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Maturity modelling of selected wells in the Orcadian Study Area

Energy and Marine Geoscience Programme

Commissioned Report CR/16/036

BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/15/122

Maturity modelling of selected wells in the Orcadian Study Area

C J Vincent

Keywords

Palaeozoic, basin modelling, maturity

Bibliographical reference

VINCENT, C J. 2016. Maturity modelling of selected wells in the Orcadian Basin. *British Geological Survey Commissioned Report*, CR/16/036. 65pp.

Keyworth, Nottingham British Geological Survey 2016

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Foreword and acknowledgements

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

The author also wishes to thank the sponsors who provided new data for this report. Platte River Associates Inc. software BasinMod™ (v. October 2014) software was used under license.

Matt Jacobs (LR Senergy) is thanked for technical review of this report. The author also wishes to thank Alison Monaghan and Robert Gatliff (BGS) for their thorough review.

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Summary

This report details maturity and migration modelling of four wells for the 21CXRM Palaeozoic project, Orcadian study area. The aim of the maturity modelling was to predict if Devonian and Carboniferous source rock intervals within the wells are, or have been, mature for hydrocarbon generation.

Wells 12/27- 1 and 20/10a- 3 were chosen for 1D modelling based on availability of maturity and geochemical data (Figure 1). As this region comprises a series of Palaeozoic structural highs and basins, two wells cannot fully represent the geological evolution of the study area. Two ‘scenario’ or ‘pseudo’ wells, 12/16- 1 and 21/06b- 5 were included to contrast the basin history.

Previous basin modelling work in the Inner Moray Firth is summarised in Greenhalgh (2016) and this study is placed in regional context in Monaghan et al. (2016).

Inner Moray Firth (IMF)

Lacustrine strata deposited during Lower and Middle Devonian times are believed to offer the main source rock potential in the IMF (see summary in Greenhalgh, 2016), as the high TOC Jurassic strata are largely immature (Fraser et al., 2003, their fig. 17.2). Well 12/27- 1 is situated on a post-Lower Devonian relative high (Figure 2), has moderate/good Total Organic Content (TOC) in the Lower Devonian Struie Formation and oil and gas shows are observed (well report; Vane et al., 2016). Two cases were modelled to accommodate uncertainty in the maturity data, with a significant impact on the timing of generation. If deepest burial was achieved during Devonian times (fitted to higher maturity values; Figure 13, 14, 15), then main hydrocarbon generation occurred during Devonian burial (Figure 17). However, if deepest burial occurred during Cretaceous – Cenozoic times (best fit to maturity values, though these data are possibly supressed; Figure 5, 7, 8) then generation occurred from the Struie Formation during both Devonian and Cretaceous – Cenozoic times (Figure 9). Please see Section 4 for more detail.

Carboniferous strata are rarely penetrated by wells in the IMF. The anomalous Firth Coal Formation to Devonian succession proven in Well 12/16- 1, close to the Great Glen and Wick faults was modelled (Figure 21, 24). Well 12/16-1 lies in a different Palaeozoic sub-basin to Well 12/27-1. It is classed as a ‘scenario’ well due to uncertainties in the constraining data. The source rock intervals contain mainly gas prone kerogens and as the Carboniferous strata only reached the main oil maturity window during deep Carboniferous burial, significant gas generation is not expected.

Given the block and basin structure of the IMF during the Palaeozoic Era and the variable distribution of facies, any single well is unlikely to provide a complete representation of the geological history and petroleum systems. The model results are useful in assessing the maturity geohistory and generation potential of the region, but must be considered in the regional context of the Orcadian study area (see Monaghan et al., 2016).

South Buchan Basin

Well 20/10a- 3 was drilled on a high at the western margin of the South Buchan Basin and was chosen for modelling based on availability of maturity data. The Firth Coal Formation source rocks are interpreted to be mainly gas prone but some condensate prone intervals were noted towards the bottom of the drilled interval. The 1D basin modelling shows that the Firth Coal Formation reached the mid mature window for oil generation during deep Cenozoic burial (Figure 288, 30, 31, 32).

To test whether the same Firth Coal Formation source rock, buried more deeply in the South Buchan Basin would likely be gas mature, the 21/06b- 5 ‘scenario’ well was modelled using

depths from seismic interpretation (the well itself terminates in Triassic strata), and source rock data from well 20/10a- 3 which lies 12 km to the west. The model results predicted that the Firth Coal Formation reached the gas maturity window during deep Cenozoic burial (Figures 35, 37, 38, 39).

1 Introduction

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

The project results are delivered as a series of reports and as digital datasets for each area. This report describes maturity modelling of selected wells in the Orcadian study area.

The aim of the modelling was to predict if Devonian – Carboniferous source rock intervals are, or have been, mature for hydrocarbon generation, and to model the timing of burial and hydrocarbon generation for two regions of the Orcadian study area (Figure 1, 2, 4). Geochemical and maturity data were extracted from CDA well reports, published papers and information generously donated by a number of Sponsor companies. A summary of the stratigraphy utilised for this report is shown in Figure 3.

This report is divided into the following sections:

- Section 2; a short section describing the modelling methodology and rationale for well selection.
- Section 3: an overview of the 1D modelling results.
- Sections 4 and 5; details of the 1D models are provided. These sections include a geological history of each of the main areas considered, data from legacy wells which lie close to the wells being studied for this report, previous maturity modelling results for the wells being studied as well as data for, and results of, the new models.

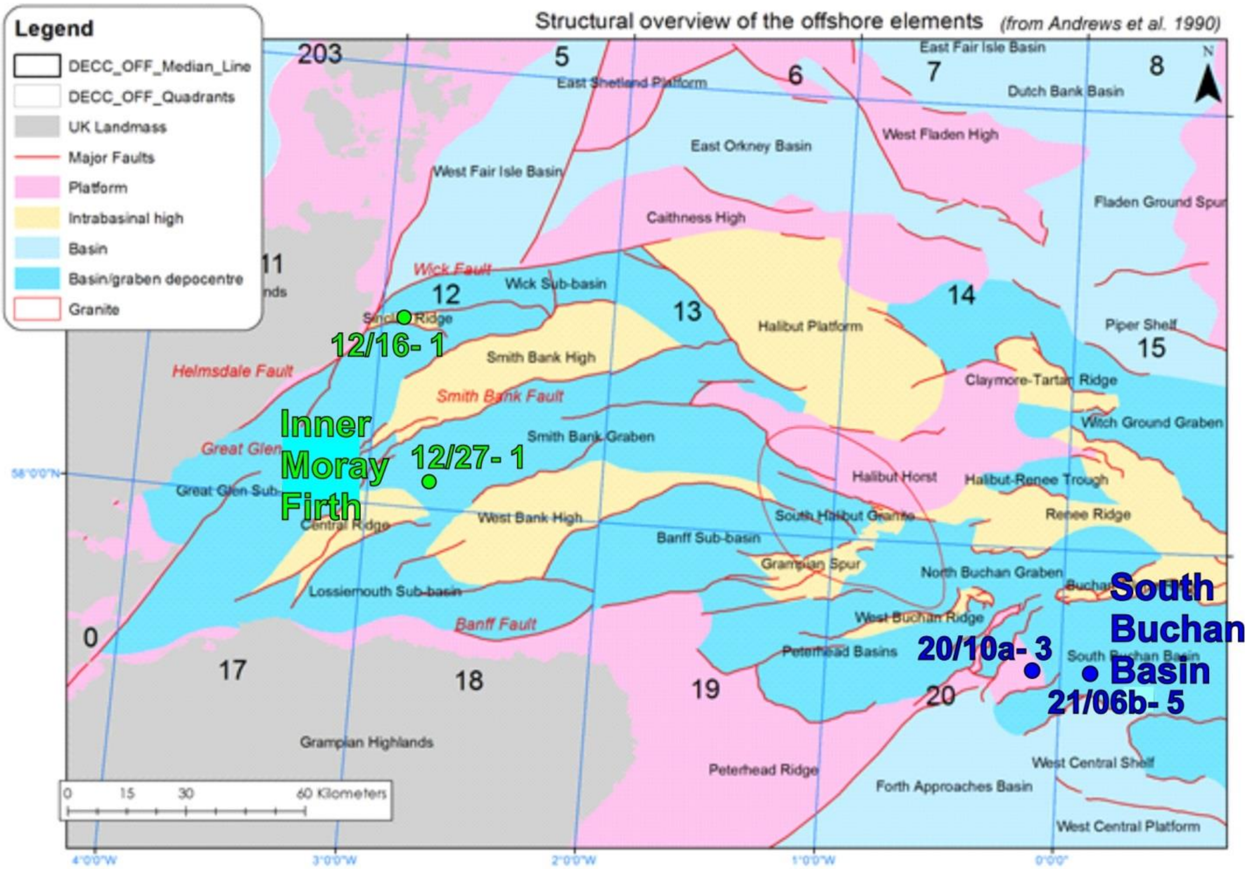


Figure 1: Location of the wells modelled in the 1D maturity study placed upon the structural framework map from Andrews et al. (1990).

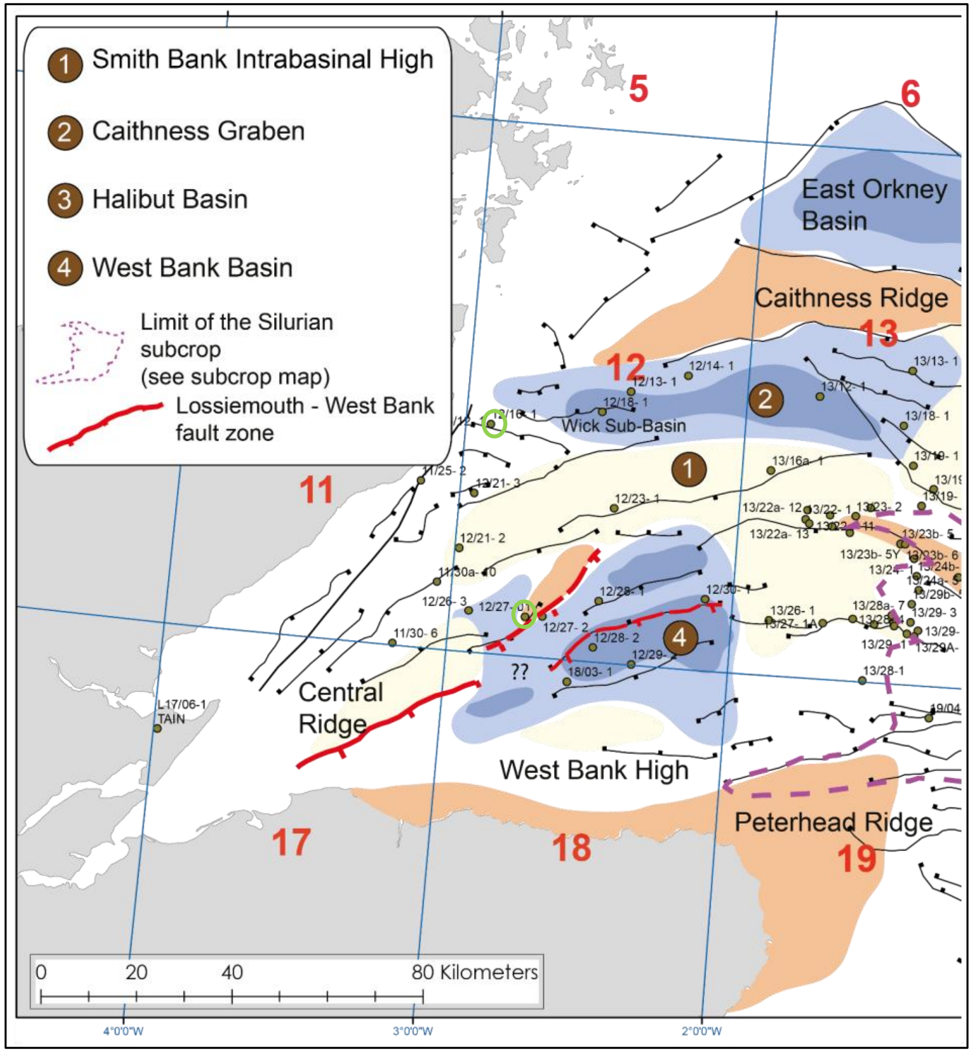


Figure 2 Structural diagram with the major Palaeozoic structural elements of the Inner Moray Firth shown (Arsenikos et al., 2016), to highlight the local high location of 12/27- 1. Blue areas are the basins/depocentres, cream coloured are the terraces/ shelves and orange areas are the highs/ ridges. 12/27- 1 and 12/16- 1 are circled in green.

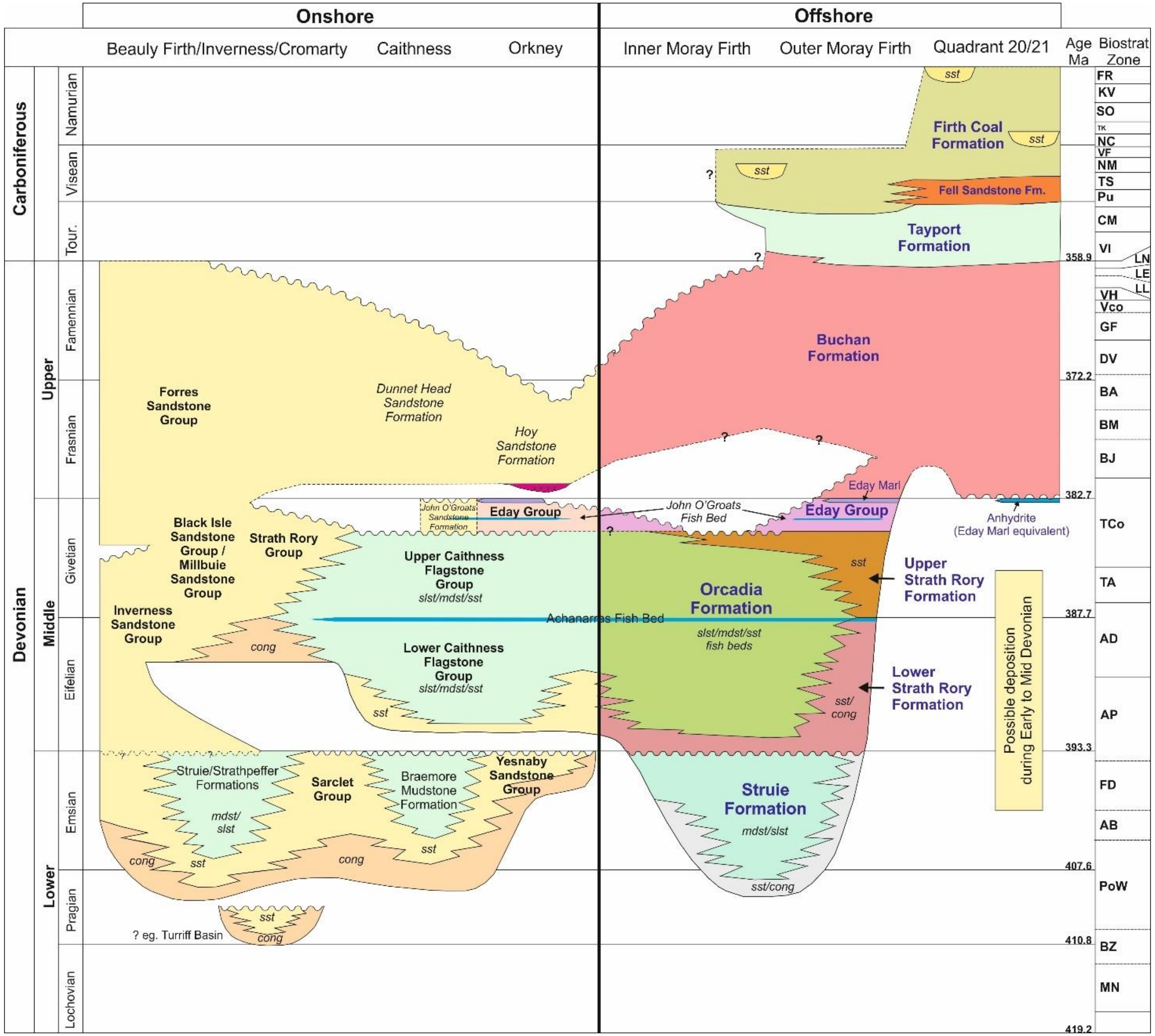


Figure 3 Stratigraphic relationships of Devonian and Carboniferous strata in the onshore and offshore regions of the Orcadian study area (Whitbread and Kearsey, 2016).

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
- To predict when hydrocarbon generation occurred
- To contrast thermal histories in different areas around the Orcadian study area

The regions of interest are the Inner Moray Firth (IMF) and the South Buchan Basin (Figure 1, Figure 2). Only limited maturity, kerogen and Rock-Eval data are available for Devonian and Carboniferous sequences within the Orcadian study area. The wells to be modelled were chosen based on availability of maturity data. The modeling work was undertaken in order to contribute to understanding the thermal maturity of two regions of interest.

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 and 1D models give an understanding of the maturity of source intervals at the specific model locations and indicate which strata have reached sufficient maturity for any organic material which is present to generate oil or gas. This information can then be used to extrapolate into the wider basin (e.g. through the use of depth structure maps) to gain further understanding of the wider maturity potential.

2.1 1D MODELLING METHODOLOGY

The 1D models were prepared using 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 was then calibrated graphically to vitrinite reflectance maturity data 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., 2015 for limitations of this technique).Where available, temperature data were included and used to calibrate the temperature model.

Kerogen typing and pyrolysis data (including Total Organic Content, TOC) were used to model the generative potential of the formations penetrated by the wells. The TOC (%) and HI (mg/g TOC) indicate the generative potential of the strata penetrated by the well. Cumulative hydrocarbon plots (with cumulative mg/g TOC 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 cumulative hydrocarbon volume on the time plot shows generative potential being realised through time during thermal maturation (see Vincent, 2015 for literature references of cumulative hydrocarbon plots).

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 1D 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 sediment 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. The temperature model was matched to temperature data (where available) as a secondary calibration method.

Regional memoirs, reports donated by sponsors and published 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 (Whitbread and Kearsey, 2016). Younger picks from are taken from composite logs and well reports
- Timing of deposition for Devonian and Carboniferous formations (Whitbread and Kearsey, 2016 and Kearsey, *pers. comm.*)
- Seismic interpretations of unconformity surfaces in/near wells to assess if estimated thicknesses of eroded strata are reasonable (M F Quinn *pers. comm.*)
- Seismic interpretations of depth to key surfaces below wells to prepare scenario wells (M F Quinn *pers. comm.*)
- Source rock organic geochemistry results and kerogen typing (Vane et al., 2016 and A Kim, *pers. comm.*)

Comparison of the models with density log analysis was not carried out as the region has a very complex history which makes interpolation of the eroded thickness of strata using this method problematic. Other compaction studies such as Hillis et al. (1994) which use sonic velocity log analysis were used in preference.

3 Overview of observations from 1D BasinMod wells

Two regions of interest were examined through 1D thermal modelling utilising BasinMod. Table 2 and the short discussion thereafter is intended to give an order of magnitude for comparison of generation potential for the most promising formations based on model results.

The model results need to be considered in the broader context of the region. An overview of the regional maturity is included below (Figure 4).

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

Region	Well	Most promising source rock/model layer	Gas or oil prone based on project team assessment and legacy reports?	Maturity window reached in model	Average TOC from Vane et al, 2016 and Kim, pers comm.)*	Approximate cumulative hydrocarbon from depth plot (mg/g TOC) (please note this is approximate and only intended for comparison purposes)	Gas/oil generated and expelled?	Comments
Inner Moray Firth	12/27- 1	Struie Formation	Oil prone	Scenario 1 (greatest burial post-Palaeozoic) – Early - Late oil mature	0.73	400	Oil and very minor gas generated during Devonian and Cenozoic burial. Minor expulsion from lower part of formation	Scenario 1 fits the VR data better. VR data may be suppressed. Oil from a Devonian source is recorded in Devonian and Jurassic sandstones in legacy reports
				Scenario 2 (greatest burial during Palaeozoic times) - mid oil to gas mature	0.73	450	Oil and very minor gas generated during Devonian burial. Significant expulsion from lower part of formation	
	12/16- 1	Firth Coal Formation	Gas prone	Mid mature for oil	1.86	50	Minor oil generation during deep Carboniferous burial	
		Poss. Mid – Upper Devonian	Oil prone but lean	Main gas	0.22	220	Oil and minor gas generation and expulsion during deep Carboniferous burial	Depths for TOC samples are over quite large intervals – difference in reported formation boundaries in composite log and Petra-Chem report, depths from Comp. log used
Buchan Graben	20/10a- 3	Firth Coal Formation (upper)	Gas prone	Early – mid mature for oil	5.75	15	Minor oil and gas generated during Cenozoic burial	Lower heat flow than average for this area used to fit VR data. As the well is on a high and given the low maturity of strata, the heat flow likely lower than average
		Firth Coal Formation (oil shale facies)	Gas prone organic sample but also contains a condensate-prone interval	Mid mature for oil	16.3	15	Minor oil and gas generated during Cenozoic burial	

		Firth Coal Formation (lower)	Gas prone organic samples but also contains a condensate-prone interval	Mid mature for oil	3.55	20	Minor oil and gas generated during Cenozoic burial	
	Scenario well 21/06b- 5	Firth Coal Formation (upper)	Used data from 20/10a-03	Late mature for oil	–	90	Oil and gas generated and expelled during deep Cenozoic burial	Well terminates in Triassic strata, depth to Palaeozoic horizons estimated from seismic data (Arsenikos et al., 2016.). Lower heat flow than average for this area used in line with heat flow used for 20/10a- 3, this gives a pessimistic estimation of maturity so more of the strata may be in the gas window
		Firth Coal Formation (oil shale facies)	Used data from 20/10a-03	Late mature for oil	–	90	Oil and gas generated and expelled during deep Cenozoic burial	
		Firth Coal Formation (lower)	Used data from 20/10a-03	Mature for gas	–	95	Oil and gas generated and expelled during deep Cenozoic burial	

* These data were taken from legacy reports. Note that this may introduce sample bias as samples are often selected for the most promising parts of the formation which could result in a too high estimate of average TOC for the formation

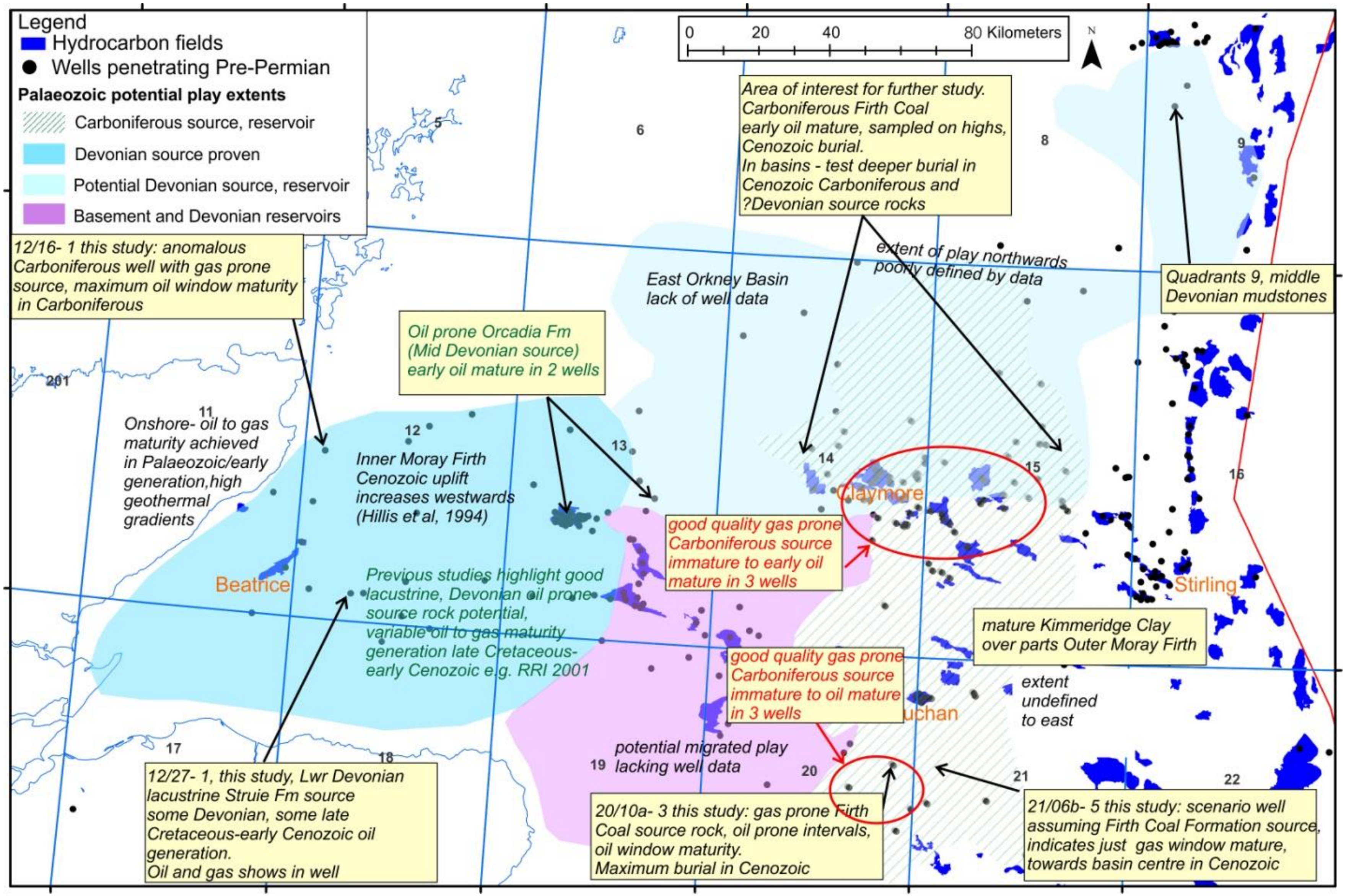


Figure 4: Summary of source rock maturity and modelled timing of maturation and generation at regional scale (Monaghan et al., 2016).

3.1 THE INNER MORAY FIRTH

The earlier work of Marshall (1998) and Marshall and Hewett (2003) suggest that Well 12/27- 1 may not be fully representative of the Palaeozoic IMF as the well lies on a relative high. Figure 2 shows the local high based on the seismic mapping of Arsenikos et al. (2016).

Well 12/16- 1 lies in a structurally complex region adjacent to the Wick and Great Glen faults on the edge of the IMF and is anomalous in recording significant deposition during Carboniferous times, most likely due to its proximity to the fault.
Vane et al. (2016) indicate that Struie Formation kerogens are mainly oil prone and could generate a good amount of hydrocarbons in Well 12/27- 1. The TOC for the upper part of the Struie Formation has moderate/good TOC. The poorer TOC value for the lowermost part of the Struie Formation may be a result of depletion through oil generation (Marshall, 1998). VR data indicate the potential source rocks reached the oil and gas maturity window (Vane et al., 2016).

