burial	2.8	190	Main oil and gas generation during Carboniferous Period. Only minor amount of oil generated. Expulsion from lower part of formation during Carboniferous and Cenozoic times. Expulsion from upper part during deep Cenozoic burial.	
		Cleveland D	Mainly inert	Late mature oil during Carboniferous burial and main gas maturity window during deep Cenozoic burial	1.8	70	Little generation, some oil and minor gas generation during Carboniferous Period (small amounts of gas can be generated when in the oil window).	
		Scremerston equivalent (Cleveland C – A)	Mainly inert with some gas prone	Late mature oil/main gas maturity window during Carboniferous burial and main gas maturity window/over mature during deep Cenozoic burial	1.6	70	Little generation, some gas and very minor oil generation during Carboniferous Period (small amounts of gas can be generated when in the oil window). Minor expulsion of gas from deeper part of formation during Cenozoic Era	

Probable kitchen area	41/20-01	Cleaver	Mainly gas	Early – mid mature oil from Triassic to Cretaceous times. Late oil mature during deep Cenozoic burial.	23.22*	205	Oil and gas generated during Carboniferous to Triassic Cenozoic times. Some expulsion from lower part of formation during Cenozoic Era.	Broad scatter of maturity data
		Westoe	Mainly gas	Early – mid mature oil from Triassic onwards. Lowest part of formation reaches gas maturity during deep Cenozoic burial	17.99*	215	Main oil and gas generation and expulsion from Cretaceous to Cenozoic times. Expulsion peaked during Cenozoic Era.	
		Caister	Mainly gas	Early – mid mature oil during Triassic burial, gas maturity window during deep Cenozoic burial	6.54*	220	Oil and gas generation initiated during Triassic times (lower part of formation) and peaked during Cenozoic times (upper part of formation). Expulsion from Triassic to Cenozoic times	
		Millstone Grit	mixed	Early – mid mature oil during Carboniferous burial, gas maturity window from Triassic times onwards. Lower part of formation over mature during deep Cenozoic burial.	1.92*	130	Oil and gas generated during Carboniferous for lower part of formation and during Triassic times for upper part of formation. Minor gas expulsion during Cenozoic burial from lower part of formation.	
		Scremerston not penetrated		*Overmature (model only)*				*Lowest part of younger Millstone Grit is overmature*
Probable kitchen area	42/10b-02	Yoredale	gas	Early mature for oil during Triassic burial, Mid mature for oil during deep Cenozoic burial	3.4^	85	Oil and gas generated but not expelled during Cenozoic burial	

		Scremerston	gas	Lower part of formation early mature for oil during Carboniferous Period. Late mature for oil – during deep Cenozoic burial	16.91*	110	Oil and gas generated and expelled during Cenozoic Era	
Probable kitchen area	43/17-02	Millstone	Type IV kerogen with some type II and III	Early mature for oil during Triassic Period. Lower part of formation late mature for oil during deep Cenozoic burial	2.0	65	Main generation during Jurassic times of oil and gas. No expulsion.	Broad scatter of maturity data
		Cleveland E	Mix of type III and type IV kerogen	Mid mature for oil during Carboniferous. Main gas maturity window during Jurassic and Cenozoic times	1.5	70	Generation initiated during Carboniferous Period. Main generation of oil and gas during Triassic – Jurassic times. No expulsion.	
		Upper Bowland		Mid mature for oil during Carboniferous. Main gas maturity window during Jurassic and Cenozoic times	1.4	70	Oil and gas generated during Carboniferous to Jurassic times. No expulsion.	
		Cleveland D		Main gas maturity window from Carboniferous Period onwards, lower part of formation over mature from late Jurassic onwards.	1.3	80	Oil and gas generated during Carboniferous Period. Minor gas expulsion from Jurassic times onwards from lower part of formation.	
		Scremerston not penetrated		*Overmature (model only)*				*Lowest part of younger Cleveland D Formation is overmature*

Possible kitchen area	29/27-01	*Scenario 2; Scremerston (not penetrated, model only)*	No kerogen data as source rock not penetrated. Assumed was mix of kerogens because of oil and gas shows in this and nearby wells	Early mature oil during Carboniferous Period. Mid mature from Jurassic onwards (Scenario 2)	No data. 2.5 used (same as 38/18-01)	55	*Oil and gas generated during Jurassic times, but not expelled(based on modelled kerogen and TOC. Minor gas generation.*	Scenario Well. Very limited data. Low confidence model. No kerogen or maturity data for Palaeozoic. Does not penetrate to Scremerston so seismic interpretation depth conversion has been used.
Possible kitchen area	38/18-01	Scenario 2; Scremerston	Few data, kerogens assessed to be oil, mixed and gas prone.	Early mature for oil during Carboniferous burial (Scenario 2)	2.5	5	Oil and gas generated Carboniferous Period but not expelled	Scenario well. Very limited data. Low confidence due to sparse data. Issues with contamination of VR data.

* These data were taken from legacy reports as no wireline log data were available for analysis from Gent (this study). Note as samples are often selected for the most promising parts of the formation this may introduce sample bias which could result in a too high estimate of average TOC for the formation

^ These data are taken from wireline logs in Well 42/10a-01 (Gent, this study)

4 Overview of observations from BasinFlow modelling

The 1D BasinMod models were used as the basis for regional 3D maturity and migration modelling across the whole CNS study area. The maturity and migration modelling was undertaken in BasinView and BasinFlow to draw together the results of the 1D models, in an attempt to provide a regional overview.

The stratigraphy was simplified so that equivalent formations across the whole study area would be included as model layers for the flow modelling (e.g. Scremerston is broadly equivalent to the Cleveland C, Cleveland B, Cleveland A combined) (See Table 13).

Due to time constraints, only one flow model series was run with the Scremerston model layer as the main source rock, and the Upper Permian model layer as the reservoir. The depth to top Scremerston Formation was included from the seismic interpretation Arsenikos et al. (this study; 5 km grids). The source rock is only considered over the region where the Scremerston has been interpreted by the project team (Arsenikos et al., this study). The maturity and kerogen information entered into the 1D models was imported into BasinView and used for the BasinFlow simulation.

This simulation only gives a regional picture of generative potential due to the low well density. Generation of oil and gas mainly occurred in the south kitchen area (around Quadrants 41 – 44 and south part of Quadrant 36; Figure 4). The main period of oil and gas generation was during deep Cenozoic burial. Oil and gas expulsion from the Scremerston Formation mainly occurred post-deposition of the Zechstein caprock. Regional oil and gas migration was generally towards the north-west from the probable kitchen area.

The Quadrant 29 and Dogger basins are not shown as prospective by the regional flow model. This is because the Scremerston Formation in the two wells modelled in 1D are immature as they lie on the basin flanks. Thus without additional 1D models in the basin depocentre which could help clarify if Palaeozoic source rocks reached maturity during the geological history of these basins, this maturity of this area is not well defined in this regional maturity model.

The migration of oil and gas is controlled by the interplay between buoyancy, capillary and hydrodynamic vectors. The 'Base Zechstein and top pre-Permian' depth-converted layer from the project seismic interpretation was used as the top reservoir horizon and partially controls migration of the hydrocarbons through time. The migration and accumulation maps are not shown in this report as due to data sparsity, the results are believed to be misleading as they indicate large accumulations where real data indicates that large accumulations do not exist.

The flow models were also run with a more detailed project depth converted grid (0.5 km spacing, permissions are not in place to show the result with this grid resolution). The regional picture of generation in the south from the mature Scremerston Formation remained the same, but the migration pathways, timing of migration and accumulations of hydrocarbons were different.

It is important to note that assumptions made during flow modelling will affect the outcome, these include; assumptions made about maturity and kerogen typing and TOC for scenario wells; well data is sparse so the lithological model will be coarse; perfect migration between source and reservoir does not take into account facies/lithological barriers or residual trapping between source and reservoir; no faults were included in the simulation; confidence in the 1D models for Wells 26/14-01, 29/27-01 and 38/18-01 is low due to data issues (See section 9.3 for more detail).

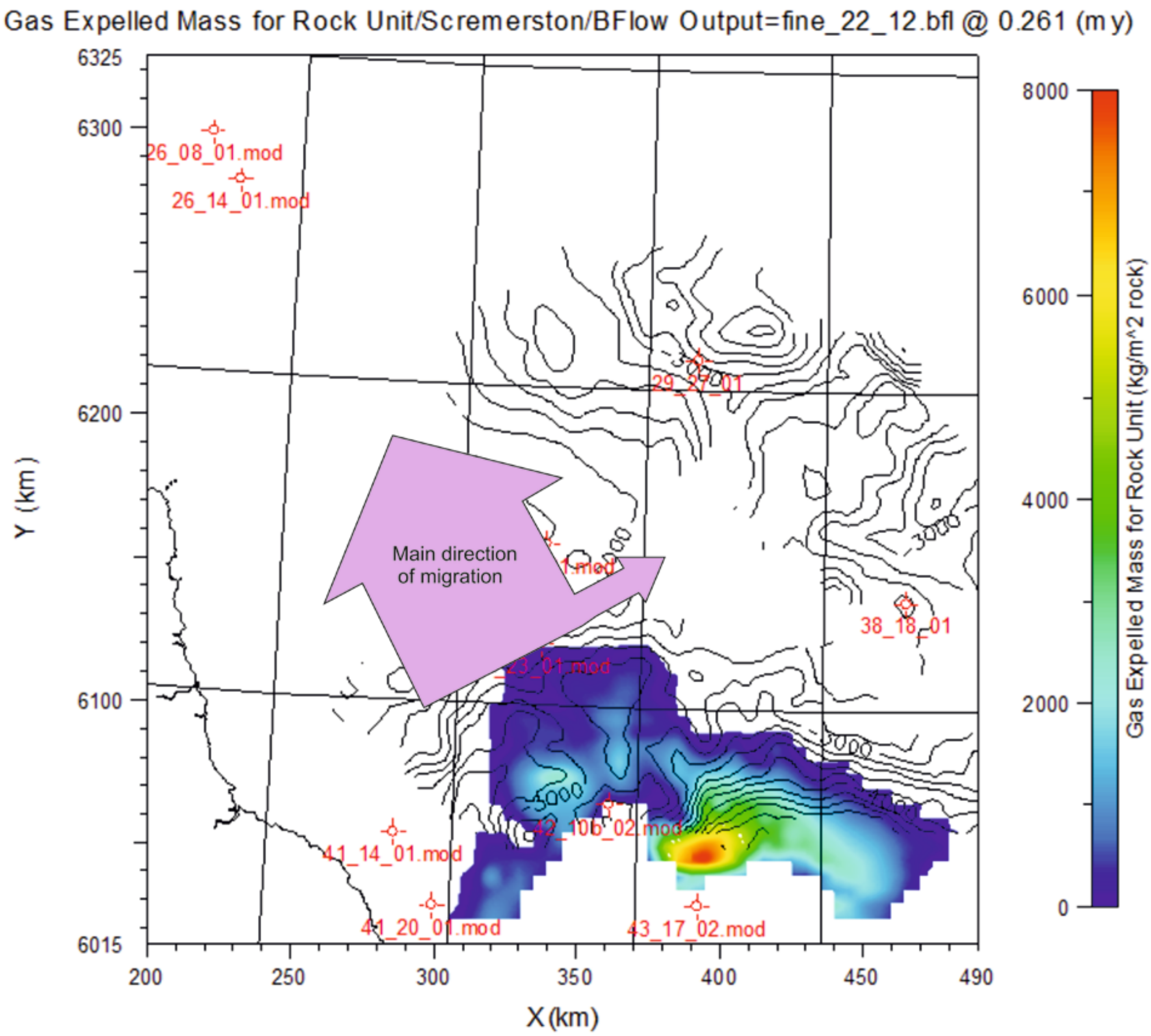


Figure 4: Model of gas expelled from the Scremerston Formation (total mass per rock unit), (model time is close to present day). Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Palaeozoic rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region.

5 Detail of Forth Approaches modelling

The sections below are structured to first give a summary of tectono-stratigraphic evolution of this area. This information was used as input to the basin modelling. Sections on previous maturity and generation assessments available from legacy reports follow, before the new modelling undertaken for this study is described.

5.1 GEOLOGICAL MODEL

Mid Silurian – Early Devonian; subsidence and inversion

The Caledonian Orogeny which ended with closure of the Iapetus Ocean in late Silurian/Early Devonian times significantly affected this area, setting the underlying structural framework (Gatliff et al., 1994; Zanella and Coward, 2003). From Mid-Silurian times onwards the Forth Approaches region lay within a larger extensional graben which was controlled by extensional reactivation of Caledonian thrusts (Coward et al., 2003).

During Early Devonian times, the region lay in a continental setting and the Lower Old Red Sandstone Supergroup was deposited (Gatliff et al., 1994).

During Early Devonian times, deformation led to inversion (Marshall and Hewett, 2003; Soper et al., 1987).

Mid Devonian uplift

During the Mid Devonian the Midland Valley of Scotland was a region of uplift. Uplift of volcanic centres resulted in erosion during mid Devonian times, this fed large volumes of clastic sediments into the adjacent basins (Coward et al., 2003). Mid Devonian strata are not present in Well 26/14-01 (which terminates in Silurian strata).

Late Devonian – Early Carboniferous sinistral transpression

Upper Devonian strata are not preserved in Well 26/14-01 which penetrates Lower Devonian strata.

During Late Devonian to Early Carboniferous times, the Forth Approaches Basin experienced the last effects of Caledonian sinistral transpression as Baltica began to transition eastwards (Leslie et al., this study).

Early Carboniferous transtensional stress and strike slip faulting

During Early Carboniferous times, major strike slip faulting occurred in this region in response to extensional stress with a regional transport direction oblique to the inherited structural features. This region was affected by plate-scale tectonic events during expulsion of Baltica eastwards (Leslie et al., this study). Crustal extension and thinning (Zanella and Coward, 2003) would be expected to be accompanied by an increase in the heat flow.

Carboniferous thermal subsidence

Carboniferous strata were deposited in the Forth Approaches Basin (Arsenikos et al., this study). Well 26/08-01 lay within this basin and Well 26/14-01 lay on southern flank of the basin. Carboniferous strata were laid down predominantly in a fluvio-deltaic system. Faulting and folding occurred during this time and volcanic activity is evident through onshore outcrops of extrusive rocks (Gatliff et al., 1994). This study and previous work (Granby Enterprises and TGS-Nopec, 2010) indicate that significant strike-slip faulting occurred within the Carboniferous, with rapid deposition of interbedded sands, shales and coals in a fluvio-deltaic environment.

Late Carboniferous – Early Permian Variscan Orogeny

There is some evidence of Late Carboniferous deposition in this region: Well 26/08-01 penetrates a late Westphalian/Stephanian red bed sequence which Hay et al. (2005) observed was very similar to the Flora Formation in Block 31/26 (the Flora Formation is of late Westphalian C to Stephanian age).

During latest Carboniferous times, the regional stress regime would have switched to dextral transpression as the directional movement of Baltica reversed. Local inherited structural features had a strong impact on local deformation resulting in significant strike slip faulting (Leslie et al., this study). The Late Carboniferous Period was dominated by Variscan deformation with uplift and erosion (Gatliff et al., 1994).

Coward et al. (2003) suggest that Early Permian volcanism in northern England and the Midland Valley of Scotland, which pre-dates Permian extension, indicates that the area was underlain by hot asthenosphere, possibly the edge of a north-west European hot spot. Permian extrusives (age 296 Ma) are present in the onshore Midland Valley (Glennie et al., 2003).

Early Permian deposition

The first Permian deposits were laid down on an unconformable surface and comprise non-marine, desert/fluvial/sabkha strata. The Forth Approaches Basin is described as having 'Basin Facies deposited during Lower Permian times' in Hay et al. (2005).

Late Permian deposition

The Rotliegend Group is expected to be present only in the basinal area (Granby Enterprises and TGS-Nopec, 2010) and to comprise strata laid down in an alluvial/fluvial environment with a minor aeolian component. Glennie et al. (2003) indicate that part of Quadrant 26 lay in an embayment on the edge of the Northern Permian Basin.

An unconformity separates the lower and upper parts of the Rotliegend Group. The sandy Auk Formation was deposited during late Permian times in a mainly aeolian environment (Hay et al., 2005).

Zechstein Group deposition

A rapid transgression due to global sea level rise marked the start of deposition of the Zechstein Group. Evaporite deposition indicates that sea level was variable (Gatliff et al., 1994). Thin calcareous reservoirs in the Zechstein Group are also proposed (Granby Enterprises and TGS-Nopec, 2010). The westernmost part of the Forth Approaches Basin was believed to be emergent (Coward et al., 2003).

Triassic deposition

Triassic strata were deposited extensively across the Central North Sea including the Forth Approaches Basin (Goldsmith et al., 2003). The Bunter Sandstone is noted as being at very shallow depths in this area by Hay et al. (2005). The Triassic is noted to comprise mainly shale with some discontinuous sandstones present (Granby Enterprises and TGS-Nopec, 2010).

During the Triassic Period, deposition was influenced by local structural features due to salt movement. On seismic reflection sections near Well 26/08-01, Triassic strata that has been deposited during salt movement is observed. In the Forth Approaches Basin, salt diapirs trend northeast – southwest (Gatliff et al., 1994).

Lower Jurassic - Mid Jurassic, mid Cimmerian unconformity

During Lower Jurassic times, the westernmost part of the Forth Approaches Basin is believed to have been emergent (Coward et al., 2003).

Lower Jurassic strata are often absent due to due to domal uplift of the northern margin of the CNS during Middle Jurassic times (mid-Cimmerian/Intra-Aalenian Unconformity). Underhill and Partington (1993) define an active rifting system present in the Central North Sea during Aalenian times related to thermal mantle doming but do not anticipate a major heat flow effect). Lava is encountered in some wells.

Late Jurassic deposition

The Forth Approaches Basin lay on a stable platform (Fraser et al., 2003). Although strata of Upper Jurassic age is not observed, a thin deposit may have been present and later eroded (Gatliff et al., 1994).

Cretaceous deposition

A major unconformity is present at the base of the Cretaceous strata and onlap of Cretaceous to older strata is observed. The strata has been eroded in the Forth Approaches but a thin (<100 m) Lower Cretaceous deposit may have been present.

During Upper Cretaceous times, widespread deposition in deep water occurred as indicated by the presence of fine grained chalk deposits in the sequence. These strata are not preserved due to erosion but could have been up to 600 m thick (Gatliff et al., 1994).

Paleocene deposition

The tectonic environment was one of tension during the Paleocene to early Eocene (the extensional tectonic environment continued until early Oligocene times). The Forth Approaches Basin lay across the margin of a Paleocene basin, with the environment ranging spatially from emergent to non-marine to coastal.

Paleocene – Eocene mantle underplating and uplift

Igneous activity was initiated with the growth of the Iceland Plume. Mantle underplating and crustal thinning related to the Iceland plume occurred around 61 – 51 Ma (Coward et al., 2003; Brodie and White, 1995). Eastern Scotland was uplifted by 0.5 – 1 km (White and Lovell, 1997). Uplift was accompanied by extensive volcanic activity in the Shetlands and low relative sea levels (Gatliff et al., 1994).

Based on the Hay et al. (2005) report, a considerable amount (in the order of 4km) of Cenozoic uplift would be expected in the Forth Approaches if the uplift contours continue along the same trend. Nearby Well 27/03-01 has an estimated 2.5 km of Early – Mid Cenozoic uplift (Hay et al., 2005). The current models include around 1 and 1.9 km of Cenozoic uplift in Well 26/08-01 and Well 26/14-01 respectively.

Paleocene - Eocene deposition

During the Palaeocene and Eocene epochs, this region lay within the inferred Tay-Forth palaeo-river system, and the sequence is expected to comprise deltaic deposits. These strata have been mainly eroded but it is expected that thin strata would originally have been present. Strata to the east mapped by Gatliff et al. (1994) show Paleocene strata <50 m and Eocene strata <150 m. On two occasions during the late Paleocene and late Eocene, low sea levels promoted the advance of deltas into the North Sea Basin.

Oligocene – Miocene deposition

The tectonic environment was extensional from latest Maastrichtian – early Oligocene times.

Oligocene sediments were apparently not deposited in the Forth Approaches region (Gatliff et al., 1994). The western extent of Miocene strata is uncertain, but thin deposits extending towards the proto-Forth River may have been present (Gatliff et al., 1994).

Miocene compression

From Mid Miocene times onwards, push from the Mid Atlantic Ridge and Alpine collision resulted in compression in Scotland (Coward et al., 2003). Uplift occurred along the margins of the North Sea Basin (Fyfe et al., 2003).

Pliocene deposition

Subsidence took place in the North Sea Basin during the Early Pliocene. There is evidence of iceberg scouring in the CNS, suggesting that sea ice reached this far south (Holmes 1997).

Late Pliocene was a time of uplift on the basin margins around the North Sea Basin (Fyfe et al., 2003).

Quaternary deposition

Thin (< 200m) Quaternary strata are mapped in the Forth Approaches by Gatliff et al. (1994) which are of Upper Pleistocene and Holocene age. However, no strata of this age are preserved in the modelled wells.

5.2 PREVIOUS WORK IN THIS REGION

The dominance of gas-prone kerogens in Carboniferous strata is supported by minor gas shows interpreted to be sourced from Carboniferous strata noted in legacy reports for wells within the Forth Approaches Basin (e.g. 26/04-01, 26/08-01, 28/05-01; Glenister et al., 2002; Ellwood, 1993; Granby Enterprises and TGS-Nopec, 2010; Farris et al., 2012; Mobil North Sea, 1993; Mobil North Sea, 1992.

Oil staining and shows from Carboniferous sources are noted in legacy reports suggesting that oil has been generated in some parts of the Forth Approaches Basin (onshore Firth of Forth-1, 26/07-01, 26/08-01; Wiggin, 1985; Ellwood, 1993; Farris et al., 2012; Granby Enterprises and TGS-Nopec, 2010; Mobil North Sea, 1992).

Farris et al. (2012) define the main play type in the Forth Approaches as thick sand-rich Rotliegend strata with hydrocarbon sourced in the mature oil/gas prone Carboniferous source rocks. However, they note confirming the deep Carboniferous subcrop as a key uncertainty.

Geohistory models suggest that Carboniferous burial was relatively shallow and that deepest burial occurred during Triassic or Cenozoic times (Granby Enterprises and TGS-Nopec, 2010; Glenister et al. (2001).

Palaeozoic source rocks and reservoirs

Fluid inclusion evidence that Ordovician/Silurian graptolite shales had produced hydrocarbons in the Forth Approaches Basin were noted in Glenister et al. (2001).

The Devonian Old Red Sandstone Supergroup was believed to contain gas from a Carboniferous and Zechstein source (Glenister et al., 2002).

Glenister et al. (2002) proposed, based on the findings from Well 26/4-01, that for this region, there was an early charge from coaly Carboniferous rocks that charged Carboniferous and older reservoirs.

Minor amounts of migrated oil and gas interpreted to be sourced from Carboniferous strata are noted in one legacy report (26/12-01; Farris et al., 2012). As the Carboniferous strata appear to have been removed by erosion outside of the depocentre on the southern flank of the basin, these hydrocarbons may have migrated in from the Forth Approaches Basin.

The Forth Approaches regional review prepared by Granby Enterprises and TGS-Nopec (2010) suggested that secondary sources in the Forth Approaches include Carboniferous coals where maturity has been reached.

Based on regional analysis of wells around Well 26/04-01, Glenister et al. (2002) suggested that Carboniferous reservoirs would have some potential though this was accompanied by a warning statement that this would require long term hydrocarbon retention by traps to preserve accumulations of hydrocarbons (Glenister et al., 2002).

In a regional review of well data, Glenister et al. (2002) noted that as mature Zechstein rock was not available, samples from the Dutch sector were artificially matured in the laboratory to determine the expected signature. The Kuperschiefer shale is thin (<1 m) and therefore unlikely to produce economic quantities of hydrocarbons, such that without Carboniferous charge the Zechstein reservoirs would not be expected to contain economic hydrocarbon accumulations (Glenister et al., 2002).

Granby Enterprises and TGS-Nopec (2010) looked at several blocks in the Firth of Forth, including seismic reflection data and noted that potential reservoir rocks of Devonian, Carboniferous, Permian and Triassic age were present in various wells. The Carboniferous reservoirs were the main target (blocks 26/4a, 5, 9, 10a and 27/1a, 6a in UKCS End of Licence Report for Licence P1315). The authors believed that the main potential source interval in the basin comprises a lacustrine oil shale within the Asbian to Brigantian interval. However, the lateral extent of this oil shale is not proven. Onshore the Midland Valley of Scotland, the oil shale bearing succession is proven where it has a thickness of up to 2 km but offshore, the sequence is only penetrated in IGS borehole 73/16 where it comprises an intercalated sequence of mudstone and sandstone (A A Monaghan, *pers comm*.). The shales within IGS borehole 73/16 have VR values of 0.8 – 0.9 (mature for oil).

Evidence of hydrocarbons were noted in 26/7-01 (oil staining in Carboniferous strata; Wiggin, 1985), 26/08-01 (gas shows in Carboniferous, oil shows in Carboniferous strata; Ellwood, 1993) and the onshore Firth of Forth-1 Well (oil shows in Carboniferous strata; Granby Enterprises and TGS-Nopec, 2010).

For Well 26/07-01, Farris et al., (2012) document that oil shows in Visean strata were interpreted to be locally sourced from Asbian coaly sediments. The Rotliegend was found to be water bearing with gas in fluid inclusions from the same Asbian source rocks (Farris et al., 2012).

Fluid inclusion studies on the Devonian strata indicated migrated hydrocarbons from a Carboniferous source in Well 26/12-01 (Farris et al., 2012).

Hydrocarbon accumulations and shows are observed quadrants adjacent to Quadrant 26. For example, Farris et al. (2012) note hydrocarbon accumulation in accumulations in Devonian to early Carboniferous strata in the Buchan field (Block 21/01a and 20/05a). Farris et al. (2012) also observe that the Carboniferous coals and shales are part of the onshore petroleum system in the Midland Valley of Scotland.

Younger source rocks and reservoirs

Glenister et al. (2002) utilised regional analysis from wells around Well 26/04-01 to assess the source and concluded that there are only indications of minor and local migration of Carboniferous gas into Rotliegend reservoirs.

Farris et al. (2012) observed that, through a study of inclusion gases trapped in the upper part of the Rotliegend Group, the trapped hydrocarbons at this level were most likely sourced from downthrown Carboniferous strata preserved to the North.

Lower Zechstein Kuperschiefer shales were believed to offer a secondary source. Fluid inclusion evidence that the Lower Zechstein Kuperschiefer shales had produced hydrocarbons in the Forth Approaches Basin is included in Glenister et al. (2001).

Gas was found in the Plattendolomite in the Zechstein (Z3) sequence; geochemical, isotopic and fluid inclusion analysis indicated the hydrocarbons probably originated from a Zechstein source rock (presumably from Kuperschiefer shales downdip of the structure) (Glenister et al., 2002).

Generally gas in Zechstein reservoirs appeared to have been produced from a Zechstein source (Glenister et al., 2002).

Evidence of hydrocarbons were noted in 26/4-01 (oil and gas shows in Zechstein carbonates; Glenister et al., 2002), 26/7-01 (one oil show in Permian strata; Wiggin, 1985) and 26/08-01 (gas shows in Rotliegend, Zechstein sequences; Ellwood, 1993).

Examination of Well 28/05-01 indicates that oil shows in the Zechstein Group appear to have been sourced locally from within the Zechstein interval which was oil-mature rather than sourced by migration from the Jurassic Kimmeridge Formation on the other side of the basin-bounding faults (Farris et al., 2012).

Jurassic shales within the intervals 6424 – 6525 feet (‘Zone B’) and 6595 – 6635 feet (Zone D) BRT were judged to have high potential for oil generation, but to be immature – marginally mature with generation expected to occur off-structure. Zone B has shales with 0.41 – 4.25% TOC including amorphous kerogen from herbaceous and woody debris. Zone B is immature. Zone D has shales with 0.5 – 2.87% TOC with dominantly amorphous kerogen with minor to significant proportions of woody and herbaceous debris. Zone D is marginally mature (Geochem Laboratories, 1977).

Geochemical service report for Well 28/05-01 (Geochem Laboratories, 1977) indicated that the Cretaceous rocks were marginally mature poor to fair source rocks for oil with minor rich interbeds. The report authors did not believe that oil had migrated into the Cretaceous rocks here based on samples from this well, i.e. shows in the Cretaceous strata were generated within the strata.

Geohistory models

Glenister et al. (2001) proposed two burial history models were; one with deepest burial during the Triassic (using VR and AFTA data) and the other with deepest burial during early – mid Cenozoic times. A model of Well 26/07-01 suggested that the lowest part of the Zechstein sequence would reach early oil maturity during post-Permian burial (Glenister et al., 2001).

The well resume report (Glenister et al., 2002) prepared after Well 26/4-01 had been drilled noted that the Rotliegend Group was absent indicating either erosion or non-deposition. The Zechstein Group rested on hard, metamorphosed Old Red Sandstone (Devonian). In addition, the Kuperschiefer shales were absent which was believed to be a result of deposition followed by mass transport taking the deposits down-flank.

In Well 26/12-01, Farris et al., (2012) indicate that Rotliegend and Carboniferous strata were absent. The Zechstein Group rested directly on Devonian strata.

The burial history proposed by Granby Enterprises and TGS-Nopec (2010) for the basin was relatively shallow Carboniferous burial followed by deeper early – Mid Cenozoic burial, constrained using VR data from Well 26/07-01.

Well 29/12-01 has a geothermal gradient of 25.5 °C/km in the adjacent block (Hay et al., 2005). Although no data from Quadrant 26 are included in that report, the geothermal gradient trend as illustrated for Quadrants 27 – 29 and 35 – 38 suggests that the geothermal gradient could be higher in Quadrant 26.

Kubala et al. (2003) give the average present day heat flow for this region as 60 – 75 mWm^{-2}.

5.3 WELL 26/08-01

Well 26/08-01 penetrates strata of Triassic to Carboniferous age. This well location lay in the centre of the Forth Approaches Basin during Carboniferous – Permian times.

5.3.1 Previous maturity and modelling work for this well

Gas shows and poor oil shows were noted in Palaeozoic strata in this well. Analysis of the shows indicates some are from a Palaeozoic source.

Oil and gas shows and generation

A weak fluorescence was encountered in sands adjoining gas prone shales and coals in the Scremerston Formation (3017.5 – 3434.8 m BRT; Mobil North Sea, 1993).

The final well report (Mobil North Sea, 1992) indicated that gas shows were recorded in the Carboniferous, Rotliegend and Zechstein sequences (Z1, Z2, Z3). Poor oil shows were noted in the Visean A and B strata with no residual oil (these oil shows are also mentioned in the UKCS End of Licence Report for Licence P1315).

Petrographic analysis of well 26/8-1 (Ellwood, 1993) notes that the replacement of kaolinite by illite and suggests that Visean strata reached Visean strata reached palaeotemperatures between 100 and 140 °C during late diagenesis. The precipitation of ferroan saddle dolomite within Visean sequence and dolomite with an undulose extinction within the Rotliegend Group also indicates these strata could reached palaeotemperatures of 60 to 150 °C during late diagenesis.

Well 26/08-01 was included in the regional analysis section of the well resume report for Well 26/04-01 (Glenister et al., 2002) where the gas from the Carboniferous is proposed to be from a Carboniferous source and the gas in the Zechstein sequence is proposed to be from a Zechstein source. The gas in the Rotliegend sequence for Well 26/04-01 is proposed to be from a marine source that matches the Zechstein source signal (Glenister et al., 2002). The model for Well 26/08-01 does not suggest that Zechstein strata reached sufficient depth or temperature to reach the gas window which implies that this gas must have migrated in from elsewhere.

A thick Rotliegend sandstone interval with good porosity was penetrated in wells, but no closure identified. The Rotliegend Group was underlain by a poor-quality Carboniferous reservoir-seal sequence. Extensive shows throughout the Visean interval were sourced locally from Asbian-Brigantian oil shales (equivalent to the Midland Valley oil shales). Intraformational seals within the Carboniferous are expected to be laterally discontinuous (Farris et al., 2012). Isotopic analysis of inclusions from Visean reservoirs indicates a similar signature to Southern North sea (SNS) Carboniferous gases. Signatures from overlying Rotliegend and Westphalian-Stephanian sandstones compare closely with the signatures from the underlying Visean section and are likely to have experienced gas migration from oil shales and coals contained within the deeper section. In contrast, one sample from the very top of the Rotliegend section (around 1585 m BRT) has a signature that compares with that for the Zechstein intervals. Shows from the top of the Rotliegend are interpreted as locally sourced Zechstein oils, probably originating from the Kupferschiefer (Farris et al., 2012).

Geohistory modelling

Coward et al. (2003) modelled the tectonic evolution of the North Sea, including the Forth Approaches region. This includes Palaeozoic continental collision and lateral plate movements, broad Mesozoic thermal subsidence (over a greater area than was affected by late Mesozoic rifting) and Cenozoic continental separation and ocean spreading. Coward et al. (2003)

supported the view that Cenozoic uplift was generally related to the Iceland plume and that the Forth Approaches Basin experienced uplift during the Paleocene around 60 – 55 Ma above this hot spot. Around this time, magmatic underplating is believed to have affected wells in the North Sea (Coward et al., 2003; White and Lovell, 1997).

5.3.2 New modelling work

Model input data are shown in Table 3. The maturity model for Well 26/08-01 was prepared using VRcalc data calculated from 16 T_{max} values (BGS NDRC accession IDA205391).

Available maturity and porosity data

T_{max} values were mainly available for the Scremerston Formation with only 1 T_{max} value recorded from the Coal Measures Group. An additional 14 VRcalc were available from Hay et al. (2005), although their Table 6.3 states that T_{max} is in Fahrenheit, using the conversion to VRcalc results in negative values and comparing the values with those from report IDA205391, it has been assumed that these are in fact already in ºC. Porosity and permeability data were also available for the Scremerston Formation from the Corex report (Corex, 1993). Additional pyrolysis data (S1, S2, S3, TOC and kerogen type) were also included in the model for the generation phase of modelling.

Table 3: Summary of model input data for Well 26/08-01 and layer maturity window from the BasinMod model

Formation/ age of strata	**N.o. of VR/ VRcalc datapoints**	**Model maturity window**	**Average measured TOC from logs**	**Kerogen**	**Oil/gas show**	**No. of porosity data**	**Comments**
Zechstein Group		Immature – early mature for oil			Trace to minor gas shows		
Rotliegend		Early mature for oil			Zero to minor gas shows		
Boulton		Early – mid mature for oil	1	Type II	Trace of gas, no oil shows		
Coal Measures	1 VRcalc	Mid mature for oil	1.7		Gas shows		
Passage		Mid mature for oil	1.1		Gas shows		
Scremerston	29 VRcalc	Mid – late mature oil	3	Gas prone (Vane et al., this study) and type II (IDA205391)	Poor gas shows. Poor oil shows.	13 points	

Model calibration

The maturity model was calibrated on the VRcalc data as no VR data were available. The porosity data were used as a secondary calibration method, with the Baldwin and Butler compaction method utilised in BasinMod as this seemed to give the best match for most models for this study where porosity data are available. The heat flow curves are based on the finite rifting model of Jarvis & McKenzie (1980) (See Section 2).

The model suggests that a relatively small amount of strata was deposited towards the end of the Carboniferous and then removed during the Variscan orogeny. However, this part of the model is quite insensitive to variations in stratigraphical thickness due to its relatively small time window, so this model parameter is largely based on the assumption that the rate of deposition would not have changed dramatically, and observations on reflection seismic data close to this borehole which suggest that a reasonable thickness of Carboniferous strata would have been deposited in this region. The burial history is given in Figure 5, the model heat flow is given in Figure 6.

It was assumed by the author that post-Cretaceous strata was deposited then removed. This fits with the regional geological model and the model is quite sensitive to thickness of deposited strata within this timeframe, so the thicknesses were adjusted to fit the maturity and porosity data. The burial model used also agrees with the Granby Enterprises and TGS-Nopec (2010) report, with deepest burial occurring during mid Cenozoic times.

Comparison with analysis of the density log conducted by the project team suggests that even deeper burial of Rotliegend strata (<2.5 km missing strata compared with the 1 km included in the model) could be feasible. However, if this much post-Cretaceous eroded strata is added to the model, the maturity and porosity model curves do not match the data, so the BasinMod model was matched using the maturity and compaction modelling entered into the model (Figure 7 and Figure 10).

<u>Model maturity and hydrocarbon generation</u>

This model suggests that that Carboniferous strata reached early oil maturity during Carboniferous burial and mid-late oil maturity during later deeper burial (Figure 7). The Coal Measures Group appear to be have reached the early oil maturity window (VRcalc = 0.65) and the Scremerston Formation appears to have reached the early to late oil maturity window (VRcalc = 0.68 – 1.09). The burial model follows the geological model suggested by Glenister et al., 2001 and Granby Enterprises and TGS-Nopec (2010) with maximum burial during the Cenozoic Era.

The current model for Well 26/08-01 proposes that the strata penetrated by the well reach a greater maturity than previous work (Granby Enterprises and TGS-Nopec, 2010) using VR data from 26/07-01, this is consistent with the fact that 26/08-01 penetrates to greater depth than Well 26/07-01.

Average present day TOC values were calculated by the project team from wireline log data for the Stephanian strata (Boulton Formation), Coal Measures Group, Millstone Grit Group and Scremerston Formation (Gent, this study). BasinMod was used to calculate the initial TOC values utilising these present day TOC values.

Assessment of the source rock potential for the Firth Coal Formation (Vane et al., this study) indicates that the Scremerston Formation organic matter has excellent potential and is type III kerogen (gas prone). It is possible that some oil prone kerogens are present since poor, possibly migrated, oil shows are mentioned in the well report. One datapoint on the Van Krevelen plot indicated the Boulton Formation (Stephanian) was type II kerogen (Vane et al., this study). The Coal Measures Group and Millstone Grit Formation were assumed to include type III kerogen based on gas shows noted in the well report (Mobil North Sea, 1992).

According to the BasinMod model and VRcalc, the gas-prone Scremerston Formation only reaches the oil window. Report IDA205391 suggests that some type II kerogen is present, so some oil may have been generated. The model generation potential for strata in the well is given in Figure 8.

Timing for generation from the most promising horizon is given in Figure 9. The cumulative hydrocarbon potential time plot shows the generated hydrocarbons, the results at time = 0 show present day volumes it is anticipated the strata penetrated by the well have generated based on the BasinMod model. At any given time, the cumulative hydrocarbon curve is inversely proportional to the hydrogen index (HI) and Total Organic Carbon (TOC) model results. The TOC (%) and HI (mg/gTOC) indicate the generative potential of the strata penetrated by the well, the cumulative hydrocarbon volume on the time plot shows the BasinMod model of this generative potential being realised through time.

The data entry sheet is shown in Figure 11.

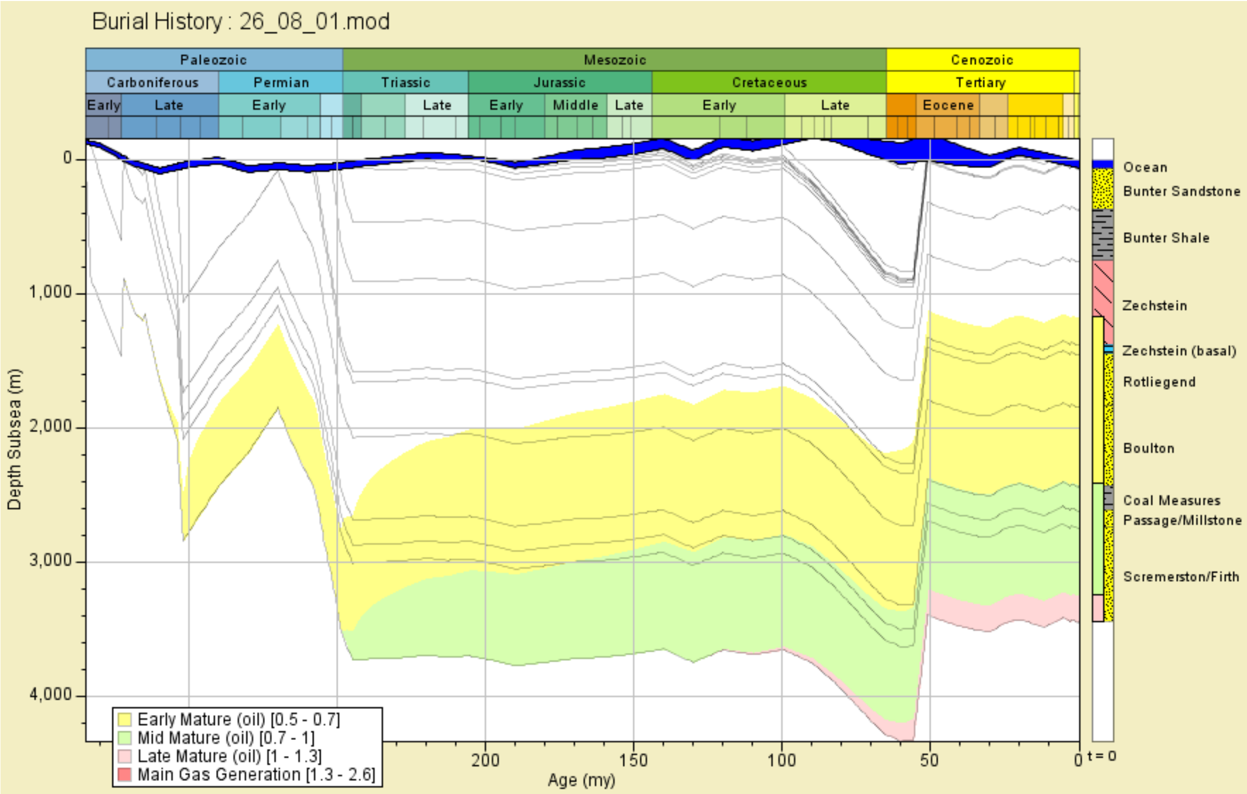


Figure 5: Modelled maturity geohistory for Well 26/08-01. The well terminates in the Scremerston Formation and the base of the Scremerston Formation is not reached.

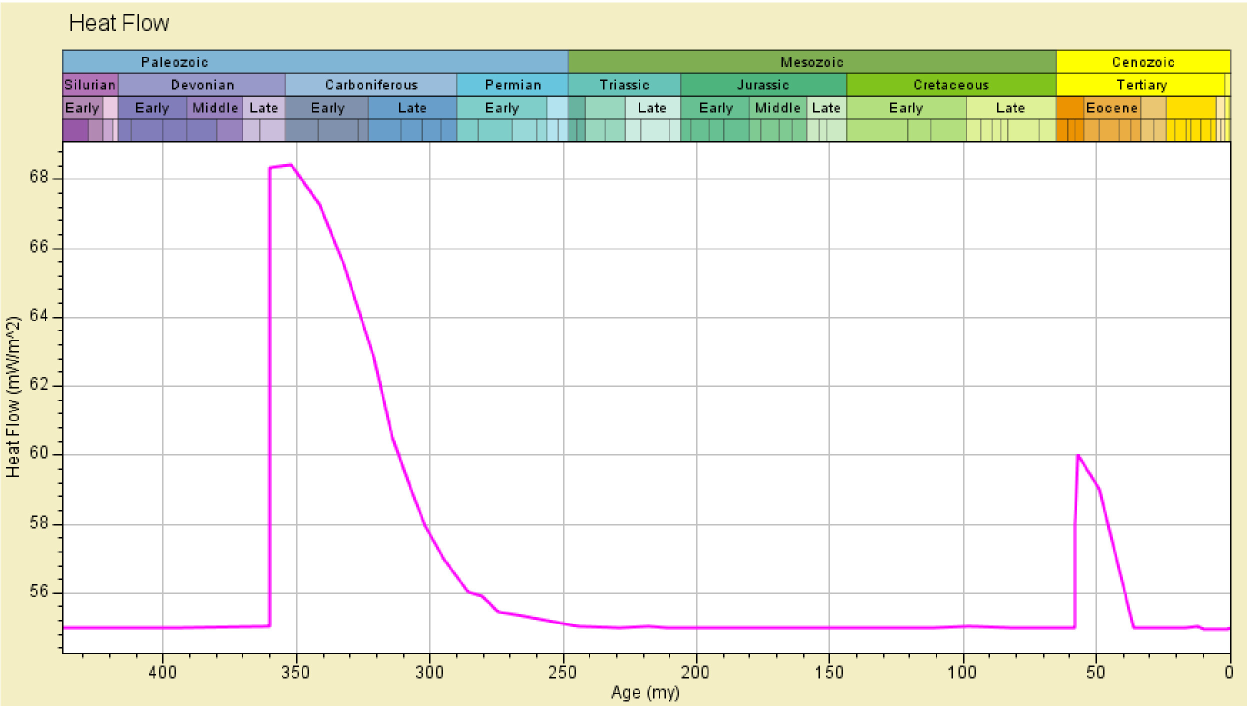


Figure 6: Modelled palaeo-heat flow for Well 26/08-01

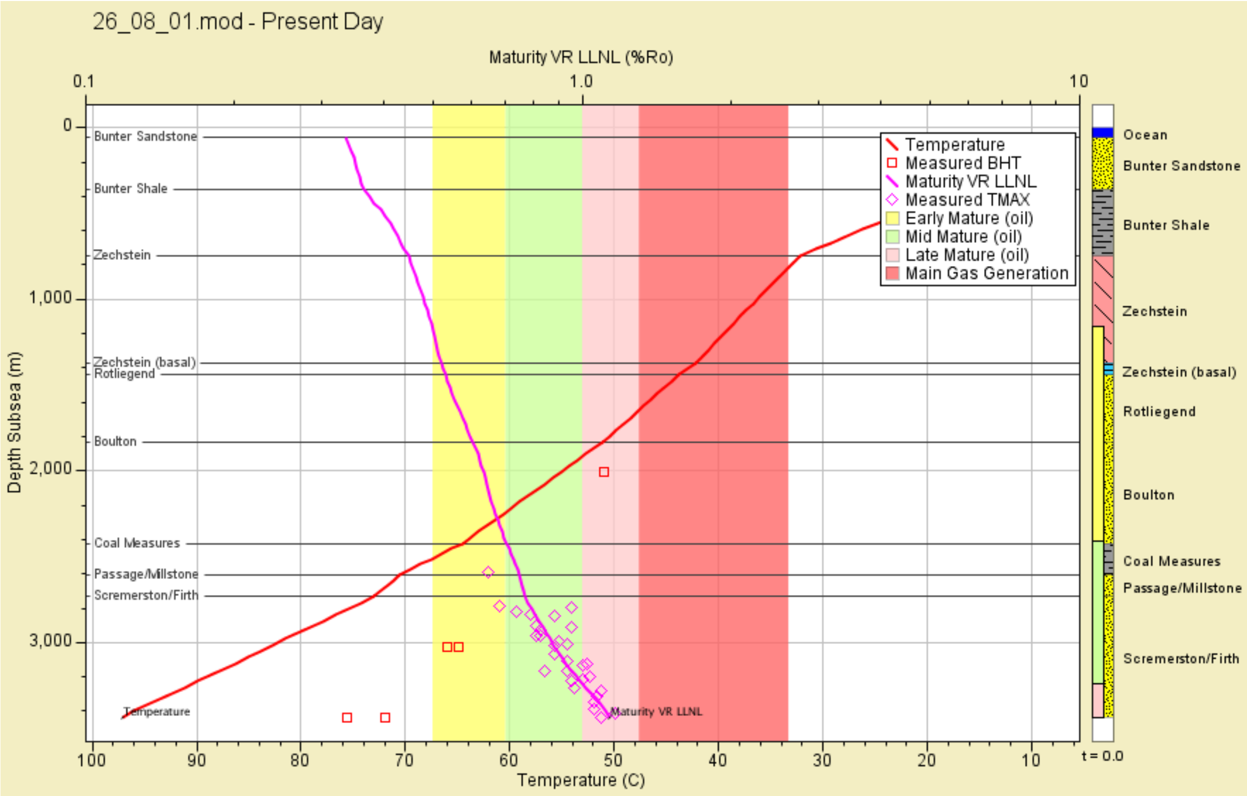


Figure 7: Depth plot for Well 26/08-01 showing model results, maturity data and maturity windows plus temperature data and model.

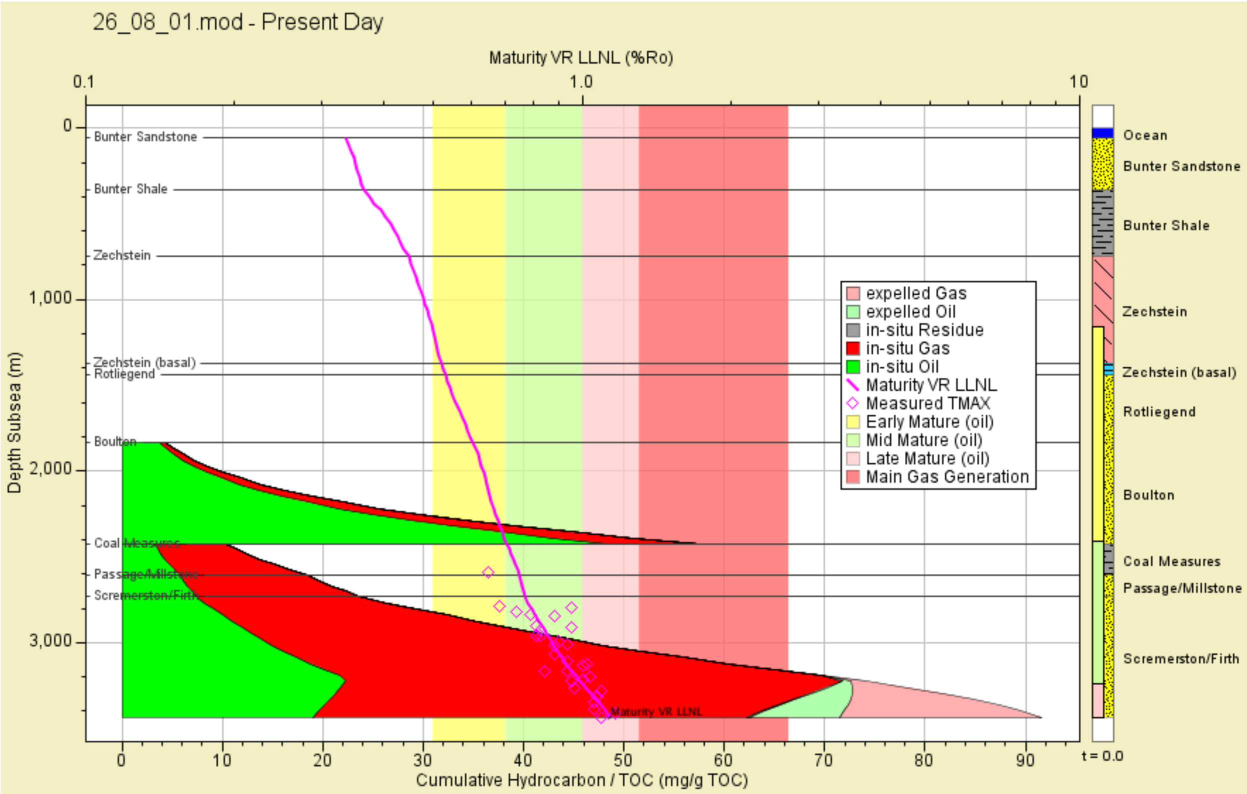


Figure 8: Depth plot for Well 26/08-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

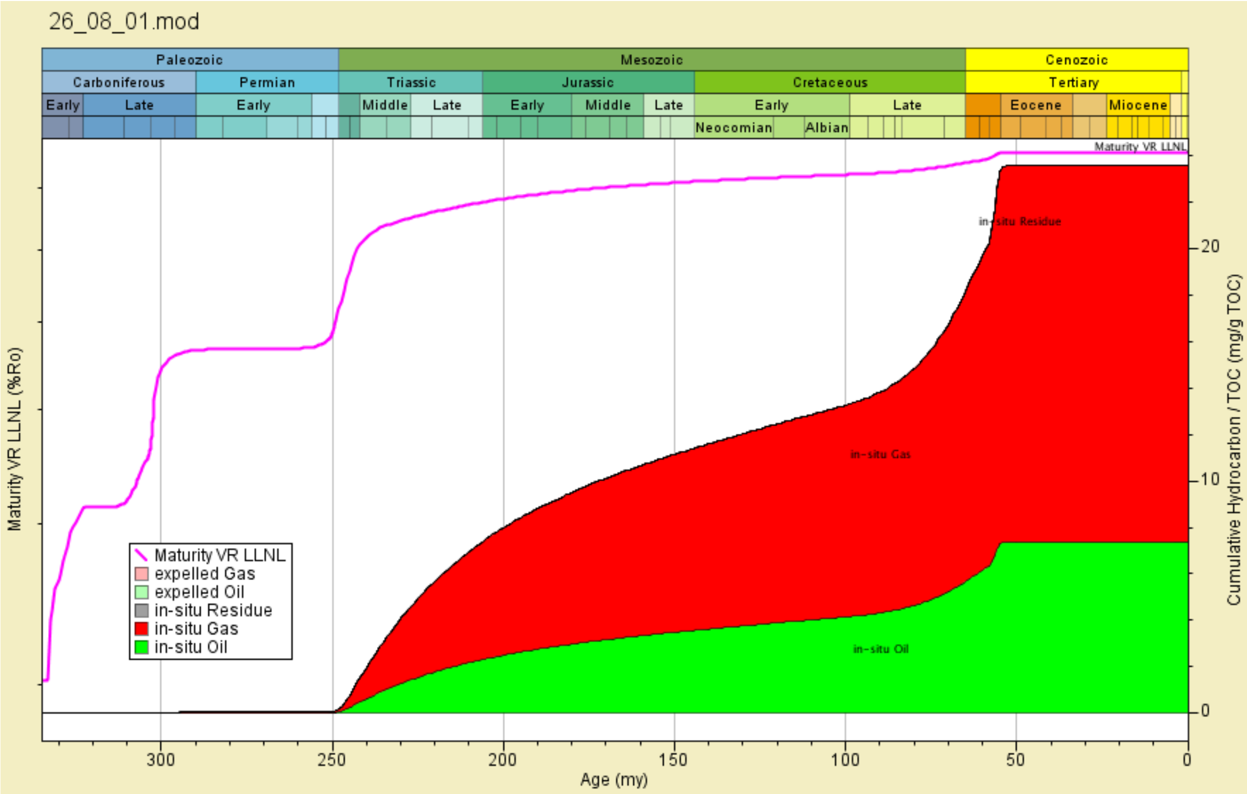


Figure 9: Time plot for Well 26/08-01 showing timing of generation for Scremerston Formation through geological history of this formation. The current model suggests that main generation occurred during deepest burial during the Mesozoic and Cenozoic eras.

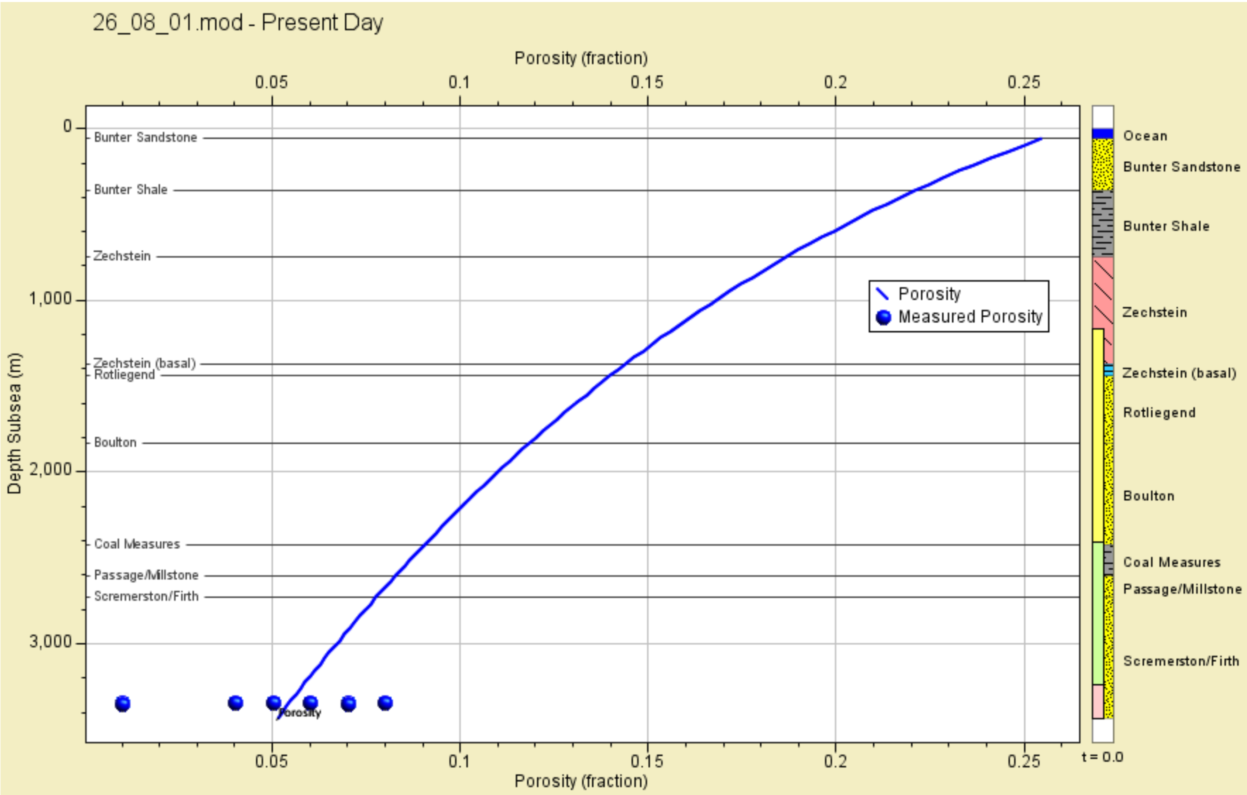
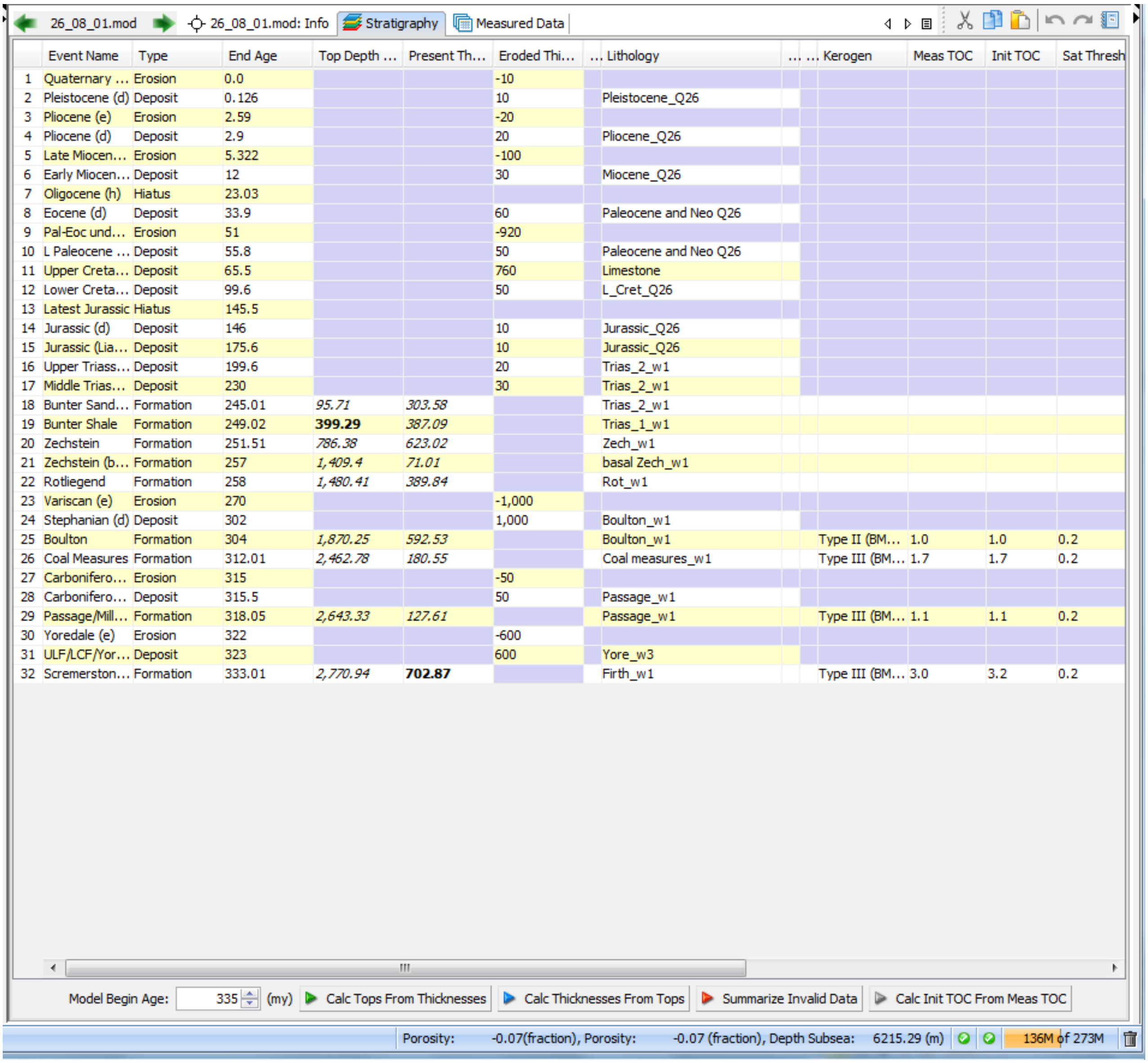


Figure 10: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 26/08-01



	Event Name	Type	End Age	Top Depth …	Present Th…	Eroded Thi…	… Lithology	… … Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary …	Erosion	0.0			-10					
2	Pleistocene (d)	Deposit	0.126			10	Pleistocene_Q26				
3	Pliocene (e)	Erosion	2.59			-20					
4	Pliocene (d)	Deposit	2.9			20	Pliocene_Q26				
5	Late Miocen…	Erosion	5.322			-100					
6	Early Miocen…	Deposit	12			30	Miocene_Q26				
7	Oligocene (h)	Hiatus	23.03								
8	Eocene (d)	Deposit	33.9			60	Paleocene and Neo Q26				
9	Pal-Eoc und…	Erosion	51			-920					
10	L Paleocene …	Deposit	55.8			50	Paleocene and Neo Q26				
11	Upper Creta…	Deposit	65.5			760	Limestone				
12	Lower Creta…	Deposit	99.6			50	L_Cret_Q26				
13	Latest Jurassic	Hiatus	145.5								
14	Jurassic (d)	Deposit	146			10	Jurassic_Q26				
15	Jurassic (Lia…	Deposit	175.6			10	Jurassic_Q26				
16	Upper Triass…	Deposit	199.6			20	Trias_2_w1				
17	Middle Trias…	Deposit	230			30	Trias_2_w1				
18	Bunter Sand…	Formation	245.01	*95.71*	*303.58*		Trias_2_w1				
19	Bunter Shale	Formation	249.02	**399.29**	*387.09*		Trias_1_w1				
20	Zechstein	Formation	251.51	*786.38*	*623.02*		Zech_w1				
21	Zechstein (b…	Formation	257	*1,409.4*	*71.01*		basal Zech_w1				
22	Rotliegend	Formation	258	*1,480.41*	*389.84*		Rot_w1				
23	Variscan (e)	Erosion	270			-1,000					
24	Stephanian (d)	Deposit	302			1,000	Boulton_w1				
25	Boulton	Formation	304	*1,870.25*	*592.53*		Boulton_w1	Type II (BM…	1.0	1.0	0.2
26	Coal Measures	Formation	312.01	*2,462.78*	*180.55*		Coal measures_w1	Type III (BM…	1.7	1.7	0.2
27	Carbonifero…	Erosion	315			-50					
28	Carbonifero…	Deposit	315.5			50	Passage_w1				
29	Passage/Mill…	Formation	318.05	*2,643.33*	*127.61*		Passage_w1	Type III (BM…	1.1	1.1	0.2
30	Yoredale (e)	Erosion	322			-600					
31	ULF/LCF/Yor…	Deposit	323			600	Yore_w3				
32	Scremerston…	Formation	333.01	*2,770.94*	**702.87**		Firth_w1	Type III (BM…	3.0	3.2	0.2

Figure 11: Model data entry sheet for Well 26/08-01. Well terminates in Scremerston Formation and additional thickness of Scremerston below TD has not been estimated. Top Depth is in m BRT

5.3.3 Key points from new modelling work for Well 26/08-01

- Geological model; maximum burial occurred during Cenozoic times
- Limited generation occurred (mainly gas prone kerogens but only oil maturity window reached) during Triassic and younger times
- Scremerston Formation is mainly gas prone but only reaches the oil maturity window
- Generation potential for Palaeozoic strata is expected to be poor at this well location as the kerogens are mainly gas prone but the strata do not reach the main gas maturity window

5.4 WELL 26/14-01

Well 26/14-01 lies on the edge of the Mid North Sea High and on the southern flank of the Forth Approaches Basin. This well penetrates strata of Permian to Silurian age.

5.4.1 Previous thermal and modelling work for this well

Silurian and Devonian samples show low TOC and are not deemed prospective in this well. Permian strata had promising TOC but were deemed to immature.

Palaeozoic source rocks and reservoirs

The Silurian strata had poor TOC and were almost barren of vitrinite but the available samples suggested the strata are overmature with very low source potential. In addition, based on n-alkane analysis it seemed samples were most likely contaminated by diesel oil from the drilling mud (PETRA-CHEM, 1984). PETRA-CHEM, 1984 observed that black wood kerogen was common in one sample from the Lower Silurian strata (1253.3 m BRT). though this sample was not rated as likely to produce hydrocarbons. The authors were clear that the lithologies assessed for the report (siltstone, claystones and limestones) only represented a small percentage of the cuttings. Silurian strata appear over-mature but it also seems these VR samples could have been contaminated (PETRA-CHEM, 1984).

Mendham (1992) was unable to draw a firm conclusion about the maturity of the Lower Devonian strata based on available samples. The PETRA-CHEM report (PETRA-CHEM, 1984) indicates that amorphous kerogen (oil prone) was common in one sample from the Lower Devonian (Buchan Formation). It was advised in the PETRA-CHEM (1984) report that that their conclusion that the Lower Devonian strata are immature depends on the single VR datapoint obtained (Buchan Formation, 1143.0 m BRT) not being derived from cavings. It was also noted that no UV spore fluorescence was evident, again suggesting that the strata are immature. To contradict this finding, small amounts of dark plant debris were present, suggesting the Devonian strata were highly mature. In either case, the TOC of samples was low and it was determined that the Lower Devonian had no source potential. Fluid inclusions within the Devonian interval were typed as Carboniferous wet gas (Farris et al., 2012).

The Devonian targets were dry and/or tight (Farris et al., 2005)

Younger source rocks and reservoirs

The Rotliegend Group was water-bearing. The well does not appear to have drilled a valid post-Palaeozoic closure (Farris et al., 2012).

Mendham (1992) indicated that the Rotliegend strata were immature. PETRA-CHEM (1984) assessed cuttings from the well and observed that the Permian and Triassic strata were immature.

The PETRA-CHEM report (PETRA-CHEM, 1984) indicates that amorphous kerogen (oil prone) was common in one sample from the Zechstein Group (960.1 m BRT). As no VR measurements were obtained from the Zechstein strata, samples were tested for exinite fluorescence under UV light and the n-alkane distribution was tested (in Z2). Both sets of experimental data indicated that the strata are immature. The TOC of Upper Permian strata was higher towards the bottom of the sequence and of the samples with a high TOC, four siltstones were identified as having good hydrocarbon potential.

The Triassic strata had poor TOC (only trace argillaceous material available from cuttings) (PETRA-CHEM, 1984).

5.4.2 New modelling work

Model input data are shown in Table 4. The maturity model for Well 26/14-01 was prepared using VR and VRcalc data.

Available maturity and porosity data

T_{max} data were available for the Zechstein Group, Lower Permian strata, Lower Devonian strata and Silurian strata and were used to produce VRcalc. VR data were available for the Rotliegend Group, Lower Devonian strata (1 datapoint for each) and Silurian strata (PETRA-CHEM, 1984). Only a small number of measurements were taken and drilling mud contamination was noted in the Devonian samples so these VR data were considered with caution. VRcalc was converted from T_{max} data in the PETRA-CHEM (1984) report (six T_{max} values) for the Zechstein Group. Two T_{max} values were available from BGS core testing (one for the Lower Devonian strata and one for the Silurian strata). One VR data from the Rotliegend strata and five VR data from the Silurian strata were included from Mendham (1992) (Ro max). Porosity data were available for the Rotliegend strata and Lower Devonian strata. Pyrolysis data (S1, S2, TOC and a few S3 and one kerogen typing) were included in the model for the generation phase of modelling.

Table 4: Summary of model input data for Well 26/14-01 and layer maturity window from the BasinMod model

Formation/ age of strata	N.o. of VR/ VRcalc datapoints	Model maturity window	Average measured TOC from logs	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Zechstein Group	6VR calc	Mid mature for oil		mixed oil/gas prone			
Rotliegend	1 VR calc	Mid mature for oil	1.82*	mixed oil/gas prone		11 data	
Lower Devonian	1 VR, 2 VR calc	Mid mature for oil	0.7	oil prone		2 data	Possible contamination of VR samples
Silurian	5 VR, 1 VRcalc	Mid - late mature for oil	0.14*				Very poor match between VR and VRcalc. Possible contamination of VR samples

* These values are provided from TOC samples reported in legacy reports instead of from log analysis as log data were not available

Model calibration

The model suggests relatively low deposition rates during Silurian and Devonian times as the trend of the VRcalc data is relatively linear. It is worth noting however that the model is quite insensitive to the thickness of eroded Devonian strata.

The eroded thickness of Carboniferous strata was estimated in light of the preserved strata in Well 26/08-01. The model is not particularly sensitive to changes in eroded Carboniferous strata and similar thicknesses to the preserved thicknesses and expected maximum thickness based on other wells in Quadrant 26 gave a relatively good fit to VRcalc, even though this well was believed to lie on the footwall of the basin bounding fault. The finalised model for the Carboniferous section is a balance between matching the data and the geological model for this area. Removal of an additional 4.8 km of strata from on top of the Carboniferous section (based on compaction of a shale lithology) would be supported by the density log work (Kimbell and Williamson, this study); this is greater than the amount suggested by the BasinMod model. Nevertheless, both the BasinMod model and density log work support deep burial and significant Variscan uplift here.

For the post-Cretaceous strata, it was assumed that as this region lay within a larger gently subsiding region that similar thicknesses to those preserved and modelled for Well 26/08-01 would have been deposited and removed. This part of the model was quite sensitive to estimated eroded strata thickness and the finalised model suggests a greater deposition then removal of strata than for Well 26/08-01. Comparison with density logs (Kimbell and Williamson, this study) supports deep burial and removal of a great thickness of post-Cretaceous strata with an estimated 3.2 km of additional strata required to achieve the compaction shown by the Rotliegend strata which is even greater than the amount suggested by the BasinMod model (1.3 km).

The maturity geohistory is given in Figure 12, the model heat flow is given in Figure 13.

Maturity and hydrocarbon generation

The maturity model was calibrated on the VRcalc data as these covered the greatest range of strata. In addition, there were some comments on possible contamination/allocthonous data and very few tests (between 1 and 8[1] readings) were used to obtain the VR readings for the Silurian VR data. The VR datapoint from the Rotliegend (which according to the depth given in Mendham (1992) actually falls in the lowest part of the Zechstein Group on the composite log) shows very low maturity. The measured VR values did not correlate well with VRcalc; in this case VR>VRcalc. The porosity data were used as a secondary method with the Baldwin and Butler compaction method utilised in BasinMod as this seemed to give the best match for most models in this study where maturity and porosity data are available (Figure 14 and Figure 17).

The values for VRcalc suggest that the Zechstein strata achieved mid maturity for oil (VRcalc 0.71 – 0.94), Lower Devonian strata reached early oil maturity (VRcalc 0.90) and the Silurian strata just reached late oil maturity (VRcalc 1.0). A sample from the Lower Devonian suggests gas generation phase was reached (VRcalc 1.83) but this data point does not agree well with the general data trend. The results of the model prepared for this project suggest that a higher level of maturity was reached than the reports prepared at the time the well was drilled.

Overall, given the mismatch between datapoints within each dataset and between the VR data and VRcalc, confidence in this BasinMod model is low.

Average TOC values were included in the model; Permian strata (1 datapoint from legacy reports), Cementstone (legacy reports and 1 new RockEval), Kyle Group (average calculated from log analysis) and Silurian strata (1 new RockEval datapoint). BasinMod was used to calculate the initial TOC values utilising these measured TOC values. Vane et al. (this study) noted that the quality of the TOC data was poor for this well.

The Permian rocks were judged have poor to excellent source potential (mixed oil/gas prone; Vane et al., this study; note this was assumed to indicate a mix of type I and type III kerogen for the generation modelling work). Lower Devonian strata appeared to have good potential but this is based on one datapoint (oil prone; note this was assumed to indicate type I kerogen for the generation modelling work) and the Silurian sample (type IV kerogen) has poor potential. Few data were available. According to the BasinMod model, the Permian rocks reached the early – mid oil window. There are thin dolomitic horizons which could have some source potential. The points indicated as having 'excellent' source potential (Vane et al., this study) all lie towards the bottom of the Zechstein sequence (Z1 and Z2 cycles), where dolomites are interspersed with the thick anhydrites. A maximum gas show of 0.0007% is noted on the composite log here.

The results show oil generation in Cenozoic times from the Lower Devonian, though as noted above, as maturity data quality is low, confidence in this model is low.

[1] It is recommended that at least 20 readings are taken to obtain a reliable VR reading (Beardsmore and Cull, 2001)

The model generation potential for strata in the well is given in Figure 15. Timing for generation from the most promising horizon is given in Figure 16. The data entry sheet is shown in Figure 18.

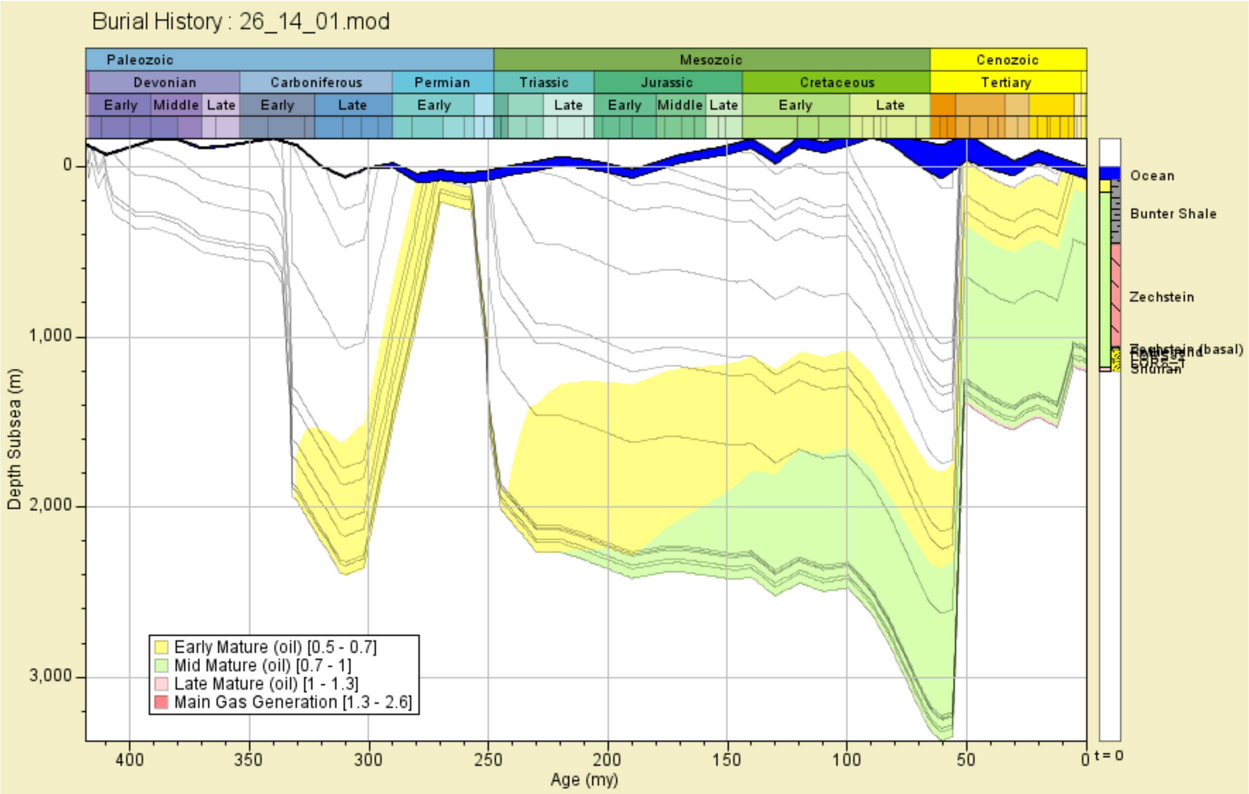


Figure 12: Modelled maturity geohistory for Well 26/14-01. The well terminates in Silurian strata.

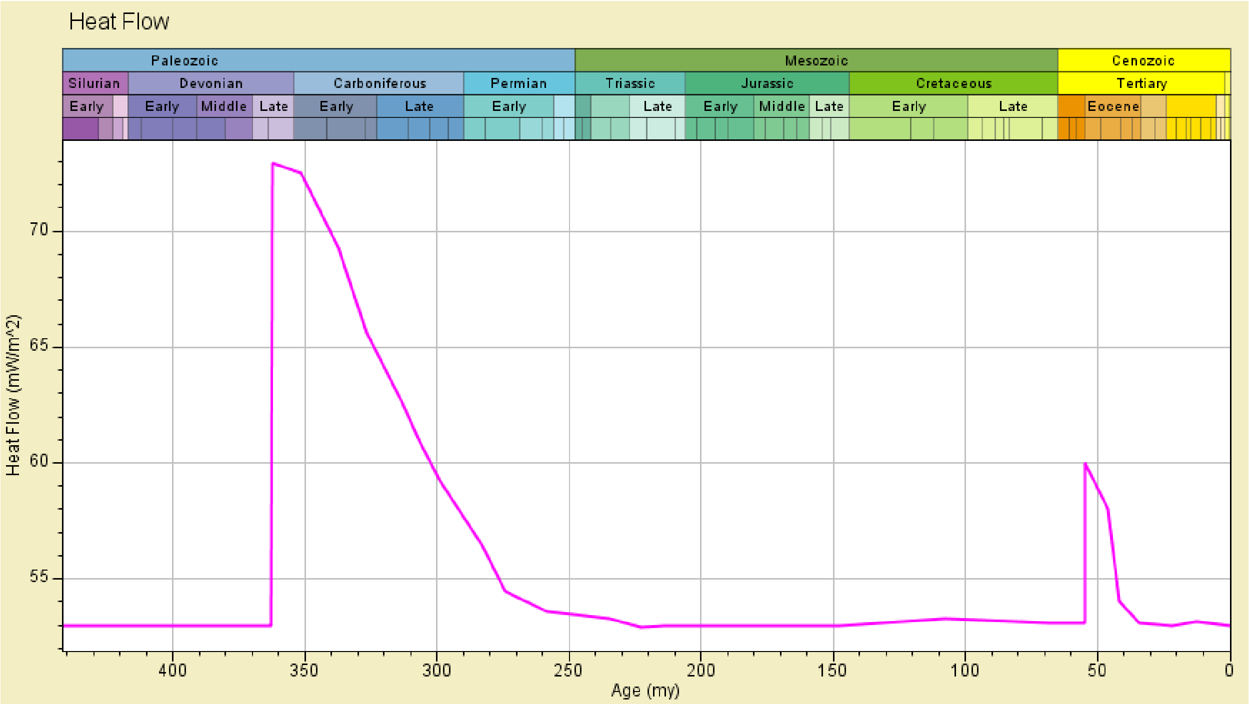


Figure 13: Modelled palaeo-heat flow for Well 26/14-01

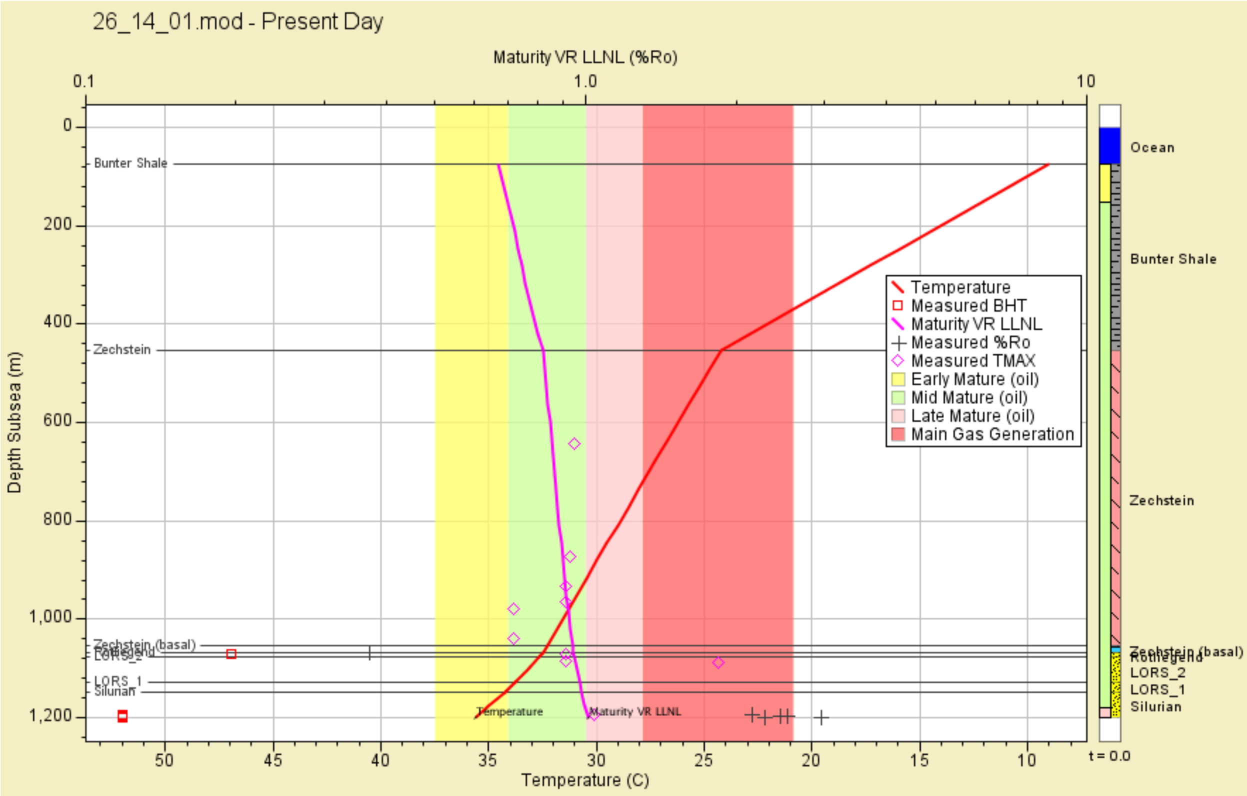


Figure 14: Depth plot for Well 26/14-01 showing model results, maturity data and maturity windows plus temperature data and model

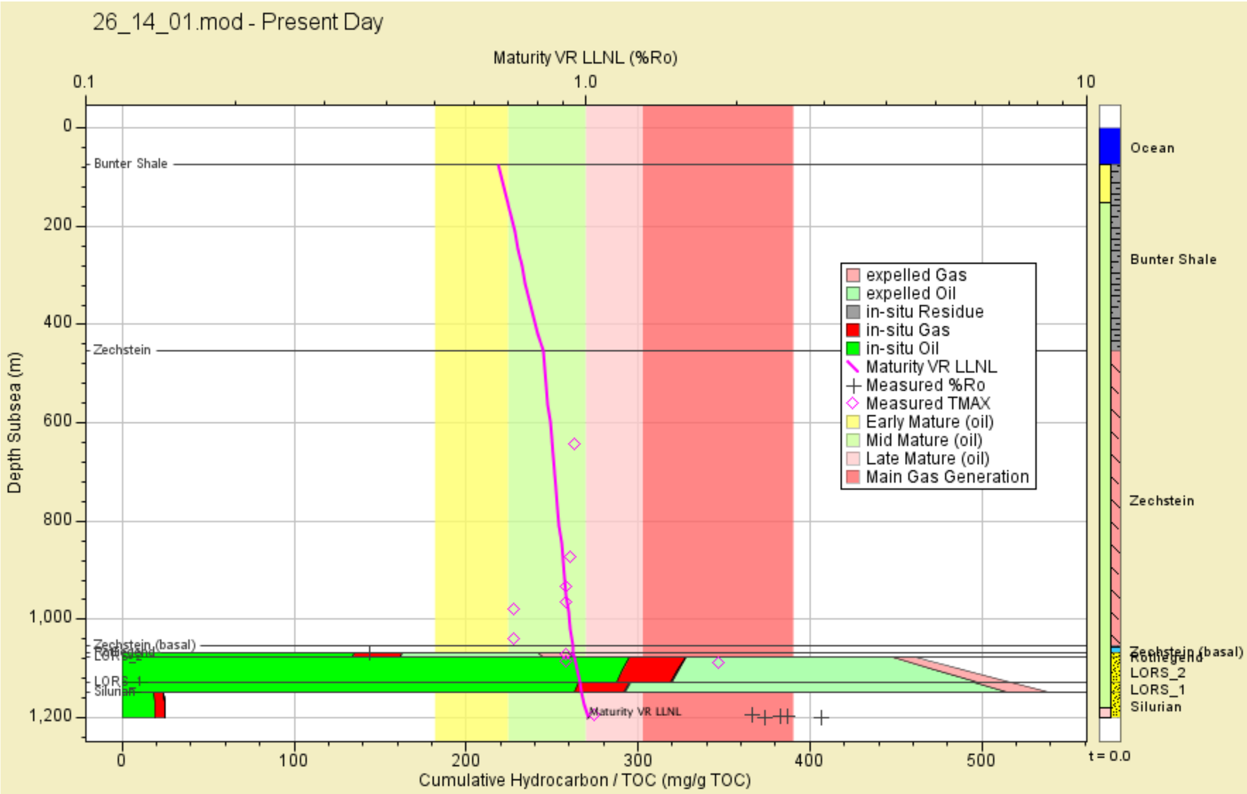


Figure 15: Depth plot for Well 26/14-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

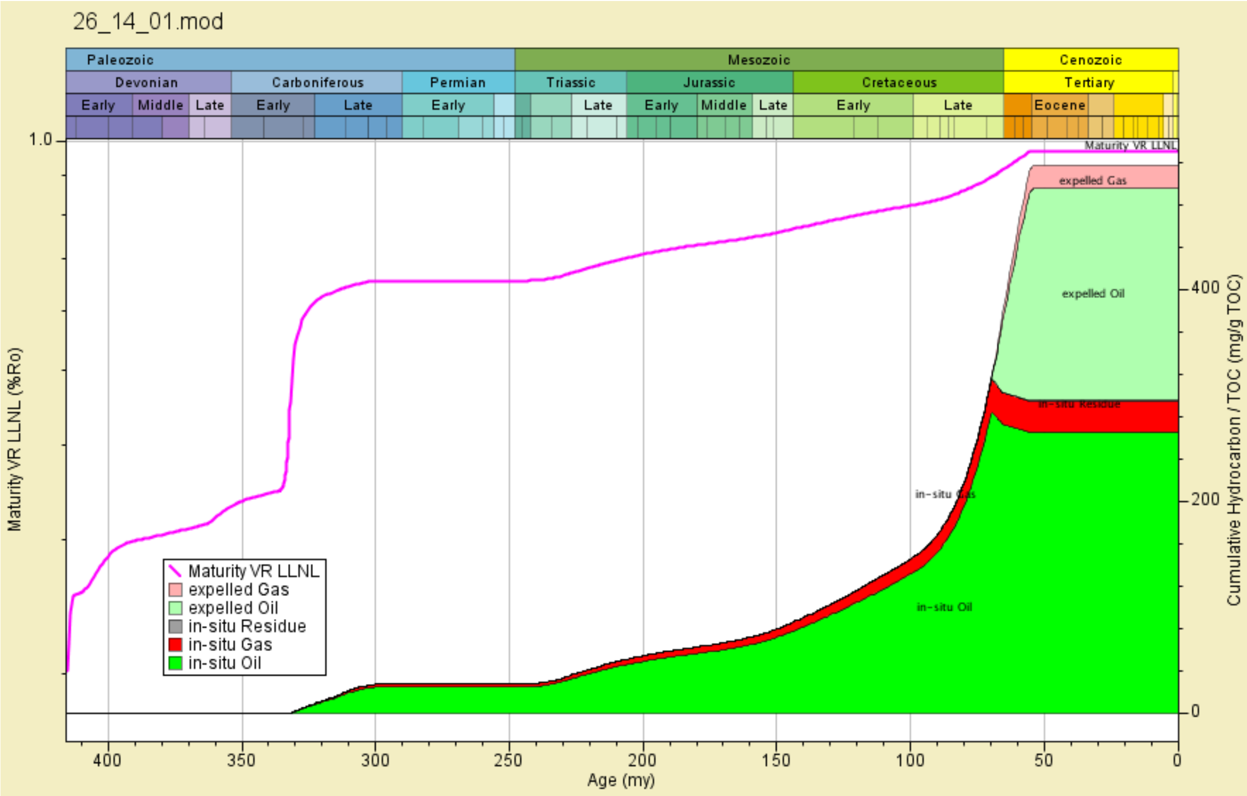


Figure 16: Time plot for Well 26/14-01 showing timing of generation for Lower Devonian strata (model layer 'LORS_1'). The current model suggests that main generation and expulsion occurred during deepest burial during the Cenozoic Era.