For the modelling work, two burial scenarios were considered for Well 12/27- 1: Scenario 1 modelled maximum burial during Cenozoic times and less deposition in Devonian times (in line with the geological model for the area described in Section 4.1) and achieves the best fit to maturity (VR) data (Section 4.3.2.1). Scenario 2 honours the highest VR values and suggests the lowermost part of the well reached gas maturity in Devonian times (Section 4.3.2.2), Scenario 2 could be supported by the presence of gas shows noted in the Well History Report if they were generated in-situ.

Scenario 1 suggests that oil was generated by the Struie Formation but only expelled from the lower part of the formation in Devonian and Cenozoic times (Figure 8, Figure 9, Figure 10). The presence of oil shows in the well from a Devonian source as reported in Paleochem (1983) support the Struie Formation being mature for oil and that the source rocks in the lower part of the well have been exhausted through oil generation.

Scenario 2, with deepest burial during Devonian – Earliest Carboniferous times, indicated that around 2.3 km of additional Palaeozoic strata would be required for the Struie Formation to reach the gas window in Well 12/27- 1 and that all generation would have occurred during this deep Palaeozoic burial (Figure 15, Figure 16, Figure 17). Please see Section 4.3 for more detail.

Scenario Well 12/16- 1 has generally poor TOC with only a few horizons (coals and mudstones) with source potential and was tested to better understand the Carboniferous IMF burial history. Based on maturity data, this well seemed to show significant deposition during the Carboniferous Period. Most kerogens were gas prone in the Carboniferous section, and as these strata did not reach the gas window, limited generation was expected. The lowermost part of the section (Possible Mid – Upper Devonian age) was oil prone but lean, some hydrocarbon generation was expected as these strata were post late mature for oil. Generation occurred during deep Carboniferous burial (Figure 21, Figure 24, Figure 25, Figure 26; please see Section 4.4).

3.2 SOUTH BUCHAN BASIN

Well 20/10a- 3 was drilled on the north-east extension of the Peterhead Ridge separating the north-eastern part of the Forth Approaches Basin and the western edge of the South Buchan Basin (Figure 1, Figure 2). Source rocks were mainly gas prone, though two gas condensate-prone intervals were also identified (Geochem Group, 1993). Source rock TOC was mainly good to very good with some rich and poor interbeds. The basin modelling supported maximum current day burial with gas prone source rocks only reaching oil maturity; generation of significant volumes of gas would not be expected. A scenario to test how much additional strata would need to have been deposited for this well to reach the gas window was run to try to assess if these strata might be mature in nearby depocentres, this indicated 2.8 km of Mesozoic strata in total would be needed. This was considered a very rough estimate as the burial profile would need additional modification to closer resemble that of a basin in the depocentre. Please see Section 5.3 for more detail.

To investigate maturity in the basin depocentre, a Scenario well was prepared, at the location of Well 21/06b- 5 using data for this well and data from Well 20/10a- 3 which lies around 12 km to the west. Based on seismic interpretation (Arsenikos et al., 2016), the depth to Palaeozoic strata was estimated. This model had deepest burial during the Cenozoic Era and the Carboniferous source rocks would just have reached the gas window. No source rock data are available to prove this theory. If the source rocks have similar TOC and source potential as those penetrated by Well 20/10a- 3, then it is expected gas generation would have occurred (Figure 35, Figure 38, Figure 39; please see Section 5.4).

Essentially both modelled wells suggest that around 4 km of burial is required to reach the gas window if the heat flow is as low in the basin as is modelled on the topographic high where 20/10a- 3 is located.

The maturity of strata from the current study all support the concept that Carboniferous and Devonian source rocks are at suitable depth to generate hydrocarbons in the Southern Buchan Graben and will be mature and maybe even over-mature within the depocentre.

4 Detail of Inner Moray Firth modelling

The sections below are structured to outline the work supporting the current models. Firstly a summary of tectono-stratigraphic evolution of this area is given. 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 work undertaken for this study is described.

4.1 GEOLOGY OF INNER MORAY FIRTH - BLOCK 12/27

The Inner Moray Firth is bounded by the Helmsdale Fault/Great Glen Fault to the west and the Wick Fault to the north. The Inner Moray Firth is delineated by a significant gravity low due to large thicknesses of accumulated sediment and lack of crustal thinning (Andrews et al., 1990).

Basement

Pre-Cambrian basement outcrops onshore adjacent to the Inner Moray Firth in the Northern Highlands and Grampian Highlands. Caledonian (Silurian – Devonian) tectonic events resulted in north-east trending structural features which influenced late Palaeozoic sedimentation patterns (Andrews et al., 1990).

Early Devonian half grabens

Well 12/27- 1 is interpreted to lie on a local north-west trending relative high within the region of Lower Devonian deposition (Figure 2; see also Whitbread and Kearsey their Figure 25).

In early Devonian times, strain partitioning in this area in response to compression to the south in the Midland Valley resulted in extensional reactivation of the Caledonian thrust faults and the formation of half graben sub-basins (Marshall and Hewett, 2003).

Earliest deposition occurred during Pragian to Emsian times in the Orcadian Basin. Strata were laid down on distal outwash plains and playa with shallow, ephemeral lakes (Whitbread and Kearsey, 2016). Well 12/27- 1 shows an alternating sequence with deposition in permanent and ephemeral lakes (Marshall and Hewett, 2003). Increasing amounts of sandstone suggest increasing fluvial activity towards the end of the Early Devonian Period (Whitbread and Kearsey, 2016).

Mid Devonian; broad depositional basin

During the main Mid-Devonian development of the Orcadian Basin, these half-grabens coalesced into a large subsiding region which contained several depocentres controlled by active faults (Marshall and Hewett, 2003). Strata were deposited in alluvial fans and on alluvial plains. Coarse clastics were again deposited in extensive alluvial fans and then in a fluvial environment. These deposits were partially overlain and partially contemporaneous with lacustrine deposits (Marshall and Hewett, 2003).

The thickness of strata is relatively thin on highs and the shores of the Orcadian lake (200 – 400 m) but exceeds 1.4 km in the centre of the Inner Moray Firth Basin (Whitbread and Kearsey, 2016).

Latest Mid Devonian – Late Devonian deposition

Further extension during latest Mid Devonian and Late Devonian times (mainly Givetian) resulted in a largely post-rift character to these basins with a more open drainage system (Marshall and Hewett, 2003). Mid Devonian strata lacustrine and fluvial strata were deposited with a varying thickness of up to 800 m recorded around the area of interest.

Late Devonian strata were deposited in a fluvial/alluvial environment. Latest Devonian strata are sometimes absent on structural highs due to erosion (Whitbread and Kearsey, 2016).

Carboniferous – no record over much of the Inner Moray Firth

Few data are available on Carboniferous strata in the Inner Moray Firth to interpret the amount of deposition (or non-deposition) and/or end Carboniferous uplift/erosion. Visean strata (Firth Coal Tayport formations mainly comprising sandstones and claystones) are present in Well 12/16- 1. This well lies in a different sub-basin to Well 12/27- 1 and is an isolated occurrence of Carboniferous strata within the Inner Moray Firth.

Sinistral motion on the Great Glen Fault throughout most of the Upper Palaeozoic is anticipated (as Baltica moves out to the north-west and following on from the Caledonian Orogeny) with E(NE)-W(SW) directed stretching in the Moray Firth region. This was then followed by strongly partitioned strain in the North Sea basin interior as Baltica moved south-westwards (Coward, 1993) with dextral shear against the Great Glen Fault during late Carboniferous times (Leslie et al., 2016).

Late Carboniferous – Early Permian uplift and erosion (Variscan Unconformity)

The Variscan Unconformity caused by Late Carboniferous – Earliest Permian uplift and a subsequent hiatus in deposition is present across the Orcadian Basin (Glennie et al., 2003). Frequently Permian strata rest directly on Devonian strata in the Inner Moray Firth (Whitbread and Kearsey, 2016).

Permian – deposition in Northern Permian Basin

The Inner Moray Firth as it exists today was initiated in Permian times as part of the extensive Northern Permian Basin. Tectonic stresses and differential movement of the bounding masses led to transtensional crustal extension with the earlier north-south extension leading to formation of the Northern Permian Basin and the later east-west extension leading to graben formation outside of the Inner Moray Firth. Transpression with crustal warping and local inversion occurred later during Rotliegend Group deposition (Glennie et al., 2003).

In the Inner Moray Firth, the first Permian strata (Late Permian in age) mainly comprise reddened clastic sequences dominated by sandstone which are interpreted to be largely aeolian in origin. The Inner Moray Firth was isolated by a zone of non-deposition/a lacustrine lake environment during early deposition of the Rotliegend Group (Glennie et al., 2003; Andrews et al., 1990).

Zechstein Group Deposition

The Zechstein Sea is not interpreted to reach the westernmost part of the Inner Moray Firth due to the presence of structural highs, instead continental clastic sediments were deposited (Glennie et al., 2003).

Triassic

Most large faults in the Inner Moray Firth were not active during the Triassic Period, the Inner Moray Firth underwent broad regional subsidence. A general pattern of westward thickening towards the Great Glen fault is taken to indicate mainly thermal subsidence (Goldsmith et al., 2003; Thomson and Underhill, 1993; Roberts et al., 1990a). Triassic strata mainly comprise red sandstones similar in character to the underlying Permian strata. A maximum preserved thickness of less than 100 m Triassic strata is proven in this area of the Inner Moray Firth (Goldsmith et al., 2003). Extension during Triassic times is believed to have been less than extension during Jurassic times (Goldsmith et al., 2003).

Lower – Middle Jurassic deposition

Lower Jurassic strata are limited to parts of the Inner Moray Firth and comprise a fining upwards sequence believed to have been deposited in an alluvial fan environment with more complete sections showing transition from estuarine to marine conditions. The transition from Lower to Middle Jurassic is spanned by an upward coarsening regressive sequence. Middle Jurassic strata are limited to sub-basins within the Inner Moray Firth (Andrews et al., 1990).

Mid Jurassic thermal doming and uplift

The Lower Jurassic sequence is truncated in Block 12/27 and the top of this Lower Jurassic sequence and the majority of the Middle and Upper Jurassic sequence is absent (mid-Cimmerian/Intra-Aalenian Unconformity). Husmo et al. (2003) describe the Inner Moray Firth as being affected by doming during the Aalenian Stage and suggest that Lower Jurassic strata might have been up 300 m thick originally.

Deposition resumed during the late Middle Jurassic Period (Husmo et al., 2003).

Late Jurassic – earliest Cretaceous rifting

A tripartite graben system which included the Moray Firth, Viking Graben and Central Graben developed (Andrews et al., 1990; Goldsmith et al., 2003). The main phase of extension in the Inner Moray Firth occurred during the Jurassic Period with around 7 km of extension (Goldsmith et al., 2003 and Roberts et al., 1990b).

Middle and Upper Jurassic strata are a major reservoir interval for oil and gas in the wider Moray Firth region (Andrews et al., 1990). Strata comprise marine deposits. Upper Jurassic strata are up to 1 km thick in the area of interest (Fraser et al., 2003).

Early Cretaceous post-rift subsidence

Lower Cretaceous strata occur widely across the Moray Firth region deposited during post-rift thermal subsidence as the principal locus of rifting shifted westwards from the North Sea into the proto-North Atlantic (Copestake et al., 2003). Depositional patterns reflect intraplate stresses superimposed on regional thermal subsidence related to Jurassic rifting.

The environment of deposition was an aerobic marine environment (Andrews et al., 1990). The general increase in sea level was punctuated by sea level falls during Hauterivian – Valangian and Aptian times (Oakman, 2005). In the west of the Moray Firth region, strata are sandier which is interpreted to show the presence of a shoreline during Early Cretaceous times. Lower Cretaceous strata can be up to 1 km thick in the Inner Moray Firth (Copestake et al., 2003).

Late Cretaceous

The Upper Cretaceous was a time of relative tectonic quiescence. In the westernmost part of the Inner Moray Firth, the top of the Lower Cretaceous strata has been removed by erosion. During Upper Cretaceous times as this area was sub-aerial. Around 300 m of carbonates are preserved in Well 12/24-2A (Surlyk et al., 2003).

Global sea level fluctuations, local tectonism resulting from continuing crustal extension and wider events affecting the water circulation, ecosystem and sediment input affected deposition during Upper Cretaceous times (Surlyk et al., 2003).

A global sea level drop occurred at the end of Maastrichtian times (Andrews et al., 1990).

Latest Cretaceous - Palaeocene uplift

During Latest Cretaceous times uplift of the main part of Scotland and Norway occurred. During the Maastrichtian – Palaeocene times, mantle underplating related to the Iceland plume occurred (Coward et al., 2003; Brodie and White, 1995). Eastern Scotland was uplifted by 0.5 – 1 km (White and Lovell, 1997; Hillis et al., 1994). The Inner Moray Firth experienced uplift during the Paleocene and Eocene Epochs (Thomson and Underhill, 1993; Ahmadi et al., 2003; Jones et al., 2003; Fyfe et al., 2003).

Strike slip motion occurred along the Great Glen Fault during early Palaeocene times (Ahmadi et al., 2003). Palaeocene strata are part of the largely unfaulted post-rift sequence deposited in a tensional tectonic regime. Well 12/24- 2 has around 100 m of Palaeocene strata, Well 12/27- 1 may have lain within an area of non-deposition (Ahmadi et al., 2003; Coward et al., 2003).

During early – Mid Miocene times, the tectonic regime became compressional (Coward et al., 2003). The Inner Moray Firth probably did not experience deposition during Neogene times as it is believed to have been uplifted (Andrews et al., 1990).

The area of interest may have been a zone of non-deposition from Palaeocene to Pliocene times (Thomson and Underhill, 1993; Ahmadi et al., 2003; Jones et al., 2003; Fyfe et al., 2003; Andrews et al., 1990).

Quaternary

Throughout late Pleistocene times, periglacial, glacial and glacio-marine conditions alternated with periods of temperate climate in the North Sea. There were periods of severe erosion due to glacial processes (Andrews et al., 1990; Fyfe et al., 2003). There is a regional unconformity of Elsterian age (caused by glacial erosion) which forms a prominent seismic reflector. Hubbard et al (2008) prepared a model of ice coverage from 38.9 ka to present day. Low rates of deposition occurred during Holocene times. Quaternary deposits are generally thin in the Inner Moray Firth (0 − 100 m thick; Andrews et al., 1990).

4.2 PREVIOUS WORK IN THIS REGION

Well 12/27- 1 and Well 12/29- 1 lie in the same Palaeozoic sub-basin. Well 12/27- 1 and 12/29- 1 Devonian strata appears to be in the oil maturity window in both wells.

Well 12/16- 1 lies in a different sub-basin and seems to reflect an anomalous Carboniferous geohistory compared with other wells in the IMF, presumably due to its proximity to the Great Glen Fault.

Geohistory modelling

Robertson Research International (2001) assessed geochemical data (oils, gas, solvent-extracted oil stains, AFTA, fluid inclusions) to assess the maturity and generation geohistory in the Inner and Outer Moray Firth basins. Hydrocarbon generation and migration from Devonian source rocks started earlier in the IMF than the Outer Moray Firth (OMF) but active generation ceased in the Early Cenozoic due to uplift. Based on the presence of oil-mature Devonian source rocks at outcrop, Robertson Research International (2001) suggests that in the western parts of the Orcadian Basin, source maturation occurred in the Carboniferous Period prior to the Variscan Orogeny and Late Palaeozoic and Mesozoic deposition (Robertson Research International, 2001).

No evidence to prove that Carboniferous strata were deposited in this area of the Inner Moray Firth was cited in Bruce and Stemmerik (2003). In common with this study, Robertson Research International (2001) suggests that the uppermost part of the 'Old Red Sandstone' in the Moray Firth is Lower Carboniferous in age but that the younger Firth Coal Formation only has restricted distribution (Quadrants 14, 15, 20, 21).

No figure for heat flow in this well is available, but extending the summary heat flow plot in Kubala et al. (2003), a low heat flow seems reasonable (the average present day heat flow is 30 - 45 mWm^{-2} across the Scottish Highlands and Blocks 18 and 19).

Palaeozoic source rock and hydrocarbon generation

Devonian strata are close to peak oil generation on structure (Paleochem Ltd, 1983). It should be noted however that Marshall (1998) also states that Lower Devonian strata tends to be restricted to half-graben areas which experienced rapid extension-related subsidence and that the deposits are not always a good source rock, thus the source rock quality of this well should not be inferred to be present across the whole area. Gearheart Geo (1989) also suggest that Well 12/27- 1 lay within a lake of limited areal extent within an isolated fault bounded basin. Marshall et al. (1985) suggest that other lakes could have been present during Lower Devonian times in the Orcadian Basin

Lower Devonian strata were interpreted as having variable potential in Well 12/29- 2 based on assessment of lithology and kerogen typing of samples. A weak light-oil show was recorded in Givetian strata in Well 12/29- 2. A show of condensate and light oil was detected in the Emsian strata (Hewett and Marshall, 1995). Upper Devonian strata comprise barren continental strata overlain by lacustrine strata. Lower Devonian strata were in the main oil generation maturity window in Well 12/29- 2 whereas the top of Devonian was marginally mature (Hewett and Marshall, 1995).

Middle Devonian strata (Rory Formation and Achanarras Fish Bed) seem to be much more extensive in the IMF, compared with Lower Devonian strata distribution, though Middle Devonian strata do thin and become dominated by fluvial strata to the south and also thin to the east due to the South Halibut Granite (Marshall, 1998). A regional overview of source rock quality is given in Greenhalgh (2016).

4.3 WELL 12/27- 1

Seismic interpretation indicates Well 12/27- 1 lies on a local NW trending high (Arsenikos et al., 2016, see Figure 2 above). Marshall (1998) indicates that Well 12/27- 1 was drilled on an extensionally rotated fault block at the western margin of the Smith Bank Graben, along structure from the Central Ridge.

Well 12/27- 1 penetrates strata of Devonian age (Lower Devonian Struie Formation and Middle Devonian Lower and Upper Strath Rory Formation sandstones) and Permian to Cretaceous age. Carboniferous strata are absent.

4.3.1 Previous maturity and modelling work for Well 12/27- 1

Oil typed to a Devonian source is recorded in Devonian and Jurassic sandstones. Generation is documented to have occurred from Devonian times onwards (Paleochem, 1983; Marshall, 1998; Gearheart Geo, 1989). Previous work suggests deepest burial occurred post-Cretaceous times. The Struie Formation is mature for oil generation and the upper part of the Struie Formation appears to have good potential. The lower part of the Struie Formation appears to have poor potential but this is believed to be a result of generation having already occurred, depleting the source rocks. The Middle Devonian strata appear to have poor potential and mainly comprise barren redbeds (Marshall, 1998; Paleochem, 1983; Gearheart Geo, 1989).

<u>Geohistory for Well 12/27 -1</u>

The age of Devonian strata in the well was confirmed as Early – Mid Devonian by the project team. Marshall (1998) suggested that Well 12/27- 1 shows extension-related sedimentation with rapid deposition over a short time interval of a limited lateral extent during the Early Devonian Period (Struie Formation in Well 12/27- 1).

Marshall (1998) suggests that deep burial and high heat flow occurred during Devonian rifting.

Marshall (1998) suggests that an intrusion emplaced under the central ridge during Mid or Late Devonian times which then stopped or reduced deposition in this area, however, given the age of the early-mid Devonian strata interpreted in the current project, cessation of deposition before Mid Devonian times is not evidenced.

Marshall (1998) stated that Well 12/27- 1 was the first well to prove generation from Devonian source rocks during deep Mesozoic burial and that this had important implications for the IMF, i.e. that since generation occurred on this relative high, then generation could have occurred widely across the IMF, not just localised in depocentres. Marshall (1998) suggests that hydrocarbon generation occurred during Palaeozoic burial and that significant source potential remained until Mesozoic times. Marshall (1998) suggests that hydrocarbon generation from the Devonian source rocks ceased during Early Cenozoic uplift of the IMF (based on solid bitumen reflectivities and organic petrography).

Marshall (1998) suggest that no or limited deposition occurred from Mid Devonian times onwards in this well before the Variscan Orogeny due to emplacement of an intrusion under the central ridge.. Keeley et al (1991) use AFTA data to suggest that maximum palaeotemperatures in the Devonian strata were reached around 350 Ma prior to Early Carboniferous cooling and uplift. In line with these previous studies it was assumed that uplift and erosion started in Early Carboniferous times for Well 12/27- 1.

Applying the Baldwin and Butler (1985) compaction model to the Struie Formation and the estimated maximum burial (using the gradient of the VR data), Marshall (1998) suggests that 1.2 km of Palaeozoic strata has been removed from 12/27- 1. Keeley et al. (1991) suggest 2 – 3.5 km of additional Palaeozoic strata based on AFTA data but this report states that not much information on the structures penetrated by Well 12/27- 1 was available in the public domain at the time the report was written. For the current study, two scenarios were tested to examine the effect of adjusting the amount of additional Palaeozoic strata deposited in this well.

Marshall (1998) suggested that although deposition resumed during Late Permian times, the area around this well remained a relative high with a thinner Permian to Lower Cretaceous sequence deposited compared with strata penetrated by wells from the surrounding area in the IMF and on seismic data (e.g. Underhill, 1991)

Keeley et al. (1991) suggest a major unconformity in the 'poorly dated' Triassic succession. The model includes 1 - 1.9 km of erosion during Late Triassic uplift. The authors state that there is not much information in the public domain for Well 12/27- 1 and given that the composite well log shows strata of Early, Mid and Late Triassic age, major Triassic erosion is not anticipated in this work.

Marshall (1998) suggested that maximum depth of burial of Devonian strata was reached during burial just prior to Early Cenozoic uplift based on VR and bitumen data. Maximum burial of Devonian strata of around 3.9 km may have occurred during Late Cretaceous burial based on mudrock compaction (Paleochem, 1983).

Hillis et al. (1994) suggested that 580 m of strata had been eroded off the top of the section during Cenozoic uplift based on compaction of the Jurassic Kimmeridge Clay Formation in Well 12/27- 1. Marshall (1998) proposes that 300 m of strata has been removed post-Cretaceous times based on the VR data (though it should be noted that the author does not appear to have utilised the Paleochem (1983) report and so the VR data from the younger section are from 'composited cuttings' sometimes composited over an interval of 100 – 200 feet). Keeley et al. (1991) propose 1 km of Early Cenozoic uplift based on AFTA data. Given the low maturity indicated by the VR data available to this study, a moderate amount of additional strata in line with the Hillis et al. (1994) estimate was proposed for the current models.

Maturity – data quality for Well 12/27 -1

Mature oil-prone source rocks comprise a significant proportion of the Lower Devonian section in Well 12/27- 1 (Marshall, 1998).

Marshall (1998) records greater VR values than the Paleochem (1983) report for Devonian strata above 2835 m BRT (in the Struie Formation), the authors state this is due to a high content of amorphous organic matter causing suppression of vitrinite reflectance readings.

Maturity of the Devonian was inferred from VR and spore colouration, both suggesting peak oil generation (Paleochem, 1983). Paleochem (1983) observed there is a sudden jump in maturity (spore index and VR) below 3045.8 m in the Struie Formation which may be a result of a local heating effect caused by mineralisation or proximity of volcanic intrusive (Paleochem, 1983, page 9). The authors suggested further study to assess if this could be the case. Paleochem (1983) also observe that this increase in maturity occurs around the same depth as the decrease in TOC in the Struie Formation. Marshall (1998) provides additional VR data which shows similar increased maturity below this depth (his Table 1) but suggests instead that the decreased readings in the Struie Formation are a result of suppression of the VR data due to high quantities of AOM.

Oil and gas shows and generation for Well 12/27 -1

The Well History report suggests that minor oil and gas shows and were present in the Devonian sequence, particularly in association with fractures. Dead oil was observed near TD (Burmah, 1982a). Oil shows are recorded in Devonian strata in Paleochem (1983). Significant oil and gas shows were recorded in the sandy Devonian sequence below 3018 m (Struie Formation) (Marshall 1998).

Marshall (1998) cautions that multiple changes of drilling bit and intermittent coring during drilling of the Devonian section are likely to have produced mixed cuttings which are likely to give an average TOC over 10 ft intervals.

Samples from the lower part of the Struie Formation (3027.6 – TD) mainly had poor TOC. The top part of the Struie Formation (2344.8 – c.3017.5 m) has moderate/good TOC and extended testing of five samples from this interval indicated highly oil prone source rocks. An oil sample from Devonian strata was tested and demonstrated to be from a Devonian source (Paleochem, 1983). Strata in the interval 2642.6 – 2651.9 m BRT (Struie Formation) are of lacustrine origin and the kerogen assemblage is dominated by oil prone amorphous kerogens. Samples from lower in the Struie Formation show a more marginal lacustrine environment and appear to be late to post-mature for oil generation, with some evidence that this part of the section has already generated hydrocarbons in the past but now only has poor potential remaining (Gearheart Geo, 1989; Marshall, 1998).

No testing was reported for Rotliegend strata (1702.0 – 2344.8 m BRT) in Paleochem (1983) as this interval comprises barren redbeds. Only trace gas shows were recorded in the Rotliegend Group (Burmah, 1982a) (note that this interval includes strata that the current project has classified as being of Middle Devonian age).

Two cores from Zechstein strata were tested. These samples had moderate TOC but low yield and therefore this interval was rated as having poor source potential. This interval is approaching maturity for oil generation (Paleochem, 1983). Only trace gas shows were recorded in Zechstein strata (Burmah, 1982a).

Three samples were tested from the Triassic interval. TOC was moderate but pyrolysis indicated poor source potential (Paleochem, 1983). Only trace gas shows were recorded in Triassic strata (Burmah, 1982a).

Samples from Lower – Middle Jurassic strata mainly had poor/moderate source potential and were gas prone. Sandstones of Early and Mid Jurassic age in Well 12/27-01 contain oil from a Devonian source (Paleochem, 1983). Upper Jurassic strata had good TOC, moderate - excellent source potential and were mixed oil/gas prone. Jurassic strata are not yet mature for oil in IMF (Paleochem, 1983; also see Figure 11 in Monaghan et al., 2016).

Gas levels rose on encountering the Kimmeridge Clay Formation. Gas levels in the Middle and Lower Jurassic strata were low (Burmah, 1982a).

4.3.2 New modelling work for Well 12/27 -1

In common with the earlier work of Marshall (1998), Marshall and Hewett (2003) and Robertson Research International (2001), seismic and well interpretations for this study (Arsenikos et al., 2016; Whitbread and Kearsey, 2016) concur that the well is not representative of the Palaeozoic evolution of the IMF basin, situated as it is on a local mid-late Devonian high. However, given the block and basin structure of the IMF, any single well is unlikely to provide a complete representation of this complex area.

Given the comments of Marshall et al. (1998) and Whitbread and Kearsey (2016), that this region is expected to have been a local high during Mid – Late Devonian times, a limited amount of additional Mid and Late Devonian strata are included in the current model. As no evidence for Carboniferous deposition is cited for this region (Marshall, 1998 and Bruce and Stemmerik, 2003), it was assumed that due to emplacement of the granite, this region was subject to erosion during Carboniferous times.

Three glaciation periods with up to 950 m of ice were included in the current model (due to limitations on age difference between model layers, no more could be included, in addition, the ice matrix density was overestimated as the minimum quantity which could be entered was 1 gcm^{-3}), however, due to the short timescales over which ice coverage was >50 m, the effect on the model is minimal

Available maturity and porosity data

Model input data are shown in Table 3. The maturity model for Well 12/27- 1 was prepared using data from Marshall et al. (1998) and Paleochem (1983). A subset of the available data were selected as the shallow data for the Marshall (1998) paper are given for cuttings composited over large intervals (< 60 m thick) and so were excluded. Marshall (1998) suggests that the VR data are suppressed in the Kimmeridge Clay and most of the Jurassic section as well as the Devonian interval above 2834.6 m (which falls within the Struie Formation). This has significant implications for the modelling work.

Table 3: Summary of model input data for Well 12/27- 1 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 samples	Kerogen	Oil/gas show	N.o. of porosity data	Comments
L Cretaceous	1VR (SWC, pyritic shale)						
Jurassic	13 VR (Cu, and SWC, pyritic shale and shale plus 2 C, lith NS,)						Jurassic oils shown to be biodegraded counterparts of the Devonian oil. Gas present thought to be of shallow biogenic origin. Kimmeridge Clay VR may be suppressed
Triassic	3 VR (2 C, lith. NS and Cu and one SWC, shale)						
Zechstein	2VR (SWC, shale)	Immature	1.02 (two samples)				
Lower Strath Rory		Early oil mature	0.1 (1 sample)	Oil prone kerogens			Lower spore colouration maturity than expected, possible contamination of samples
Struie	38 VR (SWC and C., a few Cu Lith. Shale, calcareous shale and NS).	Early – late oil mature (Scenario 1) Mid oil to gas mature (Scenario 2)	0.73	Mainly type II, small amount of type III. Increasing amounts of type IV downwards	Significa nt oil and gas shows	16	VR may be suppressed

SWC – sidewall core, C – core, Cu – cuttings, NS – not specified

Some of the measured VR show gas maturity in the Struie Formation below 3027 m though these are mixed in with other VR which show oil maturity (Vane et al., 2016) though these could be suppressed as Marshall (1998) shows a high level of AOM for most the lower values.

The VR data in Paleochem (1983) have relatively few samples and often show quite a broad scatter of values, these values were included in the study but are lower confidence where few readings were obtained. Autochthonous and allochthonous values are recorded. A greater number of readings were used to produce the VR datapoints recorded in Marshall et al. (1998). Overall there is a good match between the VR data from these reports for the Devonian strata.

Uncorrected temperature data were available from Burmah Oil Exploration Limited (1982b).

Scenarios

For the modelling work, two burial scenarios were considered: Scenario 1 shows less deposition in Devonian times and achieves the best fit to maturity (VR) data. A good match to the maturity data was achieved with 1.5 km of additional Palaeozoic strata (which is similar to the 1.2 km proposed by Marshall, 1998).

However, the Marshall (1998) paper suggests VR data may be suppressed, so in Scenario 2 the model was matched to higher VR values. Scenario 2 (which honours the highest VR values and suggests the lowermost part of the well has reached gas maturity) was prepared. The presence of oil and gas shows could support Scenario 2 if the hydrocarbons were generated in-situ (some hydrocarbon generation in-situ is supported by the decreased TOC towards the bottom of the well; Marshall, 1998).

Scenario 2 (with 2.3 km of additional Palaeozoic strata) did not provide as good a match to the maturity data (though much of the Palaeozoic VR data is potentially suppressed) but was more in line with estimates based on AFTA data from Keeley (1991) and could explain the gas shows in the well if the gas were generated in-situ.

There is insufficient data to confirm which scenario is most likely.

Previous modelling work suggests 1.2 km or 2 km of additional Palaeozoic strata were deposited for Well 12/27- 1 (Marshall, 1998, suggested 1.2 km based on the gradient of the VR dataset and Keeley et al. (1991) suggest 2 km for Well 12/27- 1 and up to 3.5 km in the Orcadian Basin as a whole based on AFTA data).

4.3.2.1 Scenario 1

This model was used to test the scenario of greatest burial during Late Cretaceous – Cenozoic times. The maturity geohistory model is shown in Figure 5. Modelled paleo-heat flow is shown in Figure 6. Maturity model and data are shown in Figure 7.

Model calibration

The model was calibrated to the VR data.

Porosity data suggest greater burial could have occurred (Figure 11), however, as the model is focused on the maturity data, the model was matched to the VR data.

Model maturity and hydrocarbon generation

Scenario 1 suggests that the strata did not reach the gas window (Figure 7) in contrast to some of the recorded VR data.

In Scenario 1 the top part of the Struie Formation generated (but did not expel) hydrocarbons during deep Devonian and deep Cenozoic burial and the lower part of the formation generated and expelled hydrocarbons during Devonian burial with additional expulsion during Cenozoic burial (Figure 8, Figure 9 and Figure 10). Therefore, this Scenario agrees with previous work (Paleochem, 1983 and Marshall, 1998) which suggests that the Struie Formation is mature for oil and that the organic matter of the lowermost part of the formation has been exhausted through oil generation. Vane et al (2016) indicates that Struie Formation kerogens are mainly oil prone and could generate a good amount of petroleum, oil shows from a Devonian source are reported in Paleochem (1983), again supporting Scenario 1.

Vane et al. (2016) indicate the Zechstein strata are gas prone, have generation potential remaining and the measured VR indicate pre-oil to early oil window maturity.

The data entry sheet is shown in Figure 12.

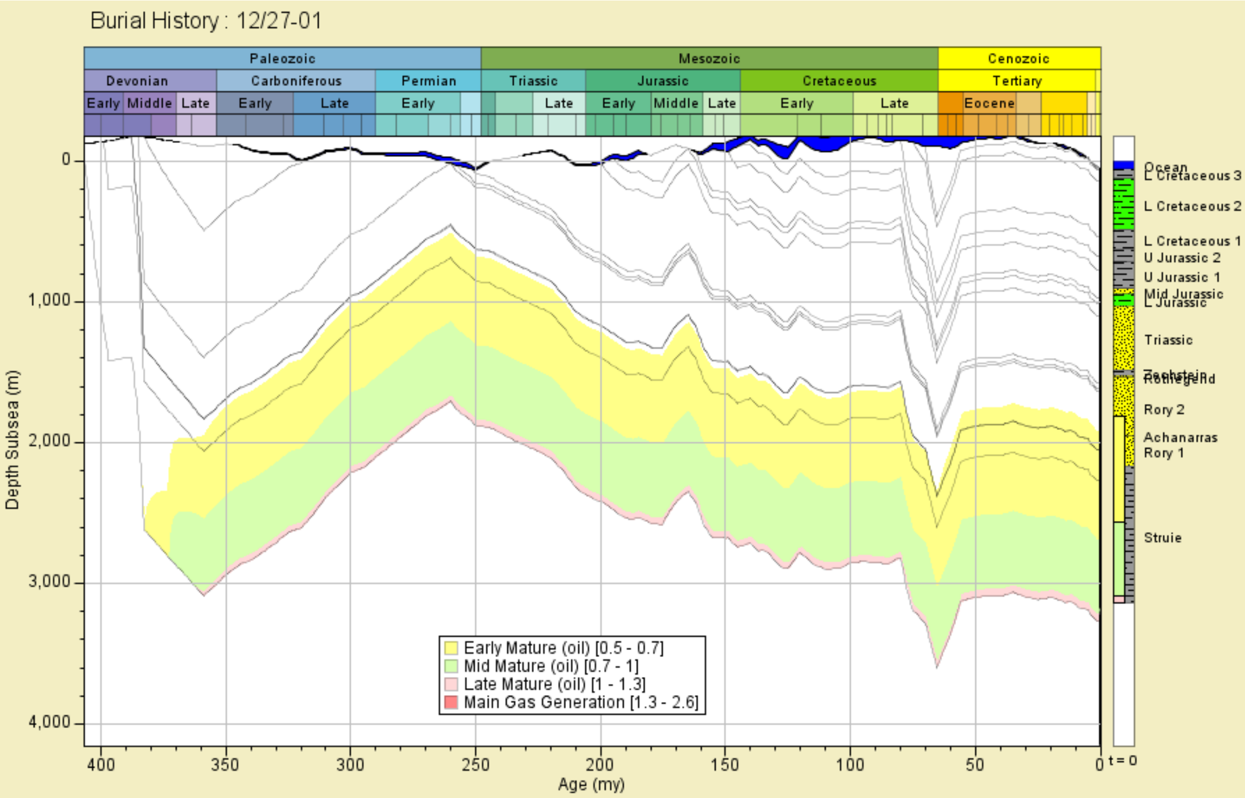


Figure 5: Modelled maturity geohistory for Well 12/27- 1. Case 1 – Oil mature. The well terminates in the Struie Formation and the base of the Struie Formation is not reached.

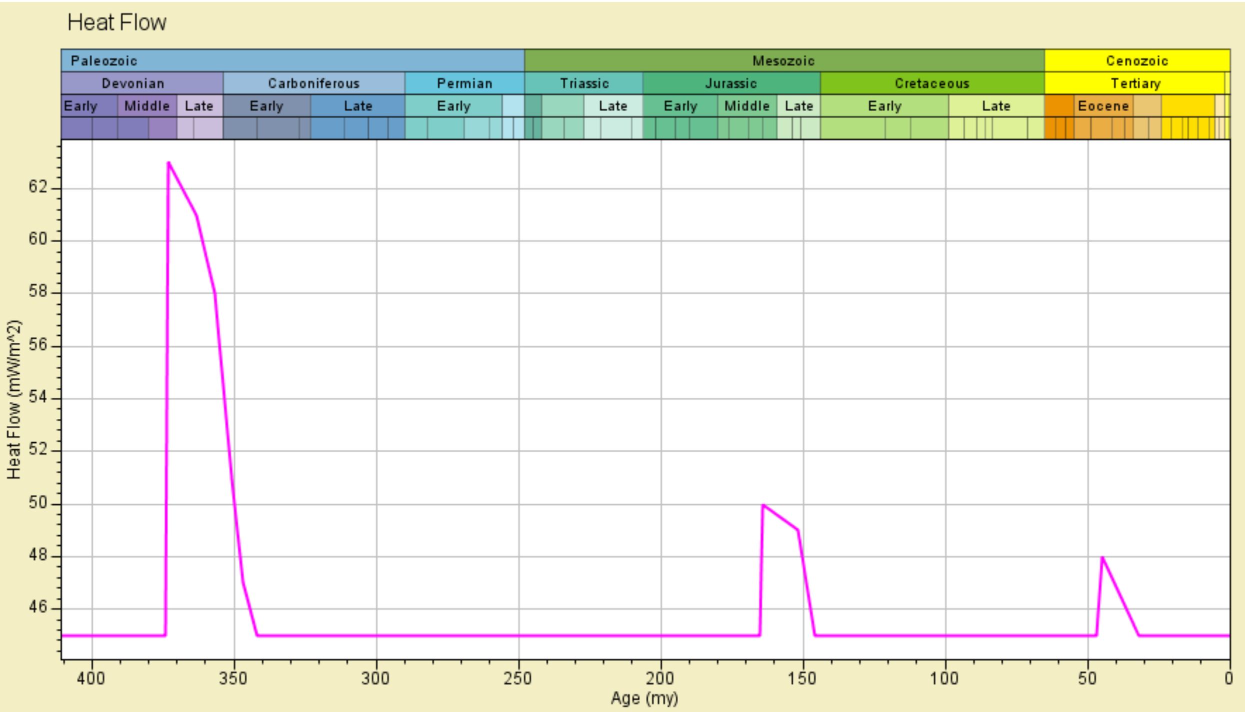


Figure 6: Modelled palaeo-heat flow for Well 12/27- 1 (Scenario 1).

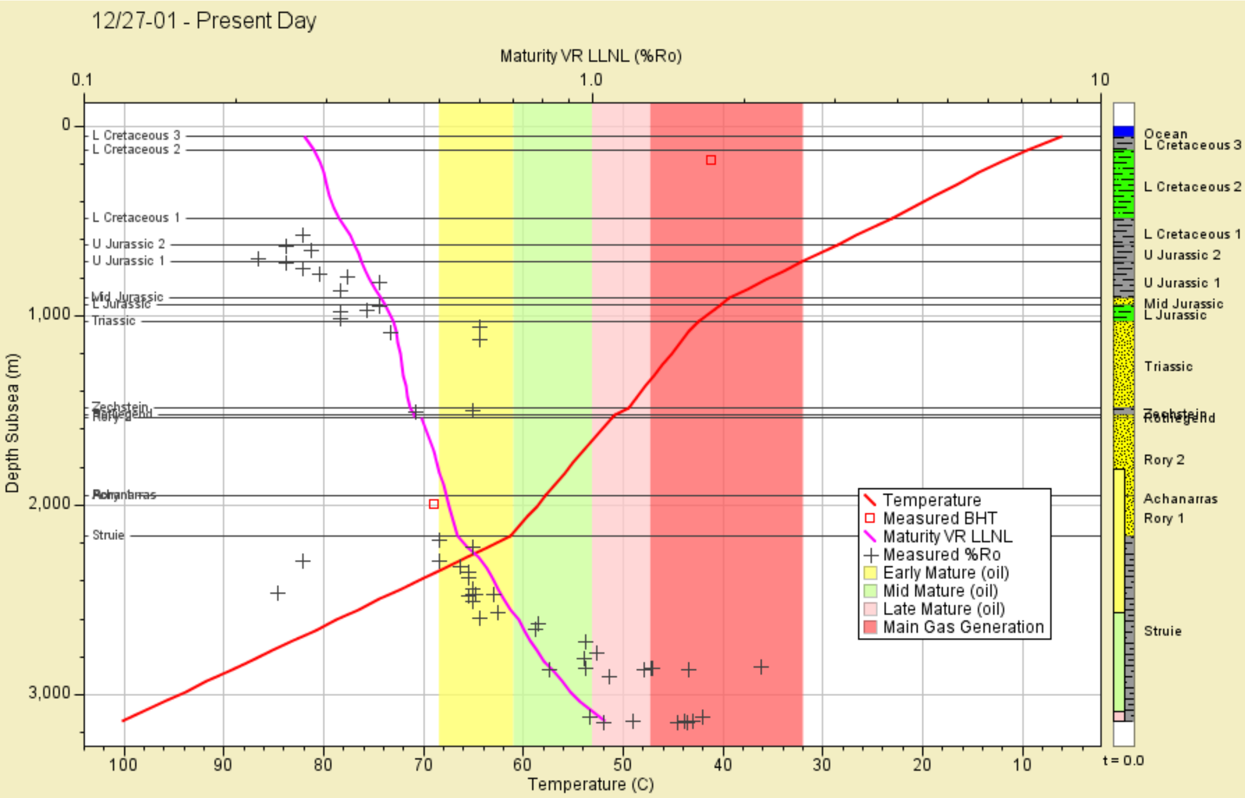


Figure 7: Depth plot for Well 12/27- 1 showing model results, maturity data and maturity windows (Scenario 1).

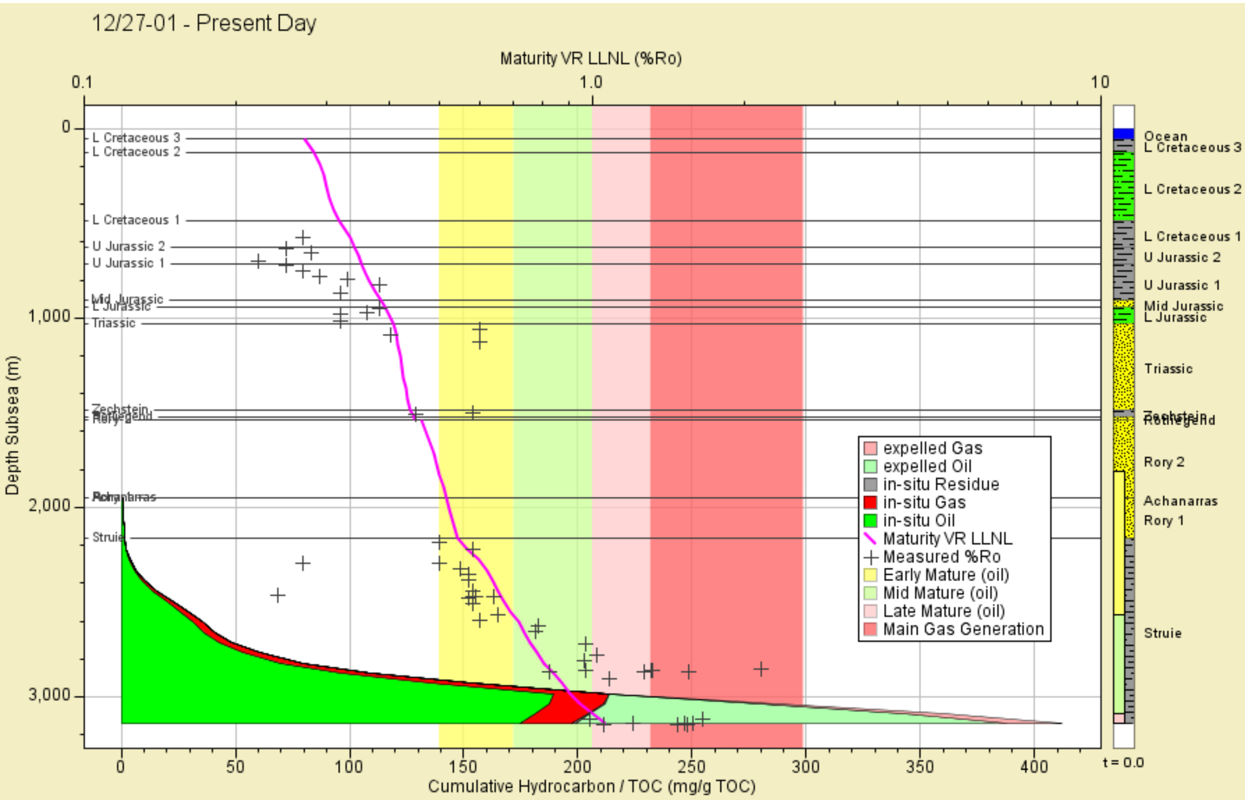


Figure 8: Depth plot for Well 12/27- 1 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model (Scenario 1).

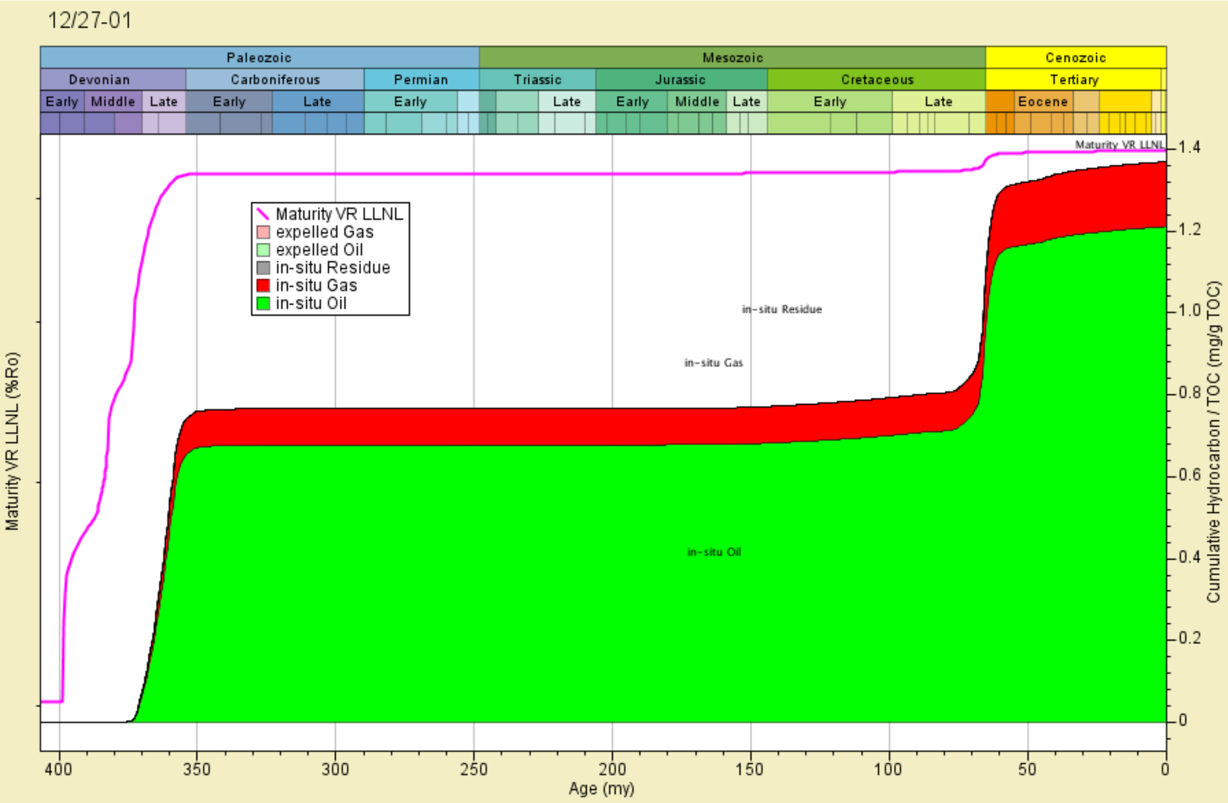


Figure 9: Time plot for Well 12/27- 1 showing timing of generation for top of Struie Formation through geological history of this formation (Scenario 1). Scenario 1 suggests that main generation occurred during Devonian and Cenozoic burial.

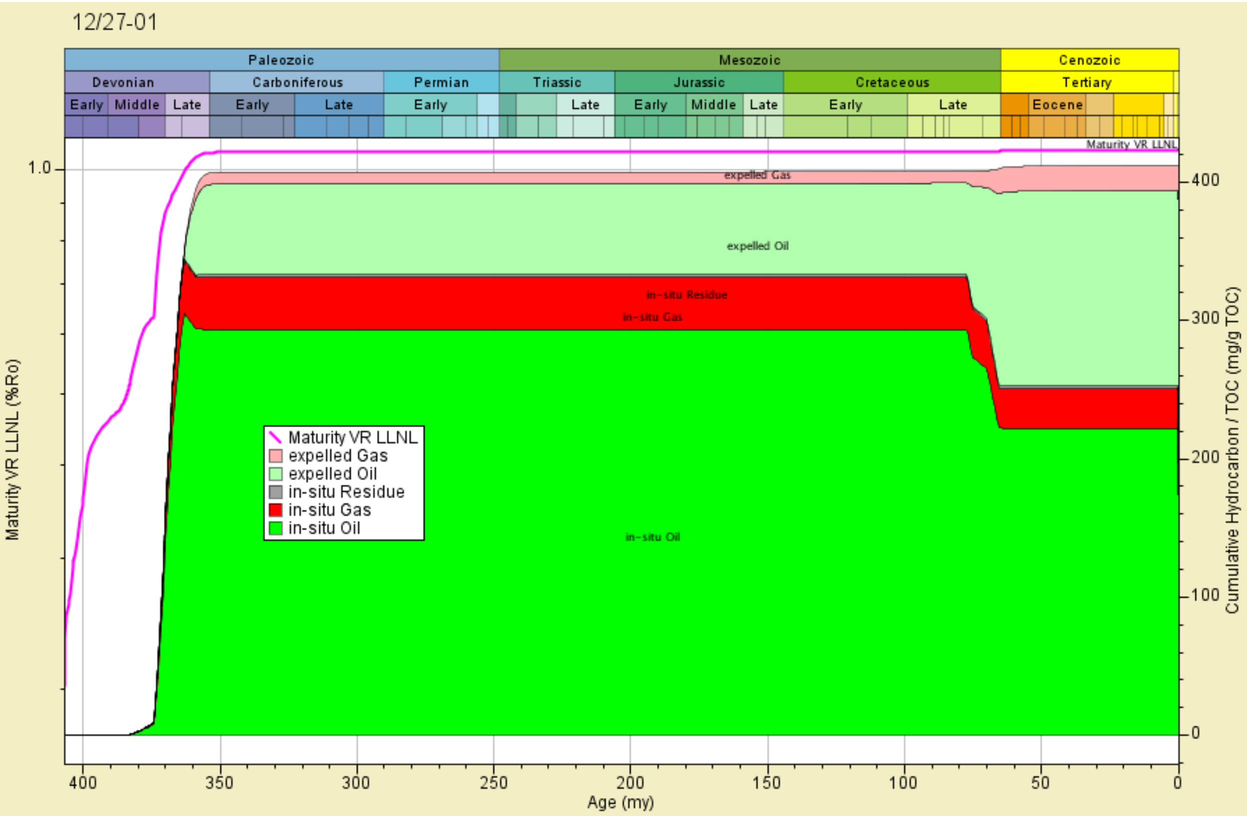


Figure 10: Time plot for Well 12/27- 1 showing timing of generation for bottom of Struie Formation model layer through geological history of this formation (Scenario 1). Scenario 1 suggests that main generation occurred during Devonian burial, with greater expulsion during Cenozoic times than Devonian times.