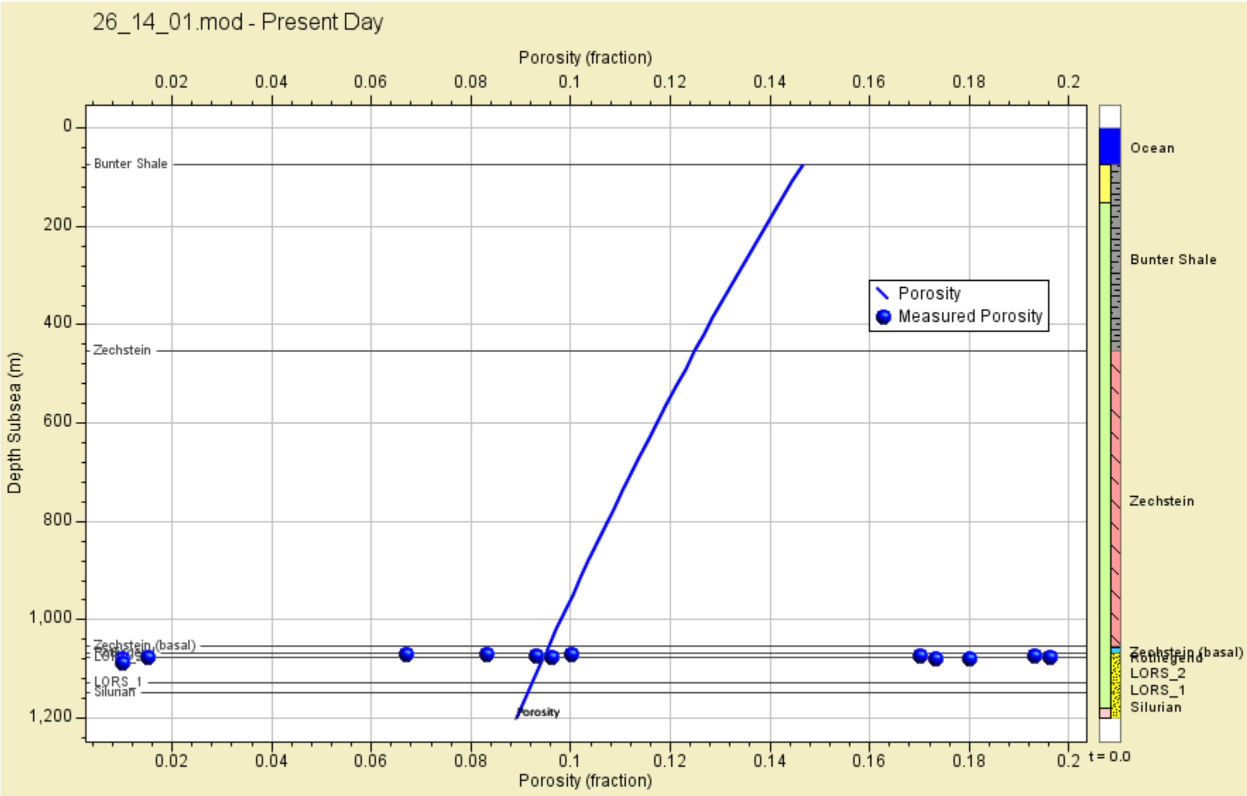


Figure 17: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 26/14-01

26_14_01.mod | 26_14_01.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	...	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10								
2	Pleistocene (d)	Deposit	0.126			10		Pleistocene_Q26						
3	Late Pliocen...	Erosion	2.59			-10								
4	Pliocene (d)	Deposit	2.9			10		Pliocene_Q26						
5	Late Miocen...	Erosion	5.322			-390								
6	Early Miocen...	Deposit	12			30		Miocene_Q26						
7	Oligocene	Hiatus	23.03					Miocene_Q26						
8	Eocene (d)	Deposit	33.9			60		Paleocene and Neo Q26						
9	Pal-Eoc und...	Erosion	51			-1,900								
10	L Paleocene ...	Deposit	55.8			100		Paleocene and Neo Q26						
11	Upper Creta...	Deposit	65.5			900		Limestone						
12	Lower Creta...	Deposit	99.6			100		L_Cret_Q26						
13	Latest Jurassic	Hiatus	145.5											
14	Jurassic (d)	Deposit	146			150		Jurassic_Q26						
15	Jurassic (Lia...	Deposit	175.6			50		Jurassic_Q26						
16	Upper Triass...	Deposit	199.6			100		Trias_w2						
17	Middle Trias...	Deposit	230			300		Trias_w2						
18	Bunter Sand...	Deposit	245			400		Trias_w2						
19	Bunter Shal...	Deposit	249.01			100		Trias_w2						
20	Bunter Shale	Formation	250	**131.67**	*380.39*			Trias_w2						
21	Zechstein	Formation	251	*512.06*	*600.76*			Zech combined w2						
22	Zechstein (b...	Formation	257	*1,112.82*	*13.42*			Zech Z1_w2						
23	Rotliegend	Formation	258	*1,126.24*	*10.05*			Rot_w2			Kerogen Mix...	1.82	2.4	0.2
24	Variscan (e)	Erosion	270			-2,210								
25	Stephanian (d)	Deposit	302			10		Sandstone						
26	Coal Measur...	Deposit	312			180		Coal measures_w1						
27	Passage/Mill...	Deposit	318			220		Mil Grit _w2						
28	ULF/LCF/Yor...	Deposit	332			600		Yoredale_w4						
29	Firth/Screm...	Deposit	333			700		Firth Coal Fm_w2						
30	Tayport	Deposit	336.22			100		Sandstone						
31	Buchan (d)	Deposit	342.01			200		Sandstone						
32	LORS_2 (d)	Deposit	397.5			100		Buchan 2_w2						
33	LORS_2	Formation	407	*1,136.29*	*50.3*			Buchan 2_w2			Type I (BMO...	0.7	1.2	0.2
34	Devonian er...	Erosion	411			-100								
35	LORS_1 (d)	Deposit	413			100		Buchan 1_w2						
36	LORS_1	Formation	415	*1,186.59*	*19.81*			Buchan 1_w2			Type I (BMO...	0.7	1.3	0.2
37	Silurian (e)	Erosion	416			-100								
38	Silurian (d)	Deposit	417			100		Silurian_w2						
39	Silurian	Formation	417.7	*1,206.4*	*51.51*			Silurian_w2			Kerogen Mix 3	0.14	0.1	0.2

Model Begin Age: 418.7 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Porosity: -0.07(fraction), Porosity: -0.07 (fraction), Depth Subsea: 6215.29 (m) | 143M of 273M

Figure 18: Model data entry sheet for Well 26/14-01. Top Depth is in m BRT.

5.4.3 Key points from new modelling work for Well 26/14-01

- Confidence in this model is low due to issues with data quality
- Scremerston Formation has been eroded
- Lower Devonian strata appears to have good generation potential but this is based on a single datapoint
- Devonian strata reached the mid mature for oil window in this well
- Main generation occurred during Cenozoic era
- Deepest burial during the Cenozoic era

6 Detail of Mid North Sea High modelling

6.1 GEOLOGICAL MODEL

<u>Early Devonian deposition and intrusion of granites, Mid Devonian deposition</u>

During Early Devonian times, this region lay in a continental setting and the Lower Old Red Sandstone Supergroup was deposited. Intrusion of the Farne and Dogger granites occurred during Early Devonian times (Gatliff et al., 1994) and formed local highs with likely limited deposition. These intrusions have been a major influence on the location of Devonian and Carboniferous basins (Gatliff et al., 1994).

A marine transgression advanced from the south during middle Devonian times resulting in deposition of limestones of the Kyle Group (Gatliff et al., 1994).

<u>Late Devonian – Early Carboniferous dextral transtension</u>

Latest Devonian-early Carboniferous extension/dextral transtension is a key part of the geological history of the MNSH (Arsenikos et al., this study; Leslie et al., this study).

Widespread deposition of the non-marine Upper Devonian (Buchan, Tayport formations) occurred between highs defined by granites.

<u>Carboniferous deposition</u>

During Carboniferous times, the MNSH was thought to be a low relief area of sediment transport feeding basins in the Southern North Sea (Gatliff et al., 1994).

Hay et al. (2005) suggest that there was limited sedimentation across this region during Carboniferous times with the exception of local extensional basins. Gatliff et al. (1994) also suggested that Carboniferous strata are thin/locally absent on MNSH.

Whilst thinner than in adjoining basins, this study has interpreted widespread deposition of Lower Carboniferous strata across parts of the MNSH (Arsenikos et al., this study).

Hay et al. (2005) observe that the Namurian and Westphalian strata in the southern gas basin show significant thinning towards the MNSH.

Where present, upper Carboniferous strata mainly comprise a coal bearing sequence deposited in a marine/deltaic environment.

<u>Late Carboniferous – Early Permian (Variscan) uplift and erosion</u>

During latest Carboniferous and earliest Permian times, regional compression and transpression associated with the Variscan Orogeny and volcanism occurred (Gatliff et al., 1994).

Hay et al. (2005) observe that there is no significant break in the maturity data across the Variscan unconformity (though there are only a few cases where data is available from both the Carboniferous and post-Variscan sequences) and interpret this as an indication that Carboniferous burial was not too deep and that Variscan uplift of the MNSH was not too severe. Hay et al. (2005) suggest that Quadrant 36 was subject to between 900 – 2100 m uplift (increasing from southwest to northeast) during the Variscan Orogeny (the authors did note there was uncertainty in the estimate for the region with greater uplift due to ‘poor Devonian stratigraphy’).

Coward et al. (2003) suggest that Early Permian volcanism in northern England and the Midland valley of Scotland which pre-dates Permian extension indicates that the area was underlain by hot asthenosphere, possibly the edge of a north-west European hot spot.

Permian hiatus

The MNSH (including most of Quadrant 36) formed a barrier that separated the Southern Permian Basin from the Northern Permian Basin during latest Carboniferous – Permian times (Gatliff et al., 1994).

Rotliegend strata are believed to pinch out on the margins of the MNSH and therefore expected to be absent from most of the MNSH including the north part of Quadrant 36 (Gatliff et al., 1994).

The sandy Auk Formation (deposited during late Permian times) is also expected to be absent on the MNSH (Hay et al., 2005; Glennie et al., 2003).

Zechstein deposition

A rapid marine transgression occurred due to global sea level rise at the start of Zechstein Group deposition and the MNSH then formed only a partial barrier between the Northern and Southern Permian basins (Gatliff et al., 1994). Sea level must have been variable to allow evaporite deposition on the MNSH (Gatliff et al., 1994). Zechstein strata are preserved in Wells 36/13-01 and 36/23-01.

Triassic deposition

During Triassic times, a major depocentre lay to the northeast of this area in the Norwegian-Danish Basin. Deposition on the MNSH is expected to have been relatively limited (<500 m thickness of strata). Extensive halokinesis occurred during early Triassic times which strongly affected the deposited and preserved thickness of strata. Triassic deposition may also have been partly controlled by rifting but this is difficult to confirm due to Late Jurassic overprinting (Gatliff et al., 1994). Normal faulting occurred in the Central Graben to the east of the MNSH and non-marine sediments were widely deposited, including on most the MNSH (Coward et al., 2003).

Early Jurassic deposition

During latest Triassic to early Jurassic times, a gradual transgression changed the environment of deposition from continental to marginal to marine environment across the CNS, though Lower Jurassic sediments are only penetrated by a few wells in the CNS.

Early - Mid Jurassic uplift and erosion

Lower Jurassic strata are expected to be thin or locally absent on the MNSH due to early-mid Jurassic domal uplift (mid Cimmerian/Intra-Aalenian Unconformity). Hay et al., (2005) suggest mid Jurassic uplift was an important feature in the history of the MNSH and estimate the amount of mid-Jurassic uplift to be 400 – 730 m in Quadrant 36 (Hay et al., 2005). Gatliff et al. (1994) observe that the proposed amount of uplift cited by various authors ranges from 250 – 2500 m. The MNSH was most likely emergent during Middle Jurassic times (Bradshaw et al., 1992). Lower Jurassic strata are preserved in Well 36/23-01 and absent in Well 36/13-01.

Late Jurassic deposition

The Late Jurassic period was a time of widespread subsidence due to crustal stretching; a widespread and gradual transgression led to a marine environment, including on the MNSH (Gatliff et al., 1994). The MNSH was a stable platform environment (Fraser et al., 2003). Late Jurassic strata are expected to be thin (<400 m) on the MNSH (Gatliff et al., 1994). Upper Jurassic strata are preserved in Well 36/13-01 (but Lower Jurassic strata are absent). During Latest Jurassic times, active rifting and faulting occurred to the east of MNSH in the Central Graben (Fraser et al., 2003). The Kimmeridge Clay Formation was deposited in largely anaerobic conditions and the top of this formation is marked by a distinct change in facies which represents a sudden sea level fall followed by a sudden rise (this boundary is the late-Cimmerian unconformity and is taken as the top of the Jurassic for regional mapping purposes; Gatliff et al., 1994).

Cretaceous deposition

Halokinesis continued into Early Cretaceous times as did some of the faulting initiated during Late Jurassic times. Both these factors impacted the thickness of strata. A relatively thin but uniform thickness (100 m) of Lower Cretaceous strata is preserved on the MNSH with some local variation due to halokinesis/faulting.

During Upper Cretaceous times, a relative sea level rise resulted in increased water depths. Lithospheric cooling caused subsidence with local influence from grabens and highs established during the Jurassic Period. Up to 600 m of Upper Cretaceous strata are expected to have been deposited on the MNSH. Chalk and chalk-marl were deposited though the Uppermost Chalk Group seems to be absent on the MNSH (Gatliff et al., 1994). The greatest thickness of chalk on the MNSH is recorded in Quadrant 36 (Hay et al., 2005).

Paleocene – Early Eocene mantle underplating and uplift

The relatively quiet tectonic regime of the Upper Cretaceous ceased during Palaeocene times and by the late Palaeocene Era, most of the current UK landmass and the eastern margin of the North Sea lay above sea level (Murray, 1992).

Across this part of the MNSH, basinal mudstones were deposited during the Palaeocene, but there is some debate on the water depths. Thin (<100 m) Palaeocene deposits are expected (Gatliff et al., 1994; Ahmadi et al., 2003). Subsidence was centred on the Mesozoic rift system to the south of the study area and major Jurassic structural highs were subject to erosion (Ahmadi et al., 2003).

Mantle underplating and crustal thinning related to the Iceland plume occurred around 61 – 51 Ma and this area was affected during the Paleocene – early Eocene times (Coward et al., 2003; Brodie and White, 1995; Gatliff et al., 1994).

Mid – Late Eocene deposition

During the Eocene Stage, this region probably was probably a deltaic to shelfal environment following underlying Cretaceous structural patterns. During Eocene times, mud-dominated marginal to shallow marine deposits (<350 m thick) were deposited. A few sandy intervals are present. Sea level appears to have been very variable (Gatliff et al., 1994; Jones et al., 2003).

Thermal post-rift subsidence continued during Eocene times (Jones et al., 2003; Fyfe et al., 2003).

Oligocene hiatus and erosion

Tectonic movements related to the Tethys Ocean to the south-east and the opening of the Atlantic Ridge to the north-west caused a local hiatus in parts of the CNS during the Early to Mid Oligocene (Coward et al., 2003). Early Oligocene erosion removed upper Eocene strata in this region (Gatliff et al., 1994).

Early Miocene – Mid Miocene

Uplift continued from Mid Miocene times until Early Pliocene times. Limited deposition is expected (Coward et al., 2003).

Mid Miocene – Late Miocene

The Mid Miocene unconformity is a significant feature on the MNSH. Beneath the unconformity the Oligocene and Lower Miocene strata have been eroded. To the west the age gap increases as there was no deposition of the Upper Miocene and Pleistocene strata. In this study area, after Mid Miocene times, there was effectively no deposition until Pliocene times (Hay et al., 2005). Hay et al. (2005) estimated 600 – 1200 m of uplift during Paleogene – Neogene times for Quadrant 36, though it should be noted this assessment is based on a limited number of wells. Japsen (1998) estimated 550 m of strata had been eroded during the Cenozoic Era from Well 36/15-01 based on Chalk Group compaction data. Japsen (1998) suggested that maximum burial occurred during the Neogene Stage and that Neogene erosion was more severe than erosion during the Paleocene Stage in this area. The current models suggest a more modest Cenozoic burial depth than these previous calculations.

Early Pliocene deposition

Renewed subsidence took place during the Early Pliocene Epoch. Pliocene strata were deposited in the west of the MNSH (Hay et al., 1995). Pliocene strata are expected to be thin (<100m) (Gatliff et al., 1994). Pliocene strata are preserved in Well 36/13-01 but absent in Well 36/23-01.

Uplift of landmasses around the North Sea Basin occurred during Late Pliocene and Early Pleistocene times (Fyfe et al., 2003; Japsen, 1998).

Pleistocene deposition

In this region, Lower Pleistocene and early Mid Pleistocene deposits comprise deltaic deposits with the top of each formation believed to indicate a highstand and a hiatus in deposition. Mid-Late Pleistocene and Holocene sediments were deposited in subglacial, glaciolacustrine and glaciomarine environments during glacier recession (Gatliff et al., 1994). Pleistocene strata are preserved in Well 36/13-01 but absent in Well 36/23-01.

6.2 PREVIOUS WORK IN THIS REGION

Limited maturity data are available in Quadrant 36; only a few wells have data and data are only available for a small part of the section. UV fluorescence is noted in wells in Quadrant 36 but economic quantities of hydrocarbons are not observed, this is believed to be due to lack of charge.

Generation and migration

Hay et al. (2005) assessed Quadrants 34 – 39 (Hay et al., 2005). The well analysis did not locate economic quantities of hydrocarbons, this was believed to be mainly due to lack of charge though lack of traps at reservoir levels was also an important factor. Quadrant 36 generally shows a thin Permian sequence including thin platform carbonates (Zechstein). The generation and migration model of Hay et al (2005) suggests that generation occurred in the south of the area and migrated northwards. Well 36/26-01 is noted as dry in Hay et al. (2005) report.

Applied Petroleum Technology (UK) Limited prepared a report for Centrica evaluating maturity across Quadrants 36, 37, 38, 41, 43 and two adjacent onshore wells (Applied Petroleum Technology, 2012). This study provided existing and new geochemical data (vitrinite reflectance, spore colour, TOC, solvent extraction) that was returned to the BGS core store and utilised for this current work.

UV Fluorescence is reported in wells in Quadrant 36 (36/15-01, 36/23-01, 36/26-01; Applied Petroleum Technology, 2012).

Maturity data

Applied Petroleum Technology (2012) noted that vitrinite reflectance sampling tended to show a wider variation in results (the histograms of individual readings are broad) for Carboniferous samples compared with Cenozoic samples.

Well 36/26-01 has one VR data from the Yoredale Formation which indicates late maturity for oil (VR = 0.59) but the number of samples is small (9) (PETRA-CHEM, 1970).

6.3 WELL 36/13-01

Well 36/13-01 lies in the centre of the MNSH on a high identified by the project team on seismic reflection data. The Farne granite, believed to be Devonian in age, was emplaced quite near to Well 36/13-01 which may have led to a greater localised heat flow.

6.3.1 Previous maturity and modelling work for this well

No significant hydrocarbon shows are reported for this well. This well was modelled by Hay et al. (2005) and the authors indicated that the Carboniferous potential source rocks were immature.

Hydrocarbon shows

No significant gas shows are recorded in the Arpet drilling history report (Arpet, 1967a). The Yoredale and Lower Zechstein strata below 1158 m (BRT) had readings of 0 – 8 units.

Triassic strata had readings of 2 – 20 units. Jurassic carbonaceous shales showed readings of 10 – 90 units. It was noted that methane was recorded in the Cretaceous chalk (0 – 31 units) but the higher readings were believed to be a result of a reaction between the drilling mud and casing since the cuttings and mechanical logs did not support these figures (Arpet, 1967a).

Minor gas shows are reported in Well 36/13-01 in the post-Palaeozoic section but the source is not given (Arpet, 1967a). UV Fluorescence is reported in Well 36/13-01 (Applied Petroleum Technology, 2012).

Geohistory modelling

Hay et al. (2005) indicated that the Carboniferous potential source rocks were immature in this well. Hay et al. (2005) include a geothermal gradient of 31.3 °C/km for this well. Hay et al. (2005) suggested that around 1.25 km of strata had been removed during the Variscan Orogeny. The Applied Petroleum Technology (2012) report suggested even greater erosion.

Hay et al. (2005) suggested 730 m of uplift had occurred during Mid Jurassic uplift (Cimmerian/Intra-Aalenian Unconformity).

Hay et al (2005) suggested around 900 m of uplift had occurred here during the Early Cenozoic Era.

6.3.2 New modelling work

Maturity and porosity data

Five VR data are available from PETRA-CHEM (1970) all within the Carboniferous section (Yoredale Formation). An additional 10 VR datapoints are available from a more recent report (Applied Petroleum Technology, 2012) which represent samples from the Yoredale Formation and the Jurassic, Palaeocene and Pliocene/Miocene sections. Eleven T_{max} assessments for the Carboniferous section were also available from PETRA-CHEM (1970). Additional pyrolysis data (S1, S2, TOC) were also included in the model (PETRA-CHEM, 1970). Model input data are shown in Table 5.

Table 5: Summary of model input data for Well 36/13-01 and layer maturity window from the BasinMod model

Formation/ age of strata	N.o. of VR/ VRcalc datapoints	Model maturity window	Average measured TOC from logs	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Pliocene	2 VR						
Paleocene	2 VR						
Upper Cretaceous					Methane recorded		Methane thought to be a result of reaction with drilling mud
Jurassic	2 VR				Minor gas shows		
Zechstein		Immature			Minor gas shows		
Yoredale	9 VR, 11 VRcalc	Early mature for oil	2.0	Gas prone			High VR values (above 0.6) believed to be reworked

<u>Model calibration</u>

There was generally good agreement between the VR and VRcalc, though the average maturity value predicted by the VRcalc is slightly higher. The maturity model was calibrated on the VR data since this covered the full section and a good number of tests were carried out to produce each VR datapoint.

The geological history for the BasinMod model suggests that deepest burial took place during the Carboniferous times. The Carboniferous sequence is quite thin and considerable uplift during the Variscan Orogeny is therefore suggested by the BasinMod model. Through analysis of density logs, Kimbell and Williamson (this study) predicted around 2 km of Carboniferous strata had been removed during the Variscan Orogeny. This is greater than the estimated ~1.3 km suggested by the BasinMod model. The BasinMod model is quite sensitive to strata variation here so this part of the model is quite well calibrated based on the maturity data. The BasinMod model was matched to the lower VR values based on comments in the Applied Petroleum Technology (2012) report about data reliability. The BasinMod model estimate for removed strata thickness agrees with the ~1.25 km uplift suggested in Hay et al. (2005) report but is less than the uplift suggested by the Applied Petroleum Technology (2012) report.

As this region remained a relative high, Rotliegend strata are absent and Upper Permian, Triassic and Jurassic strata are thin. It was estimated that mid Jurassic uplift was around 0.7 km in Hay et al. (2005). As late Triassic and Lower Jurassic strata are absent in the well, 0.5 km of additional Triassic strata were included in the model, however it is important to note there are no maturity data in this section for calibration of the model here.

In contrast to the thin preserved Permian, Triassic and Jurassic strata, the Cretaceous strata are quite thick (Hay et al., 2005). Well 36/13-01 penetrates over 500 m of Cretaceous strata.

This part of the MNSH lay close to the onlapping edge of the region of deposition of Pliocene strata with Pliocene sediments in Well 36/13-01 resting unconformably on Miocene strata (Gatliff et al., 1994). Thickness of post-Cretaceous eroded strata is suggested to be quite small in the current model (120 m) which is lower than the predicted uplift from Hay et al. (2005) and lower than the missing strata estimate prepared from the density log as calculated by Kimbell and Williamson (this study) of 430 m. However, given the low VR values recorded from post-Palaeozoic samples, a significantly greater thickness of strata would not be supported by the current model.

The maturity geohistory is given in Figure 19, the model heat flow is given in Figure 20.

Maturity and generation of hydrocarbons

The average TOC value as calculated from log data by Gent (this study) for the Yoredale Formation was used for the BasinMod model. BasinMod calculated the initial TOC based on this measured value. The Yoredale samples were gas prone (Vane et al., this study) so this was assumed to indicate type III kerogen for the purposes of modelling.

There is good agreement between the VR measured (average autochthonous values given in PETRA-CHEM, 1970 and Applied Petroleum Technology, 2012 reports) and VRcalc. VR and VRcalc indicate that the Yoredale Group reached early mature for oil during deep Carboniferous burial (a couple of VRcalc data lie in the mid mature for oil maturity window VRcalc). Strata are currently quite deeply buried and Carboniferous strata are in the oil window. A number of samples were taken in the Lower Permian and Yoredale Formation between 1264.9 – 1372.8 m BRT with TOC of 1.4 – 61.95 wt% with 7.2 – 21.4% usable carbon (PETRA-CHEM, 1970). The source rock quality is judged to be good to excellent but the samples are judged to be mainly gas prone (Vane et al., this study).

The fit of BHT to the model temperature is reasonable, but curiously, the uncorrected BHT from the BHCS log is higher than the corrected temperatures (and plots above the model line).

According to the BasinMod model, the Yoredale Formation only reached the 'early mature for oil' window though the samples are gas prone. Therefore significant generation would not be expected.

The model results are shown in Figure 21. The model generation potential for strata in the well is given in Figure 28. Timing for generation from the most promising horizon is given in Figure 29. The data entry sheet is shown in Figure 30.

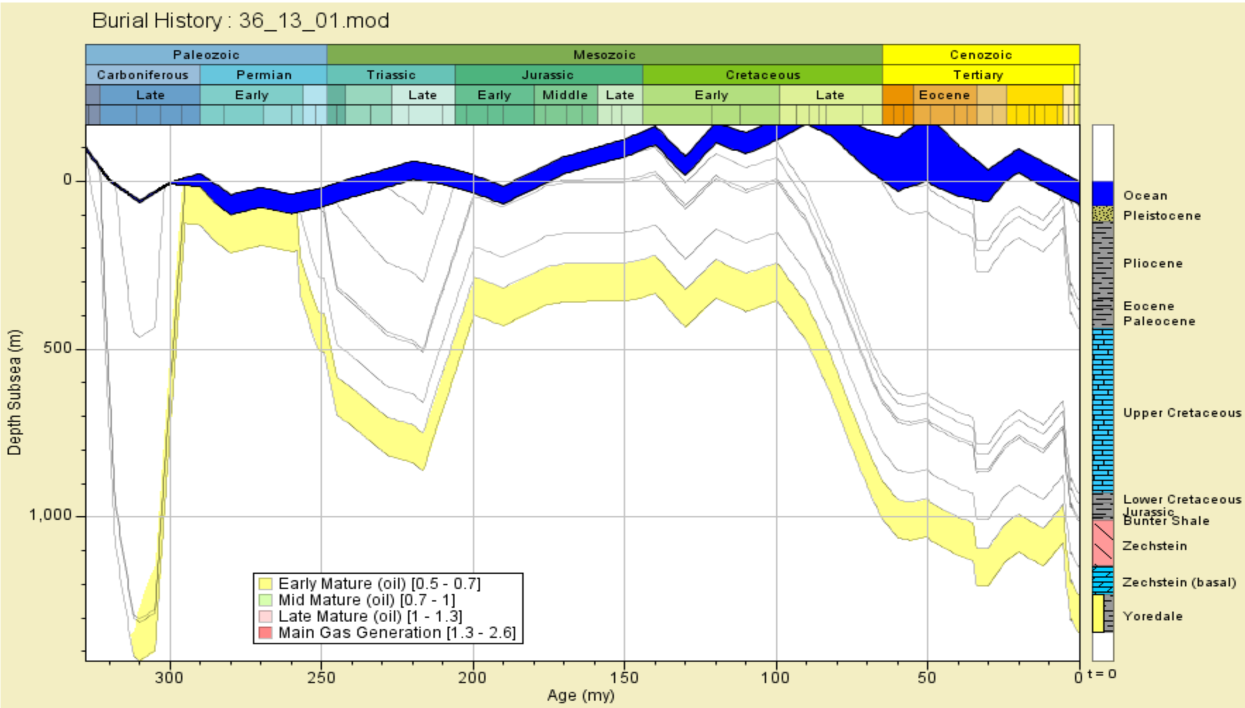


Figure 19: Modelled maturity geohistory for Well 36/13-01. Well terminates in the Yoredale Formation.

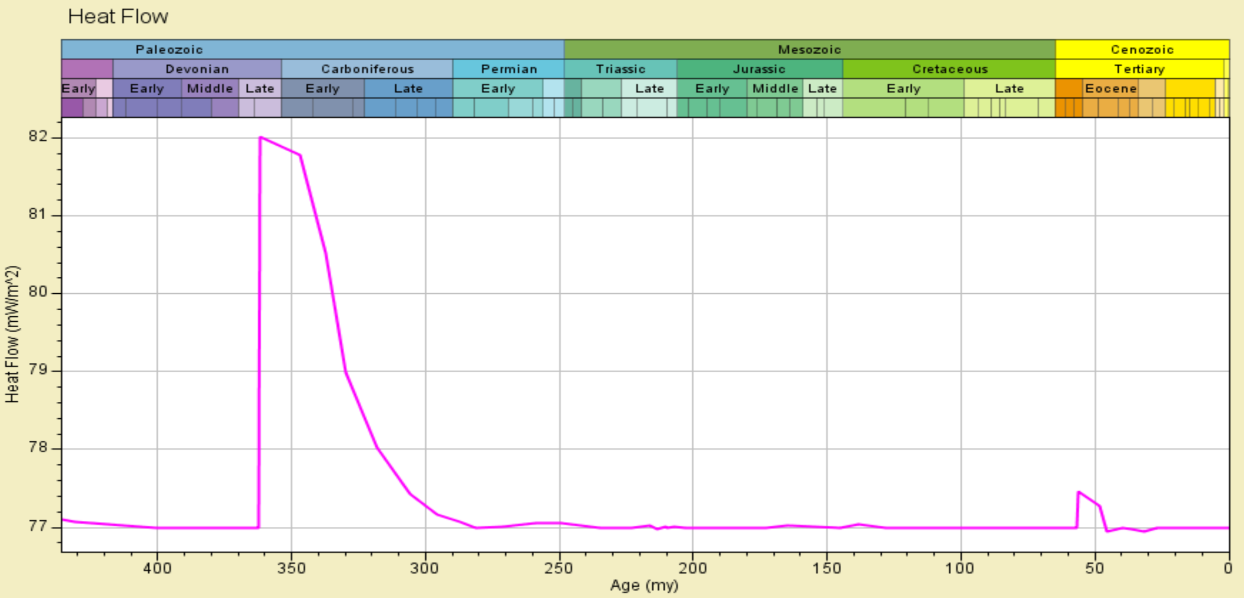


Figure 20: Modelled palaeo-heat flow for Well 36/13-01

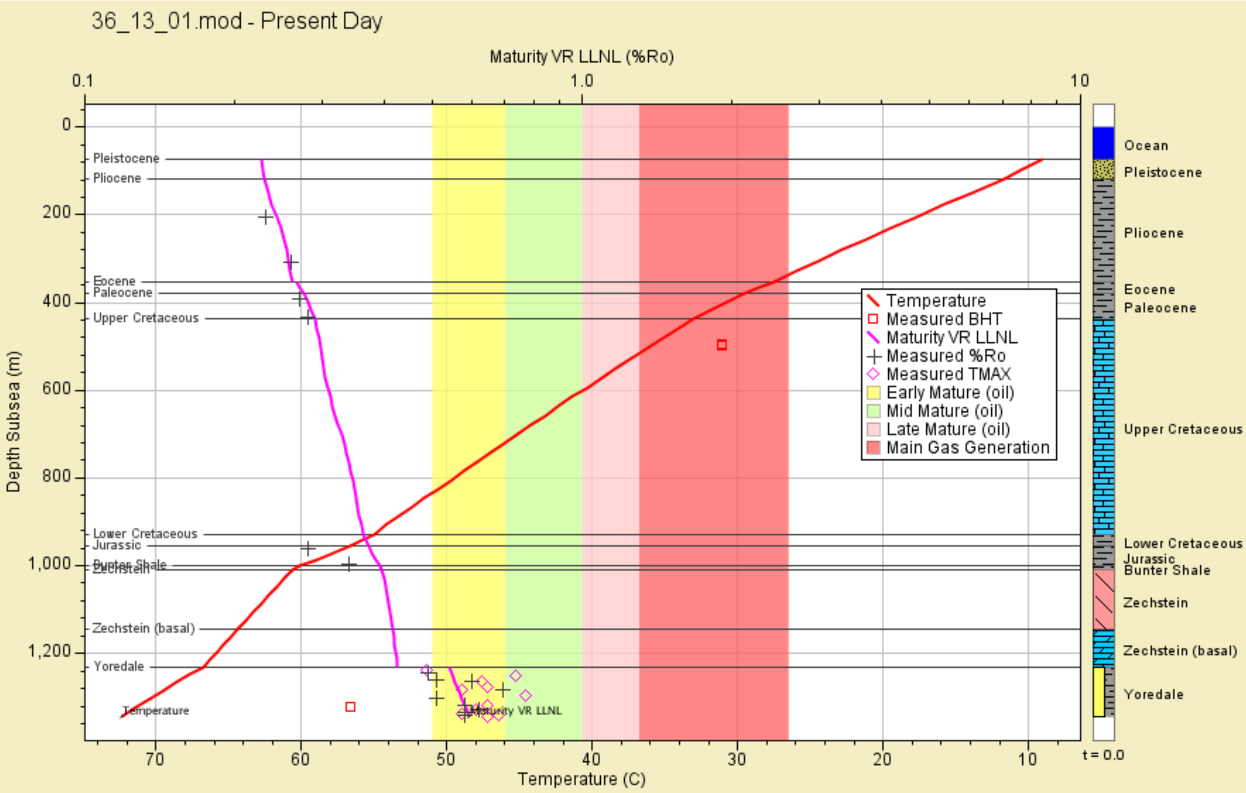


Figure 21: Depth plot for Well 36/13-01 showing model results, maturity data and maturity windows plus temperature data and model

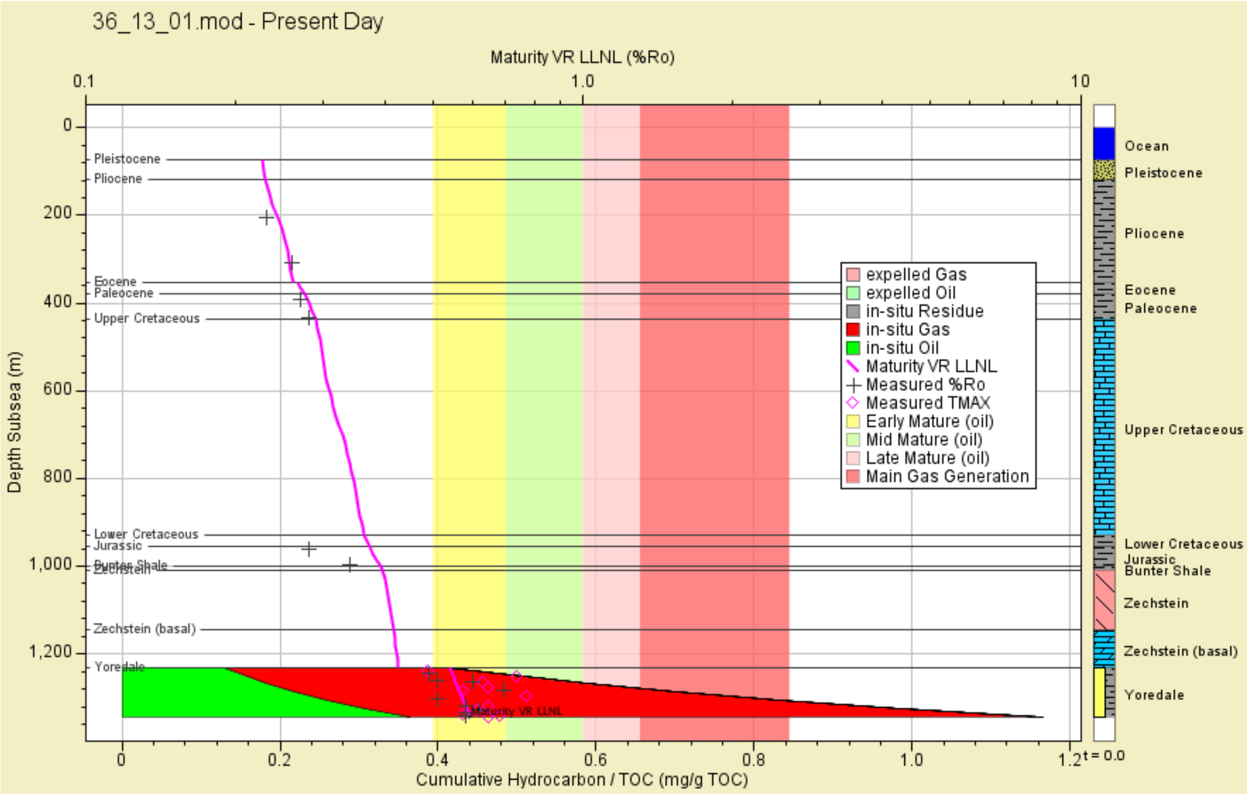


Figure 22: Depth plot for Well 36/13-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

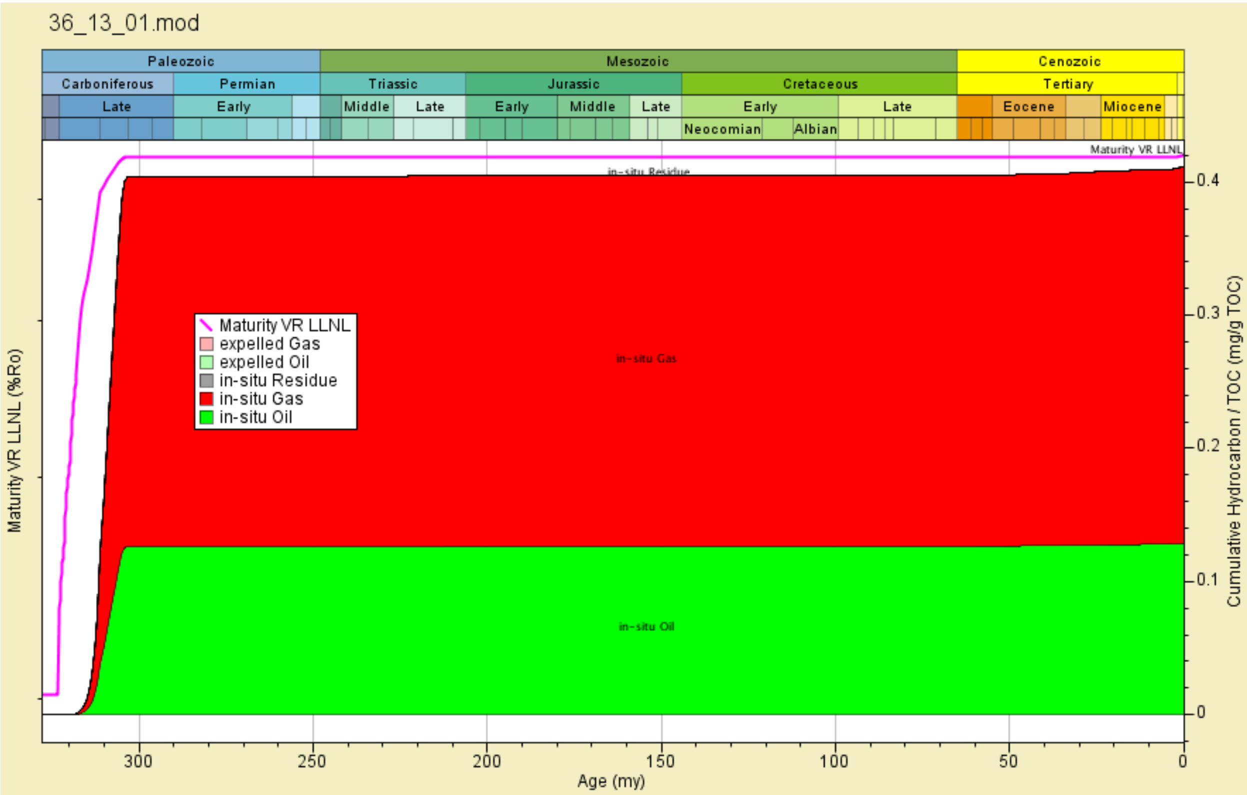
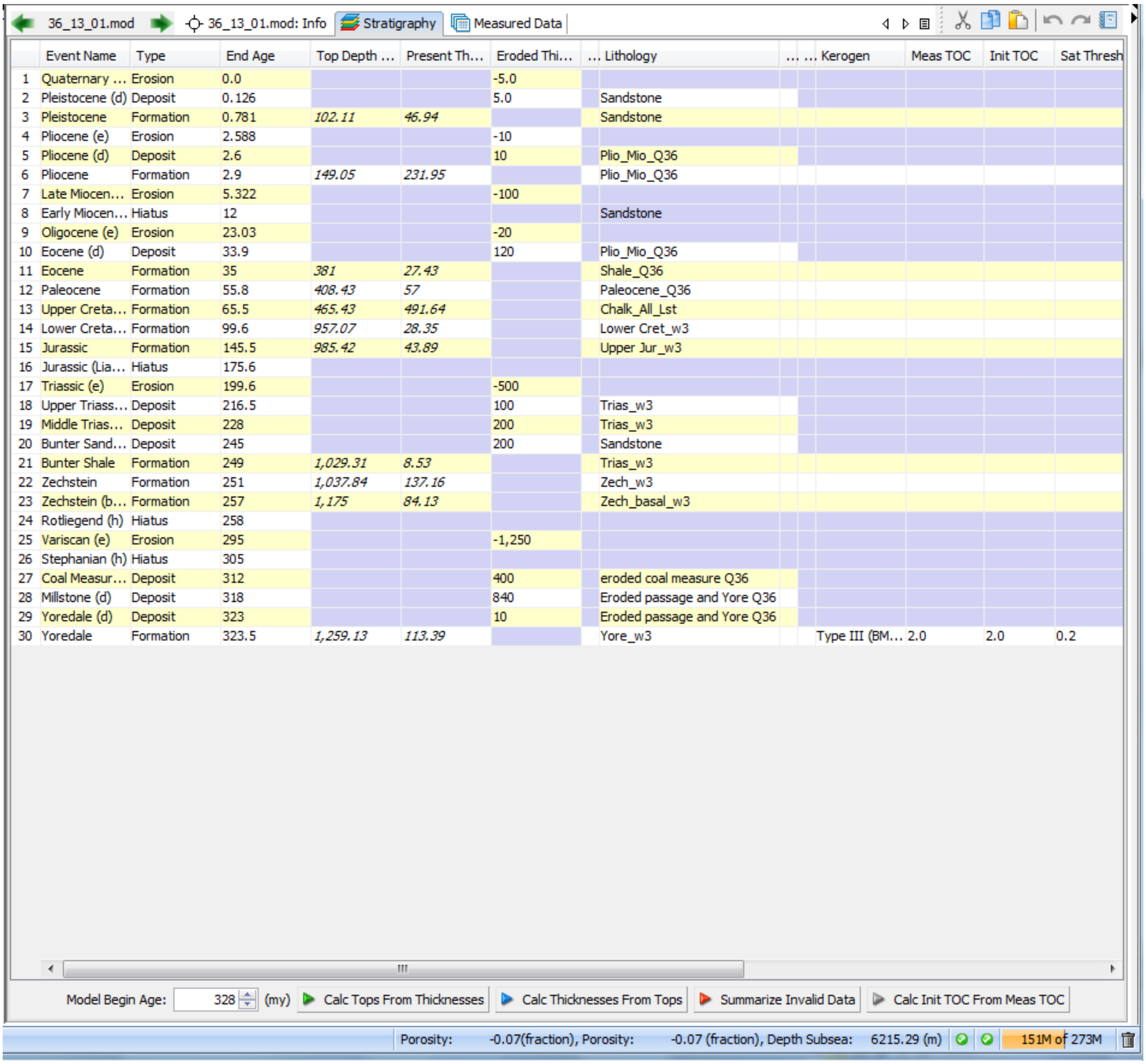


Figure 23: Time plot for Well 36/13-01 showing timing of generation for Yoredale Formation through geological history of this formation. The current model suggests that main generation occurred during deepest burial during the Carboniferous Period



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	... ... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-5.0					
2	Pleistocene (d)	Deposit	0.126			5.0	Sandstone				
3	Pleistocene	Formation	0.781	102.11	46.94		Sandstone				
4	Pliocene (e)	Erosion	2.588			-10					
5	Pliocene (d)	Deposit	2.6			10	Plio_Mio_Q36				
6	Pliocene	Formation	2.9	149.05	231.95		Plio_Mio_Q36				
7	Late Miocen...	Erosion	5.322			-100					
8	Early Miocen...	Hiatus	12				Sandstone				
9	Oligocene (e)	Erosion	23.03			-20					
10	Eocene (d)	Deposit	33.9			120	Plio_Mio_Q36				
11	Eocene	Formation	35	381	27.43		Shale_Q36				
12	Paleocene	Formation	55.8	408.43	57		Paleocene_Q36				
13	Upper Creta...	Formation	65.5	465.43	491.64		Chalk_All_Lst				
14	Lower Creta...	Formation	99.6	957.07	28.35		Lower Cret_w3				
15	Jurassic	Formation	145.5	985.42	43.89		Upper Jur_w3				
16	Jurassic (Lia...	Hiatus	175.6								
17	Triassic (e)	Erosion	199.6			-500					
18	Upper Triass...	Deposit	216.5			100	Trias_w3				
19	Middle Trias...	Deposit	228			200	Trias_w3				
20	Bunter Sand...	Deposit	245			200	Sandstone				
21	Bunter Shale	Formation	249	1,029.31	8.53		Trias_w3				
22	Zechstein	Formation	251	1,037.84	137.16		Zech_w3				
23	Zechstein (b...	Formation	257	1,175	84.13		Zech_basal_w3				
24	Rotliegend (h)	Hiatus	258								
25	Variscan (e)	Erosion	295			-1,250					
26	Stephanian (h)	Hiatus	305								
27	Coal Measur...	Deposit	312			400	eroded coal measure Q36				
28	Millstone (d)	Deposit	318			840	Eroded passage and Yore Q36				
29	Yoredale (d)	Deposit	323			10	Eroded passage and Yore Q36				
30	Yoredale	Formation	323.5	1,259.13	113.39		Yore_w3	Type III (BM...	2.0	2.0	0.2

Figure 24: Model data entry sheet for Well 36/13-01. Top Depth is in m BRT

6.3.3 Key points from new modelling work for Well 36/13-01

- Yoredale Formation has quite good source potential for gas but has relatively poor generation potential in this well since the gas maturity window was not reached
- The main generation phase for the Yoredale Formation occurred during the Carboniferous Period
- VR data available across a large age range (Pliocene – Carboniferous)
- Deepest burial occurred during the Carboniferous period but Triassic and Cenozoic burial was also important in terms of burial history for this well
- The well does not penetrate the Scremerston Formation

6.4 WELL 36/23-01

Well 36/23-01 lies on a local faulted high identified on seismic reflection data by the project team. This well location lay on the southern part of the MNSH and shows a complex history with multiple periods of non-deposition and/or erosion.

6.4.1 Previous maturity and modelling work

Hydrocarbon generation and shows

TOC values for Carboniferous samples are included PETRA-CHEM (1970).

UV Fluorescence is reported in Well 36/23-01 (Applied Petroleum Technology, 2012).

Maturity data

Two VR datapoints were provided in Applied Petroleum Technology (2012), the majority of the rest of the material was believed to be reworked, cavings or inertinite.

Geohistory models

The geothermal gradient for Well 36/23-01 given in Hay et al. (2005) is 30.6 °C/km.

Hay et al. (2005) suggested that around 0.9 – 1.2 km of strata had been removed during the Variscan Orogeny.

Hay et al. (2005) suggested 610 m of uplift had occurred during Mid Jurassic uplift (Cimmerian/Intra-Aalenian Unconformity).

Hay et al (2005) suggested around 900 m of uplift had occurred here during the Early Cenozoic Era.

6.4.2 New modelling work

Maturity data

Three VR data were available; two from the Applied Petroleum Technology (2012) report (Yoredale Formation and Late Triassic Strata), one from the PETRA-CHEM (1970) report (Yoredale Formation). An additional 11 T_{max} datapoints were available from the PETRA-CHEM (1970) report for the Yoredale Formation. Model input data are shown in Table 6.

Table 6: Summary of model input data for Well 36/23-01 and layer maturity window from the BasinMod model

Formation/ age of strata	**N.o. of VR/ VRcalc datapoints**	**Model maturity window**	**Average measured TOC from logs**	**Kerogen**	**Oil/gas show**	**N.o. of porosity data**	**Comments**
Upper Triassic	1 VR	Immature					
Yoredale	2 VR, 11 VR calc	Mid mature for oil	9.91*	Gas prone with some oil prone			

* These data were taken from legacy reports on sampled data as no log data were available for analysis

Model calibration

Only two measured VR datapoints are available for the Yoredale Formation, so VRcalc was mainly used to calibrate the Palaeozoic part of the model. It should be noted that the two measured VR data indicate the Carboniferous strata are immature but the VRcalc data indicate that Carboniferous strata did reach maturity for oil. As the BasinMod model was calibrated using the VRcalc data, the current model suggests that the Carboniferous strata reached early – mid mature for oil during deep Carboniferous burial.

Only 44 m of Carboniferous strata is penetrated by this well. Based on the BasinMod model, it appears that considerable thickness of Carboniferous strata was removed during the Variscan orogeny (~2 km based on VRcalc). This figure agrees well with the estimated thickness of eroded strata based on density logs (2.3 km; Kimbell and Williamson, this study). This is less than the just over 3 km of uplift predicted by Hay et al. (2005), though it is noted by the authors that there is considerable uncertainty on their estimate. The age of the samples which were used to produce the T_{max} data were measured is not consistently reported; they are either Carboniferous and from just below the Variscan unconformity in the Yoredale Formation (this study) or Permian strata (confidential company report). This means that there is considerable uncertainty in the amount of Carboniferous strata eroded. However, modelling of removed thickness from analysis of density logs (Kimbell and Williamson, this study) and the VRcalc from legacy reports support a reasonable amount of strata removal at the end of the Carboniferous Period and given the location of this well in a depocentre (Arsenikos et al., this study), the model was matched to the VRcalc data.

Lower Permian, Lower Triassic and Lower Cretaceous strata are absent. Late Triassic and early Jurassic strata are very thin (only about 50 m combined thickness), though a substantial thickness of chalk is present, in agreement with Hay et al. (2005). As part of the Triassic section is absent, an erosional episode was included with more than 1 km of strata removed. However, this figure is not constrained by data.

Miocene strata are expected to be absent in Well 36/23-01. This part of the MNSH lay close to the onlapping edge of the region of deposition of Pliocene strata and Pliocene sediments in Well 36/23-01 were deposited unconformably on Eocene strata (Gatliff et al., 1994). As the present day heat flow is high (the heat flow was calculated based on temperature data and available from a confidential company report), only a small amount of strata can be included in the model for pre-Alpine burial.

The maturity geohistory is given in Figure 25, the model heat flow is given in Figure 26.

The model fit to the BHT is good for the younger strata but poor in the Carboniferous section (Figure 27).

Maturity and hydrocarbon generation

The average measured TOC value for the Yoredale Formation taken from legacy well reports (PETRA-CHEM, 1970) was included in the model. BasinMod used this value to calculate the initial TOC value.

The Yoredale Formation had good to excellent source rock potential and the samples were mainly gas prone (Vane et al., this study). Therefore it was assumed that most kerogen was type III for the purposes of modelling. The Yoredale Formation did not reach the gas window in the current model therefore significant generation is not expected.

The model generation potential for strata in the well is given in Figure 28. Timing for generation from the most promising horizon is given in Figure 29. The data entry sheet is shown in Figure 30.

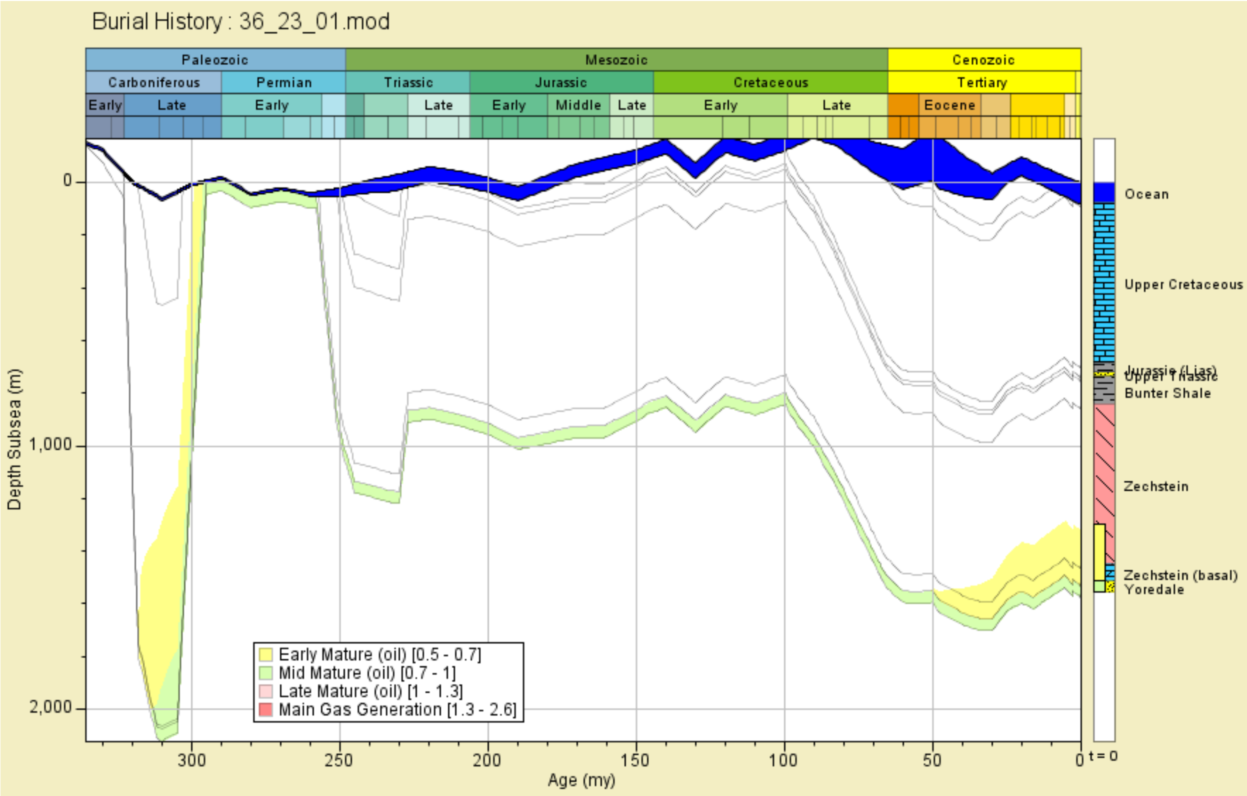


Figure 25: Modelled maturity geohistory for Well 36/23-01. The well terminates in the Yoredale Formation.

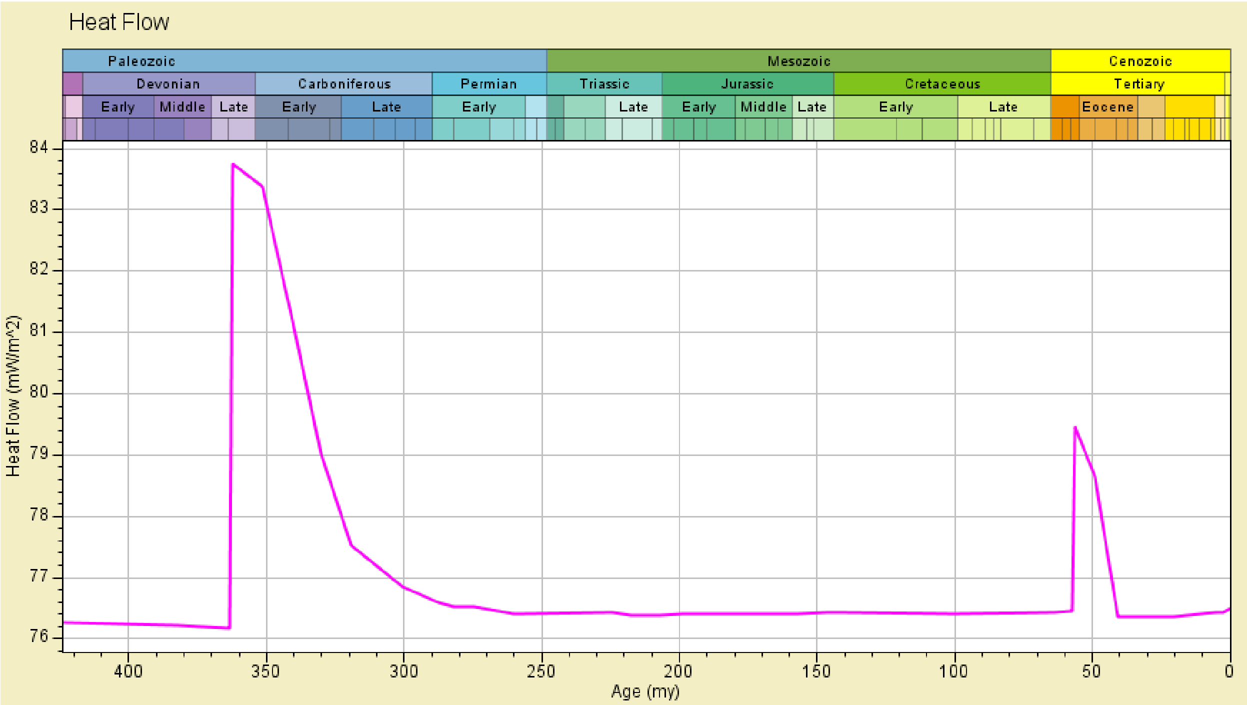


Figure 26: Modelled palaeo-heat flow for Well 36/23-01

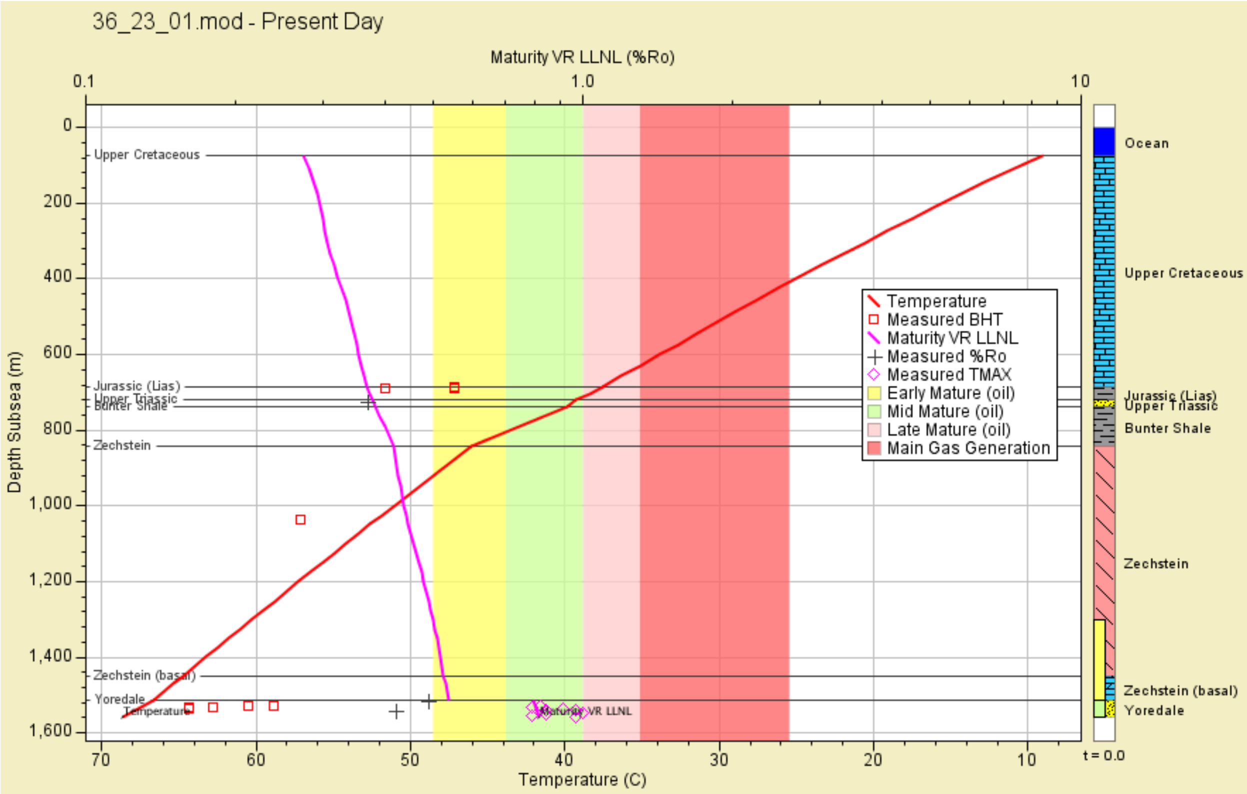


Figure 27: Depth plot for Well 36/23-01 showing model results, maturity data and maturity windows plus temperature data and model

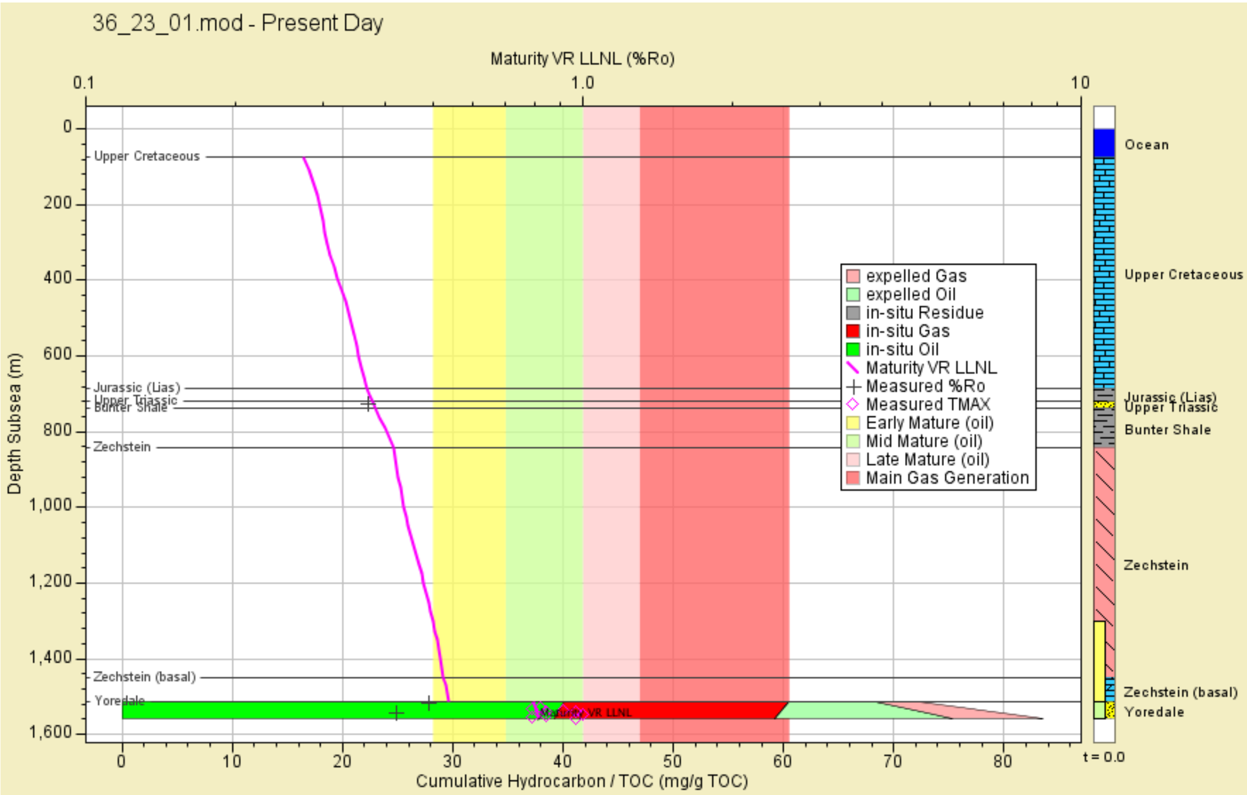
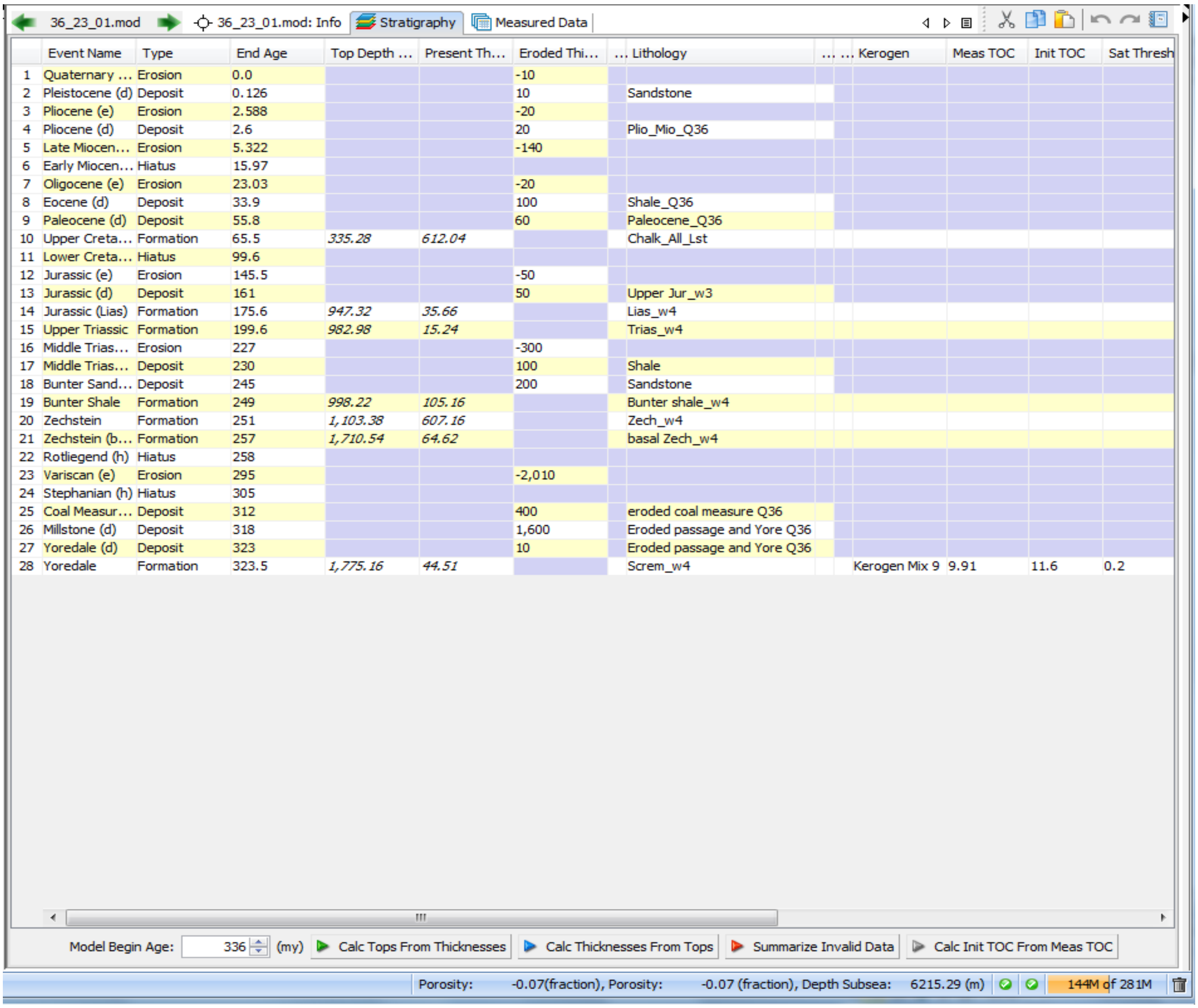


Figure 28: Depth plot for Well 36/23-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

Figure 29: Time plot for Well 36/23-01 showing timing of generation for Yoredale Formation through geological time. The current model suggests that main generation and expulsion occurred during deepest burial du ring the Carboniferous Period

6.4.3 Key points from new modelling work for Well 36/23-01

- The model is not well constrained by data
- The Yoredale Formation has relatively poor generation potential as the samples were gas prone but only reached the oil maturity window at this location
- Main generation for the Yoredale Formation occurred during the Carboniferous Period
- Deepest burial occurred during the Carboniferous Period but Triassic and Cenozoic burial was also important in terms of burial history for this well
- The well does not penetrate the Scremerston Formation



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	... ... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10					
2	Pleistocene (d)	Deposit	0.126			10	Sandstone				
3	Pliocene (e)	Erosion	2.588			-20					
4	Pliocene (d)	Deposit	2.6			20	Plio_Mio_Q36				
5	Late Miocen...	Erosion	5.322			-140					
6	Early Miocen...	Hiatus	15.97								
7	Oligocene (e)	Erosion	23.03			-20					
8	Eocene (d)	Deposit	33.9			100	Shale_Q36				
9	Paleocene (d)	Deposit	55.8			60	Paleocene_Q36				
10	Upper Creta...	Formation	65.5	*335.28*	*612.04*		Chalk_All_Lst				
11	Lower Creta...	Hiatus	99.6								
12	Jurassic (e)	Erosion	145.5			-50					
13	Jurassic (d)	Deposit	161			50	Upper Jur_w3				
14	Jurassic (Lias)	Formation	175.6	*947.32*	*35.66*		Lias_w4				
15	Upper Triassic	Formation	199.6	*982.98*	*15.24*		Trias_w4				
16	Middle Trias...	Erosion	227			-300					
17	Middle Trias...	Deposit	230			100	Shale				
18	Bunter Sand...	Deposit	245			200	Sandstone				
19	Bunter Shale	Formation	249	*998.22*	*105.16*		Bunter shale_w4				
20	Zechstein	Formation	251	*1,103.38*	*607.16*		Zech_w4				
21	Zechstein (b...	Formation	257	*1,710.54*	*64.62*		basal Zech_w4				
22	Rotliegend (h)	Hiatus	258								
23	Variscan (e)	Erosion	295			-2,010					
24	Stephanian (h)	Hiatus	305								
25	Coal Measur...	Deposit	312			400	eroded coal measure Q36				
26	Millstone (d)	Deposit	318			1,600	Eroded passage and Yore Q36				
27	Yoredale (d)	Deposit	323			10	Eroded passage and Yore Q36				
28	Yoredale	Formation	323.5	*1,775.16*	*44.51*		Screm_w4	Kerogen Mix 9	9.91	11.6	0.2

Figure 30: Model data entry sheet for Well 36/23-01. Top Depth is in m BRT

7 Detail of Lower-Mid Carboniferous probable kitchen area modelling

7.1 GEOLOGICAL MODEL

The area studied lies in the marginal area to the south of the MNSH and north of the SNS gas basin.

<u>Devonian deposition</u>

Collision of Laurentia and Baltica ceased during Late Silurian to Early Devonian times (Coward et al., 2003).

During Early Devonian times, this region lay in a continental setting and the Lower Old Red Sandstone Supergroup was deposited in an alluvial setting (Gatliff et al., 1994). A large Devonian pull-apart basin covered much of the Northern North Sea (Coward et al., 2003).

The mid Devonian Kyle Group is recognised on seismic data across the northern parts of Quadrants 42 – 44 (Arsenikos et al., this study). Onshore, in southern England limestone and marine fossil fragments of possible mid Devonian age were identified but in the south Midland Valley, Middle Devonian strata are absent and there is an angular unconformity between Lower and Upper Devonian strata (Bluck et al., 1992).

Late Devonian – Early Carboniferous dextral transtension

Late Devonian and Carboniferous structures in this region are consistent with dextral transtension (Leslie et al., this study). Regional crustal extension caused regional subsidence (Collinson and IGI, 1995 and Cameron et al., 1992). Pre-existing lineaments were activated as normal faults (Collinson and IGI, 1995).

Widespread deposition of non-marine Upper Devonian strata occurred across most of the Central North Sea (CNS) between highs defined by granites (Gatliff et al., 1994). On the southern margin of the MNSH, Late Devonian sandstone is proven in Well 42/10b-02.

Marginal marine conditions with dominantly shale deposition are indicated for Tournaisian to Chadian times by Kearsey et al. (this study). A marine transgression from the south reached the MNSH by latest Tournaisian to earliest Visean times. This region lay between the fringes of the Anglo-Dutch basin and the offshore extension of the Cleveland Basin (Cameron et al., 1992). During early Visean times, dominantly fluvial then fluvio-deltaic conditions encroached on this area from the north until deposition of the shallow marine – non-marine cyclic Yoredale facies in latest Visean times (Bluck et al., 1992; Kearsey et al., this study).

Schroot et al. (2006) noted that volcanism and an angular unconformity suggest active tectonics during Namurian times at least in the Dutch sector, contradicting a model of simple subsidence. Collinson and IGI (1995) suggest that active extension continued in the SNS until Mid – Late Visean (Latest Dinantian or early Namurian) times and that based on evidence from the Cleveland Basin, a phase of accelerated subsidence is proposed for late Dinantian – early Namurian times (Cameron et al., 1992). Church et al. (1995) interpreted the thick Namurian fluvial sand bodies which are present in the south of this to have formed during subaerial exposure and incision of the underlying highstand delta system during relative sea level falls. Most sequences across northern England suggest a regional sea level control however significant variation in distribution and stacking patterns indicates that fluctuation in sediment supply was a strong influence. Correlation work carried out by Church et al. (1992) indicated that periods of reduced sediment influx to the SNS are linked to corresponding periods of increased sediment influx onshore.

Late Carboniferous thermal subsidence

Granitic intrusions and some faults caused differential subsidence during the sag phase of tectonics during Westphalian times (Collinson and IGI 1995). Deltaic conditions persisted in the SNS. Westphalian strata are dominated by shale rich coal measures deposited in an upper delta-plain environment (Cameron et al., 1992). Cole et al. (1995) correlated Westphalian stratigraphy of eastern England and the offshore SNS gas basin describing a complex history of multiple transgressions, highstands, lowstands and regressions.

Latest Carboniferous – Early Permian compression, uplift and erosion (Variscan Orogeny)

In Late Carboniferous times, as Baltica moved back westwards, a transpressive regime developed (Leslie et al., this study). During late Westphalian times, compressive stresses related to Variscan deformation to the south caused inversion across some structural lineaments and strike slip movement in this region. This inversion culminated in Stephanian times but continued into early Permian times, controlling erosion of the sub-Permian subcrop (Collinson and IGI 1995; Arsenikos et al., this study; Leslie et al., this study).

The barren beds at the top of the Carboniferous succession (most likely of Bolsovian to Stephanian age) include alluvial redbeds which are also proven in the Dutch sector of the North Sea where they are up to 1.4 km thick. The maximum recorded thickness of Carboniferous strata in the SNS is 5 km (Cameron et al., 1992; Waters et al., 2011).

Coward et al. (2003) suggest that Early Permian volcanism in northern England and the Midland valley of Scotland which pre-dates Permian extension indicates that the area was underlain by hot asthenosphere, possibly the edge of a north-west European hot spot.

Early Permian – Early Jurassic subsidence

From Early Permian to Late Triassic times, this region lay in a gently subsiding E-W trending foreland basin (Cameron et al., 1992).

The southern Permian Basin is an east-west trending sag basin with gentle topography (Coward et al., 2003). The MNSH had its maximum influence on regional paleogeography during the Permian Period and possibly Triassic Period when it separated major basins, though its southern margin appeared not to be sharply defined by faults (Collinson and IGI 1995).

Permian Lacustrine clays were deposited in the Anglo-Dutch basin with some reworked or liquefied sands sourced from the south (Cameron et al., 1992).

Widespread transgressions inundated this region including the MNSH during Late Permian times so that the MNSH was at least partially submerged (Cameron et al., 1992). The Upper Permian Zechstein Group strata are dominated by carbonate and anhydrite on the basin margin. Extensive deformation of Upper Permian strata due to halokinesis is observed (Cameron et al., 1992).

The foreland basin established during Early Permian times persisted into Late Triassic times but due to relative sea level fall, continental and paralic deposits which had been limited to its western edges became established across the whole basin early in the Triassic Period (Cameron et al., 1992). A graben system which transacted the Northern Permian Basin transacted the MNSH during Triassic times (Coward et al., 2003).

Basal Triassic strata are dominated by red-brown mudstones with some sandstones deposited in playa-lake, floodplain and fluvial environments. Middle and Upper Triassic strata are dominated by mudstone, dolomite, anhydrite and sandstone and show a basinal environment with marine influxes (Cameron et al., 1992).

During latest Triassic times, this region was emergent before a marine transgression inundated the area again (the transgression continued with deposition of the Lias during Jurassic times; Warrington and Ivimey-Cook, 1992). Some thickness changes in the Triassic succession relate to salt diapirism (Collinson and IGI 1995).

There seems to have been very little rifting in the North Sea during the Early Jurassic Period. The sedimentation patterns suggest passive infilling of the subsiding Triassic – Lower Jurassic rift (Coward et al., 2003). During Jurassic times, a widespread transgression resulted in this region being part of an extensive basin which covered much of the SNS, southern UK, eastern Ireland and the Celtic Sea basins. Lower Jurassic strata were deposited in a marine environment (Lias Group) and are dominated by mudstones (Bradshaw et al., 1992).

Early - Mid Jurassic uplift (Cimmerian/Intra-Aalenian Unconformity)

Early-Mid Jurassic domal uplift (mid Cimmerian/Intra-Aalenian Unconformity) resulted in uplift and the MNSH was again emergent during early Mid Jurassic times, separating the (submerged) study area from the Northern Permian Basin (Coward et al., 2003; Cameron et al., 1992).

Middle Jurassic strata show a more variable environment due to widespread tectonism at the end of the early Jurassic Period plus local tectonism and halokinesis throughout the Middle Jurassic period, with clastics dominating on the southern margin of the MNSH (Cameron et al., 1992).

Mid – Late Jurassic deposition

The region of interest lay on a fluvially-dominated coastal plain with a marine basin to the south-west (Bradshaw et al., 1992; Coward et al., 2003). Mid Jurassic strata comprise marine, brackish-water, fluvio-deltaic mudstones and sandstones with oolitic and bioclastic limestones with a distribution reflecting the oscillatory nature of the shoreline (Cameron et al., 1992).

During Late Jurassic times, the MNSH and the east part of the area of interest, is believed to have been part of a large emergent area. Shales were deposited in the marine basin to the south-west (Coward et al., 2003). The preserved thickness of Jurassic strata is up to ~500 m around Block 43/21 which represents a small local depocentre but generally Jurassic strata are <100 m thick in this region (Cameron et al., 1992). Some thickness changes in the Jurassic interval relate to halokinesis (Collinson and IGI, 1995).

An important phase of rifting occurred in the North Sea Basin during the Late Jurassic (Callovian – early Kimmeridgian) when rifting in the Arctic spread to the North Sea. In the Central North Sea much of the extension was oblique-slip along faults established during the Triassic Period (Coward et al., 2003).

Cretaceous Period; thermal cooling of the lithosphere and possible Mid Cretaceous uplift

There was a marked sea level fall across the Jurassic-Cretaceous boundary. During the earliest Cretaceous, normal faults were still active. During early Cretaceous times, the rifting initiated during the Jurassic ceased and crustal extension gave way to thermal cooling of the lithosphere (Cameron et al., 1992; Cameron et al., 2003).

Japsen (2000) propose a Mid Cretaceous uplift event centred on the Sole Pit High. Significant erosion of up to 2 km is proposed. The areal extent of this event is unclear due to later overprinting by deep Cenozoic burial in most areas.

Water depths gradually increased throughout the Cretaceous Period until the Late Cretaceous chalk was deposited in relatively deep water. Cretaceous strata are present in the east of the area where they mainly comprise <200 m shallow marine shales/siltstones/sandstones/clays or carbonates (Lower Cretaceous) and <800 m shallow marine chalk facies (Upper Cretaceous).

Latest Cretaceous uplift and erosion

During latest Cretaceous times, structural inversion resulted in erosion on several structures including the Cleveland Basin. Timing of uplift is variable across the North Sea and was probably associated with early Alpine collusion in eastern Europe (Cameron et al., 1992; Coward et al., 2003). Compressional structures of Late Cretaceous age can be recognized on seismic reflection data (Van Hoorn, 1987). Cretaceous strata are absent in the Cleveland Basin and offshore extension, this is believed to be a result of erosion during latest Cretaceous uplift (Cameron et al., 1992).

Palaeocene deposition

Coward et al. (2003) support extension across the Greenland-Norwegian margin during the Paleocene, which resulted in deposition of marine strata in the study area. Paleocene strata are typically between 40 and 80 m thick (Cameron et al., 1994). Late Palaeocene strata comprising marine shelf and marginal-marine deposits usually rest unconformably on Cretaceous chalk in the west of the area of interest.

Late Paleocene – Early Eocene uplift

Hillis (2008) argue that the SNS was not significantly influenced by underplating and that uplift and erosion was controlled by Alpine tectonics during the Cenozoic Era. Hillis (2008) observe that underplating may have contributed to uplift during the Palaeocene in the CNS and NNS. Coward et al. (2003) suggest that thermal doming around 60 – 65 Ma may have affected this area.

Eocene to Oligocene; areally limited deposition

The early Eocene Ypresian transgression was probably the most widespread transgression to occur during Eocene times. Eocene strata comprise marine sediments and have a thickness of up to 800 m in the SNS (Murray 1992; Cameron et al., 1992). Onshore UK and the western part of the study area remained emergent (Coward et al., 2003).

Oligocene strata have a generally patchy distribution and usually an angular unconformity is observed at the base with the underlying Eocene strata. Oligocene strata comprise sandstone/siltstone/clay and a sequence up to 110 m thick has been penetrated by wells in this area (Cameron et al., 1992). Onshore UK and the western part of the study area remained emergent (Coward et al., 2003).

Early Miocene deposition

The Early to Middle Miocene transgression was very widespread but most strata have been removed by later erosion. Patchy Miocene strata are preserved along the axis of the SNS (around 30 m thickness) (Cameron et al., 1992). Coastal margin and marine strata were deposited in the eastern part of the area of interest. Onshore UK and the western part of the study area remained emergent (Coward et al., 2003).

Late Miocene sea level fall

There was a major regression during late Miocene times as a result of eustatic sea level fall (Cameron et al., 1992). Onshore UK and the western part of the study area remained emergent (Coward et al., 2003).

Late Miocene – Early Pliocene uplift and Pliocene deposition in the

The eastern part of the area of interest was uplifted during Late Miocene – Pliocene times after cessation of opening of the western Mediterranean basins. Onshore UK and the western part of the study area remained emergent (Coward et al., 2003).

Hillis (2008) suggest that Cenozoic uplift was less than 0.4 km based on a few wells in Quadrants 42 and 43 (this is much smaller than the amount of uplift proposed for onshore which is >2.2 km uplift). The timing of this uplift is anticipated to be mainly Neogene as Hillis et al. (2008) suggest that Late Paleocene – Early Eocene underplating had a lesser effect in the SNS compared with the effect in the CNS and NNS. The current models support greater Neogene erosion in Quadrant 41 than suggested than the work of Hillis (2008).

Pliocene strata are thin, reaching tens of metres at most (<65 m penetrated by boreholes where Pliocene sediments are infilling palaeo-valleys) (Cameron et al., 1992). Pliocene strata are preserved in Well 41/20-01.

Pleistocene deposition

Tectonic subsidence during Pleistocene times resulted in a relatively thick early – middle Pleistocene sequence. Preserved Pleistocene strata have a thickness <150 m and thicken to the west. Early to middle Pleistocene strata comprise deltaic deposits which are an offshore continuation of a major deltaic system in the Netherlands. These are capped by a thin mid – late

Pleistocene deposit of glacigenic and non-deltaic marine sediments (Cameron et al., 1992). Pleistocene strata are not reported in the modelled wells.

7.2 PREVIOUS WORK IN THIS REGION

In the south of this region, the Esmond, Forbes and Gordon gasfields (blocks 43/8a, 43/13a, 43/15a and 43/20a) produce from the Bunter Sandstone Group and the source is believed to be Westphalian coals (Ketter, 1991). East Midlands oilfields are sourced from rocks of Dinantian – Namurian age (Collinson and IGI, 1995). The main kerogen type was gas prone type III in the Collinson and IGI (1995) study with a few examples of oil prone type II kerogen observed in Carboniferous strata from wells across Quadrants 41 – 43 (Collinson et al., 1995; Schroot et al., 2006).

Gas shows were reported in Wells 41/14-01, 41/20-01, 42/10b-02 and 43/17-02. Some of these gas shows are believed to be sourced from Upper Palaeozoic strata A small gas cap is present at the top of the Bunter Sandstone in Well 41/20-01. The Agincourt discovery is proved by Wells 42/10b-2, 42/10b-2Z and 42/15b-2 (Geochem Group, 1991; Anadrill, 1990; Signal-Richfield-Marathon-Cities services, 1966; Pittion, 1981; Mobil North Sea Limited, 1995; Foden, 1996; The Geochem Group, 1988; Kaye, 1996; Premier Oil, 2008).

Total Organic Content is quite variable in this ‘probable’ kitchen area, with the Westphalian Coal Measures generally showing the highest values (Gent, this study; Geochem Group, 1991; Cooper et al., 1978; PETRA-CHEM, 1966; Norkett, 1966; Kaye, 1996)

Hydrocarbon shows and producing fields

Hay et al. (2005) lists accumulations in the Carboniferous Whitby Sandstone with two small gas (possibly uneconomic) discoveries in Wells 42/10b-02 and 42/15a-1. The sandstone flowed gas on test in Well 42/10b-2z with rapid depletion and Well 42/15a-2 also appears to penetrate a small discovery. Premier Oil (2008) gives volumes for this Crosgan discovery.

Premier Oil (2008) describes the Agincourt discovery is described (proved by Wells 42/10b-2, 42/10b-2Z and 42/15b-2). The Agincourt discovery has gas within Lower Carboniferous fluvio-deltaic sands of the Yoredale, Whitby and Scremerston formations. Gas was tested from both Well 42/10b-2Z (Whitby Sands) and Well 42/15b-2 (Scremerston Formation).

The Trent field in the north of block 43/24 lies in the western part of Silverpit basin. A large structure has been drilled; an inverted anticline that is 17 km long and up to 3.5 km wide. The field contains rocks of early Westphalian A to Middle Namurian B age which comprise shales, siltstones, sandstones and minor coals. The main reservoir is of Yeadonian age (Rough Rock) (Bowler et al., 1995).

Premier Oil (2008) indicated gas shows in the Zechstein Hauptdolomit in the Agincourt discovery (Well 42/15b-2).

The Esmond, Forbes and Gordon gasfields (blocks 43/8a, 43/13a, 43/15a and 43/20a) produce from the Bunter Sandstone Group and the source is believed to be Westphalian coals. Areas where Zechstein salt is thin or absent (generally due to halokinesis) have acted as migration pathways. Charge of the reservoirs appears to have happened during mid to late Triassic times relatively soon after pillowing of the Zechstein salts formed the initial domal traps (Ketter, 1991).

Potential Palaeozoic source rocks and reservoirs

Schroot et al. (2006) conducted an extensive study on the Dutch sector of the North Sea adjacent to this region assessing pre-Westphalian maturity (PETROPLAY project). Data from the UK and German sectors including well data, lithology, TOC, organic matter quality were considered for comparison. The southern part of ‘Area 2’ in the Petroplay project study lies close to the region of interest.

The presence of the Kyle Group (mid Devonian) including its basal layer was anticipated from seismic interpretation in the Dutch Sector but not penetrated by wells so organic content could not be confirmed. Other Devonian source rocks were not expected in ‘Area 2’ (Schroot et al., 2006). Well E06-01 penetrated the Devonian sequence and TOC was negligible (higher readings were thought to be a result of contamination) so although the strata was expected to be in the late oil to early gas maturity, the source rock quality was interpreted to be poor (Schroot et al., 2006).

Collinson and IGI (1995) assessed the source potential of the pre-Westphalian strata of the southern margin of the MNSH. The authors stated that there was insufficient well data to allow a full assessment of potential in their study area (covering part of Quadrants 39, 42, 43, 44, 47, 48 and onshore area adjacent to Quadrant 47) but Palaeozoic source rocks were expected to be present on the basis that East Midlands oilfields are sourced from rocks of Dinantian – Namurian age, and that dead oil had been encountered in wells which was interpreted to come from a source other than Westphalian coals.

Collinson and IGI (1995) indicated that the principal source rocks were coals of the Scremerston Formation (mainly on the MNSH) and basinal mudstones and siltstones of Dinantian – Namurian age in the SNS with potential to generate gas.

Collinson and IGI (1995) indicated that Visean gas-prone basinal shales offered the most promising source unit with consistently rich TOC readings (< 5.26 wt%). These data are based on offshore Well 42/17b-02 which was the only well to penetrate this unit for that study. Considering the Collinson and IGI (1995) study area more broadly, basinal mudstones have an average TOC of 4.46 wt% from well samples, slope siltstones have a TOC of 3.72 wt% from well samples and shales in the Scremerston Formation have an average TOC of 5.09 wt% from well samples.

For ‘Area 2’ of the PETROPLAY project, Schroot et l (2006) noted that “there is fair present-day remaining source rock potential in the Namurian and Dinantian units, and even good potential in the sequences near the Dinantian to Namurian transition…a substantial part of the generation has been recent”. The authors note that black, organic shales deposited in deep water in local depocentres are expected to form part of the Dinantian and Namurian sequences.

On the MNSH and possibly on the margins of this structural high, coals and shales of the Scremerston Formation also offer gas source potential. Marine bands had an average TOC of 4.06 wt% and tended to be more oil prone (Collinson and IGI, 1995).

Marine bands were proposed to offer enhanced source rock potential (Collinson and IGI 1995).

In the Dutch Sector, the Cementstone Formation, Fell Sandstone Formation, Scremerston Formation and Yoredale Formation contain a variety of marine shales and coals. The coals generally showed Type III kerogen (gas prone). Schroot et al., (2006) noted that no Type II kerogen was identified in the samples from the Dutch Sector but that wells in the UK sector near ‘Area 2’ did show some Type II (oil prone) kerogen and suggested that local deep water areas could have been areas of deposition for black shales with oil-generating potential.

The Bowland Shale Formation is a deeper water deposit laid down contemporaneously with part of the Yoredale facies (see Kearsey et al., this study). The Upper Bowland Shale Formation is one of the Dinantian to Namurian transition units expected to have good potential by Schroot et al., (2006) based on work carried out in the UK Sector where TOC was on average 3% (maximum 6%) and as oil produced from fields in the East Midlands are believed to be sourced from rocks of late Dinantian – early Namurian age (Cornford, 1998).

Assessment of the TOC of the Yoredale facies in the Dutch Sector indicated that organic matter is concentrated in the thin coal seams which are found throughout the succession. TOC was assessed to be around 3% for shales and up to 50 – 70% for coal seams ‘Area 2’ of the PETROPLAY study (Schroot et al., 2006). Minor source potential was offered by deltaic coals and mudstones of the Yoredale Formation and Millstone Grit Group in the UK SNS study area of Collinson and IGI (1995).

Turbidites deposited above the Bowland Shale Formation in the Dutch Sector may offer some reservoir potential but reservoir quality is likely to be poor based on well data (Schroot et al., 2006).

In the Dutch Sector, the Millstone Grit Group comprises a sequence of coarsening upwards cycles with marine shales at the base (Van Adrichem Boogaert and Kouwe, 1993-1997 as referenced in Scroot et al., 2006). Marine shale samples from ‘Area 2’ of Schroot et al., (2006) were expected to show Type II kerogen but analyses did not reveal this, possibly due to advanced coalification. Namurian coals had Type III kerogen and were deemed gas prone. The marine shales showed a TOC of up to 6%. The Dutch Sector was considered mature for oil but not gas at Millstone Grit levels and but the UK Sector adjacent to ‘Area 2’ was considered mature for gas generation (Schroot et al., 2006).

Schroot et al. (2006) felt that the best seals in ‘Area 2’ were offered by Zechstein evaporites where present and where sufficiently thick. The authors also noted that shales of the Yoredale Formation/Upper Cleveland Group (Namurian age) or Rotliegend Group shales could offer a potential seal where present.

Pittion (1981) assessed the TOC of Permian strata to investigate if this could be a potential source rock, however, TOC was low (Upper Magnesian Limestone and Middle Magnesium Limestone Formation in Well 41/20-01 tested). These low TOC indicate there is no possibility of generating economic quantities of hydrocarbons (Pittion, 1981).

Maturity modelling

Devonian reservoir potential of the Kyle Group (carbonates) and Old Red Sandstone Supergroup in the Dutch Sector was considered to be highly speculative as it is only penetrated in one well in ‘Area 2’. Sandstones of the Fell Sandstone Group and the Whitby Member of the Scremerston Formation offer potential Visean age reservoirs (Schroot et al., 2006).

Dinantian Strata were expected to be early immature to mature for oil and gas generation. Late Dinantian – early Namurian age strata in ‘Area 2’ are currently in the oil to early gas maturity window (Schroot et al., 2006).

Collinson and IGI (1995) undertook 3D maturity modelling with most gas generated from basinal shale facies which then migrated vertically into the Millstone Grit Group and laterally into Yoredale deltaic sands on the MNSH. Some gas reached Triassic sandstones. Generation of gas occurred at Visean source rock level (Scremerston Formation coals or Visean basinal mudstones) from late Carboniferous to present day. Maturity modelling of the Collinson and IGI (1995) study area indicated that only a limited part of the MNSH is fully mature for gas generation but large areas of the Namurian and Dinantian succession are fully mature (VR>2) in the depocentre of the SNS. It should be noted that in contrast to the Collinson and IGI (1995) study, for the thermal models prepared for this project it was not assumed that the heat flow had remained constant from Carboniferous to present day times, as documented tectonic events are expected to affect palaeo-heat flow. In contrast, for this study, the palaeo-heat flow profile has been adjusted to take into account tectonic events which would be expected to influence the heat flow.

Pittion (1981) assessed the maturity of Carboniferous strata in Wells 41/20-01, 44/02-01 and 44/21-01. Pittion (1981) observed that the younger Carboniferous strata (Namurian – Westphalian age) in Well 41/20-01 is more mature than the older Carboniferous strata (Visean – Namurian) in Well 44/02-01 despite being currently at a shallower depth, suggesting that maximum burial was greater in the western part of the North Sea than the Central part though the authors also observed this could have been result of a thermal effect of the Variscan Orogeny. Pittion (1981) thus suggested that the western part of the North Sea would probably therefore have generated more gaseous hydrocarbons than Quadrant 44. If generation happened prior to the Variscan Orogeny then a proportion of the generated hydrocarbons were probably lost due to lack of seal, if generation happened post Permian, then the generated hydrocarbons would have been better preserved (Pittion, 1981).

Applied Petroleum Technology (2012) assessed wells in Quadrants 41 and 43. This study utilised existing and new geochemical data (vitrinite reflectance, spore colour, TOC, solvent extraction) to assess the thermal history, maturity and source potential.

7.3 WELL 41/14-01

Well 41/14-01 lies outside the region covered by seismic data examined for the project but seismic data nearby suggests that strata are rising towards a regional high.

7.3.1 Previous maturity and modelling work

Variable gas shows were recorded in this well. Palaeozoic TOC was good but the organic matter was judged to be of generally poor quality. The organic matter was deemed to be largely exhausted (Anadrill, 1990; Geochem Group, 1991)

Hydrocarbon shows

The end of well report (Anadrill, 1990) recorded gas shows of variable amounts in most formations; Lias (0.01-0.28% with an average between 0.04 – 0.07%), Triassic Haisborough Group (trace < 0.09%), Bunter Sandstone (average 0.01 – 0.05%), Bunter Shale (trace < 0.01 though some samples lost), Zechstein Group (0.002 – 0.26%), top part of the Carboniferous strata (down to middle of Cleveland C Formation at 2890.7 m BRT within the Cleveland Group 0.02 – 6.22% including peaks) and the lower part of the Carboniferous strata (0.02 – 20.41% including peaks).

Palaeozoic source rocks and reservoirs

The final geological well report (Greene, 1991) stated that the primary objective of Well 41/14--01 was to evaluate the gas-bearing potential of the Namurian age delta-front turbiditic and fluvial channel sandstones.

The Carboniferous succession was judged to be very mature to over-mature using vitrinite reflectance (VR = 1.2 – 2.24) and spore colouration data. Prior to hydrocarbon generation the Carboniferous claystones were probably good (but not rich) gas source rocks; the Carboniferous claystones had a high TOC but the material was of poor quality (Geochem Group, 1991). The TOC of the Carboniferous claystones was generally around 1.46 – 2.38% with a few rich intervals (e.g. 11.8% at 2807.2 m in the Cleveland Group C formation. However, the organic matter is of poor quality comprising mainly inertinite with some amorphous material and gas-prone wood material.

The Carboniferous organic matter has now realised almost all of its potential for hydrocarbons (Geochem Group, 1991).

Post-Palaeozoic source rocks

The geochemical report (Geochem Group, 1991) assessed the Lias strata to be unproductive in this well (would be early mature for oil if oil prone, but most organic matter comprised inertinite). Autochthonous vitrinite had VR values around 0.45 in the Jurassic sequence.

Maturity data and models

The Geochem Group (1991) report notes that above 2499.4 m (i.e. the middle of the Cleveland C Group succession) it is difficult to identify true vitrinite and as a result, there is a wide variation in VR results.

Maturity and Geohistory models

Deepest burial (over 1300 m deeper than present day according to models) occurred during post-Jurassic times when the organic matter was exhausted for hydrocarbon generation (Geochem Group, 1991).

7.3.2 New modelling work

Maturity and porosity data

Forty-two VR and 49 T_{max} data were available from the Geochem Group (1991) report. VR data were available for the Lias Group and Cleveland Group, VRcalc were available for the Cleveland Group. Uncorrected BHT were taken from the DST logs (Read, 1990). Porosity and permeability data were available for the Rotliegend Group, and Millstone Grit (1 datapoint) from the Aberdeen Petroleum Services (1990) report. Additional pyrolysis data (S1, S2 and TOC) were included from the Geochem Group (1991) report. One BGS calculated S3 value was also available. Model input data are shown in Table 7.

Model calibration

Vitrinite reflectance data are available for Jurassic and Carboniferous strata, this is useful in constraining the model above and below the major stratigraphical break caused by Variscan uplift.

In general, the VRcalc values suggested greater maturity of the Carboniferous strata than the measured VR. The model was matched to the VR data as several of these data had a good number of samples (>20) and a good linear trend with a reasonably tight grouping was observed on the depth plot.

The kerogen type was type I for the top of the Cleveland Formation. A kerogen mix was entered into the current model for the rest of the Cleveland Group based on the kerogen type graph in the Geochem Group (1991) report.

Well 41/14-01 shows a period of rapid deposition at the end of the Carboniferous, for the current model it was assumed this trend continued until Variscan-related uplift resulted in erosion. The current BasinMod model is not particularly sensitive to additional Carboniferous stratigraphical thickness, but adding more strata does result in a slightly worse fit to the maturity (VR/VRcalc) data. The thickness of eroded strata could be increased up to 3.6 km and a reasonable fit to the Carboniferous VR data still achieved.

In agreement with the Schroot et al. (2006) study, an extended period of increased heat flow and a non-simple depositional pattern seemed to best fit the maturity data. It was assumed for the current model that heat flow was high during Devonian and Carboniferous times due to regional extension and crustal thinning.

A thin section of Rotliegend sandstone (around 20 m thickness) rests on Carboniferous Millstone Grit which is in turn underlain by potential source rocks of Carboniferous age (Upper Bowland

Shale and Cleveland Group). The current model suggests that Carboniferous burial placed the potential source rocks in the oil then the main gas maturity window.

Table 7: Summary of model input data for Well 41/14-01 and layer maturity window from the BasinMod model

Formation/ age of strata	N.o. of VR/ VRcalc datapoints	Model maturity window	Average measured TOC from logs	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Lias	10 VR	Early mature for oil			Poor gas shows		
Bunter Sandstone		Mid mature for oil			Gas shows		
Bunter Shale		Mid – late mature for oil			Trace of gas		
Zechstein Group		Late mature for oil - Main gas generation			Gas shows		
Lower Permian		Main gas generation				16 data	
Millstone		Main gas generation	2.4	Mainly type IV		1 data	
Cleveland E	5 VR, 14 VR calc	Main gas generation	3.2	Type IV but also a mix of oil and gas prone	Gas shows		
Bowland Shale	6 VR	Main gas generation	2.8		Gas shows		
Cleveland D	5 VR	Main gas generation	1.8	Mainly type IV	Gas shows		
Cleveland C	25 VR	Main gas generation – overmature	1.8	Mainly type IV, some gas prone	Gas shows		
Cleveland B	5 VR	overmature	1.7	Mainly type IV			
Cleveland A		overmature	1.4	Mainly type IV			

Cameron et al., (1992) suggest that considerable thicknesses of Jurassic and younger strata could have been deposited in this area. The model was adjusted to try to align with the results analysis of the density log (Kimbell and Williamson, this study) but the amount of eroded Permian strata estimated from analysis of the density logs is much greater than for the current BasinMod model (5.6 km additional strata from analysis of the density log compared with 2.8 km for the BasinMod model). The porosity depth plot from BasinMod does however suggest that an even greater amount of Jurassic and younger strata could be included but the current model fits wells with the maturity data (VR/VRcalc) and the regional geological interpretation.

Deepest burial was achieved during Cretaceous times when the potential Carboniferous source rocks reached the main and late gas generation maturity windows.

The maturity geohistory is given in Figure 31, the model heat flow is given in Figure 32. The model results are given in Figure 33.

A good match to the BHT was achieved for the data from the Cretaceous and Carboniferous strata, however, the BHT reading from the Bunter Sandstone Formation is much higher than the modelled value.

Maturity and hydrocarbon generation

TOC values calculated for the Millstone Grit, Yoredale and Scremerston formations from the wireline logs (Gent, this study) were included in the BasinMod models. These TOC values were used by BasinMod to calculate the initial TOC values for modelling purposes. Based on the Geochem Group (1991) report and data from Well 41/20-01 it was assumed the kerogen typing for the Millstone Grit was mainly comprised type IV kerogen. Cleveland E Group (equivalent of top part of the Yoredale Formation) was assessed to include mainly type IV kerogen based on the well geochemistry report but a mixture of oil and gas prone kerogen was also included based on legacy reports (Geochem Group, 1991). One datapoint from the Yoredale Formation generated by the project team indicated the presence of gas prone kerogen (Vane et al., this study). The Scremerston Formation was assumed to mainly comprise type IV kerogen based on the Geochem Group (1991) report. Vane et al. (this study) considered that this well was an excellent gas source and that most the organic matter had been exhausted through hydrocarbon generation.

The VR datapoints recorded for the deepest part of the Carboniferous succession penetrated by the well were generated using a reasonable number of readings (>20) and these data show VR>2.12 (i.e. main gas generation).

Pre-Alpine burial is more significant than Carboniferous burial in terms of the burial history of the current model. However, the main gas maturity window was first reached during Carboniferous burial. If gas were generated, intraformational seals in the older parts of the Cleveland Group and could have trapped the gas, however, the relatively silty/arenaceous Upper Bowland Shale and younger parts of the Cleveland Group and Millstone Grit may not have provided good seals.

Deep burial during the Cenozoic Era when the Permian Zechstein Group evaporites and argillaceous Triassic strata were present to trap the gas would potentially offer a better reservoir-seal pairing if the organic matter was not exhausted. Unfortunately, the Geochem Group (1991) report suggested that by the Cenozoic period, the organic matter was exhausted for hydrocarbon generation. In addition, the source potential of the Cleveland strata is rated as poor by both Vane et al. (this study) and Geochem Group (1991). However, the end of well report (Anadrill, 1990) recorded gas in most formations in this well with some peaks in the lower part of the Cleveland Group, so it could be that either the main generation phase was during Cenozoic burial and the organic matter was not completely exhausted as suggested by the current BasinMod model or this gas has migrated from elsewhere. Given the conflicting messages, this well merits further investigation.

The model generation potential for strata in the well is given in Figure 34. Timing for generation from the most promising horizons is given in Figure 35 and Figure 36. The data entry sheet is shown in Figure 38.

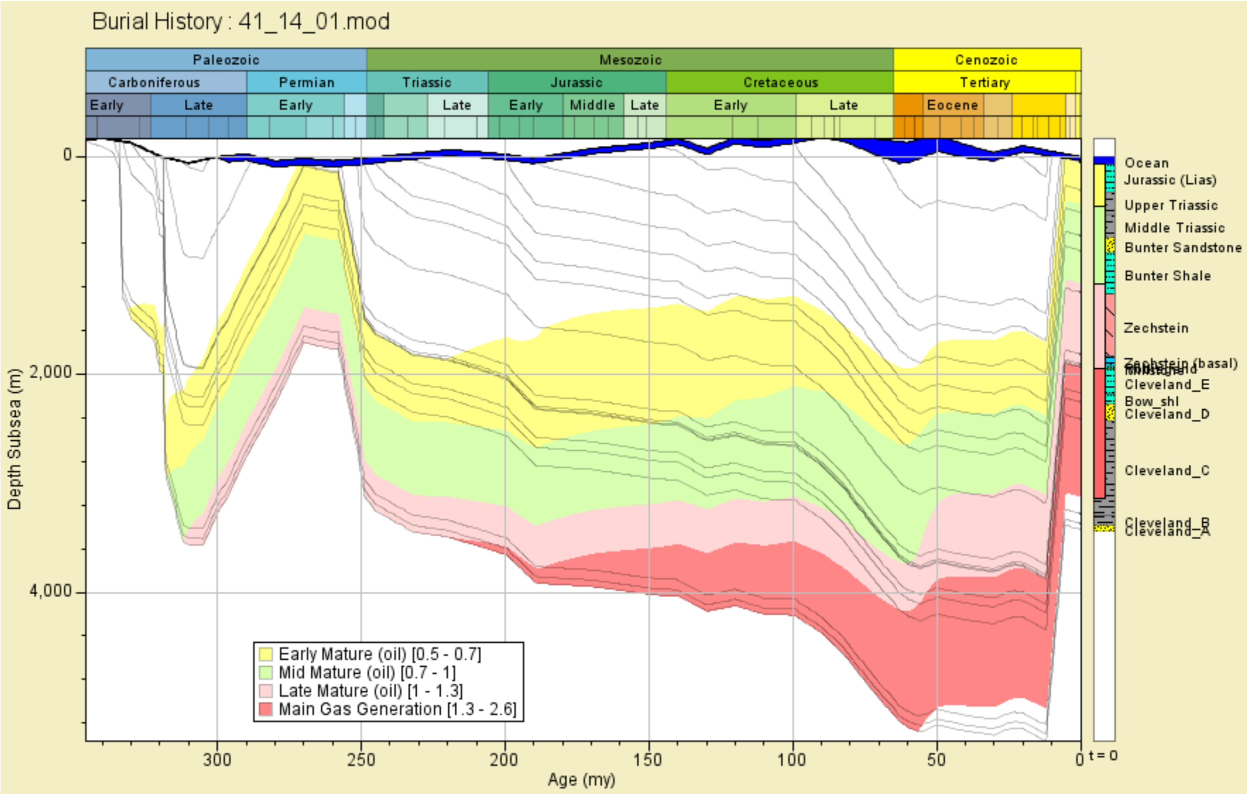


Figure 31: Modelled maturity geohistory for Well 41/14-01. The well terminates in the Cleveland Group

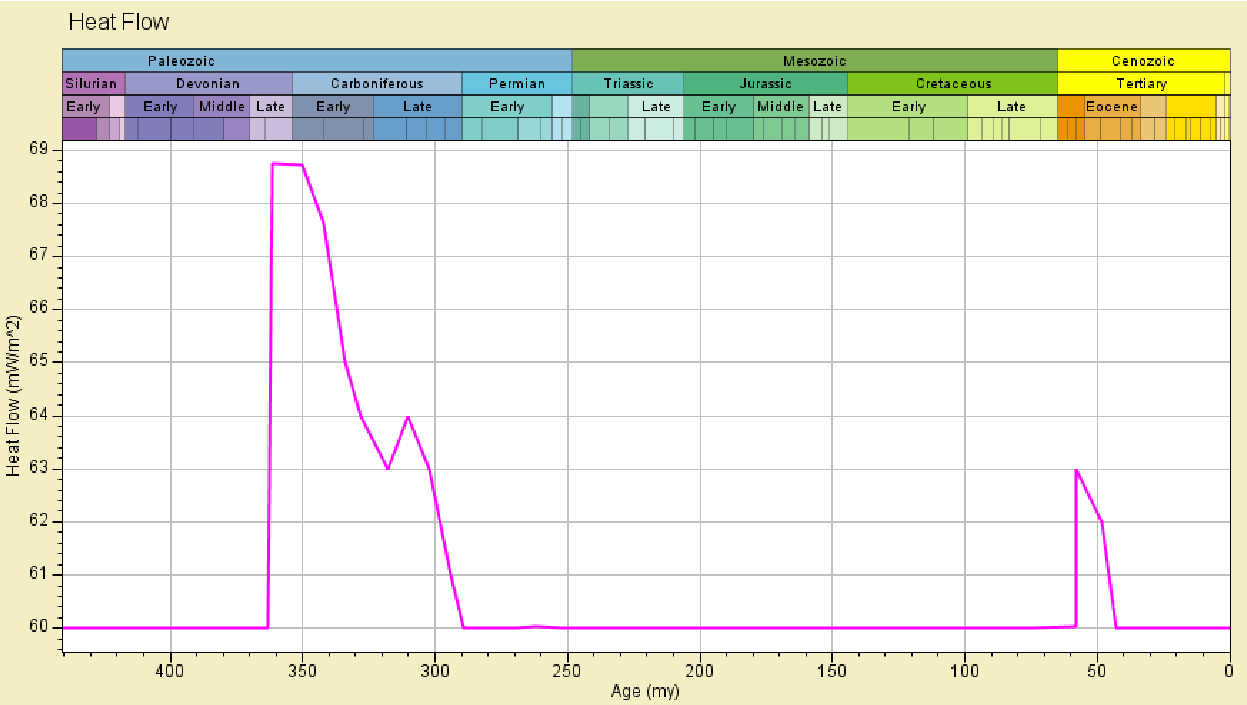


Figure 32: Modelled palaeo-heat flow for Well 41/14-01

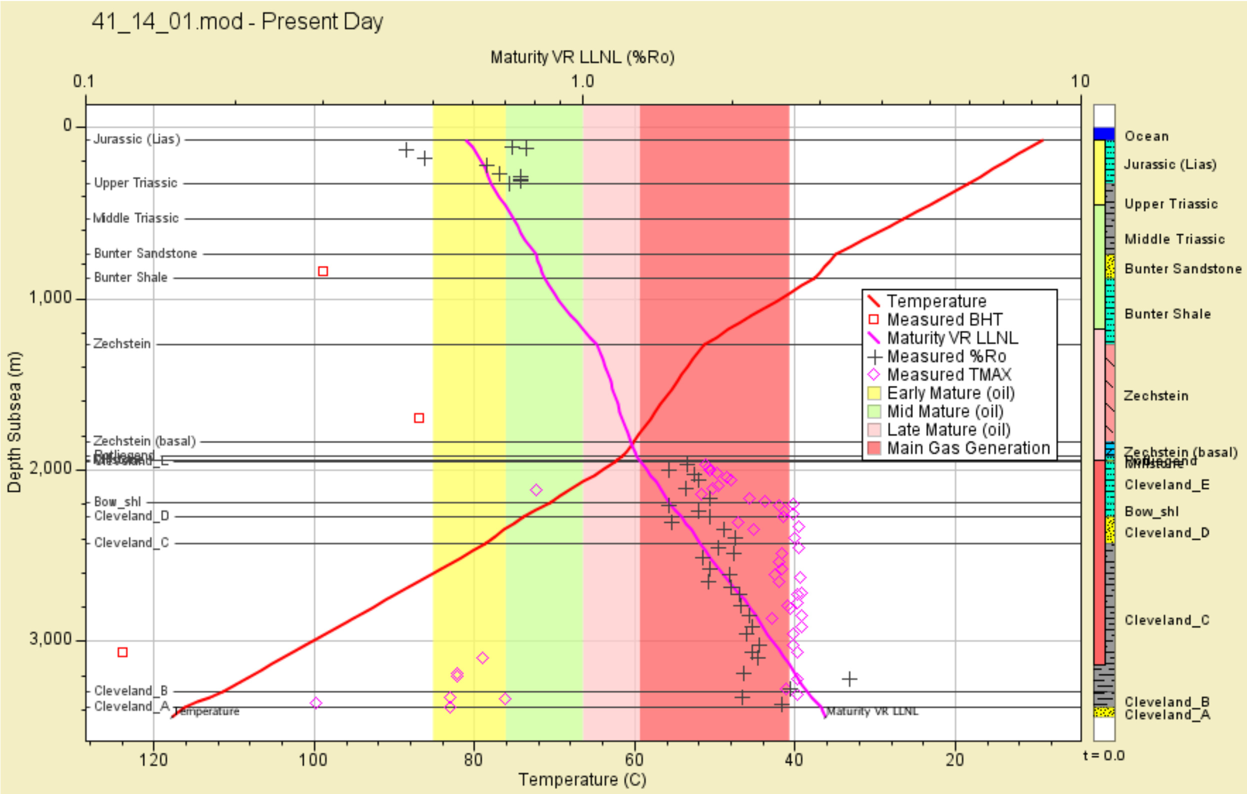


Figure 33: Depth plot for Well 41/14-01 showing model results, maturity data and maturity windows plus temperature data and model

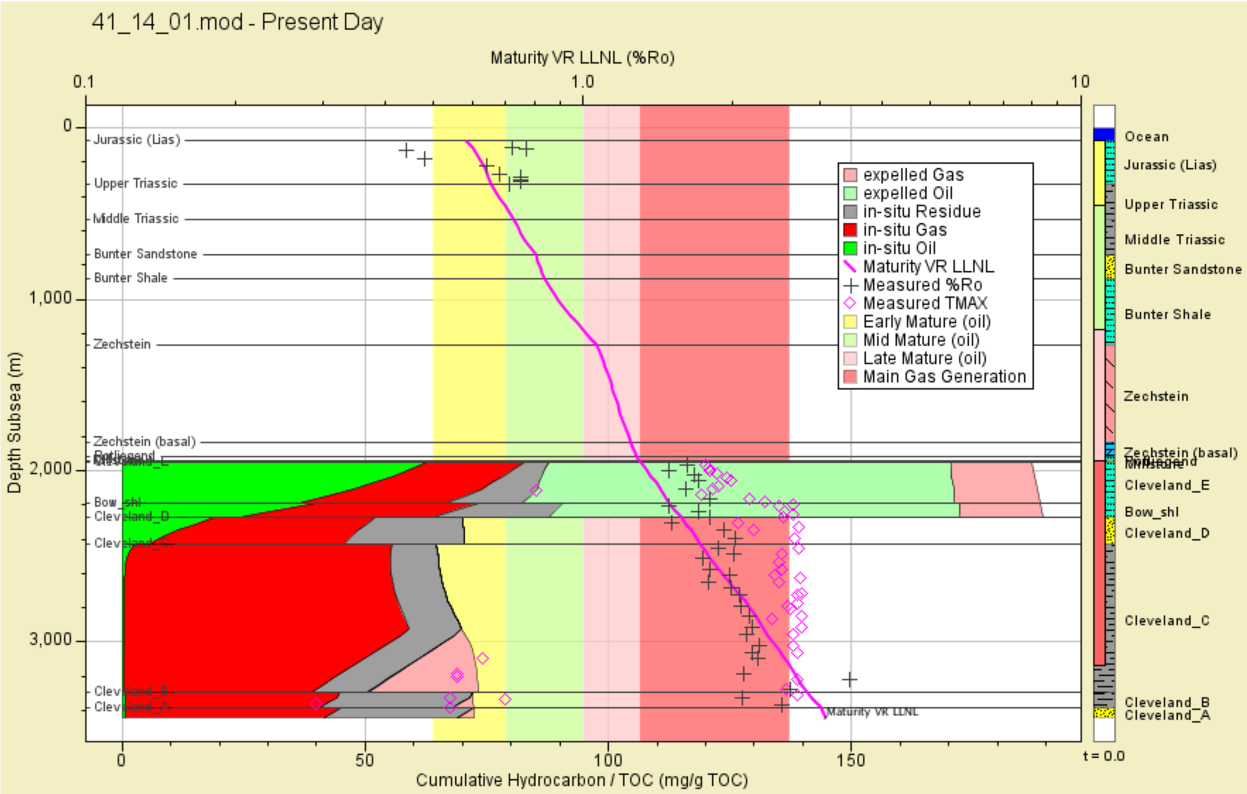


Figure 34: Depth plot for Well 41/14-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

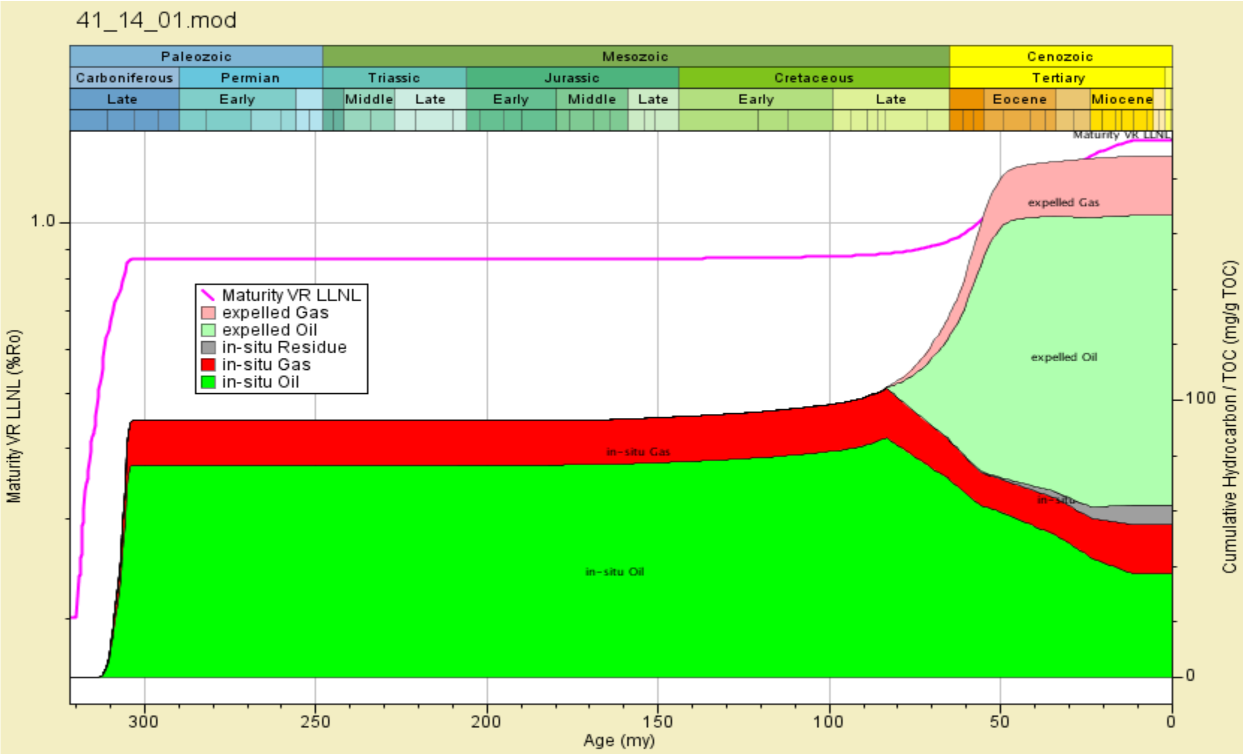


Figure 35: Time plot for Well 41/14-01 showing timing of generation for Cleveland E model layer. The current model suggests that generation started during the Carboniferous Period but expulsion of hydrocarbons only occurred during deepest burial during the Cenozoic Era.

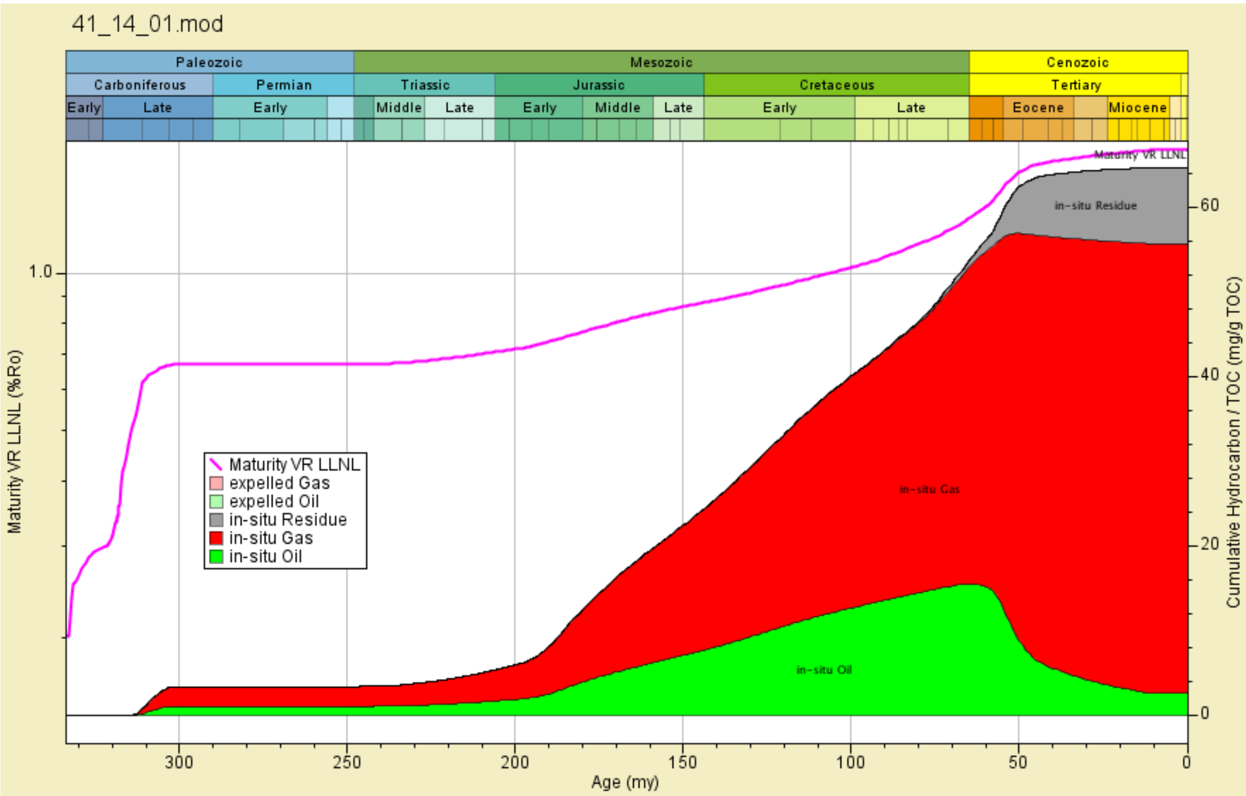


Figure 36: Time plot for Well 41/14-01 showing timing of generation for Cleveland C model layer. The current model suggests that main generation occurred during deep burial during the Carboniferous Period.

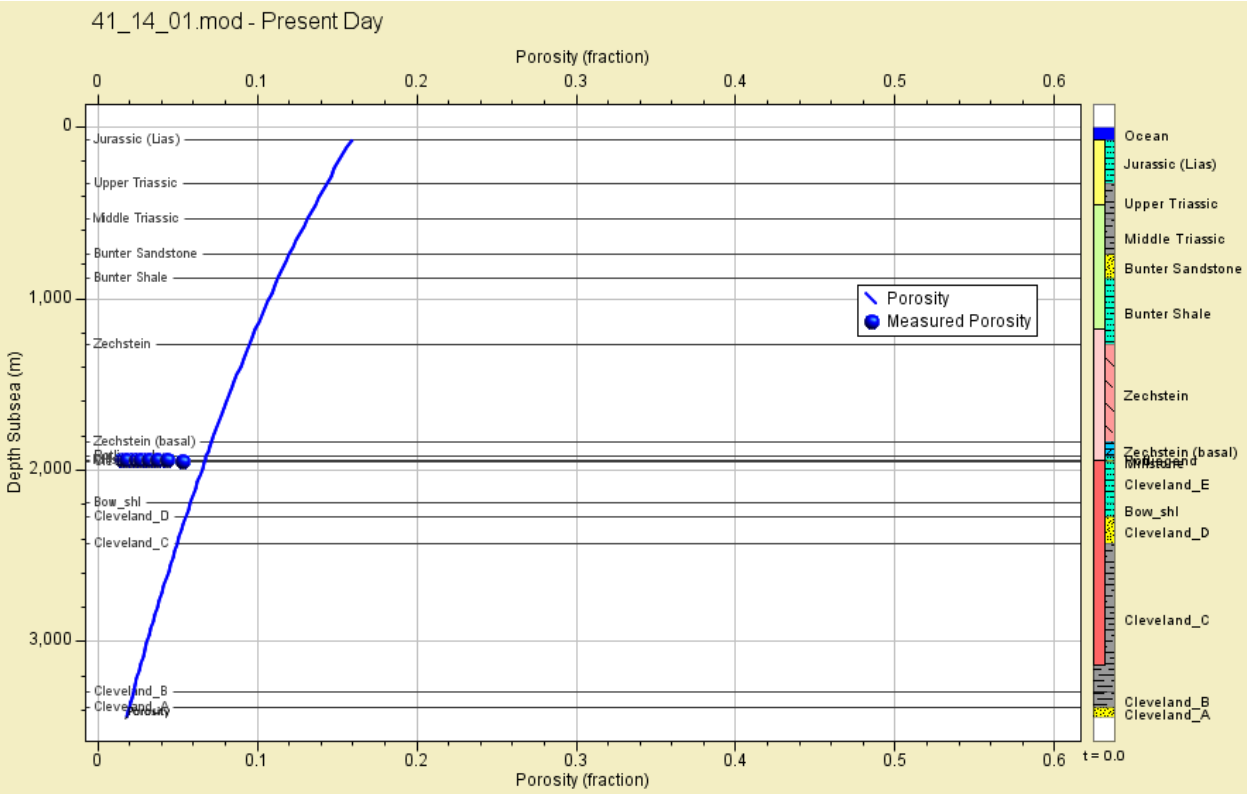
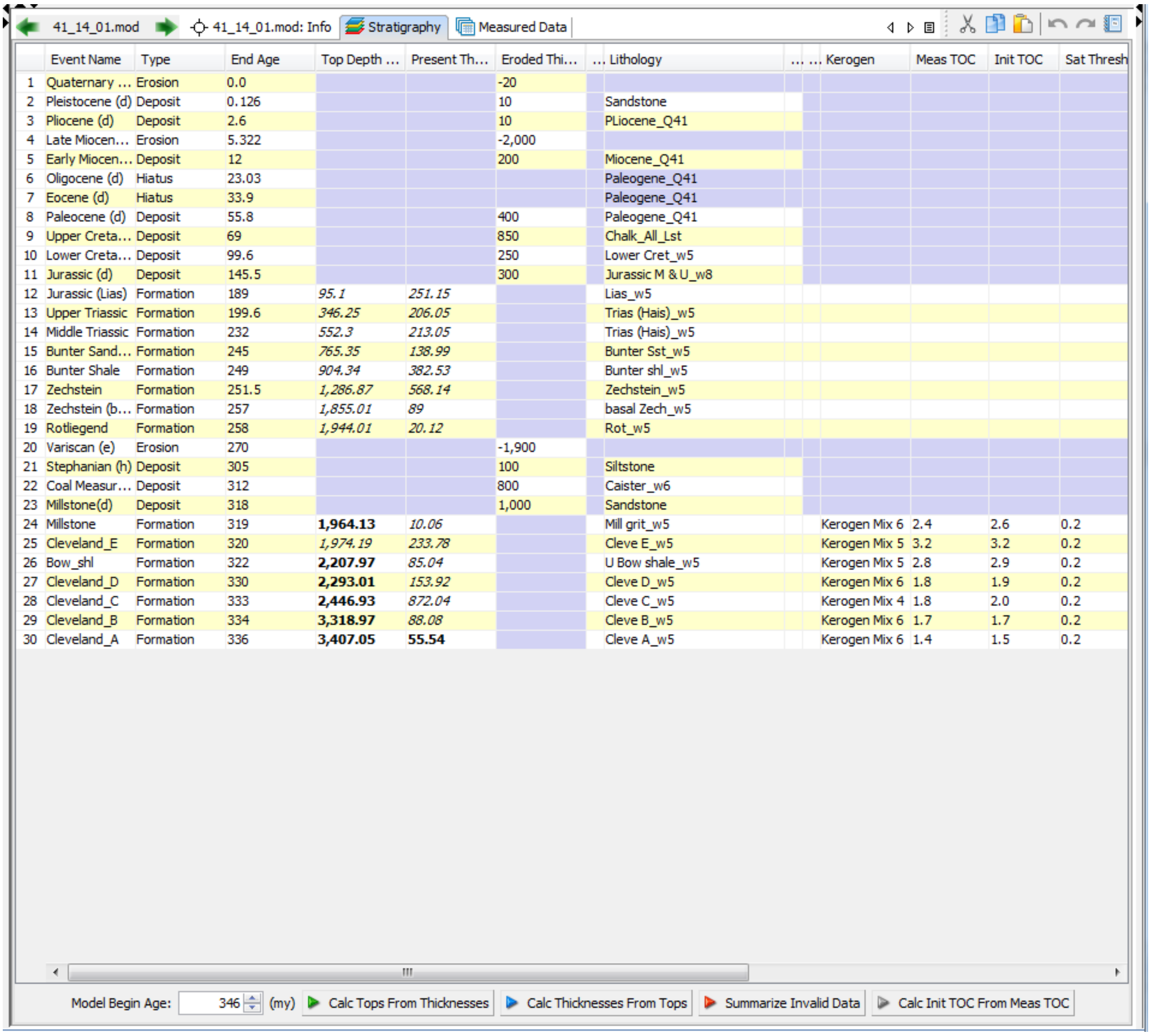


Figure 37: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 41/14-01

7.3.3 Key points from new modelling work for Well 41/14-01

- All the Palaeozoic strata reached the gas maturity window
- The top of the Cleveland Group (Yoredale equivalent) has moderate generation potential in some formations
- Main generation started during the Carboniferous Period for the Cleveland Group
- The Scremerston Formation is assumed to have poorer potential than the Yoredale Formation based on legacy reports
- The Scremerston Formation is in the gas maturity window and contains a mix of oil and gas prone kerogens
- Deepest burial occurred during the Cenozoic Era



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	... ... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-20					
2	Pleistocene (d)	Deposit	0.126			10	Sandstone				
3	Pliocene (d)	Deposit	2.6			10	PLiocene_Q41				
4	Late Miocen...	Erosion	5.322			-2,000					
5	Early Miocen...	Deposit	12			200	Miocene_Q41				
6	Oligocene (d)	Hiatus	23.03				Paleogene_Q41				
7	Eocene (d)	Hiatus	33.9				Paleogene_Q41				
8	Paleocene (d)	Deposit	55.8			400	Paleogene_Q41				
9	Upper Creta...	Deposit	69			850	Chalk_All_Lst				
10	Lower Creta...	Deposit	99.6			250	Lower Cret_w5				
11	Jurassic (d)	Deposit	145.5			300	Jurassic M & U_w8				
12	Jurassic (Lias)	Formation	189	95.1	251.15		Lias_w5				
13	Upper Triassic	Formation	199.6	346.25	206.05		Trias (Hais)_w5				
14	Middle Triassic	Formation	232	552.3	213.05		Trias (Hais)_w5				
15	Bunter Sand...	Formation	245	765.35	138.99		Bunter Sst_w5				
16	Bunter Shale	Formation	249	904.34	382.53		Bunter shl_w5				
17	Zechstein	Formation	251.5	1,286.87	568.14		Zechstein_w5				
18	Zechstein (b...	Formation	257	1,855.01	89		basal Zech_w5				
19	Rotliegend	Formation	258	1,944.01	20.12		Rot_w5				
20	Variscan (e)	Erosion	270			-1,900					
21	Stephanian (h)	Deposit	305			100	Siltstone				
22	Coal Measur...	Deposit	312			800	Caister_w6				
23	Millstone(d)	Deposit	318			1,000	Sandstone				
24	Millstone	Formation	319	1,964.13	10.06		Mill grit_w5	Kerogen Mix 6	2.4	2.6	0.2
25	Cleveland_E	Formation	320	1,974.19	233.78		Cleve E_w5	Kerogen Mix 5	3.2	3.2	0.2
26	Bow_shl	Formation	322	2,207.97	85.04		U Bow shale_w5	Kerogen Mix 5	2.8	2.9	0.2
27	Cleveland_D	Formation	330	2,293.01	153.92		Cleve D_w5	Kerogen Mix 6	1.8	1.9	0.2
28	Cleveland_C	Formation	333	2,446.93	872.04		Cleve C_w5	Kerogen Mix 4	1.8	2.0	0.2
29	Cleveland_B	Formation	334	3,318.97	88.08		Cleve B_w5	Kerogen Mix 6	1.7	1.7	0.2
30	Cleveland_A	Formation	336	3,407.05	55.54		Cleve A_w5	Kerogen Mix 6	1.4	1.5	0.2

Figure 38: Model data entry sheet for Well 41/14-01. Top Depth is in m BRT

7.4 WELL 41/20-01

Well 41/20-01 lies on a local high identified on seismic data north of the Flamborough Fault zone.

Well 41/20-01 is deviated by around 8° below 2123 m BRT, i.e. from the Caister Coal Formation downwards though this does not appear to have affected the fit of the model significantly.

7.4.1 Previous maturity and modelling work

Carboniferous strata reached the gas window. TOC for Visean and Namurian strata is generally fair with some very high TOC samples. Samples are mainly gas prone but potential was highly variable. Carboniferous coals were described as ‘very gaseous’. A Carboniferous source has been proved by fluid inclusion testing from two samples from the Millstone Grit Group (Pittion, 1981; Cooper et al., 1978; PETRA-CHEM, 1966; Norkett, 1966; Signal-Richfield-Marathon-Cities services, 1966).

Palaeozoic source rocks

Below 1828.8 m BRT (in the Coal Measures Formation), only minor traces of hydrocarbons were detected, usually in association with coal and/or carbonaceous shales. Minor traces of gas and occasional staining were observed (Signal-Richfield-Marathon-Cities services, 1966). The well was abandoned due to low porosities, lack of encouraging gas shows in Carboniferous strata and the fact that no massive Visean limestones were penetrated by this well. Signal-Richfield-Marathon-Cities services (1966) concluded that the well had been drilled at the site of a Visean – Tournasian age basin where clastic rather than carbonate strata were deposited.

Pyrolysis analysis carried out by Pittion (1981) indicated a low (<60 mg/g) hydrogen index for Carboniferous strata in Well 41/20-01. The kerogen type is humic and mainly comprises small coaly particles. Vitrinite reflectance and spore colour were used to confirm that the Carboniferous strata reached the wet and dry gas maturity windows (Pittion, 1981).

Cooper et al. (1978) assessed Visean and Namurian strata from 3016.0 – 3450.3 m BRT; the report stated that VR data indicated these strata had reached the dry gas maturity window with an average TOC of 1.66% (with the exception of a coaly sample at 3441.0 m BRT and a higher TOC sample at 3444 m BRT which have TOC of 13.89 % and 4.58 % respectively). Spore colour analysis indicated a slightly lower maturity but nevertheless indicated the samples were through the main oil maturity window and into the main gas maturity window.

In the upper part of the Millstone Grit Group, the quality of organic material is a little lower but TOC is still between 1 and 2% . In the lower part of the Millstone Grit Group, TOC is mostly between 1.5 and 3% (Pittion, 1981). Analysis of extracts from two samples taken from the Millstone Grit Group suggest a high maturity and confirm a Carboniferous source. Vitrinite analysis indicates the Carboniferous strata reached the wet and dry gas maturity windows (Pittion, 1981). Gas prone samples were observed in the Millstone Grit, though it is noted that some samples within these intervals only had finely disseminated material considered to have no potential. Other samples within the Millstone Grit had mixed/no potential or no potential (PETRA-CHEM, 1966). Other cores from the Millstone Grit had no shows (Norkett, 1966).

Signal-Richfield-Marathon-Cities services (1966) described the coals in the Carboniferous as ‘very gaseous’ and observed that although no shows were observed in the Carboniferous sand bodies due to low porosity, any sand bodies with good porosity could offer reservoir potential. The authors suggest that regional metamorphism has affected the Carboniferous rocks of this area, though the Millstone Grit Group appears to have been less affected and appears to show higher porosities (Signal-Richfield-Marathon-Cities services, 1966).

Few samples were available for Westphalian B strata (Westoe Formation) but coals are plentiful, suggesting that the TOC is likely to be high (Pittion, 1981). No shows were observed in Westphalian B cores from 1878.5 – 1879.2 m BRT and 1904.7 – 1912.3 m BRT or Westphalian A cores from 2502.1 – 2513.4 m (Norkett, 1966).

Samples from Carboniferous strata were noted as being gas prone in PETRA-CHEM (1966); including in the Cleaver Formation (1907.4 m BRT) and Caister Formation (2505.8 m BRT). However, other samples within these same intervals tested as having no potential. Some samples from the Caister Formation were rated as having mixed/no potential (2322.6 – 2325.6 m BRT).

In the Caister Formation, TOC is high (almost always >2% and up to 20%) due to the presence of coaly lenses and coaly shales.

A strong gas show was observed in Zechstein strata (Upper Magnesian Limestone), this interval was assumed to be unproductive based on DST data, though it was noted that the Plattendolomite (an algal biostrome) is a major gas producer for the Netherlands and Germany so the possibility of generation from this formation could not be excluded (Signal-Richfield-Marathon-Cities services, 1966).

Although a gas accumulation was observed in fractured salt, it was noted in the engineering and geological well report (Signal-Richfield-Marathon-Cities services, 1966) that productivity of the Zechstein is limited by lack of permeability so production from the salt would be expected to be uneconomic. A DST test in the Zechstein Group (1113.4 – 1171.0 m BRT) was interpreted as showing the section was either very tight or part of a reservoir with sealed boundaries or decreasing permeability away from the wellbore (or a combination of these). Many air permeabilities reported in Signal-Richfield-Marathon-Cities services (1966) for the Zechstein Group are zero. Another DST test indicated a tight reservoir with low (<0.1 mD) permeability (at 1188.1 – 1237.2 m BRT) (Signal-Richfield-Marathon-Cities services, 1966).

Pittion (1981) assessed the TOC of Permian strata to investigate if this could be a potential source rock, however, TOC was low: Upper Magnesian Limestone and Middle Magnesium Limestone Formation in Well 41/20-01 (most TOC <0.4% with only two samples with TOC 0.5 – 0.7) indicating no possibility of generating economic quantities of hydrocarbons. The Permian strata in this well are believed to be a poor source rock thus this gas was not generated in this interval (Pittion, 1981). This contrasts with the earlier observations of Signal-Richfield-Marathon-Cities services (1966).

Post-Palaeozoic reservoirs

Donato (1968) indicated that porosity in the Bunter sandstone was good (10 – 25% from the sediment log graph) due to the lack of clay particles. A small number of samples from 444.7 – 450.8 m (BRT) were tested.

Hydrocarbon shows

A high pressure, low volume gas distillate accumulation is present in fractured salt at 1153.7 m BRT. The source of the gas was initally assumed to lie in the Zechstein strata (Signal-Richfield-Marathon-Cities services, 1966) but later testing by Pittion (1981) suggested that TOC are so low that the gas was not generated in this interval.

A small gas cap is present at the top of the Bunter Sandstone (432.8 – 435.3 m BRT). The remainder of the Bunter Sandstone is water bearing (Signal-Richfield-Marathon-Cities services, 1966).

Further gas shows were present in the Zechstein (Lower Magnesian Limestone) and Permian strata.

Maturity data

Cooper et al. (1978) noted that few reliable pyrolysis data were achieved due to a high level of maturity and/or kerogen comprising mainly inertinite. The samples from Well 41/20-01 mainly comprised inertinite with subordinate/minor vitrinite.

Cooper et al. (1978) assessed Visean and Namurian strata from 3016.0 – 3450.3 m BRT; the report stated that VR data indicated these strata had reached the dry gas maturity window. In Well 41/20-01, the Carboniferous strata reached the wet and dry gas maturity windows (Pittion, 1981).

Geohistory models

Signal-Richfield-Marathon-Cities services (1966) suggest that the high grade coal and altered sandstones indicate regional metamorphism has affected the Carboniferous rocks of this area.

Well 41/20-01 was modelled by Collinson and IGI (1995) with a present day heat flow of 63 MWm^{-2}.

7.4.2 New modelling work

Maturity and porosity data

Seventeen VR data (VRo average) and 61 VRcalc data were available from the PETRA-CHEM (1966). An additional seven T_{max} and 15 VR data were available from Pittion (1981). Additional data (6 VR and 2 T_{max}) were available from Cooper et al. (1978). Seven additional VRcalc values were available from Vane et al (this study). Uncorrected BHT were taken from the DST (Halliburton, 1965) and a corrected BHT was taken from Collinson and IGI (1995) for the Millstone Grit Group. Porosity data were available for the Bunter Sandstone Formation and Zechstein Group (Norkett, 1966). In this study, additional pyrolysis data (S1, S2, TOC plus seven sets of S1, S2, S3 and TOC) were also included in the model for the generation phase of modelling. Model input data are shown in Table 8.

Table 8: Summary of model input data for Well 41/20-01 and layer maturity window from the BasinMod model

Formation/ age of strata	N.o. of VR/ VRcalc datapoints	Model maturity window	Average measured TOC from logs	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Bunter Sandstone		Early mature for oil			Small gas cap	12 data	
Zechstein	2 VRcalc	Mid - late mature for oil	0.3*	Type IV	Strong gas show in Upper Magnesian Limestone plus other gas shows	60 data	
Cleaver	2 VR, 3 VR calc	Late mature for oil	23.22*	Mainly gas prone (but some mixed potential and inert matter)			
Westoe	2 VR, 8 VRcalc	Late mature for oil – main gas generation	17.99*	Mainly gas prone (but some mixed potential and inert matter)			
Caister	11 VR, 15 VRcalc	Main gas generation	6.54*	Mainly gas prone (but some mixed potential and inert matter)			
Millstone Grit	24 VR, 45 VRcalc	Main gas generation	1.92*	Type III and mixed potential			

* These data are taken from samples from legacy reports as no calculated wireline log data were available from this study

Model calibration

The VR data showed a reasonably linear trend in the Carboniferous strata, but the VRcalc data showed a broad scatter, particularly for the Millstone Grit Group. The model was matched to the new VRcalc data from this study and the VR data from previous reports as these were believed to offer the most reliable dataset; a reasonable number of samples per VR datapoint were available (generally >30 samples for the Pittion (1981) report and mostly >20 samples per datapoint for the Petrachem report). The model fit to the BHT data is good for this well.

Well 41/20-01 is modelled here with high Devonian/Carboniferous high heat flow as it is reasonably expected that regional extension and crustal thinning would result in a relatively high heat flow.

The nearest well with a density log available was Well 42/20-01 so the eroded stratigraphical thicknesses included in the current model were compared with results of the analysis of the density log carried out for 42/20-02 by Kimbell and Williamson (this study). The quality of the density log for nearby Well 42/20-02 is generally quite poor, so although it seems that the thermal model significantly underestimates burial (0.4 km additional strata at the end of the Carboniferous and 1.4 km for pre-Alpine burial for the current BasinMod model compared with an expected additional 9.2 km of strata for the Carboniferous strata and 3.9 km Triassic and Younger additional strata burial from analysis of density log; Williamson et al., this report), given the poor quality of the density log, and the burial history for the other BasinMod models in this region in this report, this is not considered a significant issue. The current modelled porosity would also support a greater thickness of Triassic and younger strata but as this section of the project work is focused on the thermal maturity data, the fit was preferentially matched to the maturity data.

The BasinMod model suggests that deepest burial occurred during post-Permian burial, which is a positive indicator for preservation of generated hydrocarbons, given the comments made by Pittion (1981); i.e. that a proportion of hydrocarbons generated during Carboniferous burial would most likely have migrated out of the reservoir due to lack of seal. The Millstone Grit Group (with its high TOC but poor source potential) and Coal Measures Group reached the main gas maturity window.

The model maturity geohistory is given in Figure 39, the model heat flow is given in Figure 40. Model results are shown in Figure 41. Comparison of the porosity data and modelled porosity is given in Figure 45.

<u>Maturity and hydrocarbon generation</u>

Vane et al. (this study) suggest that organic matter from the Coal Measures Group mainly comprises type III kerogen (though additional analyses indicated some organic matter is prone to both oil and gas so a kerogen mixture was included in the BasinMod model) and that organic matter in the Millstone Grit Formation mainly comprises type III kerogen. However the source potential of the Millstone Grit Formation was generally considered to be poor. Vane et al. (this study) considered the Millstone Grit Formation to have mixed potential for oil/gas. One geochemistry report (Pittion, 1981) indicates mainly humic organic matter for Namurian samples.

The source potential of the samples from the Coal Measures Group was promising (Vane et al., this study). The Westoe Formation had a couple of samples with ‘excellent potential’, these were near thin coal seams indicated on the composite log. The Cleaver and Caister formations had high TOC and S2 and were plotted as coals on the S2/TOC plot (Vane et al., this study). This well was classed as an excellent gas source by Vane et al. (this study).

Samples from the Permian strata had quite low TOC based on legacy reports (average 0.3% from samples).

Average measured TOC values were included from legacy well reports (PETRA-CHEM, 1966 and Cooper et al., 1978) and new rock evaluation work for the Coal Measures Group and Millstone Grit Formation (Vane et al., this study). Measured TOC values from legacy well reports were included for the Zechstein Group strata. These TOC values were utilised by BasinMod to calculate initial TOC value for these strata.

Gas shows and a gas cap are reported for this well in Permian strata which are believed to have been sourced from the Carboniferous strata. Coals in the Carboniferous strata are described as very gaseous (Pittion, 1981, PETRA-CHEM, 1966 and Signal-Richfield-Marathon-Cities services, 1966). These legacy reports support the current model which suggest the Coal Measures Group and older Palaeozoic strata reached the gas window.

The current model suggests the main generation phase was from Triassic times onwards. At this time Zechstein evaporites and younger argillaceous strata would have offered a potential seal to trap migrating hydrocarbons.

The model generation potential for strata in the well is given in Figure 42. Timing for generation from the most promising horizons is given in Figure 43 and Figure 44. The data entry sheet is shown in Figure 46.

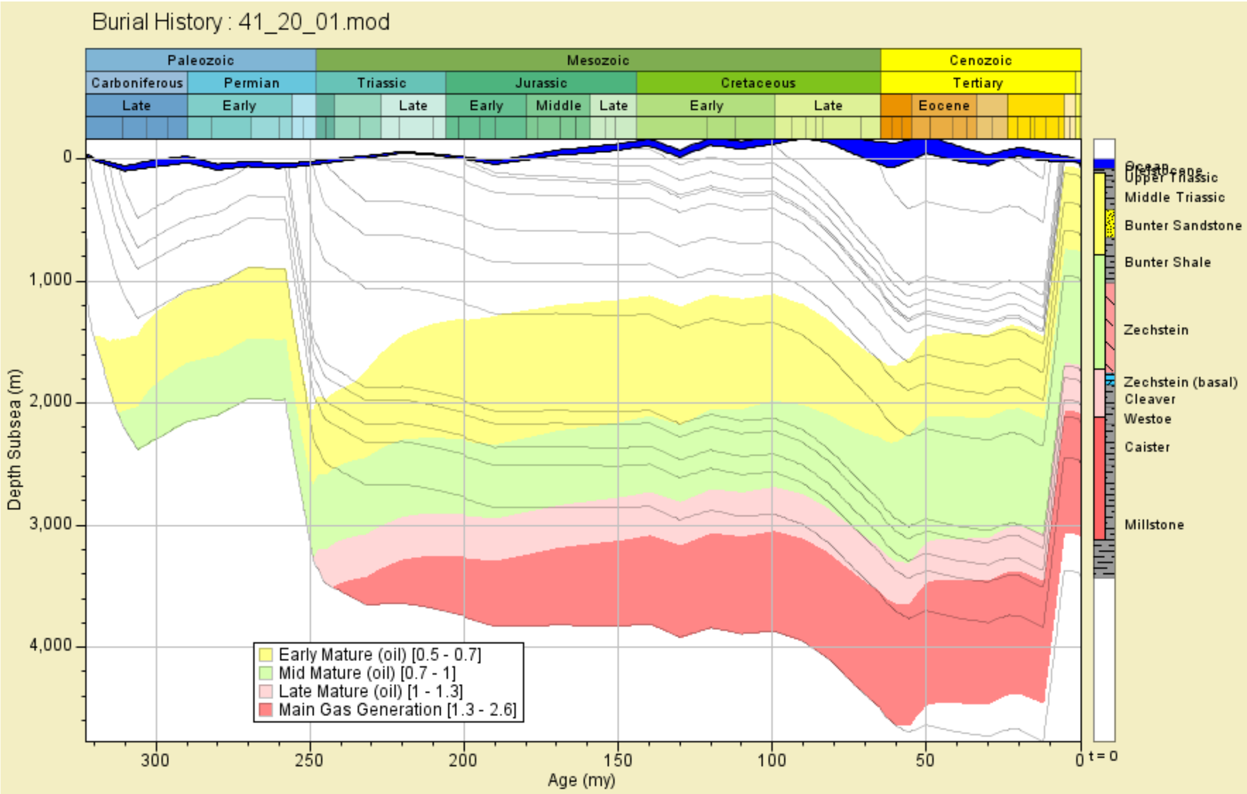


Figure 39: Modelled maturity geohistory for Well 41/20-01. Well terminates in the Millstone Grit Formation

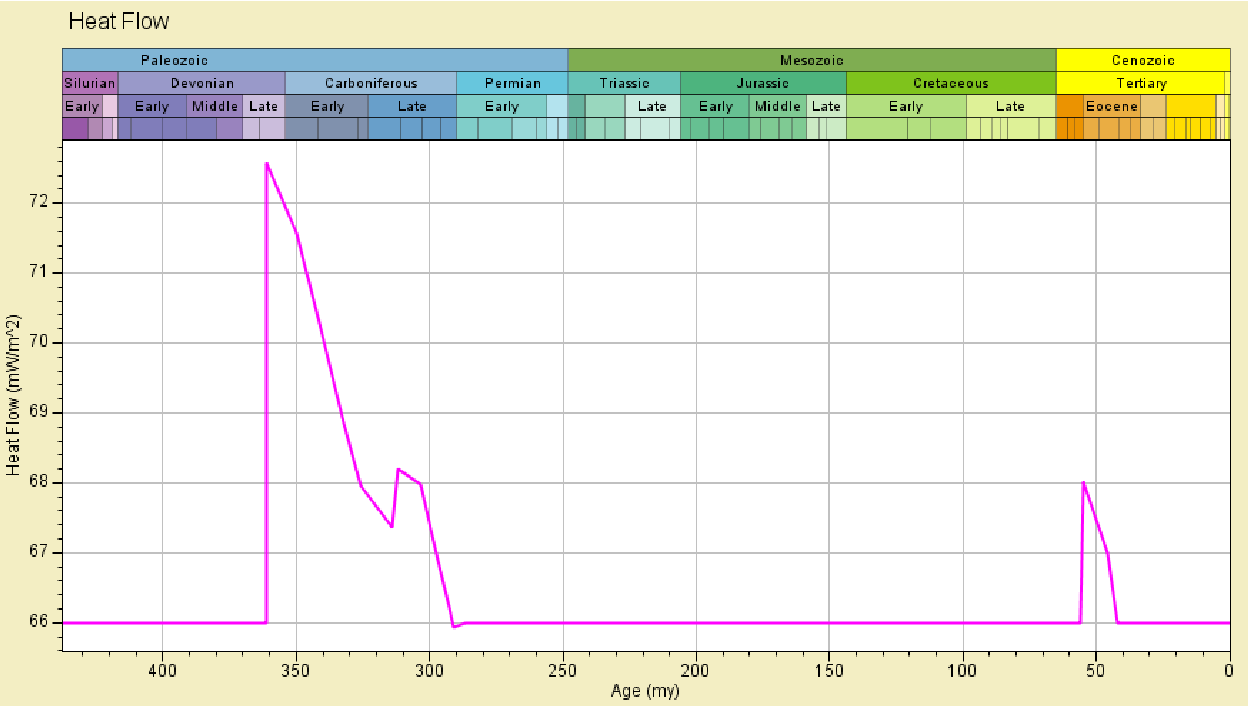


Figure 40: Modelled palaeo-heat flow for Well 41/20-01

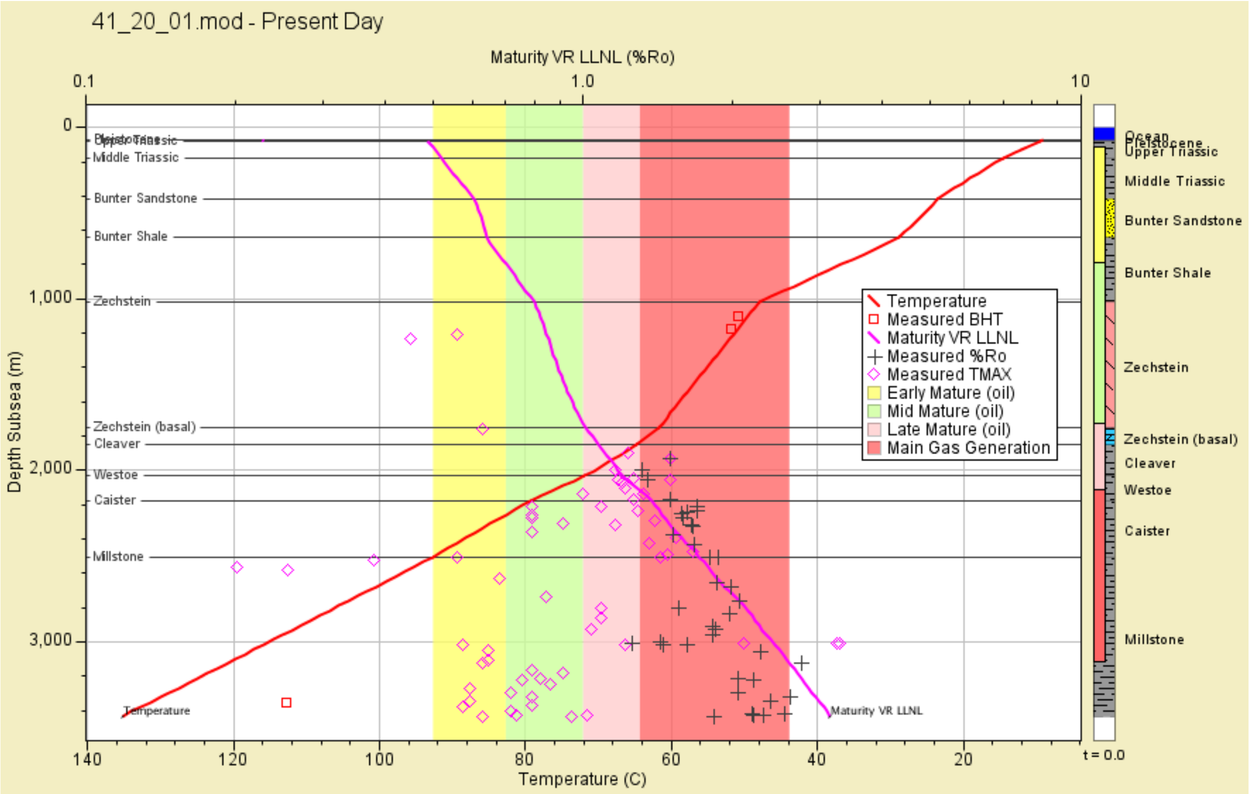


Figure 41: Depth plot for Well 41/20-01 showing model results, maturity data and maturity windows plus temperature data and model

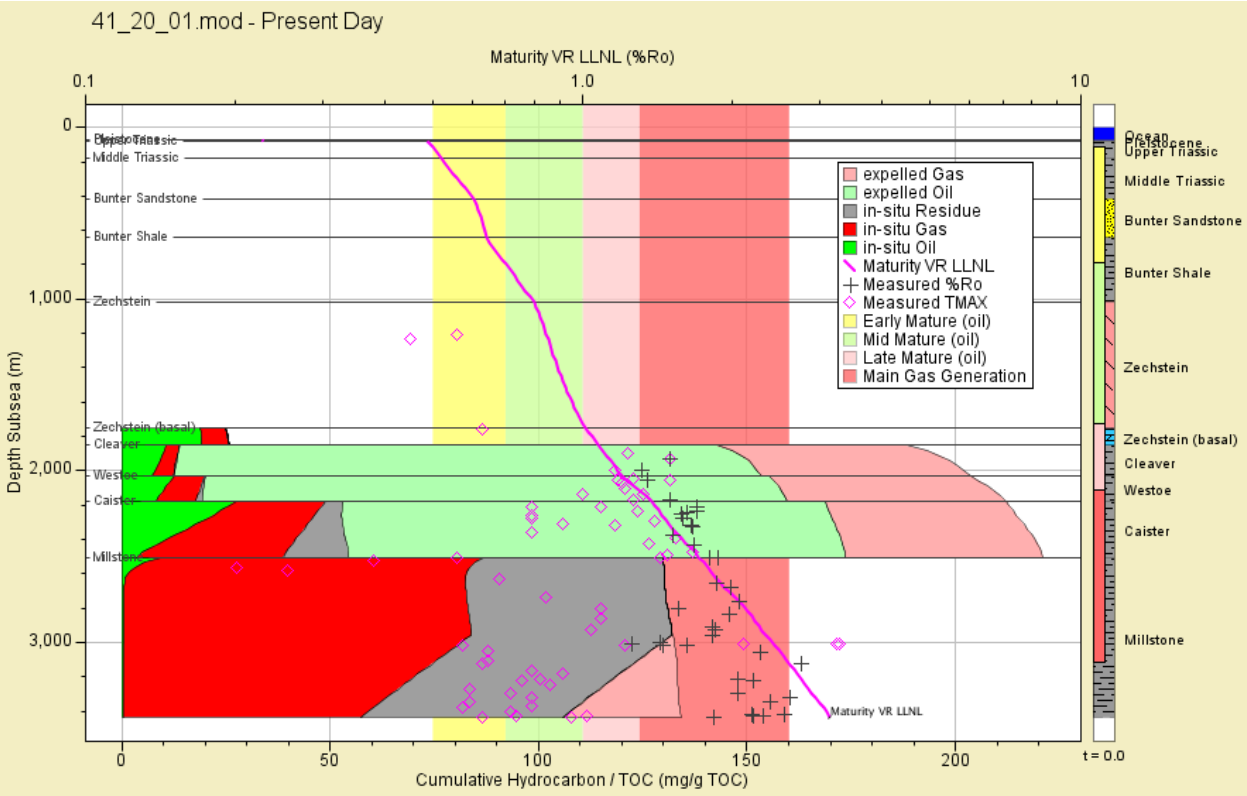


Figure 42: Depth plot for Well 41/20-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

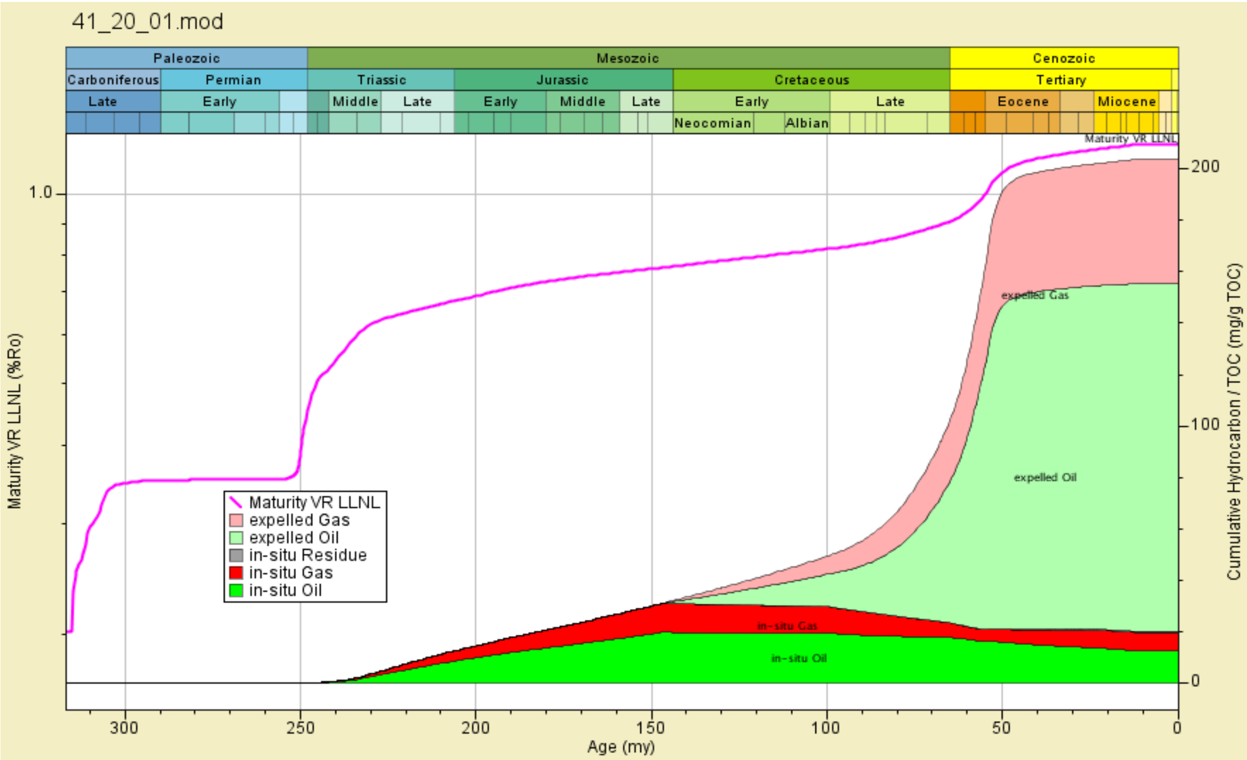


Figure 43: Time plot for Well 41/20-01 showing timing of generation for Westoe Formation. The current model suggests that main generation and expulsion occurred during deepest burial during the Cenozoic Era

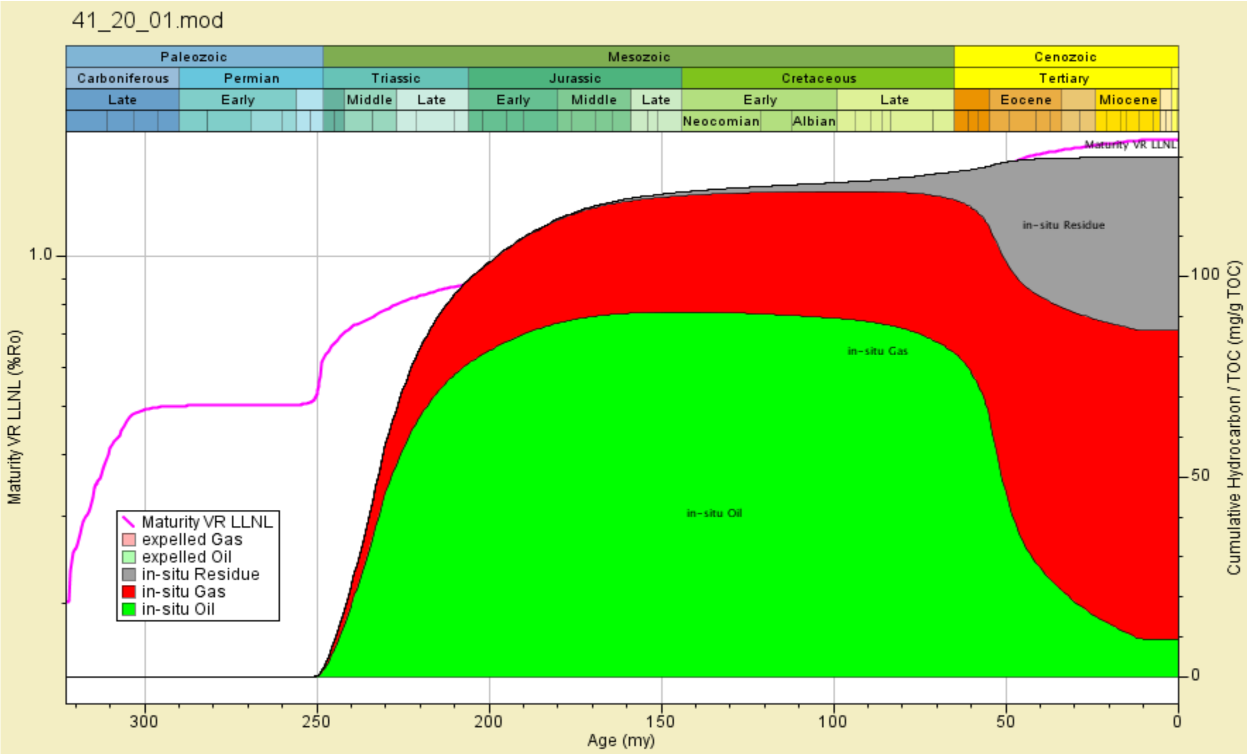


Figure 44: Time plot for Well 41/20-01 showing timing of generation for Millstone Grit Formation. The current model suggests that main generation occurred during deep burial during the Mesozoic Era and that no expulsion occurred from strata at the top of the formation

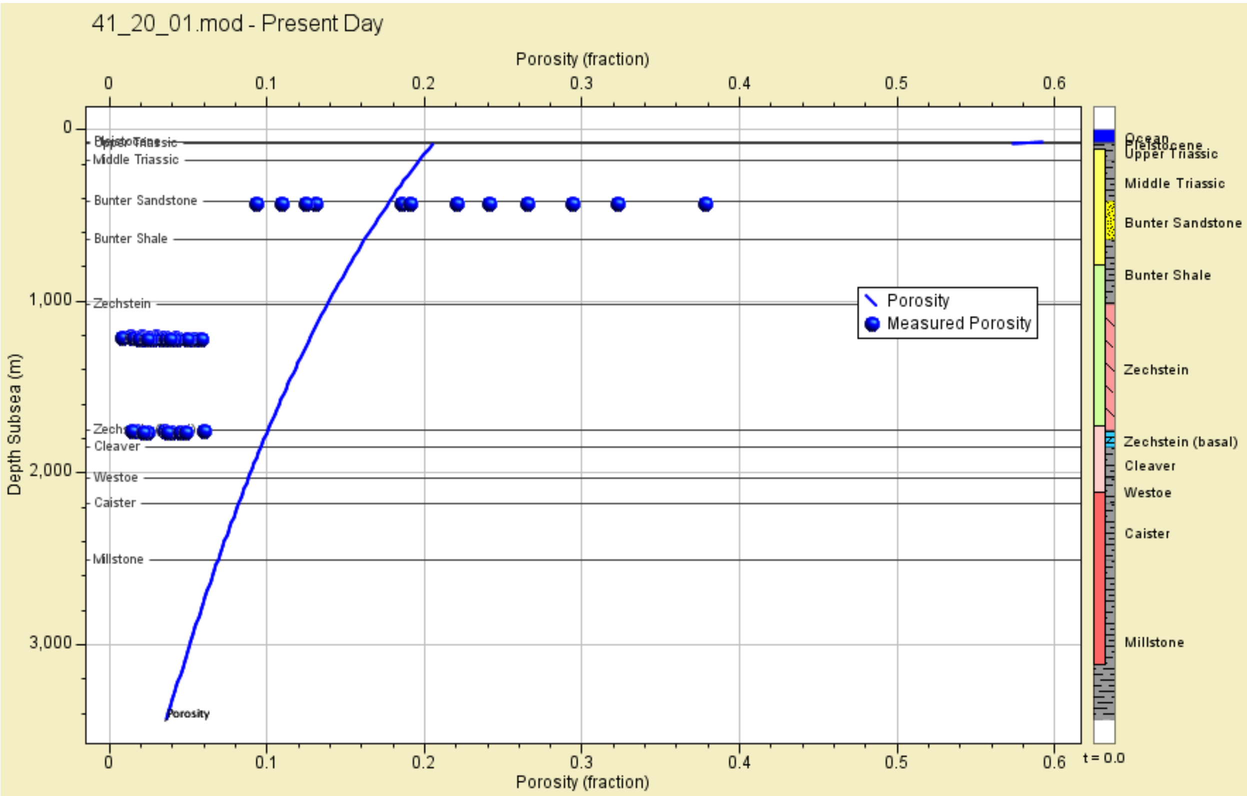


Figure 45: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 41/20-01

7.4.3 Key points from new modelling work for Well 41/20-01

- All the Palaeozoic strata reached the gas maturity window, some are now overmature
- Coal Measures Group (Cleaver, Westoe, Caister formations) have good generation potential for gas
- Generation was from Triassic times onwards with main generation during the Cenozoic Era
- The well does not penetrate the Scremerston Formation
- Deepest burial was during the Cenozoic Era

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	... ... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-20					
2	Pleistocene (d)	Deposit	0.126			20	Pleistocene_w6				
3	Pleistocene	Formation	0.781	*89*	*7.0*		Pleistocene_w6				
4	Pliocene (h)	Hiatus	2.588								
5	Late Miocen...	Erosion	5.322			-1,400					
6	Early Miocen...	Deposit	12			150	Miocene_Q41				
7	Oligocene (d)	Hiatus	23.04				Paleogene_Q41				
8	Eocene (d)	Hiatus	33.9				Paleogene_Q41				
9	Paleocene (d)	Deposit	55.8			350	Paleogene_Q41				
10	Upper Creta...	Deposit	65.5			600	Chalk_All_Lst				
11	Lower Creta...	Deposit	99.6			100	Lower Cretaceous_w6				
12	Jurassic (d)	Deposit	145.52			90	Jurassic M & U_w8				
13	Jurassic (Lia...	Deposit	175.6			90	Shale				
14	Upper Triass...	Deposit	199.59			20	Trias_top_w6				
15	Upper Triassic	Formation	200	**96**	*96.02*		Trias_top_w6				
16	Middle Triassic	Formation	232	**192.02**	*238.36*		Trias_M_w6				
17	Bunter Sand...	Formation	245.01	*430.38*	*228.9*		Bunter Sst_w6				
18	Bunter Shale	Formation	249.02	*659.28*	*372.77*		Salif Marl_w6				
19	Zechstein	Formation	251.51	*1,032.05*	*737.31*		Zechstein_combined_w6				
20	Zechstein (b...	Formation	257	*1,769.36*	*99.64*		basal Zech_w6	Kerogen Mix 3	0.3	0.3	0.2
21	Rotliegend (h)	Hiatus	258								
22	Variscan (e)	Erosion	270			-400					
23	Warwickshir...	Deposit	306			400	Siltstone				
24	Cleaver	Formation	312	*1,869*	*180*		Cleaver_w6	Kerogen Mix 7	23.22	29.2	0.2
25	Westoe	Formation	315.2	**2,049**	*141.5*		Westoe_w6	Kerogen Mix 7	17.99	18.2	0.2
26	Caister	Formation	317	**2,190.5**	*330*		Caister_w6	Kerogen Mix 7	6.54	6.7	0.2
27	Millstone	Formation	322	*2,520.5*	*930.55*		Mill grit_w6	Kerogen Mix 1	1.92	2.3	0.2

Model Begin Age: 323 (my)

Figure 46: Model data entry sheet for Well 41/20-01. Top Depth is in m BRT

7.5 WELL 42/10B-02

Well 42/10b-02 lies within a four-way dip closed structure (Premier Oil, 2008). Well 42/10b-02 also lies on a gravity anomaly (Kimbell and Williamson, this study).

7.5.1 Previous maturity and modelling work

Gas shows are recorded in Palaeozoic strata. Shales in the upper part of the Fell Sandstone Formation, coals within the Namurian and Dinantian strata, shales, bituminous shales and coals in the Scremerston and Yoredale were all suggested as potential source rocks where TOC was good - excellent (TOC was variable with low TOC samples also recorded). The lower part of the Dinantian (from the lower part of the Fell Sandstone Formation downwards) was described as being depleted in terms of source potential. The Yoredale and Scremerston formations are immature for gas generation. Deeper in the well, in the lower part of the Fell Sandstone Formation to Upper Old Red Sandstone Supergroup, the succession is mature for gas (Kaye, 1996; Premier Oil, 2008; Foden, 1996).

Previous maturity Geohistory modeling suggested three scenarios including high heat flow Visean – late Permian and late Cretaceous - recent times (Gibson, 1996), however, given the complex history of this region reported by several studies, the current report includes a more complex geohistory model.

<u>Hydrocarbon shows</u>

Gas shows are recorded in the Yoredale Formation according on the well composite log (Mobil North Sea Limited, 1995). Gas shows are recorded Yoredale Formation according to the well history (Maersk Jutlander, 1996) but the geological final well report only notes hydrocarbon shows in the Yoredale Formation indicated by fluorescence and small gas peaks. No significant shows were encountered in the Whitby Sandstone Member (Foden, 1996).

Premier Oil (2008) suggests a more optimistic view than earlier authors: the Agincourt discovery is described as being proved by Wells 42/10b-2, 42/10b-2Z and 42/15b-2. Gas was tested in Well 42/10b-2Z (Whitby Sands).

Gas shows are recorded in the Zechstein Group on the well composite log (Mobil North Sea Limited, 1995). Foden (1996) described only minor gas shows in the Zechstein strata within limestones, siltstones and poor quality thin sands. No gas shows in the Zechstein were included in the geological final well report (Foden, 1996).

<u>Palaeozoic source rocks and reservoirs</u>

Argillaceous horizons in the Upper Old Red Sandstone SuperGroup are considered organically lean with negligible source rock potential (Kaye, 1996).

Potential source rocks had an average TOC of 1.4% in the Cementstone Formation. Kaye (1996) also indicated the presence of unexpelled liquid hydrocarbons in the Cementstone Formation. Claystone horizons in the Cementstone Formation have negligible to poor source potential.

The lower part of the Fell Sandstone Formation and older strata have much poorer source rock potential than younger Palaeozoic rocks as the source rock is depleted. The production index decreases through the upper part of the Carboniferous section reflecting the expulsion of hydrocarbons and cracking of unexpelled liquids (Kaye, 1996). Isolated shales in the upper part of the Fell Sandstone Formation have a good TOC, offering moderate to excellent source potential with gas prone, vitrinite-dominated type III kerogen assemblages (Kaye, 1996). Kaye (1996) predicted significant dry gas generation from these potential source rocks. With caved samples removed from the dataset, other argillaceous layers within the Fell Sandstone have poor to moderate source potential Kaye, 1996).

Foden (1996) described Well 42/10b-02 in the geological final well report. The well was drilled to target the Dinantian (including Whitby Sandstone Member) on the flank of an identified structure. No significant shows were encountered in the Whitby Sandstone Member according to the author.