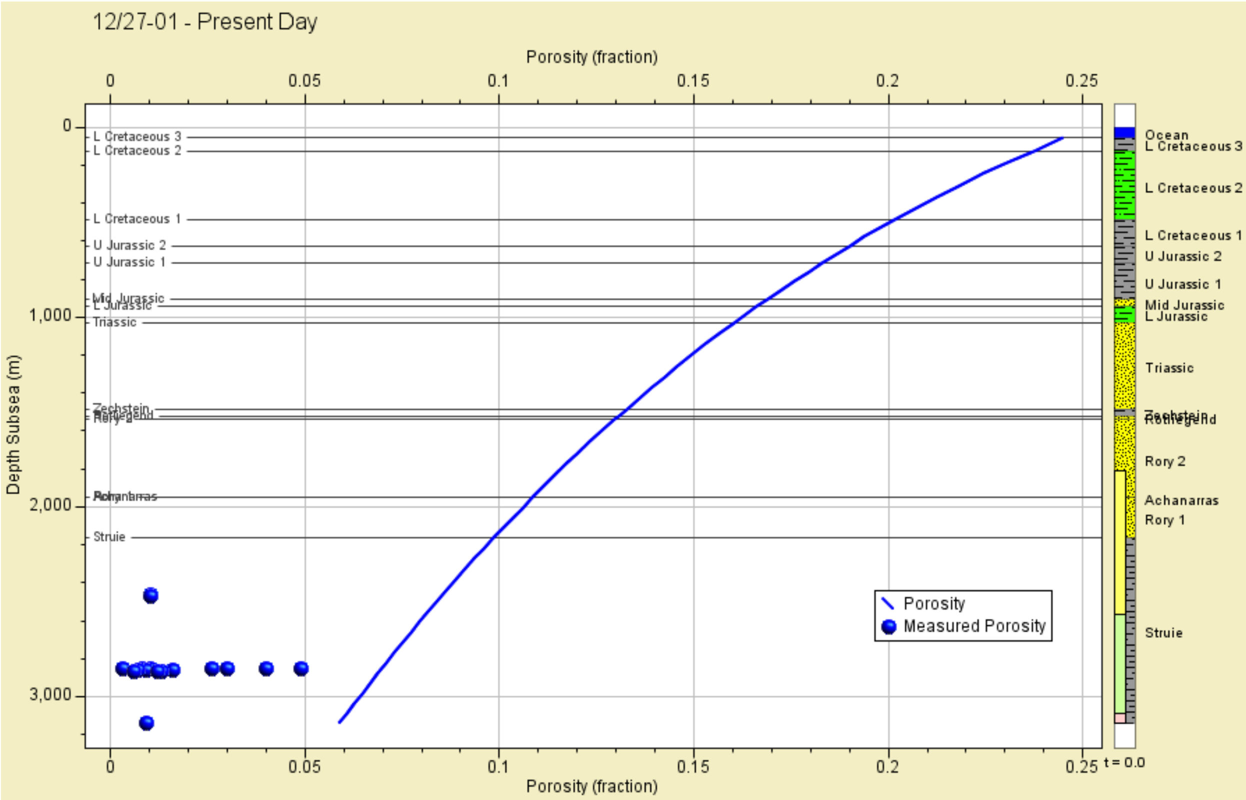
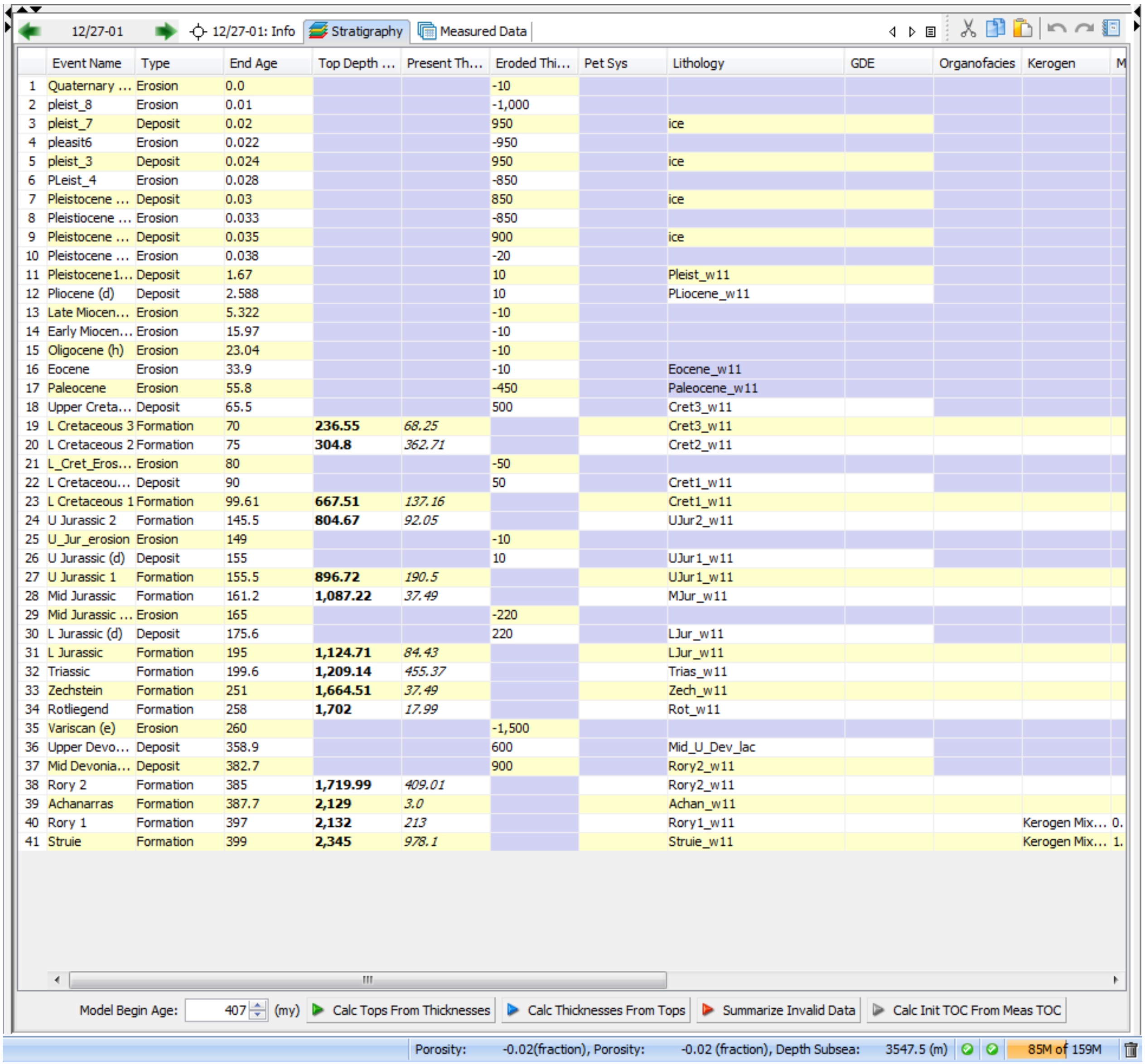


Figure 11: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 12/27- 1



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	Pet Sys	Lithology	GDE	Organofacies	Kerogen	M
1	Quaternary ...	Erosion	0.0			-10						
2	pleist_8	Erosion	0.01			-1,000						
3	pleist_7	Deposit	0.02			950		ice				
4	pleasit6	Erosion	0.022			-950						
5	pleist_3	Deposit	0.024			950		ice				
6	PLeist_4	Erosion	0.028			-850						
7	Pleistocene ...	Deposit	0.03			850		ice				
8	Pleistiocene ...	Erosion	0.033			-850						
9	Pleistocene ...	Deposit	0.035			900		ice				
10	Pleistocene ...	Erosion	0.038			-20						
11	Pleistocene1...	Deposit	1.67			10		Pleist_w11				
12	Pliocene (d)	Deposit	2.588			10		PLiocene_w11				
13	Late Miocen...	Erosion	5.322			-10						
14	Early Miocen...	Erosion	15.97			-10						
15	Oligocene (h)	Erosion	23.04			-10						
16	Eocene	Erosion	33.9			-10		Eocene_w11				
17	Paleocene	Erosion	55.8			-450		Paleocene_w11				
18	Upper Creta...	Deposit	65.5			500		Cret3_w11				
19	L Cretaceous 3	Formation	70	**236.55**	*68.25*			Cret3_w11				
20	L Cretaceous 2	Formation	75	**304.8**	*362.71*			Cret2_w11				
21	L_Cret_Eros...	Erosion	80			-50						
22	L Cretaceou...	Deposit	90			50		Cret1_w11				
23	L Cretaceous 1	Formation	99.61	**667.51**	*137.16*			Cret1_w11				
24	U Jurassic 2	Formation	145.5	**804.67**	*92.05*			UJur2_w11				
25	U_Jur_erosion	Erosion	149			-10						
26	U Jurassic (d)	Deposit	155			10		UJur1_w11				
27	U Jurassic 1	Formation	155.5	**896.72**	*190.5*			UJur1_w11				
28	Mid Jurassic	Formation	161.2	**1,087.22**	*37.49*			MJur_w11				
29	Mid Jurassic ...	Erosion	165			-220						
30	L Jurassic (d)	Deposit	175.6			220		LJur_w11				
31	L Jurassic	Formation	195	**1,124.71**	*84.43*			LJur_w11				
32	Triassic	Formation	199.6	**1,209.14**	*455.37*			Trias_w11				
33	Zechstein	Formation	251	**1,664.51**	*37.49*			Zech_w11				
34	Rotliegend	Formation	258	**1,702**	*17.99*			Rot_w11				
35	Variscan (e)	Erosion	260			-1,500						
36	Upper Devo...	Deposit	358.9			600		Mid_U_Dev_lac				
37	Mid Devonia...	Deposit	382.7			900		Rory2_w11				
38	Rory 2	Formation	385	**1,719.99**	*409.01*			Rory2_w11				
39	Achanarras	Formation	387.7	**2,129**	*3.0*			Achan_w11				
40	Rory 1	Formation	397	**2,132**	*213*			Rory1_w11			Kerogen Mix...	0.
41	Struie	Formation	399	**2,345**	*978.1*			Struie_w11			Kerogen Mix...	1.

Figure 12: Data entry sheet for Well 12/27- 1 (Scenario 1)

4.3.2.2 SCENARIO 2

This model was used to test the impact of greater Devonian burial by matching with higher VR values indicative of gas maturity. The modelled maturity geohistory is shown in Figure 13. Maturity model and data are shown in Figure 15. The modelled paleo-heat flow is shown in Figure 14.

<u>Model calibration</u>

As the maturity of the post-Palaeozoic section is low (only Kimmeridge Clay VR data are described as suppressed by Marshall, 1998), and the Carboniferous Period is believed to have been largely a time of non-deposition due to uplift, in order to reach gas maturity more burial must have occurred during Devonian times. An extra 1.1 km of Devonian strata was added to the model compared with Scenario 1. Given that this region lay within the large, subsiding Orcadian Basin, this is not unreasonable (this value is also within the limits suggested by Keeley et al., 1991), however Scenario 2 does not give as good a fit to the maturity data as Scenario 1.

The model was calibrated to the VR data which is within the gas window. Gas shows in the Struie Formation support gas maturity (provided these hydrocarbons were generated in-situ) but the fit to the VR data is not as good as Scenario 1. A higher heat flow could be included to steepen the gradient of the maturity model but given that a significant increase in heat flow is already included, an exceptional event would need to have occurred to cause this and other than a potential local heating event possibly caused by a nearby intrusion suggested in Paleochem (1983), such an event is not anticipated.

It is interesting to note that even this deep burial does not produce a satisfactory match of the porosity model to the porosity data.

Model maturity and hydrocarbon generation

Scenario 2 suggests that nearly all hydrocarbon generation occurred during Devonian times (Figure 16, Figure 17 and Figure 18) that the source rocks would be likely exhausted by the present day). The contrasts with the model of Marshall (1998) and the good TOC values obtained for samples from the upper part of the Struie Formation (Vane et al., 2016; Paleochem, 1983). However, measured VR data from the lowermost part of the Struie Formation do indicate that the gas window was reached.

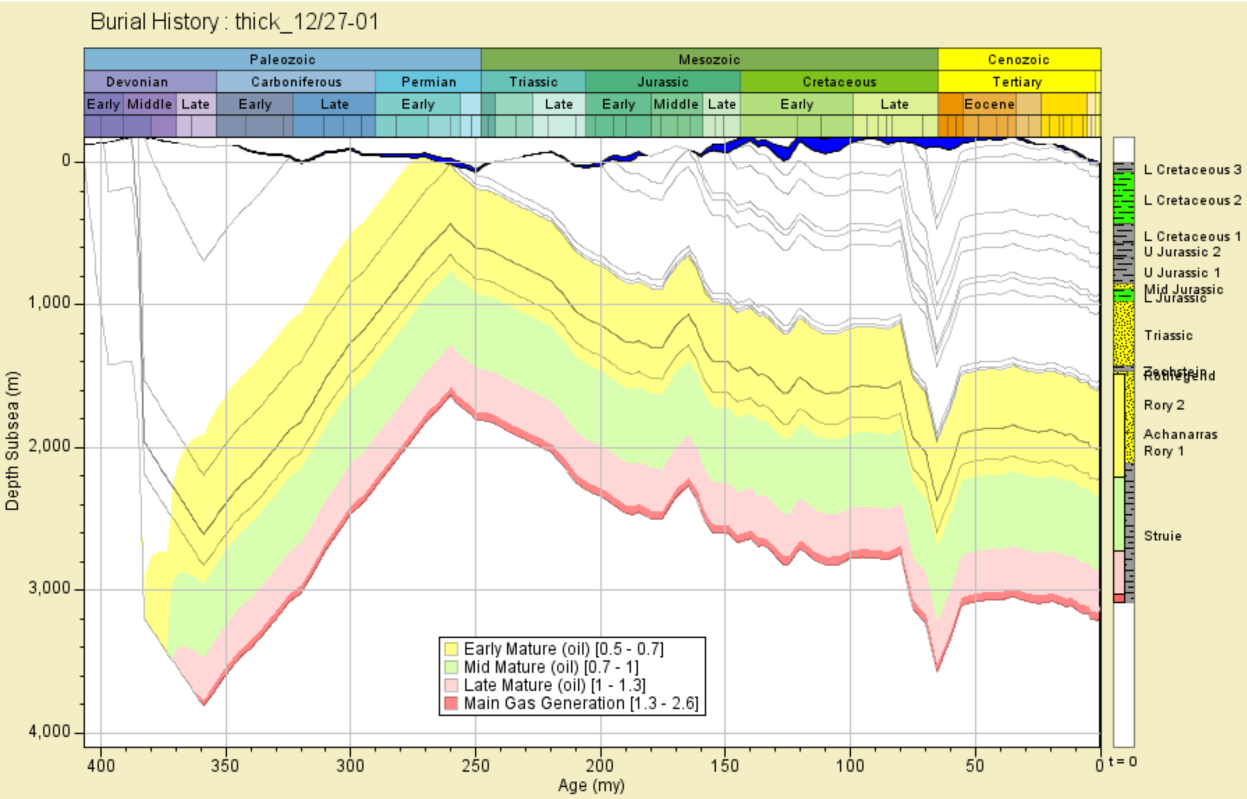


Figure 13: Modelled maturity geohistory for Well 12/27- 1. Scenario 2 – gas mature due to Devonian burial. The well terminates in the Struie Formation and the base of the Struie Formation is not reached.

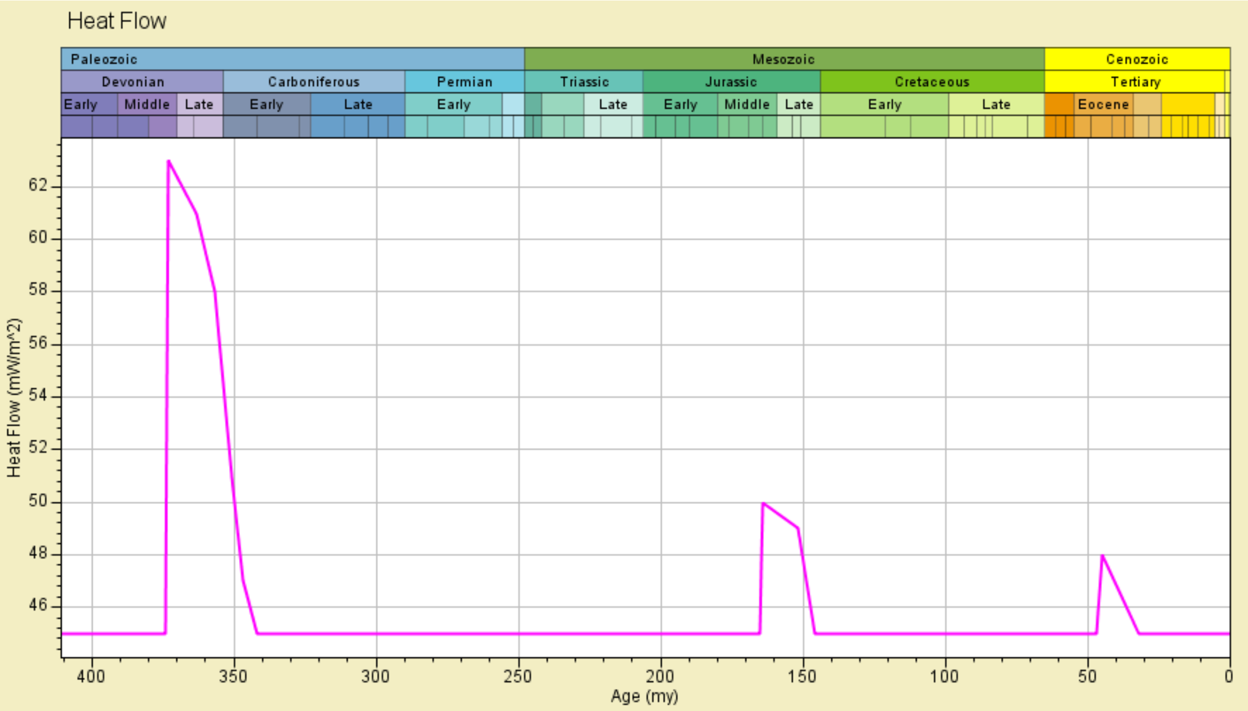


Figure 14: Modelled palaeo-heat flow for Well 12/27- 1 (Scenario 2).

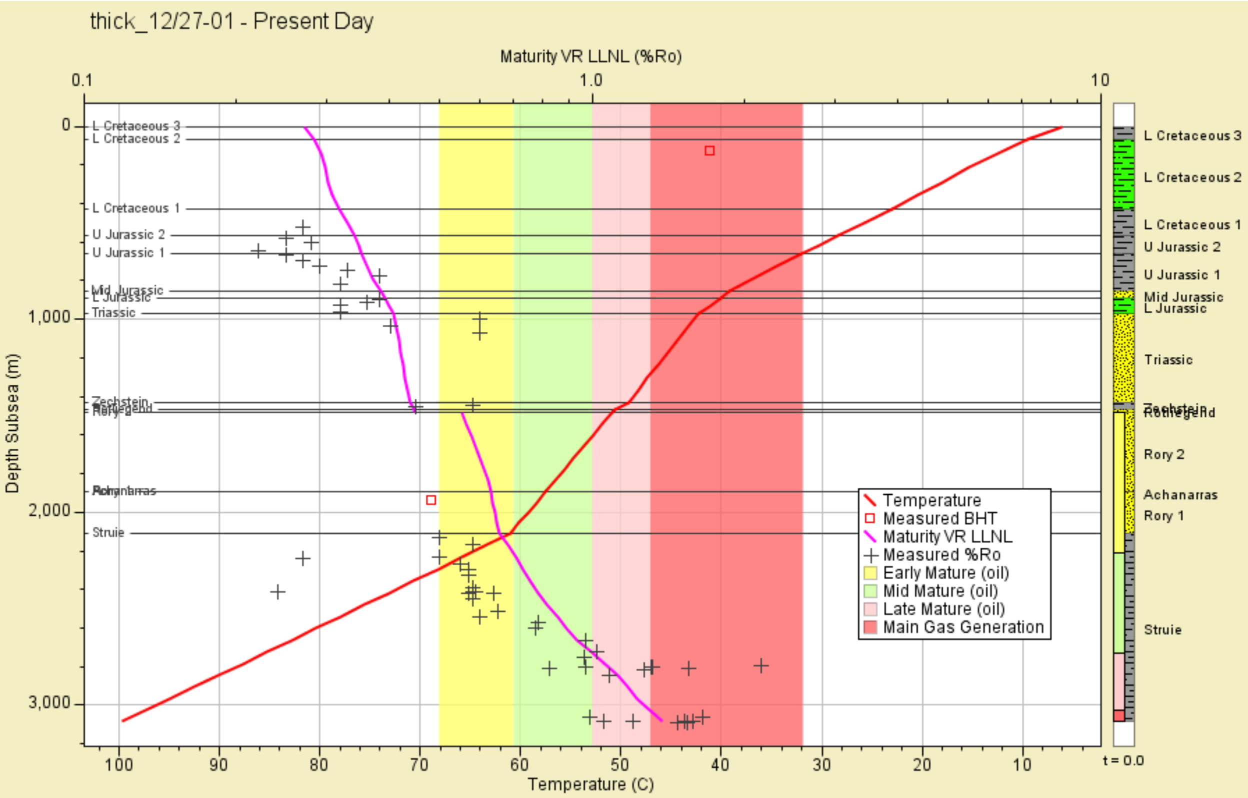


Figure 15: Depth plot for Well 12/27- 1. Scenario 2; gas mature. The well terminates in the Struie Formation and the base of the Struie Formation is not reached.

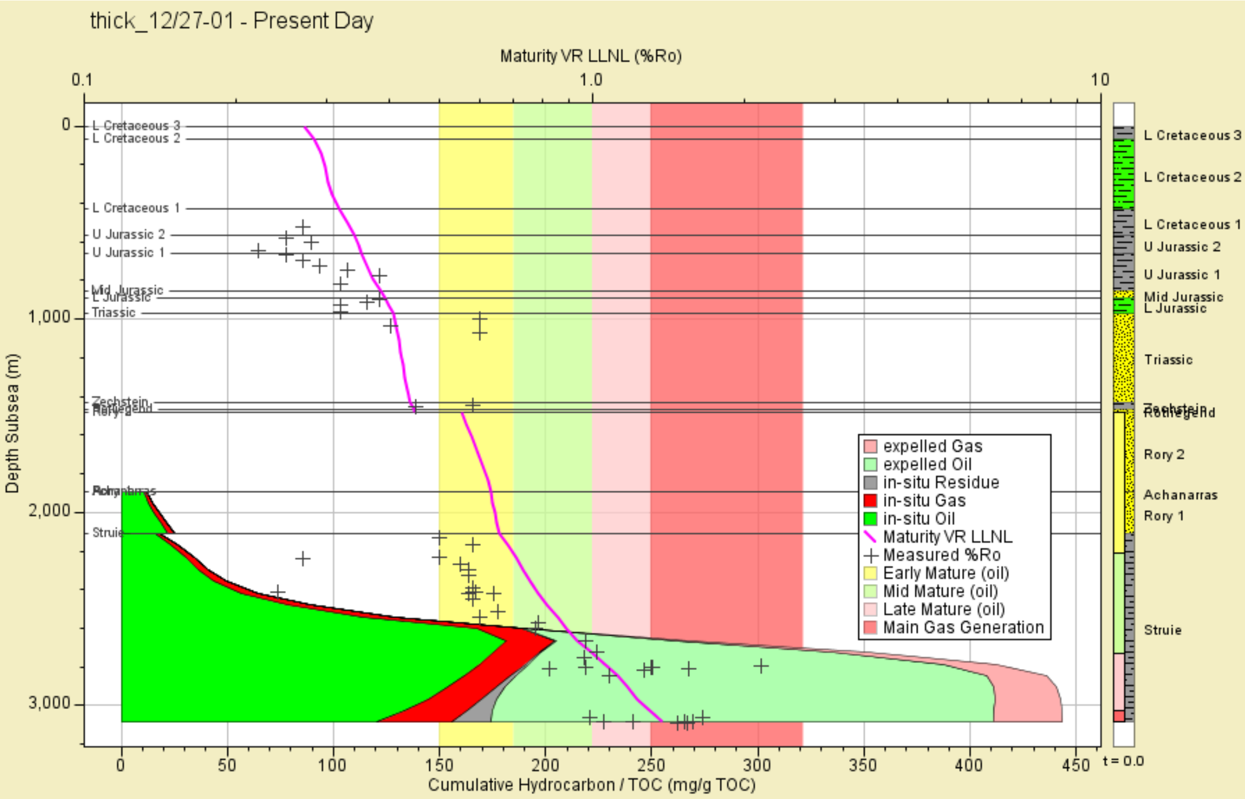


Figure 16: Depth plot for Well 12/27- 1 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model (Scenario 2).

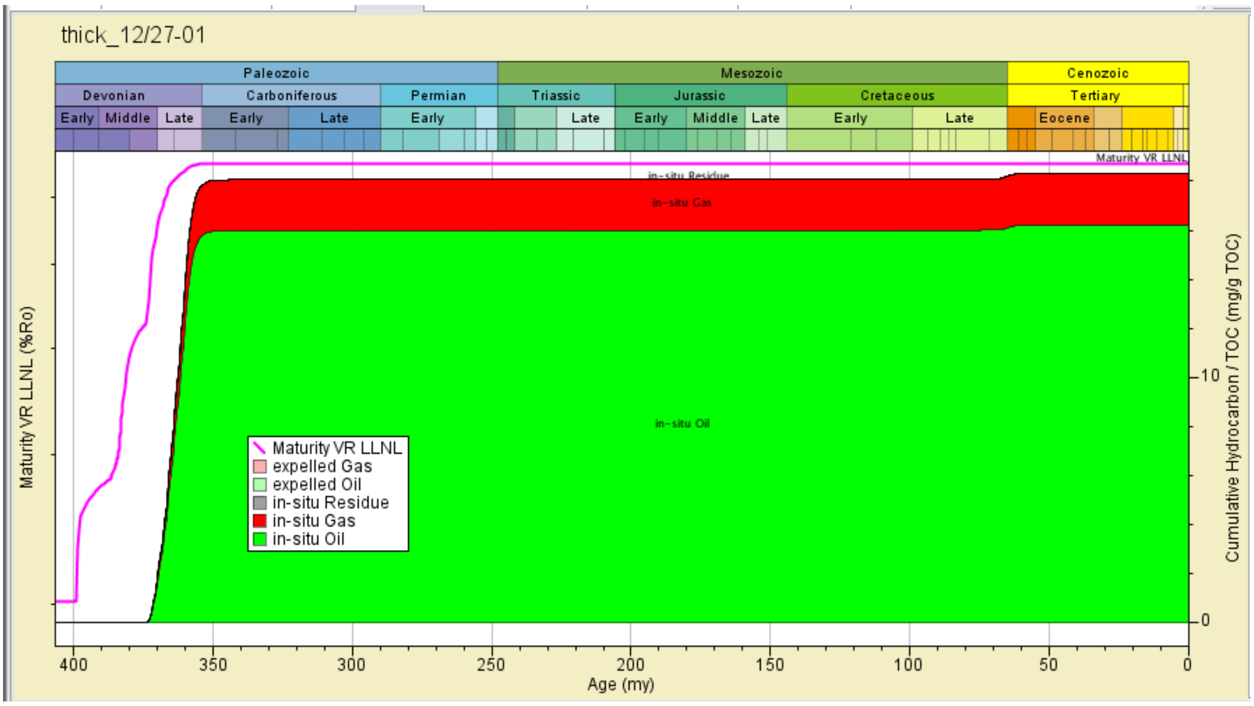


Figure 17: Time plot for Well 12/27- 1 showing timing of generation for Struie Formation through geological history of this formation. Scenario 2 suggests that main generation occurred during deepest burial during the Devonian times.