The Agincourt discovery has gas-bearing sands in the Yoredale, Whitby and Scremerston formations and in the Zechstein Hauptdolomit. The Whitby Sandstone Member was described as the main Carboniferous reservoir in this report. The main source rock was believed to be coals within the Namurian and Dinantian strata. A flow test in the Whitby Sandstone in Well 42/10b-2Z indicated quite limited flow, believed to be due to heterogeneous permeability and compartmentalisation of the reservoir by a sealing fracture zone, but was also interpreted by the authors as being a more positive indictor than previous tests. The licence was allowed to lapse due to issues with reaching an agreement for further seismic acquisition work (Premier Oil, 2008).

Spore colour analysis, vitrinite reflectance data and T_{max} data analysis indicated that shales, bituminous shales and coals in the Scremerston and Yoredale are organically rich, offering moderate to excellent source potential with gas prone, vitrinite-dominated type III kerogen assemblages (Kaye, 1996). TOC of shales/bituminous shales within the Scremerston and Yoredale formations was good with some excellent peaks (Kaye, 1996).

Coals from the Yoredale Formation, Whitby Sandstone Member and Scremerston Formation have high TOC. Residual organic content is quite high but Kaye (1996) indicated that the TOC and potential high yield of this source indicated excellent source potential for the Yoredale and Scremerston formations. Shales/bituminous shales of the Yoredale and Scremerston formations have poor to excellent source rock potential. Argillaceous sediments in the Yoredale and Scremerston formations contain type III, gas prone kerogen assemblages, dominated by vitrinite with inertinite and exinite (Kaye, 1996).

The secondary target of Well 42/10b-02 was the Zechstein reef. The well encountered only minor gas shows in the Zechstein strata within limestones, siltstones and poor quality thin sands (Foden, 1996).

<u>Geohistory and maturity modelling</u>

Thermal modelling carried out by Kaye (1996) showed two different maturity gradients due to the different thermal properties of these lithologies; a younger shale dominated Carboniferous succession and an older Carboniferous sandstone/siltstone dominated sequence. Headspace gas analyses of sidetrack samples for the Carboniferous and Devonian strata were consistent with mature and late mature source rocks (Kaye, 1996). The Yoredale and Scremerston formations are immature for gas generation. Deeper in the well, in the lower part of the Fell Sandstone Formation to Upper Old Red Sandstone Supergroup, the succession is mature for gas (Kaye, 1996).

Gibson et al. (1996) assessed the VR (Ro max equivalent as converted from the Ro random values provided by Kaye, 1996 and three Ro max values measured by Keiraville Konsultants) and AFTA data for Well 42/10b-02 and modelled three potential scenarios with different timing of the maximum palaeotemperatures: High heat flow only during late Cretaceous – recent times; high heat flow during Triassic – early Cretaceous and late Cretaceous – recent times; high heat flow Visean – late Permian and late Cretaceous - recent times. Gibson et al. (1996) noted that any of these models would fit the data but that these models did not consider the geological history of the region. The authors assumed that the palaeo-surface temperature was 5°C and heating rates of 5°C/Ma were applied. Based on the geological history of the area of interest, the last scenario (scenario ‘C’) with high heat flow during the Visean – late Permian and late Cretaceous – recent seems most likely as this would tie in with some of the major regional tectonic events, however, given the complex history of this area and the number of erosional unconformities penetrated by the well, it seems likely that the thermal history may be even more complex.

Gibson et al. (1996) estimated removed thickness of strata by assuming that the palaeo-geothermal gradient was linear (valid unless palaeo-thermal effects were due to fluid flow) using VR (Ro max converted from Ro random values used only) and AFTA data. For scenario ‘C’ around 2.9 km of additional strata on top of the existing Yoredale Formation and between 1.0 – 1.4 km of strata above the top Chalk unconformity were included in the model.

Nearby Well 42/10-01 was modelled by Collinson and IGI (1995) with a present day heat flow of 63 MWm^{-2} and a Horner-plot corrected BHT of 128.3 °C.

7.5.2 New modelling work

Maturity data

Thirty-one VR data are available from the Gibson et al. (1996) report (28 Romax equivalent as converted from the Ro random values provided by Kaye, 1996 plus three Ro max values measured by Keiraville Konsultants). An additional 110 T_{max} values were available from Kaye, (1996). Three additional T_{max} data were available from Vane et al. (this study). Corrected BHT were available from the Geotrack report. Pyrolysis data (S1, S2, TOC and three new Rock-Eval data from Vane et al. (this study) for S1, S2, S3, TOC) were included for the generation phase of modelling.

Model input data are shown in Table 9.

Model calibration

The VR and VRcalc data suggest a similar maturity for the Yoredale Formation but the VRcalc generally suggest a greater maturity for the older Carboniferous strata. There is a great deal of scatter for VRcalc for the oldest Carboniferous and Devonian strata. The VR data from Kaye (1996) have a good number of samples (>17 samples for most datapoints and majority with >50 samples). Kaye (1996) observed that the low source rock potential and low sample yields of the Cementstone Group resulted in inaccurately low T_{max} values and that only four T_{max} values are reliable, these reliable samples suggest the inference that strata reached the main gas maturity window is correct (the current BasinMod model also suggests the Cementstone Formation reaches the late gas maturity window). In addition, Kaye (1996) observed that VR reflectance histograms from the lower part of the Fell Sandstone Formation to within Tayport Formation show a broad scatter due to limited vitrinite recovery and the presence of reworked and caved material. The two VRcalc values at the top of the Yoredale Formation are anomalously low in comparison with the trend of the rest of the data, it is assumed this is due to oxidation during weathering.

Nearby Well 43/6-1 suggests than a good thickness of around 650 m of Palaeogene – Neogene so it was assumed (Tertiary) strata were originally present in this region. Analysis of the density log data (Kimbell and Williamson, this study) did not generate any eroded strata thickness values for the lithology types in the well for comparison of the thermal model. No porosity data were available for calibration of the current BasinMod model. Thus, the burial models for other wells in this region were used to inform the modelled geohistory for this well. The model is quite insensitive to eroded thickness of Carboniferous and Triassic material due to the short timescales involved. The model is relatively sensitive to thickness of Palaeogene strata and the thickness of eroded sediment included in the current model is similar to the preserved thickness of strata in Well 43/06-01. The current burial model adopts a similar approach to scenario ‘C’ from the Geotrack report (Gibson et al.,1996), i.e. a relatively complex thermal and burial history with high heat flow during Visean – late Permian and late Cretaceous - recent times, to coincide with major tectonic episodes affecting this region.

The maturity geohistory is given in Figure 47, the model heat flow is given in Figure 48.

Table 9: Summary of model input data for Well 42/10b-02 and layer maturity window from the BasinMod model

Formation/ age of strata	**N.o. of VR/ VRcalc datapoints**	**Model maturity window**	**Average measured TOC from logs**	**Kerogen**	**Oil/gas show**	**N.o. of porosity data**	**Comments**
Zechstein		Mid mature for oil			Gas shows		
Yoredale (upper)	6 VR, 12 VRcalc	Mid – late mature for oil	3.4^	Gas prone	Gas shows and some minor oil staining noted		
Whitby Member	2 VRcalc	Late mature for oil					
Yoredale (lower)	1 VR, 2 VRcalc	Late mature for oil					
Scremerston	9 VR, 31 VRcalc	Late mature for oil – main gas generation	16.91*	Gas prone			
Fell	9 VR, 22 VRcalc	Main gas generation	2.13*	Gas prone	Interpreted to show residual hydrocarbons and pyrobitumen		
Cementstone	6 VR, 28 VRcalc	Main gas generation	1.37*	Mainly inert			
Tayport	3 VRcalc	Main gas generation	0.06*	Mainly inert			

^ These data are taken from Gent (this study) for Well 42/10a-01
* These data are based on samples from legacy reports as no calculated wireline log data were available from this study

According to the current BasinMod model, the Yoredale Formation strata reached the late mature oil maturity window (VR<1.07). The Scremerston Formation reached late oil maturity with the deepest part of the formation reaching the main gas maturity window (VR<1.55). The Fell Sandstone and Cementstone formations reached the main gas maturity window and the Tayport Formation reached main gas generation maturity – overmature. It should be noted that the VRcalc values are higher than the measured VR values which were used for the current BasinMod model, suggesting that the Scremerston and Fell Sandstone formations reached well into the main gas maturity window and the Cementstone Group is overmature (VRcalc <1.97 for Scremerston Formation; VRcalc <1.92 for Fell Sandstone Formation; VRcalc <2.75 for Cementstone Group).

<u>Maturity and hydrocarbon generation</u>

Average measured TOC values for the Scremerston, Fell, Cementstone formations and Devonian strata from legacy well reports were entered into BasinMod (Kaye, 1996). These values were utilised by BasinMod to calculate an initial TOC value for these strata. The average value for the Yoredale TOC was taken from Well 42/10a-01 where logs were available to calculate an average value (Gent, this study).

Samples from the Yoredale Formation were identified as gas prone thus these were entered into BasinMod as type III in order to model gas generation. The majority of samples from the Scremerston and Fell Sandstone formations were determined to be mainly gas prone (Vane et al., this study), so these were entered as type III kerogen for the generation modelling. The Yoredale, Scremerston and Fell Sandstone strata were judged to have poor – excellent potential by Vane et al. (this study). This current analysis takes a slightly more optimistic view than Cooper et al. (1978) based on the large number of samples judged to be gas prone by Vane et al (this study) and the more optimistic view of Kaye (1996) that the Yoredale and Scremerston formations had samples of poor to excellent potential plus the Agincourt gas discovery described by Premier Oil (2008) indicates gas is present in this region. The current model suggests that the Yoredale did not reach the main gas maturity window and that only the very oldest part of the Scremerston Formation reached the main gas maturity window. The majority of samples from the Cementstone Formation were determined to be type IV kerogen (i.e. no generation potential) by Vane et al. (this study) (which agrees with the analysis of Kaye (1996) that suggests the Cementstone Formation has negligible source potential). Gas shows are recorded in the Zechstein Group and Yoredale Formation according to the well history (Maersk Jutlander, 1996) and the Premier Oil (2008) licence relinquishment report.

According to the BasinMod model, hydrocarbon generation mainly occurred during deep Cenozoic burial when the evaporite-rich Zechstein and younger argillaceous strata could have offered a potential seal.

The model generation potential for strata in the well is given in Figure 50. Timing for generation from the most promising horizons is given in Figure 51 and Figure 52. The data entry sheet is shown in Figure 53.

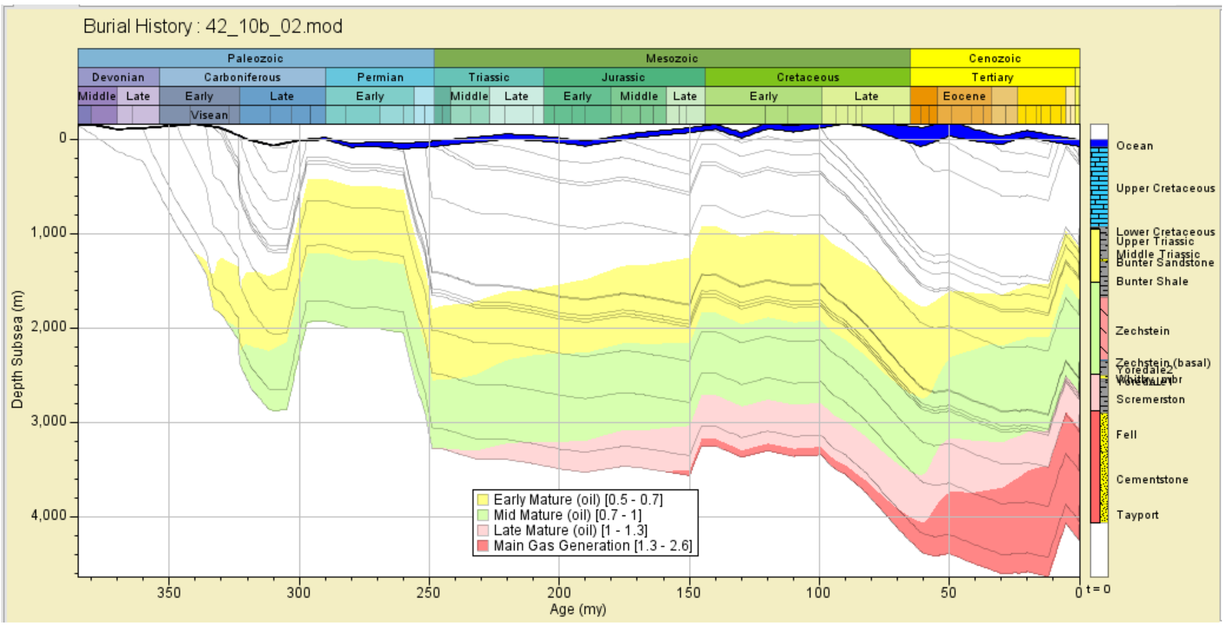


Figure 47: Modelled maturity geohistory for Well 42/10b-02. The well terminates in the Tayport Formation

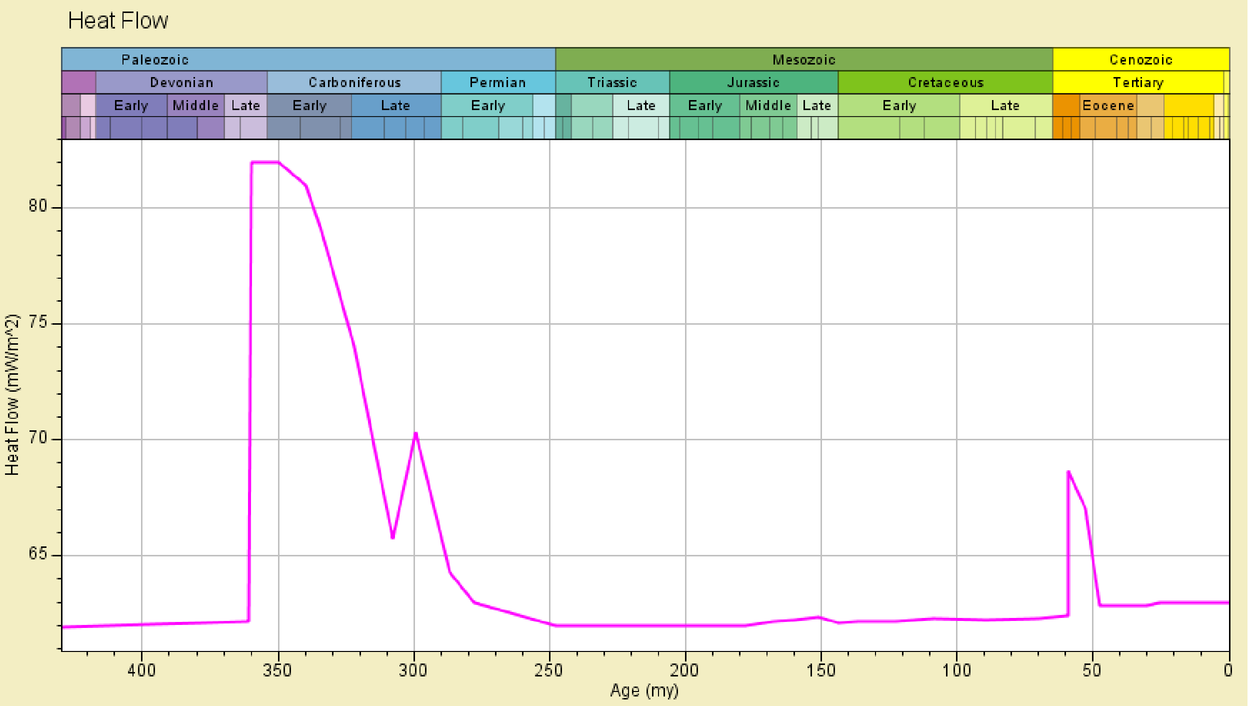


Figure 48: Modelled palaeo-heat flow for Well 42/10b-02

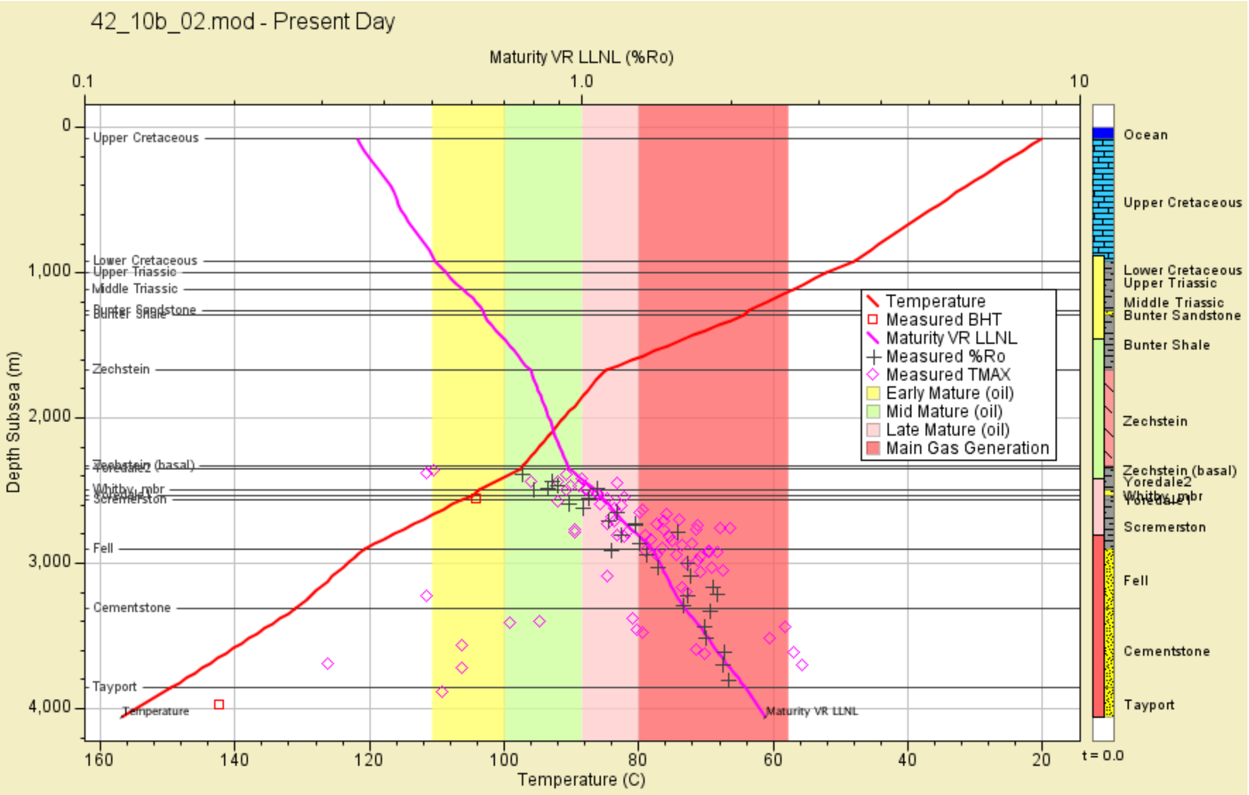


Figure 49: Depth plot for Well 42/10b-02 showing model results, maturity data and maturity windows plus temperature data and model

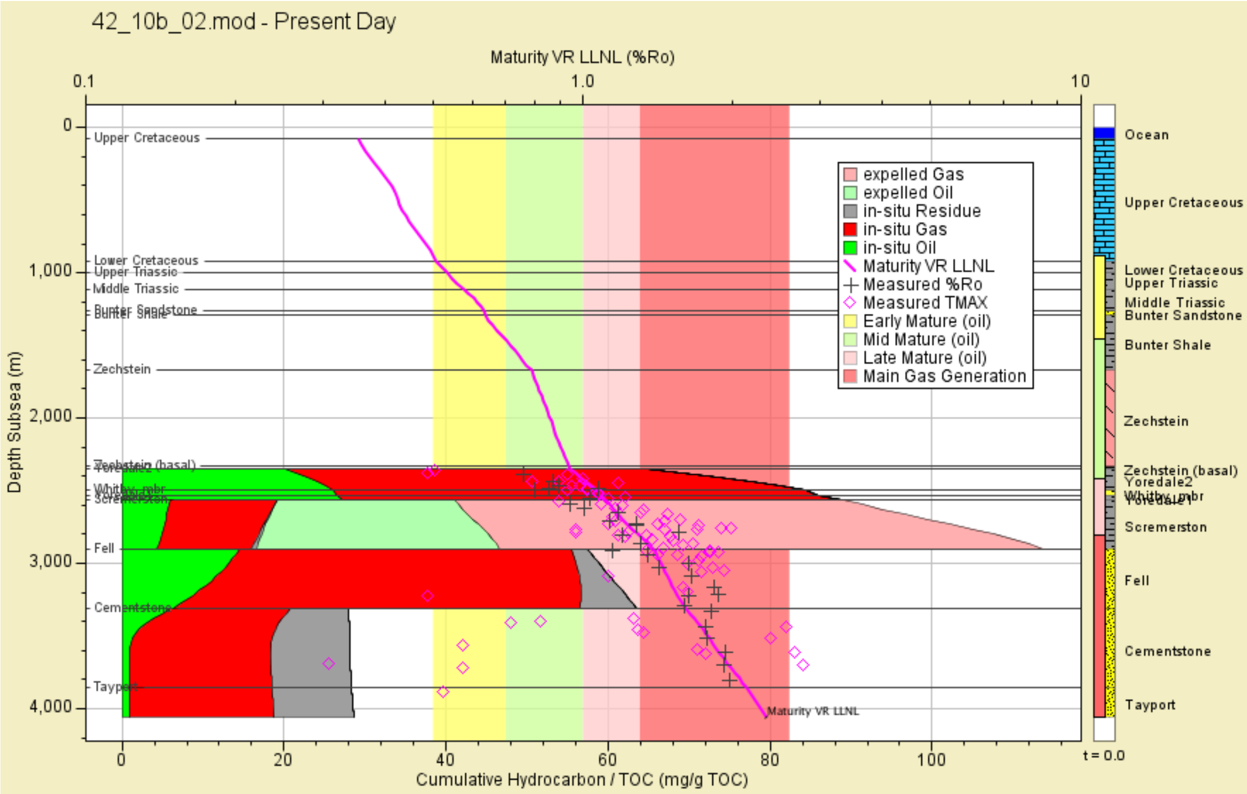


Figure 50: Depth plot for Well 42/10b-02 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

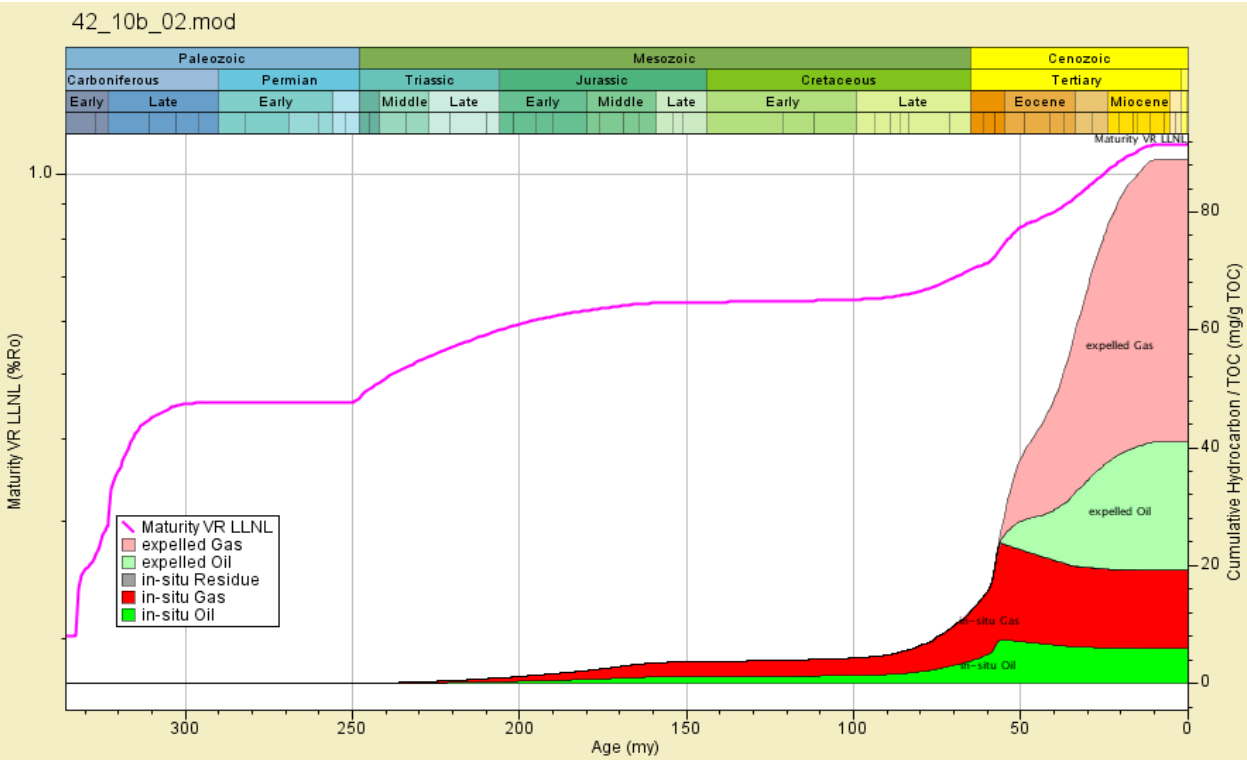


Figure 51: Time plot for Well 42/10b-02 showing timing of generation for Scremerston Formation. The current model suggests that main generation and expulsion occurred during deepest burial during the Cenozoic Era

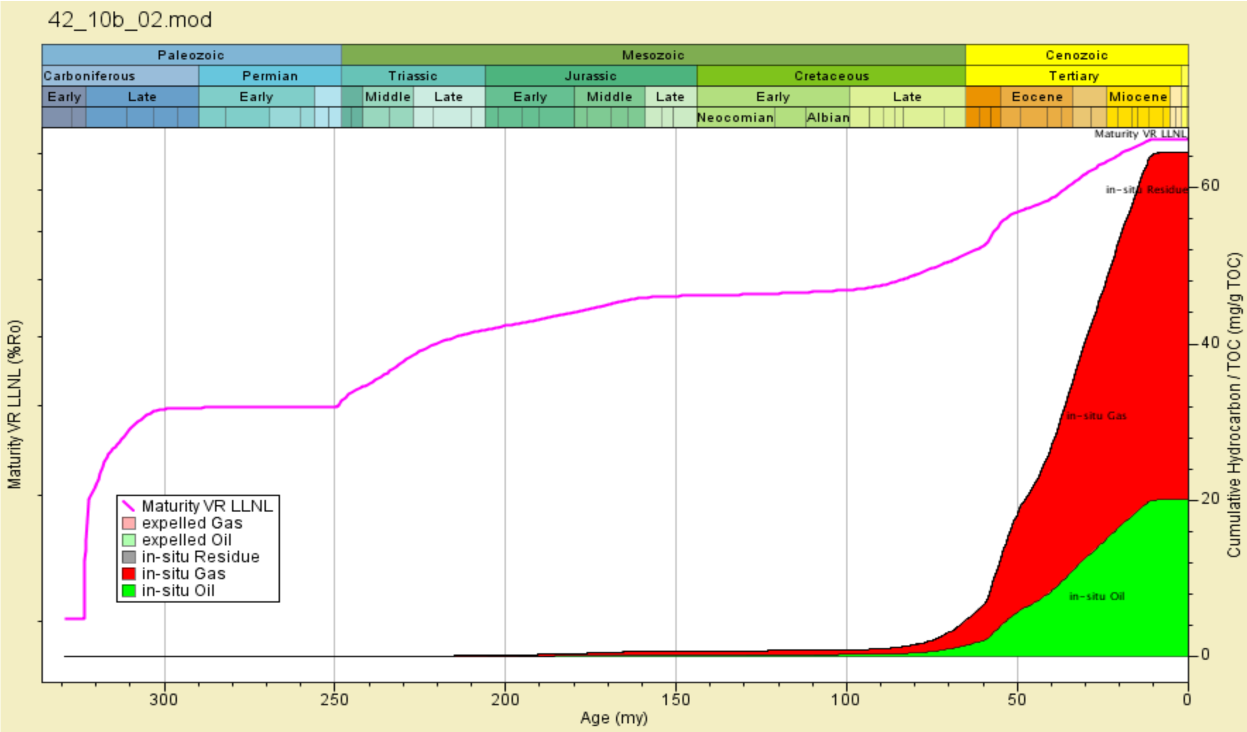


Figure 52: Time plot for Well 42/10b-02 showing timing of generation for upper Yoredale Formation (model layer 'Yoredale 2'). The current model suggests that main generation and occurred during deepest burial during the Cenozoic Era

7.5.3 Key points from new modelling work for Well 42/10b-02

- The Scremerston and Yoredale formations have moderate generation potential in the current BasinMod model
- The bulk of the Scremerston Formation reached the late mature for oil maturity window but contains gas prone kerogens. The lowest part of the Scremerston Formation reached the gas maturity window
- The main generation phase was during the Cenozoic Era
- Deepest burial was during the Cenozoic Era

42_10b_02.mod | 42_10b_02.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	... ... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10					
2	Pleistocene (d)	Deposit	0.126			10	Sandstone				
3	Pliocene (e)	Erosion	2.588			-100					
4	Pliocene (d)	Deposit	2.6			100	PLiocene_Q41				
5	Late Miocen...	Erosion	5.322			-710					
6	Early Miocen...	Deposit	12			30	Miocene_Q41				
7	Oligocene (d)	Deposit	23.03			100	Paleogene_Q41				
8	Eocene (d)	Deposit	33.9			500	Paleogene_Q41				
9	Paleocene (d)	Deposit	55.8			80	Paleogene_Q41				
10	Upper Creta...	Formation	65.5	*96.01*	*848.57*		Chalk_All_Lst				
11	Lower Creta...	Formation	99.6	*944.58*	*77.11*		Lower Cretaceous_w6				
12	Cimmerian (e)	Erosion	145.5			-200					
13	Jurassic (d)	Deposit	167			100	Jurassic M & U_w8				
14	Jurassic (Lia...	Deposit	175.6			100	Shale				
15	Upper Triassic	Formation	199.6	*1,021.69*	*113.08*		Upper Trias (Hais)_w7				
16	Middle Triassic	Formation	232	*1,134.77*	*153.92*		Middle Trias (Hais)_w7				
17	Bunter Sand...	Formation	245	*1,288.69*	*26.52*		Bunter Sst_w7				
18	Bunter Shale	Formation	249	*1,315.21*	*376.73*		Bunter Shl_w7				
19	Zechstein	Formation	251.5	*1,691.94*	*665.08*		Zechstein_w7				
20	Rotliegend (h)	Hiatus	258								
21	Zechstein (b...	Formation	260	*2,357.02*	*10.67*		Zech 1_w7				
22	Variscan (e)	Erosion	270			-900					
23	Stephanian (h)	Deposit	305			50	Siltstone				
24	Coal Measur...	Deposit	312			250	Yoredale_w7				
25	Millstone (d)	Deposit	318			300	Mill grit_w5				
26	Yoredale (d)	Deposit	323			300	Yoredale_w7				
27	Yoredale2	Formation	323.5	*2,367.69*	*152.4*		Yore_top_w7	Type III (BM...	3.4	3.8	0.2
28	Whitby_mbr	Formation	329	**2,520.09**	*34.13*		whitby_w7	Type III (BM...	3.4	3.8	0.2
29	Yoredale1	Formation	330	**2,554.22**	*28.04*		Yore_lower_w7	Type III (BM...	3.4	3.8	0.2
30	Scremerston	Formation	333	*2,582.26*	*338.64*		Scremerston_w7	Type III (BM...	16.91	19.4	0.2
31	Fell	Formation	336	*2,920.9*	*417.57*		Fell_w7	Kerogen Mix 4	2.13	2.3	0.2
32	Cementstone	Formation	347	*3,338.47*	*539.25*		Cementstone_w7	Kerogen Mix 3	1.37	1.4	0.2
33	Tayport	Formation	360	*3,877.72*	*202.08*		UORS_w7	Kerogen Mix 3	0.06	0.1	0.2

Model Begin Age: 385.3 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Figure 53: Model data entry sheet for Well 42/10b-02. Top Depth is in m BRT

7.6 WELL 43/17-02

Well 43/17-02 lies within an antiform created by faulting of Permian and older strata. Salt withdrawal above this structure has deformed the Zechstein and younger sediments.

7.6.1 Previous maturity and modelling work for this well

The shales in the lower part of the Cleveland E Formation are expected to be exhausted in terms of source potential. Minor gas shows were observed in the Millstone Grit Group, these are believed to charged by local migration and sourced from thin but very good to rich gas-prone coaly shales and mudstones/claystones/shales in the same interval. Gas shows are reported towards the base of the Rotliegend Group (The Geochem Group, 1988; Exploration Logging North Sea, 1988).

Hydrocarbon shows

Light hydrocarbon shows were reported in sandstone-dominated and claystone–dominated sequences within Cleveland Group (basinal equivalent to the Yoredale Group). Dry gas generated from highly mature source rocks is observed in the Cleveland Group (The Geochem Group, 1988).

The targets for Well 43/17-02 were late Westphalian plus top and lower Namurian sandstones. Dry gas (ranging from trace to significant volumes) was identified throughout the assessed Carboniferous section (The Geochem Group, 1988).

<u>Palaeozoic source rocks and reservoirs</u>

The shales below 4041 m BRT (lower part of the Cleveland E Formation) have limited potential and are expected to have been exhausted (The Geochem Group, 1988).

DST testing indicated gas flow in the Millstone Grit Formation but issues were reported, including unsuccessful sealing and lower than expected reported reservoir pressures (Exploration Logging North Sea, 1988). Light hydrocarbon shows were reported in sandstone-dominated and claystone–dominated sequences within the Millstone Grit Formation (Exploration Logging North Sea 1988; top Millstone Grit Formation reassessed this study at 3118.41 m BRT). Gas flow peaks in the Millstone Grit Formation were believed to be a result of local hydrocarbon migration from mature coals in the underlying sandy sequence. Traces of dry gas, believed to be a result of generation from thin coals and claystones are observed within the Millstone Grit Formation (The Geochem Group, 1988).

Thin but very good to rich gas-prone coaly shales and mudstones (around 3139.4 – 3596.6 m BRT) were identified by The Geochem Group (1988) within Namurian strata (Millstone Grit Formation). Here TOC readings were almost all good to rich. The coaly shales/mudstones are very good to rich source rocks for gas condensate and are mature. Peaks in gas flow are observed adjacent to the coals. Kerogen type was mainly wood or inertinite. It is noted that multiple reflection populations are observed around 3169.9 m BRT (in the Millstone Grit Formation) due to readings being made on exinite (The Geochem Group, 1988).

Core from the Millstone Grit Formation indicates porosities of 0.9 – 17.8 % with bands of higher and lower porosity (Baldwin, 1988).

Light hydrocarbon shows were reported in sandstones towards the base of the Rotliegend Group (labelled as Carboniferous age in the original well report, (Exploration Logging North Sea, 1988), but re-evaluated in this study).

Nil to trace hydrocarbons were recorded in Permian strata (2418.3 – 3106.5 m BRT; Zechstein Group and Rotliegend Group) with the exception of the Hauptdolomite where an average of 450 ppm was recorded (Parkin, 1989).

<u>Post-Palaeozoic source rocks and reservoirs</u>

Trace hydrocarbon readings were recorded in Triassic strata (1155.2 – 2418.3 m BRT). Trace hydrocarbon readings were recorded in the Lias Group (577.0 – 1155.2 m BRT) (Parkin, 1989).

<u>Geohistory and maturity modelling</u>

Vitrinite reflectance and spore colour maturation assessment were conducted by The Geochem Group (1988). Strata is expected to encounter the gas window around 3048 m BRT (in Lower Permian strata) down to around 4041 m BRT (in the Bowland Shale Formation) (The Geochem Group, 1988).

The sidetrack Well 43/17b-02 was modelled by Collinson and IGI (1995) with a present day heat flow of 55 MWm^{-2} and a Horner-plot corrected BHT of 226.7 °C.

7.6.2 New modelling work

Maturity and porosity data

Twenty measured VR datapoints and 89 VRcalc were available from the Geochem Group report (1988). An additional 11 VR calc were available from Vane et al. (this study). Porosity and permeability data were available from the geological completion report (Parkin, 1989). Pyrolysis data (S1, S2, TOC from Parkin (1989) and eleven new data from Vane et al. (this study) for S1, S2, S3, TOC) were included for the generation phase of modelling. Porosity data from Baldwin (1988) (also included in the final well completion report; Parkin, 1989) were included in the model. Model input data are shown in Table 10.

Table 10: Summary of model input data for Well 43/17-02 and layer maturity window from the BasinMod model

Formation/ age of strata	N.o. of VR/ VRcalc datapoints	Model maturity window	Average measured TOC from logs	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Triassic					Trace		
Lias		Immature			Trace		
Zechstein Group		Mid mature for oil			Nil to trace		
Rotliegend		Mid mature for oil			Nil to trace		
Millstone	2 VR, 25 VRcalc	Late mature for oil	2.0	Type IV kerogen with some type II and III	Peaks in gas flow are observed adjacent to the coals	322 data	
Cleveland E	8 VR, 47 VRcalc	Main gas generation	1.5	Mix of type III and type IV kerogen	Dry gas, ranging from trace to gas flow peaks		
U Bowland Shale	2 VRcalc	Main gas generation	1.4	Mix of type III and type IV kerogen			
Cleveland D	20 VRcalc	Main gas generation - overmature	1.3	Mix of type III and type IV kerogen			

Model calibration

The VR and VRcalc data suggest a similar maturity but overall, VRcalc data suggest a higher maturity than VR data. The VR data have a reasonable number of samples and a reasonably linear trend but given that gas shows are present in the lower parts of the Millstone Grit and that these are believed to have been generated locally, the model was matched to the VRcalc data. For the Yoredale Formation, VRcalc are data quite scattered, but there is a good cluster of points with a reasonably linear trend. The model is quite insensitive to eroded thickness of Carboniferous and Triassic material due to the short timescales involved. The model is relatively sensitive to thickness of Palaeogene strata. Even if the model is tested with no additional strata, the model will not honour the scattered low VRcalc datapoints (VRcalc<0.5) suggesting they are erroneous.

The maturity geohistory is given in Figure 54, the model heat flow is given in Figure 55. Model results are given in Figure 56. Comparison of the porosity data and porosity model is shown in Figure 60.

Nearby Wells 41/20-01, 42/10b-01 and 41/14-01 include greater thicknesses of removed thicknesses of strata of Palaeocene – Miocene age, however the current model for this well was quite insensitive to changes of eroded Cenozoic strata (around 30 m of removed thickness fitted the model to the VR data and up to 0.9 km of strata could be included with a reasonable fit to the VRcalc data) so a median value was selected.

Compaction modelling conducted by Kimbell and Williamson (this study) suggested that less than 2 km of additional strata was deposited before Variscan erosion. The current BasinMod model agrees with this, having only 1.4 km of additional Carboniferous strata deposited. However it should be noted that the BasinMod model is not very sensitive to thickness of eroded Carboniferous strata. A good match to the porosity data from the Millstone Grit was achieved which also supports the final BasinMod model.

Maturity and hydrocarbon generation

Though TOC values are uniformly good (> 2%), much of the organic matter has poor potential with the exception of gas prone samples obtained from the Millstone Grit (Vane et al., this study). This is possibly because the mature source rock has generated hydrocarbons and is depleted, or could be due to low quantities of pyrolisable kerogen/high inertinite content.

The organic matter mainly comprises type IV kerogen with some type II and III based on legacy and new data. Average TOC values for the Cleveland Group and Millstone Grit Formation calculated by the project team from wireline log data were included (Gent, this study). These average TOC values were used by BasinMod to calculate the initial TOC. The samples from the Millstone Grit Formation and Cleveland Group comprised a mix of type III and type IV kerogen.

The mudstone-dominated Cleveland D Formation generated gas and a small amount of expulsion is suggested by the BasinMod model. The Cleveland Group reached the main gas maturity window.

The model suggests the Millstone Grit Formation reached the late oil maturity window and the oldest part of the Millstone Grit succession reached the early gas maturity window. The model was adjusted to take into account gas shows recorded in the well and the comments made in the geochemistry report. Gas is modelled to have been generated during Jurassic and later times from organic matter in the Millstone Grit. The evaporite-rich Zechstein Group and argillaceous Triassic and Jurassic strata could have offered a potential seal to migrating hydrocarbons at that time.

The model generation potential for strata in the well is given in Figure 57. Timing for generation from the most promising horizons is given in Figure 58 and Figure 59. The data entry sheet is shown in Figure 61.

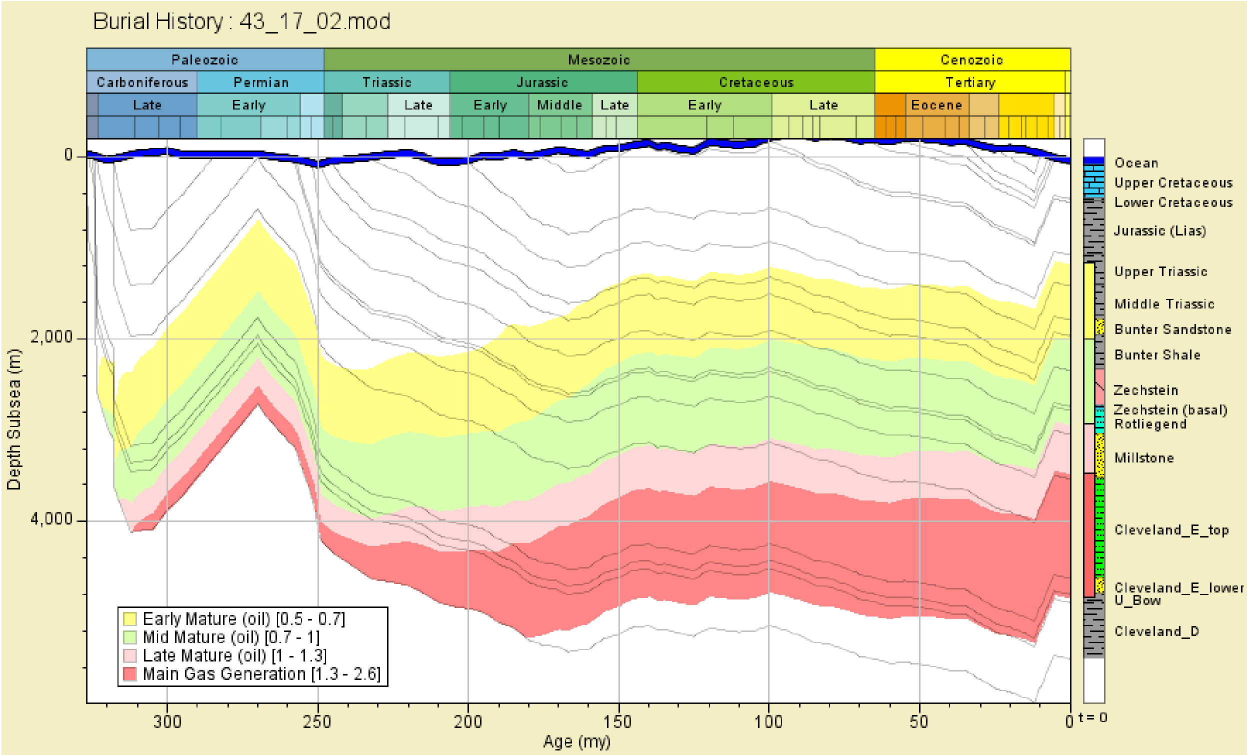


Figure 54: Modelled maturity geohistory for Well 43/17-02. The well terminates in the Cleveland Group.

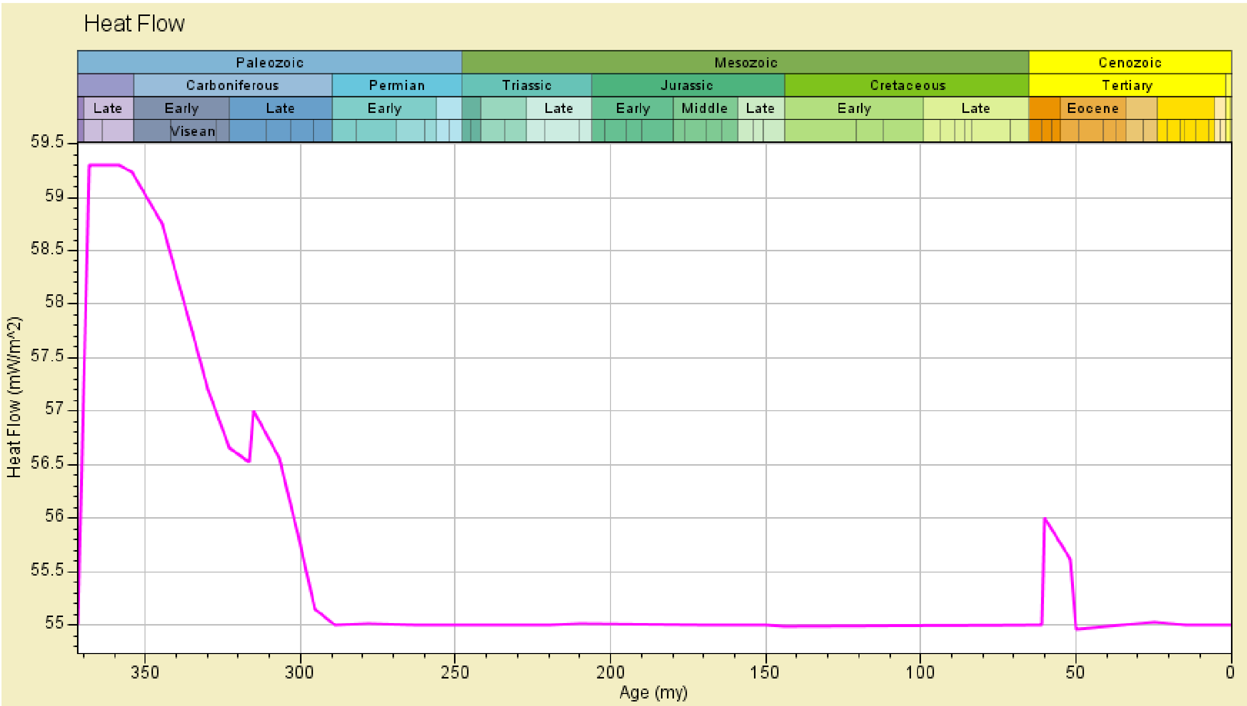


Figure 55: Modelled palaeo-heat flow for Well 43/17-02

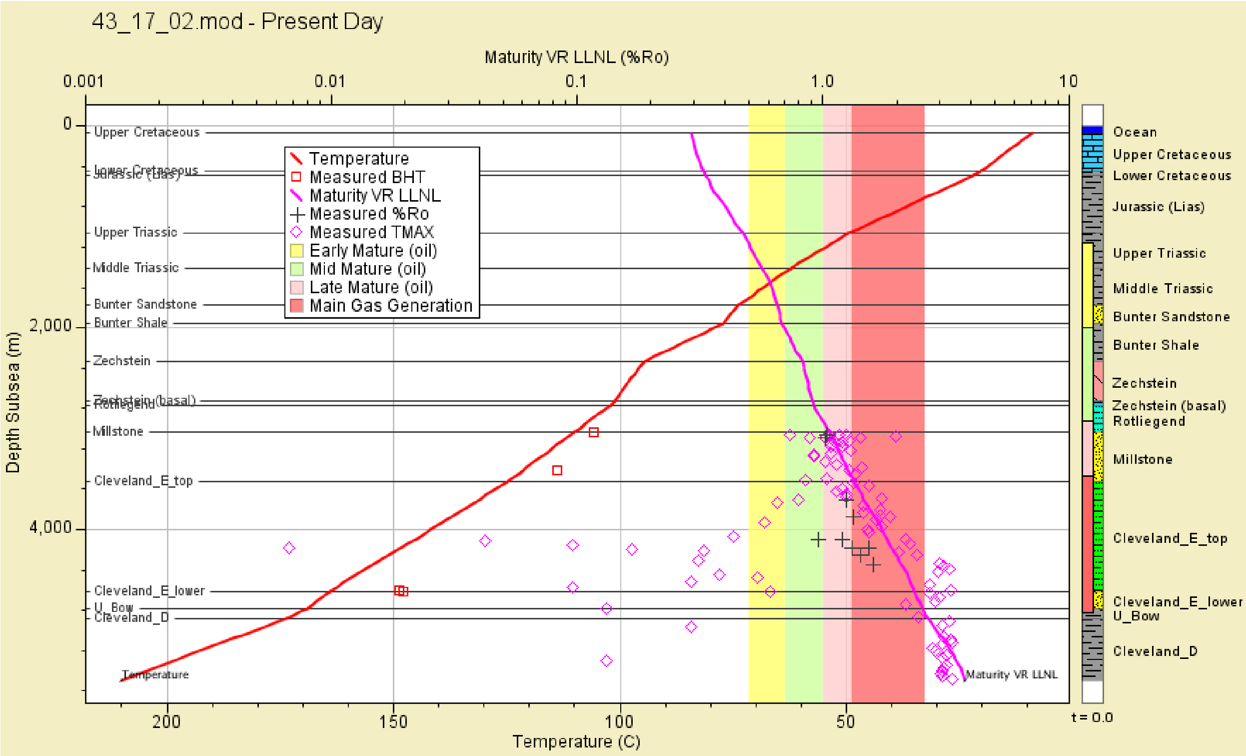


Figure 56: Depth plot for Well 43/17-02 showing model results, maturity data and maturity windows plus temperature data and model

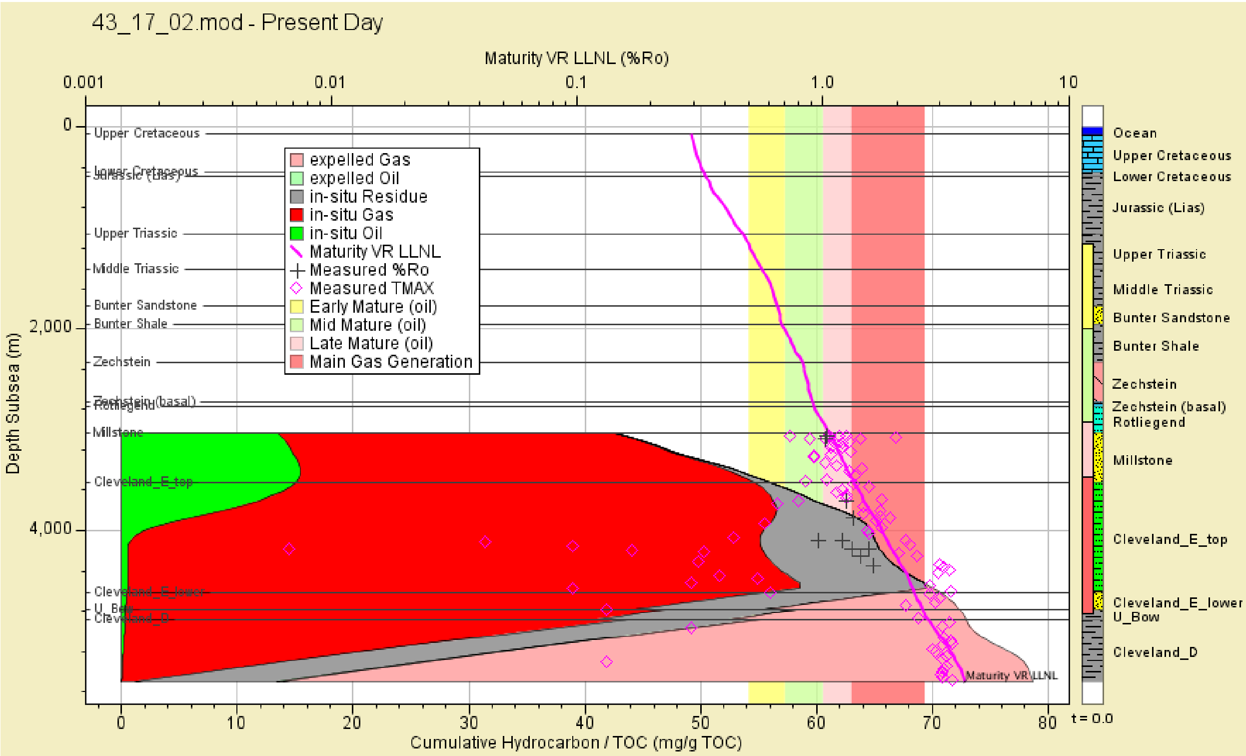


Figure 57: Depth plot for Well 43/17-02 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

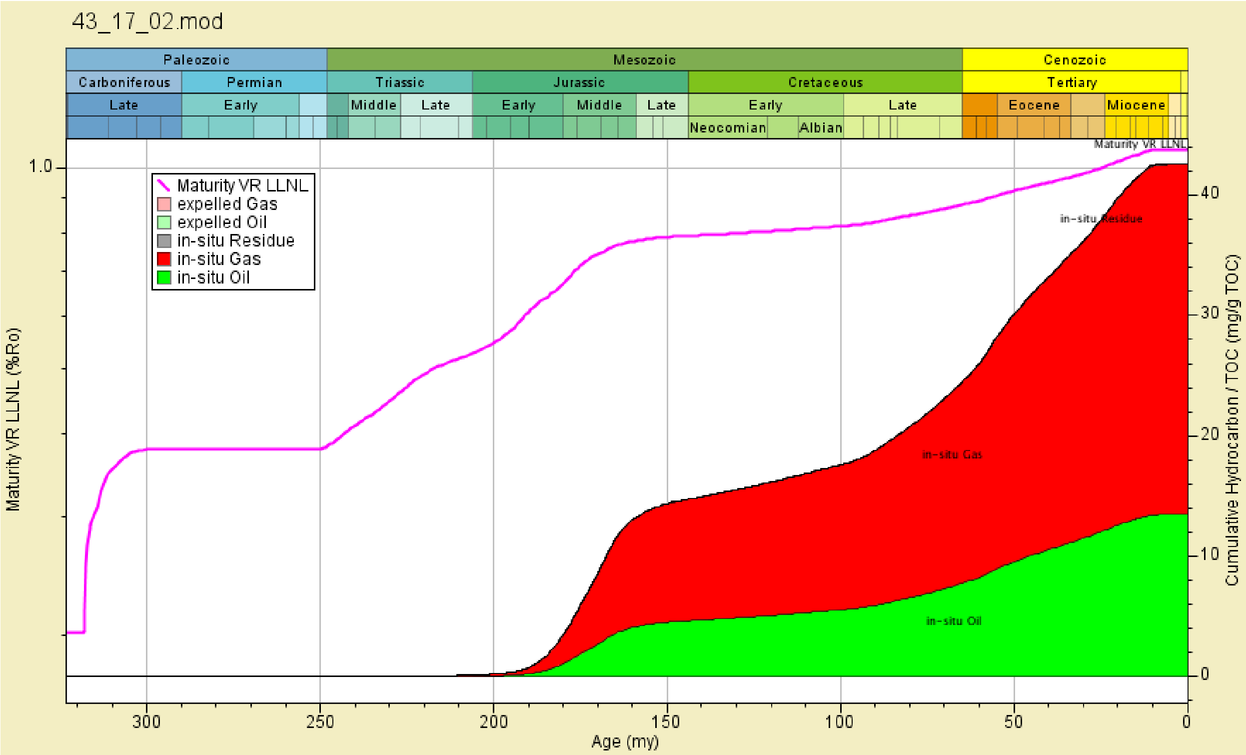


Figure 58: Time plot for Well 43/17-02 showing timing of generation for Millstone Grit Formation. The current model suggests that main generation occurred during deep burial during the Mesozoic and Cenozoic eras.

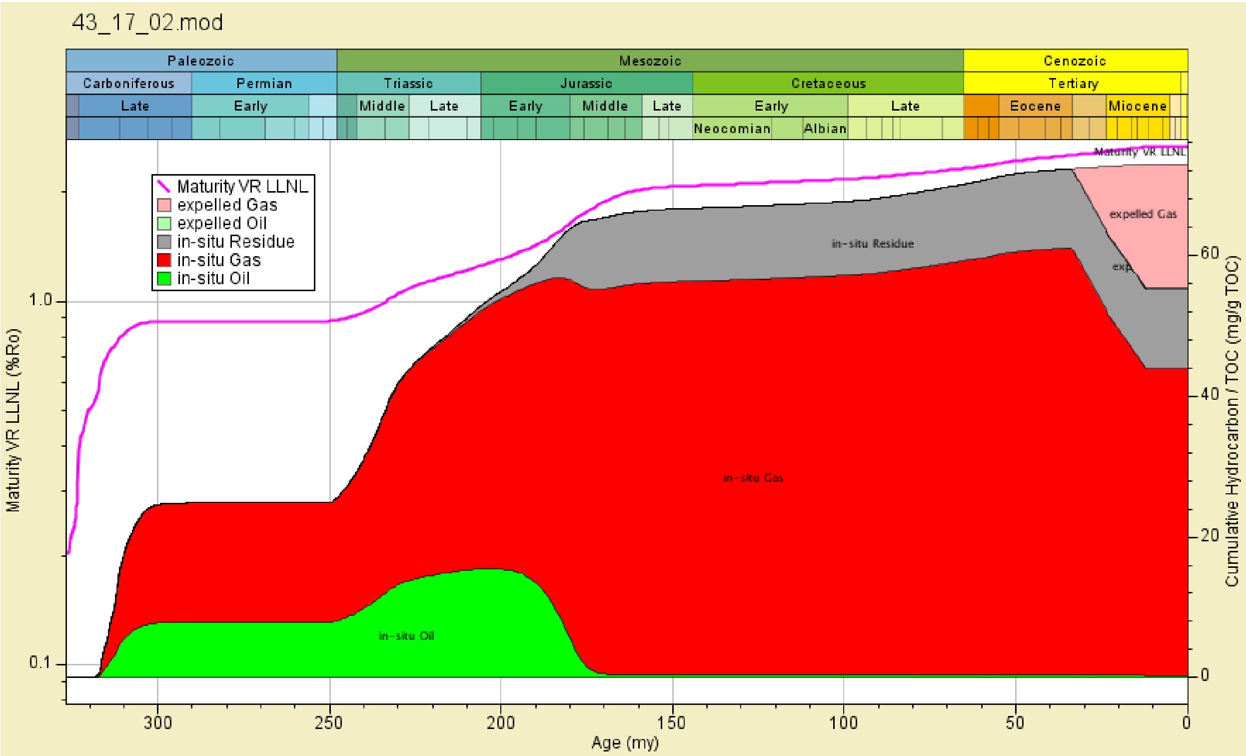


Figure 59: Time plot for Well 43/17-02 showing timing of generation for Cleveland D Formation (note that no expulsion is shown on this plot as this graph shows the model for the top of the Cleveland D layer). The current model suggests that generation started during the Carboniferous Period but that main generation occurred during deep burial during the Mesozoic Era.

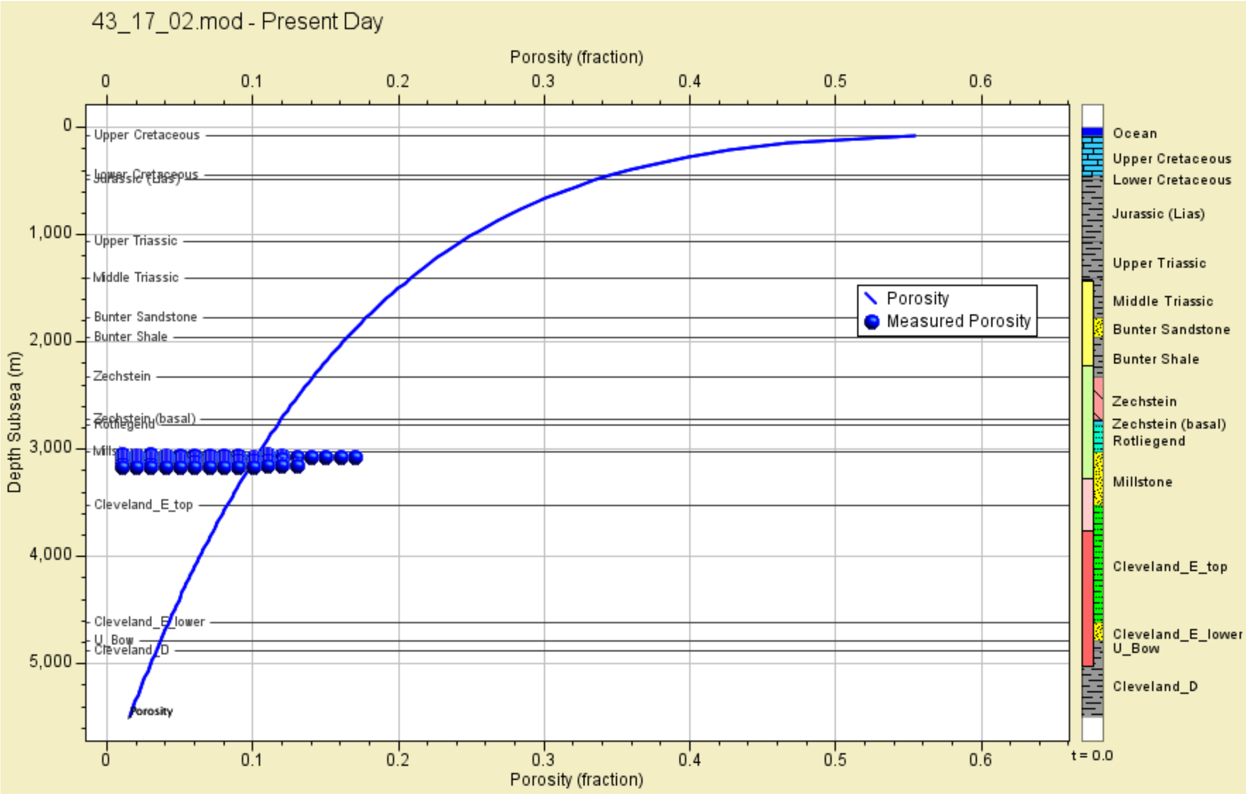
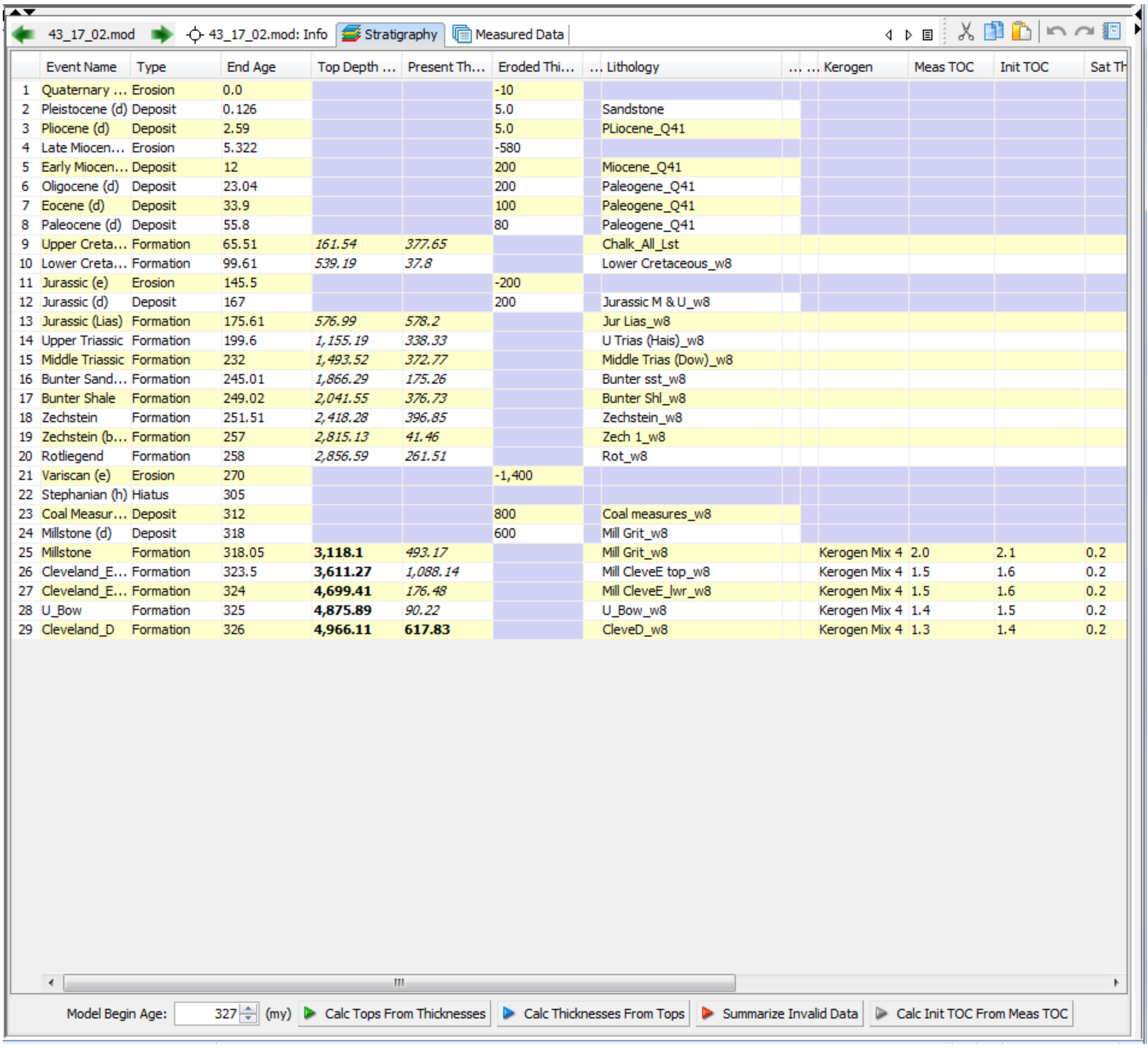


Figure 60: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 43/17-02

7.6.3 Key points from new modelling work for Well 43/17-02

- Due to the low TOC, only a small amount of expelled gas is suggested for the Cleveland Group. There are no other nearby wells available for this study that penetrate the Cleveland Group for comparison.
- In the current model, the Millstone Grit Formation has relatively poor generation potential and the Cleveland Group has moderate generation potential. However, gas shows are encountered in the well near coals so the model could be overly pessimistic
- The Scremerston Formation equivalent was not penetrated
- Main generation was from Jurassic times onwards
- Deepest burial was during the Cenozoic Era



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	... ... Kerogen	Meas TOC	Init TOC	Sat Th
1	Quaternary ...	Erosion	0.0			-10					
2	Pleistocene (d)	Deposit	0.126			5.0	Sandstone				
3	Pliocene (d)	Deposit	2.59			5.0	PLiocene_Q41				
4	Late Miocen...	Erosion	5.322			-580					
5	Early Miocen...	Deposit	12			200	Miocene_Q41				
6	Oligocene (d)	Deposit	23.04			200	Paleogene_Q41				
7	Eocene (d)	Deposit	33.9			100	Paleogene_Q41				
8	Paleocene (d)	Deposit	55.8			80	Paleogene_Q41				
9	Upper Creta...	Formation	65.51	161.54	377.65		Chalk_All_Lst				
10	Lower Creta...	Formation	99.61	539.19	37.8		Lower Cretaceous_w8				
11	Jurassic (e)	Erosion	145.5			-200					
12	Jurassic (d)	Deposit	167			200	Jurassic M & U_w8				
13	Jurassic (Lias)	Formation	175.61	576.99	578.2		Jur Lias_w8				
14	Upper Triassic	Formation	199.6	1,155.19	338.33		U Trias (Hais)_w8				
15	Middle Triassic	Formation	232	1,493.52	372.77		Middle Trias (Dow)_w8				
16	Bunter Sand...	Formation	245.01	1,866.29	175.26		Bunter sst_w8				
17	Bunter Shale	Formation	249.02	2,041.55	376.73		Bunter Shl_w8				
18	Zechstein	Formation	251.51	2,418.28	396.85		Zechstein_w8				
19	Zechstein (b...	Formation	257	2,815.13	41.46		Zech 1_w8				
20	Rotliegend	Formation	258	2,856.59	261.51		Rot_w8				
21	Variscan (e)	Erosion	270			-1,400					
22	Stephanian (h)	Hiatus	305								
23	Coal Measur...	Deposit	312			800	Coal measures_w8				
24	Millstone (d)	Deposit	318			600	Mill Grit_w8				
25	Millstone	Formation	318.05	**3,118.1**	493.17		Mill Grit_w8	Kerogen Mix 4	2.0	2.1	0.2
26	Cleveland_E...	Formation	323.5	**3,611.27**	1,088.14		Mill CleveE top_w8	Kerogen Mix 4	1.5	1.6	0.2
27	Cleveland_E...	Formation	324	**4,699.41**	176.48		Mill CleveE_lwr_w8	Kerogen Mix 4	1.5	1.6	0.2
28	U_Bow	Formation	325	**4,875.89**	90.22		U_Bow_w8	Kerogen Mix 4	1.4	1.5	0.2
29	Cleveland_D	Formation	326	**4,966.11**	**617.83**		CleveD_w8	Kerogen Mix 4	1.3	1.4	0.2

Figure 61: Model data entry sheet for Well 43/17-02. Top Depth is in m BRT

8 Detail of North Dogger and Quadrant 29 basin modelling

Two Wells (29/07-01 and 38/18-01) constrained by little/no data in the Carboniferous section were modelled as 'scenario' wells to predict if oil and gas generation were possible or likely in the North Dogger and Quadrant 29 basins. As few data are available, the degree of uncertainty attached to these models is high. Three possible geohistory scenarios were modelled to examine hydrocarbon generation potential. As Well 29/27-01 does not penetrate the base of the Rotliegend Group, the depth grids produced by the project team (Arsenikos et al., this study) were used to predict the expected depths for Palaeozoic strata below TD for this well.

8.1 GEOLOGY FOR BLOCK 29/27

Early Devonian continental deposition and Mid Devonian marine transgression

During Early Devonian times, continental sediments of the Lower Old Red Sandstone Supergroup were deposited in an alluvial/fluvial setting (Bluck et al., 1992). In adjacent areas, on the Auk ridge, in Well 30/16-05, Mid Devonian strata rests directly on what is believed to be lower Palaeozoic basement. During mid-Devonian times, a marine transgression from the Rheic Ocean to the south (Ziegler, 1982 as referenced in Gatliff et al., 1994) resulted in deposition of marine sediments. The top of the mid-Devonian Kyle Group limestones forms a strong reflector in the Auk and Argyll oilfields which lies to the east of Block 29/27, and are mapped seismically across central and southern Quadrant 29 (Arsenikos et al., this study).

Late Devonian – Early Carboniferous dextral transtension and extensional faulting

Latest Devonian-early Carboniferous extension/dextral transtension is a key part of the geological history of this region. Active extension is observed on seismic data from late Devonian times (Arsenikos et al., this study; Leslie et al., this study).

During late Devonian times, during regional extension, pre-existing lineaments were activated as normal faults (Collinson and IGI, 1995). Widespread deposition of the non-marine Upper Old Red Sandstone Supergroup occurred across most of the CNS during Upper Devonian times between highs defined by granites (Gatliff et al., 1994). In Well 29/25-01 on an adjacent block, Permian strata is underlain by 80 m of sandy Devonian strata.

During Early Carboniferous times, continued regional crustal extension caused regional subsidence (Collinson and IGI, 1995 and Cameron et al., 1992). Block 29/27 lay within the Quadrant 29 basin (Figure 1). During Earliest Dinantian times, a marine transgression from the south resulted in marine deposition in this region. This quickly gave way to a more deltaic environment with only occasional marine incursions during Arundian times and periodic marine inclusions that resulted in cyclical deposition during Brigantian times. (Gatliff et al., 1994 and Bluck et al., 1992).

During Namurian times, extensive cyclical Yoredale facies were deposited in a deltaic environment across this area, though during mid Namurian times, alluvial facies may have played a larger role (Bluck et al., 1992).

During early Westphalian times, deltaic conditions may have continued across this region, sourced from the north. During latest Westphalian to Stephanian times, alluvial conditions may have dominated (Bluck et al., 1992).

Variscan (Late Carboniferous – Permian) uplift and erosion

Hay et al., (2005) did not estimate the Variscan uplift of Block 29/27, but the north part of Quadrant 37 shows significant uplift of up to 3 km. Timing of uplift is expected to be late Stephanian (Hay et al., 2005).

Early Permian hiatus

Much of the Early Permian interval was a time of non-deposition in the area of interest due to Variscan uplift and late Carboniferous to Early Permian volcanic activity (which was centred around the MNSH and Danish sector) (Farris et al., 2012). Lower Permian strata in the CNS comprise volcanics (Glennie et al., 2003).

On the adjacent Auk-Flora ridge, a Permo-Carboniferous succession is recorded in the Flora field (Blocks 31/26a and 31/26c); Westphalian/Stephanian Flora Sandstone and Flora volcanic unit overlain by the Grensen Formation and Inge or Karl Volcanics Formation (Kearsey et al., this study).

Late Permian extension

The Late Permian Period is expected to have been a time of active extension (Farris et al., 2012). The southern limit of the Northern Permian Basin during the Late Permian times and deposition of the younger Rotliegend Group strata was controlled by earlier Permian volcanic activity. Thickness of strata in the Northern Permian Basin was fault controlled. The oldest units of the Rotliegend Group successively onlap on to the margins of the Northern Permian Basin showing pronounced lateral thickness variation (Farris et al., 2012).

Rotliegend Group strata are dominated by red sandstone deposited in an alluvial desert/fluvial/sabkha environment (Gatliff et al., 1994 and Farris et al., 2012). In the south of

Quadrant 29, Rotliegend Group strata mainly comprise the sandstone-dominated, Auk Formation which across the CNS shows a variety of non-marine environments of deposition. Well penetrations indicate that Auk Formation is thickest around the Clyde and Auk fields to the east of Block 29/27 where the Auk Formation is over 525 m thick (Gatliff et al., 1994). Igneous rocks associated with the Auk Fm are limited to thin intrusives in Block 29/14 (Farris et al., 2012).

<u>Zechstein Group deposition</u>

During Late Permian times, a marine transgression resulted in shallow marine conditions. Evaporites and carbonates were deposited. The Zechstein Group is up to 1830 m thick (Gatliff et al., 1994).

Within Quadrant 37 there was a thin basin connecting Quadrants 28 and 29 with the major basins to the south during deposition of the Zechstein Group (Hay et al., 2005).

Thermal basin relaxation occurred by the end of the Permian (Farris et al., 2012).

<u>Triassic continental deposition</u>

The onset of rifting in the Central Graben occurred during the Triassic Period (Hay et al., 2005).

During the Triassic Period, the south part of Quadrant 29 lay on the West Central Shelf (Goldsmith et al., 2003). Triassic strata of the Bunter Sandstone and Smith Bank formations are represented by continental red beds which are up to 500 m thick. On seismic data, salt withdrawal creates pods of Triassic sandstone resting directly on Permian carbonates, particularly in the Central Graben (Gatliff et al., 1994). The Triassic sequence is highly compressed on the MNSH (Hay et al., 2005).

<u>Early - Mid Jurassic uplift and erosion</u>

Lower Jurassic strata are expected to be thin or locally absent on the MNSH due to early-mid Jurassic domal uplift (mid Cimmerian/Intra-Aalenian Unconformity). During Jurassic times, this region lay on the ‘Auk shelf’. Jurassic strata are expected to be thin/locally absent (Coward et al., 2003; Gatliff et al., 1994).

Lower Jurassic strata are proved in the Central Graben in the northern part of Quadrant 30 by a few wells but are absent in the southern part of Quadrant 29 (Gatliff et al., 1994; Husmo et al., 2003).

Extensive volcanism, with at least three major centres (including the Puffin volcanic centre in Quadrant 29) occurred during Middle Jurassic times, and a mantle plume may also have contributed to the extruded material (Latin et al., 1990 as cited in Gatliff et al 1994).

Middle Jurassic strata are between 150 – 410 m thick in the north part of Quadrant 29, but to the south of the Puffin volcanic centre (including Block 29/27), Middle Jurassic strata are not recorded. If deposited, Middle Jurassic strata would most likely have comprised non-marine sediments intercalated with volcanic debris based on the interpretation of Gatliff et al. (1994).

<u>Late Jurassic deposition</u>

Upper Jurassic strata are widespread across the CNS. The environment of deposition was coastal-plain or lagoonal, changing to marine by the end of the Upper Jurassic due to a widespread marine transgression. Upper Jurassic strata are expected to be less than 400 m thick in the south of Quadrant 29 (Gatliff et al., 1994). Well 29/27-01 penetrates around 46 m of Jurassic strata assigned to the Kimmeridge Clay Formation (Upper Jurassic age).

<u>Cretaceous deposition</u>

The end of the Kimmeridge Clay deposition is believed to mark a sudden eustatic sea level fall followed by a rapid rise. The Lower Cretaceous Cromer Knoll Group is widely distributed but has very variable thickness. Less than 100 m was anticipated in the south of Quadrant 29 in Gatliff et al (1994), though local variations due to halokinesis and small scale normal faulting were expected. The Cromer Knoll Group mainly comprises claystone/calcareous claystone/marl (Gatliff et al., 1994).

During Late Cretaceous times, the CNS was inundated by a relative sea level rise. Thick chalk and chalk-marl sequences were deposited (Gatliff et al., 1994).

<u>Palaeocene deposition</u>

Marine conditions persisted into the Palaeogene Era and basinal mudstones were deposited across much of the CNS (Gatliff et al., 1994; Ahmadi et al., 2003).

<u>Paleocene – Eocene mantle underplating and uplift</u>

Mantle underplating and crustal thinning related to the Iceland plume occurred around 61 – 51 Ma. This area experienced uplift but is not believed to have been emergent (Coward et al., 2003; Brodie and White, 1995).

<u>Late Palaeocene deposition</u>

Thin, fine-grained sandstones of Late Paleocene age are observed in Well 29/27-01 (Hay et al., 2005). Basinal conditions persisted through Paleocene and Eocene times with deposition of basinal muds, silts and marls, although water depths fluctuated. Paleocene strata are relatively thin (<100 m; Kerr-McGee et al., 1997).

<u>Eocene deposition</u>

Eocene strata are thin in this area (<150 m; Gatliff et al., 1994).

Hay et al. (2005) note that compressional folding of the chalk and Palaeogene succession resulted in the Palaeogene – Neogene structures following the Zechstein salt structures, and that the compressional regime must have ceased around the late Eocene Epoch based on interpretation of seismic data.

<u>Oligocene deposition</u>

Oligocene strata in this area show a basal unconformity, are quite thin (<150 m), and mainly comprise mudstones (Gatliff et al., 1994). Well 29/27-01 penetrates around 46 m of Oligocene strata.

<u>Early Miocene – Mid Miocene deposition</u>

Miocene strata are up to 100 m thick in Quadrant 29. To the west of block 29/27, Miocene strata show a basal unconformity. Miocene strata are dominated by mudstone but sandstones become more abundant higher in the sequence (Gatliff et al., 1994).

<u>Mid Miocene – Late Miocene</u>

The mid-Miocene unconformity surface is a significant boundary on the MNSH. The boundary alters from conformable in the graben, to Oligocene directly overlain by Pliocene in the west of Quadrant 38. Beneath the unconformity, the Oligocene and Lower Miocene strata have been progressively eroded towards the west (Hay et al., 2005). Hay et al. (2005) suggest that over 300 m of strata were removed during erosion. Japsen (1998) suggest that 400 – 600 m of strata were removed during Cenozoic erosion in this area.

<u>Early Pliocene deposition</u>

Renewed subsidence took place during the Early Pliocene Epoch (Fyfe et al., 2003). Around 172 m of Pliocene strata are preserved in Well 29/27-01.

<u>Pleistocene deposition</u>

Quaternary (Pleistocene and Holocene) strata could be quite thick here (<600 m) (Gatliff et al., 1994). Around 65 m of Pleistocene strata are penetrated by Well 29/27-01 at a depth of 457.2 m BRT.

8.2 PREVIOUS WORK IN THIS REGION

Gas and oil shows are reported in a number of wells in Quadrant 29 and in some cases a Carboniferous source is identified suggesting that source rocks reached maturity somewhere nearby. However, the well that was modelled and another well on this flank of the Quadrant 29 basin were both dry (Hay et al., 2005; Shell, 1970; Carr, 2009; Copestake et al., 2009; Farris et al., 2012).

Palaeozoic source rocks and reservoirs

Hay et al. (2005) assessed Quadrants 27 – 29 and Quadrants 34 - 39. The well analysis carried out here indicated that the 49 wells in that region did not locate economic quantities of hydrocarbons mainly due to lack of charge since this would have required long range migration (which did not occur due to lack of and tortuosity of migration pathways). Lack of traps at reservoir levels was also deemed to be an important factor. The report additionally concluded that the wells in these quadrants did not adequately test the potential for a local source kitchen including from Carboniferous sources and that where deep burial occurred, such as in the south-central part of Quadrant 29, this could offer a possible source. An exception to this was the accumulation in the Tay Sands penetrated by Well 28/02-01 with long distance migration in Tertiary strata suggested.

Maturity modelling

Hay et al. (2005) maturity and migration modelling did indicate oil and gas generation in the central – southern portion of Quadrant 29 from Lower Carboniferous source rocks (Scremerston Formation). The main risk noted was the distribution of these source rocks, since so few wells prove the pre-Permian succession. Migration modelling in Hay et al. (2005) suggests that hydrocarbons would pool locally in Quadrant 29 and migrate up to 80 km across the base Zechstein surface (in the unlimited migration scenario) to the south and south-west.

Additional work to assess potential plays in Quadrant 29 (prospective if Carboniferous source rocks present due to deep burial) and Quadrant 37 (Lower Cretaceous Fairway) were recommended (Hay et al., 2005).

Hydrocarbon shows (and dry wells)

The final well report for Well 29/25-01 indicates that faint fluorescence was observed in strata of Lower Permian to Devonian age (3100 m to around 3109 m BRT). No data were given for gas chromatography. Carboniferous strata are absent from the well and Permian strata rest directly on Devonian strata. No hydrocarbon indications were observed in Devonian strata below this depth (Shell, 1970).

Carr (2009) assessed oils from cuttings samples and fluid inclusions from Well 29/20-01. The oils were generated from early mature lacustrine source rocks. Carr (2009) suggested that the Permian Kupferschiefer and Devonian shales were potential source rocks, but indicated that the Lower Carboniferous Oil Shales and Scremerston Formation coals were the most likely source rocks based on the geochemical signatures. Devonian strata are expected to offer poor source potential (Carr, 2009). Modelling undertaken for this well by Carr (2009) indicated that the Lower Carboniferous source rocks inferred to lie below the TD of the Well 29/20-01 would be early mature for hydrocarbon generation (which matched the maturity of oil samples from the Fulmar Formation and Zechstein Group).

Minor traces of gas were recorded in shallow sections and minor traces of gas and light fluorescence were recorded near the base of the Rotliegend Group in Well 29/23-01 (Farris et al., 2012). Copestake et al. (2009) indicated gas shows were reported in Well 29/23-01 (Auk sandstone).

Copestake et al. (2009) indicated data from a proprietary report indicated that oil shows were present in the Fulmar Sandstone, Zechstein Group and Auk Sandstone from Well 29/20-01 (which contrasts with Farris et al. 2012). The source for the accumulations in Well 29/20-01 was interpreted to be Carboniferous in age (Copestake et al., 2009 and Carr, 2009).

Copestake et al. (2009) indicated that minor oil shows were observed in 29/25-01 (Rotliegend Group).

Farris et al., (2012) indicated that Well 29/20-01 had oil shows in the Zechstein carbonates as indicated by fluorescence. Zechstein dolomites and tuffs are described as having no apparent reservoir quality and no shows were described in the Rotliegend strata from the original well report.

Breaches in the Zechstein sequence that appeared to be related to gas chimneys and shallow gas occurrences were proposed as a possible indicator of an active hydrocarbon system in Quadrant 29.

Copestake et al. (2009) reported gas shows in Well 29/18-01 (weak gas shows in Auk Sandstone).

Well 29/23b-02 which lies on the same flank of the Quadrant 29 Basin as Well 29/27-01 was described as dry due to lack of charge (Copestake et al., 2009). The authors considered lack of charge the main risk to exploitation of blocks 29/20b, 29/20c, 29/19a, 29/24 & 29/25.

Wells 29/18-01, 29/19a-3 and 30/17-01 were reported as having no shows in Farris et al (2012).

Post-Palaeozoic source rocks and reservoirs

Copestake et al. (2009) reported gas shows in Well 29/18-01 (weak gas shows in Chalk, though this may be a shallow gas effect).

Gas shows were also reported in Well 29/19-02 in Pliocene sandstones, this was interpreted as being of biogenic origin (Copestake et al., 2009).

On the high to the east of the Quadrant 29 Basin, the Permian and Jurassic strata produce from Permian and Jurassic strata indicating that older strata are or were mature for generation during the geological history of this region (e.g. the Auk Oil Field (Wells 30/16-01, 30/16-02), Argyll Field (Wells 30/24-11, 30/24b-T1, 30/24b-T2, field now renamed Ardmore field) and Innes Field). Oil-bearing Devonian sandstones were also encountered (Block 30/24) but these were more challenging to exploit (Farris et al., 2012). Alongside oil and gas shows identified in legacy reports for Quadrant 29 wells, these accumulations and shows suggest that the Quadrant 29 Basin could have productive Palaeozoic source rocks.

Maturity Geohistory wells

Pseudo wells were modelled in this region by Hay et al. (2005). Pseudo well #1 and #2 are close to Block 29/27. These models include three periods of uplift (Late Carboniferous – Early Permian, Late Jurassic, mid Cenozoic) with Rotliegend uplift being the most significant, followed by the Late Jurassic uplift and relatively minor Cenozoic uplift.

8.3 WELL 29/27-01

8.3.1 Previous maturity and modelling work

The final well report recorded no significant hydrocarbon shows for Mesozoic strata though weak fluorescence was reported at the top of the Jurassic strata. Gas shows were indicated in strata of Eocene to Pliocene age though these are thought to be a shallow gas pocket or drilling mud contamination. Maturity data of Lower Cretaceous to Permian age indicate the section is immature (Shell, 2015; Amerada Hess Limited, 1988a; Kerr-McGee et al., 1997)

Palaeozoic source rocks and reservoirs

Kerr-McGee et al. (1997) suggests that the maturity at base Permian is around 0.5 – 0.6% from their regional map of the MNSH.

This well terminates in the Rotliegend Group and does not prove Carboniferous strata. The final well report (Amerada Hess Limited, 1988a) indicates no significant hydrocarbon shows for Well 29/27-01. Throughout the Mesozoic section, including in the Rotliegend Group, background gas levels were very low (<0.2%).

The main target for this well indicated in the Amerada Hess (1988b) were the discontinuous mounds observed on seismic data at the base of Zechstein Group, interpreted to be algal build-ups on the basin flanks, with porous and permeable dolomites and gritstones that offered potential reservoirs sealed by lime muds. The source was expected to lie within the Zechstein Group strata. Sandstones of the Rotliegend Group were the secondary objective.

The Amerada Hess summary of results report (Amerada Hess, 1988b) indicated no porosity and no shows in the Hauptdolomit (which comprises dolomite and limestone). The Rotliegend sandstones were described as having an average porosity of 15.5% and net:gross of 0.95. No shows were reported in the Rotliegend Group in this report. The Jurassic sandstones were described as having an average porosity of 27% and net:gross of 0.99.

The presence of oil at the top of the Jurassic succession was suggested by the presence of a weak solvent hydrocarbon fluorescence recorded at 1582 m BRT (Amerada Hess Limited, 1988a).

Shows in the post-Palaeozoic sequence

Gas shows (<9.7%) were indicated in strata of Eocene to Pliocene age (570 – 771 m BRT) which the well report indicated could be a shallow gas pocket or drilling mud contamination (Amerada Hess, 1988b).

Maturity geohistory modelling

Hay et al. (2005) indicated the geothermal gradient in Block 29/27 is expected to be around 29 °C/km

8.3.2 New modelling work

Maturity data

Maturity data (7 VR) from the Lower Cretaceous-Zechstein intervals were made available by Shell (Shell, 2015) for this project.

Model calibration

In 29/27-01, the younger (Cenozoic) sequence seems relatively complete on the well log, but Miocene strata are thin and modelling work on the density logs from nearby Wells 29/23-01 and 29/25-01 (Kimbell and Williamson, this study) suggest a greater thickness of Miocene strata may have been present (an additional 1.5 km is suggested for Well 29/25-01). Hay et al., (2005) suggest that mid Jurassic uplift was around 2 km and Tertiary uplift was around 1.2 km.

For Well 29/25-01, an additional 1 km of Carboniferous strata is proposed by density log work- (Kimbell and Williamson, this study). This was used as a starting point for estimating the amount of Carboniferous strata eroded during the Variscan Orogeny.

Lower Jurassic and the majority of Middle Jurassic strata appear to be absent from Well 29/27-01.

No information is available on the heat flow, but to obtain a good agreement between the model and the VRcalc data, a relatively low heat flow is proposed. No BHT were available for this well.

In order to construct the scenario models for Well 29/07-01, a seismic line passing through the well and the (5 km grid spacing) depth grids from Arsenikos et al. (this study) were used. The well penetrates the Rotliegend Group (Auk Formation) and on the seismic line the well penetrates almost to the Variscan unconformity so the thickness of the Rotliegend Group is most likely not much greater than the thickness observed in the well. The 5 km depth grids indicate the following depths for major horizons below the well; Scremerston Formation, 3250 m, Fell Sandstone Formation, 3500 m, Cementstone Formation 4250 m, Kyle Limestone Formation around 5550 m (the well falls a little off the 5500 m contour line).

<u>Maturity and hydrocarbon generation</u>

As the well does not penetrate the Palaeozoic strata, there is no information on kerogen types. Therefore, the kerogen type was set as a mixture of kerogens based on oil shows reported in legacy reports from surrounding wells and the gas shows reported in the Rotliegend Group for this well (Farris et al., 2012 and Copestake et al., 2009). It was assumed type IV kerogen was also present given the relatively weak oil and gas shows reported in this well and nearby wells. Model input data are shown in Table 11.

Table 11: Summary of model input data for Well 29/27-01 and layer maturity window from the BasinMod model

Formation/ age of strata	**N.o. of VR/ VRcalc datapoints**	**Model maturity window**	**Average measured TOC from logs**	**Kerogen**	**Oil/gas show**	**N.o. of porosity data**	**Comments**
Pliocene to Eocene					Gas shows		Gas thought to be shallow gas pocket or drilling mud contamination
Lower Cretaceous	2 VRcalc		2 data *				
Jurassic	3 VR calc		3 data *		Trace of gas and weak oil show suggested by weak fluorescence		
Upper Triassic	1 VRcalc		1 data*		Trace of gas		
Zechstein	1 VRcalc	Immature	1 data*		Trace of gas		
Rotliegend		Early mature for oil			Trace of gas		VRcalc suggests is immature
Scremerston		Early mature for oil					Not penetrated in well

* These data were provided to the project team as 'restricted' data

8.3.2.1 Scenario 1: no extra stratigraphy

For the first scenario, the well stratigraphy was entered and no additional strata related to previous burial and uplift were included to test the lowest possible level of maturity for this well. This model used the assumption the heat flow had not changed through time. The well only penetrates to the Rotliegend Group, depth to horizons below this point in the well have been estimated. The top of Scremerston Formation, top of Fell Sandstone Formation, top of Cementstone Formation and top of the Kyle Group were estimated based on the 5 km depth grids produced by the project team (Arsenikos et al., this study). The base of the Rotliegend Group and top of the Yoredale Formation and top of the UORS were estimated based on the geological history of this region. The thickness of the Kyle Group was chosen arbitrarily.

The burial history is given in Figure 62, model results are given in Figure 63.

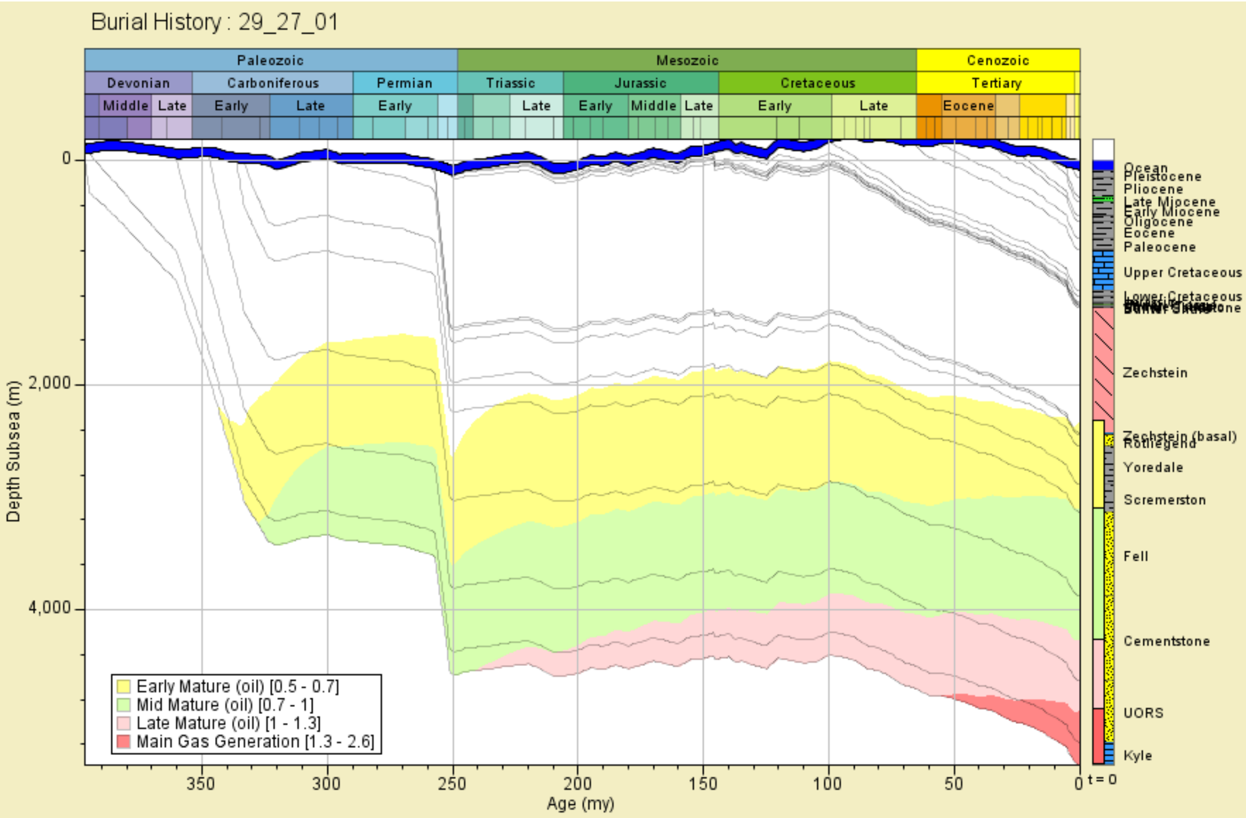


Figure 62: Modelled maturity geohistory for Well 29/27-01, scenario 1. The well terminates in the Rotliegend Group. The depth to the base of the Rotliegend and depth to top of formations below this have been estimated from depth grids (Arsenikos et al., this study).

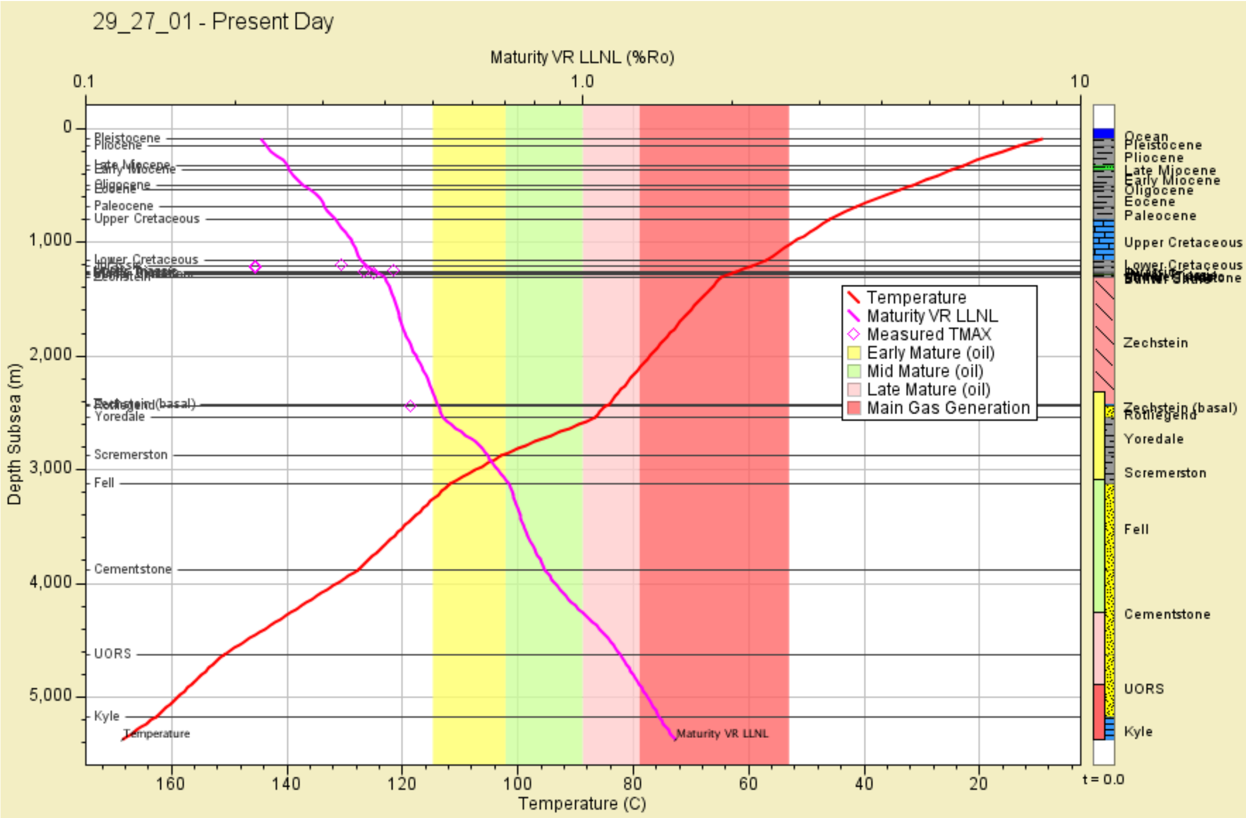


Figure 63: Depth plot for Well 29/27-01 (Scenario 1) showing model results, maturity data and maturity windows plus temperature model

8.3.2.2 SCENARIO 2: BURIAL HISTORY REFINED

Scenario 2 was prepared using the data from regional reports, legacy well reports and density log modelling work (Kimbell and Williamson, this study), as described above.

- Additional strata of Miocene age added (100 m)
- Additional Jurassic strata (500 m) and Mid Jurassic erosion event added
- Assumed Stephanian strata had been present (500 m)
- Assumed Coal Measures had been present (500 m)
- Assumed Millstone Grit has been eroded (400 m)
- Assumed Yoredale Formation was originally thicker (+100 m)
- Assumed the layer of strata above the Scremerston Formation on the seismic (this makes it around 393 m thick based on assumption Rotliegend Group is around 100 m thick and depth to top Scremerston Formation as taken from the 5km depth grid.

This model suggests that the Scremerston Formation is in the oil window. This uses around 1.5 km of additional burial at the end of the Carboniferous Period.

The maturity geohistory is shown in Figure 64, palaeo-heat flow is shown in Figure 65. Model results are given in Figure 66. The model generation potential for strata in the well is given in Figure 67. Timing for generation from the most promising horizon is given in Figure 68. The data entry sheet is shown in Figure 69.

Maturity data for the post-Palaeozoic section is quite low and this provided control for the post-Variscan part of the model. Deepest burial during the Cenozoic Era is included in this model but Carboniferous and Jurassic burial was also important.

As the well did not penetrate the Scremerston Formation, depth, kerogen data or maturity data were not available for this formation. Given the expected depth of this formation, the early to mid mature for oil window would have been reached.

Minor gas shows are noted throughout the well, the source is not defined in the well reports so it is not clear if this supports the current BasinMod model where Palaeozoic source rocks reach the gas window.

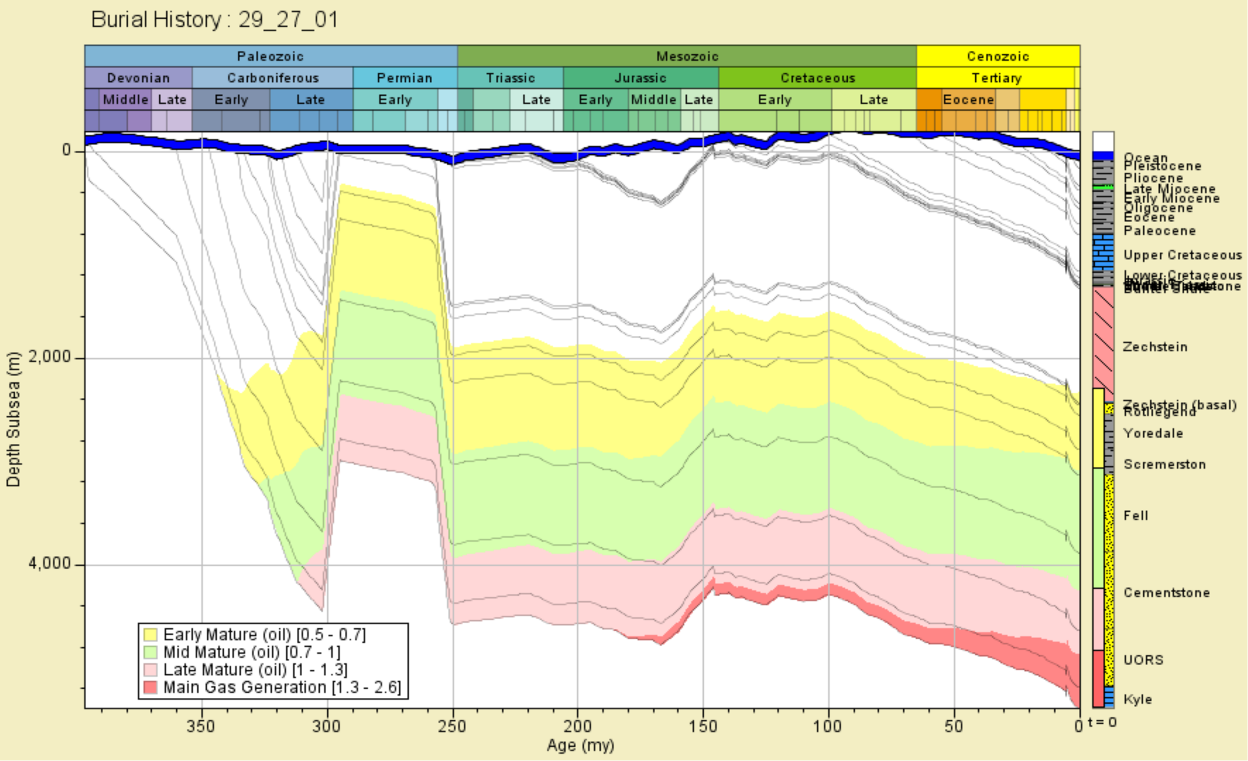


Figure 64: Modelled maturity geohistory for Well 29/27-01, Scenario 2. The well terminates in the Rotliegend Group. The depth to the base of the Rotliegend and depth to top of formations below this have been estimated from depth grids (Arsenikos et al., this study).

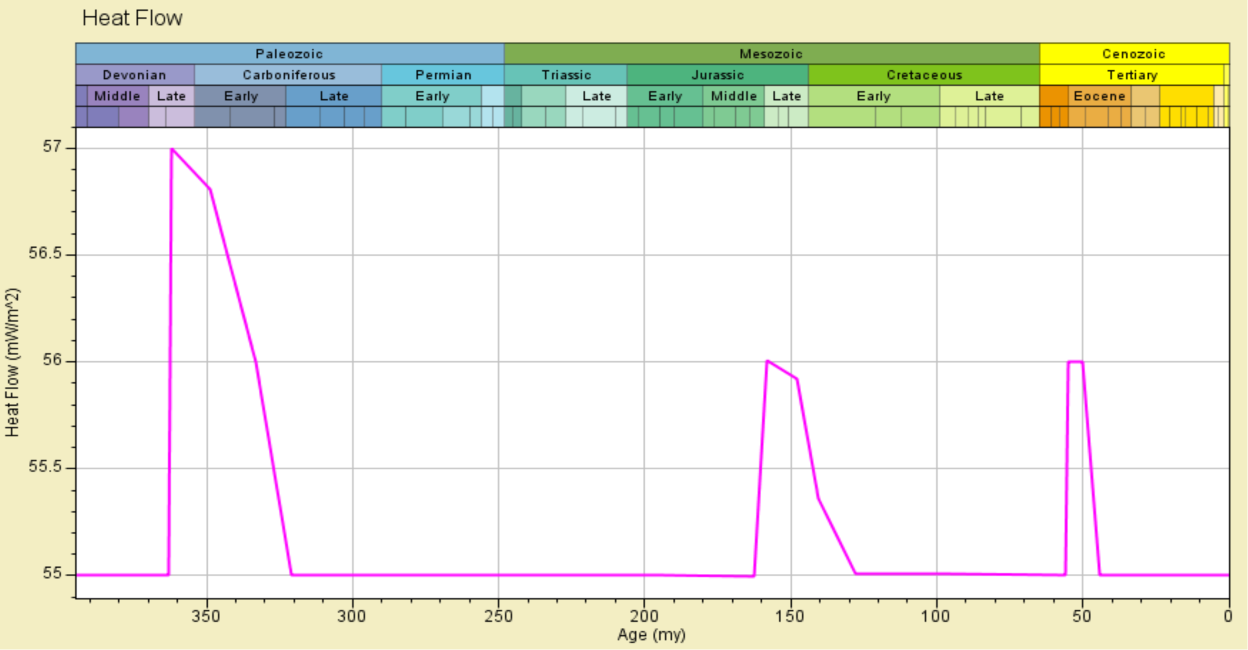


Figure 65: Modelled palaeo-heat flow for Well 29/27-01, Scenario 2

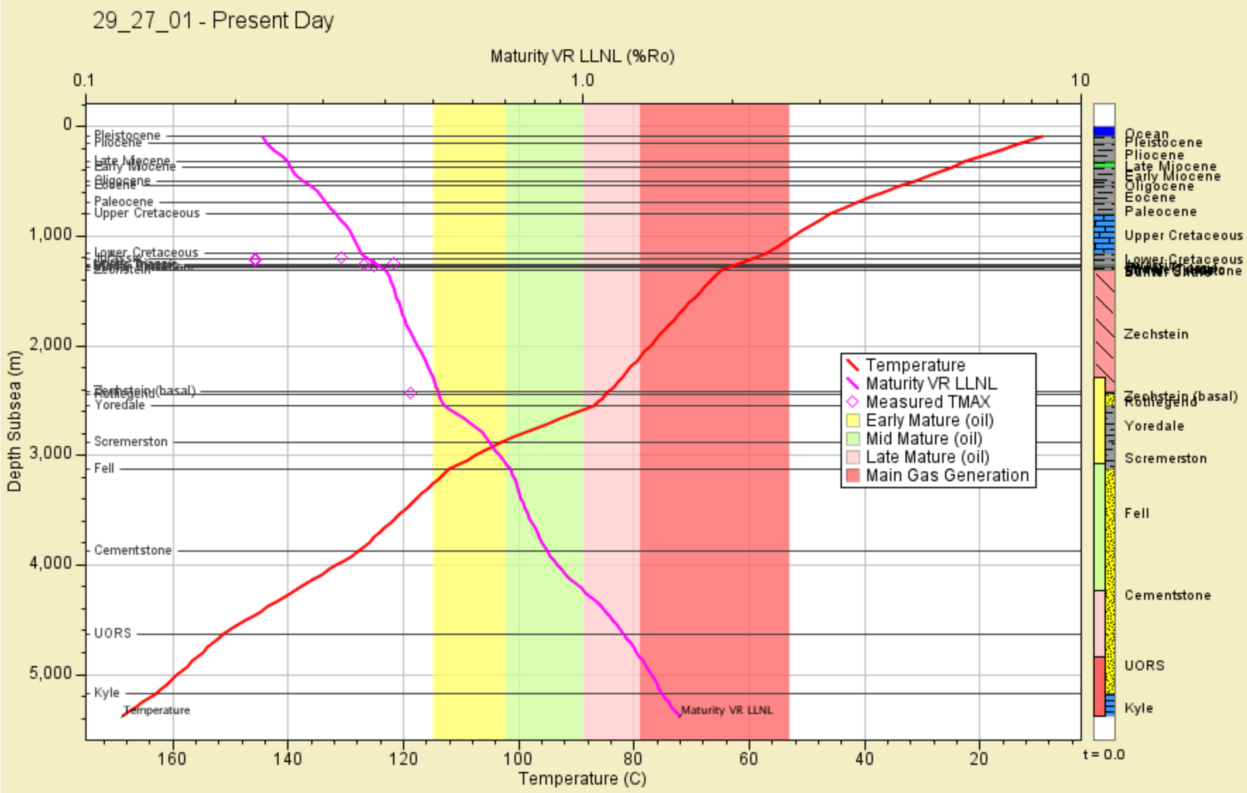


Figure 66: Depth plot for Well 29/27-01 (Scenario 2) showing model results, maturity data and maturity windows plus temperature model

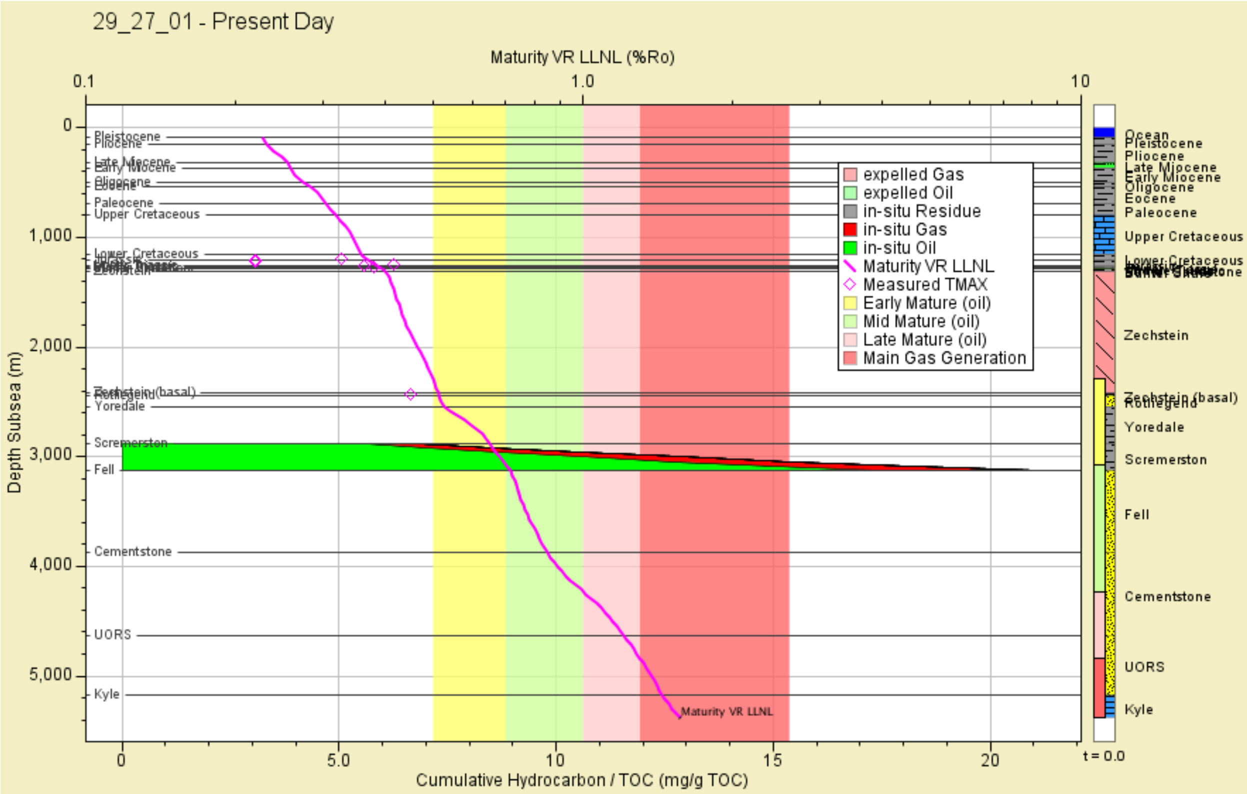


Figure 67: Depth plot for Well 29/27-01 (Scenario 2) showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

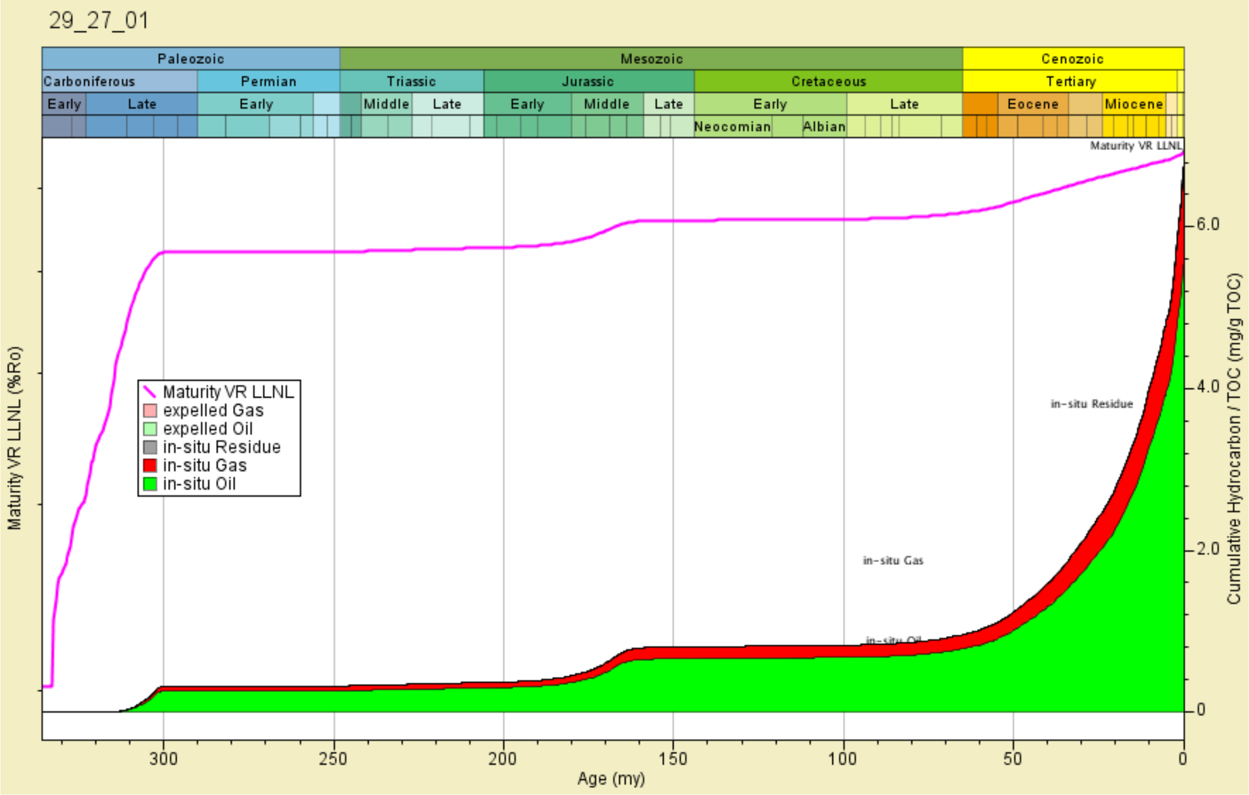


Figure 68: Time plot for Well 29/27-01 (Scenario 2) showing timing of generation for Scremerston Formation. Scenario 2 suggests that main generation occurred during deep burial during the Jurassic Period and Cenozoic Era.

29_27_01 | 29_27_01: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth …	Present Th…	Eroded Thi…	…	Lithology	…	…	Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary …	Erosion	0.0			-10								
2	Pleistocene (d)	Deposit	0.126			10		pleistocene_w9						
3	Pleistocene	Formation	0.781	*457.2*	*65.53*			pleistocene_w9						
4	Pliocene	Formation	2.6	**522.73**	*172.21*			pliocene_w9						
5	Late Miocen…	Erosion	5.322			-100								
6	Late Miocen…	Deposit	5.326			100		late_mio_w9						
7	Late Miocene	Formation	5.4	**694.94**	*45.72*			late_mio_w9						
8	Early Miocene	Formation	12	**740.66**	*128.02*			early_mio_w9						
9	Oligocene	Formation	23.03	**868.68**	*45.72*			olig_w9						
10	Eocene	Formation	33.9	**914.4**	*151.18*			eoc_w9						
11	Paleocene	Formation	55.8	**1,065.58**	*104.85*			paleocene_w9						
12	Upper Creta…	Formation	65.5	*1,170.43*	*356.62*			u_cret_w9						
13	Lower Creta…	Formation	99.61	*1,527.05*	*57.91*			early_cret_w9						
14	Jurassic	Formation	145.5	*1,584.96*	*46.33*			Jurassic_Q26						
15	Cimmerian	Erosion	146			-500								
16	Jurassic	Deposit	167			500		jurassic_w9						
17	Upper Triassic	Formation	199.6	*1,631.29*	*14.63*			u_trias_w9						
18	Middle Triassic	Formation	228	**1,645.92**	*10.67*			m_trias_w9						
19	Bunter Sand…	Formation	245	**1,656.59**	*6.09*			bunter_sst_w9						
20	Bunter Shale	Formation	249	**1,662.68**	*22.86*			bunter_shl_w9						
21	Zechstein	Formation	251	*1,685.54*	*1,110.7*			Zech_w9						
22	Zechstein (b…	Formation	257	*2,796.24*	*20.11*			basal_zech_w9						
23	Rotliegend	Formation	258	*2,816.35*	**100**			rot_w9						
24	Variscan (e)	Erosion	295			-1,500								
25	Stephanian (d)	Deposit	302			500		stephanian_w9						
26	Coal Measur…	Deposit	312			500		Coal Measures_w9						
27	Millstone (d)	Deposit	318			400		Mill_w9						
28	Yoredale (d)	Deposit	323			100		Yore_w9						
29	Yoredale	Formation	323.5	**2,916.35**	*333.65*			Yore_w9						
30	Scremerston	Formation	333	**3,250**	*250*			SCrem_w9			Kerogen Mix 5	2.5	2.6	0.2
31	Fell	Formation	336.01	**3,500**	*750*			Fell_w9						
32	Cementstone	Formation	347	**4,250**	*750*			Cementstone_w9						
33	UORS	Formation	360	**5,000**	*550*			UORS_w9						
34	Kyle	Formation	395	**5,550**	**200**			Kyle_w9						

Model Begin Age: 397 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Figure 69: Model data entry sheet for Well 29/27-01 (Scenario 2). Top Depth is in m BRT

8.3.2.3 Scenario 3: Burial required to achieve gas generation from Scremerston Formation

Modelling was carried out to estimate how much additional Carboniferous burial was required to push the Scremerston Formation into the gas window. Post-Palaeozoic stratigraphic thicknesses were kept the same as for Scenario 2 as these were better constrained by well data.

In order for the Scremerston Formation to reach the gas window, Scenario 3 shows that around 3.5 km of additional Carboniferous strata would be required.

The model maturity geohistory is given in Figure 70 and palaeo-heat flow in Figure 71. Model results are given in Figure 72. The model generation potential for strata in the well is given in Figure 73. Timing for generation from the most promising horizon is given in Figure 74. The model data entry sheet is shown in Figure 75.

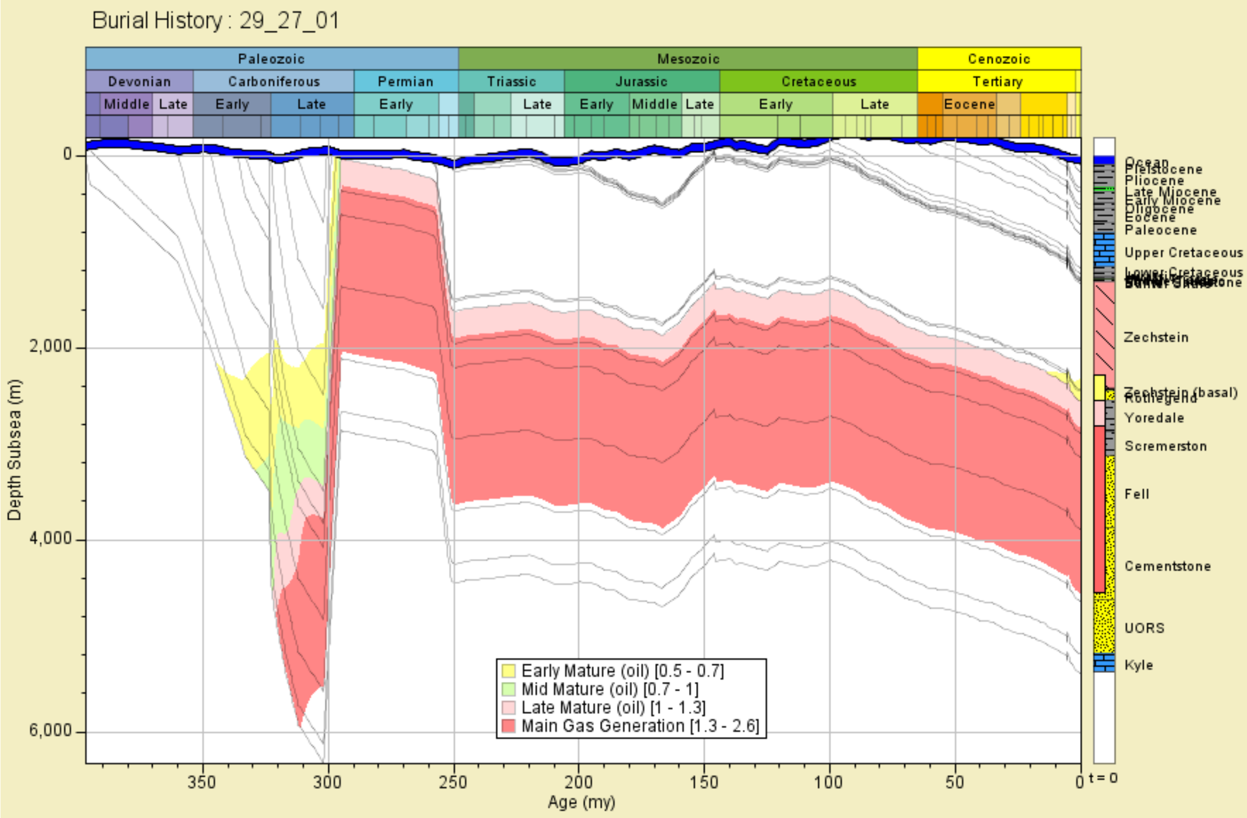


Figure 70: Modelled maturity geohistory for Well 29/27-01, Scenario 3. The well terminates in the Rotliegend Group. The depth to the base of the Rotliegend and depth to top of formations below this have been estimated from depth grids (Arsenikos et al., this study).

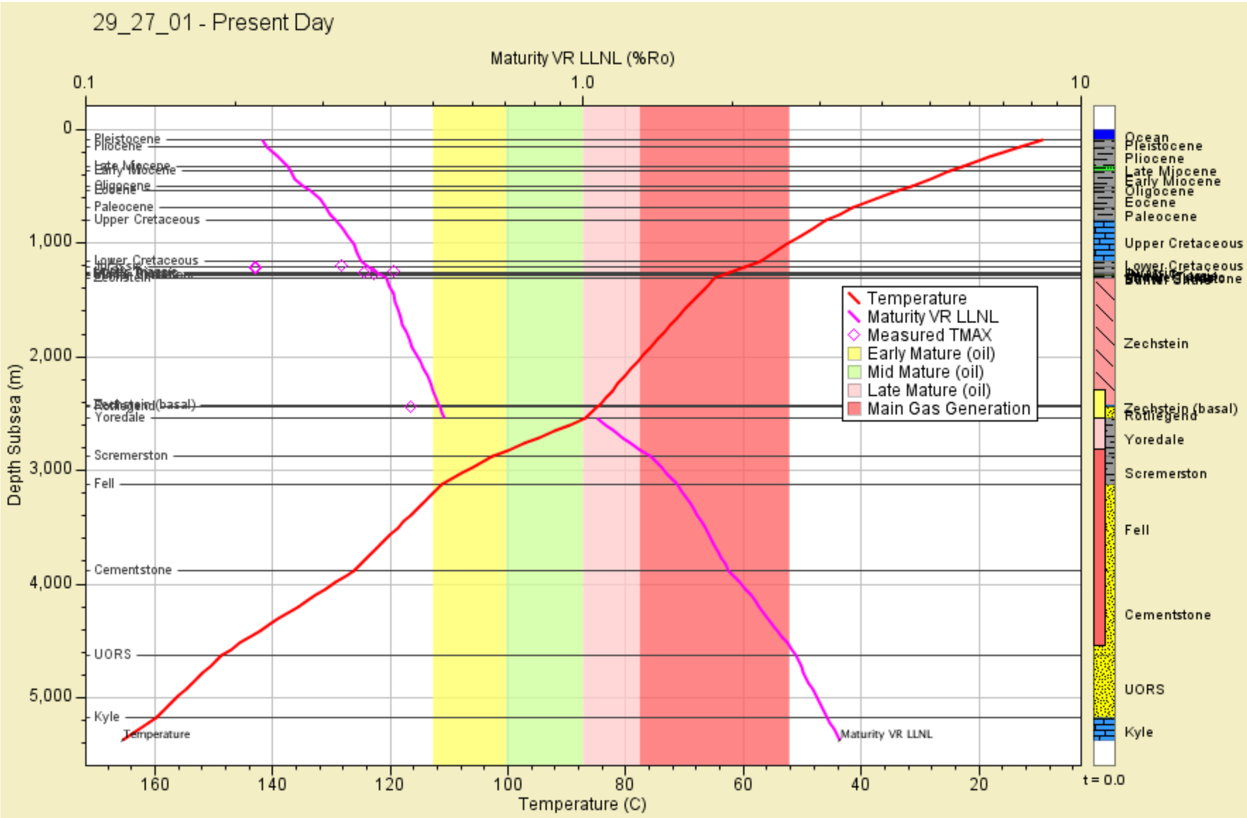


Figure 71: Depth plot for Well 29/27-01 (Scenario 3) showing model results, maturity data and maturity windows plus temperature model

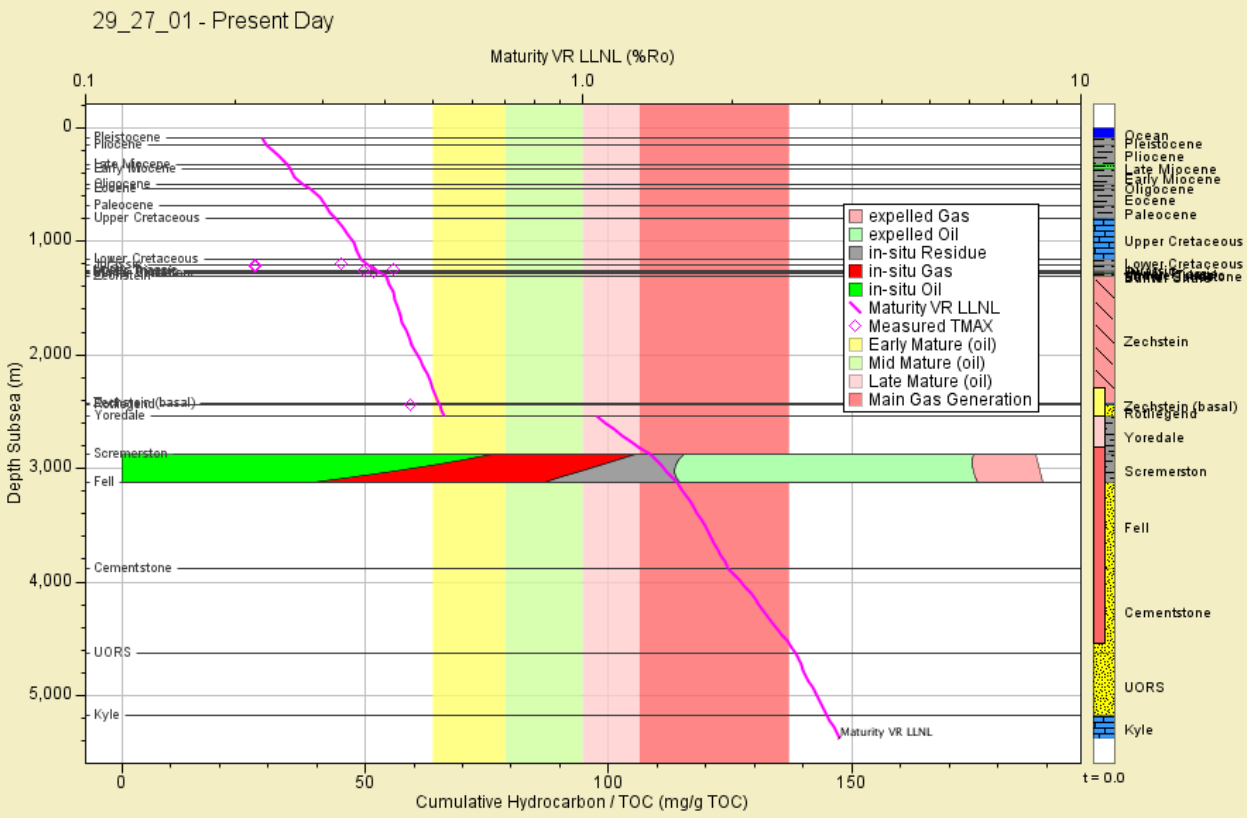


Figure 72: Depth plot for Well 29/27-01 (Scenario 3) showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

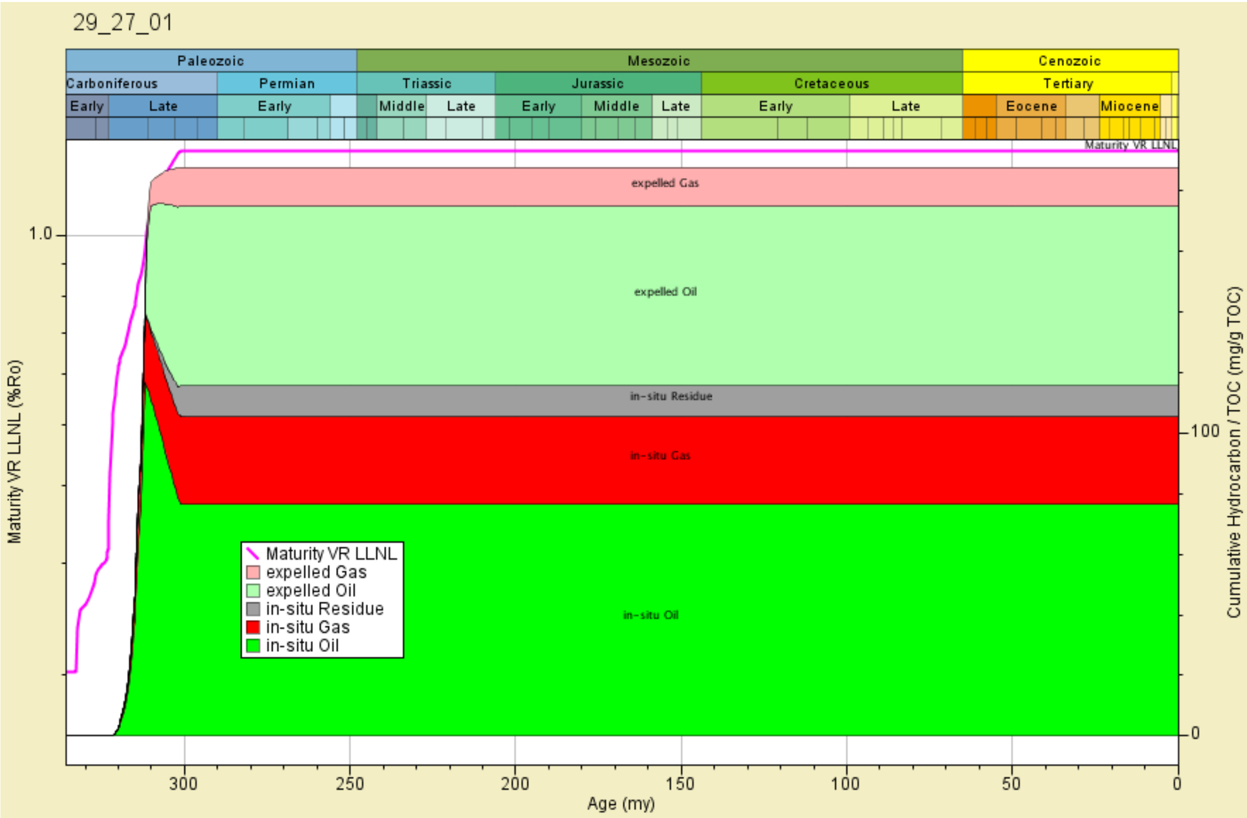
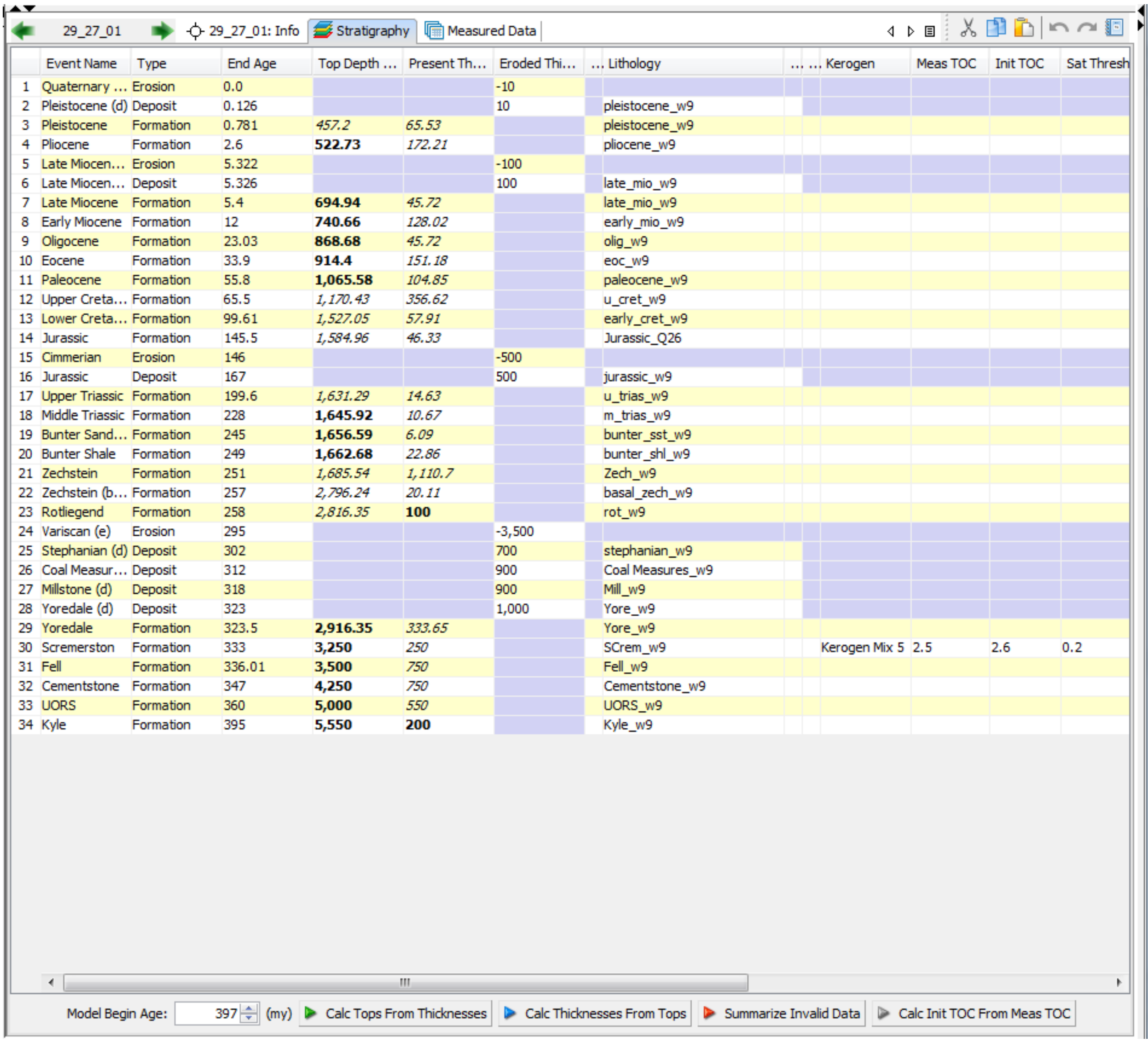


Figure 73: Time plot for Well 29/27-01 (Scenario 3) showing timing of generation for Scremerston Formation. Scenario 3 suggests that main generation and expulsion occurred during deepest burial during the Carboniferous Period.



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	...	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10								
2	Pleistocene (d)	Deposit	0.126			10		pleistocene_w9						
3	Pleistocene	Formation	0.781	457.2	65.53			pleistocene_w9						
4	Pliocene	Formation	2.6	522.73	172.21			pliocene_w9						
5	Late Miocen...	Erosion	5.322			-100								
6	Late Miocen...	Deposit	5.326			100		late_mio_w9						
7	Late Miocene	Formation	5.4	694.94	45.72			late_mio_w9						
8	Early Miocene	Formation	12	740.66	128.02			early_mio_w9						
9	Oligocene	Formation	23.03	868.68	45.72			olig_w9						
10	Eocene	Formation	33.9	914.4	151.18			eoc_w9						
11	Paleocene	Formation	55.8	1,065.58	104.85			paleocene_w9						
12	Upper Creta...	Formation	65.5	1,170.43	356.62			u_cret_w9						
13	Lower Creta...	Formation	99.61	1,527.05	57.91			early_cret_w9						
14	Jurassic	Formation	145.5	1,584.96	46.33			Jurassic_Q26						
15	Cimmerian	Erosion	146			-500								
16	Jurassic	Deposit	167			500		jurassic_w9						
17	Upper Triassic	Formation	199.6	1,631.29	14.63			u_trias_w9						
18	Middle Triassic	Formation	228	1,645.92	10.67			m_trias_w9						
19	Bunter Sand...	Formation	245	1,656.59	6.09			bunter_sst_w9						
20	Bunter Shale	Formation	249	1,662.68	22.86			bunter_shl_w9						
21	Zechstein	Formation	251	1,685.54	1,110.7			Zech_w9						
22	Zechstein (b...	Formation	257	2,796.24	20.11			basal_zech_w9						
23	Rotliegend	Formation	258	2,816.35	100			rot_w9						
24	Variscan (e)	Erosion	295			-3,500								
25	Stephanian (d)	Deposit	302			700		stephanian_w9						
26	Coal Measur...	Deposit	312			900		Coal Measures_w9						
27	Millstone (d)	Deposit	318			900		Mill_w9						
28	Yoredale (d)	Deposit	323			1,000		Yore_w9						
29	Yoredale	Formation	323.5	2,916.35	333.65			Yore_w9						
30	Scremerston	Formation	333	3,250	250			SCrem_w9			Kerogen Mix 5	2.5	2.6	0.2
31	Fell	Formation	336.01	3,500	750			Fell_w9						
32	Cementstone	Formation	347	4,250	750			Cementstone_w9						
33	UORS	Formation	360	5,000	550			UORS_w9						
34	Kyle	Formation	395	5,550	200			Kyle_w9						

Figure 74: Model data entry sheet for Well 29/27-01 (Scenario 3). Top Depth is in m BRT

8.3.3 Key points from new modelling work for Well 29/27-01

- The well only penetrates to Rotliegend Group. Depth grids (5km) were used to extend the well downwards for the scenarios
- Kerogen data is not available for this well, assumptions have been made based on the presence of gas shows here and in and nearby wells for Scremerston Formation
- The Scremerston Formation (major source rock) is not penetrated
- Scenario 2 indicates mid maturity for oil at Scremerston Formation depths
- Source potential seems low based on legacy reports and lack of significant shows in this and Well 29/23b-02 which also lies on the same flank of the Quadrant 29 Basin
- Main generation was during Jurassic and Cenozoic burial for Scenario 2 (and during Carboniferous Period for Scenario 3)
- Maturity data for the post-Palaeozoic section is quite low and this provided some control for the post-Variscan part of the model
- Deepest burial occurred during the Cenozoic Era (Scenario 2) but Carboniferous and Jurassic burial was also important
- An additional 3.5 km of burial was required for the Scremerston Formation to reach the main gas maturity window (Scenario 3)

8.4 GEOLOGY OF BLOCK 38/18

Block 38/18 lies in the central part of Quadrant 38 on the margins of the North Dogger Basin (Figure 1). The Devonian and Carboniferous basin was adjacent to the Dogger Granite block and the orientation of NW-SE basin bounding faults was controlled by pre-Carboniferous structures (Corfield and Gawthorpe, 1995; Arsenikos et al., this study; Leslie et al., this study).

<u>Early Devonian continental deposition and Mid Devonian marine transgression</u>

The Devonian and Carboniferous tectono-stratigraphic evolution of the North Dogger Basin is similar to that described for Well 29/27-01 above. During Early Devonian times, continental sediments of the Lower Old Red Sandstone Group were deposited in an alluvial/fluvial setting.

During mid-Devonian times, a marine transgression from the Rheic Ocean to the south (Ziegler, 1982 as referenced in Gatliff et al., 1994) resulted in deposition of marine sediments. Middle Devonian rocks (Kyle Limestone) are proved in wells in Quadrant 38 (Kearsey et al., this study). Well 38/03-01 shows a succession of argillaceous strata around 100 m thick above limestone, believed to be of latest Middle Devonian age (Gatliff et al., 1994).

Active extension is observed on seismic data from late Devonian times (Arsenikos et al., this study). The Tayport Formation (Upper Devonian) is proved in Well 38/29-01 and Well 37/25-01. In Well 38/22-1 porosities in Devonian strata reach 27% at 2134 m suggesting burial was not too deep (Hay et al., 2005).

<u>Late Devonian – Early Carboniferous dextral transtension and extensional faulting</u>

During latest Devonian to early Carboniferous times, the central part of Quadrant 38 lay in a marginal marine environment (Kearsey et al., this study). Carboniferous (Courceyan) clastics and thin carbonates form predominantly high-frequency reflectors and display divergence in basin-bounding faults (Corfield and Gawthorpe, 1995). During Visean times, fluvial conditions prevailed (Kearsey et al., this study). The Fell Sandstone is well developed across most the MNSH (Hay et al., 2005). Chadian/Holkerian stacked channel sandstones form high amplitude, laterally continuous reflectors. This sequence also thickens into the central graben (Corfield and Gawthorpe, 1995). During Visean times, this region had abundant ‘coal mires’ (Kearsey et al., this study). Although not preserved, this region also likely had deposition of cyclical marine to non-marine Yoredale facies (Kearsey et al., this study and Bluck et al., 1992). The younger parts of the Yoredale sequence in blocks adjacent to 38/18 indicate the onset of regional post-rift subsidence and it oversteps all the underlying sequences onto structural highs though there is limited preservation of this sequence in Quadrant 38 (Corfield and Gawthorpe, 1995; Arsenikos et al., this study; Kearsey et al., this study). Although not preserved, it is anticipated that coarse sandstones of the Millstone Grit Formation would have been deposited here (Kearsey et al., this study).

During early Westphalian times, deltaic conditions may have continued across this region, sourced from the north. During latest Westphalian to Stephanian times, alluvial conditions may have dominated (Bluck et al., 1992).

<u>Variscan (Late Carboniferous – Permian) uplift and erosion</u>

Hay et al., (2005) estimated the Block 38/18 was uplifted by around 3.5 km during the Variscan Orogeny. The current model suggests a more moderate uplift.

<u>Early Permian hiatus</u>

Much of the Early Permian interval was a time of non-deposition in the area of interest due to Variscan uplift and late Carboniferous to Early Permian volcanic activity (which was centred around the MNSH and Danish sector) (Farris et al., 2012). Lower Permian strata in the CNS comprise volcanics (Glennie et al., 2003).

Late Permian extension

The Late Permian Period is expected to have been a time of active extension (Farris et al., 2012) but the area of interest is expected to have remained sub-aerially exposed (Glennie et al., 2003).

Late Permian strata mainly comprise the Zechstein Group, deposited in a marine environment (Smith and Taylor, 1992). In Well 38/18-01, around 381 m of the Zechstein Group succession is penetrated.

Triassic deposition

The onset of rifting in the Central Graben occurred during the Triassic Period (Hay et al., 2005). Block 38/18 lay within a Triassic basin (Goldsmith et al., 2003).

Triassic rifting centred in the Norwegian sector (Farris et al., 2012) caused halokinesis of the Zechstein Group, particularly in the Central Graben. Salt withdrawal and rift-related subsidence resulted in basins in which fluvio-lacustrine strata were deposited (Gatliff et al., 1994).

Mudstones of the Triassic Smith Bank Formation were deposited in a widespread floodplain environment. Sediment transport from the Fennoscandian Shield by Early – Mid Triassic times resulted in sheetflood and braided channel sandstones (Bunter Sandstone and basal Skaggerak Formation) (Gatliff et al., 1994).

Early - Mid Jurassic uplift and erosion

Lower Jurassic strata are expected to be thin or locally absent on the MNSH due to early-mid Jurassic domal uplift (mid Cimmerian/Intra-Aalenian Unconformity). During Jurassic times, this region lay on a high and Jurassic strata are expected to be thin/locally absent.

Mid – Late Jurassic hiatus

Wells 38/3-1 and 37/10-1 contain thin local occurrences of Mid Jurassic strata (Hay et al., 2005) and the Jurassic sands in Well 39/2-1 are regarded as probably Callovian in age (Wakefield et al., 1993 as referenced in Hay et al., 2005). Middle Jurassic strata are absent in Well 38/18-01. Hay et al. (2005) stated that the Pentland Formation was too thin to map on seismic but was probably confined to a series of palaeovalleys which drained the MNSH.

Collinson and IGI (1995) note the region around Quadrants 38 and 39 is expected to have been affected by a late Jurassic heat flow pulse.

Cretaceous deposition

The end of the Kimmeridge Clay deposition (latest Jurassic) is believed to mark a sudden eustatic sea level fall followed by a rapid rise. The Lower Cretaceous Cromer Knoll Group is widely distributed but has very variable thickness. Less than 100 m is anticipated in the middle of Quadrant 38 by Gatliff et al. (1994), though local variations due to halokinesis and small scale normal faulting are expected. The Cromer Knoll Group mainly comprises claystone/calcareous claystone/marl.

During Late Cretaceous times, this part of the CNS was inundated by a relative sea level rise. Thick chalk and chalk-marl sequences were deposited. Gatliff et al. (1994) anticipate 400 – 600 m of Upper Cretaceous deposits in this block.

Palaeocene deposition

Marine conditions persisted into the Palaeogene Era and basinal mudstones were deposited across much of the CNS (Gatliff et al., 1994; Ahmadi et al., 2003).

Paleocene – Eocene mantle underplating and uplift

Mantle underplating and crustal thinning related to the Iceland plume occurred around 61 – 51 Ma. This area experienced uplift but is not believed to have been emergent (Coward et al., 2003; Brodie and White, 1995).

Late Palaeocene - Eocene deposition

Marine conditions persisted into the Palaeogene Period and basinal mudstones were deposited across much of the CNS (Gatliff et al., 1994). Basinal conditions persisted through Paleocene and Eocene times with deposition of basinal muds, silts and marls, although water depths fluctuated. Paleocene strata are expected to be relatively thin (<100 m), Eocene strata are expected to be around 300 – 450 m thick. Paleocene and Eocene strata comprise basinal mudstones. Well 38/18-01 penetrates around 60 m of Paleocene strata and around 333 m of Eocene strata. Well 36/16-01 penetrates around 7 m of Palaeocene strata and 370 m of Eocene strata.

Hay et al. (2005) suggest that the compressional regime which was initiated during the Palaeogene must have ceased around the late Eocene Epoch based on interpretation of seismic data.

Oligocene deposition

A basal unconformity is expected at the base of the Oligocene strata. Here Oligocene strata are quite thin (<150 m) and mainly comprise mudstones (Gatliff et al., 1994). Well 38/18-01 penetrates around 207 m and Well 38/16-01 penetrates around 111 m of Oligocene strata.

Lower Miocene deposition

Miocene strata are up to 100 m thick in Quadrant 38. A unconformity may be present at the base of the Miocene strata in Block 38/18. Miocene strata are dominated by mudstone but sandstones become more abundant higher in the sequence (Gatliff et al., 1994).

Mid Miocene to Late Pliocene uplift

The Mid Miocene unconformity is significant on the MNSH. The time gap across the boundary increases westwards. The succession is conformable in the Central Graben, Oligocene strata are directly overlain by Pliocene in Well 38/16-1 and underlain by Eocene strata further west in Quadrant 37 (Hay et al., 2005; Gatliff et al., 1994). Miocene strata are overlain by Pliocene strata in Well 38/18-01.

Pleistocene deposition

A renewed phase of subsidence began in the Pleistocene (Hay et al., 2005). Quaternary (Pleistocene and Holocene) strata could be quite thick in Quadrant 38 (600 – 700 m) (Gatliff et al., 1994).

8.5 PREVIOUS WORK IN THIS REGION

Limited work is available in the public domain for this region. Palaeozoic strata are expected to contain mainly gas prone source rocks with some oil generation potential. Small gas shows are indicated but the Carboniferous rocks are only expected to be in the oil maturity window on the Dogger Basin margins in Quadrant 38 (Amoco, 1967; Hay et al., 2005; Robertson Research, 1967a).

Hydrocarbon shows

Gas shows are indicated on the composite log in the Scremerston Formation for Well 38/16-01 and coals are expected to be gas prone (Amoco, 1967).

Maturity

The Carboniferous (Dinantian) section is described as early-mid mature for oil generation in Well 38/16-1 (Robertson Research, 1967a).

Palaeozoic source rocks and reservoirs

The coals are good quality source rocks in Well 38/16-1. Coals at 2115.9, 2118.4 and 2161.0 m BRT have TOC vales of 31.63% to 50.34%. Most potential is for gas generation from these coals but based on the high expected yields from pyrolysis data, the authors observed that these coals could also offer a good quality oil source rock (Robertson Research, 1967a). The interbedded mudstones, shales and sandstones offer poor potential for gas generation based on pyrolysis data. A mudstone sample at 1947.7 – 1950.7 m BRT is a fair quality source rock for oil. No migrant hydrocarbons were observed in the Carboniferous section (Robertson Research, 1967a).

<u>Post-Palaeozoic source rocks and reservoirs</u>

Well 39/16-1 tested gas at very low rates, the main target was (Pliocene) strata (Hay et al., 2005). This well only penetrated the Cretaceous and younger succession.

8.6 WELL 38/18-01

This well penetrates 107 m into the Scremerston and Fell Sandstone formations beneath the Zechstein Group. Limited geochemical and maturity data are available.

8.6.1 Previous maturity and modelling work

The Carboniferous section appears to be early or late mature for oil generation depending on confidence in maturity data. The Scremerston Formation has high TOC values, the shales are oil prone at the top of the formation and more gas prone in the lower part of the formation. Oil staining is observed in the Scremerston Formation but the source of this oil is not definable. Minor gas shows are observed in the post-Palaeozoic sequence and these are thought to be sourced from the post-Palaeozoic sequence (Robertson Research, 1967b; Kerr-McGee et al., 1997; Paleochem Ltd, 1984; Arpet, 1967; PETRA-CHEM, 1970).

<u>Palaeozoic source rocks</u>

Organic-rich shales are present with TOC values of 4.81 – 24.67% recorded (Robertson Research, 1967b). The shales in the Scremerston Formation are oil source rocks to a depth of about 2401 m, then they are more gas prone. The source rock data quality is described as fair and the maturation data quality is described as poor in this legacy report. (Robertson Research, 1967b). Coaly layers and mudstones in the Scremerston Formation have good TOC values and excellent source potential for oil and gas (Paleochem Ltd., 1984; Robertson Research, 1967a).

Paleochem Ltd (1984) note samples from coaly layers and mudstones have good TOC values (>6%) in the Scremerston Formation and pyrolysis data suggests excellent potential. Kerogens suggest mixed oil and gas with some gas prone layers.

<u>Hydrocarbon shows</u>

There is insufficient evidence to demonstrate whether the oil staining in the Scremerston Formation in Well 38/18-01 is a result of in-situ generation or migrating oil from more mature rocks off-structure (Paleochem Ltd, 1984).

No migrant hydrocarbons were observed for the Carboniferous section for Well 38/18-01 (Robertson Research, 1967b).

Fluorescence is reported in the Zechstein Group (Lower Magnesian Limestone) between 2300.6 – 2307.3 m in the well report (Arpet, 1967b).

Kerr-McGee et al. (1997) suggest that hydrocarbons generated from the Late Jurassic Kimmeridge Clay Formation has migrated through faults into Paleocene clastics trapped underneath lower Eocene shales. An unproven source from the Dutch sector and migration through faults into Paleocene clastics is also indicated as a possible play.

Minor gas shows are reported throughout the well (average 0 – 5 units of methane) with variable but higher averages in sections of the Oligocene to Pleistocene strata (averaging 5 – 400 with unit peaks of >1000 in sections from 274 – 704 m BRT and 786 – 846 m BRT). Pleistocene sands are believed to account for the gas recorded in Pleistocene strata from 274 m BRT to the top of the casing at 762 m BRT (Arpet, 1967). Sand bodies and carbonaceous wood from in the Miocene – Oligocene strata appear to account for gas from 782 – 803 m BRT (Arpet, 1967b). Note that in the Carboniferous section, the log for methane appears to be a constant background with a few tiny peaks.

Maturity data and maturity modelling

For Well 38/18-01 Robertson Research (1967b) indicates the Carboniferous section is middle to late mature for oil generation but immature for gas generation. The maturity interpretation was based on VR values ranging from 0.37 to 0.71% and the authors' regional interpretation. Only 1 VR sample was recorded with VR = 0.71%. The authors indicated that lignite from the drilling mud was believed to be responsible for all the VR readings below 0.4% (though the deepest datapoint with VR = 0.4 has 30 samples). No migrant hydrocarbons were observed.

VR data suggests samples are immature but spore colouration suggests the Scremerston is early mature for oil (Paleochem Ltd, 1984). PETRA-CHEM (1970) indicates the Scremerston Formation is early mature for oil with VR>0.44.

Kerr-McGee et al. (1997) indicate that the maturity at base Permian is VR=0.46% for Well 38/18-01 on their regional map of the MNSH.

Geohistory modelling

Around 2.4 km mid-Jurassic uplift and 3.5 km of Variscan uplift is proposed by Hay et al. (2005). The current model suggests more moderate burial.

8.6.2 New modelling work

Maturity data

Two VR data and 15 T_{max} data were available from PETRA-CHEM (1970). Pyrolysis data from PETRA-CHEM (1970) were included. Three VR were available from Robertson Research (1967b). There are some issues with the reliability of the VR data: Two of the VR data from Robertson Research (1967b) only have 1 sample. Lignite contamination from the drilling mud was noted and quite a large number of samples for each datapoint seem to fall below VR = 0.4 which is given as the cutoff point for lignite contamination by the authors. Any VR data interpreted by Robertson Research (1967b) to be lignite from the drilling mud were excluded from this BasinMod model.

Model calibration

Well 38/18-01 was modelled by Collinson and IGI (1995) with a present day heat flow of 57 MWm^{-2}. In contrast to their well models across most their regional study area, Collinson and IGI (1995) proposed that wells in Quadrant 38 had been subject to a late Jurassic heat flow pulse and did allow variation of the heat flow in these wells. One Horner-plot corrected BHT was provided by Collinson and IGI (1995) for the Fell Sandstone Formation.

In Well 38/18-01, the Paleocene and younger sequence seems relatively complete. However, much of the Upper Permian and Lower – Middle Jurassic strata appear to be absent. Around 660 m of additional burial is suggested for Permian strata proposed by Kimbell and Williamson (this study).

Maturity and hydrocarbon generation

The Scremerston Formation is considered to have excellent source rock quality and to contain a mixture of gas and oil prone organic matter (Vane et al., this study).

The average TOC values for the Scremerston Formation were taken from Gent (this study) and included in the model. The upper part of the Scremerston Formation is described as being oil prone and the lower part as being gas prone (Robertson Research, 1967b). A mixture of kerogens was entered into BasinMod 1D for the Zechstein Group and Scremerston Formation based on the project team assessment (Vane et al., this study) but there were few datapoints available so there is considerable uncertainty in the generation potential.

Model input data are shown in Table 12.

Table 12: Summary of model input data for Well 38/18-01 and layer maturity window from the BasinMod model

Formation/ age of strata	**N.o. of VR/ VRcalc datapoints**	**Model maturity window**	**Average measured TOC from logs**	**Kerogen**	**Oil/gas show**	**N.o. of porosity data**	**Comments**
Pleistocene					Minor gas shows, gas shows, several 100 unit peaks and 1000+ unit peaks towards base		
Pliocene					Gas shows, with 1000+ unit peaks near top of section		
Miocene					Gas shows		
Oligocene		Immature			Gas shows		
Zechstein	4 VRcalc	Early mature for oil		Gas prone, oil prone and inert	0-5 units methane (background level)		
Scremerston	5 VR, 10 VRcalc	Early mature for oil	2.5	Gas prone, mixed and oil prone	0-5 units methane (background level). Oil staining.		
Fell	1 VRcalc	Early mature for oil			0-5 units methane (background level)		

8.6.2.1 Scenario 1: no extra stratigraphy

For the first scenario, the well stratigraphy was entered and no additional strata relating to previous burial and uplift were included, to test the lowest possible level of maturity for this well.

The maturity geohistory is given in Figure 76, model results are given in Figure 77. The current model (Scenario 1) suggests the Scremerston Formation would be early mature for oil.

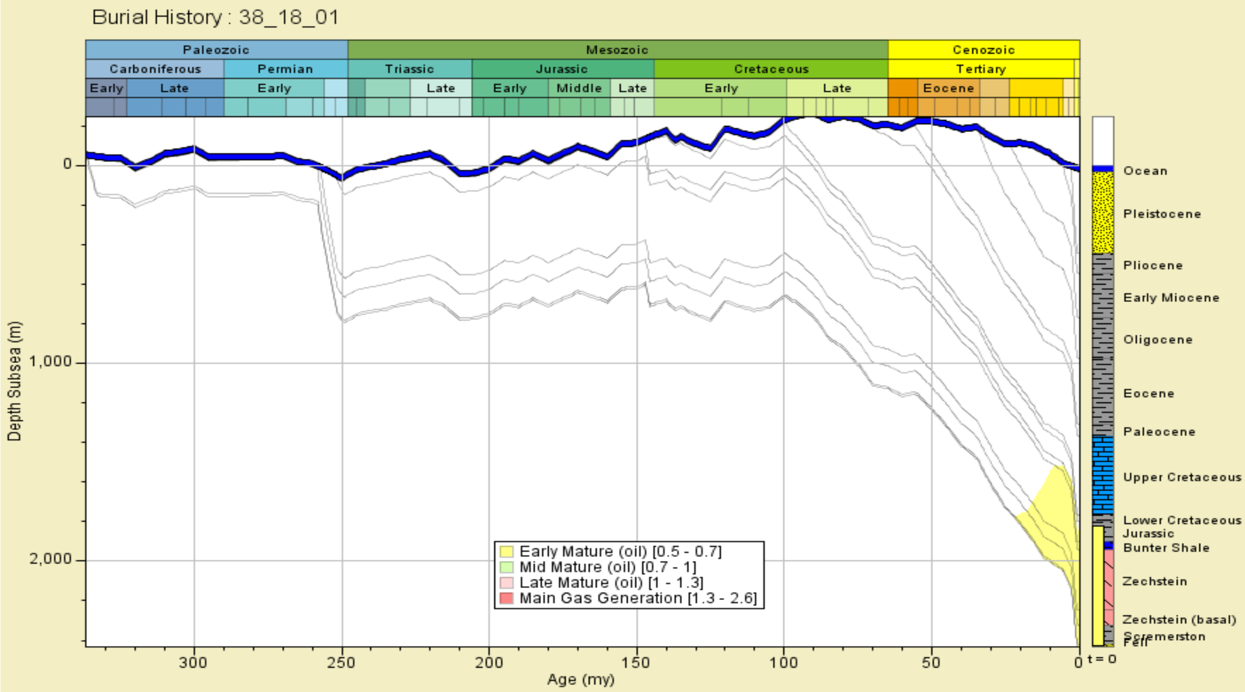


Figure 75: Modelled maturity geohistory for Well 38/18-01, Scenario 1. The well terminates in the Fell Sandstone Formation.

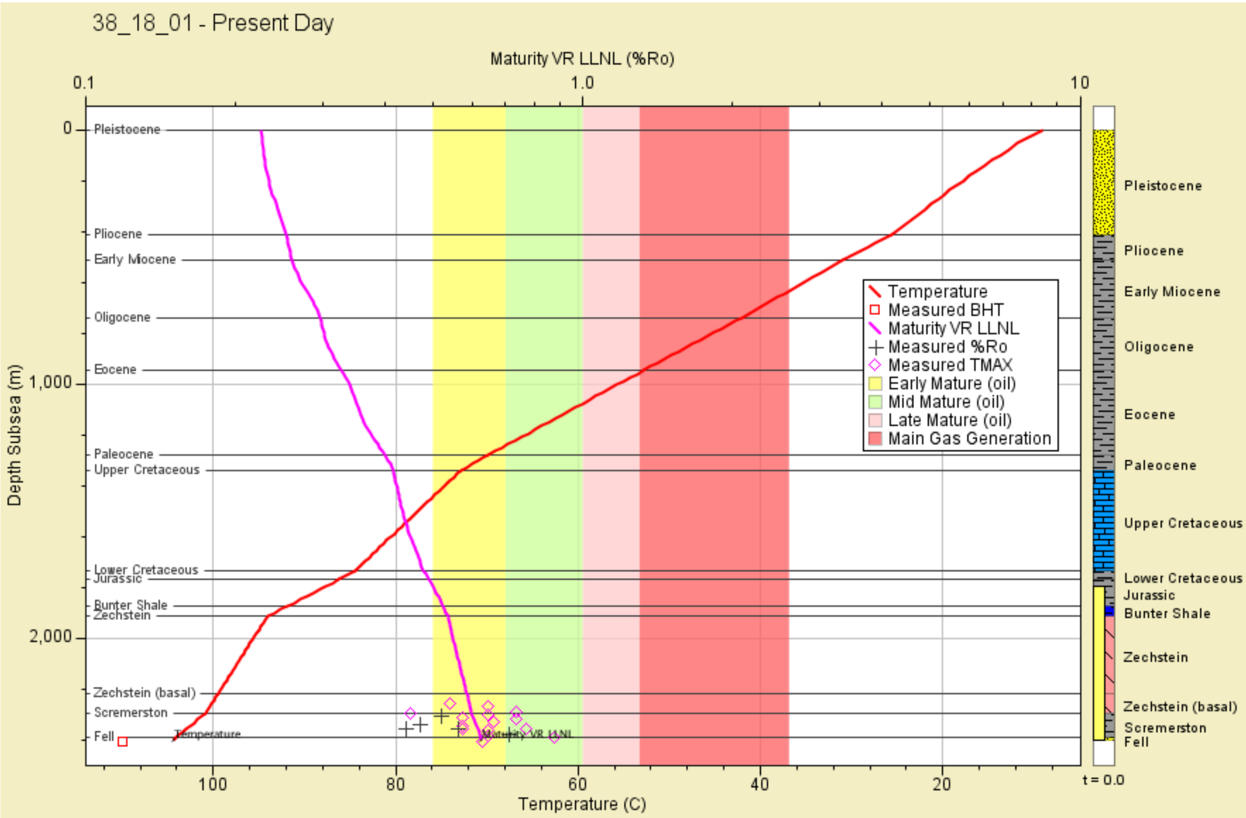


Figure 76: Depth plot for Well 38/18-01 (Scenario 1) showing model results, maturity data and maturity windows plus temperature model

8.6.2.2 Scenario 2: Burial History refined

Scenario 2 was prepared using the data from regional reports, legacy well reports and density log modelling work (Kimbell and Williamson, this study) described above.

Stratigraphy for this model uses the following layers:

- Additional strata of Miocene age added (200 m)

- Additional Lower Jurassic and Triassic strata (310 m) and Mid Jurassic erosion event added
- Assumed Stephanian strata had been eroded (200 m)
- Assumed Coal Measures Group had been eroded (750 m)
- Assumed Millstone Grit has been eroded (950 m)
- Assumed Yoredale Formation had been eroded (600 m)
- Assumed Scremerston Formation was thicker (added 100 m)

This model suggests that the Scremerston Formation is in the oil window. This uses around 2.6 km of additional burial at the end of the Carboniferous Period and around 0.3 km Jurassic or Cenozoic burial.

The legacy reports which provide VR data contain caveats suggesting the data may not be very reliable, but as the majority do plot in the low mature for oil window, thus this model seems reasonable. The VRcalc data also broadly support this maturity evaluation.

This BasinMod model uses considerably lower values for eroded strata thickness than the values proposed by Kimbell and Williamson (this study) and Hay et al. (2005). The model is sensitive to Cenozoic burial but insensitive to Jurassic or Carboniferous burial. There is limited maturity data for the Carboniferous strata, reported quality issues with the VR data and no maturity data for the post-Palaeozoic section. Therefore, confidence in this model is low.

The modelled maturity geohistory is given in Figure 78. Model results are given in Figure 80. The model fits the maturity data (VR and VR calc) well but appears to underestimate the temperature compared with the BHT data. The model generation potential for strata in the well is given in Figure 81. Timing for generation from the most promising horizon is given in Figure 82. The model data entry sheet is shown in Figure 83.

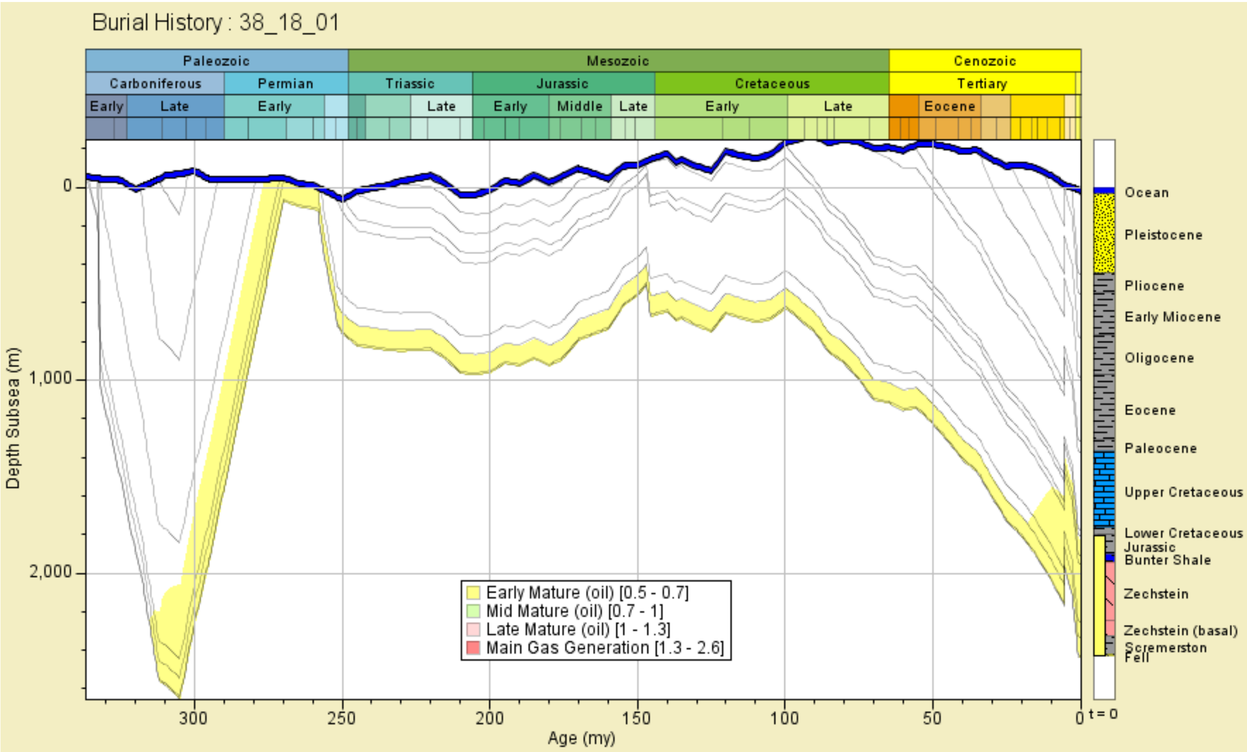


Figure 77: Modelled maturity geohistory for Well 38/18-01, Scenario 2. The well terminates in the Fell Sandstone Formation.

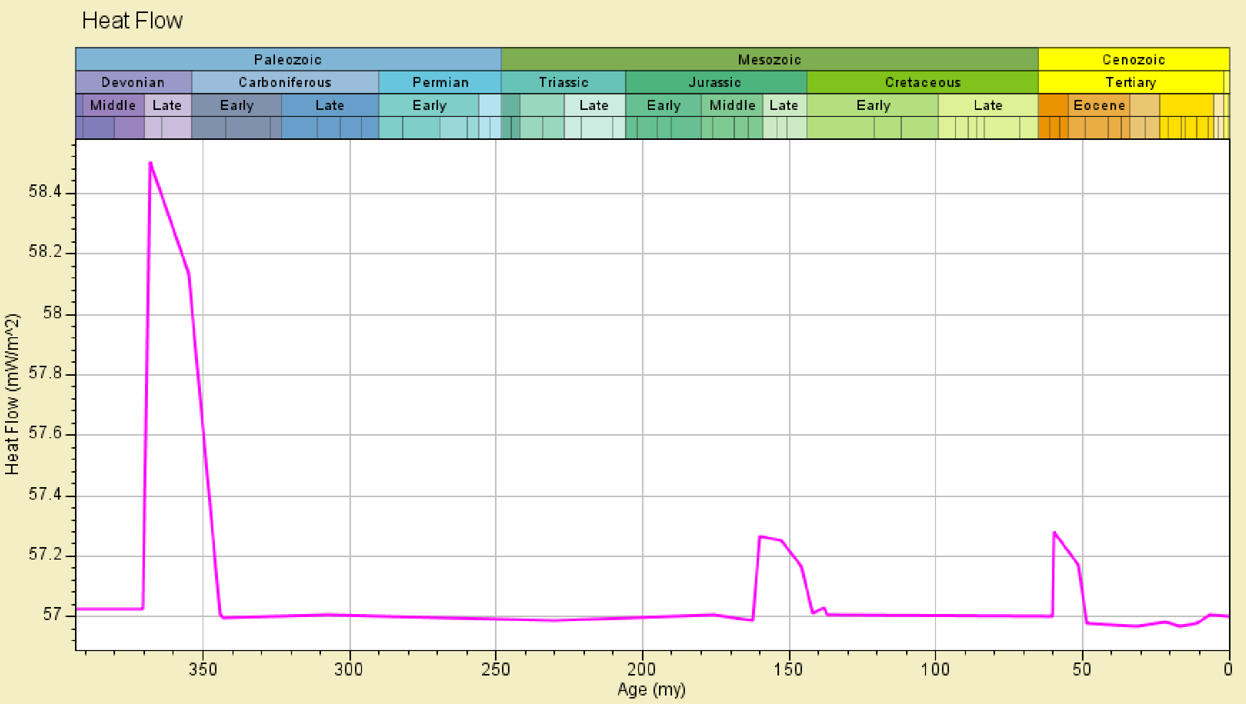


Figure 78: Modelled palaeo-heat flow for Well 38/18-01, Scenario 2

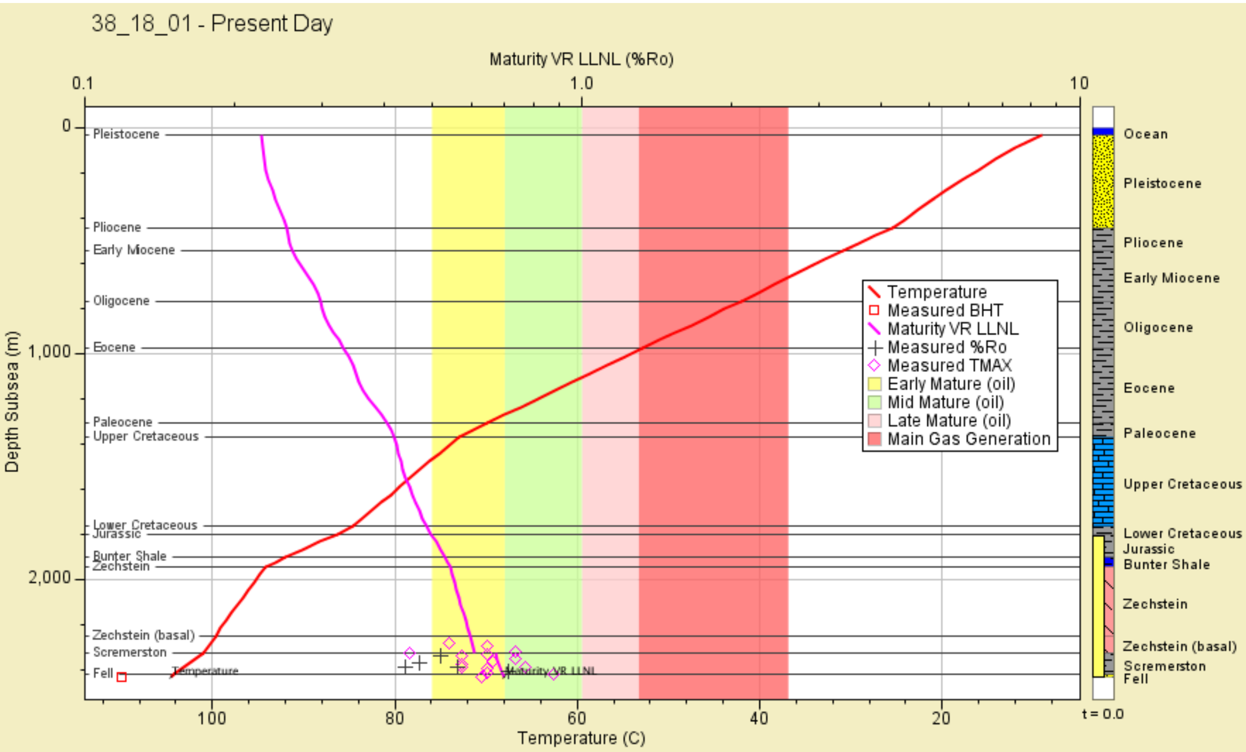


Figure 79: Depth plot for Scenario Well 38/18-01 (Scenario 2) showing model results, maturity data and maturity windows plus temperature model

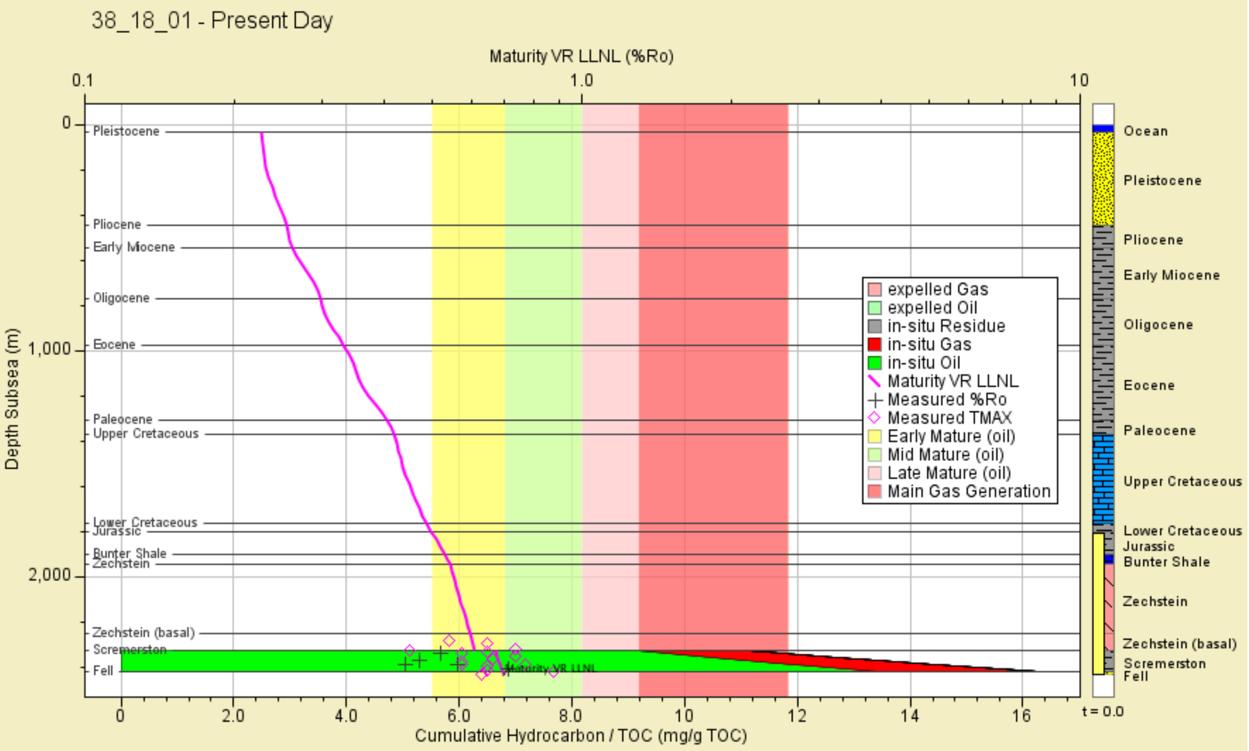


Figure 80: Depth plot for Well 38/18-01 (Scenario 2) showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

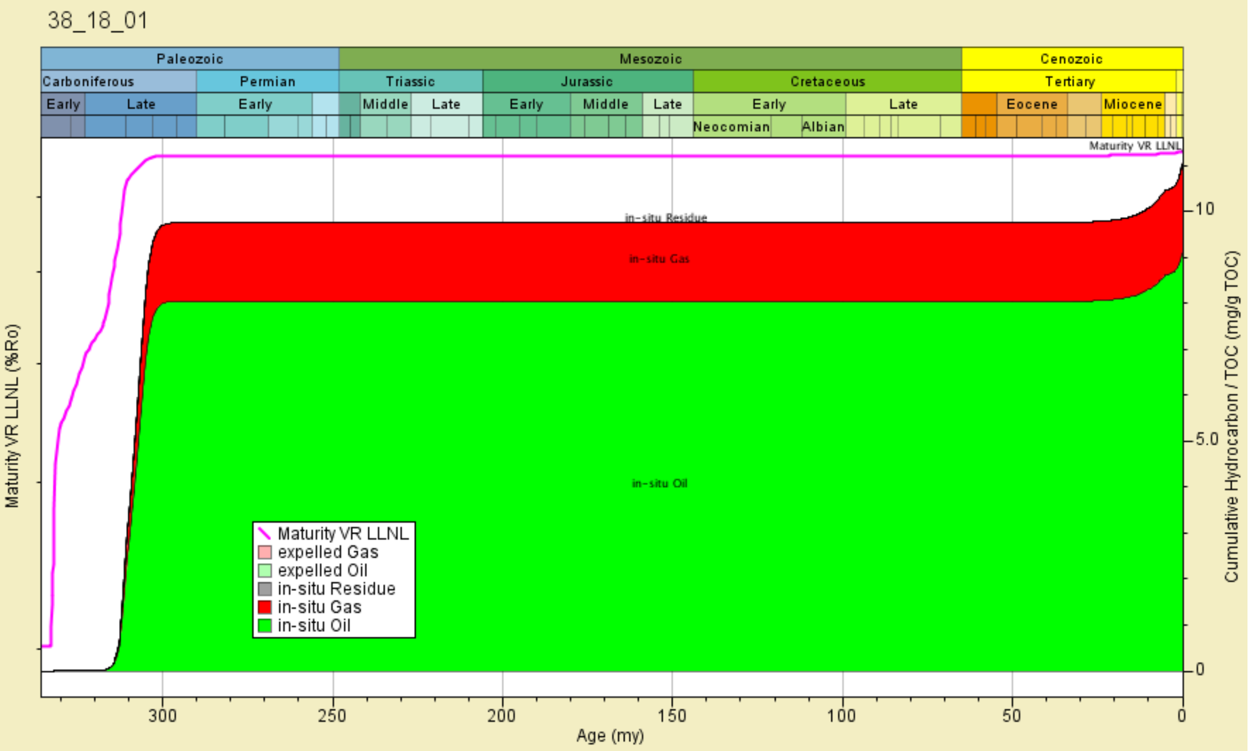


Figure 81: Time plot for Well 38/18-01 (Scenario 2) showing timing of generation for Scremerston Formation. Scenario 2 suggests that main generation occurred during The Carboniferous Period.