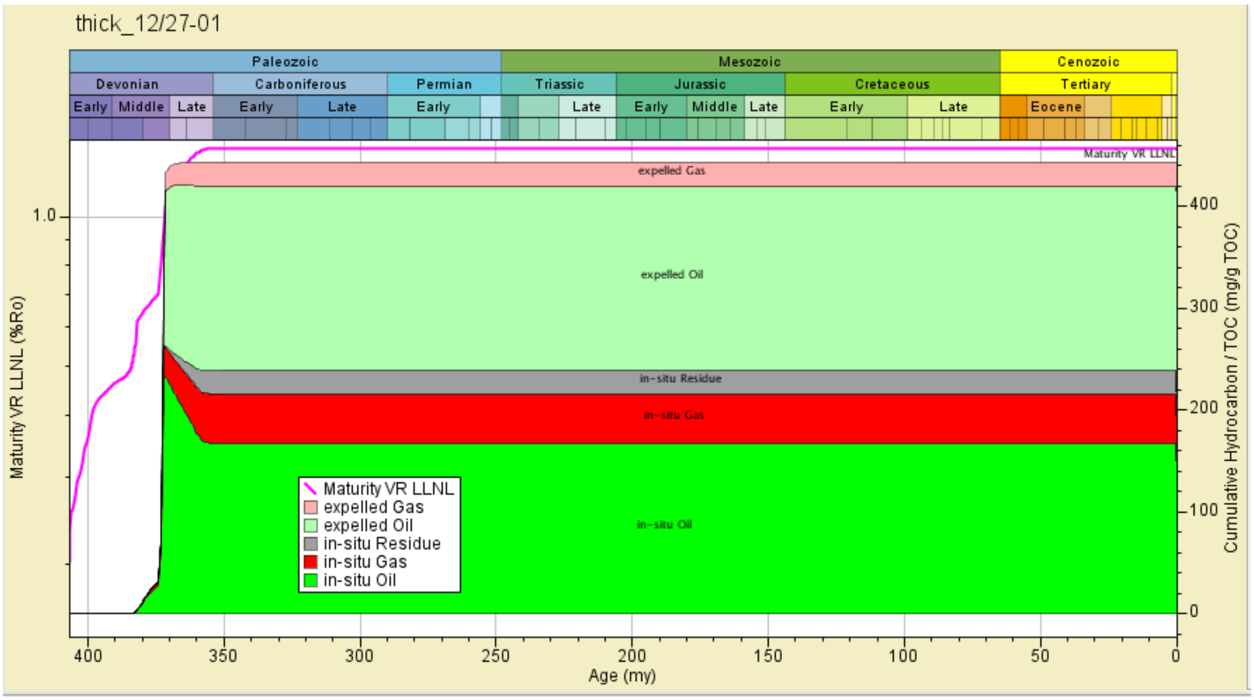


Figure 18: Time plot for Well 12/27- 1 showing timing of generation for bottom of Struie Formation model layer through geological history of this formation. Scenario 2 suggests that main generation occurred during deepest burial during Devonian times.

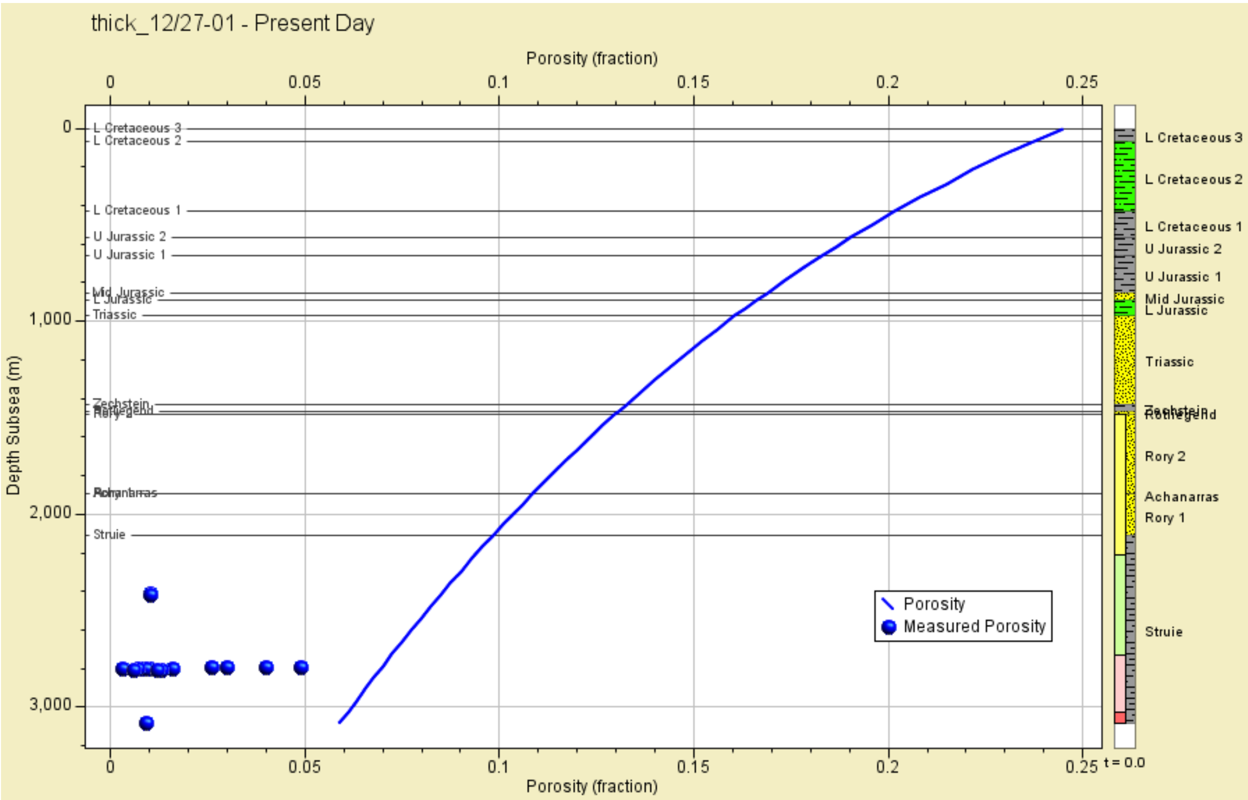
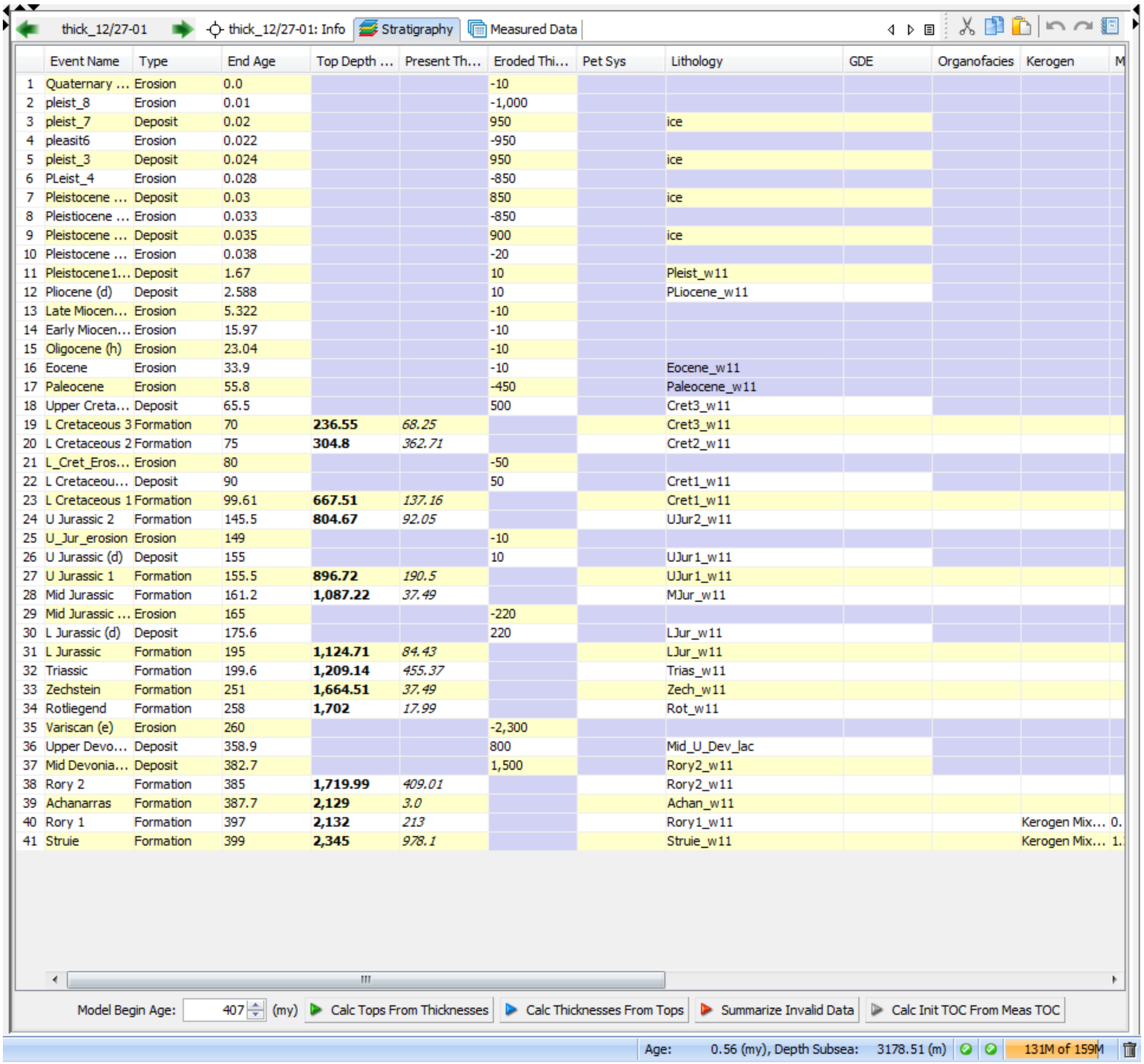


Figure 19: Depth plot of available measured porosity data (circles) and porosity model (solid line) for Well 12/27- 1



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	Pet Sys	Lithology	GDE	Organofacies	Kerogen	M
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6	PLeist_4	Erosion	0.028			-850						
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13	Late Miocen...	Erosion	5.322			-10						
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22	L Cretaceou...	Deposit	90			50		Cret1_w11				
23	L Cretaceous 1	Formation	99.61	**667.51**	*137.16*			Cret1_w11				
24	U Jurassic 2	Formation	145.5	**804.67**	*92.05*			UJur2_w11				
25	U_Jur_erosion	Erosion	149			-10						
26	U Jurassic (d)	Deposit	155			10		UJur1_w11				
27	U Jurassic 1	Formation	155.5	**896.72**	*190.5*			UJur1_w11				
28	Mid Jurassic	Formation	161.2	**1,087.22**	*37.49*			MJur_w11				
29	Mid Jurassic ...	Erosion	165			-220						
30	L Jurassic (d)	Deposit	175.6			220		LJur_w11				
31	L Jurassic	Formation	195	**1,124.71**	*84.43*			LJur_w11				
32	Triassic	Formation	199.6	**1,209.14**	*455.37*			Trias_w11				
33	Zechstein	Formation	251	**1,664.51**	*37.49*			Zech_w11				
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36	Upper Devo...	Deposit	358.9			800		Mid_U_Dev_lac				
37	Mid Devonia...	Deposit	382.7			1,500		Rory2_w11				
38	Rory 2	Formation	385	**1,719.99**	*409.01*			Rory2_w11				
39	Achanarras	Formation	387.7	**2,129**	*3.0*			Achan_w11				
40	Rory 1	Formation	397	**2,132**	*213*			Rory1_w11			Kerogen Mix...	0.
41	Struie	Formation	399	**2,345**	*978.1*			Struie_w11			Kerogen Mix...	1.

Figure 20: Model data entry sheet for Well 12/27- 1. Well terminates in Struie Formation. Top Depth is in m BRT

4.3.3 Key points from new modelling work for Well 12/27- 1

- Limited maturity and geochemical data is available for the IMF, so whilst the sequence recorded in this well is lacking the typical Middle-Upper Devonian sequence, the choice of alternatives was limited. This well does give important evidence on the maturity and generative potential of the Lower Devonian strata.
- Timing of main generation is dependent on depth of Devonian burial, if deepest burial was achieved during Devonian times then main generation occurred during Devonian burial (Scenario 2). However, if deepest burial occurred during Cretaceous – Cenozoic times (Scenario 1) then generation occurred during both Devonian and Cretaceous – Cenozoic times from the Struie Formation.
- A period of uplift is modelled in 12/27- 1 from the Middle Devonian to Early Permian times to match the sedimentary record in the well and its location on a structural high.

4.4 SCENARIO WELL 12/16- 1

Well 12/16- 1 lies on the margin of the IMF to the north of the Smith Bank High and close to the intersection of the Great Glen, Helmsdale and Wick faults. The well proves Carboniferous strata and the lowermost part of the section may be Early or Mid Devonian in age (Whitbread and Kearsey, 2016). Due to uncertainty of the age of the lowermost part of the section and the uncertainty over the Carboniferous section thickness and collation of cuttings samples over quite a large depth range for the VR data, this is considered a 'Scenario' well.

4.4.1 Previous maturity and modelling work for Well 12/16- 1

Geohistory for Well 12/16- 1

The Late Tournaisian – Visean and possibly earliest Namurian sequence is dominated by sandstones and claystones. The current project assigned these strata to the Firth Coal Formation and Tayport Formation (Whitbread and Kearsey, 2016). The oldest part of the section was assigned a Carboniferous/Devonian age and comprised a predominantly red sandstone-claystone succession with no palynological data.

AFTA data from Well 12/16- 1 suggests cooling during the Cenozoic during uplift. However, VR data suggest that maximum palaeotemperatures were reached during Palaeozoic burial (Green et al., 1995). Cenozoic uplift is expected to be around 1.1 km based on compaction data (Hillis, 1995).

Outcrop data reveal oil mature Devonian source rocks under immature/early mature Mesozoic sedimentary rocks in areas on both sides of the Moray Firth (Robertson Research International, 2001).

Maturity and oil shows for Well 12/16- 1

Oil generation is expected to have started during Westphalian times based on basin modelling carried out by Petra-Chem (1988).

Poor oil shows were encountered in the Kimmeridge Clay and Heather formations (Kerr-McGee et al., 1988)

4.4.2 New modelling work for Well 12/16- 1

Maturity data

VR and T_{max} data were available from legacy reports for the Palaeozoic section. TOC data and source rock assessment were also available (Petra-Chem, 1988). Some of the VR data were collated from cuttings data over quite large intervals (~20 m) and so this increases uncertainty in the data. Autochthonous and allochthonous data were identified. One VR datapoint which was believed to be lignite from a mud additive was discarded. About half the VR datapoints were generated using >20 samples.

One uncorrected temperature datapoint was available from Robertson Research International (1988).

Table 4: Summary of model input data for Well 12/16- 1 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 samples	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Volgian/Kimmeridge Clay	4 VR (Cu, siltstone/calcareous silt/mudst.)		2.08	Mixed oil and gas prone, variable TOC	Poor oil shows		Depths for TOC samples are over quite large intervals
Heather	1 VR (Cu, calc mudst.)		3.64		Poor oil shows		
Piper	1 VR (Cu, calc mudst.)		2.07				
A Sand		Immature – early mature for oil	1.19 (1 sample)				
Mid Shale	1 VR (Cu, siltst.)	Early mature for oil	31.38 (2 samples, one from coal)	Gas prone coal and oil prone mudstone			
B Sand		Early mature for oil	1.45				
Fladen		Early mature for oil	0.89				
Lower Jurassic		Early mature for oil	1.01	Gas prone			Depths for TOC samples are over quite large intervals – different formation names reported in composite log and Petra-Chem report, Comp. log used
Triassic		Early mature for oil	0.22				
Firth Coal	2 VRcalc	Mid mature for oil	1.86	Mudstones gas prone			
Tayport	2VR (SCW, CU, mudst.), 2 VRcalc	Mid – late mature for oil	0.49	Coals and mudstones gas prone			
Poss. U. Devonian	2 VR (Cu, calc. siltst.)	Late mature for oil	0.13	Coals and mudstones gas prone			Depths for TOC samples are over quite large intervals – different formation names reported in composite log and Petra-Chem report, Comp. log used
Poss. M. or U. Devonian	2 VR (Cu, slightly calc. siltst.and mudst. 1 C, mudst.)	Main gas	0.22	Oil prone but lean			

Model calibration

The Devonian strata are gas mature but the Mesozoic strata are immature. This suggests that a relatively low present day heat flow is reasonable and that significant heating or burial occurred during Palaeozoic times. A low present day heat flow (similar to Well 12/27- 1) was used to model the Mesozoic maturity data. The Model was calibrated to the VR and VRcalc data. When modelling the two VR populations (pre- and post-Variscan), the data could only be matched with significant Carboniferous deposition or an extremely high Palaeozoic heat flow. The maturity geohistory is shown in Figure 21 for this ‘scenario’ model. Scenario model results and modelled palaeo-heat flow are shown in Figure 22 and Figure 23 respectively. The model data entry sheet is shown in Figure 27.

A smaller amount of Mesozoic uplift was included in the current model compared with the 1.1 km suggested by Hillis (1995) due to the low maturity of Jurassic strata. The amount of uplift could be increased by decreasing the model heat flow further but this would require even more deposition/even higher heat flow to be included in the model for the Carboniferous Period.

Maturity and hydrocarbon generation

Vane et al (2016) judged the Firth Coal Formation as having poor to excellent potential and being gas prone. The Tayport Formation was rated as having poor to fair potential and being gas prone (Vane et al., 2016). Legacy reports suggested that the possible Upper Devonian strata were gas prone and the possible Mid to Upper Devonian strata in the lowermost section of the well were oil prone but with poor potential (PetraChem, 1988).

The Carboniferous formations are modelled as having reached the oil maturity window during late Carboniferous times, but contain gas prone kerogens so are unlikely to have generated significant amounts of hydrocarbons (minor amounts of gas and oil are shown to have been generated, Figure 24, Figure 25, Figure 26), this model layer was given a mix of type III and type IV kerogens). The lowermost (possibly) Devonian strata contain oil prone but lean source rocks so are also not expected to generate significant amounts of hydrocarbons.

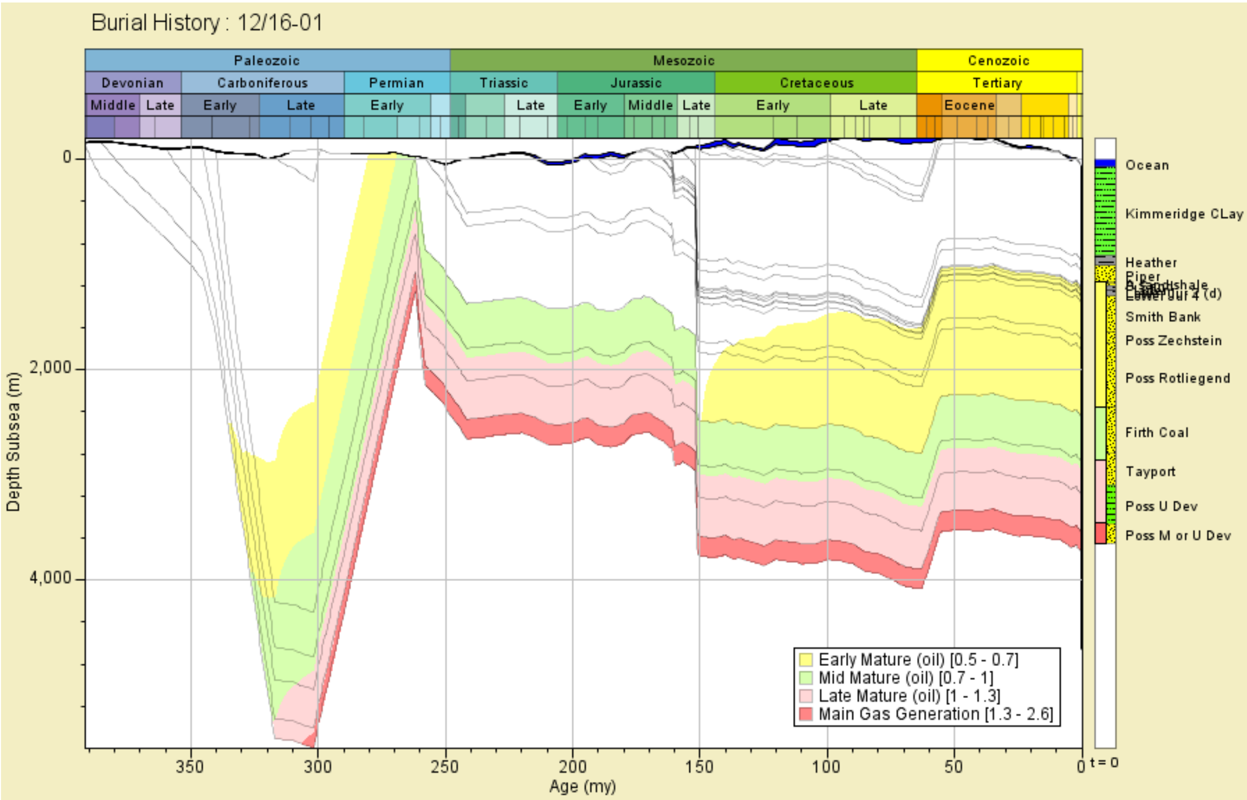


Figure 21: Modelled maturity geohistory for Well 12/16- 1. Well terminates in Possible Mid – Upper Devonian Strata. Base of the (possible) Devonian strata is not penetrated.

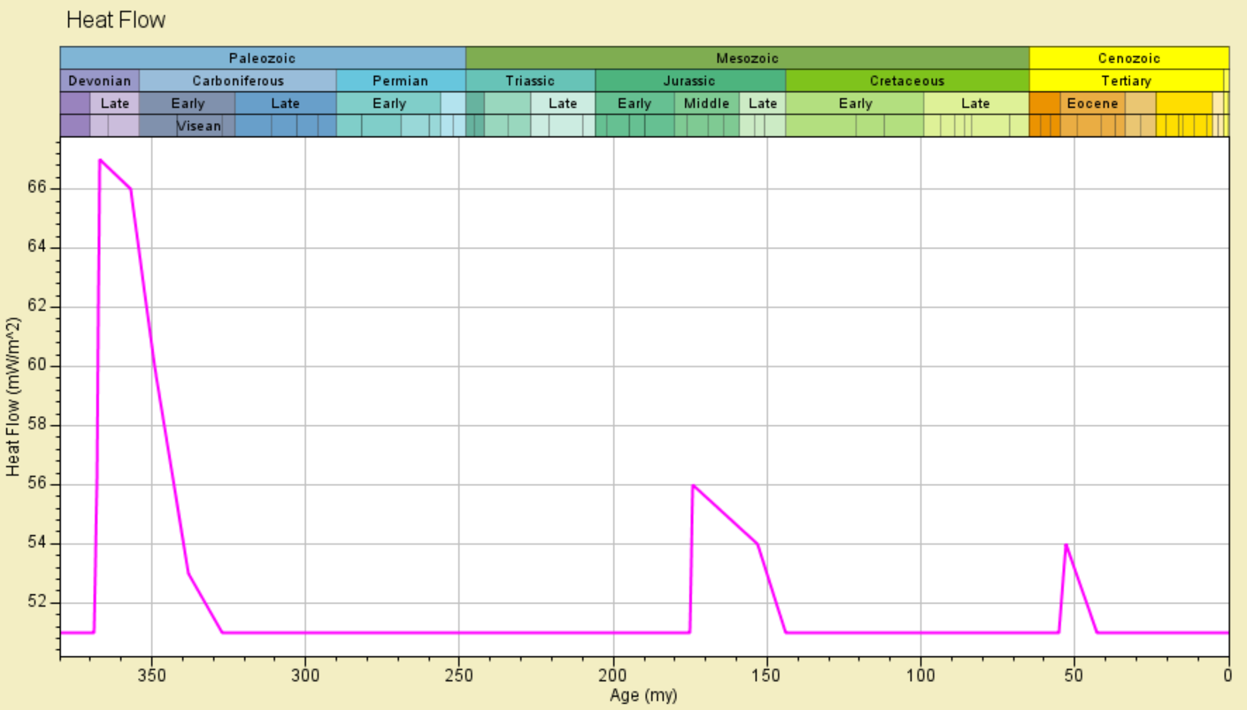


Figure 22: Modelled palaeo-heat flow for Well 12/16- 1.

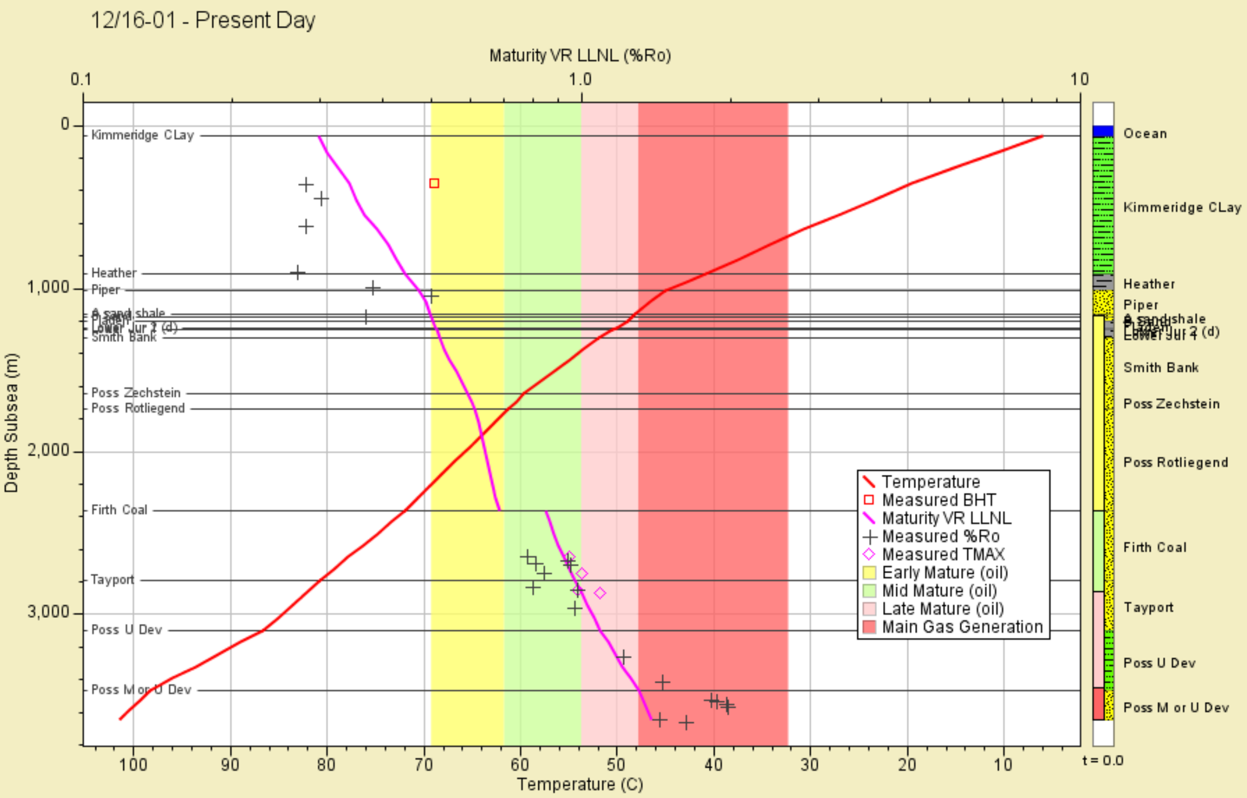


Figure 23: Depth plot for Well 12/16- 1 showing model results, maturity data and maturity windows plus the temperature model.

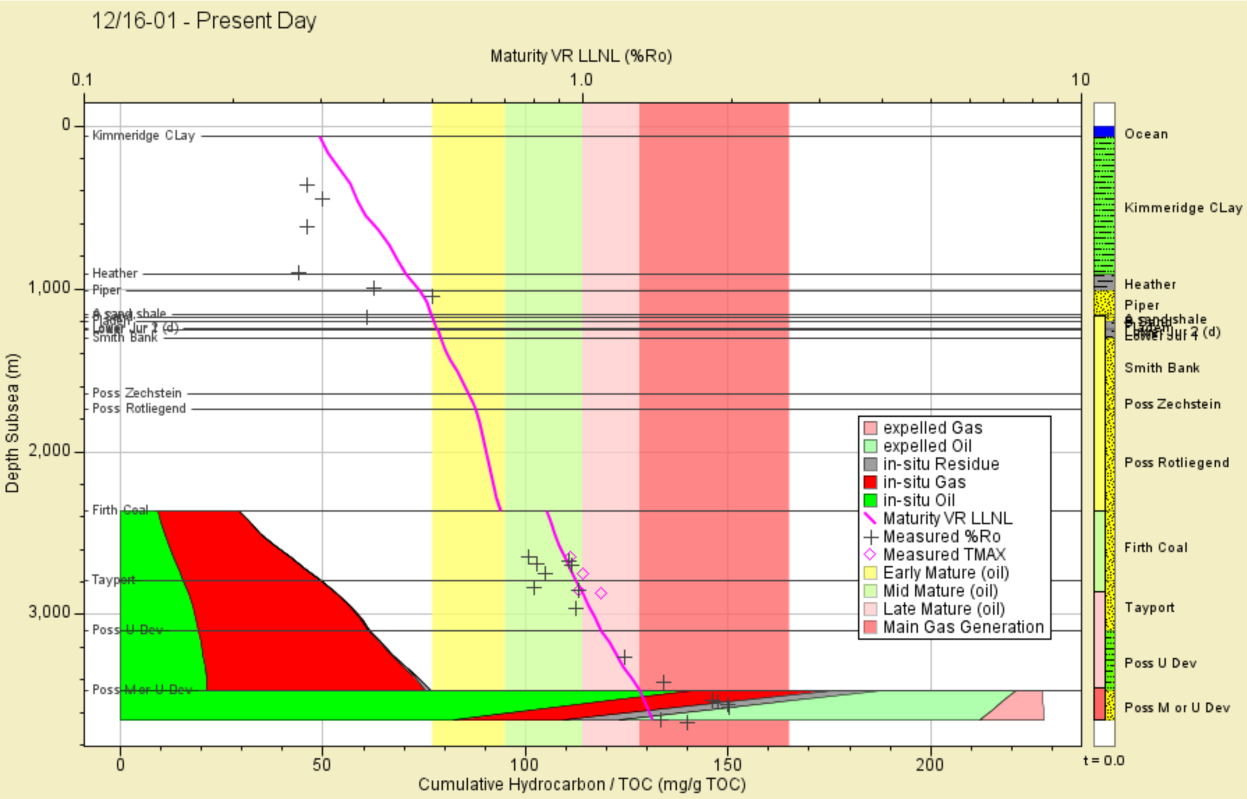


Figure 24: Depth plot for Well 12/16- 1 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model.

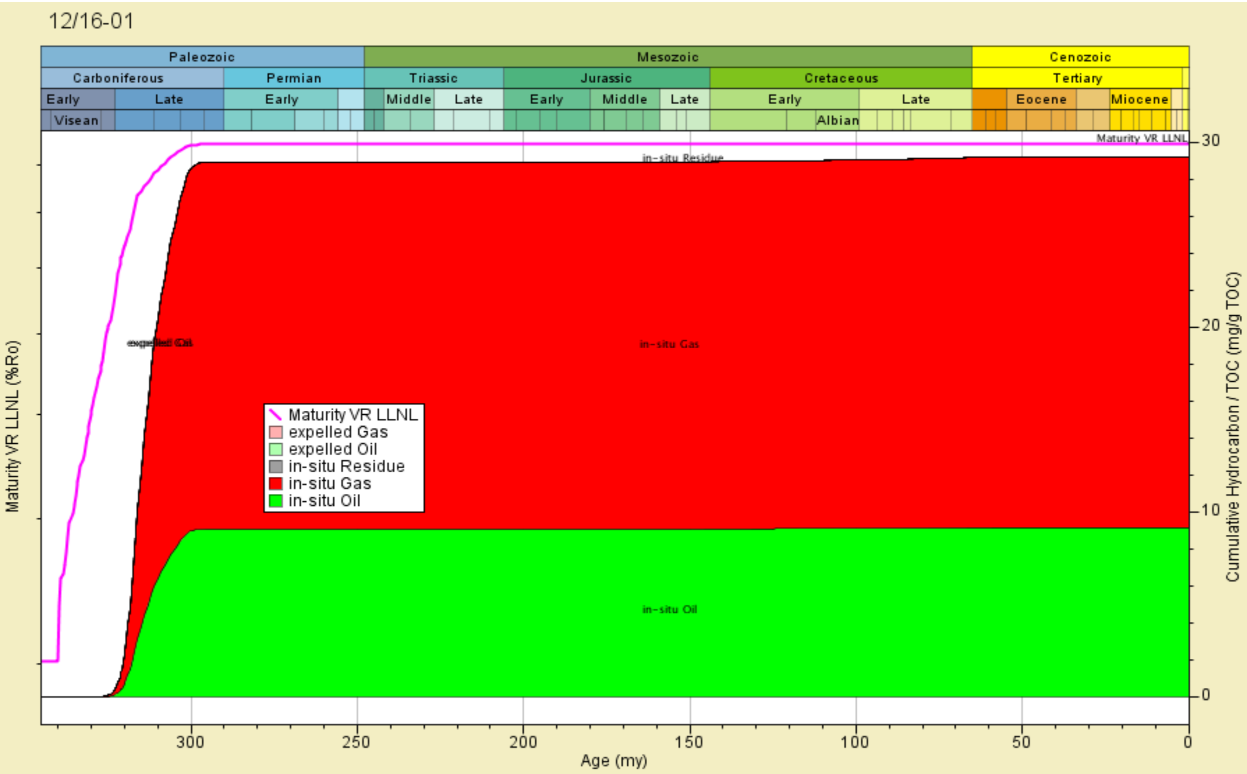


Figure 25: Time plot for Well 12/16- 1 showing timing of generation for top of the Firth Coal Formation through geological history of this formation. The current model suggests that main generation occurred during deepest burial during the Carboniferous Period.

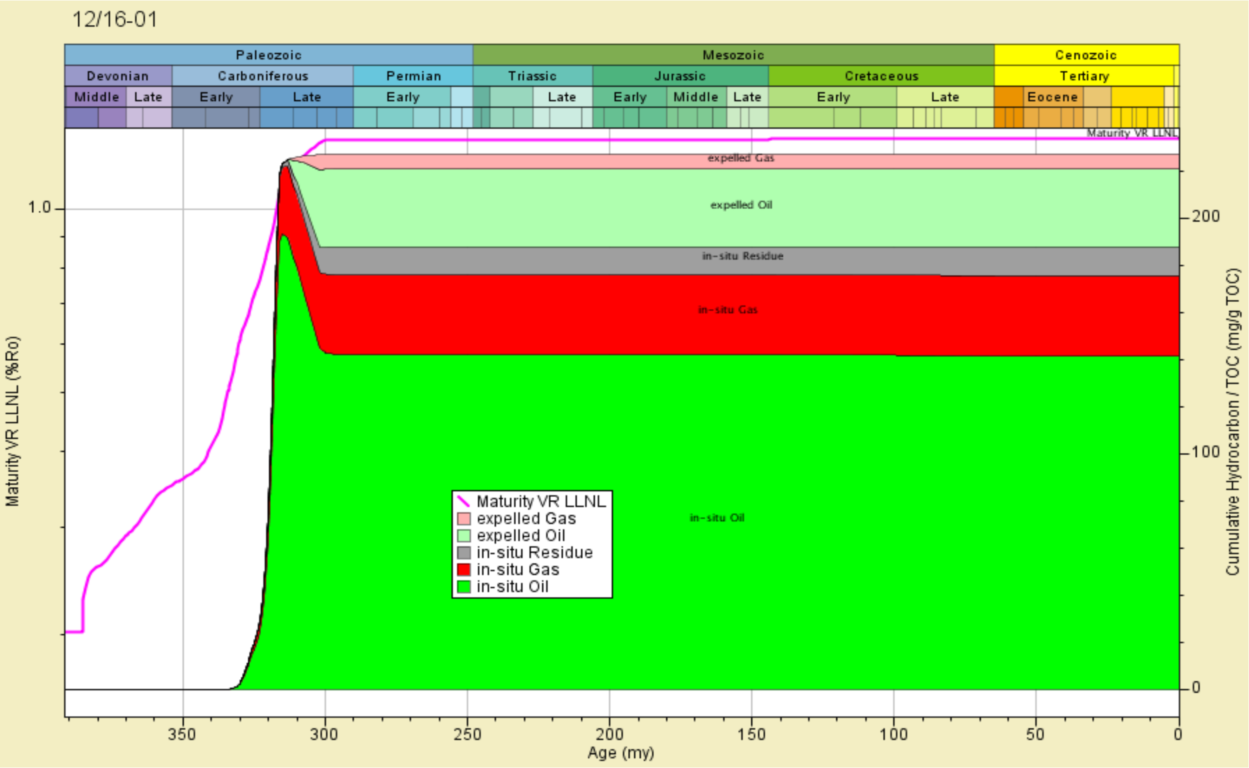


Figure 26: Time plot for Well 12/16- 1 showing timing of generation for top of 'Upper or Middle Devonian' model layer through geological history of this formation. The current model suggests that main generation occurred during deepest burial during the Carboniferous Period.

12/16-01 | 12/16-01: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	Pet Sys	Lithology	GDE	Organofacies	Kerogen
3	pleist_7	Deposit	0.02			950		ice			
4	pleasit6	Erosion	0.022			-950					
5	pleist_3	Deposit	0.024			950		ice			
6	PLeist_4	Erosion	0.028			-850					
7	Pleistocene ...	Deposit	0.03			850		ice			
8	Pleistiocene ...	Erosion	0.033			-850					
9	Pleistocene ...	Deposit	0.035			900		ice			
10	Pleistocene ...	Erosion	0.038			-10					
11	Pleistocene1...	Deposit	1.67			10		Pleist_w11			
12	pliocene (h)	Hiatus	2.588								
13	Pliocene	Hiatus	3.6								
14	Late Mio (e)	Erosion	5.322			-20					
15	Early Miocene	Deposit	12			10		mio_w12			
16	Oligocene (e)	Erosion	23.03			-20					
17	Eocene	Erosion	33.91			-30		eoc_w12			
18	Late Pal	Erosion	55.8			-500					
19	Paleocene	Deposit	63			10		late_pal_2_w12			
20	Upper Creta...	Deposit	65.5			400		chalk_w12			
21	Lower Creta...	Deposit	99.6			100		l_cret_w12			
22	Jurassic (d)	Deposit	145.5			50		u_jur_w12			
23	Kimmeridge ...	Formation	151	**91.44**	*846.43*			kimm_w14			
24	Heather	Formation	152	**937.87**	*95.4*			heather_w14			
25	Jurassic (e4)	Erosion	157			-10		Shale			
26	Jurassic (d4)	Deposit	158			10		piper_w14			
27	Piper	Formation	160	**1,033.27**	*151.79*			piper_w14			
28	Jurassic (e3)	Erosion	161			-10					
29	Jurassic (d3)	Deposit	161.5			10		Asand_w14			
30	A sand,shale	Formation	162	**1,185.06**	*14.33*			Asand_w14			
31	B Sand	Formation	163	**1,199.39**	*23.77*			Bsand_w14			
32	Fladen	Formation	164.7	**1,223.16**	*41.76*			Fladen_w14			
33	Jurassic (e2)	Erosion	172			-10					
34	Jurassic (d2)	Deposit	173			10		L_Jur_Aalen_w14			
35	Lower Jur 2 ...	Formation	174	**1,264.92**	*7.62*			L_Jur_Aalen_w14			
36	Jurassic (e1)	Erosion	177			-100					
37	Jurassic (d1)	Deposit	185			100		Sinermur_w14			
38	Lower Jur 1	Formation	190	**1,272.54**	*51.51*			Sinermur_w14			
39	Lower Jur (h)	Hiatus	194								
40	Smith Bank	Formation	241.7	**1,324.05**	*346.25*			Smith_w14			
41	Poss Zechstein	Formation	251	**1,670.3**	*97.54*			Zech_w14			
42	Poss Rotlieg...	Formation	258	**1,767.84**	*618.76*			Rot_w14			
43	Variscan (e)	Erosion	262			-4,400					
44	Stephanian (d)	Deposit	302			300		Sandstone			
45	Carbonifero...	Deposit	317			4,100		Firth_w14			
46	Firth Coal	Formation	340	**2,386.6**	*427.4*			Firth_w14			Kerogen Mix...
47	Tayport	Formation	345.3	**2,814**	*307.55*			Tay_w14			Kerogen Mix...
48	Poss U Dev	Formation	359.2	**3,121.55**	*366.45*			UDEv_w14			Kerogen Mix...
49	Poss M or U ...	Formation	385.3	**3,488**	**187**			MDev_w14			Kerogen Mix...

Model Begin Age: 391.8 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Age: 375.42 (my), Heat Flow: 50.25 (mW/m^2) | 82M of 139M

Figure 27: Model data entry sheet for Well 12/16- 1. Top Depth is in m BRT

4.4.3 Key points from new modelling work for Well 12/16- 1

- This well was chosen to examine Carboniferous burial history that is not typical of the IMF, but few maturity data are available so the choice of wells to model was limited
- A considerable thickness of Carboniferous strata was required to match the VR data, this thickness could be reduced by increasing the heat flow, but unless an even larger Carboniferous heat flow peak is included in the model, then even less Mesozoic strata could be included to match the lower post-Variscan VR values.
- The gas prone possible Middle – Upper Devonian strata reach the gas window but as these strata are lean, significant hydrocarbon generation is not expected
- The current model suggests that main generation occurred during deep Carboniferous burial.

5 Detail of South Buchan Basin modelling

5.1 GEOLOGY

The South Buchan Basin is described here in the context of the wider Buchan Basin and Outer Moray Firth (OMF) areas.

Caledonian Orogeny

The Caledonian South Halibut Granite was emplaced to the north of the Buchan Graben, remaining a local high until latest Jurassic to Cretaceous times (Marshall and Hewett, 2003).

Early - Mid Devonian, non-deposition

In early Devonian times, compression to the south in the Midland Valley resulted in extensional reactivation of the Caledonian thrust faults and the formation of half graben sub-basins. The Outer Moray Firth generally has relatively thin Devonian strata with the exception of the Buchan Graben (Marshall and Hewett, 2003).

Early Devonian and the oldest Mid Devonian strata are not proven in the Buchan Graben (Marshall and Hewett, 2003).

Late Mid Devonian – Late Devonian deposition

Late Middle Devonian to Upper Devonian strata were deposited in alluvial fan/plain, lacustrine, and sabkha plain environments (Marshall and Hewett, 2003). The oldest Devonian strata proven in the north part of Quadrant 20 is the Eday Marl equivalent which is of Givetian age (Whitbread and Kearsey, 2016).

Carboniferous deposition

Lower Carboniferous strata were deposited in an extensive non-marine basin which covered the Witch Ground Graben, Moray Firth Basins, Forth Approaches Basin and West Central Shelf (Bruce and Stemmerik, 2003).

Coal bearing Visean and Namurian strata were deposited in the Outer Moray Firth Basin in a fluvial or deltaic environment with some evidence of lacustrine sedimentation in Well 20/10a- 3 (Bruce and Stemmerik, 2003; Whitbread and Kearsey, 2016).

There is some evidence to suggest that Westphalian strata were deposited across a broad region in a terrestrial environment (Bruce and Stemmerik., 2003; Coward et al., 2003).

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

During Late Carboniferous times, reversal of movement along Caledonian structures resulted in basin inversion. As part of this inversion, the Outer Moray Firth, was subaerially exposed (Coward et al., 2003).

Permian deposition

During Permian times, the Moray Firth region lay in an embayment on the margin of the Northern Permian Basin (Andrews et al., 1990; Glennie et al., 2003). Development of the Northern Permian Basin was controlled by depth-dependent stretching and accompanied by the initiation of deep and steep planar faults (Goldsmith et al., 2003).

Rotliegend strata were deposited in a desert environment in late Permian times in the Buchan Graben area (Glennie et al., 2003). Upper Permian halites and anhydrites were deposited in the south of the Buchan Graben area as part of the wide shallow marine shelf environment which stretched across most the Moray Firth region (Glennie et al., 2003; Andrews et al., 1990).

Triassic extension and deposition

The transition from Permian to Triassic strata is usually conformable (Goldsmith et al., 2003). Triassic strata were deposited in intra-continental basins controlled by local and regional tectonics (Goldsmith et al., 2003). A Triassic graben system that transected the northern Permian Basin modified the Permian structural pattern (Coward et al., 2003). Triassic extension occurred across Block 20/10, but the main phase of extension occurred during Jurassic times. North-east to south-westerly opening of Triassic faults controlled deposition patterns (Coward, 1995; Chadwick and Evans, 1995; Goldsmith et al., 2003).

Movement of Zechstein salt strongly influenced Triassic sedimentation (Coward et al., 2003).

Lower Triassic strata were deposited in a widespread lacustrine/floodplain environment. Mid and Late Triassic strata were deposited in alluvial/fluvial environments (Andrews et al., 1990).

Lower – Middle Jurassic deposition

Lower Jurassic times seem to have been tectonically quiescent with broad subsidence (Husmo et al., 2003).

Mid Jurassic thermal doming and uplift

Most the Middle Triassic and all Upper Triassic strata have been removed by erosion from Block 20/10 (Andrews et al., 1990).

Husmo et al. (2003) suggest that deposition of Jurassic strata may have begun during Pliensbachian times with coastal/alluvial plain deposits, followed by Toarcian marine shales in Block 20/10. 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. Husmo et al. (2003) describe the Outer Moray Firth as being affected by doming during Aalenian – Bajocian times (Cimmerian/Intra-Aalenian Unconformity).

Late Jurassic – earliest Cretaceous rifting

A tripartite graben system which included the Moray Firth, Viking Graben and Central Graben developed (Andrews et al., 1990).

Late Jurassic rifting was influenced by the rifting pattern established during Triassic extension. The most widespread rifting occurred from mid Callovian – early Kimmeridgian times. In the Outer Moray Firth, rifting seems to have occurred from late Oxfordian – early to Mid Volgian times. Upper Jurassic strata were deposited in shallow to deep marine or coastal-shelf environments (Husmo et al., 2003; Fraser et al., 2003). Upper Jurassic strata are present in Well 20/10a- 3.

Based on gravity anomalies, previous studies have calculated that the crust is thinned by around 5 km in the Buchan graben area (Andrews et al., 1990; Christie and Sclater, 1980; Donato and Tully 1981; Barr 1985; Zervos, 1987). The Outer Moray Firth Basin follows the McKenzie (1978) model during Late Jurassic to Early Cretaceous rifting: large scale extension causes rapid thinning and stretching of the crust. Initial rifting and normal faulting result in rapid subsidence during Late Jurassic and Early Cretaceous times (Andrews et al., 1990).

Early Cretaceous post-rift subsidence

Lower Cretaceous strata occur widely across the Moray Firth region deposited during post-rift thermal subsidence as the principal locus of rifting shifted westwards from the North Sea into the proto-North Atlantic (Copestake et al., 2003). Active plate margins adjacent to the study area and halokinesis affected depositional patterns. The lowermost Cretaceous sequence is absent in Well 20/10a- 3. The environment of deposition during Early Cretaceous times was an aerobic marine environment (Andrews et al., 1990). The general increase in sea level was punctuated by sea level falls during Hauterivian – Valanginian and Aptian times (Oakman, 2005).

Late Cretaceous

During Late Cretaceous times, a thick sequence of chalk and chalk marl with minor mudstones was widely deposited during passive thermal subsidence. Over 500 m of Upper Cretaceous strata is recorded in the Buchan Graben area (Surlyk et al., 2003; Coward et al., 2003). Compressed and partial sequences are present on local highs. Sea level rise started in Albian times and reached a peak during Maastrichtian times. A global sea level drop occurred at the end of Maastrichtian times. Global Sea level fluctuations, local tectonism resulting from continuing crustal extension and wider events affecting the water circulation, ecosystem and sediment input affected deposition during Upper Cretaceous times (Andrews et al., 1990).

Latest Cretaceous - Palaeocene uplift

During Latest Cretaceous times uplift of the main part of Scotland and Norway occurred. During the Maastrichtian – Palaeocene times, mantle underplating related to the Iceland plume occurred. Some of the uplift is believed to be tectonic, but most the uplift is attributed to development of a Palaeogene North Atlantic hotspot/Iceland plume (Coward et al., 2003; Brodie and White, 1995). Much of the OMF remained submerged and marine sediments were deposited (White and Lovell, 1997; Coward et al., 2003).

Chalk Group deposition continued into earliest Palaeocene times. Palaeocene and Eocene strata form a thick sequence in the Buchan Graben (<1100 m; Andrews et al., 1990). During the Paleocene, basin margin deposition dominated (Ahmadi et al., 2003). Rapid subsidence of the North Sea basin is evident during Palaeocene times with thick clastic sequences sourced from the uplifted areas.

Late Palaeocene – early Miocene deposition

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

The Oligocene sequence shows a change to a more distal basin environment (Fyfe et al., 2003).

Mid – Late Miocene

During the mid-late Miocene, uplift occurred on the margins of the North Sea basin (Fyfe et al., 2003).

Pliocene deposition

Renewed subsidence took place during the Pliocene Epoch. Uplift occurred during Late Pliocene and Early Pleistocene times (Fyfe et al., 2003).

Quaternary

Throughout later Pleistocene times, periglacial, glacial and glacio-marine conditions alternated with periods of temperate climate in the North Sea. The Outer Moray Firth was covered by sea ice with a few exposed areas of land (Andrews et al., 1990; Fyfe et al., 2003). There is a regional unconformity of Elsterian age (caused by glacial erosion) which forms a prominent seismic reflector. Hubbard et al (2008) prepared a model of ice coverage from 38.9 ka to present day. Low rates of deposition occurred during Holocene times (Andrews et al., 1990).

5.2 PREVIOUS WORK IN THIS REGION

Oil and gas generation and accumulation

While the IMF was experiencing Early Cenozoic uplift, the OMF continued to subside and burial and maturation continued resulting in oil then gas generation in the Mid Cenozoic Era, mainly from the Kimmeridge Clay source rocks (Kubala et al., 2003). In the OMF, Upper Jurassic strata are a major source of oil and gas (Fraser et al., 2003; Kubala et al., 2003;) but in depocentres the

Carboniferous coal-bearing interval may also generate gas. The composition of the gas in the Buchan Graben appears to indicate a Devonian source (Robertson Research International, 2001).

The Buchan oil field (blocks 20/5a and 21/1a) produces oil from a highly fractured Upper Devonian – Lower Carboniferous sandstone reservoir (Edwards, 1991).

Geohistory modelling

A phase of extension and intermittent subsidence occurred during Devonian and Carboniferous times in the Moray Firth (Arsenikos et al., 2016; Whitbread and Kearsey, 2016). Robertson Research International (2001) state that data for core samples of Devonian age from the Buchan-Glenn Horst and Buchan Graben indicate deep burial during the Devonian/Carboniferous/Permo-Triassic and Early Jurassic, followed by uplift associated with doming during the Middle Jurassic Period.

5.3 WELL 20/10A- 3

Well 20/10a- 3 was drilled on an extension of the Peterhead Ridge separating the north-east part of the Forth Approaches Basin and the western edge of the South Buchan Basin (Figure 1). The well penetrates the Carboniferous Firth Coal Formation source rock. Oil shales described in this well may be equivalent to the lacustrine West Lothian Oil Shales present onshore in the Midland Valley of Scotland (Bruce and Stemmerik, 2003).

5.3.1 Previous maturity and modelling work for Well 20/10a- 3

Palaeozoic source rock potential and hydrocarbon generation

The Geochem Group (1993) report analysed 26 samples from the Firth Coal Formation, including the oil shale facies. The analysed claystones were determined to comprise good or very good source facies (3 – 10 mg/g TOC) though some rich (>10 mg/g TOC) and poor (<2 mg/g TOC) source quality interbeds are noted. The main source potential is for gas from woody kerogens though two intervals with potential for gas condensate were also noted, one in the oil shale facies and one in the lower part of the underlying Firth Coal Formation. The woody kerogens were generally associated with significant amounts of herbaceous material and minor amounts of inertinite. Amorphous kerogens are also noted, generally increasing amounts with depth were recorded, suggesting the lower part of the formation would have some potential to generate oil, but overall the potential was believed to be for gas (Geochem Group, 1993).

The source rocks were not considered mature for gas and therefore were not expected to have generated significant volumes of hydrocarbons (Geochem Group, 1993). Minor early condensate generation from some of the deeper source rocks was considered possible. It was noted that the well was drilled on the top of a structure and that generation could have occurred off-structure if sufficiently deep burial had been achieved Geochem Group (1993).

Maturity data

Kubala et al. (2003) indicate the average present day heat flow in this part of Quadrant 20 is 60 – 75 mWm^{-2}. However, using a heat flow in that range would mean that the VR data could not be matched by the model even if no additional stratigraphy were added to the present day preserved stratigraphy, so a lower heat flow was selected for the current models.

Hydrocarbon shows

The mud loggers completion report (Exploration Logging North Sea Limited, 1985) indicates that hydrocarbon shows were detected in the cuttings recovered from sandstone and siltstone stringers in the Rotliegend Group. The report also indicates that hydrocarbons may be present in the Firth Coal Formation from 3547.9 – 3564.6 m depth, but recorded fluorescence was weak and may actually be contamination from oil based drilling mud. The Permian and Carboniferous intervals were judged to contain no mobile hydrocarbons and therefore were not tested (Exploration Logging North Sea Limited, 1985).

5.3.2 New modelling work

The source rock geochemistry, facies and maturity levels appear to be similar to many of the Firth Coal bearing wells in Quadrants 14, 15, 20 and 21, so the well is representative in geochemical terms (Vane et al., 2016).

As Well 20/10a- 3 lies on a relative high, a scenario to test how much additional Mesozoic burial would be required for the Firth Coal Formation to reach the gas window was tested.

Two glaciation periods where up to 950 m of ice were included in the current geohistory model based on Hubbard et al. (2008). This has a small impact on maturity model results.

5.3.3 New model for Well 20/10a- 3

Available maturity and porosity data

Sixteen T_{max} values are available from the Geochem Group (1993) report. The seven VR data in the same report were obtained using a good number of measurements (>50[1] per VR datapoint) and the data histograms indicated tight groupings of data (i.e. the samples were from one population of autochthonous data) indicating the data are reliable. Geochem Group (1993) comments that these samples do not form a linear trend when plotted against depth due to the heterogeneity of the (coaly) organic matter over this relatively small interval (450 m) but that the thermal alteration index agrees with the VR data.