38_18_01 | 38_18_01: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	...	... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10						
2	Pleistocene (d)	Deposit	0.126			10	Pleist_w10					
3	Pleistocene	Formation	0.781	*65.23*	*413.92*		Pleist_w10					
4	Pliocene	Formation	2.6	*479.15*	*99.97*		PLio_w10					
5	Late Miocen...	Erosion	5.322			-200						
6	Late Miocen...	Deposit	5.326			200	Mio_w10					
7	Early Miocene	Formation	12.1	**579.12**	*223.11*		Mio_w10					
8	Oligocene	Formation	23.05	**802.23**	*206.66*		Olig_w10					
9	Eocene	Formation	33.91	**1,008.89**	*333.45*		Eoc_w10					
10	Paleocene	Formation	55.81	**1,342.34**	*59.74*		Palc_w10					
11	Upper Creta...	Formation	70	*1,402.08*	*397.76*		U_Cret_W10					
12	Lower Creta...	Formation	99.61	*1,799.84*	*33.84*		L_Cret_w10					
13	Jurassic	Formation	145.53	*1,833.68*	*103.02*		U_Jur_w10					
14	Cimmerian (e)	Erosion	147			-310						
15	Jurassic (Lia...	Deposit	175.6			10	Lias_L_Jur_w10					
16	Upper Triass...	Deposit	199.59			100	U_Trias_w10					
17	Middle Trias...	Deposit	230			100	M_Tria_w10					
18	Bunter Sand...	Deposit	245			100	Sandstone					
19	Bunter Shale	Formation	249.02	**1,936.7**	*39.93*		Shale					
20	Zechstein	Formation	251.51	*1,976.63*	*304.8*		Zech_w10					
21	Zechstein (b...	Formation	257	*2,281.43*	*76.57*		bas_Zech_w10					
22	Rotliegend (h)	Hiatus	258									
23	Variscan (e)	Erosion	270			-2,600						
24	Stephanian (d)	Deposit	305			200	Sandstone					
25	Coal Measur...	Deposit	312			750	Coal Measures_w9					
26	Millstone (d)	Deposit	318			950	Mill_w9					
27	Yoredale (d)	Deposit	332			600	Yore_w9					
28	Scremerston...	Deposit	332.5			100	Screm_w10					
29	Scremerston	Formation	333	*2,358*	*97.16*		Screm_w10		Kerogen Mix 5	2.5	2.5	0.2
30	Fell	Formation	336	*2,455.16*	*9.84*		Fell_w10					

Model Begin Age: 337 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Figure 82: Model data entry sheet for Well 38/18-01 (Scenario 2). Top Depth is in m BRT

8.6.2.3 Scenario 3: Burial required to achieve gas generation from Scremerston Formation

In order for the Scremerston Formation to reach the gas window, if the Cenozoic strata thickness is the same as for Scenario 2 but an additional thickness of Jurassic strata is added (in line with analysis of the density log; Kimbell and Williamson, this study), then around 4.4 km of additional Carboniferous burial is required.

The model maturity geohistory is given in Figure 84. Model results are given in Figure 86. The model data entry sheet is shown in Figure 89.

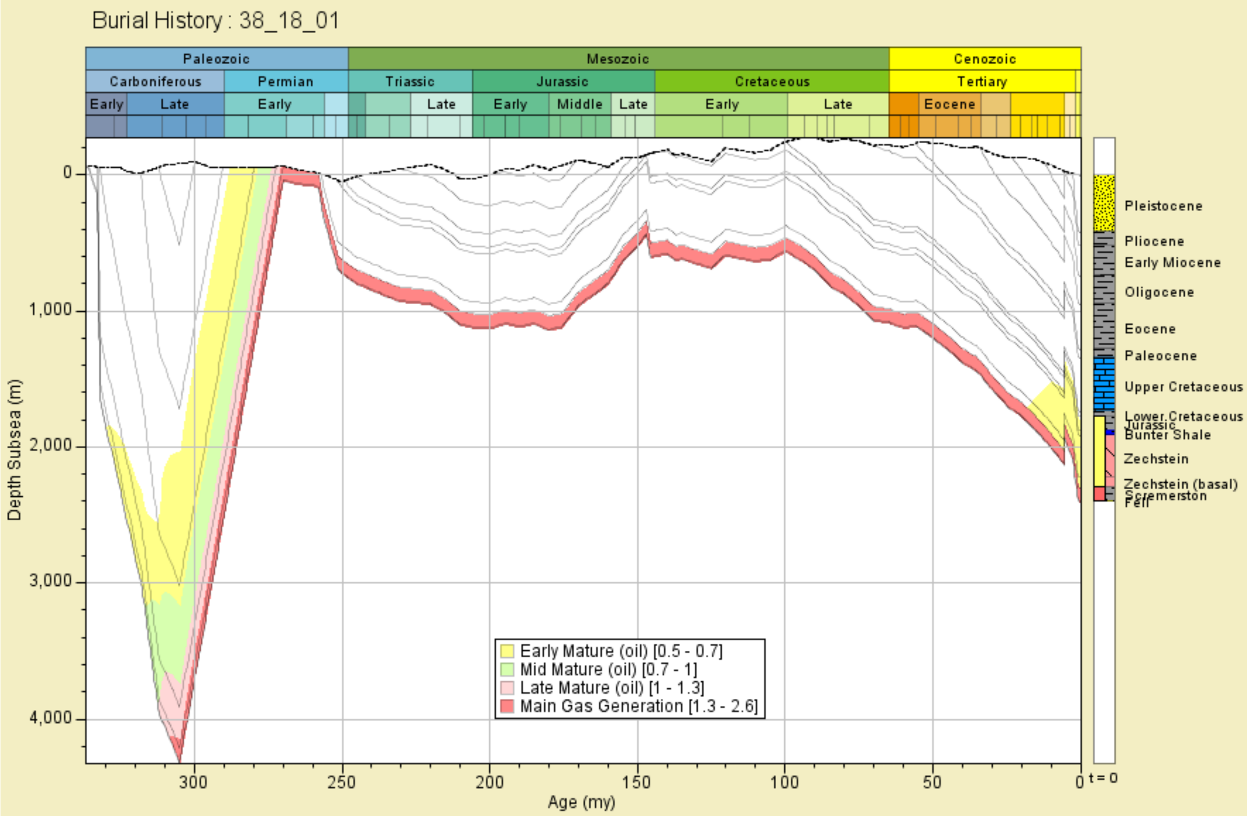


Figure 83: Modelled maturity geohistory for Well 38/18-01, Scenario 3. The well terminates in the Fell Sandstone Formation.

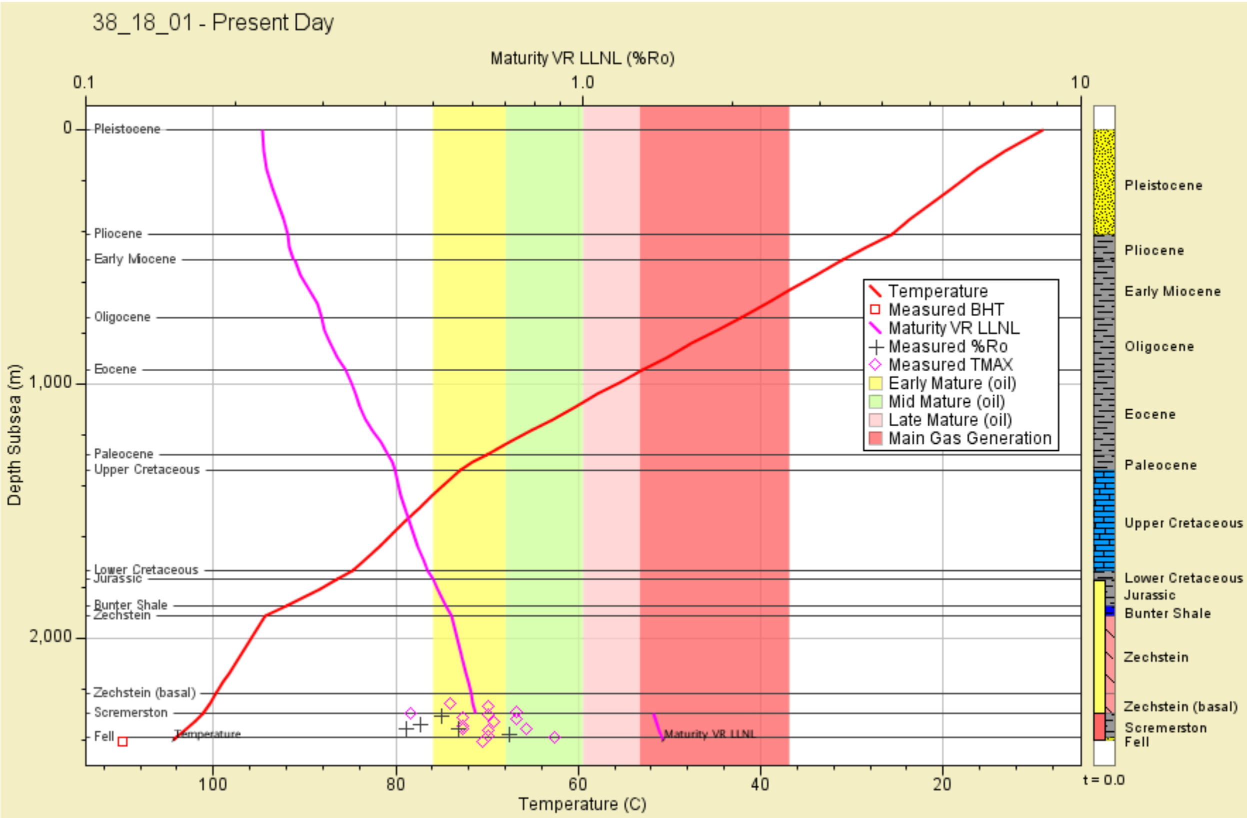


Figure 84: Depth plot for Well 38/18-01 (Scenario 3) showing model results, maturity data and maturity windows plus temperature model

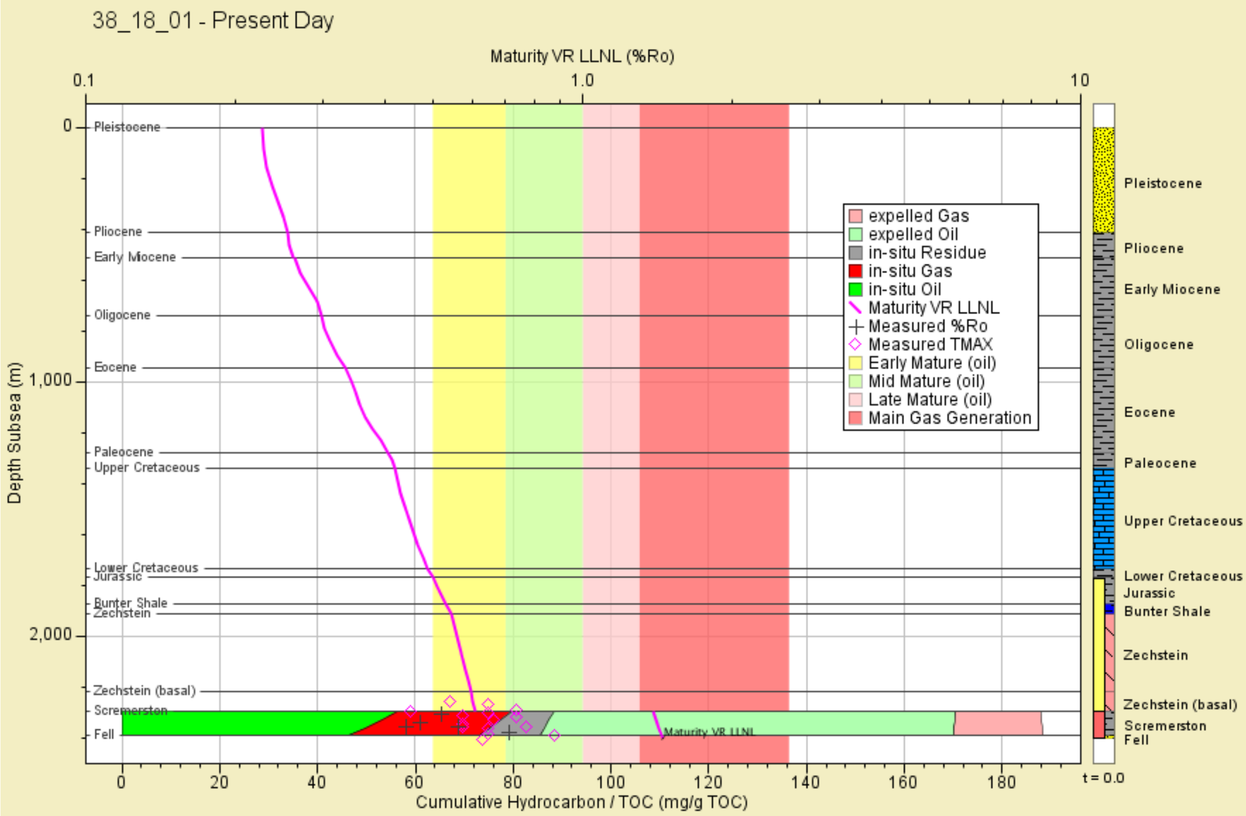


Figure 85: Depth plot for Well 38/18-01 (Scenario 3) showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

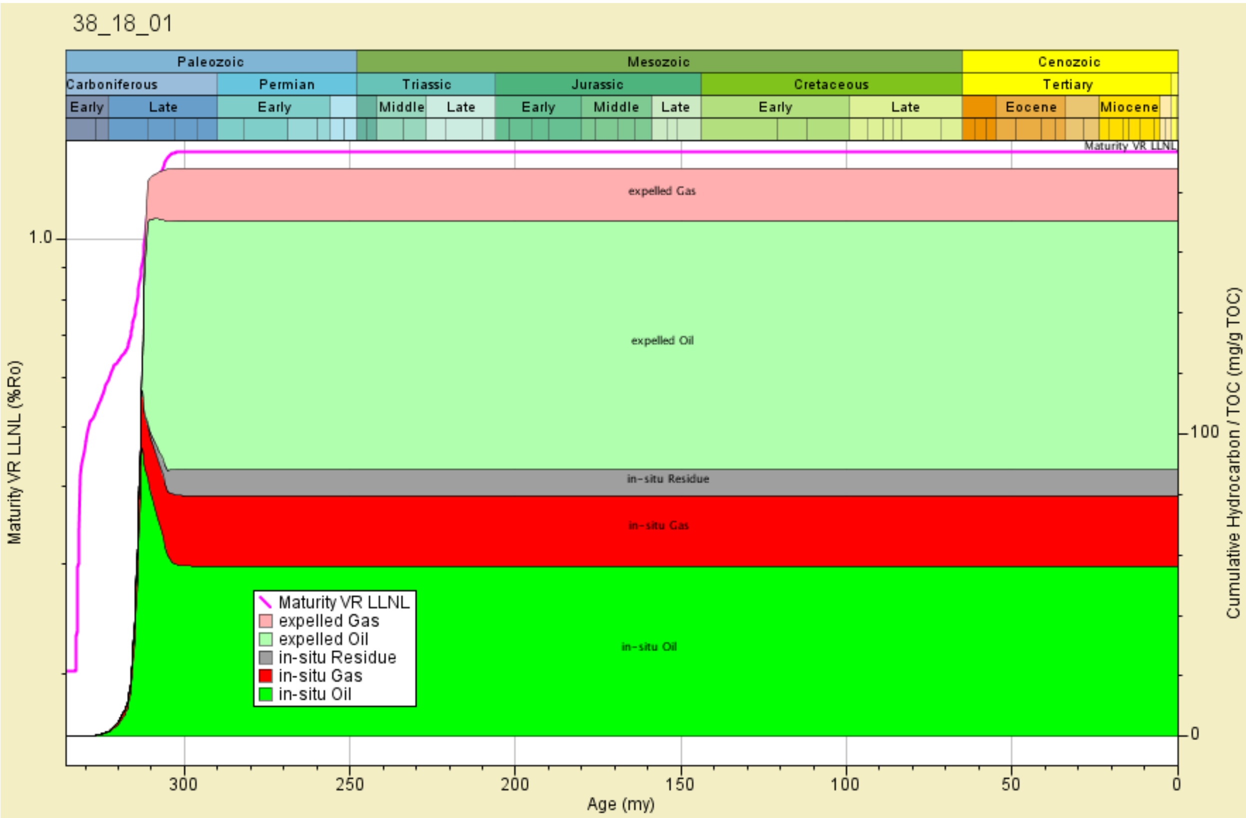


Figure 86: Time plot for Well 38/18-01 (Scenario 3) showing timing of generation for Scremerston Formation. Scenario 3 suggests that main generation and expulsion occurred during deepest burial during the Carboniferous Period.

38_18_01 | 38_18_01: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	... Lithology	...	... Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10						
2	Pleistocene (d)	Deposit	0.126			10	Pleist_w10					
3	Pleistocene	Formation	0.781	*65.23*	*413.92*		Pleist_w10					
4	Pliocene	Formation	2.6	*479.15*	*99.97*		PLio_w10					
5	Late Miocen...	Erosion	5.322			-200						
6	Late Miocen...	Deposit	5.326			200	Mio_w10					
7	Early Miocene	Formation	12.1	**579.12**	*223.11*		Mio_w10					
8	Oligocene	Formation	23.05	**802.23**	*206.66*		Olig_w10					
9	Eocene	Formation	33.91	**1,008.89**	*333.45*		Eoc_w10					
10	Paleocene	Formation	55.81	**1,342.34**	*59.74*		Palc_w10					
11	Upper Creta...	Formation	70	*1,402.08*	*397.76*		U_Cret_W10					
12	Lower Creta...	Formation	99.61	*1,799.84*	*33.84*		L_Cret_w10					
13	Jurassic	Formation	145.53	*1,833.68*	*103.02*		U_Jur_w10					
14	Cimmerian (e)	Erosion	147			-650						
15	Jurassic (Lia...	Deposit	175.6			50	Lias_L_Jur_w10					
16	Upper Triass...	Deposit	199.59			200	U_Trias_w10					
17	Middle Trias...	Deposit	230			200	M_Tria_w10					
18	Bunter Sand...	Deposit	245			200	Sandstone					
19	Bunter Shale	Formation	249.02	**1,936.7**	*39.93*		Shale					
20	Zechstein	Formation	251.51	*1,976.63*	*304.8*		Zech_w10					
21	Zechstein (b...	Formation	257	*2,281.43*	*76.57*		bas_Zech_w10					
22	Rotliegend (h)	Hiatus	258									
23	Variscan (e)	Erosion	270			-4,400						
24	Stephanian (d)	Deposit	305			600	Sandstone					
25	Coal Measur...	Deposit	312			1,000	Coal Measures_w9					
26	Millstone (d)	Deposit	318			1,300	Mill_w9					
27	Yoredale (d)	Deposit	332			1,000	Yore_w9					
28	Scremerston...	Deposit	332.5			500	Screm_w10					
29	Scremerston	Formation	333	*2,358*	*97.16*		Screm_w10		Kerogen Mix 5	2.5	3.1	0.2
30	Fell	Formation	336	*2,455.16*	*9.84*		Fell_w10					

Model Begin Age: 337 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Figure 87: Model data entry sheet for Well 38/18-01 (Scenario 3). Top Depth is in m BRT

8.6.3 Key points from new modelling work for Well 38/18-01

- The current model is constrained by limited Carboniferous data
- Confidence in the model is low as there are few VR data, there are data quality issues and the difference between VR and VRcalc datasets is quite large over a small depth range.
- Main generation occurs during Cenozoic burial for Scenario 2 (and during Carboniferous for Scenario 3)
- The Model suggests that the Scremerston Formation was early mature for oil (and the organic matter is reported as being oil prone in the upper part of the Scremerston Formation) thus some generation could be expected (Scenario 2).
- Legacy reports suggest the Scremerston Formation has excellent source potential, but it is not clear if the oil staining in the Scremerston Formation is from oil generated in-situ or oil that has migrated in from more mature source rocks
- Deepest burial was during the Cenozoic Era (Scenario 2)
- Gas shows observed in the younger section suggest gas has migrated in from elsewhere or been generated in younger strata as the Scremerston Formation is not mature for gas in this well
- An additional 4.4 km of burial would be required for the Scremerston Formation to reach the main gas maturity window at this location

9 BasinView and BasinFlow modelling

The 1D BasinMod models were used as the basis for regional 3D maturity and migration modelling across the whole CNS study area. The maturity and migration modelling was undertaken in BasinView and BasinFlow to draw together the results of the 1D models, in an attempt to provide a regional overview.

9.1 STRATIGRAPHY SIMPLIFICATION

In order to generate grids and models across the whole region, the stratigraphy had to be simplified so that a common name was used for each layer in all wells. In order to simplify the well stratigraphy for this exercise, formations were renamed and in some cases combined as detailed in Table 13. The ages for these layers were also made consistent to allow the flow modelling process to work. The simplified models used as input for the BasinView gridding and BasinFlow modelling are shown in Appendix 1. The Scenario wells were added for the second attempt at gridding which is shown in this section of the report.

Table 13: Simplification of stratigraphy

BasinFlow model layer	1D model simplification
Pleistocene	Sometimes given as Pliocene – Pleistocene so arbitrary divisions made (Well 29/27-01). Pleistocene and recent layer used as Pleistocene for Well 36/13-01. Recent layer used as Pleistocene for Well 41/20-01.
Pliocene	Sometimes given as Pliocene – Pleistocene so arbitrary divisions made (Well 29/27-01)
Late Miocene	Miocene subdivided as Late Miocene was frequently a period of erosion across the CNS (arbitrary division; Well 29/27-01 where Mid – Late Miocene is indicated)
Early Miocene	Miocene subdivided as Late Miocene was frequently a period of erosion across the CNS (arbitrary division; Well 29/27-01, layer is labelled as Early – Mid Pliocene but assume this is Early – Mid Miocene)
Split into Middle and Upper Triassic	Triassic sometimes undifferentiated Arbitrary division (Wells 41/14-01, 41/20-01)
Bunter sandstone and Bunter shale	Triassic, sometimes undifferentiated Divided Triassic strata based on lithology (Well 26/08-01) Assumed all Bunter Shale as lithology comprised all mudstone (Well 26/14-01)
Zechstein divided only into Upper Evaporite rich part and basal lower limestone part	Zechstein had sub-divisions in some wells (26/14-01, 41/20-01, 41/20-01) and was undivided in others (Well 36/13-01)
Rotliegend	Simplified to 'Lower Permian' model layer
Stephanian strata	Boulton Formation present in Well 26/08-01
Coal Measures	Cleaver, Westoe, Caister combined (Well 41/20-01)

Millstone Grit	Passage Formation (Well 26/08-01) Millstone Grit, Cleveland E (Well 43/17-02)
Yoredale	Cleveland E, Upper Bowland shale, Cleveland D combined (Well 41/14-01, 43/17-02) Upper Bowland Shale combined Cleveland D (Well 43/17-02)
Scremerston	Cleveland C, Cleveland B, Cleveland A combined (Well 41/14-01)
Fell	Same
Cementstone	Same
Upper Old Red Sandstone	Assumed Tayport was equivalent (Well 42/10b-02)
Kyle	Same
Lower Old Red Sandstone	Assumed Lower Devonian strata was equivalent to LORS (Well 26/14-01)

9.2 BASINVIEW GRIDDING

The 1D wells were input to BasinView and gridded. BasinView is used to generate grids for input to BasinFlow and to display the BasinFlow results.

Due to time limitations, only one source-reservoir scenario was considered: The source rock considered was the Scremerston Formation, the reservoir rock was the Lower Permian model layer (equivalent to the Rotliegend Group).The top of the Lower Permian model layer was generated using the depth converted grid (5 km spacing) from seismic interpretation which is the ‘Base Zechstein and top pre-Permian’ grid.

An initial coarse grid (380 nodes) was generated to test the process through to flow modelling. The first attempt did not include the scenario wells. As generation appeared to be concentrated in the extreme south of the area, a second coarse grid was generated including the scenario wells, where assumptions were made about the kerogen type and TOC (see previous sections for more detail on assumptions). When the BasinFlow models had been generated with the coarse grid (with 380 nodes) to confirm the process would run, a more refined grid was generated (around 2800 nodes). Increasing the number of grid nodes made a significant difference to the flow model results.

Some example input grids for BasinFlow are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The refined grid (around 2800 nodes) is shown in Figure 90.

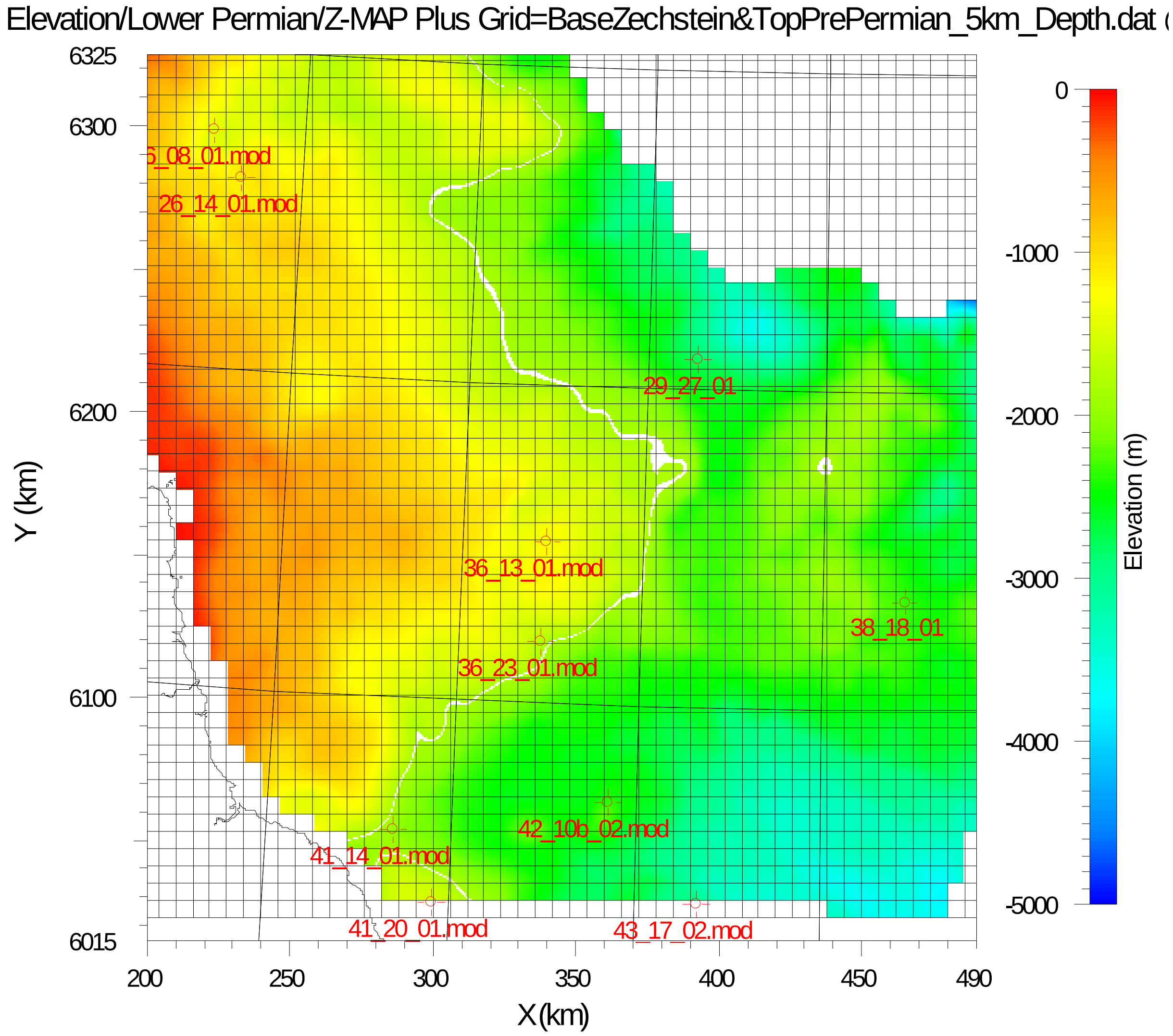


Figure 88: Grid nodes (small squares outlined in black) and depth to top Lower Permian model layer (colour). Grid area was selected to cover Lower Permian depth grid

9.2.1 Scremerston Formation maturity

As the Scremerston Formation and equivalents was shown to be a source rock in the 1D modelling and seismic grids were available for this horizon over a wide area, this layer was selected for maturity modelling. The first grid was generated in BasinView from the well data. This covered the whole area of interest (**Error! Reference source not found.Error! Reference source not found.**).

The depth to top Scremerston Formation was included from the seismic Arsenikos et al. (this study; 5 km grids). At this point, the maturity grid in BasinView was restricted to the area covered by the interpretation surface (Figure 91).

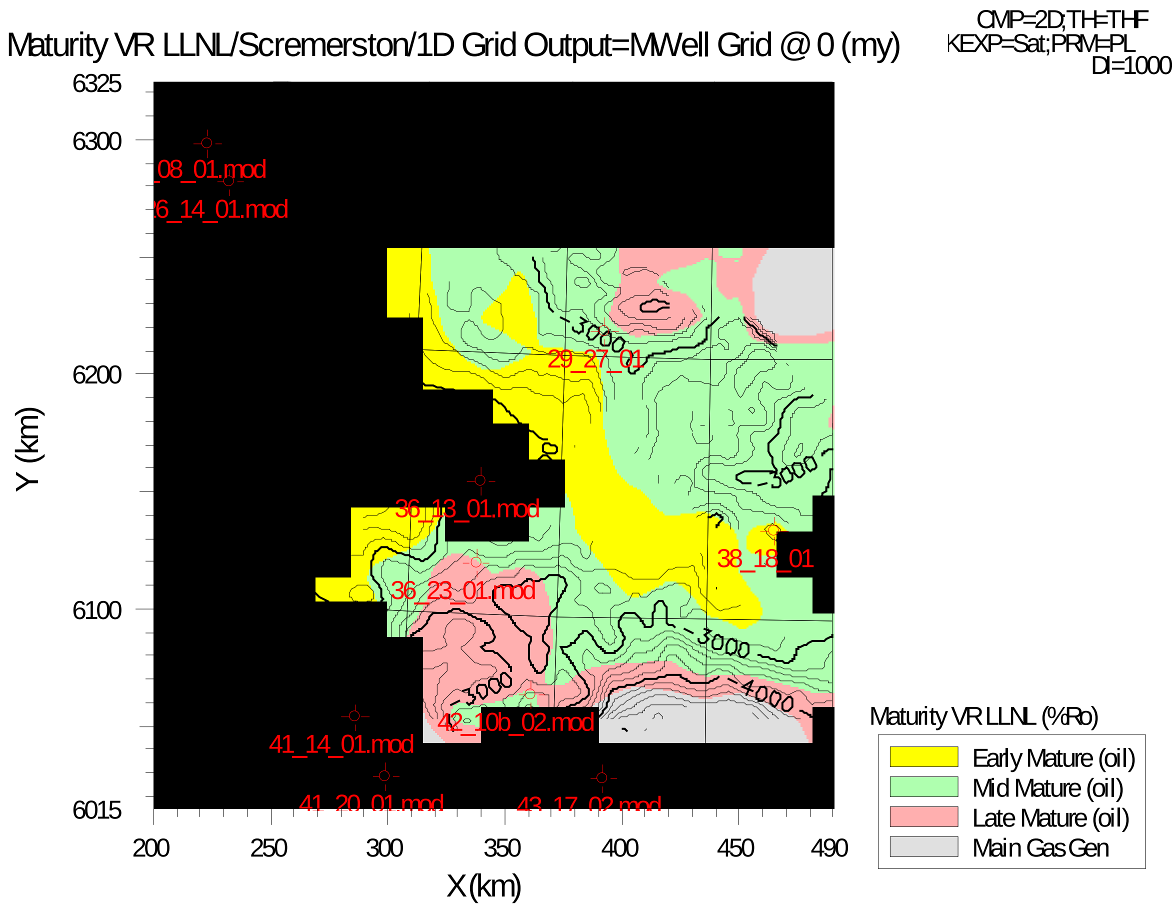


Figure 89: Maturity grid after inclusion of the top Scremerston depth grid in the BasinView model. Colour indicates maturity window, contours show depth to top Scremerston Formation from seismic interpretation (5 km grid). Model time is present day. No Scremerston is present in the centre (the large area indicated as early mature for oil). The contours show the area where Scremerston has been interpreted on seismic (Arsenikos et al., this study). The area in the north of Quadrant 30 is not covered by base Zechstein depth converted grid and there are no wells so during the gridding process the BasinView software has interpolated depth to base Zechstein across this region based on the nearest contours from the depth conversion grid and the 1D well models. Therefore, results from this area are considered to be spurious.

9.3 FLOW MODELS

For the BasinFlow model, a source and reservoir layer is selected. The main source rock was assumed to be the Scremerston Formation and lateral equivalents (Figure 91). This was because it is the source rock interval with the most widespread extent across the study area and has seismic grids to constrain it. The Rotliegend Group (the Lower Permian layer) was chosen as the reservoir layer with the top of the reservoir represented by the depth-converted 'Base Zechstein and top pre-Permian' grid.

This model only represents one potential flow scenario, with the source as the Scremerston Formation and the reservoir as the Rotliegend/top pre-Permian layer.

The maturity and kerogen information entered into the 1D models was imported into BasinView and used for the BasinFlow simulation. Considering the results of the flow models, the following assumptions used for the 1D models are included here as caveats as they may have affected the results: As kerogen data were not available for Well 29/27-01, an arbitrary value was entered based on Well 38/18-01 which lies in the continuation of the same basin. Minor gas shows were also reported in the 29/27-01 well log. For Well 42/10b-02, average TOC from wireline data were not available and so averages from legacy RockEval reports were used which is likely to produce a more optimistic TOC value for this well. Confidence in the models for Wells 26/14-01, 29/27-01 and 38/18-01 is low due to data issues.

For the BasinFlow modelling, the reservoir is the Lower Permian layer (the equivalent of the Rotliegend Group using the simplified strata layers set out in Table 13), beneath the seismic depth converted grid of the base Zechstein.

Several underlying assumptions will affect the flow migration modelling:

- BasinFlow assumes perfect migration between the chosen source and reservoir layers,
- Lithological and facies variation only considers the well data entered, no areal deposition model is included
- Perfect migration between source and reservoir does not take into account facies/lithological barriers or residual trapping between source and reservoir
- No faults are included in the current model
- The Rotliegend was chosen as the main reservoir, however, only the 'Base Zechstein and top pre-Permian' depth surface was available as a 2D grid for inclusion in the model so this will introduce some error where the Rotliegend Group was not deposited and the depth grid is contiguous with the top Carboniferous instead

BasinFlow was used to assess the generation potential of the Scremerston Formation. The main kitchen area is the 'probable kitchen area' in the south of the study area and the south part of Quadrant 36 (figures 92 – 95).

The migration of oil and gas is controlled by the interplay between buoyancy[2], capillary[3] and hydrodynamic[4] vectors. The 'Base Zechstein and top pre-Permian' depth-converted layer from the project seismic interpretation was used as the top reservoir horizon and partially controls migration of the hydrocarbons through time. The grid represents the present day depth to base of the Zechstein Group. The thickness of eroded Lower Permian and the present day depth grid were utilised to calculate the topography of this surface through time by BasinView. Hydrodynamic drive appears important as this controls a large accumulation located in the north-west of the area. This accumulation is unlikely to actually be present due to a number of factors relating to sparse data and the presence of intraformational seals and other lithological complexities between the chosen source rock and chosen carrier bed.

The flow models were run with the more detailed project depth converted grid (0.5 km spacing) to test if the results were different. The regional picture of generation in the south from the mature Scremerston Formation remained the same, but the migration pathways, timing of migration and accumulations of hydrocarbons were different. In general, for the model with the finer grid, oil migration started a little later and oil did not migrate as far north and less oil migrated to the north-east. In general, for the model with the finer grid, gas migration started later but the migration distance and amounts were similar, though a little less gas migrated to the south-east.

The model results should be considered with caution:

- Wells are sparse, this model gives a regional overview only
- The reservoir elevation grid is regional, oil/gas could be trapped along migration lines in traps which are too small to see on this coarse grid

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[2] Buoyancy drive is caused by the density difference between hydrocarbons and formation water and variations in structure. BasinFlow uses this to predict structural traps (Platte River Associates, 2012)

[3] Capillary drive is caused by variations in oil-water capillary pressure, which is a function of permeability. BasinFlow uses this to predict stratigraphic traps (Platte River Associates, 2012)

[4] Hydrodynamic drive is water drive caused by groundwater flow. BasinFlow uses this to predict hydrodynamic traps (Platte River Associates, 2012)

- Running the models with the finer resolution depth grids showed that the depth grid has a important influence on the migration and accumulation of hydrocarbons, particularly oil. This strongly suggests that adding more wells and using higher resolution depth grids would improve the models.
- Thickness of the reservoir horizon has been calculated from the 'Lower Permian' layer in wells, this is highly simplified as it is currently only present in the five out of 10 wells from the BasinMod work. For the model time-steps prior to present day, the eroded thickness of the Lower Permian layer included in the 1D models will be used as part of the gridding process as well as the present day depth grid. Accumulations under this layer where it is not proven in the BasinMod 1D wells are based on the depth converted grid.
- For the model a source bed and a reservoir bed is selected, oil or gas could actually have been trapped in formations below the reservoir bed in areas where the intermediate formations are argillaceous (i.e. intraformational Carboniferous traps)
- Limited data are available from the project work for the horizons in-between the selected source and reservoir rock and there is very sparse well coverage so the grids generated by BasinView will be poorly constrained
- Wells 38/18-01 and 29/27-01 are 'scenario wells'. For Well 29/27-01, there is no information on whether source rocks are gas or oil prone and the source rock interval has not been penetrated by wells in the Quadrant 29 Basin.
- Generally the average formation TOC was used, in a few cases this was not available so average data from legacy reports was used, which is likely to have higher values due to sample bias

The accumulation of hydrocarbons from these flow simulations appear over-optimistic and results suggested that accumulations would be present in areas where dry wells have been drilled, thus the results were deemed to be potentially misleading and therefore are not included in this report.

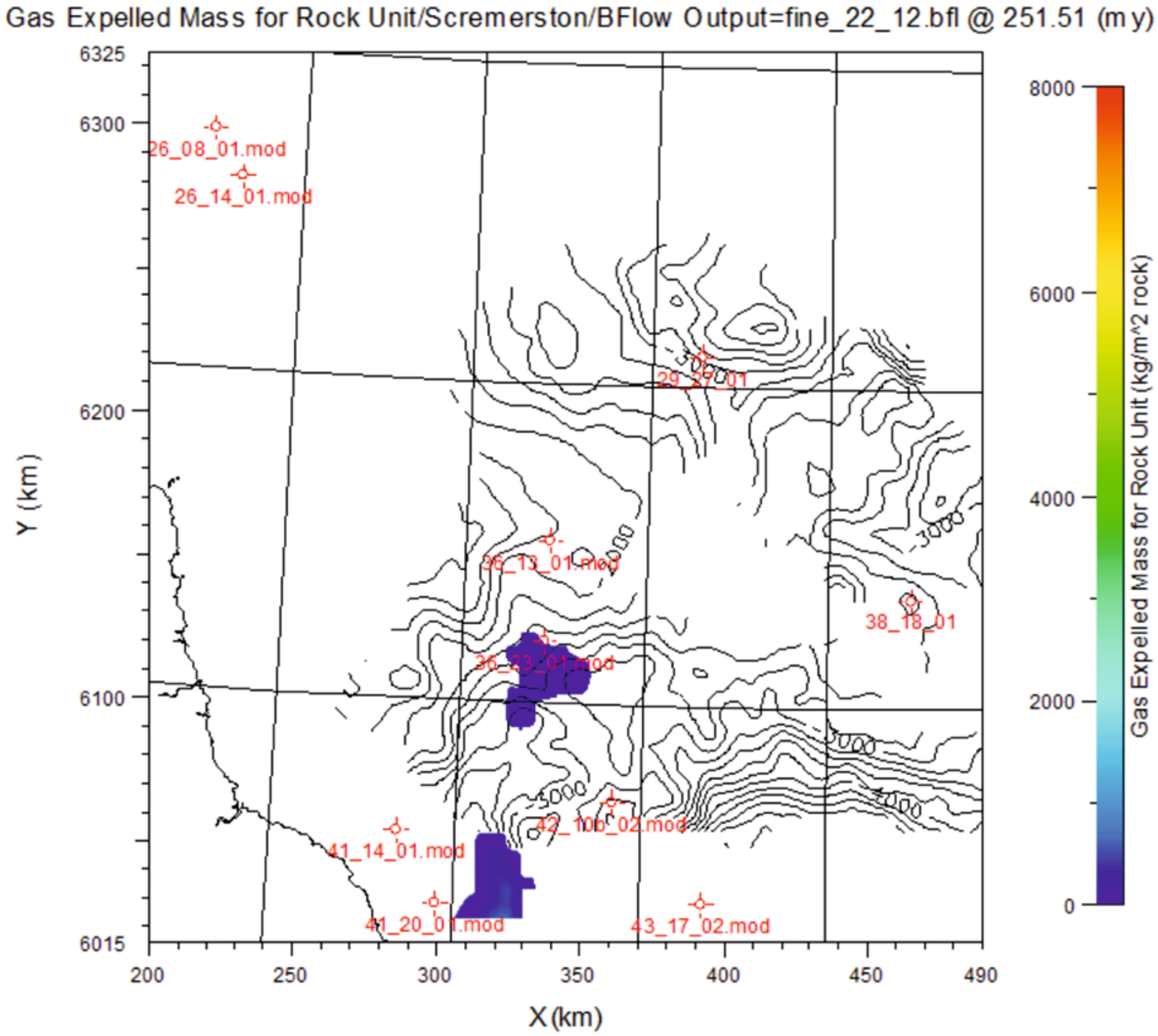

Figure 90: Model of gas expelled from the Scremerston Formation (total mass per rock unit), around end Permian times (i.e. just after deposition of the Zechstein Group). Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Palaeozoic rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region. Well 36/23-01 does not penetrate to the Scremerston Formation, but based on the depth grid, it would be expected that the Scremerston Formation reached sufficient maturity to generate hydrocarbons over the geological history of this region

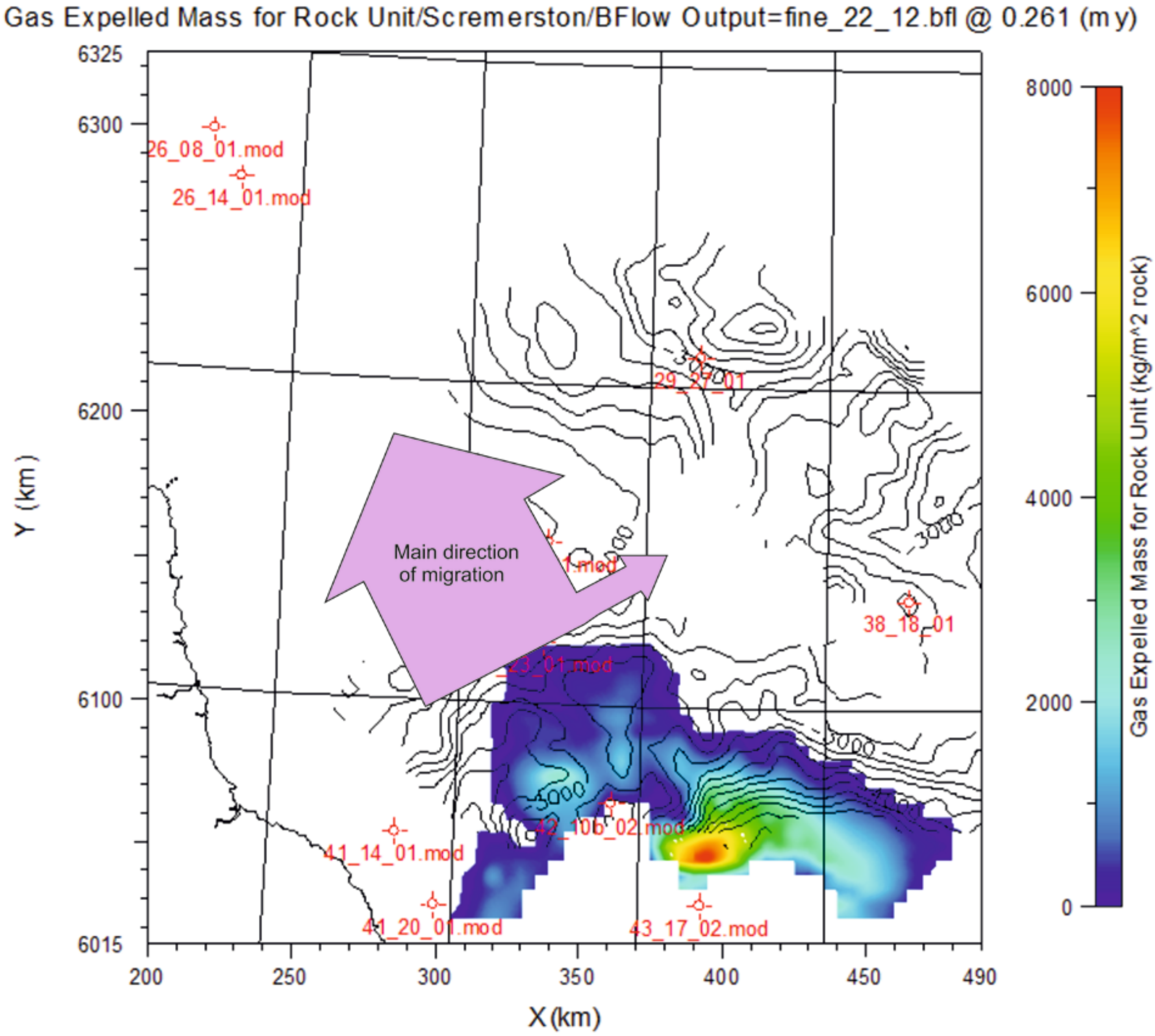

Figure 91: Model of gas expelled from the Scremerston Formation (total mass per rock unit), (model time is close to present day). Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Palaeozoic rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region.

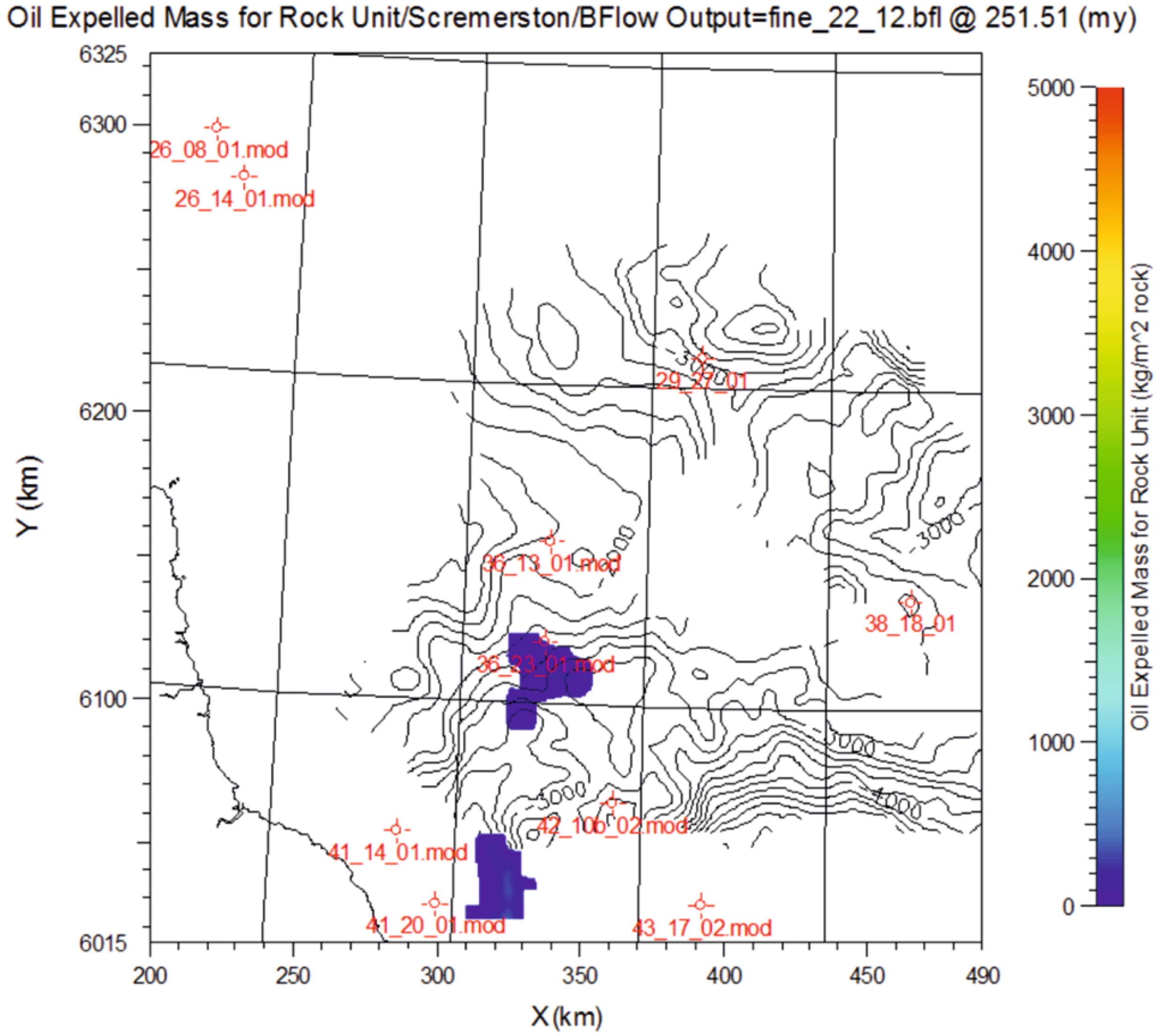

Figure 92: Oil expelled from the Scremerston Formation (total mass per rock unit), at end Permian times (i.e. just after deposition of the Zechstein Group). Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Palaeozoic rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region. Well 36/23-01 does not penetrate to the Scremerston Formation, but based on the depth grid, it would be expected that the Scremerston Formation reached sufficient maturity to generate hydrocarbons over the geological history of this region

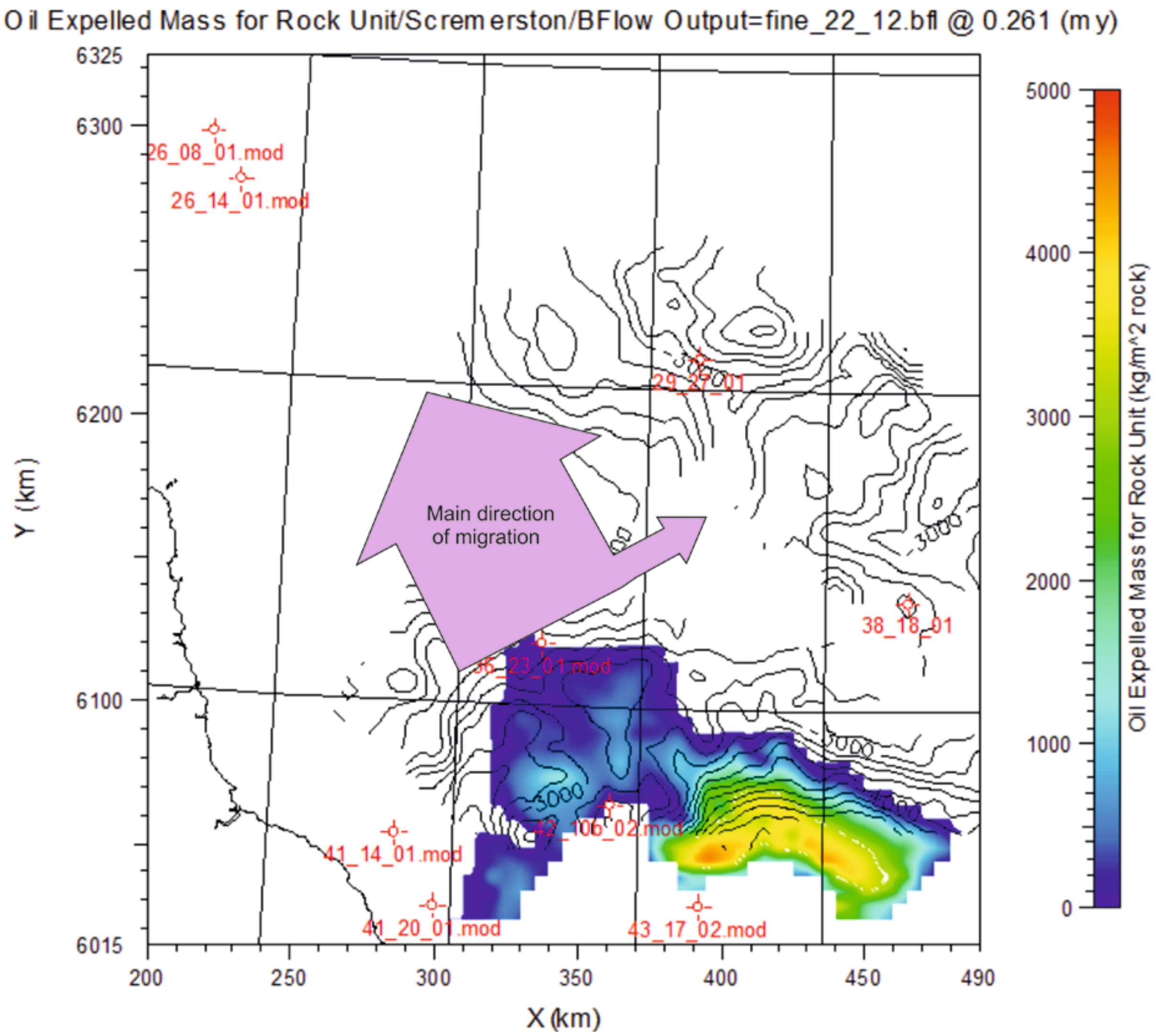

Figure 93: Oil expelled from the Scremerston Formation (total mass per rock unit) at time close to present day. Wells 43/17-02 and 41/20-01 do not penetrate to the Scremerston Formation, but based on maturity of younger Palaeozoic rocks, it would be expected that the Scremerston in this region reached the oil and gas maturity windows over the geological history of this region.

9.3.1 Key points from flow modelling

For the flow models, the source rock considered is the Scremerston Formation and the reservoir rock considered is the Lower Permian model layer (equivalent to the Rotliegend Group). BasinFlow assumes perfect migration between the source and reservoir rock. The source rock is only considered over the region where the Scremerston has been interpreted by the project team. The top of the Lower Permian model layer was generated using the depth converted grid (5 km spacing) from seismic interpretation which is the 'Base Zechstein and top pre-Permian' grid.

- The flow modelling results should be considered with caution due to the reasons given in at the end of Section 9.3 (sparseness of data, large spacing of wells, coarseness of grids, assumptions made during modelling, assumption of perfect migration between source and carrier bed etc)
- The regional assessment of the source potential seems more reliable than the migration modelling as the migration pathways will be controlled strongly by local features. Re-running the simulation with the higher resolution depth grids indicated that the flow migration timing, pathways and accumulations were affected more that the

generation/expulsion model output grids suggesting that the migration simulation is more sensitive to the lower resolution of data.

- Generation of oil and gas mainly occurred in the south kitchen area (around Quadrants 41 – 44 and south part of Quadrant 36). The main period of oil and gas generation was during deep Cenozoic burial
- Oil and gas expulsion from the Scremerston Formation mainly occurred post-deposition of the Zechstein caprock
- Regional oil and gas migration was generally north-westwards from the probable kitchen area. Migration was controlled by buoyancy, capillary and hydrodynamic vectors. Over geological time, oil and gas migrated towards highs in the reservoir layer (mainly controlled by buoyancy drive). Hydrodynamic drive also appeared to be important in controlling location of the main accumulations
- The model accumulations of hydrocarbons, particularly oil, are sensitive to the resolution of the depth converted grid. This strongly suggests that accumulations will also be sensitive to the density of well data, and as well data density is low, the accumulations are considered low confidence.

Glossary

Allochthonous vitrine Reworked vitrinite

Autochthonous vitrinite Vitrinite indigenous to the rock in which it is found

Cumulative hydrocarbon volume (mg/gTOC) The total amount of oil or gas generated (mg) per gram of organic carbon. On the figures in this report, oil and gas expelled, in-situ and residue of organic carbon which will not generate any more hydrocarbons are shown. The cumulative hydrocarbon potential plot shows the generated hydrocarbons. On time plots, the results at time = 0 show present day volumes of hydrocarbons it is anticipated the strata penetrated by the well have generated based on the BasinMod model. The time plot includes the model of the hydrogen index (HI). The HI indicates the generative potential of the rocks in the well, the cumulative hydrocarbon volume on the time plot shows the BasinMod model of this generative potential being realised and the HI model through time.

Drive vectors Drive vectors show expected migration direction of hydrocarbons (if they are present)

Fetch areas fetch areas segregate the region based on the drive vectors to show areas which would be expected to contribute to individual hydrocarbon accumulations if hydrocarbons were present

Hydrogen Index (HI) The HI is derived from the ratio of hydrogen to TOC, a higher HI indicates a greater potential to generate oil. Vane et al. (this study) used HI > 300 mg/g TOC to indicate oil prone source rocks that will generate mainly oil

Mean Ro max Mean maximum vitrinite reflectance (mean R_o max). In order to measure this, the sample is rotated 360° in order to determine maximum reflectance (which will occur at two orientations at 180° to each other). An Ro max equivalent is sometimes calculated from Ro random (e.g. using the method of Zhang and Davis (1993) where a linear relationship between Ro max and Ro random is established from data or from bitumen reflectance). Above Ro = 1.3, Ro max is said to be a more accurate measure of maturity (Beardsmore and Cull, 2001)).

Mean Ro random Mean vitrinite reflectance at random orientation (mean R_o random)

Total Organic Carbon (TOC) Total Organic Carbon is the amount of organic carbon present in a sample and is an indicator of the source potential of rocks. Organic carbon which has broken down through bacterial/chemical processes to form kerogen which has then been subject to thermal maturation (due to temperature, pressure and time) generates hydrocarbons (Crain, 2015). A higher TOC generally indicates a greater source rock potential.

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Appendix 1 Simplified models for flow modelling

The figures in Appendix 1 show the simplified versions of the BasinMod models which were used as the input for the BasinView and BasinFlow work. The layer names and ages have been simplified as indicated in Table 13 compared with the BasinMod models in the main section of the report.

26/08-01

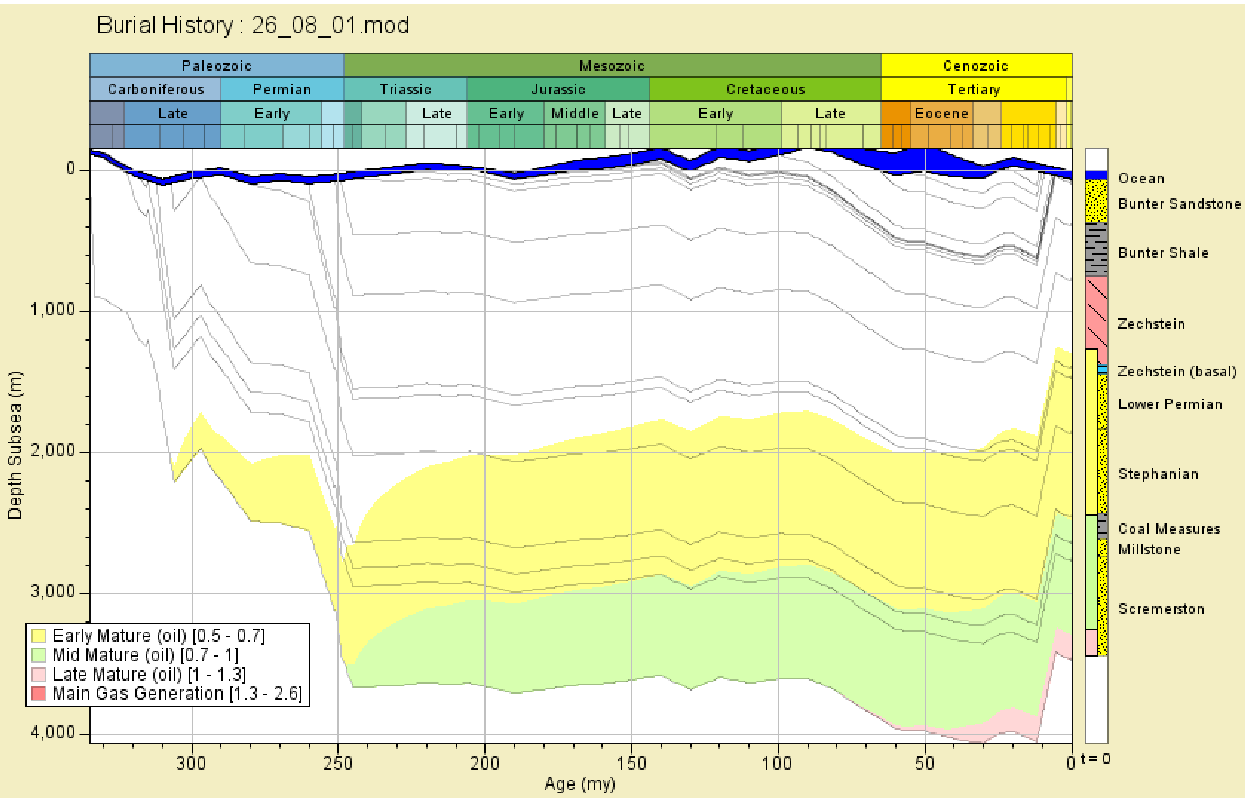


Figure 94: Burial history for Well 26/08-01 using simplified stratigraphy

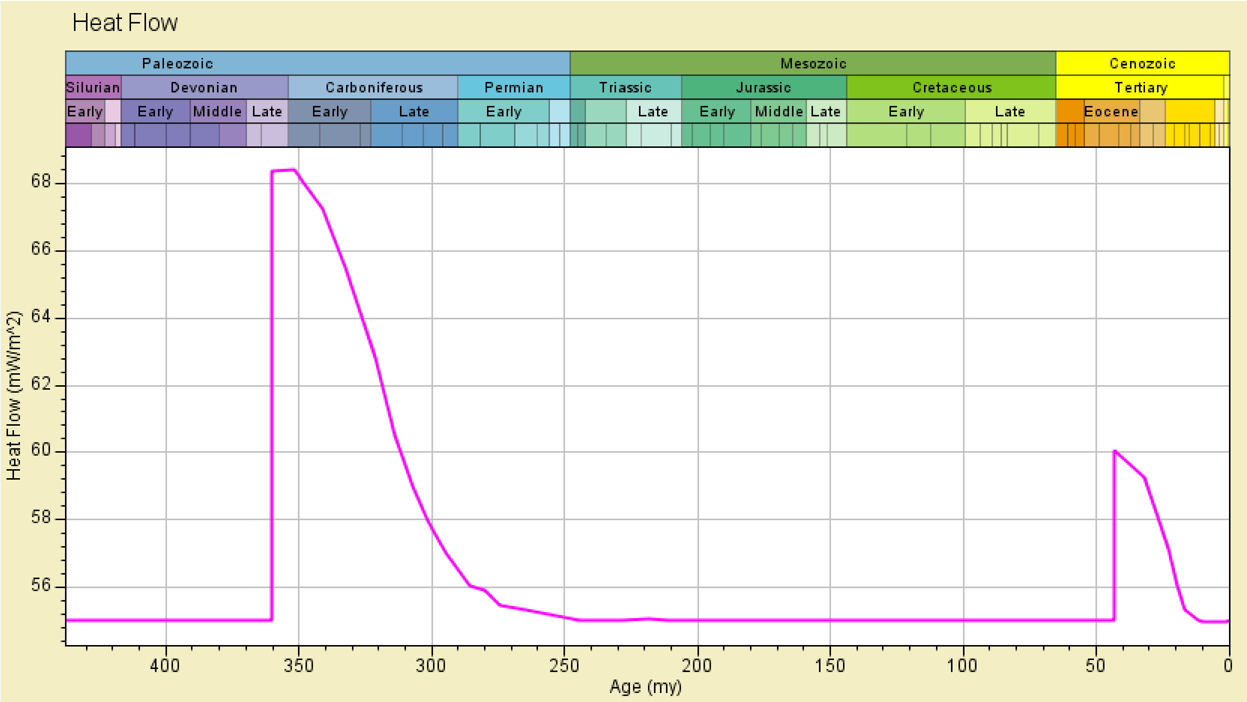


Figure 95: Palaeo-heat flow for Well 26/08-01

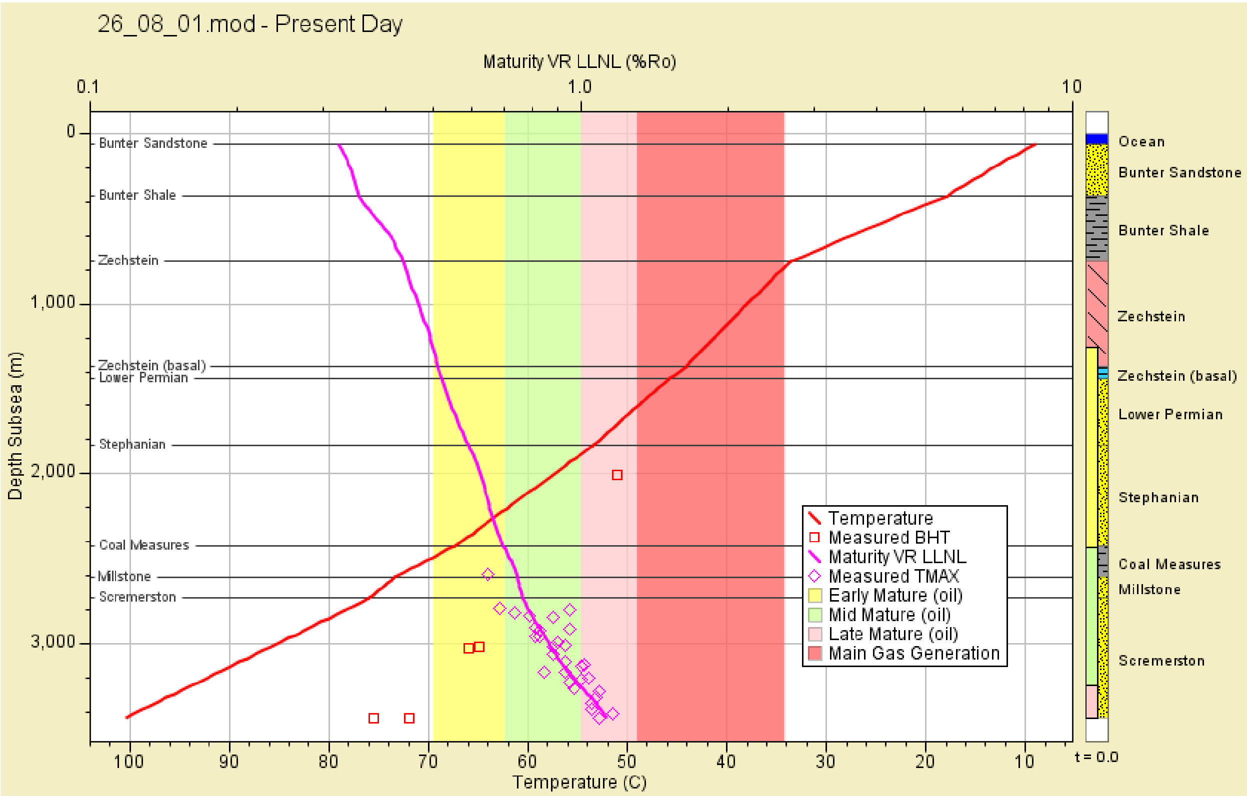


Figure 96: Depth plot for Well 26/08-01 showing model results, maturity data and maturity windows plus temperature data and model

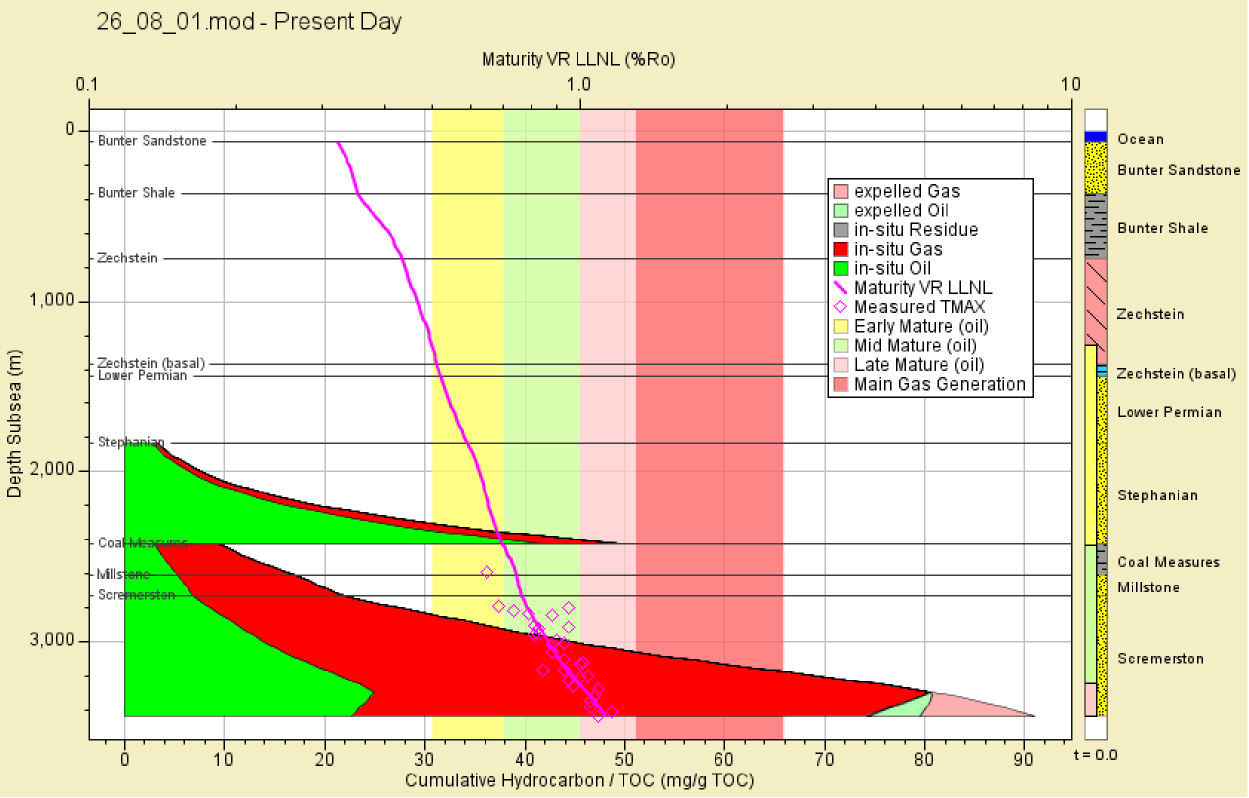


Figure 97: Depth plot for Well 26/08-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

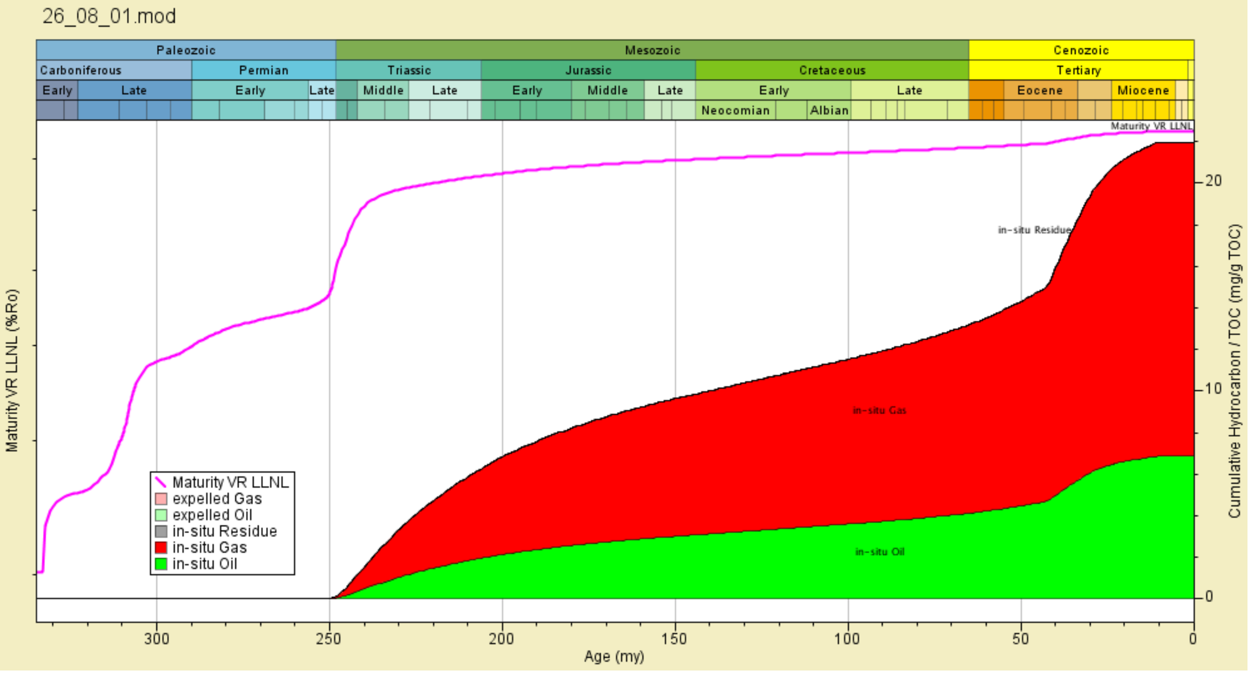


Figure 98: Time plot for Well 26/08-01 showing timing of generation for Scremerston Formation

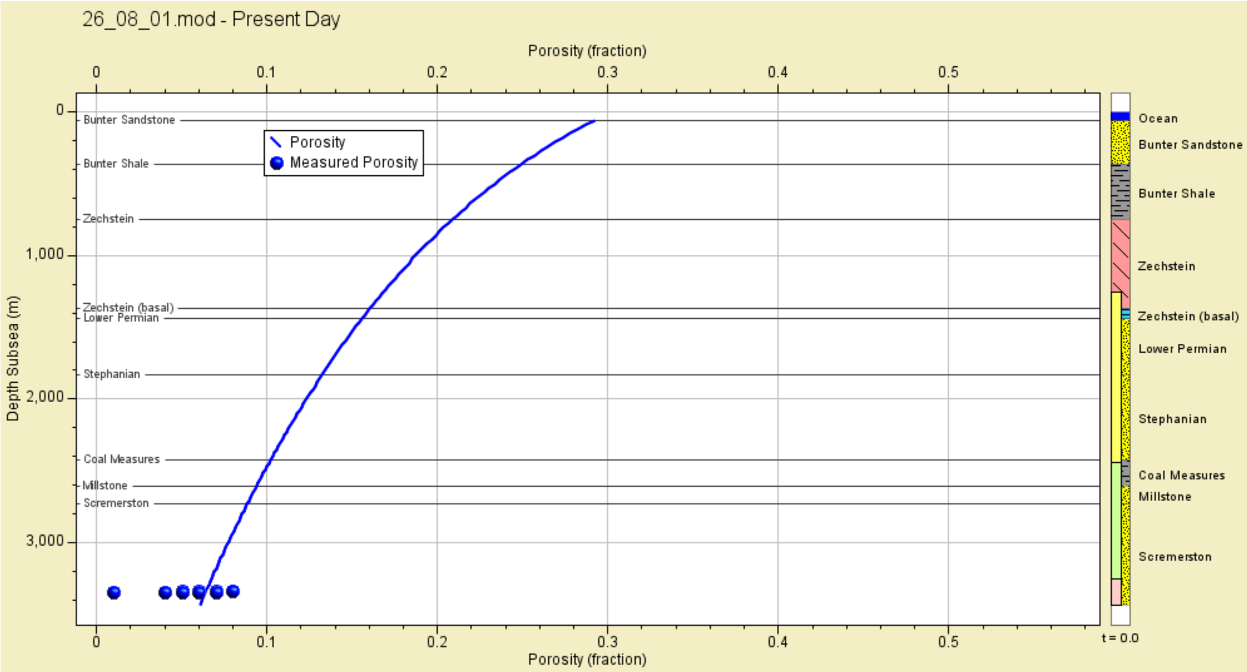


Figure 99: Depth plot for Well 26/08-01 with compaction model and data

26_08_01.mod | 26_08_01.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Prese...	Erode...	...	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh	Effecti
1	Quaternary (e)	Erosion	0.0			-30									
2	Pleistocene (d)	Deposit	0.126			10		Pleistocene_Q26							
3	Pliocene (d)	Deposit	2.59			20		Pliocene_Q26							
4	Late Miocene (e)	Erosion	5.322			-670									
5	Early Miocene (d)	Deposit	12			100		Miocene_Q26							
6	Oligocene (h)	Hiatus	23.03												
7	Eocene (d)	Deposit	33.9			80		Paleocene and Neo Q26							
8	Paleocene (d)	Deposit	55.8			100		Paleocene and Neo Q26							
9	Upper Cretaceous (d)	Deposit	65.5			250		Limestone							
10	Lower Cretaceous (d)	Deposit	99.6			80		L_Cret_Q26							
11	Jurassic (d)	Deposit	145.52			5.0		Jurassic_Q26							
12	Jurassic (Lias)(d)	Deposit	175.6			5.0		Jurassic_Q26							
13	Upper Triassic (d)	Deposit	199.59			20		Trias_2_w1							
14	Middle Triassic (d)	Deposit	230			30		Trias_2_w1							
15	Bunter Sandstone	Formation	245.01	*95.71*	*303.58*			Trias_2_w1							
16	Bunter Shale	Formation	249	**399.29**	*387.09*			Trias_1_w1							
17	Zechstein (late) (h)	Hiatus	251												
18	Zechstein	Formation	251.51	*786.38*	*623.02*			Zech_w1							
19	Zechstein (basal)	Formation	260	*1,409.4*	*71.01*			basal Zech_w1							
20	Lower Permian	Formation	280	*1,480.41*	*389.84*			Rot_w1							
21	Variscan (e)	Erosion	297			-200									
22	Stephanian (d)	Deposit	306			200		Boulton_w1							
23	Stephanian	Formation	307	*1,870.25*	*592.53*			Boulton_w1			Type II (BM...	1.0	1.0	0.2	
24	Coal Measures	Formation	312.01	*2,462.78*	*180.55*			Coal measures_w1			Type III (BM...	1.7	1.7	0.2	
25	Carboniferous (e)	Erosion	315			-50									
26	Carboniferous(d)	Deposit	315.5			50		Passage_w1							
27	Millstone	Formation	318.05	*2,643.33*	*127.61*			Passage_w1			Type III (BM...	1.1	1.1	0.2	
28	Yoredale (e)	Erosion	322			-10									
29	Yoredale (d)	Deposit	323			10		Yore_w3							
30	Scremerston	Formation	333.01	*2,770.94*	*702.87*			Firth_w1			Type III (BM...	3.0	3.2	0.2	

Figure 100: Model data entry sheet for Well 26/08-01

26/14-01

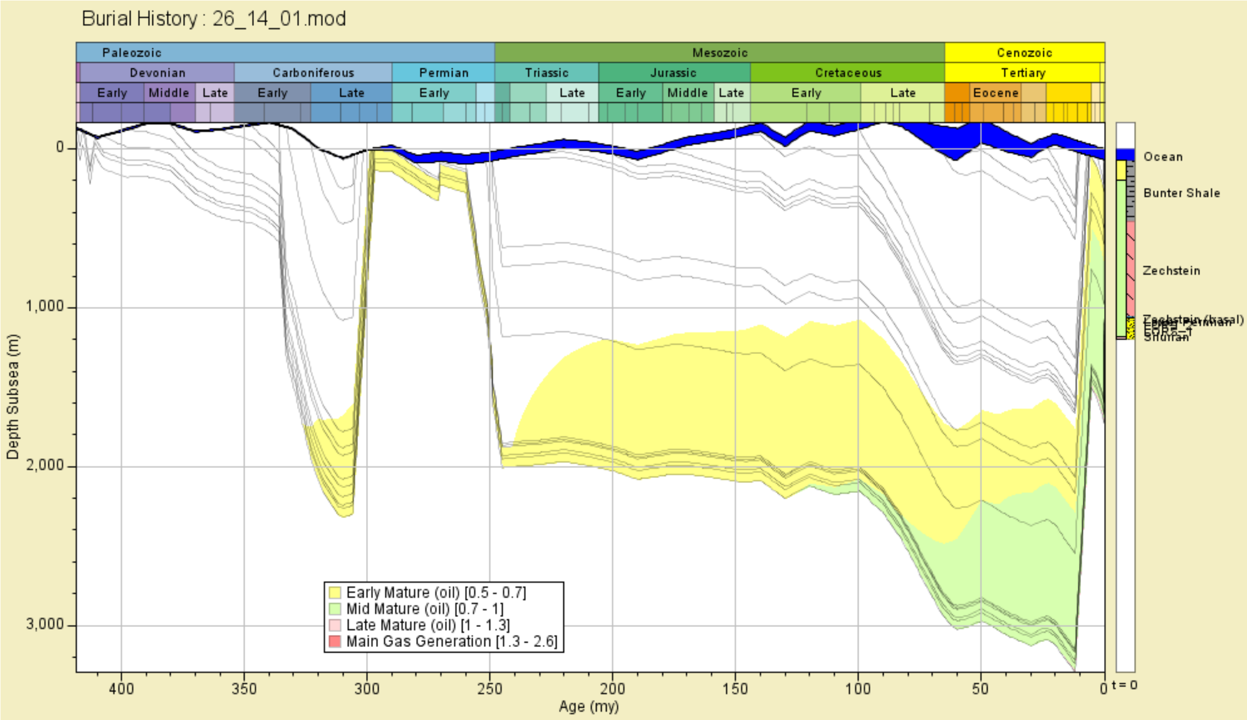


Figure 101: Burial history for Well 26/14-01

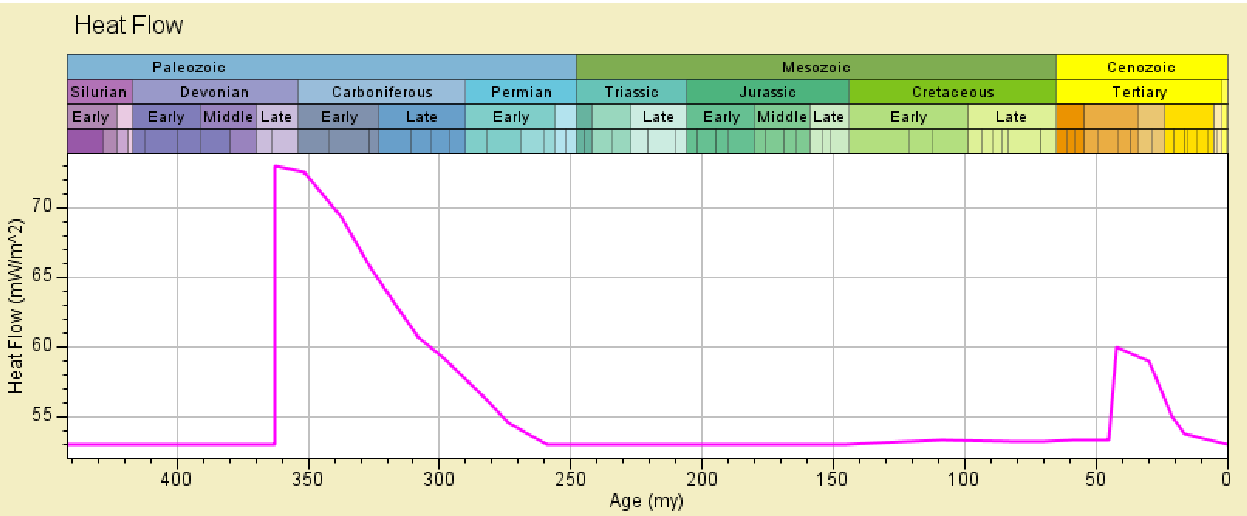


Figure 102: Palaeo-heat flow for Well 26/14-01

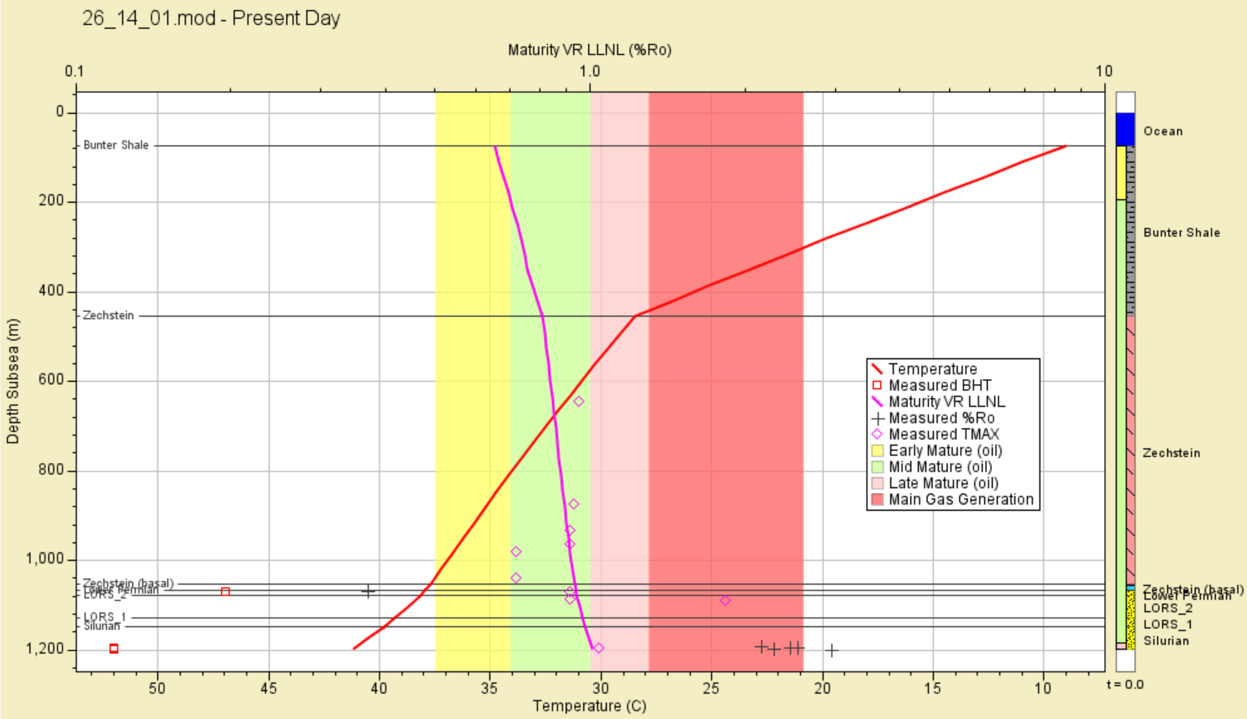


Figure 103: Depth plot for Well 26/14-01 showing model results, maturity data and maturity windows plus temperature data and model

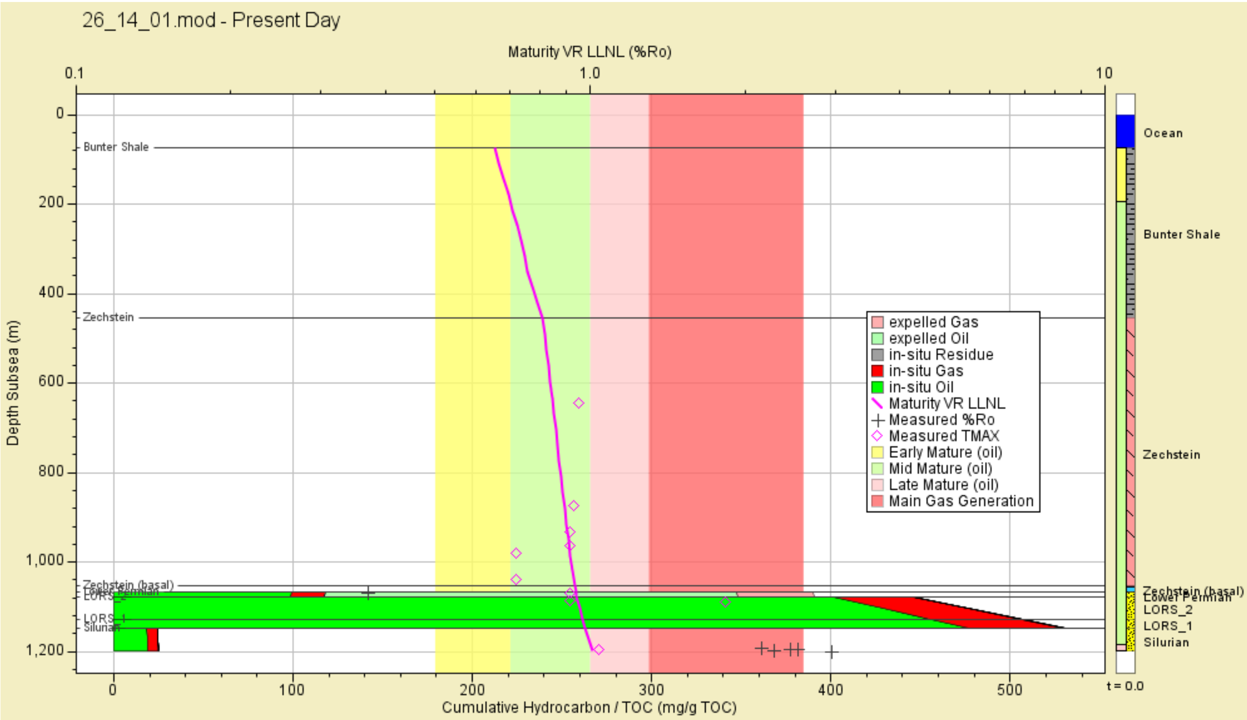


Figure 104: Depth plot for Well 26/14-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

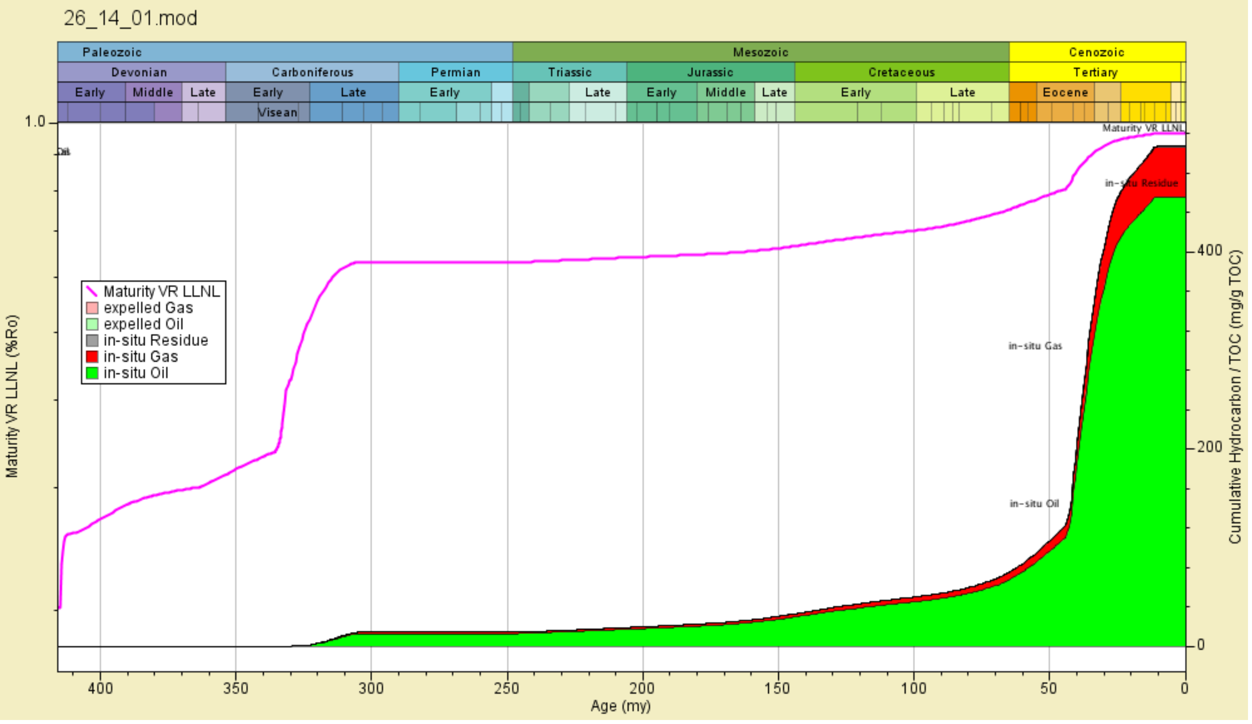


Figure 105: Time plot for Well 26/14-01 showing timing of generation for Lower Devonian Strata (model layer 'LORS_1')

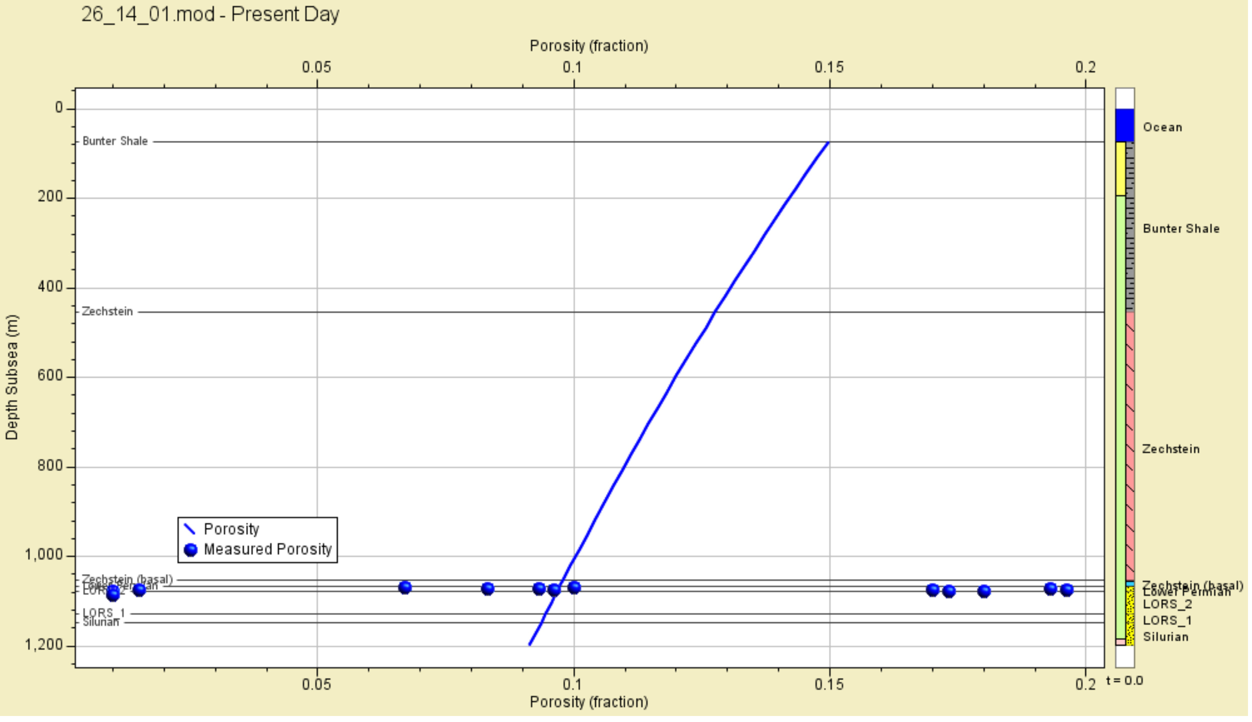


Figure 106: Depth plot for Well 26/14-01 with compaction model and data

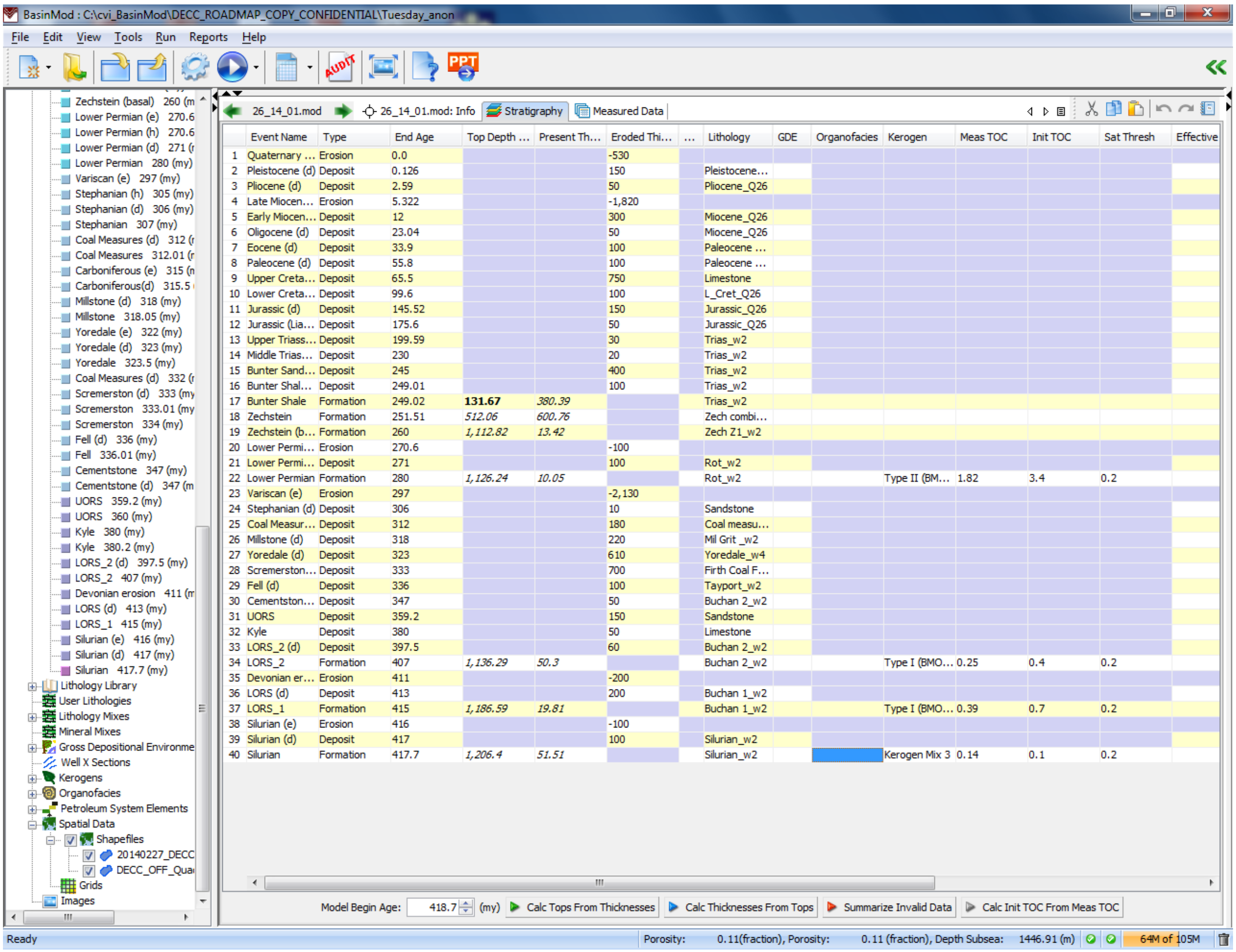


Figure 107: Model data entry sheet for Well 26/14-01

29/27-01

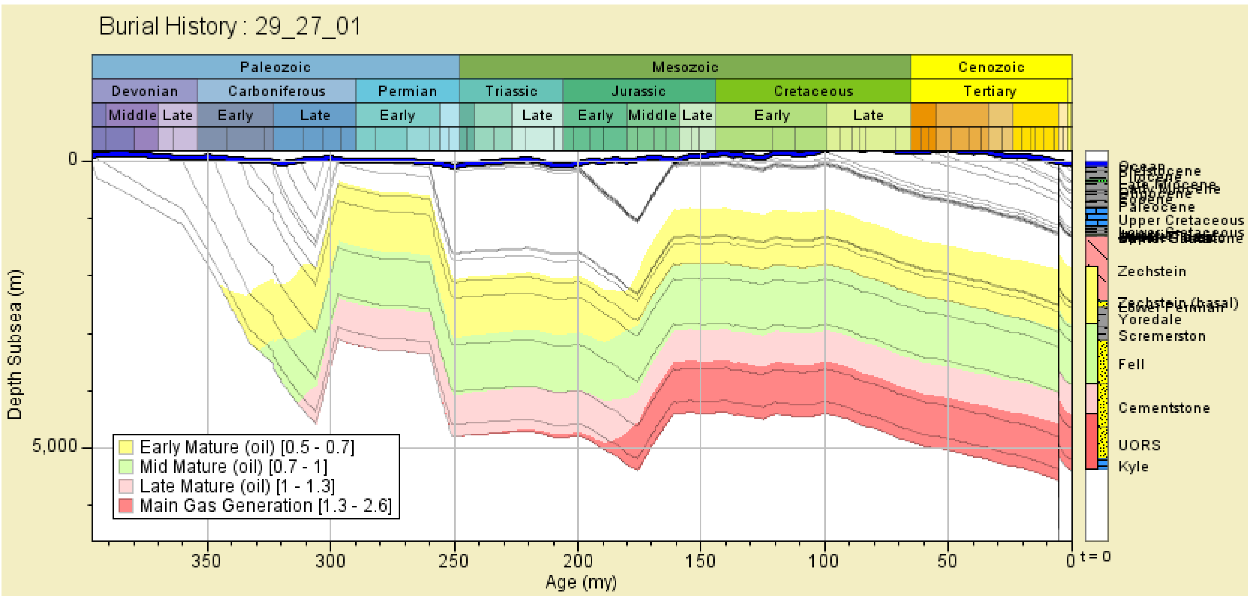


Figure 108: Burial history for Scenario Well 29/27-01 (Scenario 2)

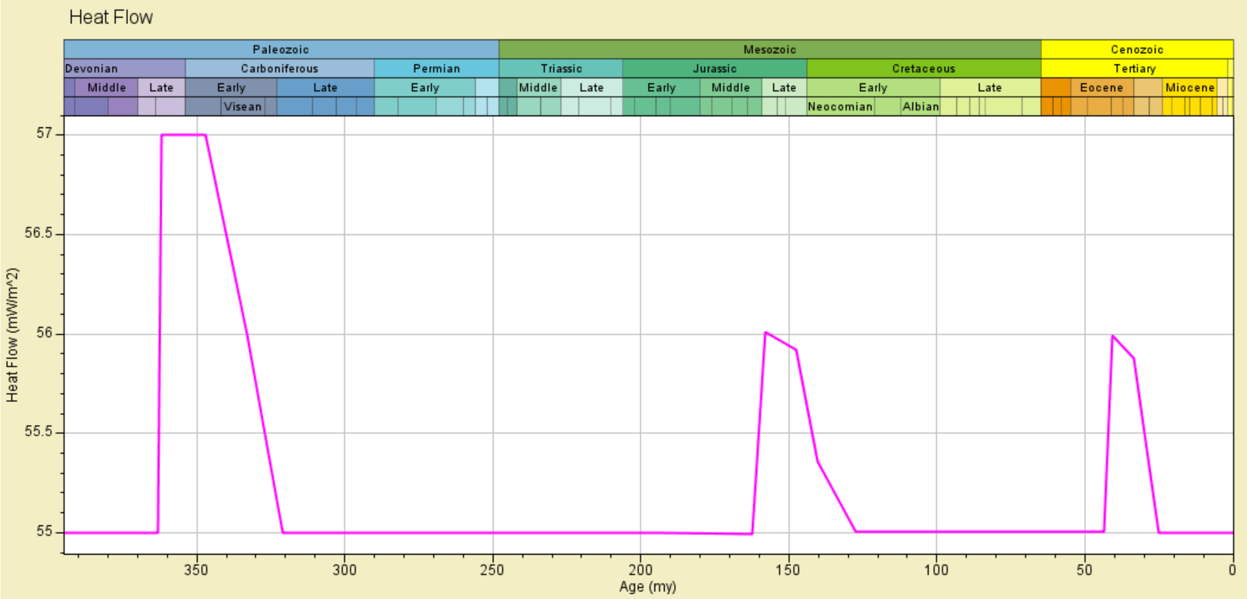


Figure 109: Palaeo-heat flow for Scenario Well 29/27-01 (Scenario 2)

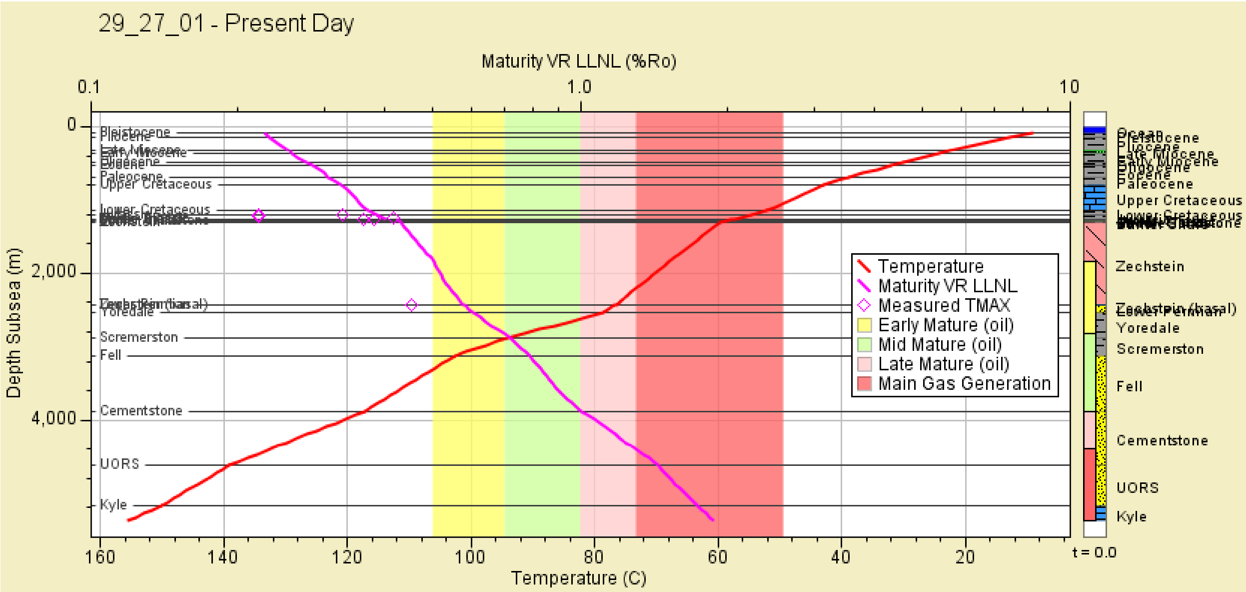


Figure 110: Depth plot for Scenario Well 29/27-01 (Scenario 2) showing model results, maturity data and maturity windows plus temperature model

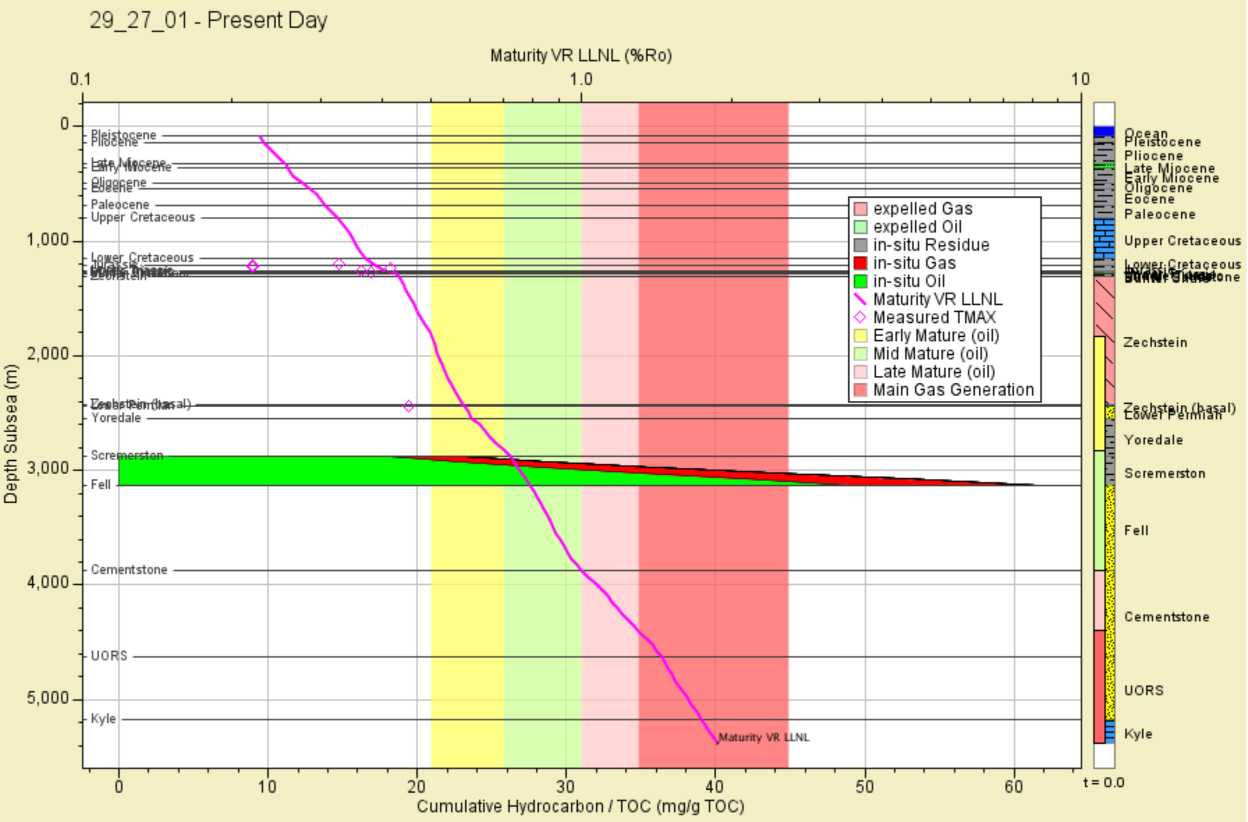


Figure 111: Depth plot for Scenario Well 29/27-01 (Scenario 2) showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

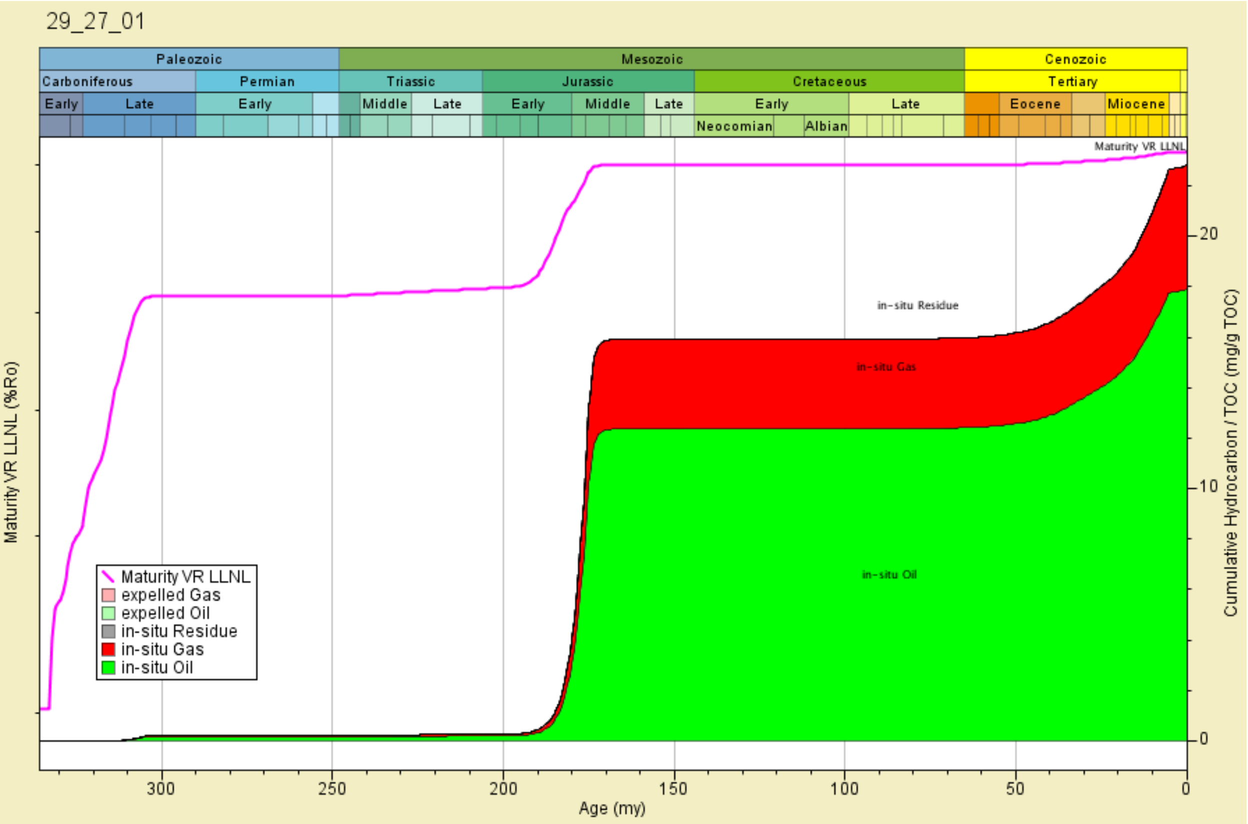
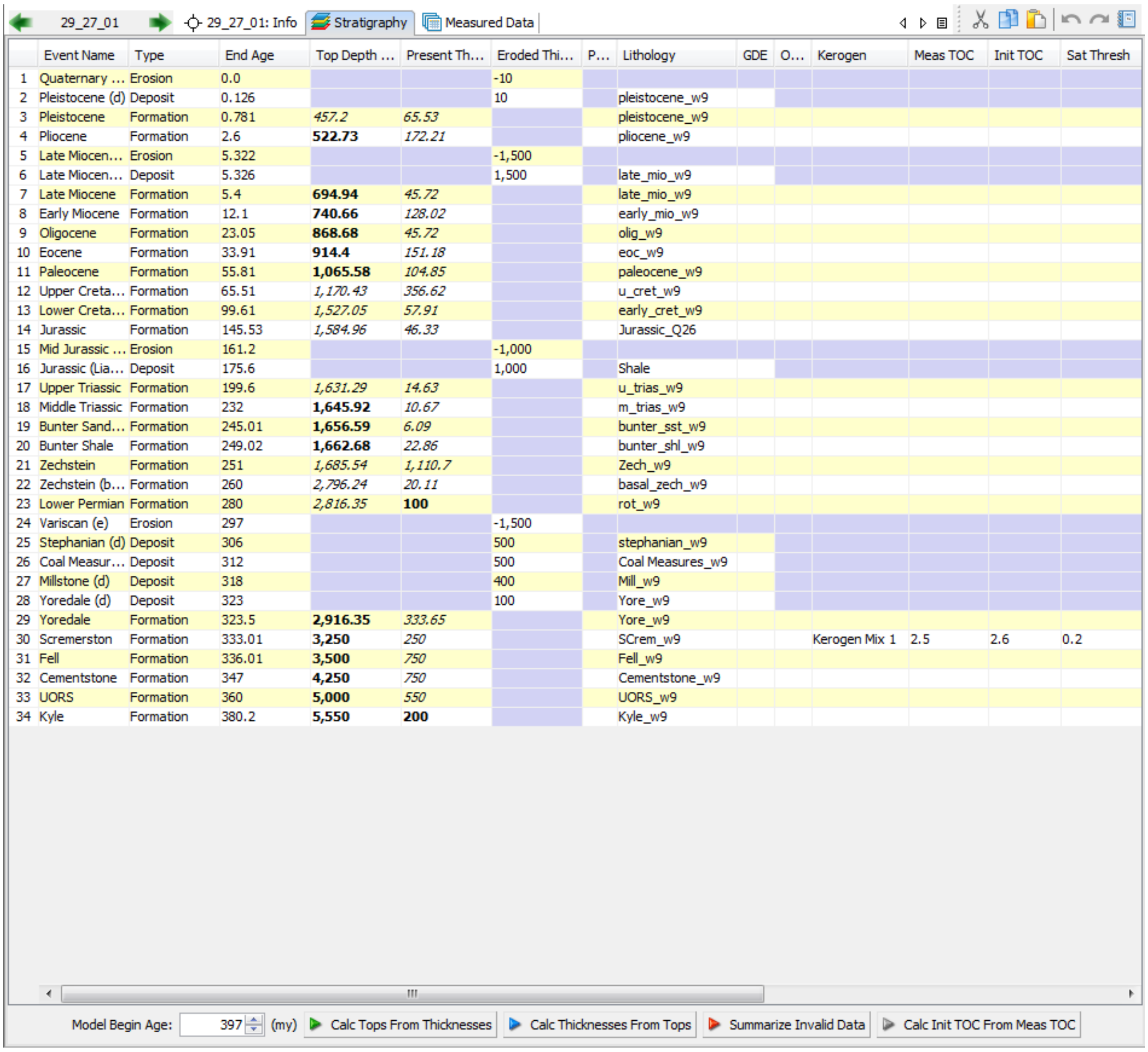


Figure 112: Time plot for Scenario Well 29/27-01 (Scenario 2) showing timing of generation for Scremerston Formation



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	P...	Lithology	GDE	O...	Kerogen	Meas TOC	Init TOC	Sat Thresh
1	Quaternary ...	Erosion	0.0			-10								
2	Pleistocene (d)	Deposit	0.126			10		pleistocene_w9						
3	Pleistocene	Formation	0.781	*457.2*	*65.53*			pleistocene_w9						
4	Pliocene	Formation	2.6	**522.73**	*172.21*			pliocene_w9						
5	Late Miocen...	Erosion	5.322			-1,500								
6	Late Miocen...	Deposit	5.326			1,500		late_mio_w9						
7	Late Miocene	Formation	5.4	**694.94**	*45.72*			late_mio_w9						
8	Early Miocene	Formation	12.1	**740.66**	*128.02*			early_mio_w9						
9	Oligocene	Formation	23.05	**868.68**	*45.72*			olig_w9						
10	Eocene	Formation	33.91	**914.4**	*151.18*			eoc_w9						
11	Paleocene	Formation	55.81	**1,065.58**	*104.85*			paleocene_w9						
12	Upper Creta...	Formation	65.51	*1,170.43*	*356.62*			u_cret_w9						
13	Lower Creta...	Formation	99.61	*1,527.05*	*57.91*			early_cret_w9						
14	Jurassic	Formation	145.53	*1,584.96*	*46.33*			Jurassic_Q26						
15	Mid Jurassic ...	Erosion	161.2			-1,000								
16	Jurassic (Lia...	Deposit	175.6			1,000		Shale						
17	Upper Triassic	Formation	199.6	*1,631.29*	*14.63*			u_trias_w9						
18	Middle Triassic	Formation	232	**1,645.92**	*10.67*			m_trias_w9						
19	Bunter Sand...	Formation	245.01	**1,656.59**	*6.09*			bunter_sst_w9						
20	Bunter Shale	Formation	249.02	**1,662.68**	*22.86*			bunter_shl_w9						
21	Zechstein	Formation	251	*1,685.54*	*1,110.7*			Zech_w9						
22	Zechstein (b...	Formation	260	*2,796.24*	*20.11*			basal_zech_w9						
23	Lower Permian	Formation	280	*2,816.35*	**100**			rot_w9						
24	Variscan (e)	Erosion	297			-1,500								
25	Stephanian (d)	Deposit	306			500		stephanian_w9						
26	Coal Measur...	Deposit	312			500		Coal Measures_w9						
27	Millstone (d)	Deposit	318			400		Mill_w9						
28	Yoredale (d)	Deposit	323			100		Yore_w9						
29	Yoredale	Formation	323.5	**2,916.35**	*333.65*			Yore_w9						
30	Scremerston	Formation	333.01	**3,250**	*250*			SCrem_w9			Kerogen Mix 1	2.5	2.6	0.2
31	Fell	Formation	336.01	**3,500**	*750*			Fell_w9						
32	Cementstone	Formation	347	**4,250**	*750*			Cementstone_w9						
33	UORS	Formation	360	**5,000**	*550*			UORS_w9						
34	Kyle	Formation	380.2	**5,550**	**200**			Kyle_w9						

Figure 113:Data entry sheet for Scenario Well 29/27-01 (Scenario 2)

36/13-01

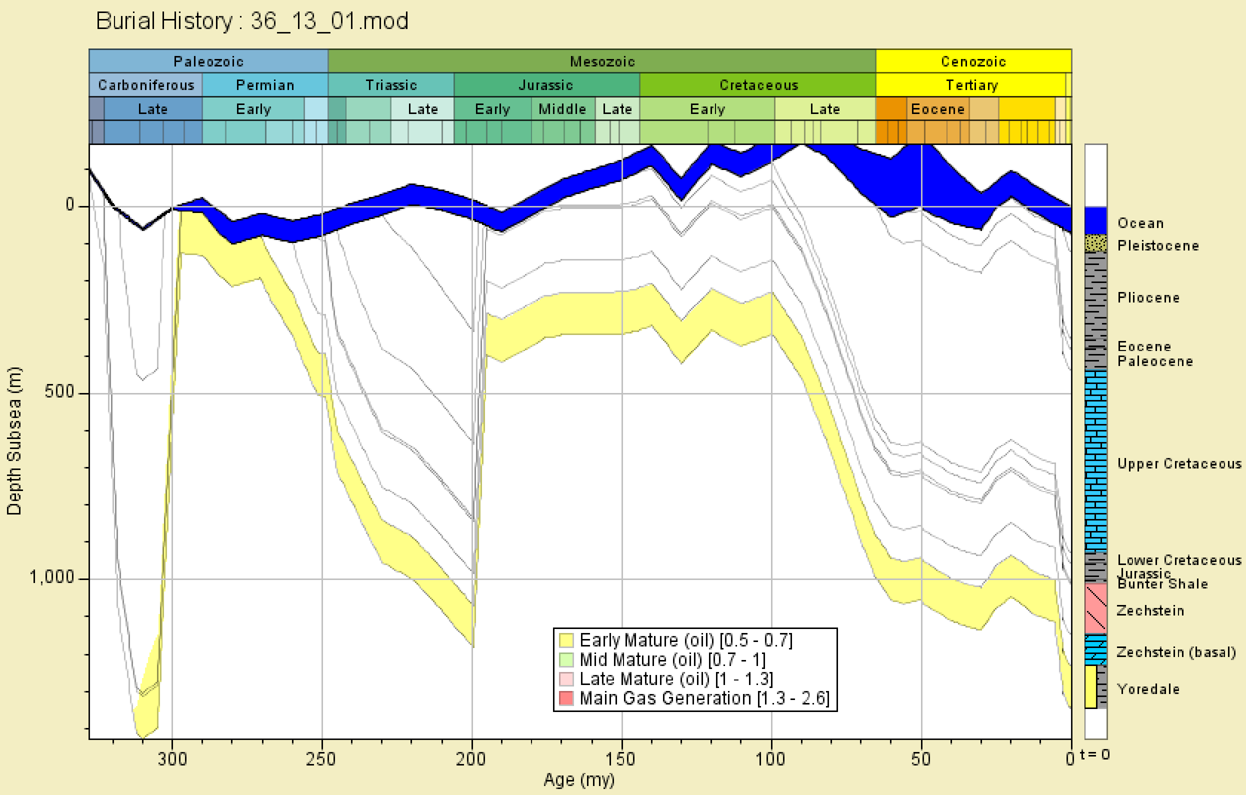


Figure 114: Burial history for Well 36/13-01

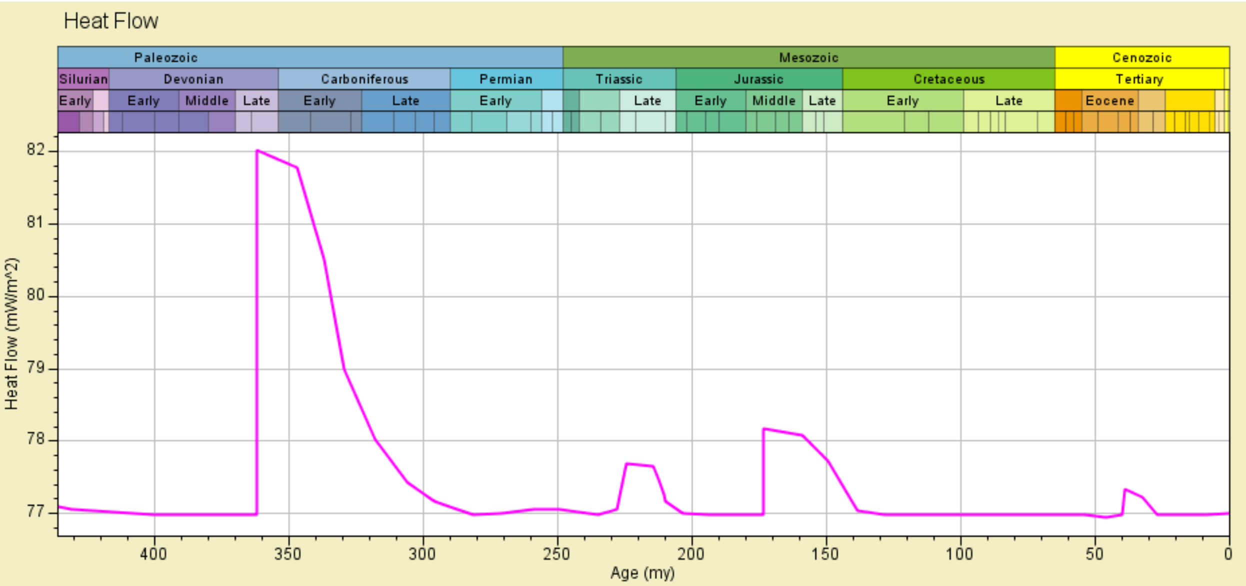


Figure 115: Palaeo-heat flow for Well 36/13-01

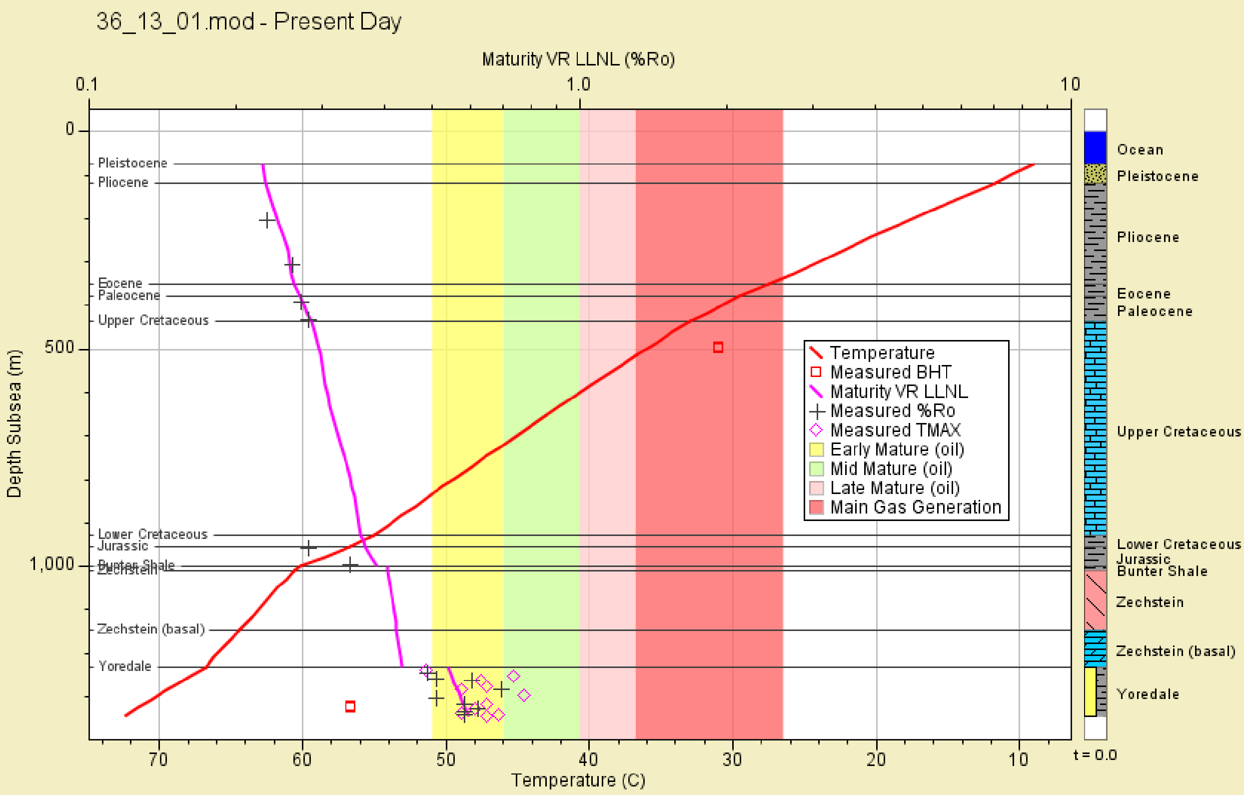


Figure 116: Depth plot for Well 36/13-01 showing model results, maturity data and maturity windows plus temperature data and model

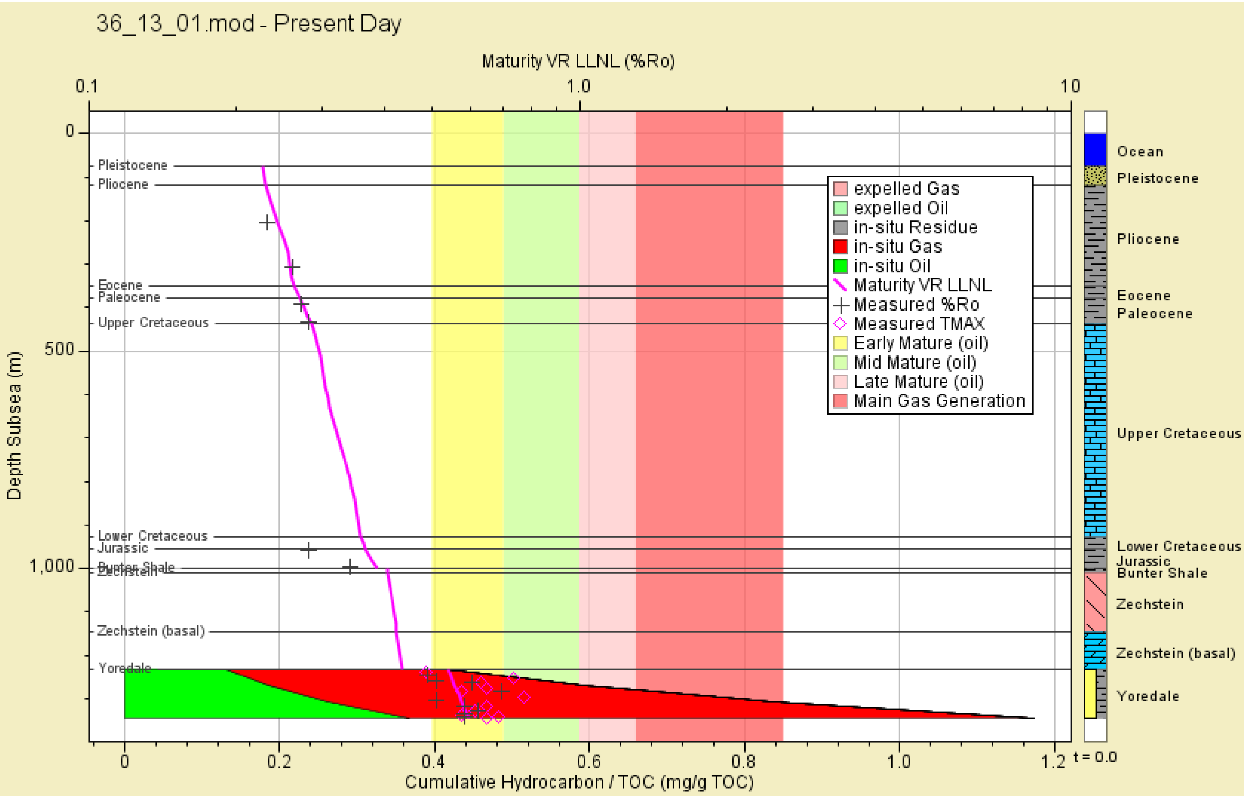


Figure 117: Depth plot for Well 36/13-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

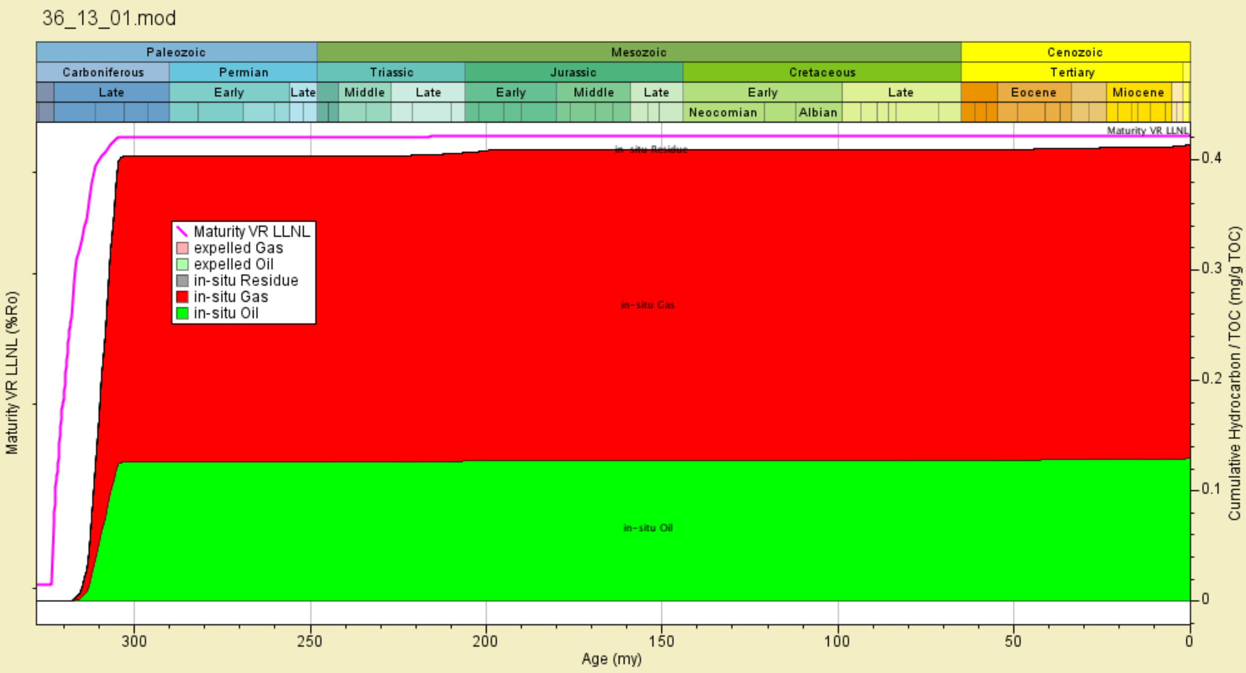


Figure 118: Time plot for Well 36/13-01 showing timing of generation for Yoredale Formation

36_13_01.mod | 36_13_01.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Prese...	Erode...	...	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh	Effecti
1	Quaternary (e)	Erosion	0.0			-5.0									
2	Pleistocene (d)	Deposit	0.126			5.0		Sandstone							
3	Pleistocene	Formation	0.781	102.11	46.94			Sandstone							
4	Pliocene (e)	Erosion	2.586			-10									
5	Pliocene (d)	Deposit	2.59			10		Plio_Mio_Q36							
6	Pliocene	Formation	2.6	149.05	231.95			Plio_Mio_Q36							
7	Late Miocene (e)	Erosion	5.322			-10									
8	Early Miocene (d)	Deposit	12			10		Sandstone							
9	Oligocene (h)	Hiatus	23.03												
10	Eocene	Formation	33.91	381	27.43			Shale_Q36							
11	Paleocene	Formation	55.81	408.43	57			Paleocene_Q36							
12	Upper Cretaceous	Formation	65.51	465.43	491.64			Chalk_All_Lst							
13	Lower Cretaceous	Formation	99.61	957.07	28.35			Lower Cret_w3							
14	Jurassic	Formation	145.6	985.42	43.89			Upper Jur_w3							
15	Jurassic (Lias)(h)	Hiatus	175.59												
16	Triassic (e)	Erosion	195			-800									
17	Upper Triassic (d)	Deposit	199.59			300		Trias_w3							
18	Middle Triassic (d)	Deposit	230			300		Trias_w3							
19	Bunter Sandstone (d)	Deposit	245			200		Sandstone							
20	Bunter Shale	Formation	249.02	1,029.31	8.53			Trias_w3							
21	Zechstein	Formation	251.51	1,037.84	137.16			Zech_w3							
22	Zechstein (basal)	Formation	260	1,175	84.13			Zech_basal_w3							
23	Lower Permian (h)	Hiatus	270.61												
24	Variscan (e)	Erosion	297			-1,250									
25	Stephanian (h)	Hiatus	305												
26	Coal Measures (d)	Deposit	312			400		eroded coal measure ...							
27	Millstone (d)	Deposit	318			840		Eroded passage and ...							
28	Yoredale (d)	Deposit	323			10		Eroded passage and ...							
29	Yoredale	Formation	323.5	1,259.13	113.39			Yore_w3			Type III (BM...	2.0	2.0	0.2	

Figure 119: Model data entry sheet for Well 36/13-01

36/23-01

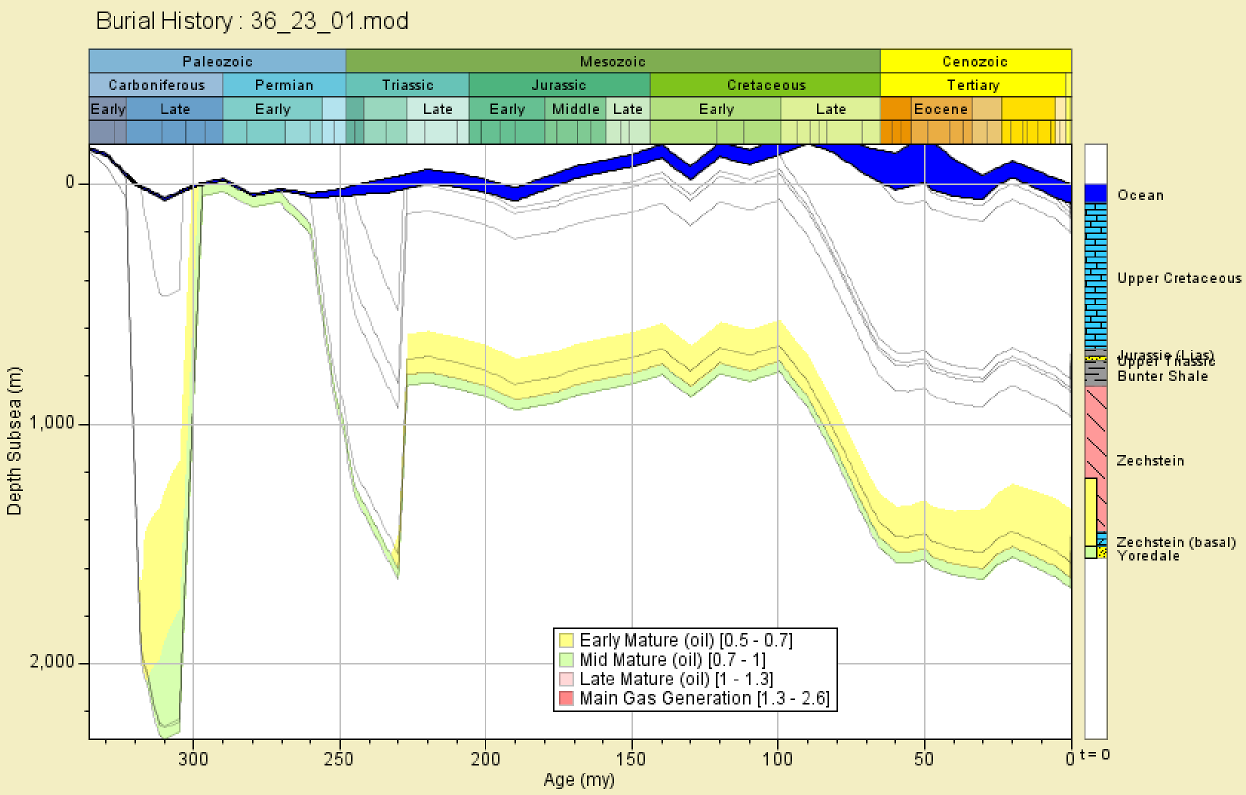


Figure 120: Burial history for Well 36/23-01

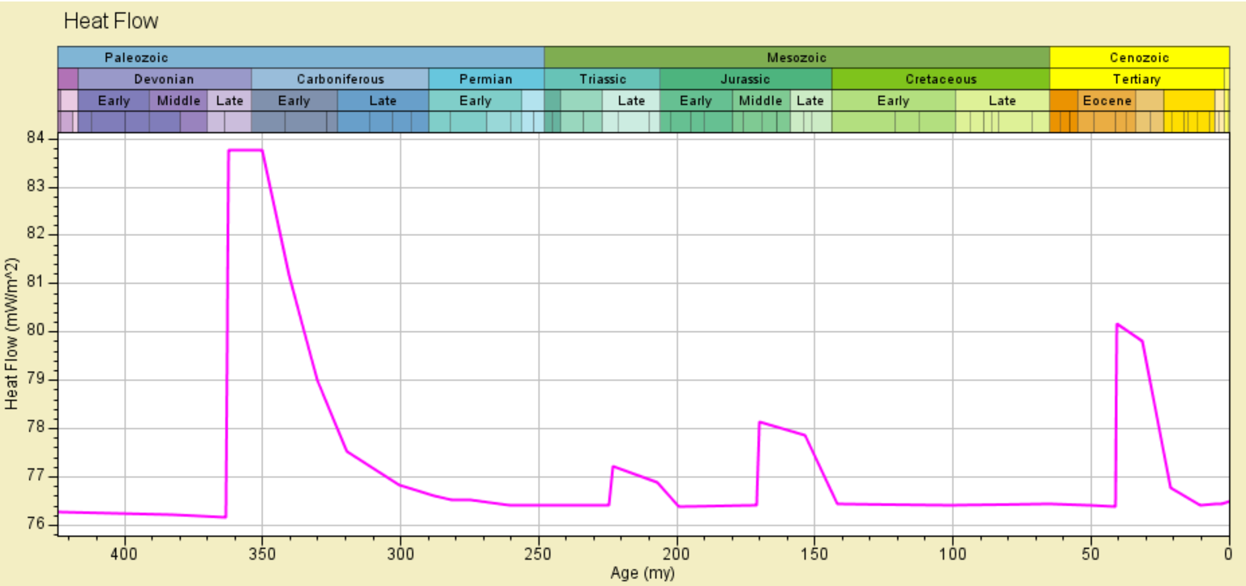


Figure 121: Palaeo-heat flow for Well 36/23-01

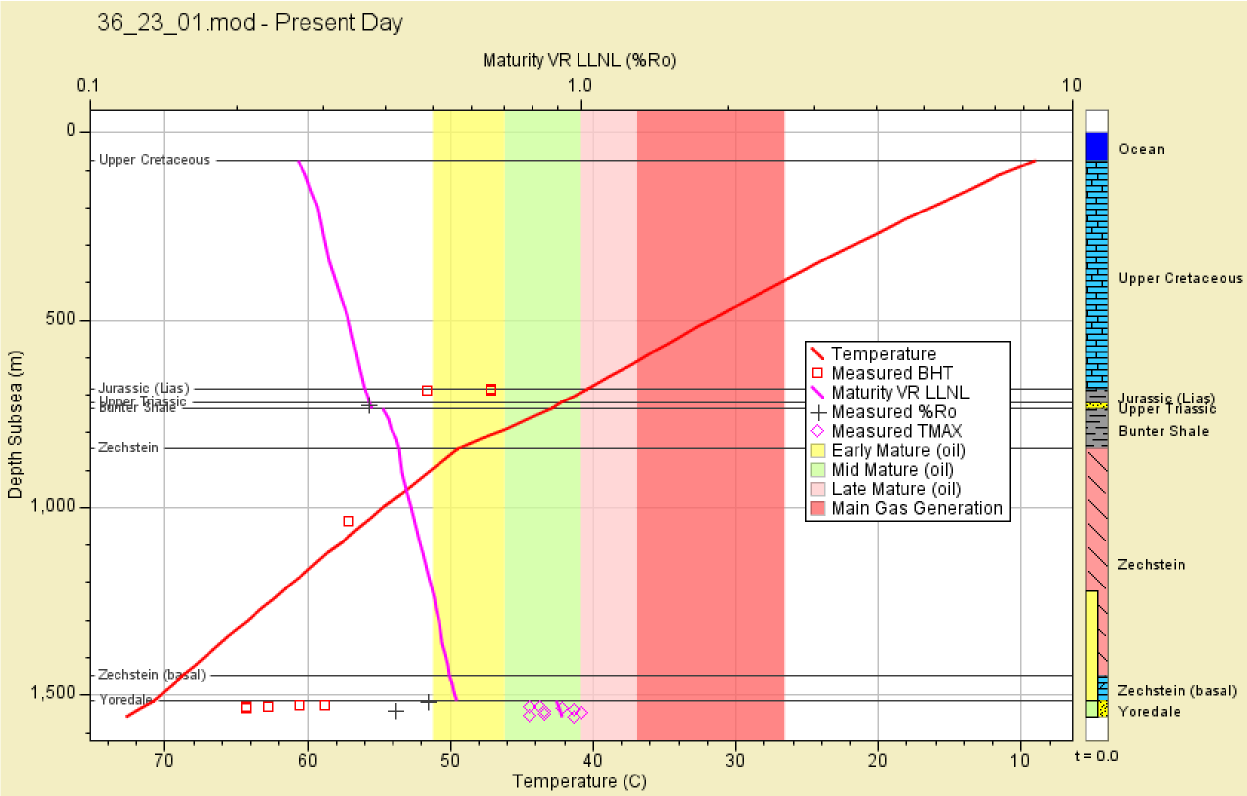


Figure 122: Depth plot for Well 36/23-01 showing model results, maturity data and maturity windows plus temperature data and model

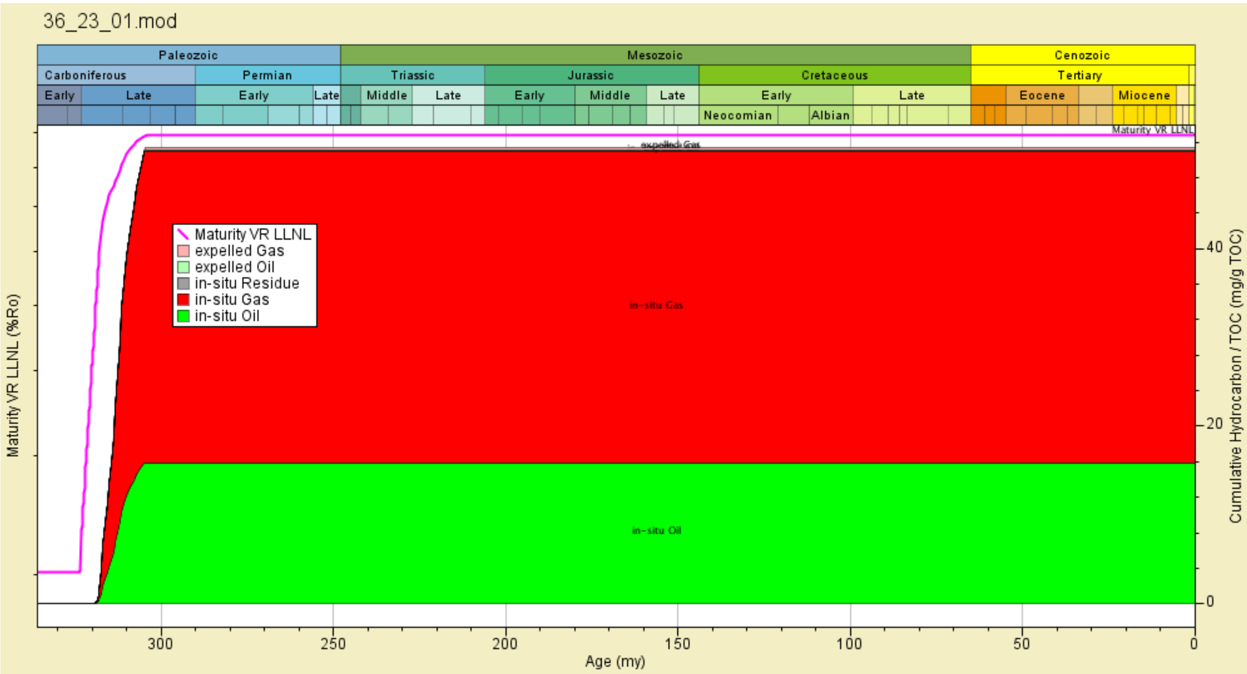


Figure 123: Time plot for Well 36/23-01 showing timing of generation for Yoredale Formation

36_23_01.mod | 36_23_01.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Prese...	Erode...	...	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh	Effecti
1	Quaternary (e)	Erosion	0.0			-120									
2	Pleistocene (d)	Deposit	0.126			20		Sandstone							
3	Pliocene (d)	Deposit	2.59			20		Plio_Mio_Q36							
4	Late Miocene (h)	Hiatus	5.324												
5	Early Miocene (h)	Hiatus	11.99												
6	Oligocene (h)	Hiatus	23.03												
7	Eocene (d)	Deposit	33.9			20		Shale_Q36							
8	Paleocene (d)	Deposit	55.8			60		Paleocene_Q36							
9	Upper Cretaceous	Formation	65.51	*335.28*	*612.04*			Chalk_All_Lst							
10	Lower Cretaceous (h)	Hiatus	99.59												
11	Jurassic (h)	Hiatus	145.51												
12	Jurassic (Lias)	Formation	175.61	*947.32*	*35.66*			Lias_w4							
13	Upper Triassic	Formation	199.6	*982.98*	*15.24*			Trias_w4							
14	Middle Triassic (e)	Erosion	227			-800									
15	Middle Triassic (d)	Deposit	230			500		Shale							
16	Bunter Sandstone (d)	Deposit	245			300		Sandstone							
17	Bunter Shale	Formation	249.02	*998.22*	*105.16*			Bunter shale_w4							
18	Zechstein	Formation	251.51	*1,103.38*	*607.16*			Zech_w4							
19	Zechstein (basal)	Formation	260	*1,710.54*	*64.62*			basal Zech_w4							
20	Lower Permian (h)	Hiatus	270.61												
21	Variscan (e)	Erosion	297			-2,200									
22	Stephanian (h)	Hiatus	305												
23	Coal Measures (d)	Deposit	312			400		eroded coal measure ...							
24	Millstone (d)	Deposit	318			1,790		Eroded passage and ...							
25	Yoredale (d)	Deposit	323			10		Eroded passage and ...							
26	Yoredale	Formation	323.5	*1,775.16*	*44.51*			Screm_w4			Type III (BM...	9.91	12.1	0.2	

Figure 124: Model data entry sheet for Well 36/23-01

38/18-01

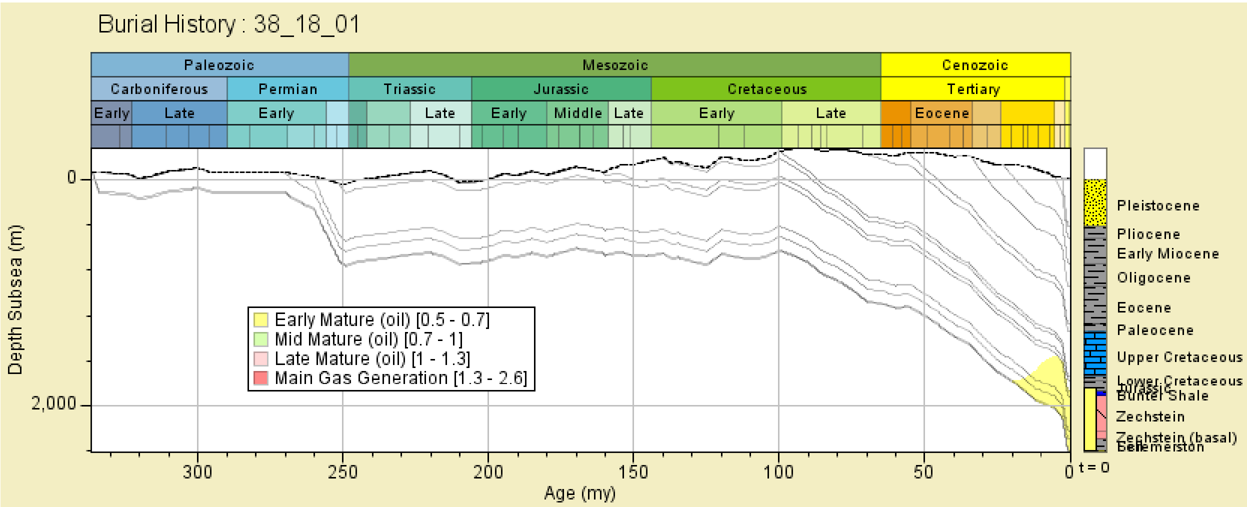


Figure 125: Burial history for Scenario Well 38/18-01 (Scenario 2)

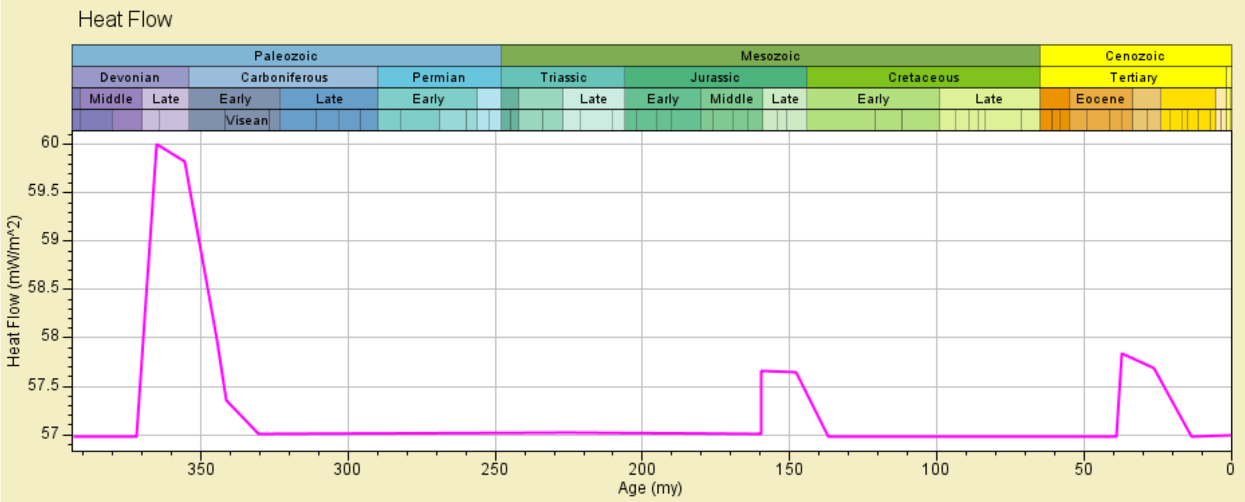


Figure 126: Palaeo-heat flow for Scenario Well 38/18-01 (Scenario 2)

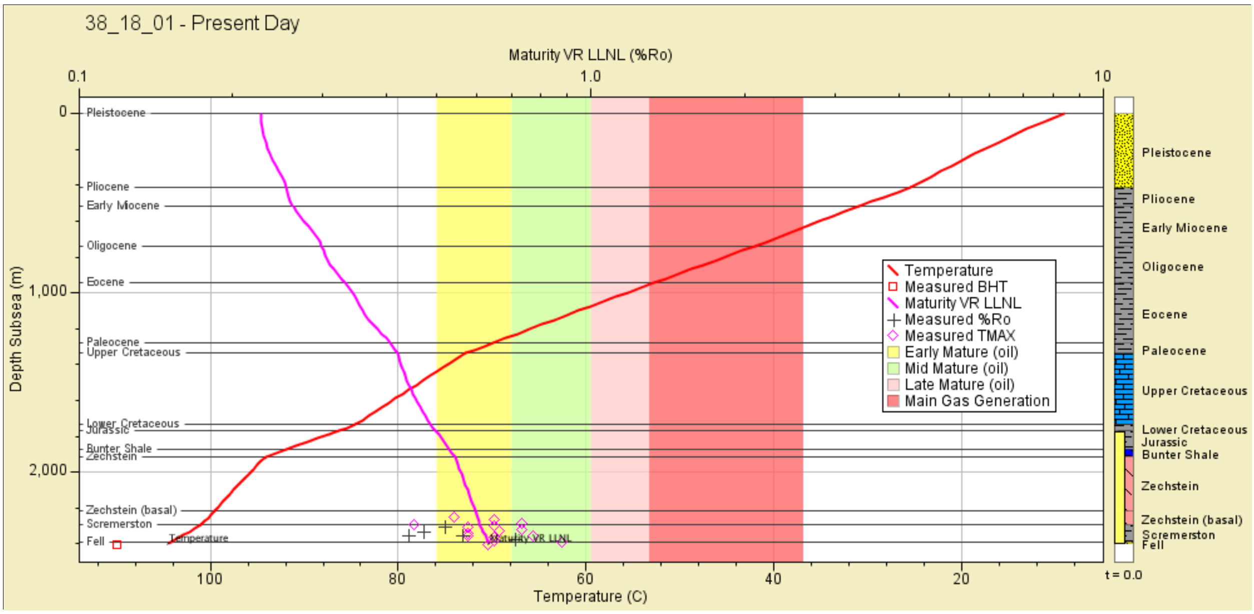


Figure 127: Depth plot for Scenario Well 38/18-01 showing model results, maturity data and maturity windows plus temperature data and model (Scenario 2)

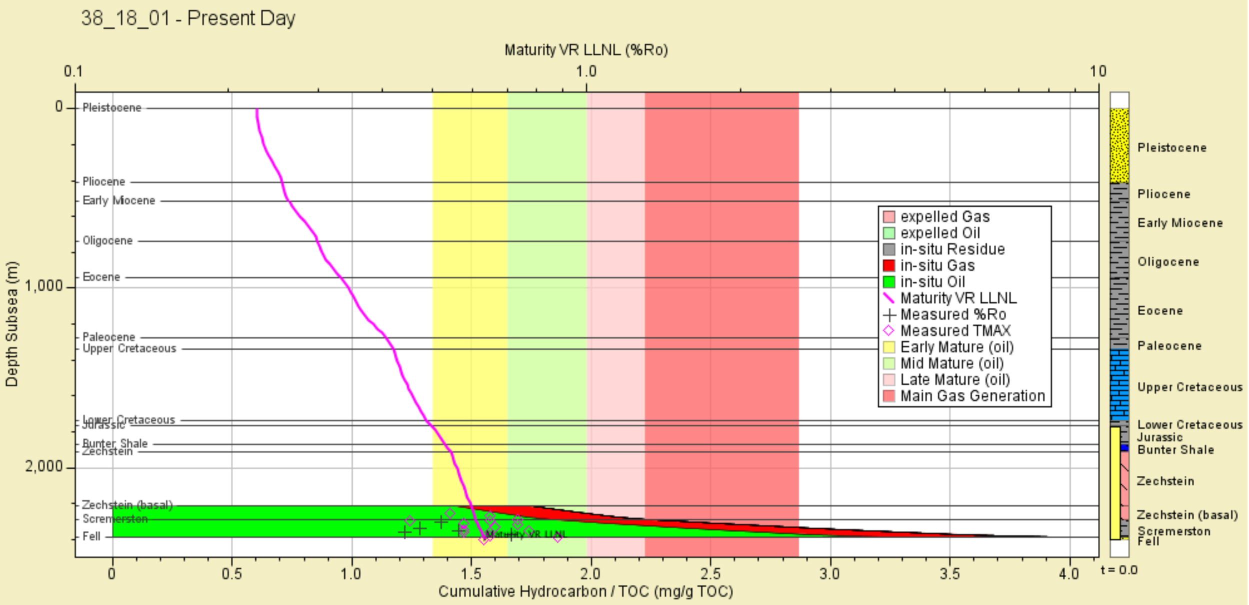


Figure 128: Depth plot for Scenario Well 38/18-01 (Scenario 2) showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

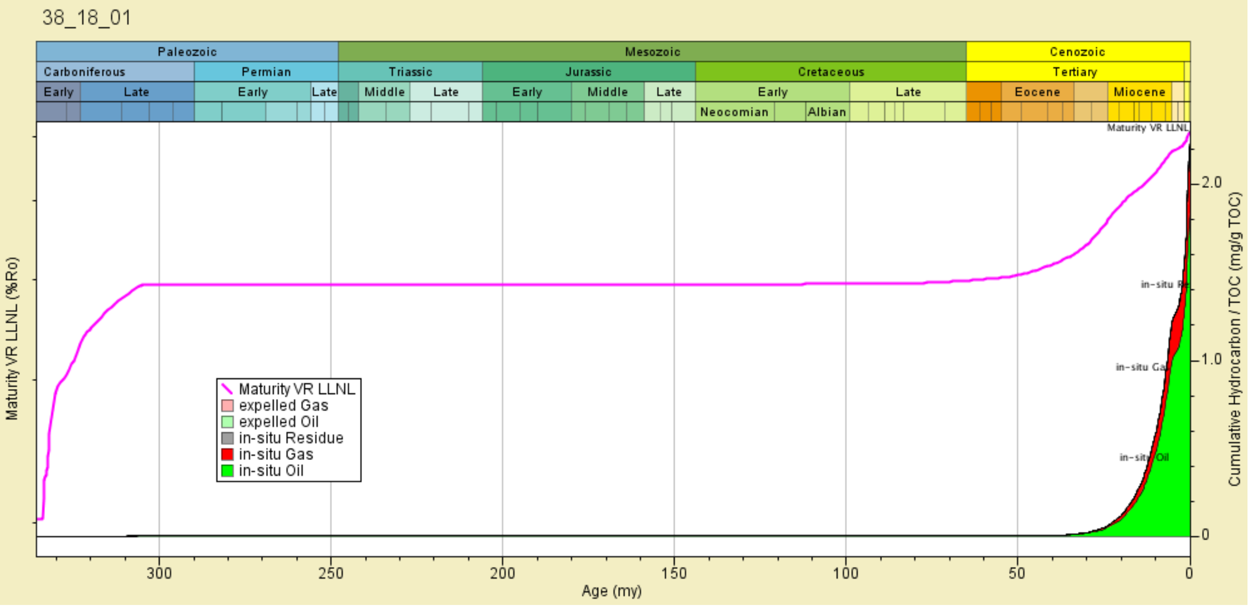
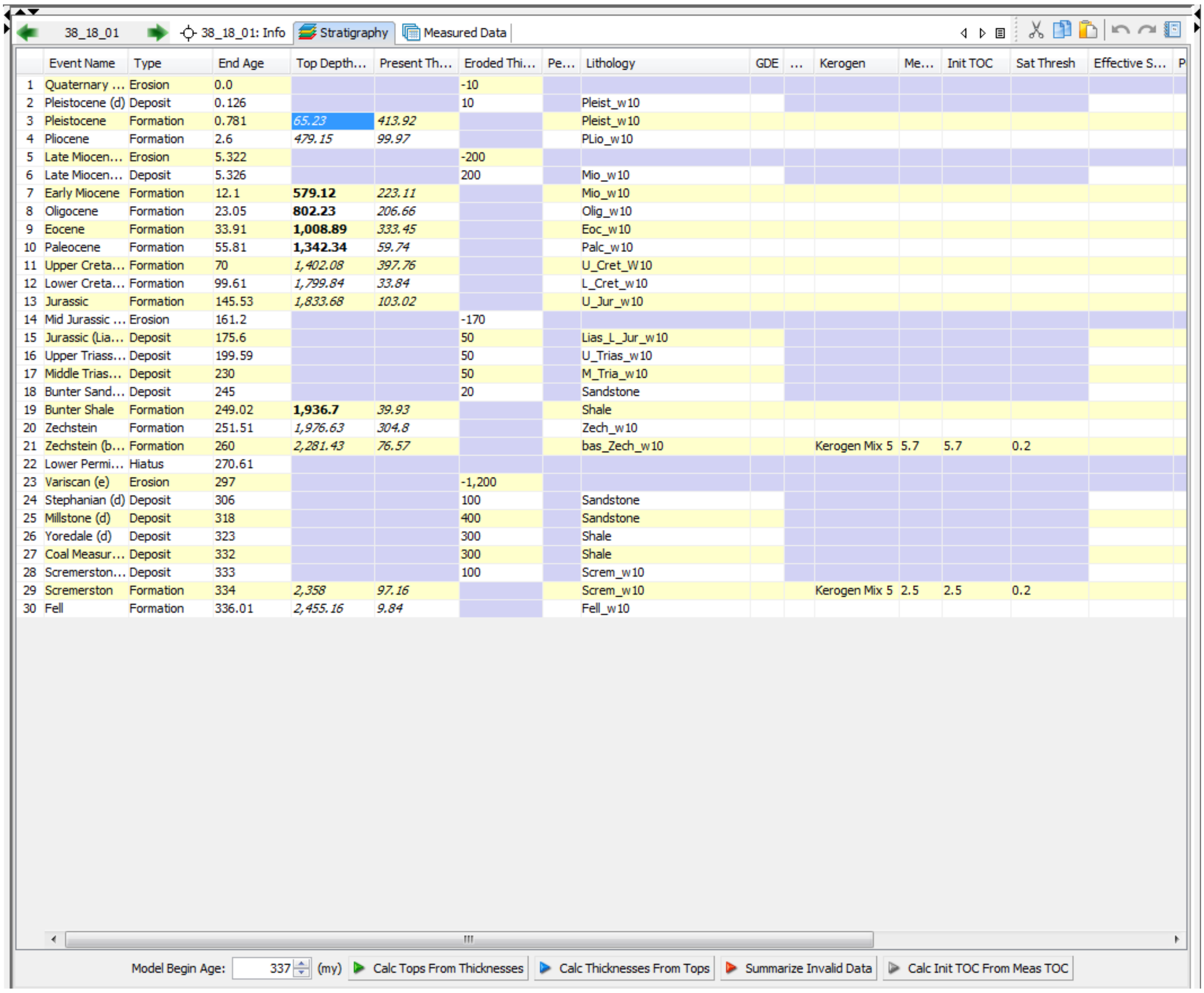


Figure 129: Time plot for Scenario Well 38/18-01 (Scenario 2) showing timing of generation for Scremerston Formation



38_18_01 | 38_18_01: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth...	Present Th...	Eroded Thi...	Pe...	Lithology	GDE	...	Kerogen	Me...	Init TOC	Sat Thresh	Effective S...	P
1	Quaternary ...	Erosion	0.0			-10										
2	Pleistocene (d)	Deposit	0.126			10		Pleist_w10								
3	Pleistocene	Formation	0.781	65.23	413.92			Pleist_w10								
4	Pliocene	Formation	2.6	479.15	99.97			PLio_w10								
5	Late Miocen...	Erosion	5.322			-200										
6	Late Miocen...	Deposit	5.326			200		Mio_w10								
7	Early Miocene	Formation	12.1	**579.12**	223.11			Mio_w10								
8	Oligocene	Formation	23.05	**802.23**	206.66			Olig_w10								
9	Eocene	Formation	33.91	**1,008.89**	333.45			Eoc_w10								
10	Paleocene	Formation	55.81	**1,342.34**	59.74			Palc_w10								
11	Upper Creta...	Formation	70	1,402.08	397.76			U_Cret_W10								
12	Lower Creta...	Formation	99.61	1,799.84	33.84			L_Cret_w10								
13	Jurassic	Formation	145.53	1,833.68	103.02			U_Jur_w10								
14	Mid Jurassic ...	Erosion	161.2			-170										
15	Jurassic (Lia...	Deposit	175.6			50		Lias_L_Jur_w10								
16	Upper Triass...	Deposit	199.59			50		U_Trias_w10								
17	Middle Trias...	Deposit	230			50		M_Tria_w10								
18	Bunter Sand...	Deposit	245			20		Sandstone								
19	Bunter Shale	Formation	249.02	**1,936.7**	39.93			Shale								
20	Zechstein	Formation	251.51	1,976.63	304.8			Zech_w10								
21	Zechstein (b...	Formation	260	2,281.43	76.57			bas_Zech_w10			Kerogen Mix 5	5.7	5.7	0.2		
22	Lower Permi...	Hiatus	270.61													
23	Variscan (e)	Erosion	297			-1,200										
24	Stephanian (d)	Deposit	306			100		Sandstone								
25	Millstone (d)	Deposit	318			400		Sandstone								
26	Yoredale (d)	Deposit	323			300		Shale								
27	Coal Measur...	Deposit	332			300		Shale								
28	Scremerston...	Deposit	333			100		Screm_w10								
29	Scremerston	Formation	334	2,358	97.16			Screm_w10			Kerogen Mix 5	2.5	2.5	0.2		
30	Fell	Formation	336.01	2,455.16	9.84			Fell_w10								

Model Begin Age: 337 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Figure 130: Model data entry sheet for Well 38/18-01 (Scenario 2)