One uncorrected temperate data point was available from Geochem Group (1993).

Table 5: Summary of model input data for Well 20/10a- 3 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 samples	Kerogen	Oil/gas show	N.o. of porosity data	Comments
Rotliegend		Early mature for oil			Few trace oil shows		
Firth Coal (upper)	5 VR (Cu, clayst.), 12 VRcalc	Early – mid mature for oil	5.75	Mainly gas prone			VR suggests only early mature for oil
Firth Coal (oil shale facies)	1 VRcalc	Mid mature for oil	16.3	Mainly gas prone, contains a condensate prone interval			
Firth Coal (lower)	2 VR (Cu, clayst), 3 VRcalc	Mid mature for oil	3.55	Mainly gas prone, contains a condensate prone interval			

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

Model calibration

As the Firth Coal Formation has very slow deposition rates (Kearsey, *pers comm*) it was assumed that slow deposition of Carboniferous strata continued until Variscan uplift and erosion. The model could be calibrated to the VR data using only a small amount of additional Carboniferous deposition. The maturity geohistory is shown in Figure 28. Figure 30 shows the model maturity and maturity data. The model data entry sheet is shown in Figure 34.

The modelled palaeo-heat flow is shown in Figure 29. A low heat flow was selected to calibrate to the VR data but this disagrees with the regional heat flow in this region in Kubala et al. (2003).

VR data from Geochem (1993) indicated a good number of readings were used to generate the VR data and so the model was preferentially matched to these data. The VRcalc data suggest the Firth Coal Formation is more mature but as reliable VR data are available the model was matched only to the VR data.

Model maturity and hydrocarbon generation

The Firth Coal Formation is largely gas prone and has good to very good generative potential (Vane et al., 2016). The TOC varies between 1.86% and 15.0% with a mean of 5.58% over the 445 m depth interval. The TOC of the Firth Coal Formation (oil shale facies) is very high but this only represents a thin interval and only one datapoint is available. The Firth Coal Formation may have some oil prone intervals (at 3910.6 and 3956.3 m BRT; Vane et al., 2016).

For the BasinMod model, a mix of type III and type IV kerogens was included, with the majority of kerogen being type III based on the data available to this study. A small amount of oil prone kerogen was included in the Firth Coal Formation oil shale facies. The modelled hydrocarbon generation is shown in Figure 31, Figure 32 and Figure 33.

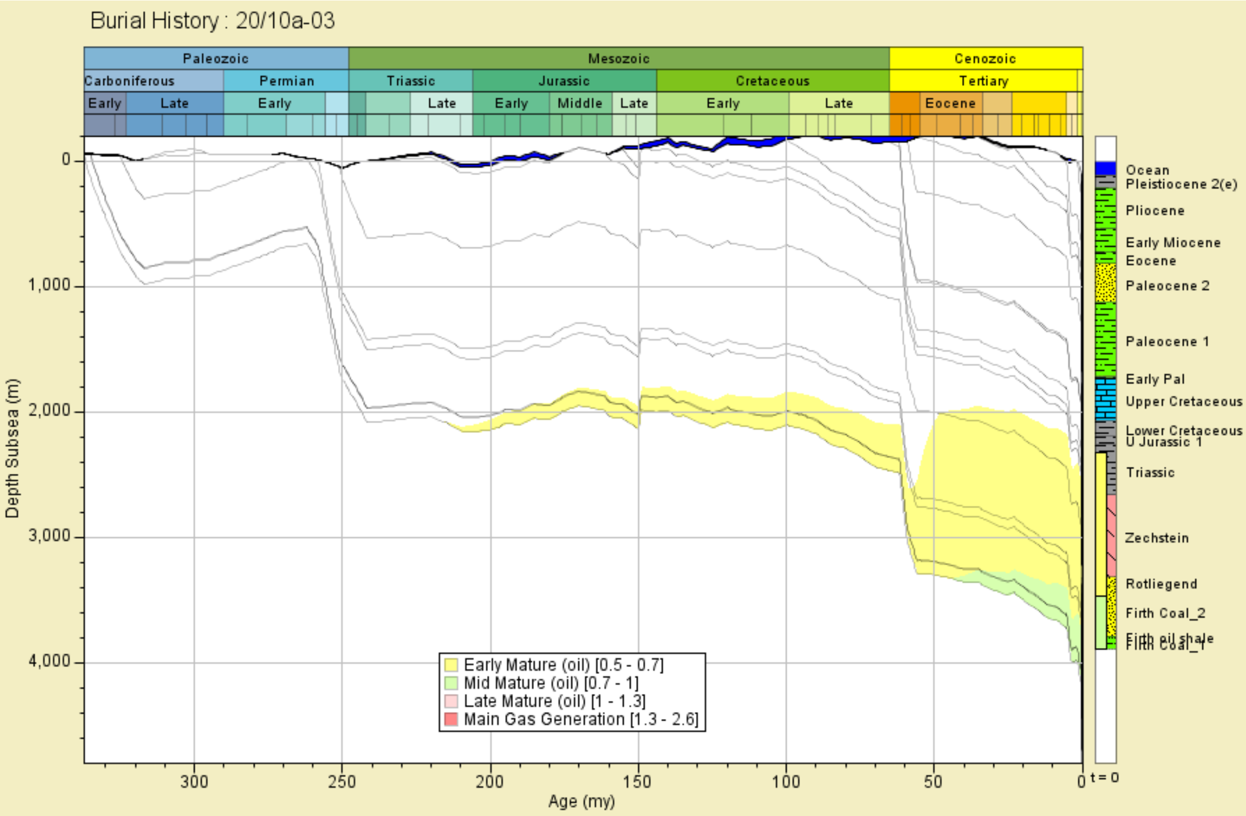


Figure 28: Modelled maturity geohistory for Well 20/10a- 3. The well terminates in the Firth Coal Formation and the base of the Firth Coal Formation is not penetrated.

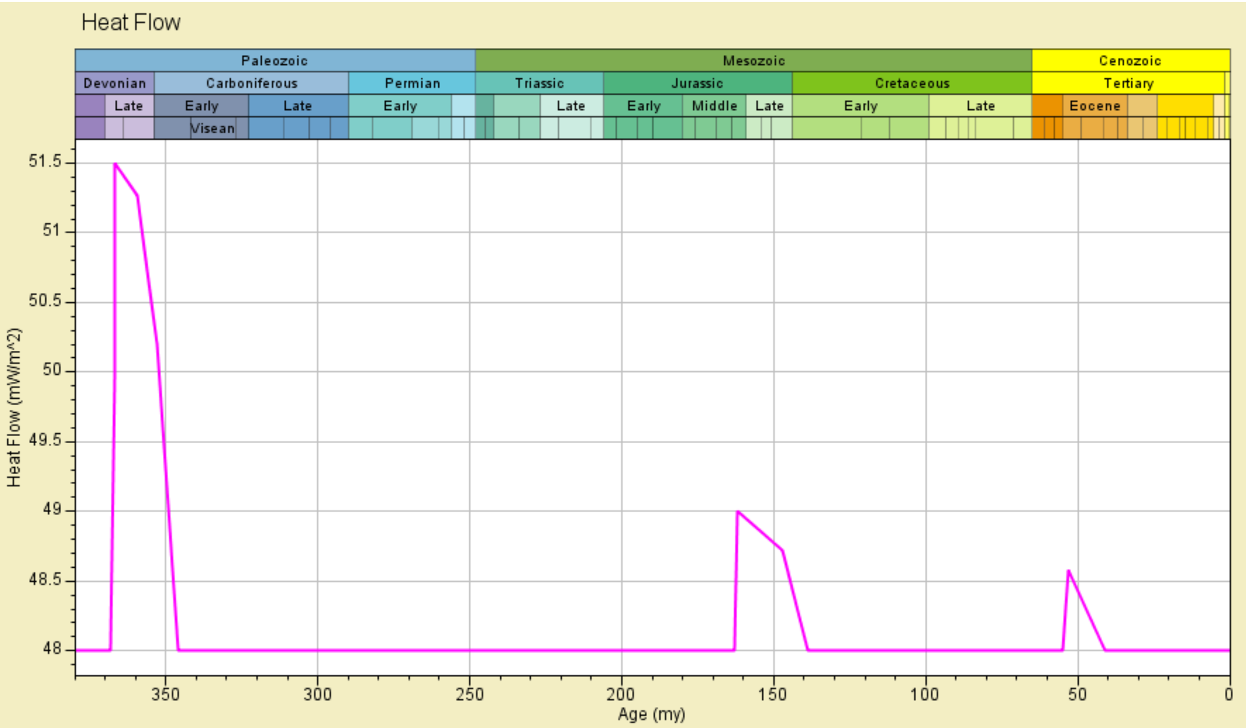


Figure 29: Modelled palaeo-heat flow for Well 20/10a- 3

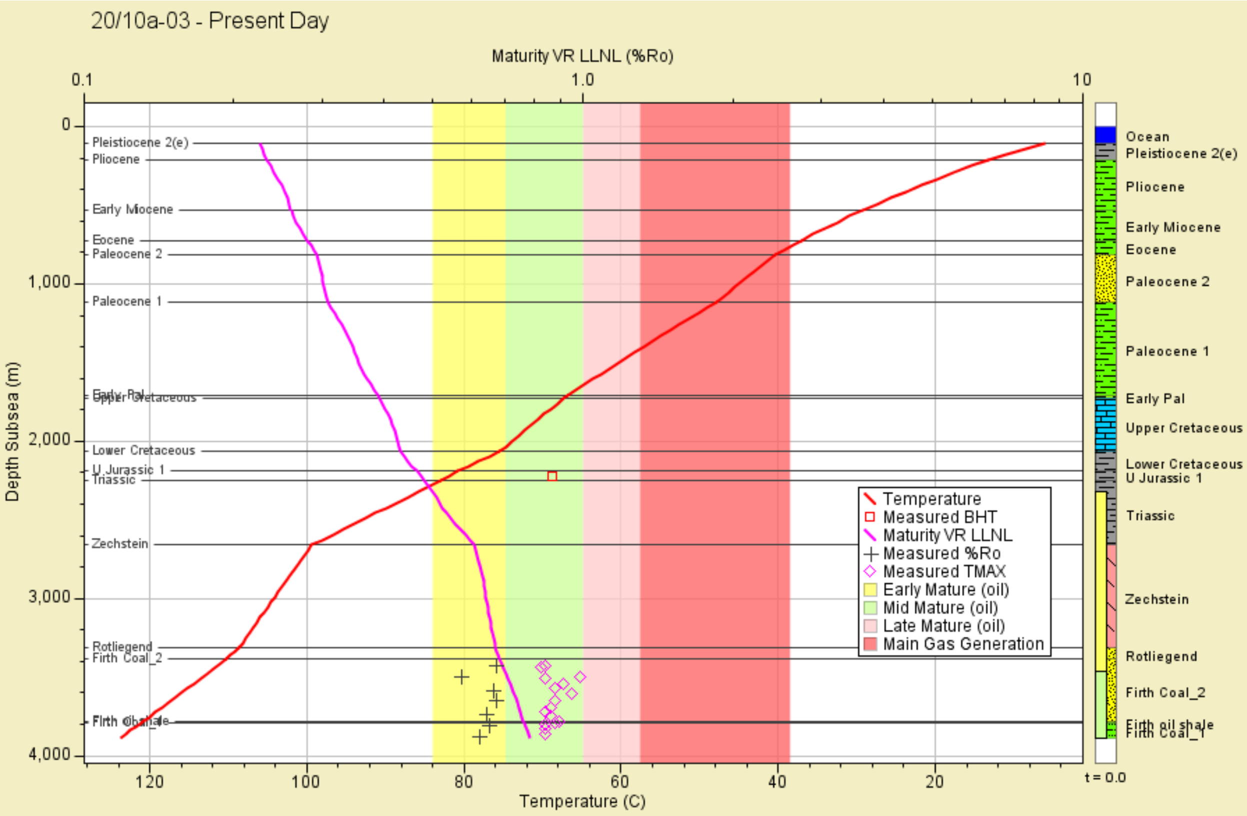


Figure 30: Depth plot for Well 20/10a- 3 showing model results, maturity data and maturity windows plus temperature data and model.

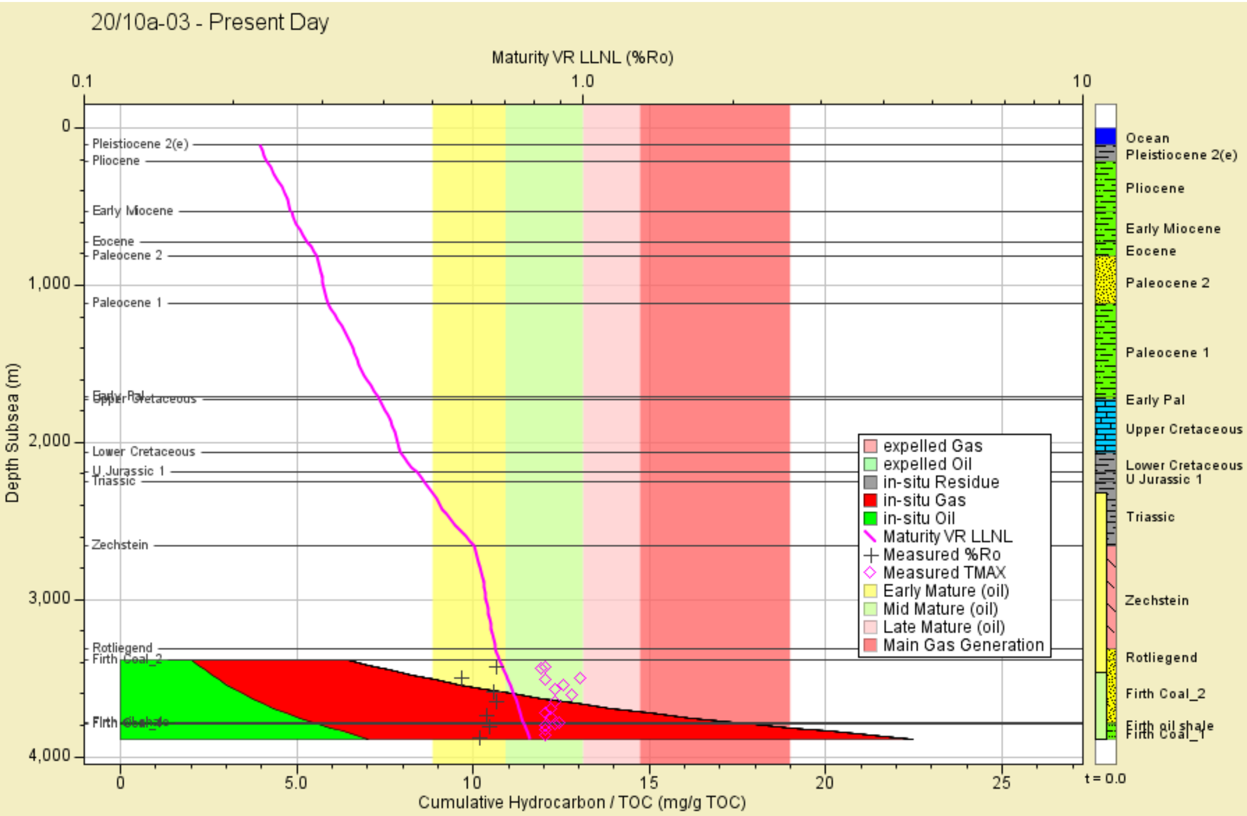


Figure 31: Depth plot for Well 20/10a- 3 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model.

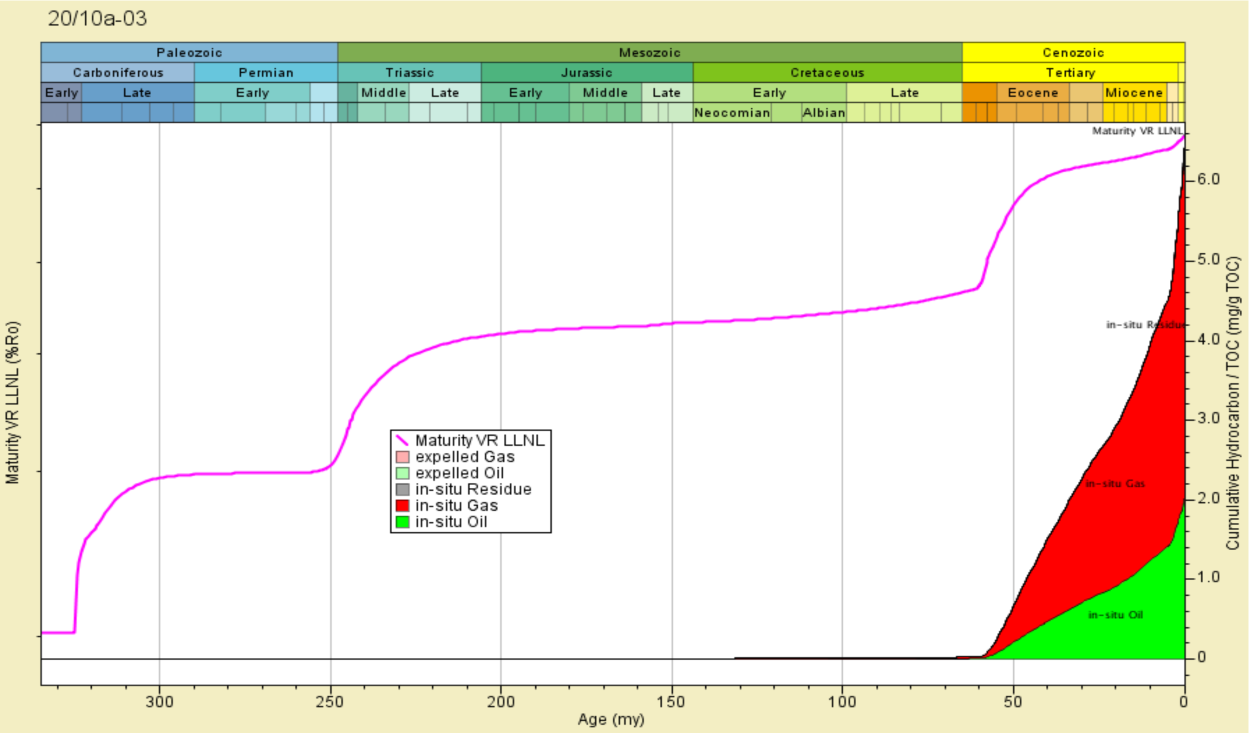


Figure 32: Time plot for Well 20/10a- 3 showing timing of generation for top of the upper part of the Firth Coal Formation through geological history. The current model suggests that main generation occurred during deepest burial during the Cenozoic Era.

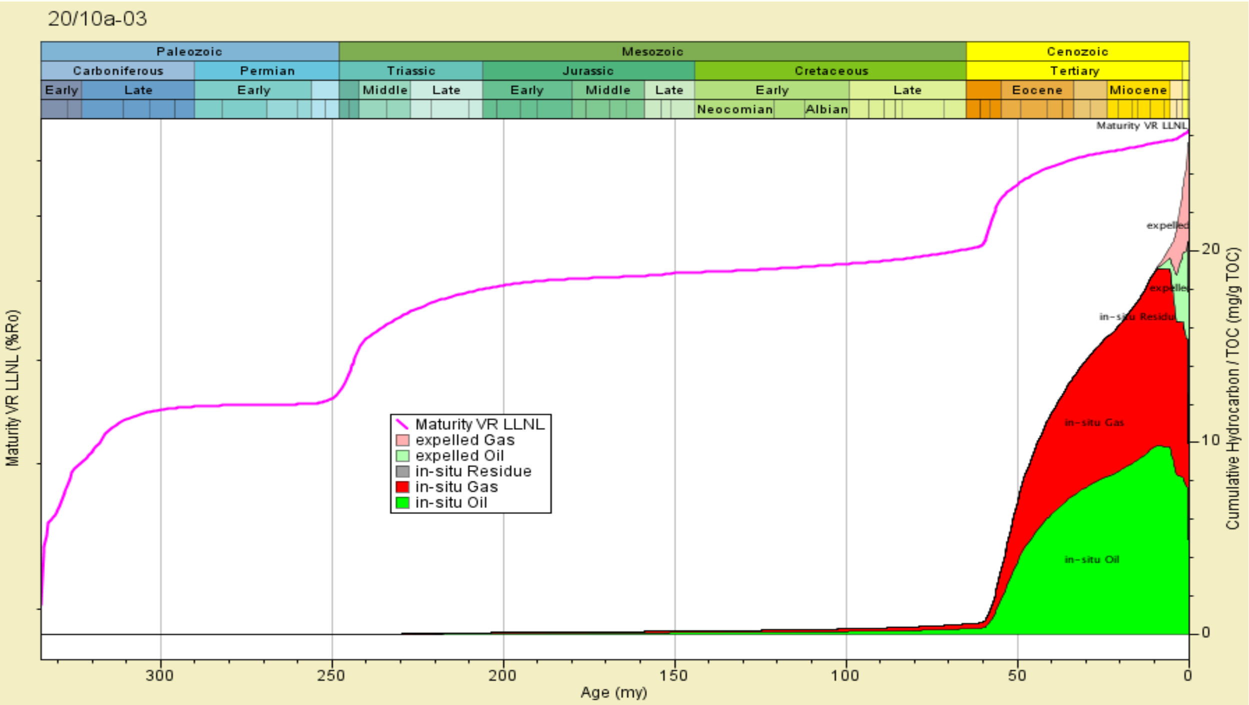
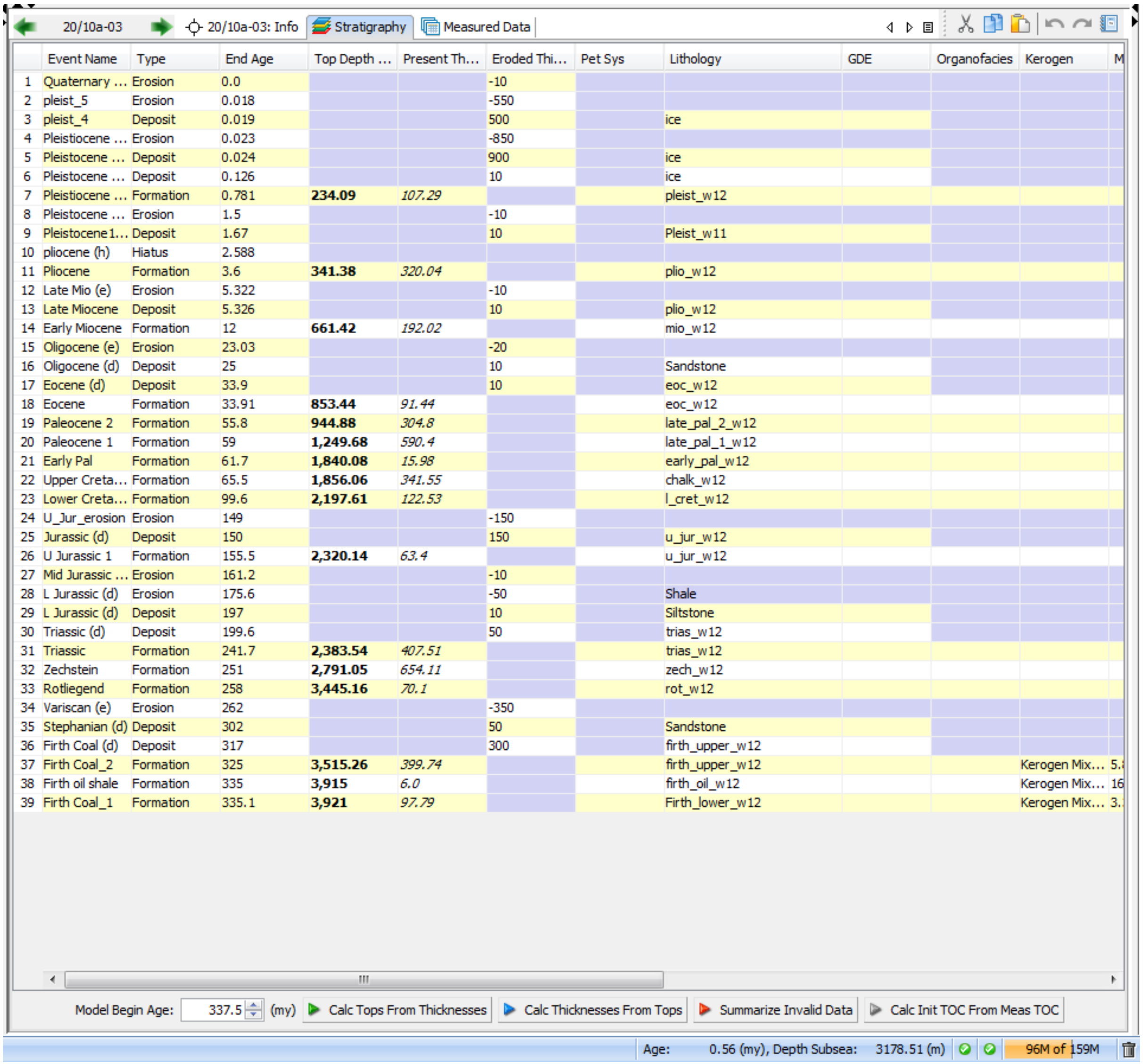


Figure 33: Time plot for Well 20/10a- 3 showing timing of generation for top of Firth Coal Formation (oil shale facies) through geological history of this formation. The current model suggests that main generation occurred during deepest burial during the Cenozoic Era.



	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	Pet Sys	Lithology	GDE	Organofacies	Kerogen	M
1	Quaternary ...	Erosion	0.0			-10						
2	pleist_5	Erosion	0.018			-550						
3	pleist_4	Deposit	0.019			500		ice				
4	Pleistiocene ...	Erosion	0.023			-850						
5	Pleistocene ...	Deposit	0.024			900		ice				
6	Pleistocene ...	Deposit	0.126			10		ice				
7	Pleistiocene ...	Formation	0.781	**234.09**	*107.29*			pleist_w12				
8	Pleistocene ...	Erosion	1.5			-10						
9	Pleistocene1...	Deposit	1.67			10		Pleist_w11				
10	pliocene (h)	Hiatus	2.588									
11	Pliocene	Formation	3.6	**341.38**	*320.04*			plio_w12				
12	Late Mio (e)	Erosion	5.322			-10						
13	Late Miocene	Deposit	5.326			10		plio_w12				
14	Early Miocene	Formation	12	**661.42**	*192.02*			mio_w12				
15	Oligocene (e)	Erosion	23.03			-20						
16	Oligocene (d)	Deposit	25			10		Sandstone				
17	Eocene (d)	Deposit	33.9			10		eoc_w12				
18	Eocene	Formation	33.91	**853.44**	*91.44*			eoc_w12				
19	Paleocene 2	Formation	55.8	**944.88**	*304.8*			late_pal_2_w12				
20	Paleocene 1	Formation	59	**1,249.68**	*590.4*			late_pal_1_w12				
21	Early Pal	Formation	61.7	**1,840.08**	*15.98*			early_pal_w12				
22	Upper Creta...	Formation	65.5	**1,856.06**	*341.55*			chalk_w12				
23	Lower Creta...	Formation	99.6	**2,197.61**	*122.53*			l_cret_w12				
24	U_Jur_erosion	Erosion	149			-150						
25	Jurassic (d)	Deposit	150			150		u_jur_w12				
26	U Jurassic 1	Formation	155.5	**2,320.14**	*63.4*			u_jur_w12				
27	Mid Jurassic ...	Erosion	161.2			-10						
28	L Jurassic (d)	Erosion	175.6			-50		Shale				
29	L Jurassic (d)	Deposit	197			10		Siltstone				
30	Triassic (d)	Deposit	199.6			50		trias_w12				
31	Triassic	Formation	241.7	**2,383.54**	*407.51*			trias_w12				
32	Zechstein	Formation	251	**2,791.05**	*654.11*			zech_w12				
33	Rotliegend	Formation	258	**3,445.16**	*70.1*			rot_w12				
34	Variscan (e)	Erosion	262			-350						
35	Stephanian (d)	Deposit	302			50		Sandstone				
36	Firth Coal (d)	Deposit	317			300		firth_upper_w12				
37	Firth Coal_2	Formation	325	**3,515.26**	*399.74*			firth_upper_w12			Kerogen Mix...	5.
38	Firth oil shale	Formation	335	**3,915**	*6.0*			firth_oil_w12			Kerogen Mix...	16
39	Firth Coal_1	Formation	335.1	**3,921**	*97.79*			Firth_lower_w12			Kerogen Mix...	3.