41/14-01

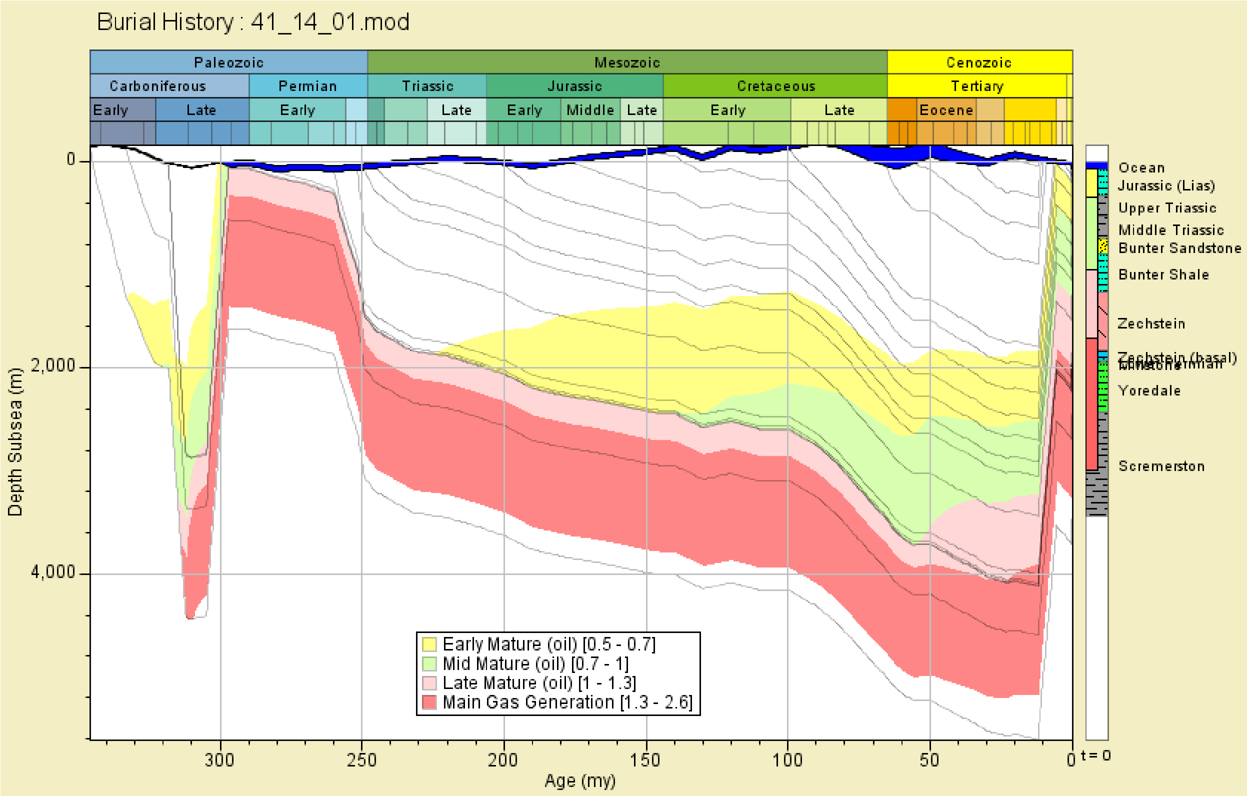


Figure 131: Burial history for Well 41/14-01

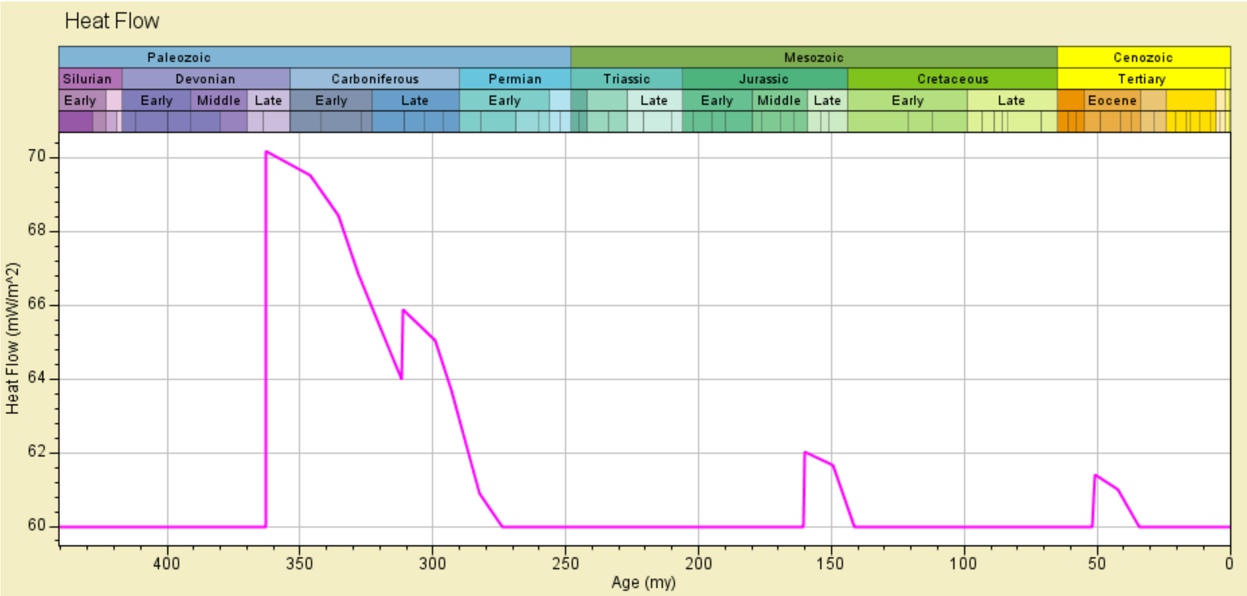


Figure 132: Palaeo-heat flow for Well 41/14-01

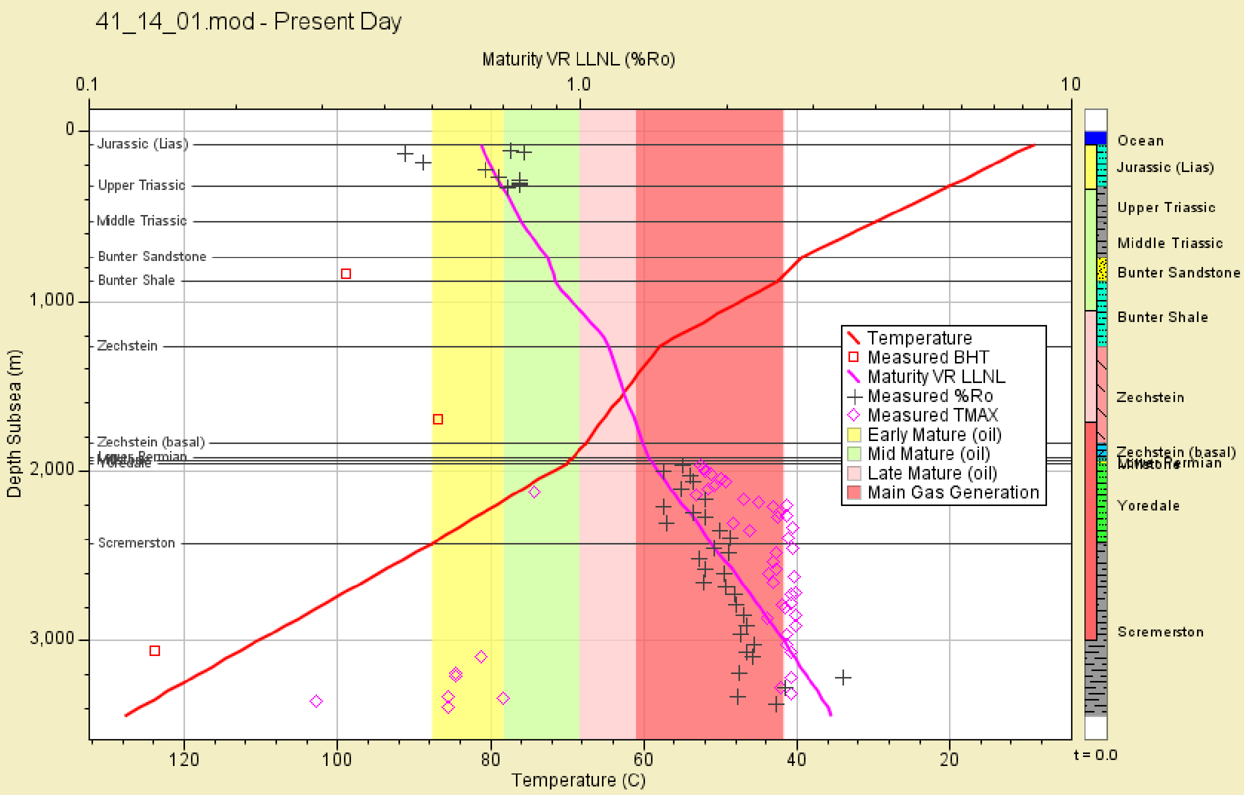


Figure 133: Depth plot for Well 41/14-01 showing model results, maturity data and maturity windows plus temperature data and model

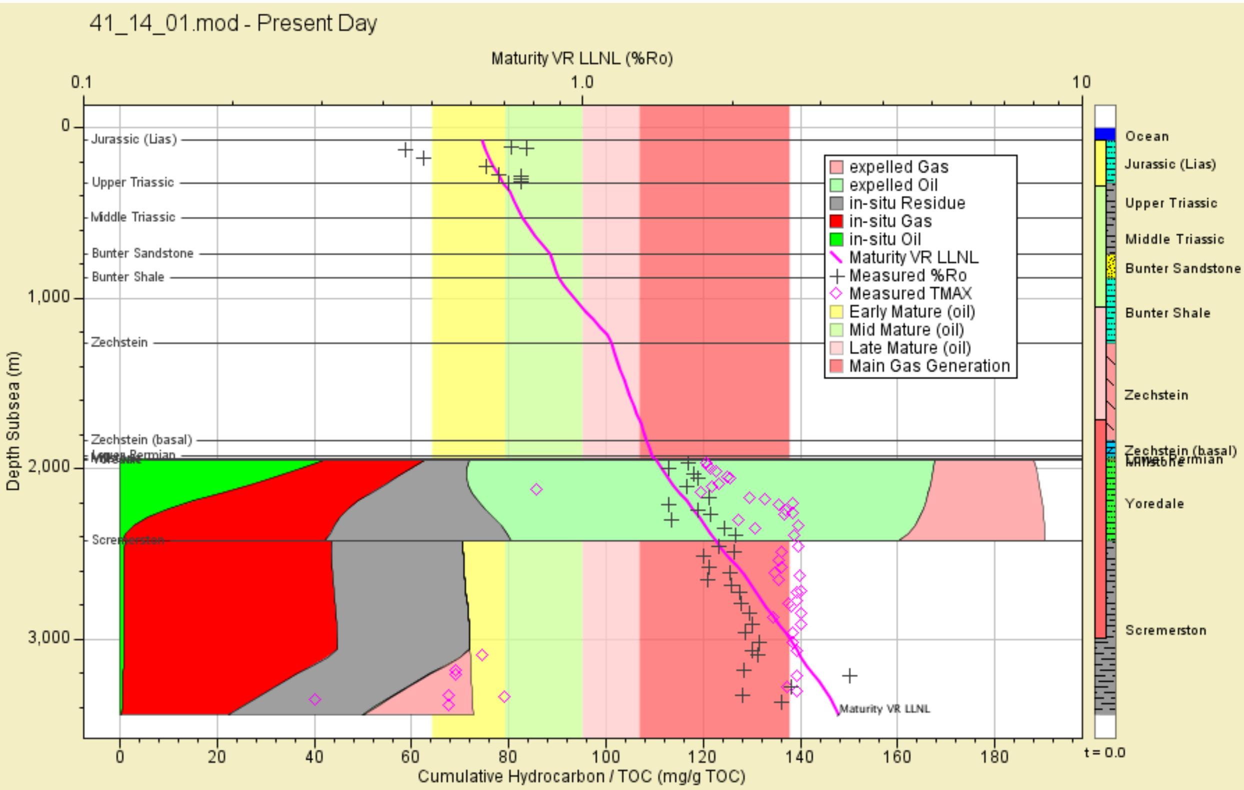


Figure 134: Depth plot for Well 41/14-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

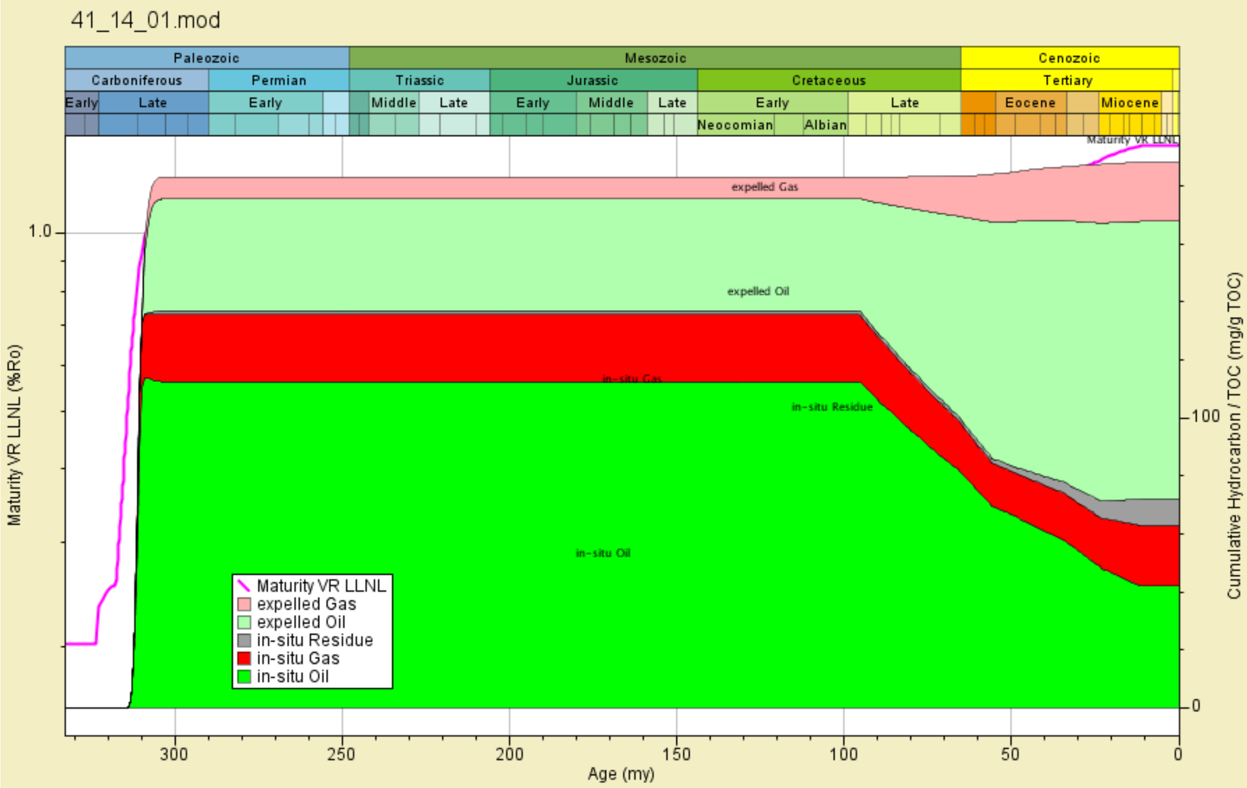


Figure 135: Time plot for Well 41/14-01 showing timing of generation for Yoredale Formation

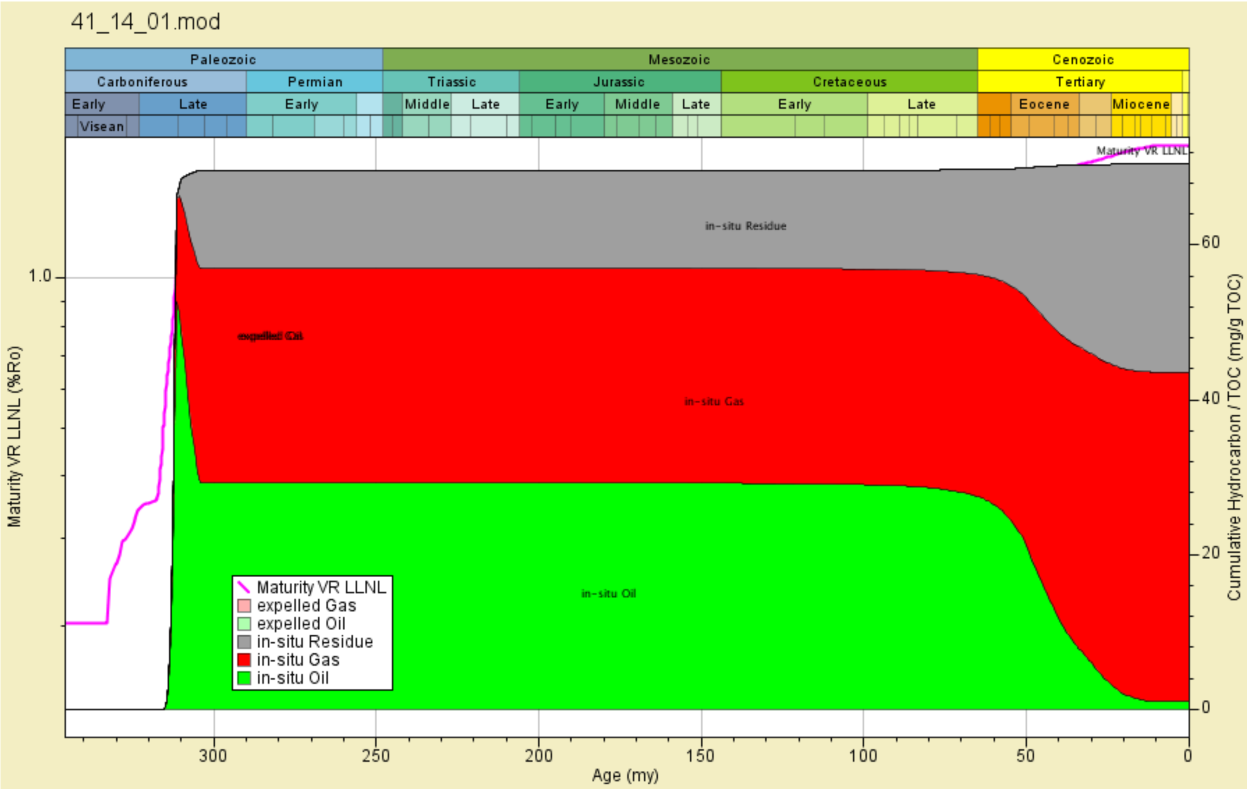


Figure 136: Time plot for Well 41/14-01 showing timing of generation for Scremerston Formation

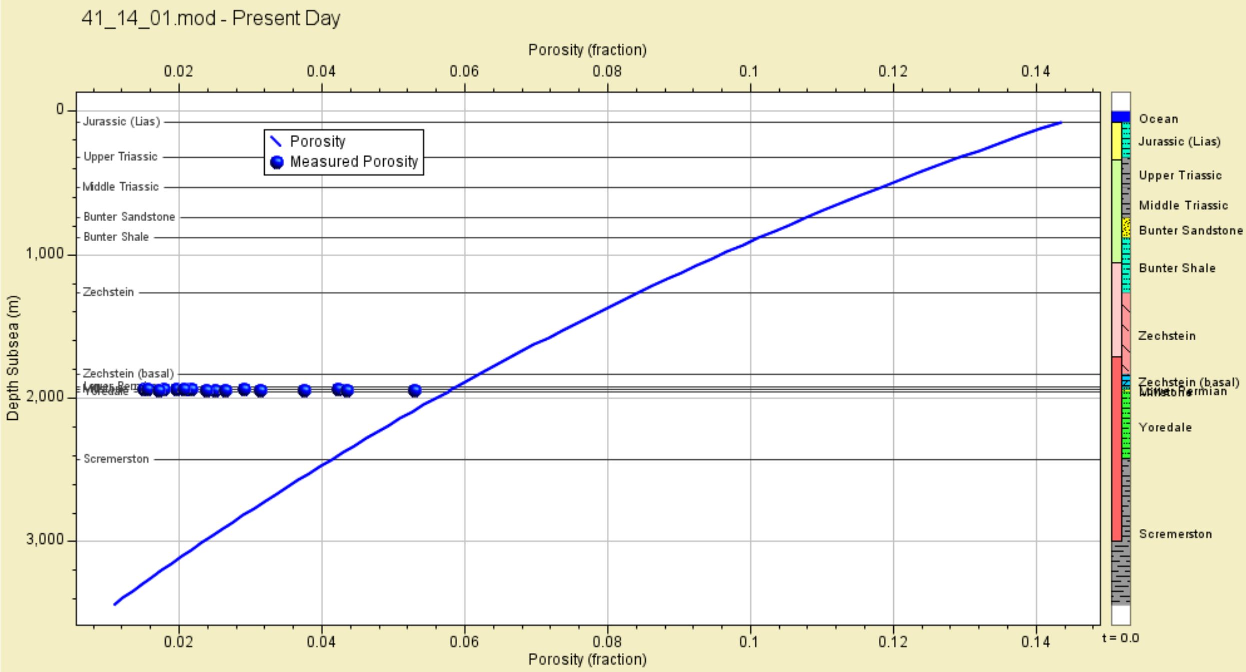
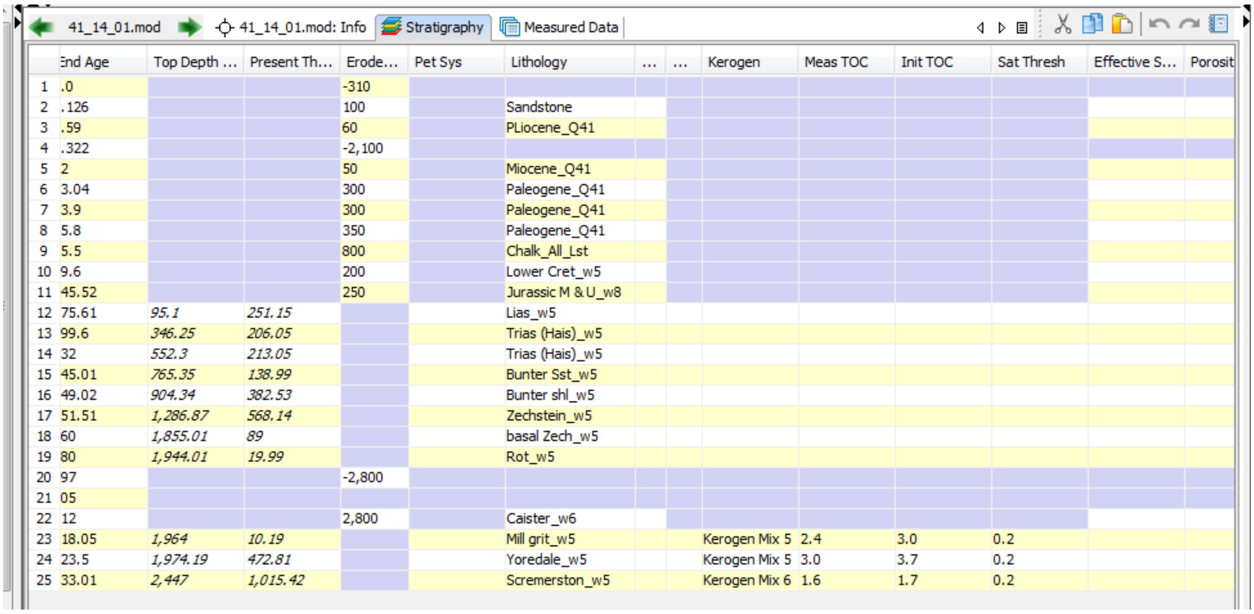


Figure 137: Depth plot for Well 41/14-01 with compaction model and data



	End Age	Top Depth ...	Present Th...	Erode...	Pet Sys	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh	Effective S...	Porosit
1	.0			-310										
2	.126			100		Sandstone								
3	.59			60		PLiocene_Q41								
4	.322			-2,100										
5	2			50		Miocene_Q41								
6	3.04			300		Paleogene_Q41								
7	3.9			300		Paleogene_Q41								
8	5.8			350		Paleogene_Q41								
9	5.5			800		Chalk_All_Lst								
10	9.6			200		Lower Cret_w5								
11	45.52			250		Jurassic M & U_w8								
12	75.61	*95.1*	*251.15*			Lias_w5								
13	99.6	*346.25*	*206.05*			Trias (Hais)_w5								
14	32	*552.3*	*213.05*			Trias (Hais)_w5								
15	45.01	*765.35*	*138.99*			Bunter Sst_w5								
16	49.02	*904.34*	*382.53*			Bunter shl_w5								
17	51.51	*1,286.87*	*568.14*			Zechstein_w5								
18	60	*1,855.01*	*89*			basal Zech_w5								
19	80	*1,944.01*	*19.99*			Rot_w5								
20	97			-2,800										
21	05													
22	12			2,800		Caister_w6								
23	18.05	*1,964*	*10.19*			Mill grit_w5			Kerogen Mix 5	2.4	3.0	0.2		
24	23.5	*1,974.19*	*472.81*			Yoredale_w5			Kerogen Mix 5	3.0	3.7	0.2		
25	33.01	*2,447*	*1,015.42*			Scremerston_w5			Kerogen Mix 6	1.6	1.7	0.2		

Figure 138: Model data entry sheet for Well 41/14-01

41/20-01

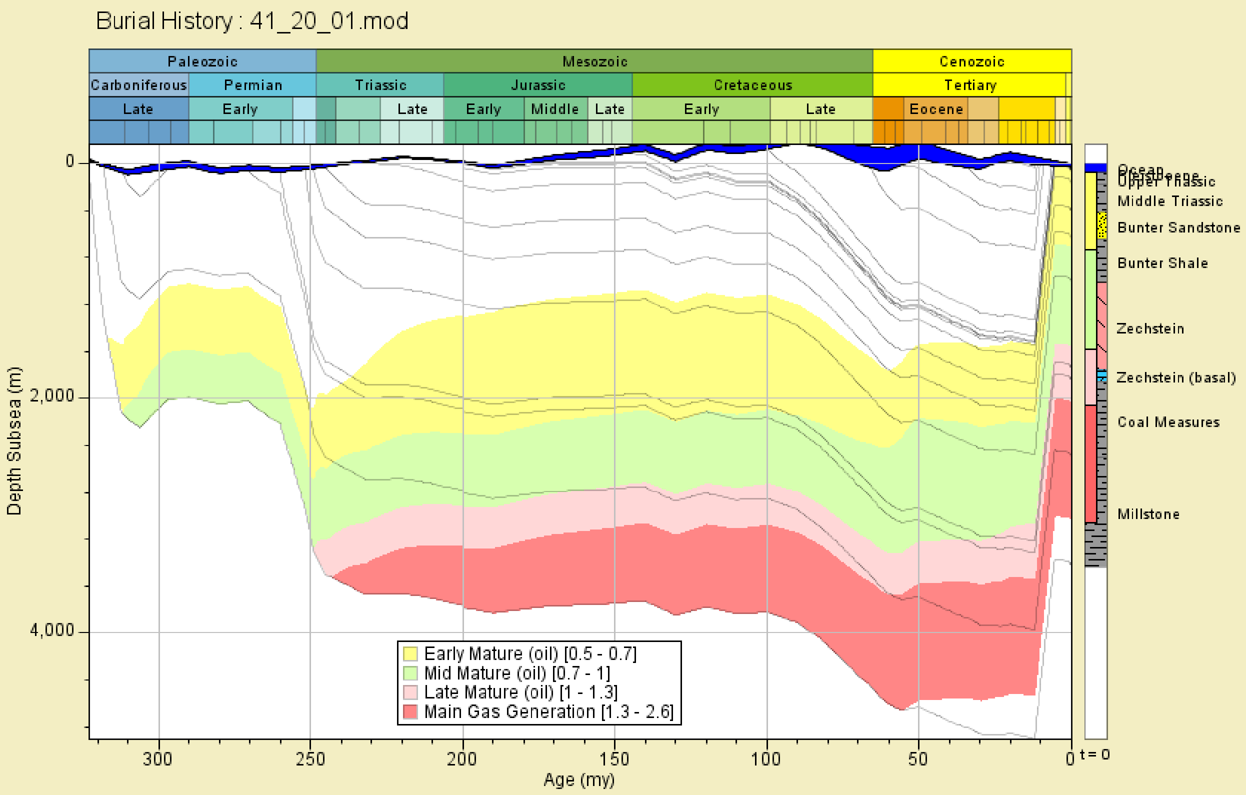


Figure 139: Burial history for Well 41/20-01

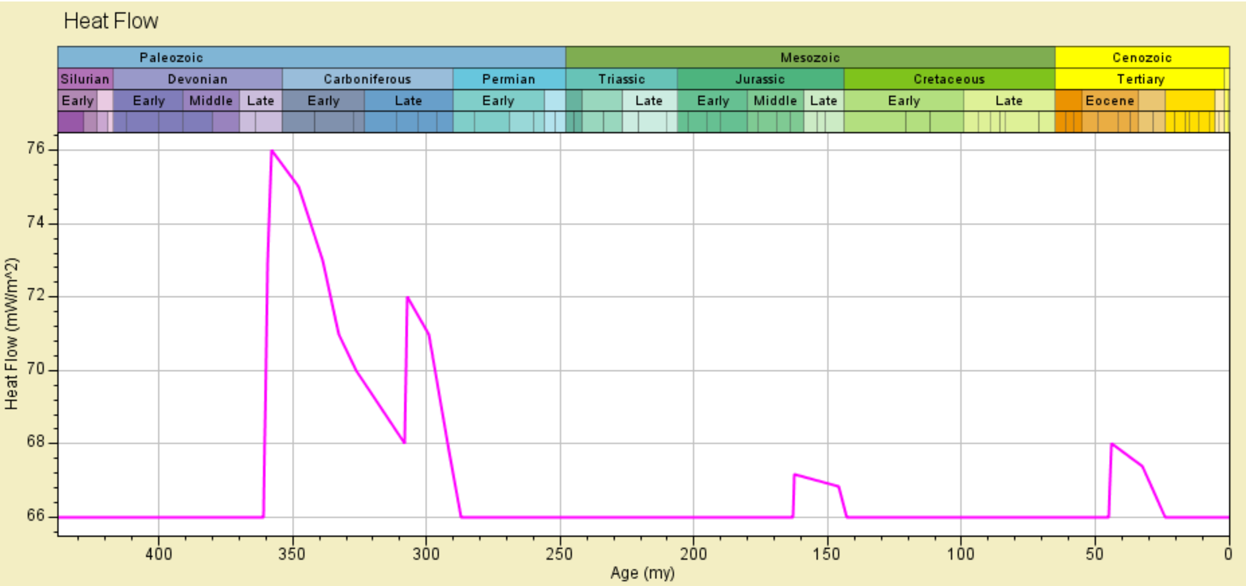


Figure 140: Palaeo-heat flow for Well 41/20-01

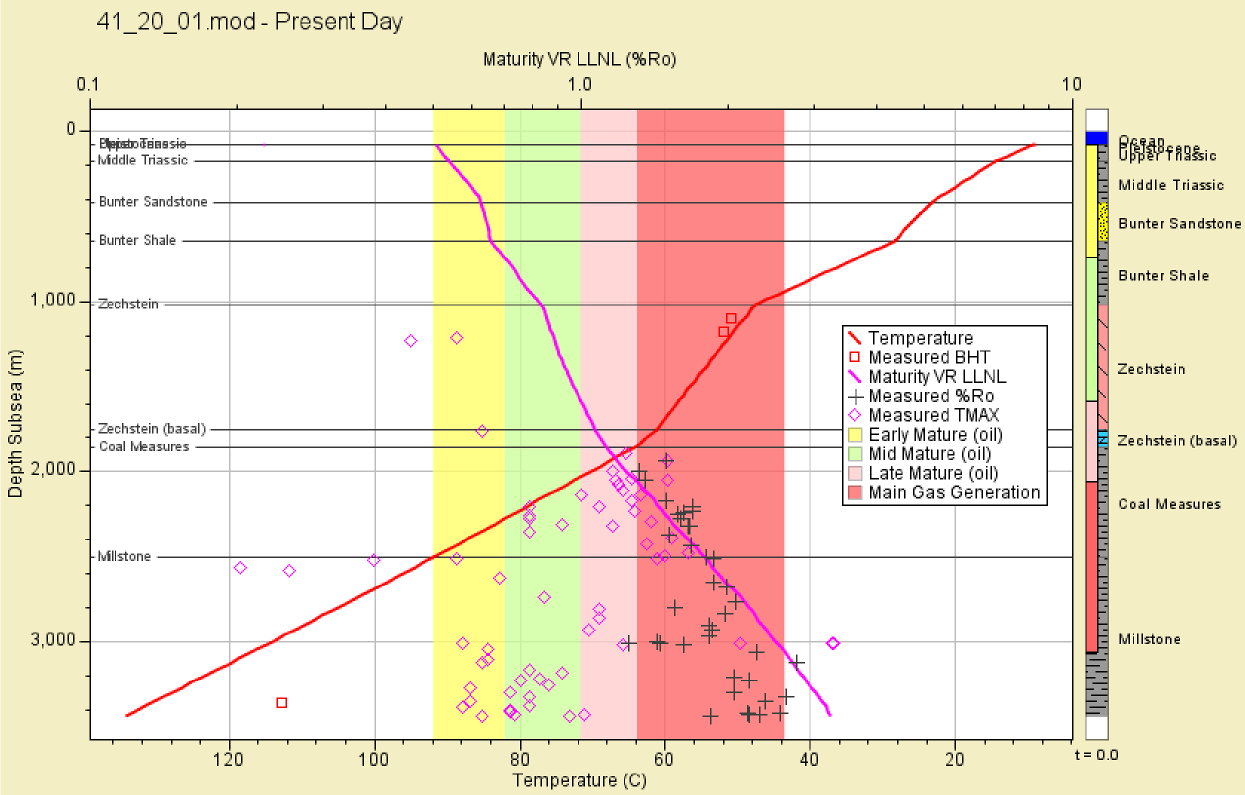


Figure 141: Depth plot for Well 41/20-01 showing model results, maturity data and maturity windows plus temperature data and model

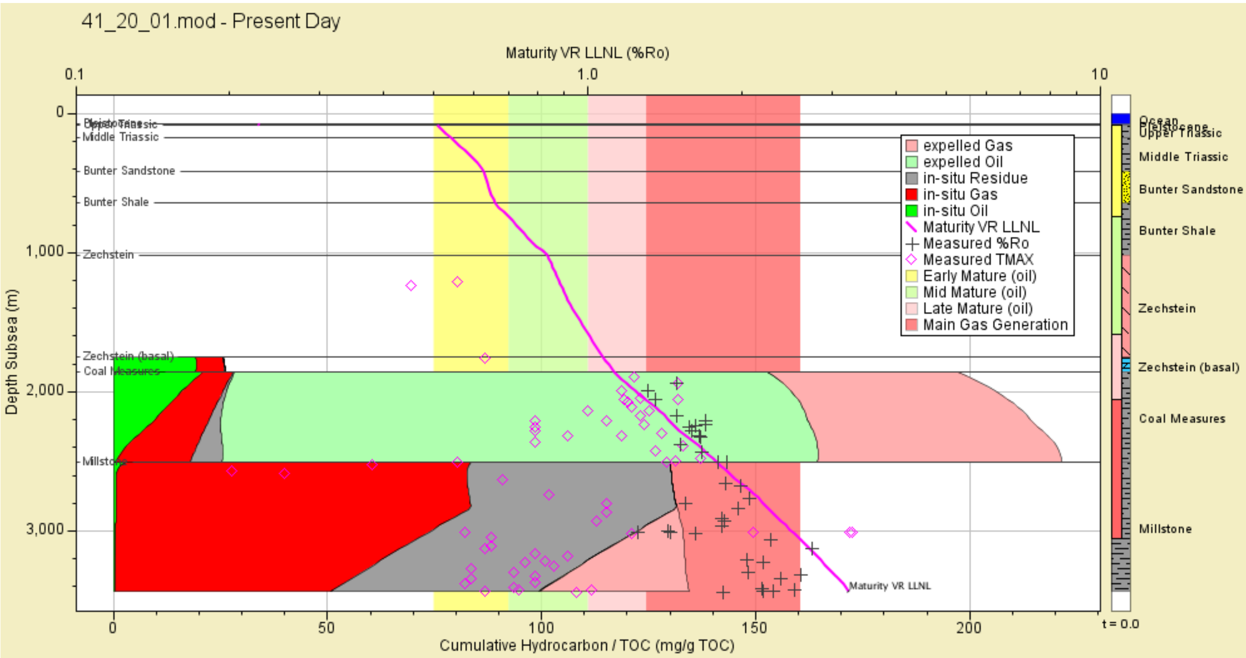


Figure 142: Depth plot for Well 41/20-01 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

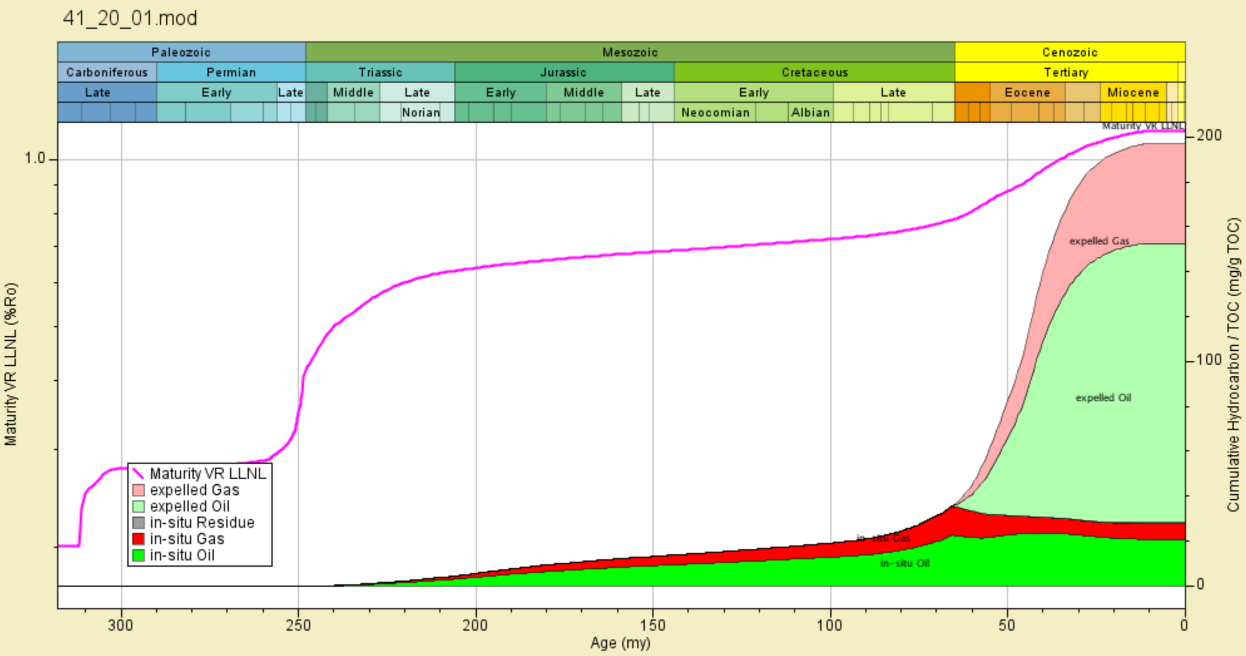


Figure 143: Time plot for Well 41/20-01 showing timing of generation for Coal Measures Group

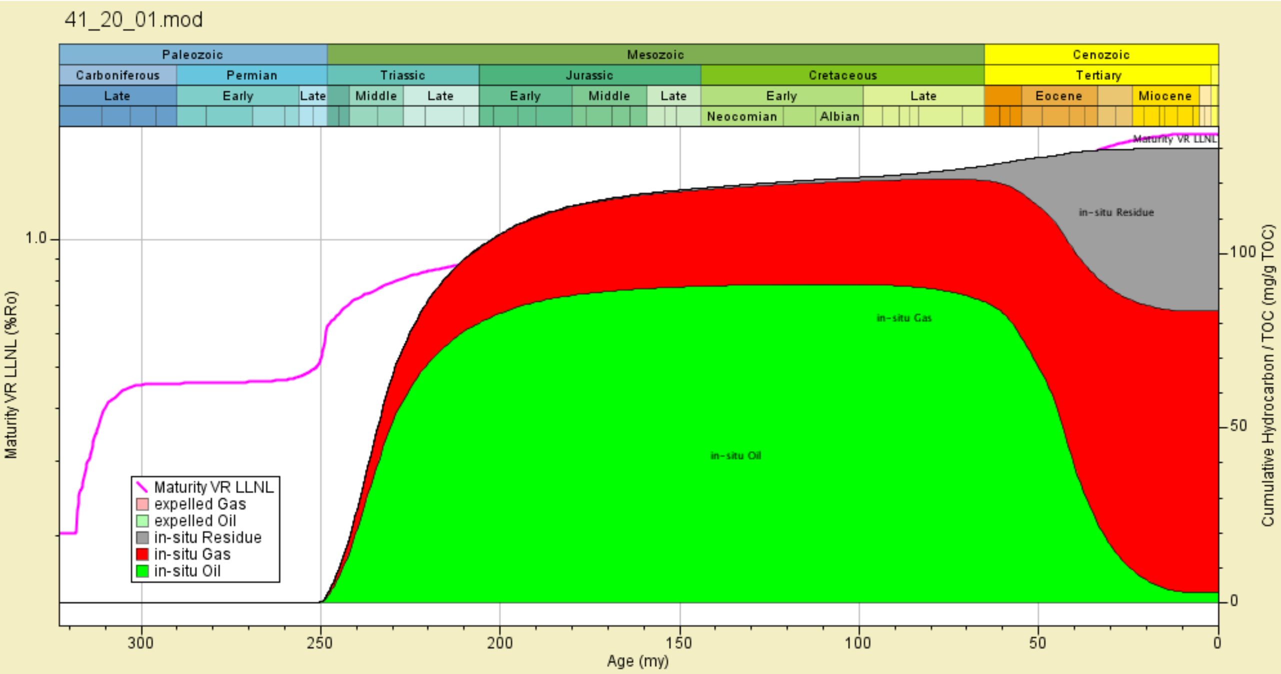


Figure 144: Time plot for Well 41/20-01 showing timing of generation for Millstone Grit Formation

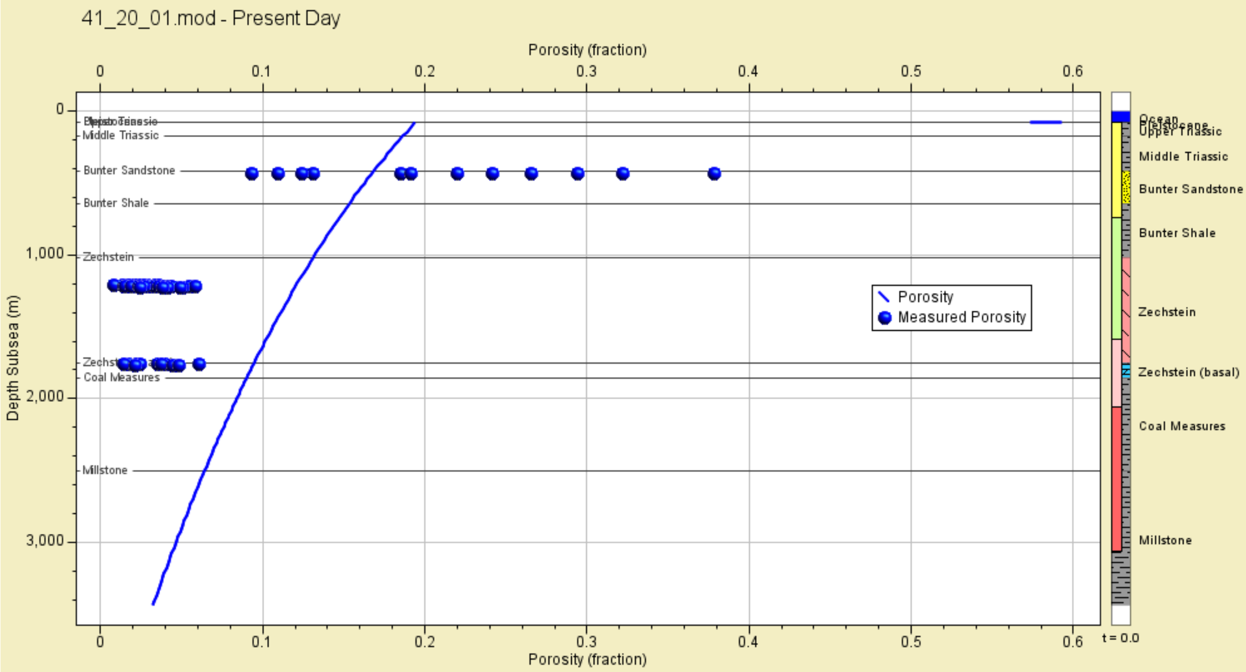
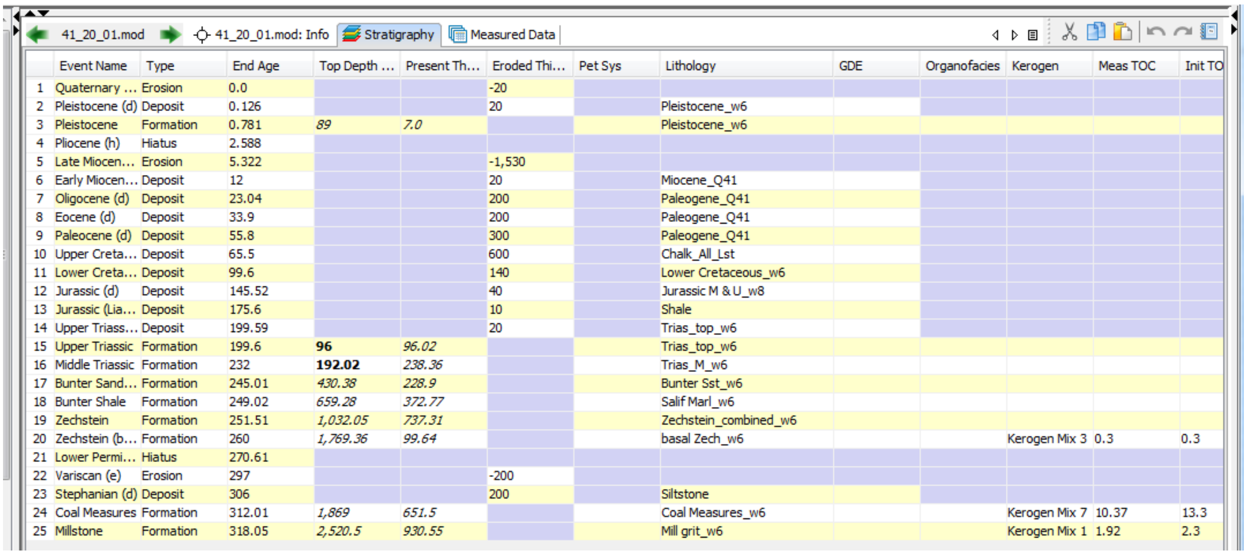


Figure 145: Depth plot for Well 41/20-01 with compaction model and data



41_20_01.mod | 41_20_01.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	Pet Sys	Lithology	GDE	Organofacies	Kerogen	Meas TOC	Init TO
1	Quaternary ...	Erosion	0.0			-20							
2	Pleistocene (d)	Deposit	0.126			20		Pleistocene_w6					
3	Pleistocene	Formation	0.781	*89*	*7.0*			Pleistocene_w6					
4	Pliocene (h)	Hiatus	2.588										
5	Late Miocen...	Erosion	5.322			-1,530							
6	Early Miocen...	Deposit	12			20		Miocene_Q41					
7	Oligocene (d)	Deposit	23.04			200		Paleogene_Q41					
8	Eocene (d)	Deposit	33.9			200		Paleogene_Q41					
9	Paleocene (d)	Deposit	55.8			300		Paleogene_Q41					
10	Upper Creta...	Deposit	65.5			600		Chalk_All_Lst					
11	Lower Creta...	Deposit	99.6			140		Lower Cretaceous_w6					
12	Jurassic (d)	Deposit	145.52			40		Jurassic M & U_w8					
13	Jurassic (Lia...	Deposit	175.6			10		Shale					
14	Upper Triass...	Deposit	199.59			20		Trias_top_w6					
15	Upper Triassic	Formation	199.6	**96**	*96.02*			Trias_top_w6					
16	Middle Triassic	Formation	232	**192.02**	*238.36*			Trias_M_w6					
17	Bunter Sand...	Formation	245.01	*430.38*	*228.9*			Bunter Sst_w6					
18	Bunter Shale	Formation	249.02	*659.28*	*372.77*			Salif Marl_w6					
19	Zechstein	Formation	251.51	*1,032.05*	*737.31*			Zechstein_combined_w6					
20	Zechstein (b...	Formation	260	*1,769.36*	*99.64*			basal Zech_w6			Kerogen Mix 3	0.3	0.3
21	Lower Permi...	Hiatus	270.61										
22	Variscan (e)	Erosion	297			-200							
23	Stephanian (d)	Deposit	306			200		Siltstone					
24	Coal Measures	Formation	312.01	*1,869*	*651.5*			Coal Measures_w6			Kerogen Mix 7	10.37	13.3
25	Millstone	Formation	318.05	*2,520.5*	*930.55*			Mill grit_w6			Kerogen Mix 1	1.92	2.3

Figure 146: Model data entry sheet for Well 41/20-01

42/10B-02

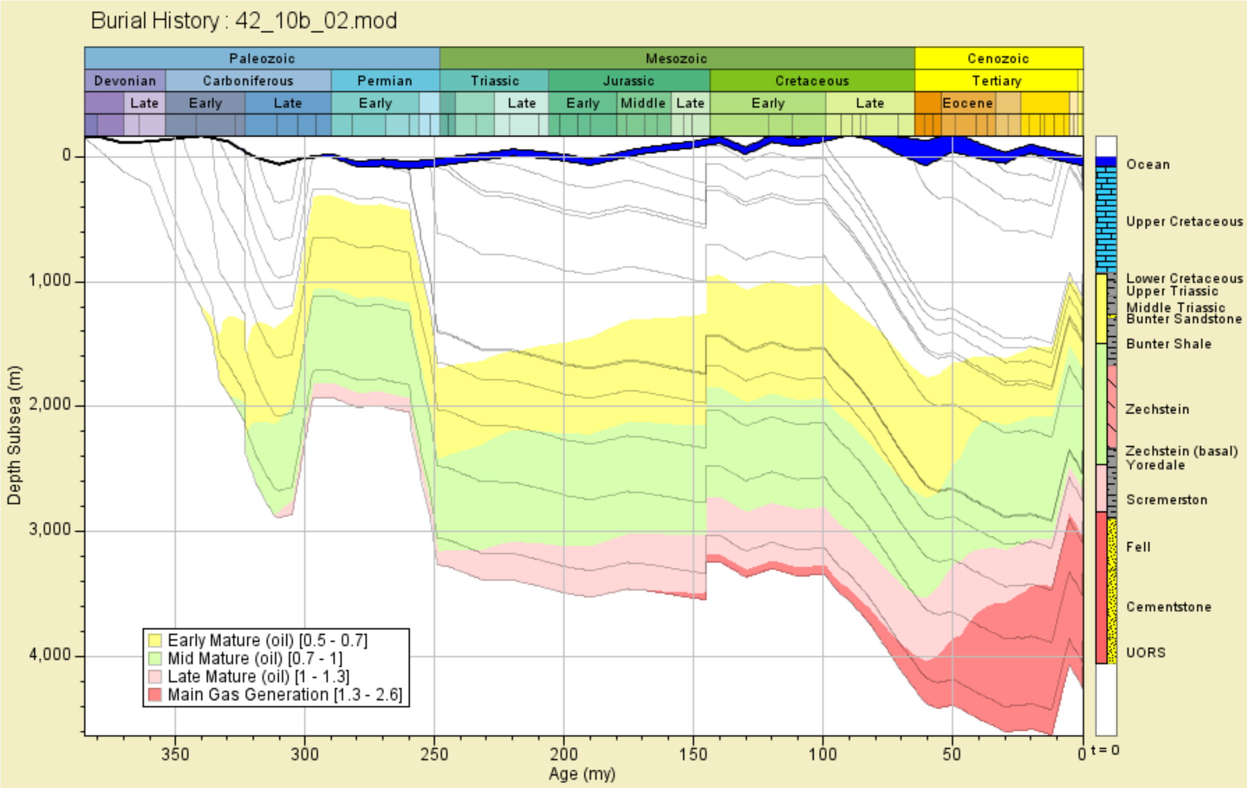


Figure 147: Burial history for Well 42/10b-02

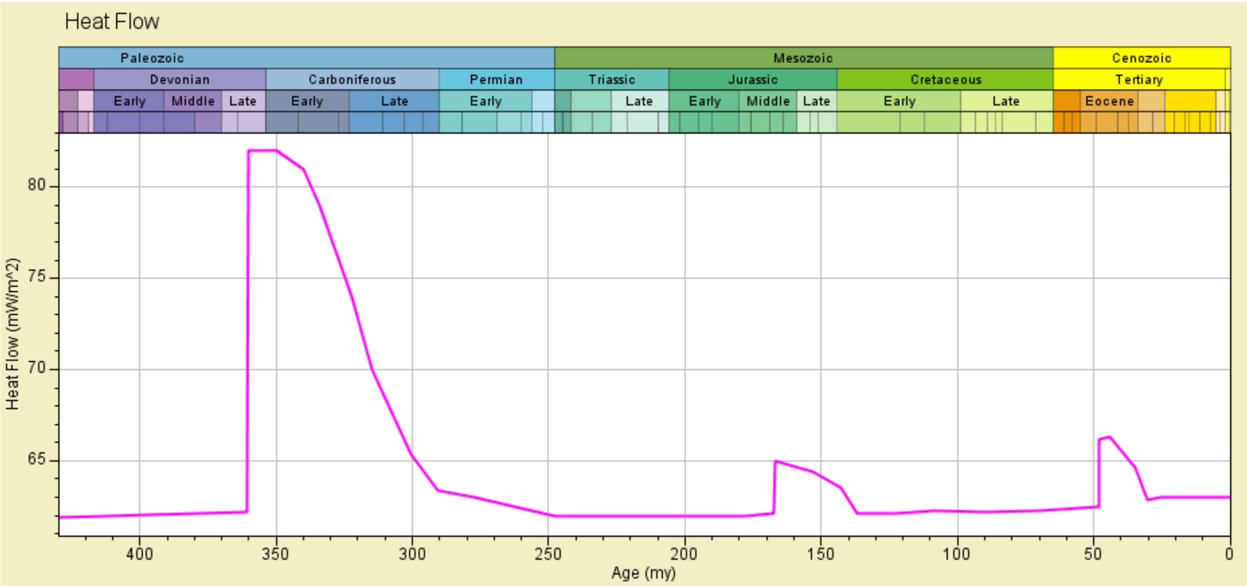


Figure 148: Palaeo-heat flow for Well 42/10b-02

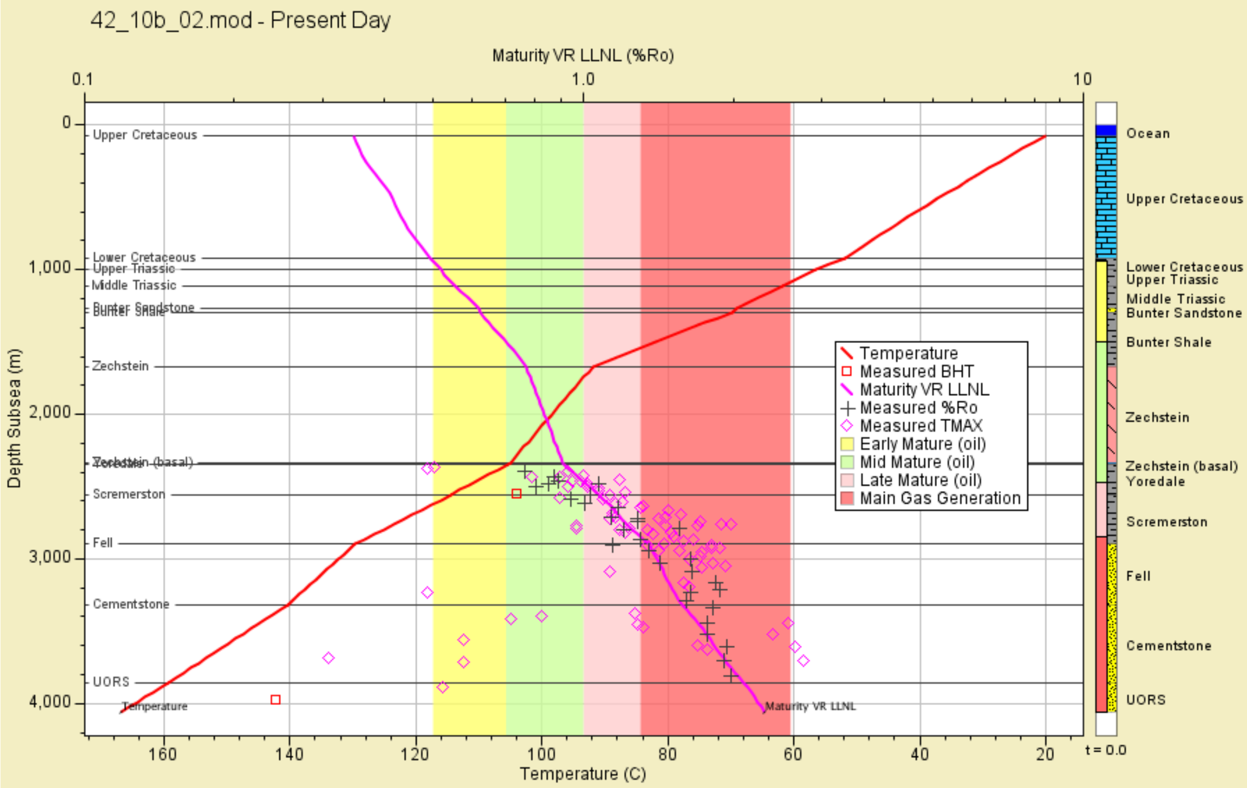


Figure 149: Depth plot for Well 42/10b-02 showing model results, maturity data and maturity windows plus temperature data and model

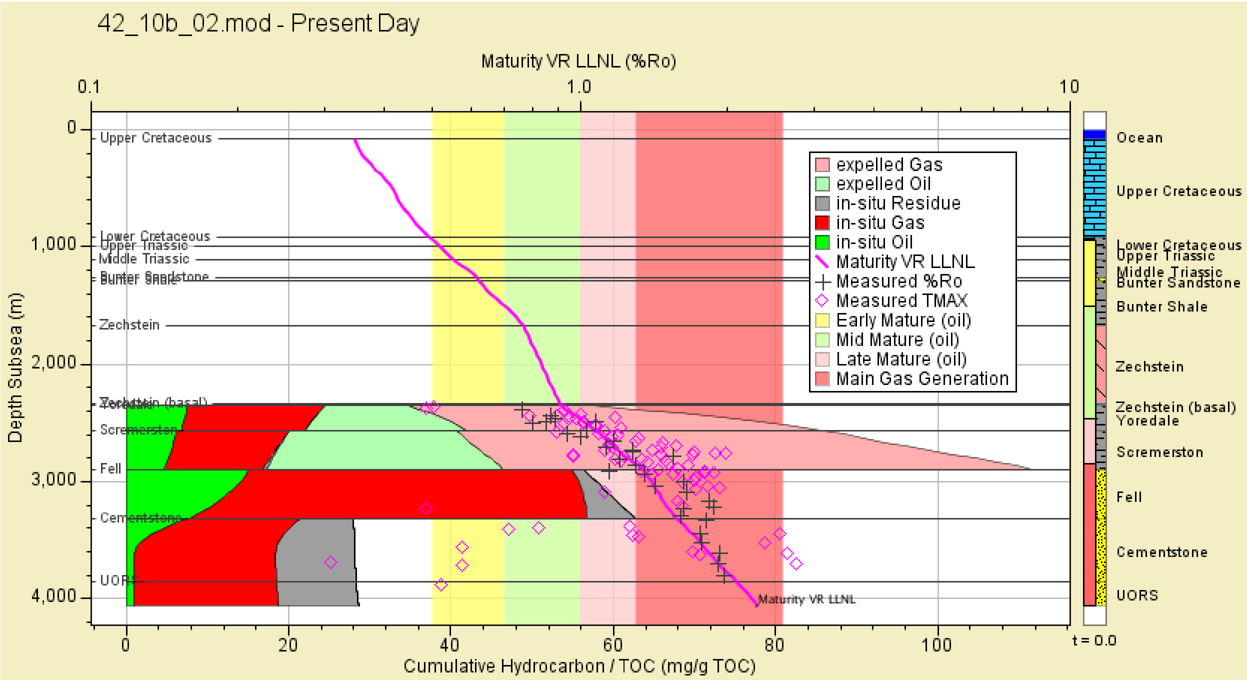


Figure 150: Depth plot for Well 42/10b-02 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

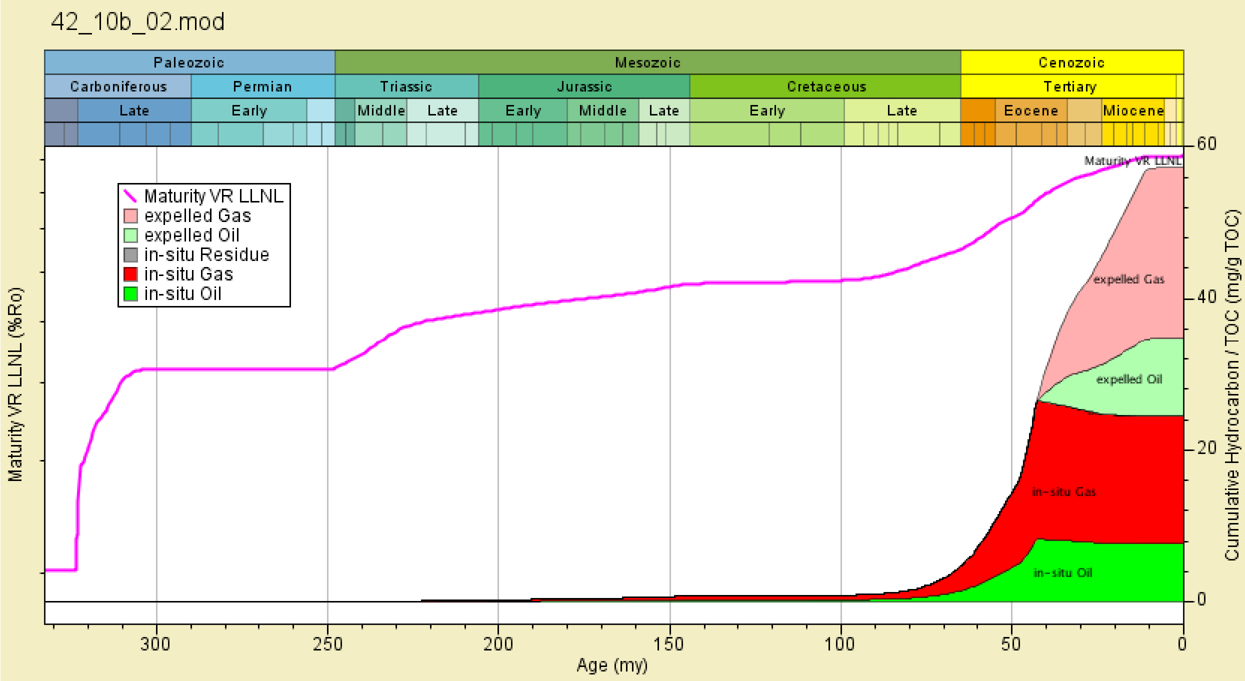


Figure 151: Time plot for Well 42/10b-02 showing timing of generation for Yoredale Formation

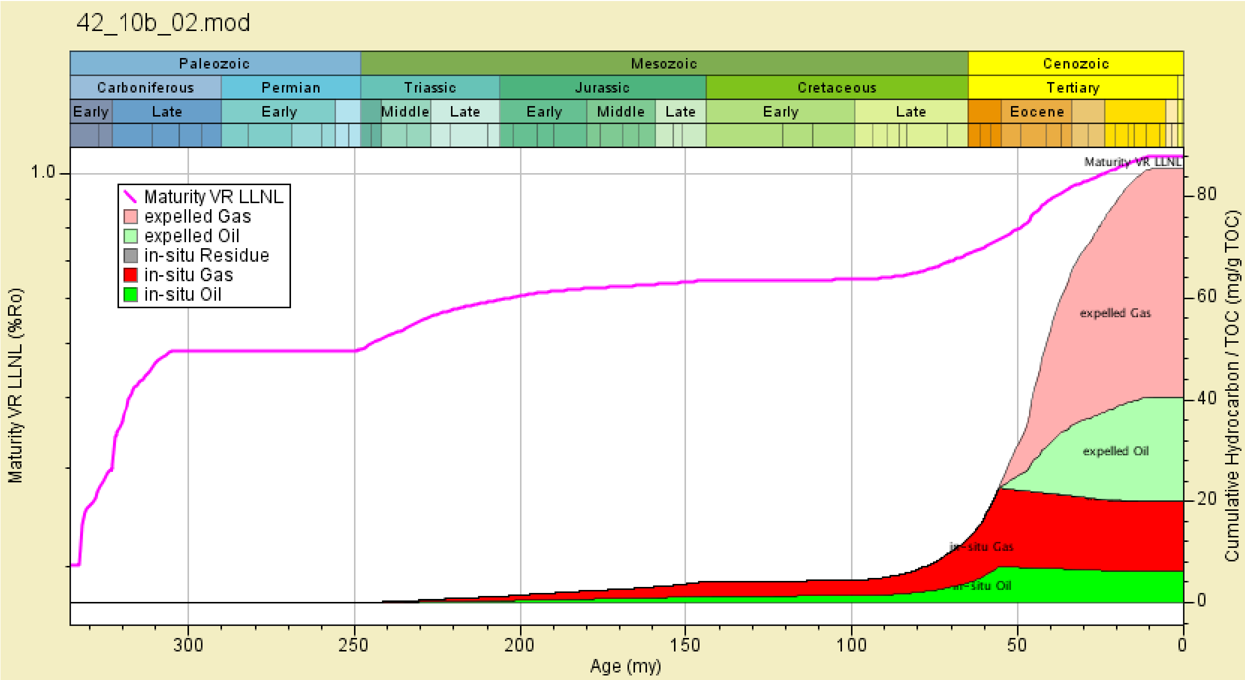


Figure 152: Time plot for Well 42/10b-02 showing timing of generation for Scremerston Formation

42_10b_02.mod | 42_10b_02.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Erode...	Pet Sys	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Tl
1	Quaternary ...	Erosion	0.0			-195								
2	Pleistocene (d)	Deposit	0.126			100		Sandstone						
3	Pliocene (d)	Deposit	2.59			65		PLiocene_Q41						
4	Late Miocen...	Erosion	5.322			-600								
5	Early Miocen...	Deposit	12			30		Miocene_Q41						
6	Oligocene (d)	Deposit	23.04			150		Paleogene_Q41						
7	Eocene (d)	Deposit	33.9			200		Paleogene_Q41						
8	Paleocene (d)	Deposit	55.8			250		Paleogene_Q41						
9	Upper Creta...	Formation	65.51	*96.01*	*848.57*			Chalk_All_Lst						
10	Lower Creta...	Formation	99.61	*944.58*	*77.11*			Lower Cretaceou...						
11	Jurassic (e)	Erosion	145.5			-300								
12	Jurassic (d)	Deposit	145.52			300		Jurassic M & U_w8						
13	Jurassic (Lia...	Hiatus	175.59											
14	Upper Triassic	Formation	199.6	*1,021.69*	*113.08*			Upper Trias (Hais)...						
15	Middle Triassic	Formation	232	*1,134.77*	*153.92*			Middle Trias (Hais...						
16	Bunter Sand...	Formation	245.01	*1,288.69*	*26.52*			Bunter Sst_w7						
17	Bunter Shale	Formation	249.02	*1,315.21*	*376.73*			Bunter Shl_w7						
18	Zechstein	Formation	251.51	*1,691.94*	*665.08*			Zechstein_w7						
19	Zechstein (b...	Formation	260	*2,357.02*	*10.67*			Zech 1_w7						
20	Lower Permi...	Hiatus	270.61											
21	Variscan (e)	Erosion	297			-900								
22	Stephanian (h)	Hiatus	305											
23	Coal Measur...	Deposit	312			300		Yoredale_w7						
24	Millstone (d)	Deposit	318			300		Yoredale_w7						
25	Yoredale (d)	Deposit	323			300		Yoredale_w7						
26	Yoredale	Formation	323.5	*2,367.69*	*214.57*			Yoredale_w7			Type III (BM...	16.06	17.7	0.2
27	Scremerston	Formation	333.01	*2,582.26*	*338.64*			Scremerston_w7			Type III (BM...	16.91	19.3	0.2
28	Fell	Formation	336.01	*2,920.9*	*417.57*			Fell_w7			Kerogen Mix 4	2.13	2.3	0.2
29	Cementstone	Formation	347	*3,338.47*	*539.25*			Cementstone_w7			Kerogen Mix 3	1.37	1.4	0.2
30	UORS	Formation	360	*3,877.72*	*202.08*			UORS_w7			Kerogen Mix 3	0.06	0.1	0.2

Figure 153: Model data entry sheet for Well 42/10b-02

43/17-02

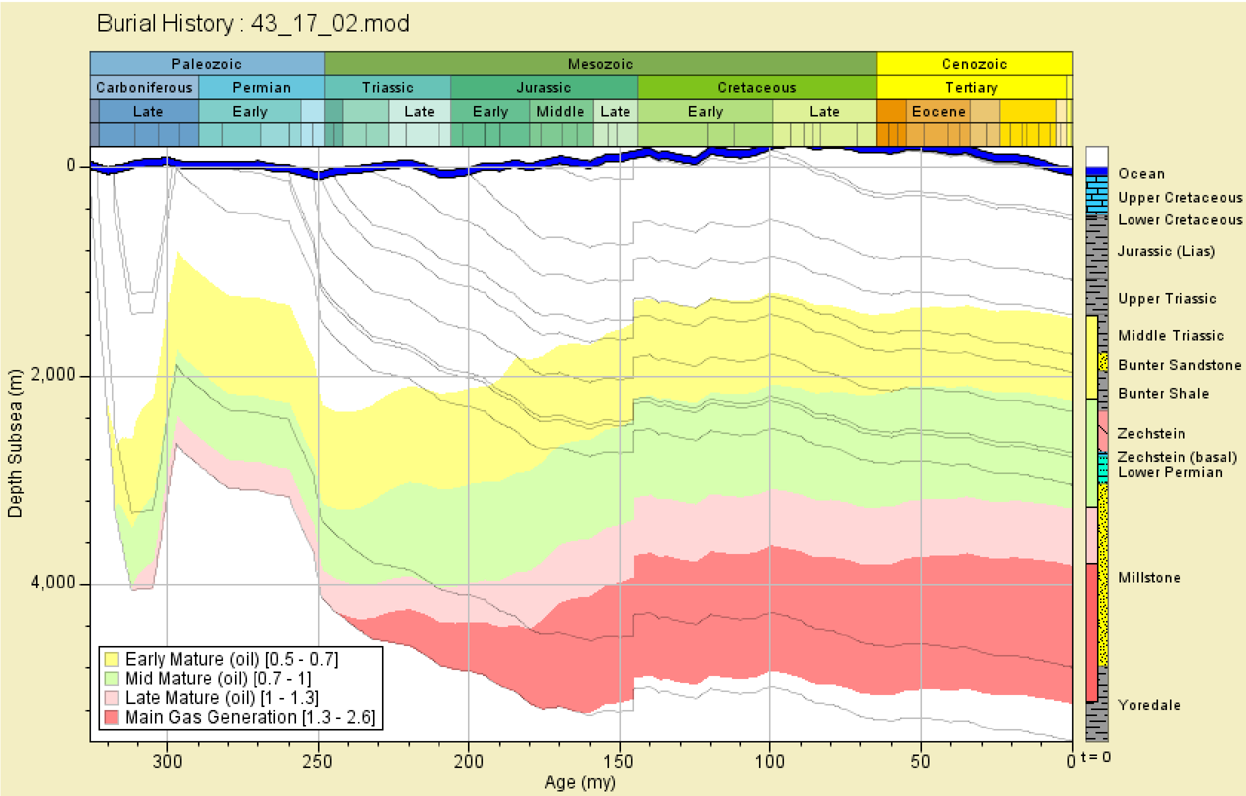


Figure 154: Burial history for Well 43/17-02

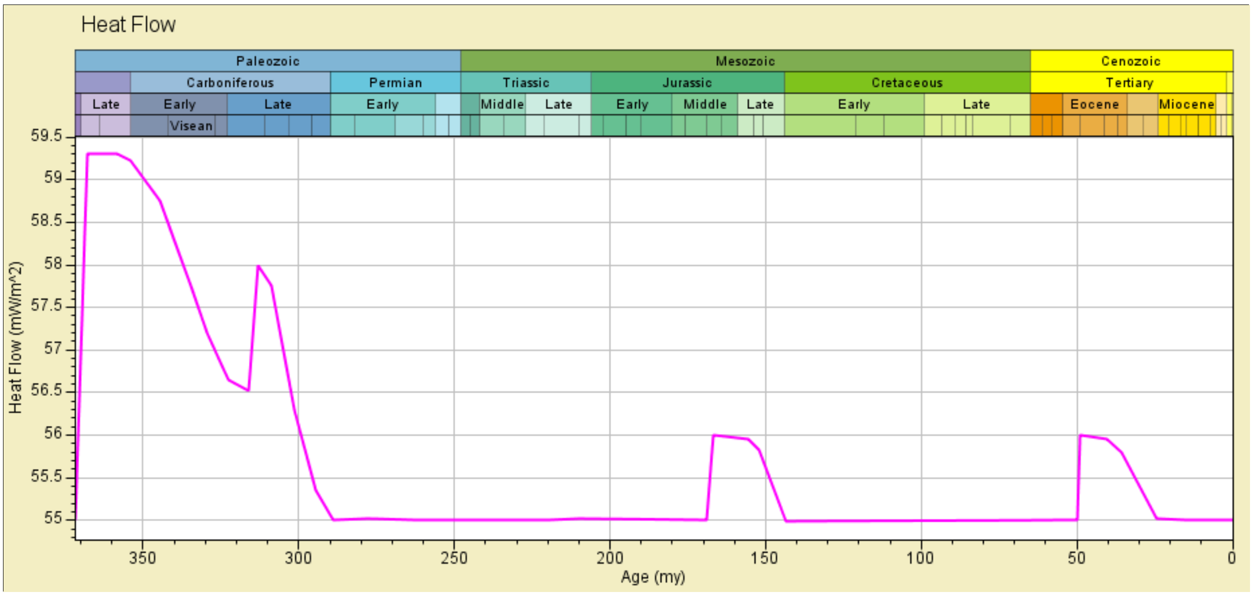


Figure 155: Palaeo-heat flow for Well 43/17-02

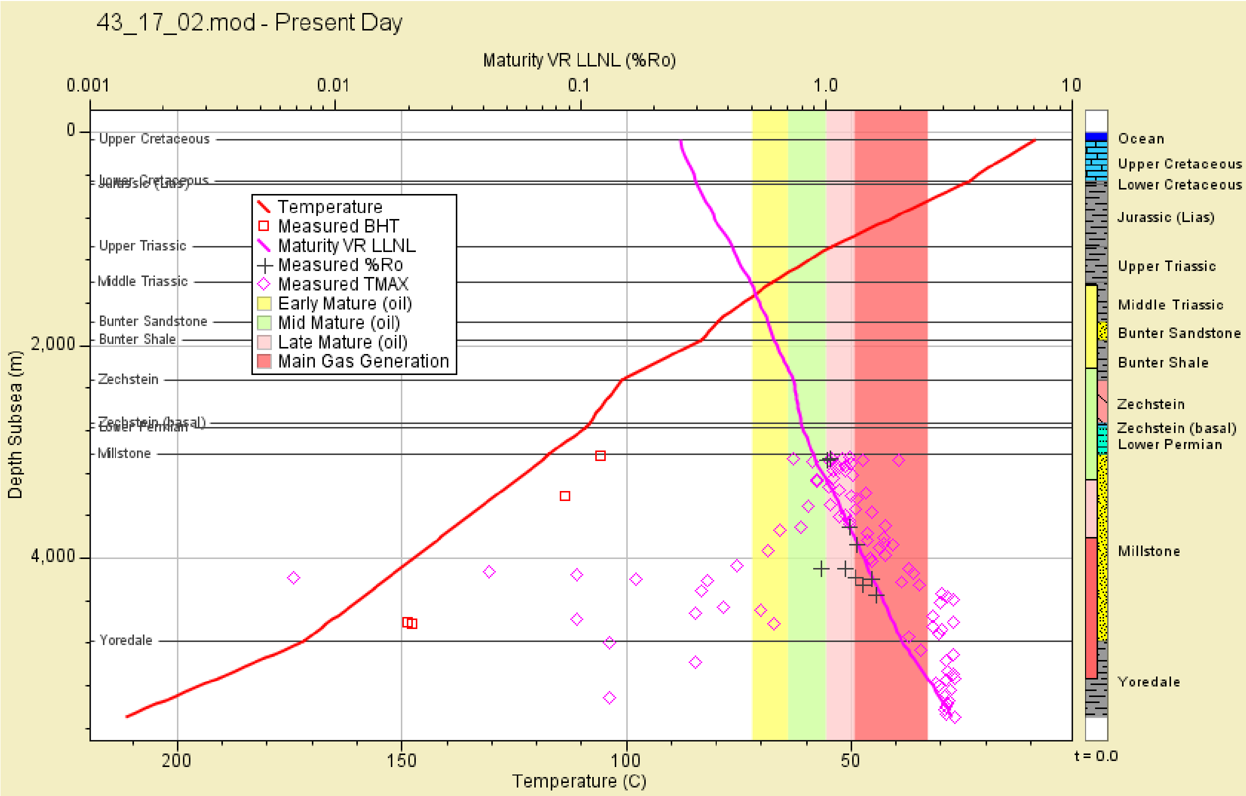


Figure 156: Depth plot for Well 43/17-02 showing model results, maturity data and maturity windows plus temperature data and model

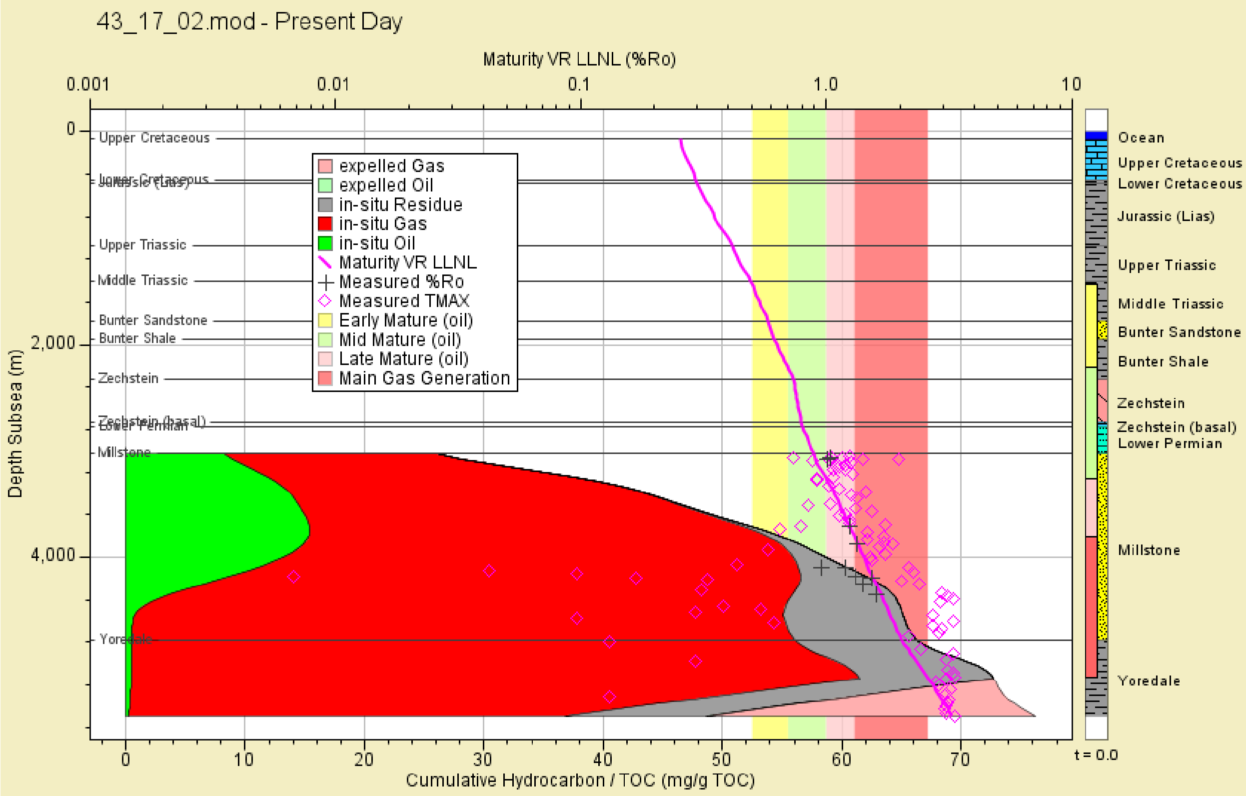


Figure 157: Depth plot for Well 43/17-02 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model

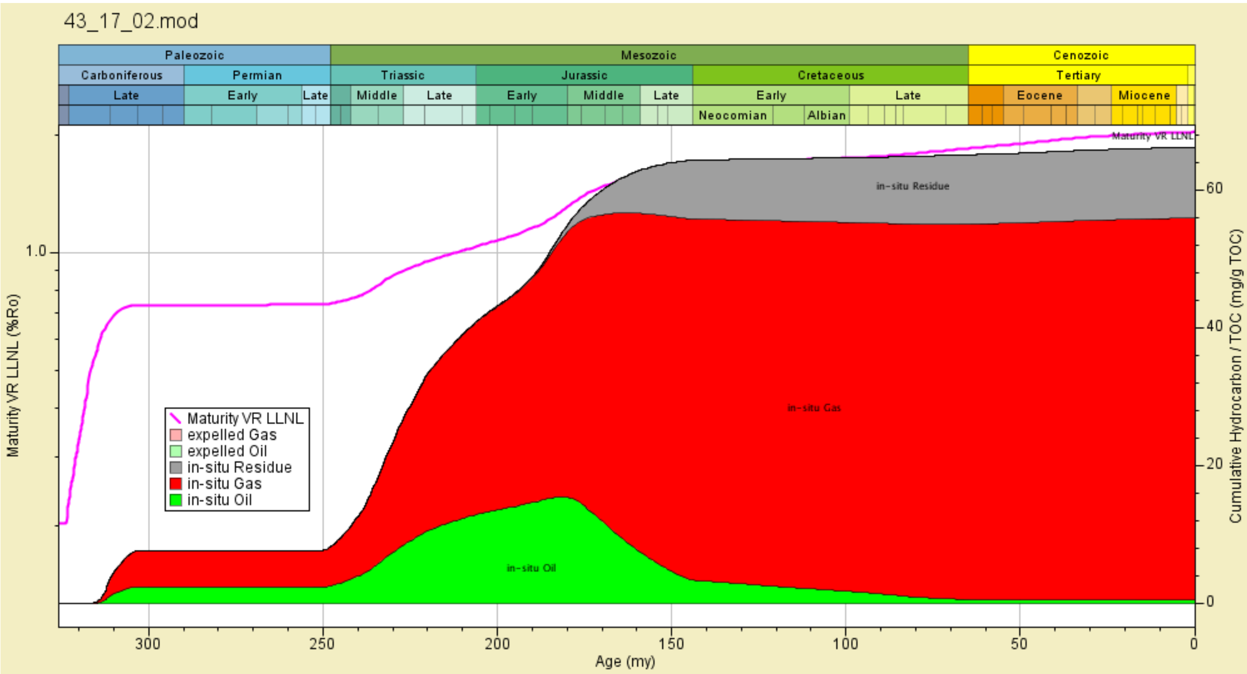


Figure 158: Time plot for Well 41/20-01 showing timing of generation for Yoredale Formation

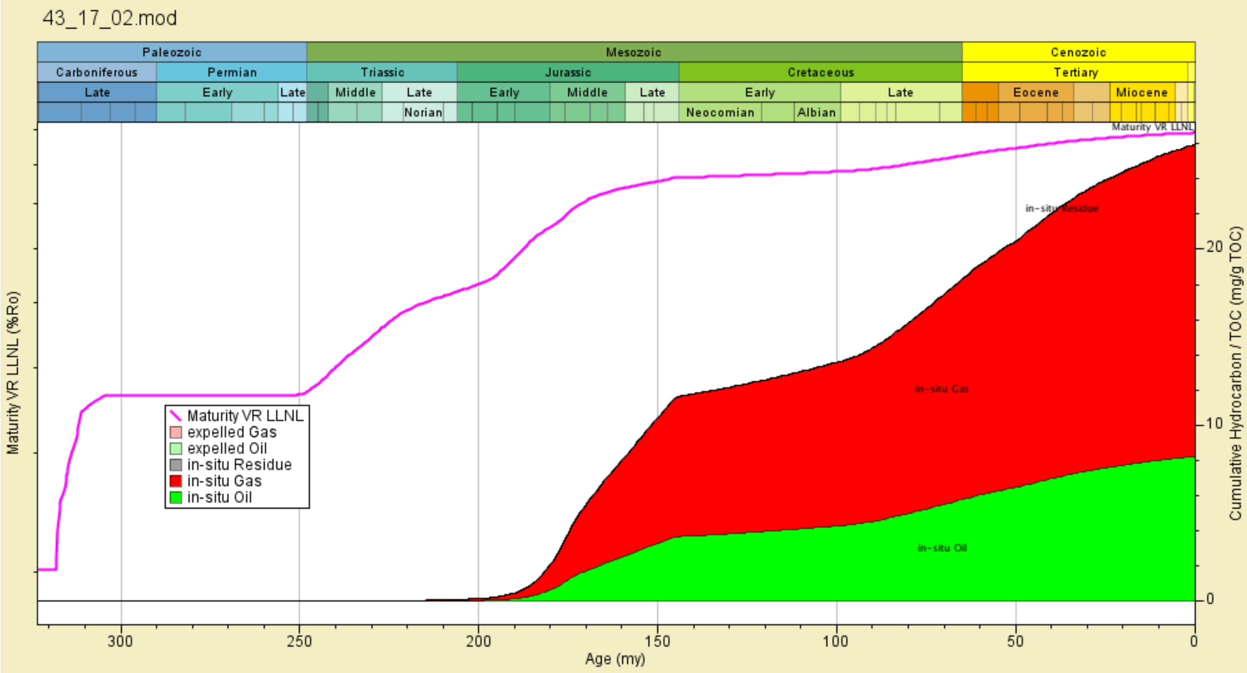


Figure 159: Time plot for Well 43/17-02 showing timing of generation for Millstone Grit Group

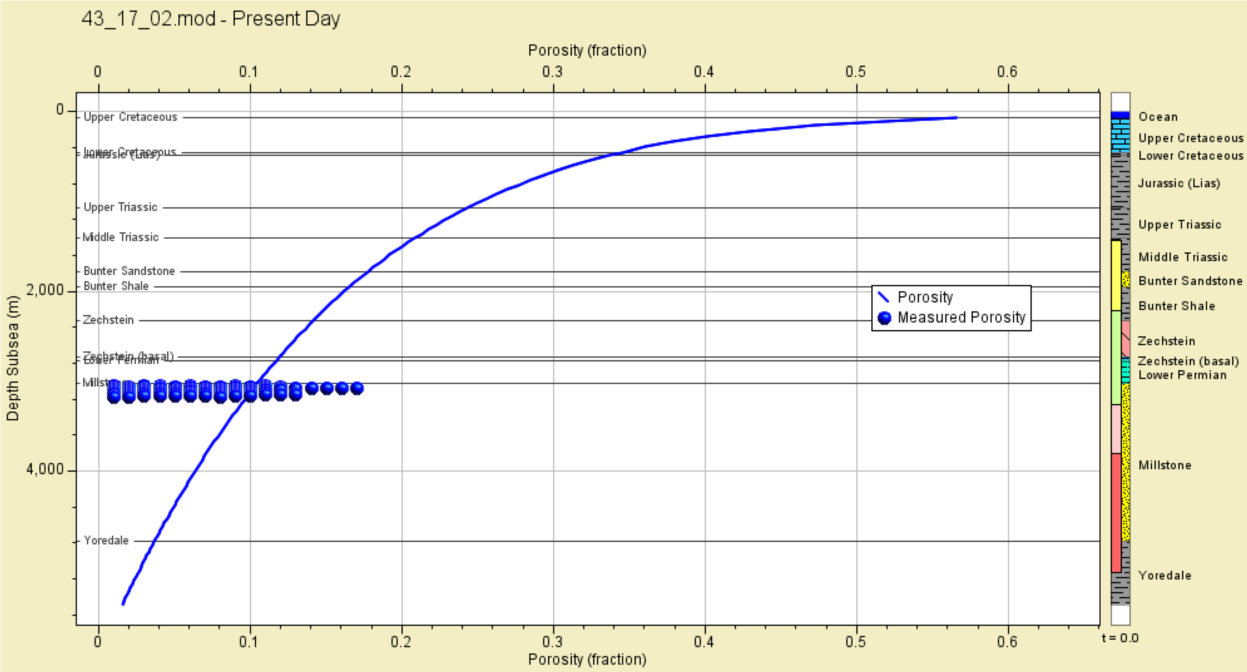


Figure 160: Depth plot for Well 43/17-02 with compaction model and data

43_17_02.mod | 43_17_02.mod: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Prese...	Erode...	...	Lithology	...	...	Kerogen	Meas TOC	Init TOC	Sat Thresh	Effecti
1	Quaternary (e)	Erosion	0.0			-10									
2	Pleistocene (d)	Deposit	0.126			5.0		Sandstone							
3	Pliocene (d)	Deposit	2.59			5.0		PLiocene_Q41							
4	Late Miocene (e)	Erosion	5.322			-30									
5	Early Miocene (d)	Deposit	12			5.0		Miocene_Q41							
6	Oligocene (d)	Deposit	23.04			5.0		Paleogene_Q41							
7	Eocene (d)	Deposit	33.9			10		Paleogene_Q41							
8	Paleocene (d)	Deposit	55.8			10		Paleogene_Q41							
9	Upper Cretaceous	Formation	65.51	*161.54*	*377.65*			Chalk_All_Lst							
10	Lower Cretaceous	Formation	99.61	*539.19*	*37.8*			Lower Cretaceous_w8							
11	Jurassic (e)	Erosion	145.5			-200									
12	Jurassic (d)	Deposit	145.52			200		Jurassic M & U_w8							
13	Jurassic (Lias)	Formation	175.61	*576.99*	*578.2*			Jur Lias_w8							
14	Upper Triassic	Formation	199.6	*1,155.19*	*338.33*			U Trias (Hais)_w8							
15	Middle Triassic	Formation	232	*1,493.52*	*372.77*			Middle Trias (Dow)_w8							
16	Bunter Sandstone	Formation	245.01	*1,866.29*	*175.26*			Bunter sst_w8							
17	Bunter Shale	Formation	249.02	*2,041.55*	*376.73*			Bunter Shl_w8							
18	Zechstein	Formation	251.51	*2,418.28*	*396.85*			Zechstein_w8							
19	Zechstein (basal)	Formation	260	*2,815.13*	*41.46*			Zech 1_w8							
20	Lower Permian	Formation	280	*2,856.59*	*261.51*			Rot_w8							
21	Variscan (e)	Erosion	297			-1,400									
22	Stephanian (h)	Hiatus	305												
23	Coal Measures (d)	Deposit	312			1,200		Coal measures_w8							
24	Millstone (d)	Deposit	318			200		Mill Grit_w8							
25	Millstone	Formation	318.05	**3,118.1**	*1,751.69*			Mill Grit_w8			Kerogen Mix 4	2.0	2.1	0.2	
26	Yoredale	Formation	323.5	**4,869.79**	**707.94**			Yoredale_w8			Kerogen Mix 4	1.4	1.5	0.2	

Figure 161: Model data entry sheet for Well 43/17-02