Figure 34: Model data entry sheet for Well 20/10a- 3. Top Depth is in m BRT

5.3.4 Key points from new model for Well 20/10a- 3

- The lower part of the Firth Coal Formation may have some oil prone intervals and generation may have occurred since these strata are in the early – mid oil maturity window
- The geological model indicates deepest burial and main generation (and expulsion) occurred during Cenozoic times

5.3.5 Scenario for Well 20/10a- 3

In addition to the basin model prepared in the previous section, a scenario with greater Mesozoic burial was prepared to estimate how much additional Mesozoic burial would be required for the Firth Coal Formation to reach the gas window.

Additional strata were added to the Triassic, Lower and Upper Jurassic model layers as it is expected that in more basinward wells the thickness of the post-Palaeozoic sequence would be much greater but the Palaeozoic strata would have a similar thickness (A A Monaghan, pers. comm.) in order to assess if more basinal wells with deeper burial might have reached the gas maturity window (The top depth to the Upper Jurassic in the well was removed to allow the model to run). An additional 2.8 km of post-Palaeozoic strata was required for this well to reach the gas window.

5.4 SCENARIO WELL 21/06B- 5

Well 21/06b- 5 is located east and basinwards of 20/10a- 3. This well terminates in Triassic strata and no maturity data are available. The well is slightly deviated in the Balder and Smith Bank formations.

As sufficient data to prepare a Palaeozoic maturity model are not available, this well was used as a 'scenario well' to assess if the South Buchan Basin could be mature for hydrocarbon generation from a Palaeozoic source rock if the same Firth Coal Formation source interval as in 20/10a- 3 were more deeply buried.

5.4.1 Previous maturity and modelling work

No shows are recorded and no fluorescence is reported in the final well report (Amerada Hess Ltd, 1999). The well does not reach Palaeozoic strata.

5.4.2 New scenario modelling work

Available maturity and porosity data

No maturity or porosity data were available for this study for Well 21/06b- 5. Uncorrected temperature data were available from Amerada Hess Limited (1999).

Scenario model input

As the well does not penetrate to the Carboniferous strata, depths to stratigraphical tops below TD were estimated from seismic interpretation (line offset 100 m to south west from well; Arsenikos et al., 2016 and M F Quinn, pers comm.). Kerogen data from Well 20/10a- 3 that lies 12 km to the west were used for the Firth Coal Formation.

The following additional stratigraphy was added to the model to extend the well downwards for the scenario:

- Additional preserved Triassic strata below TD (90 m)
- Zechstein strata (980 m) (1.5 times the thickness in Well 20/10a-03)
- Rotliegend Group (100 m, c.f. 67 m in Well 20/10a-03)
- Eroded Palaeozoic strata (350 m, same as Well 20/10a-03)
- Firth Coal Formation (420 m, c.f. 402 m in Well 20/10a-03)
- Firth Coal Formation, oil shale facies (10 m, c.f. 6 m in Well 20/10a-03)
- Firth Coal Formation (110 m, c.f. 104 m in Well 20/10a-03)

Model calibration

There were no maturity data available to this study for model calibration. The maturity geohistory for this scenario well is shown in Figure 35. The palaeo-heat flow (Figure 36) is based on Well 20/10a- 3. The model results are shown in Figure 37. The model data entry sheet is shown in Figure 40.

Model maturity and hydrocarbon generation

The model indicates that the Firth Coal Formation would just reaches the gas window during late Cenozoic times (Figure 38, Figure 39). If the Firth Coal Formation is gas prone (as in Well

20/10a- 3), then gas generation would be expected. However, no gas shows are recorded in the post Palaeozoic strata so if generated, the gas has not migrated into this part of the section.

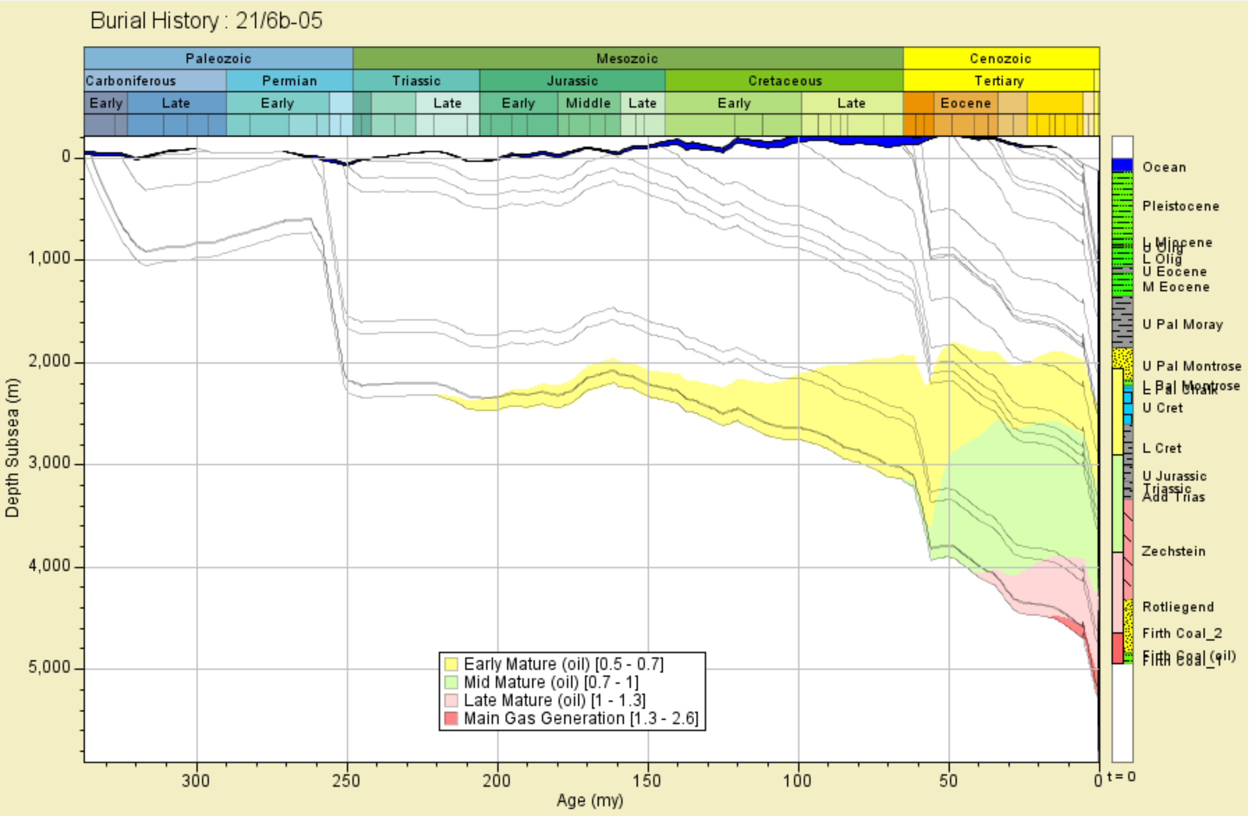


Figure 35: Modelled maturity geohistory for Well 21/06b- 5. The modelled 'scenario' well terminates in the Firth Coal Formation. The base of the Firth Coal Formation is not penetrated.

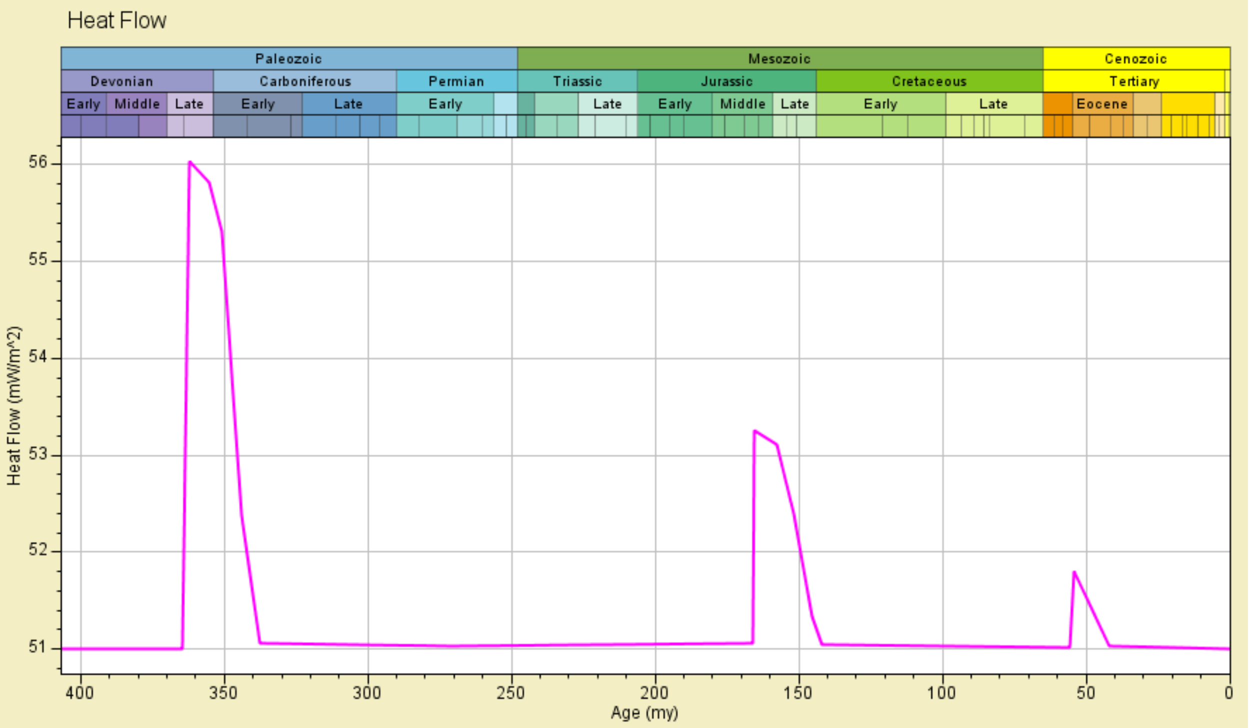


Figure 36: Modelled palaeo-heat flow for Well 21/06b- 5.

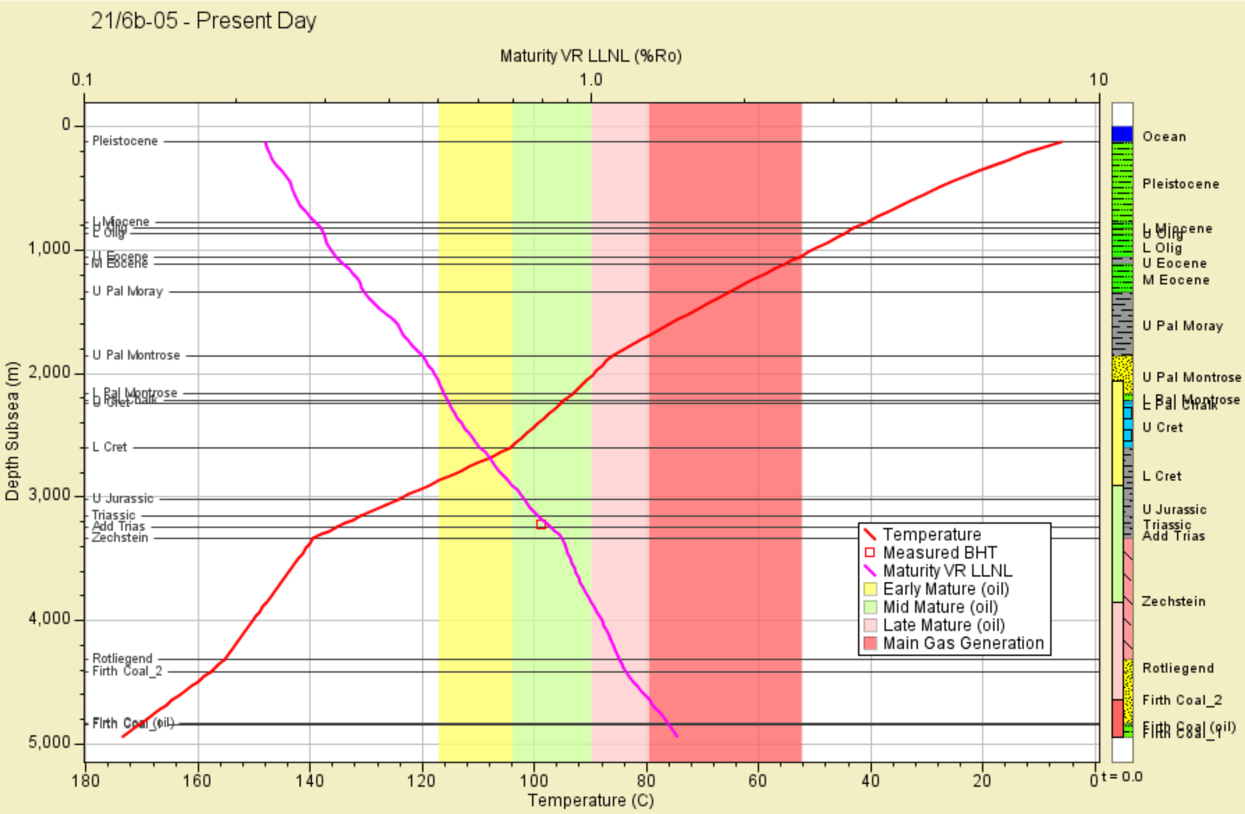


Figure 37: Depth plot for Well 21/06b- 5 showing model results.

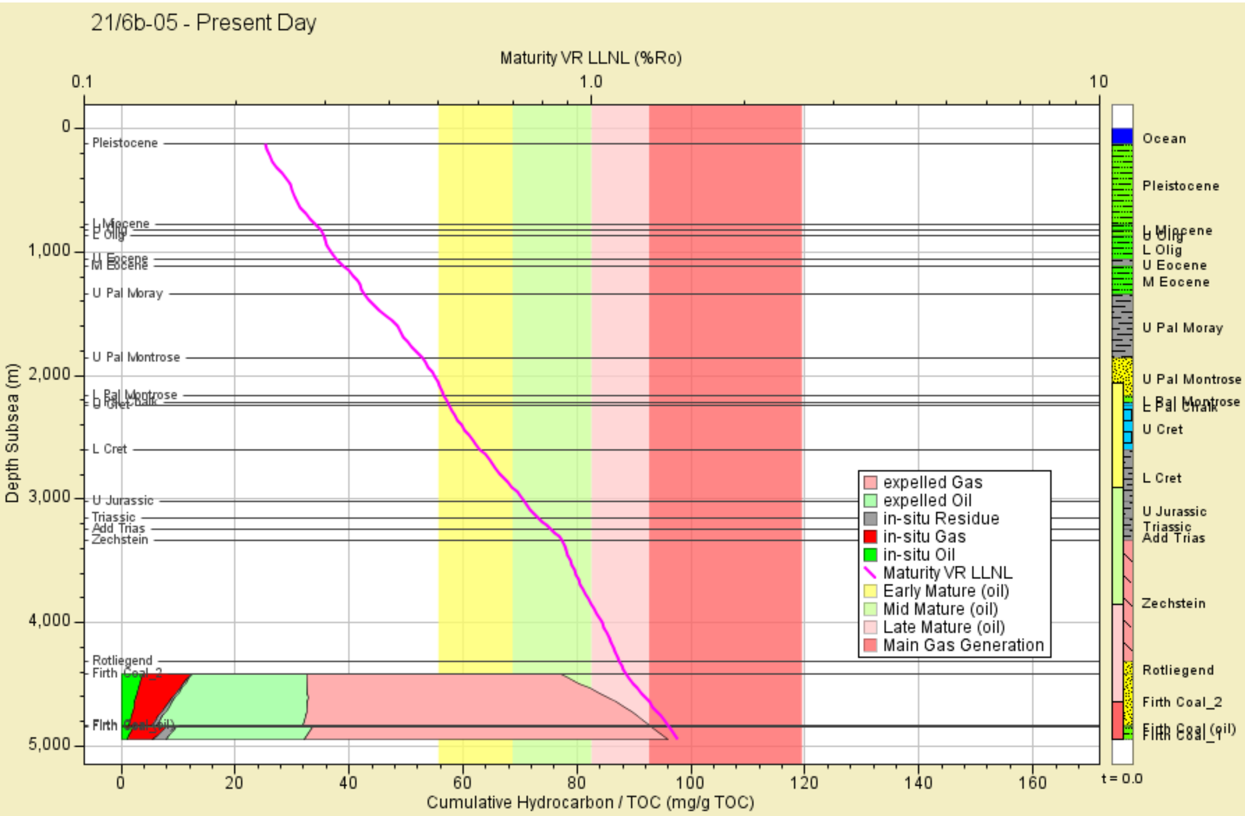


Figure 38: Depth plot for Well 21/06b- 5 showing generation potential for stratigraphic units in the well where kerogen data have been entered into the model (kerogen data taken from Well 20/10a- 3).

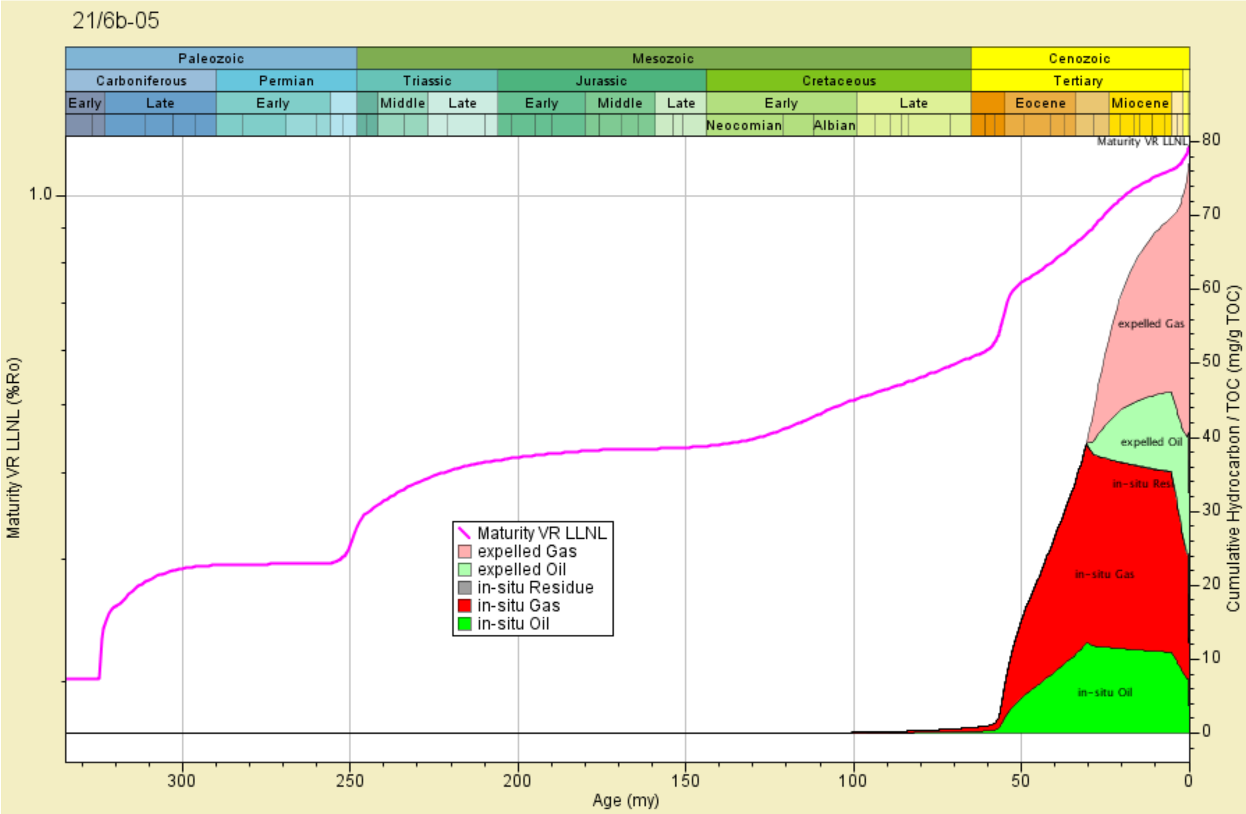


Figure 39: Time plot for Well 21/06b- 5 showing timing of generation for top of Firth Coal Formation through geological history of this formation (using kerogen data taken from Well 20/10a- 3). The current scenario model suggests that main generation occurred during deepest burial during the Cenozoic Era.

21/6b-05 | 21/6b-05: Info | Stratigraphy | Measured Data

	Event Name	Type	End Age	Top Depth ...	Present Th...	Eroded Thi...	Pet Sys	Lithology	GDE	Organofacies	Kerogen	M
1	Quaternary	Erosion	0.0			-10						
2	pleist_5	Erosion	0.018			-600						
3	pleist_4	Deposit	0.019			500		ice				
4	Pleistiocene ...	Erosion	0.023			-850						
5	Pleistocene ...	Deposit	0.024			950		ice				
6	Pleist 3	Deposit	0.126			10		Tert_w13				
7	Pleistocene	Formation	0.781	**148.74**	*649.84*			Tert_w13				
8	U Mio (e)	Erosion	5.322			-50						
9	U Mio	Deposit	5.326			50		Tert_w13				
10	L Miocene	Formation	12	**798.58**	*54.86*			L_Mio_w13				
11	U Olig	Formation	23.03	**853.44**	*36.57*			U_Olig_w13				
12	L Olig	Formation	28.4	**890.01**	*192.03*			L_OLig_w13				
13	U Eocene	Formation	33.9	**1,082.04**	*54.86*			U_Eoc_w13				
14	M Eocene	Formation	37.2	**1,136.9**	*231.65*			M_Eoc_w13				
15	L Eocene	Hiatus	48.6									
16	U Pal Moray	Formation	55.8	**1,368.55**	*512.98*			Moray_w13				
17	U Pal Montrose	Formation	59	**1,881.53**	*309.98*			UPal_Mont_w13				
18	L Pal Montrose	Formation	61.7	**2,191.51**	*57.91*			LPal_Mont_w13				
19	L Pal Chalk	Formation	65	**2,249.42**	*20.12*			LPal_chalk_w13				
20	U Cret	Formation	65.5	**2,269.54**	*355.7*			CHalk_w13				
21	L Cret	Formation	99.6	**2,625.24**	*414.23*			L_Cret_w13				
22	U Jurassic	Formation	145.5	**3,039.47**	*142.11*			U_Jur_w13				
23	M Jurassic	Erosion	161.2			-210						
24	L Jurassic	Deposit	175.6			10		Shale				
25	Triassic (d)	Deposit	199.6			200		Trias_w13				
26	Triassic	Formation	245	**3,181.58**	*89.84*			Trias_w13				
27	Add Trias	Formation	249.7	**3,271.42**	*88.58*			Trias_w13				
28	Zechstein	Formation	251	**3,360**	*980*			zech_w12				
29	Rotliegend	Formation	258	**4,340**	*100*			rot_w12				
30	Variscan (e)	Erosion	262			-350						
31	Stephanian	Deposit	302			50		Sandstone				
32	Firth Coal (d)	Deposit	317			300		firth_upper_w12				
33	Firth Coal_2	Formation	325	**4,440**	*420*			firth_upper_w12			Kerogen Mix...	5.
34	Firth Coal (oil)	Formation	335	**4,860**	*10*			firth_oil_w12			Kerogen Mix...	16
35	Firth Coal_1	Formation	335.1	**4,870**	**100**			Firth_lower_w12			Kerogen Mix...	3.

Model Begin Age: 337.5 (my) | Calc Tops From Thicknesses | Calc Thicknesses From Tops | Summarize Invalid Data | Calc Init TOC From Meas TOC

Age: 312.04 (my), Depth Subsea: 5848.68 (m) | 118M of 186M

Figure 40: Model data entry sheet for Well 21/06b- 5. Top Depth is in m BRT. All formation tops from 'Add Trias' downwards have been estimated based on seismic interpretation

5.4.3 Key points from new modelling work for Scenario Well 21/06b- 5

- This well was chosen to examine burial of Carboniferous source rocks deeper into a basin. The well terminates in the Triassic strata and depths to key underlying horizons were estimated.
- The Firth Coal Formation is modelled as at least oil and possibly gas mature at this location. If the organic matter content is similar to Well 20/10a- 3 (i.e. similar TOC and mainly gas prone kerogens) then gas generation would be expected.
- The current model suggests that main generation occurred during deep Cenozoic burial.

5.5 SOUTH BUCHAN BASIN MATURITY

Well 20/10a -3 was modelled as a reasonable number of maturity data, TOC and source rock data are available. As Well 20/10a- 3 lies on a relative high, a scenario to test how much additional Mesozoic burial would be required for the Firth Coal Formation to reach the gas window, and scenario Well 21/06b- 5 were modelled. Both scenarios indicated that a considerable thickness of Mesozoic strata (of the order of 1.3 - 2.8 km) would be required for the lower part of the Firth Coal Formation to reach the gas window.

In the depocentre of the South Buchan Basin, the thickness of Mesozoic strata is likely to be even greater than modelled in the two scenario wells, such that the Firth Coal Formation would be expected to have reached the gas maturity window.

Essentially, both modelled wells suggest that around 4 km of burial is required to reach the gas window in the South Buchan Basin. This relies on the assumption that the heat flow is as low at the location of Well 21/06b- 5 as it is on the topographic high where 20/10a- 3 is located. It is possible that the heat flow within the basin will be higher if the crust is thinned. In that case the gas maturity window would be reached at a shallower depth within the depocentre than predicted here, i.e. it is possible that Firth Coal Formation is more mature at the location of Well 21/06b- 5 than indicated by the current scenario model.

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.

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. (2016) 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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