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Maturity modelling of well 110/07b- 6

Energy and Marine Geoscience Programme

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Foreword and acknowledgements

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

Malcolm Gall (OGA) is thanked for technical review of this report.

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Summary

This report details one-dimensional (1D) maturity modelling of well 110/07b- 6 in the Carboniferous rocks of the UK Irish Sea for the 21CXRM Palaeozoic project. The aim of the maturity modelling was to predict when the source rock reached the oil and gas maturity windows, and predict the timing of generation of potential hydrocarbons.

Unravelling the burial and thermal history of the Irish Sea has entertained geologists for over 25 years and been subject to numerous studies (e.g. Cowan et al., 1999; Quirk et al., 1999; and references therein). This study specifically focusses on the 1D burial and thermal modelling of well 110/07b- 6 in the East Irish Sea area using BasinMod™ (Platte River Associates software). The regional Palaeozoic stratigraphy is described in Wakefield et al. (2016), the regional source rock geochemistry from legacy well reports is described in Vane et al. (2016) and the regional petroleum system analysis in Pharaoh et al. (2016b).

Well 110/07b- 6 was chosen from a restricted number of potential wells as it contained the most comprehensive collection of geochemical data collected from released legacy well reports. The modelled maturity curve with depth was matched to best fit both measured maturity data (vitrinite reflectance) and calculated maturity data (calculated from RockEval T_{max} values).

A Variscan uplift of 700 m was modelled, as well as a 150 m Cimmerian uplift event and a two-stage Cenozoic uplift of 650 m in the Palaeocene and 450 m from the Eocene to recent. The uplift amount falls to the lower end of the published 1-3 km Cenozoic uplift estimates, and was modelled with a base heat flow of 50 mWm^{-2} increasing to a 70 mWm^{-2} peak during the Palaeocene.

Deepest burial was reached in the early Cenozoic and the base of the drilled section of Bowland Shale Formation reached main gas generation (base of formation not reached). Main oil and gas generation for the Millstone Grit Group occurred equally in the Jurassic, Cretaceous and early Cenozoic. Oil and gas generation for the Bowland Shale Group occurred mainly in the late Mesozoic and early Cenozoic, with minor oil generation also in the Late Carboniferous. Both the Millstone Grit Group and Bowland Shale Formation in this well have fair source potential remaining.

The use of one well for a regional scale study has its obvious limitations. The well chosen is fairly representative of the southern area of the East Irish Sea Basin (EISB) hydrocarbon province, south of the large Morecambe fields and near to the recently discovered Conwy Field (Figure 1). For a more complete understanding of the Solway and Peel-Manx basins to the north-west and Quadrant 109 (Figures 1, 3), geochemical sampling of well cuttings and/or core would be required.

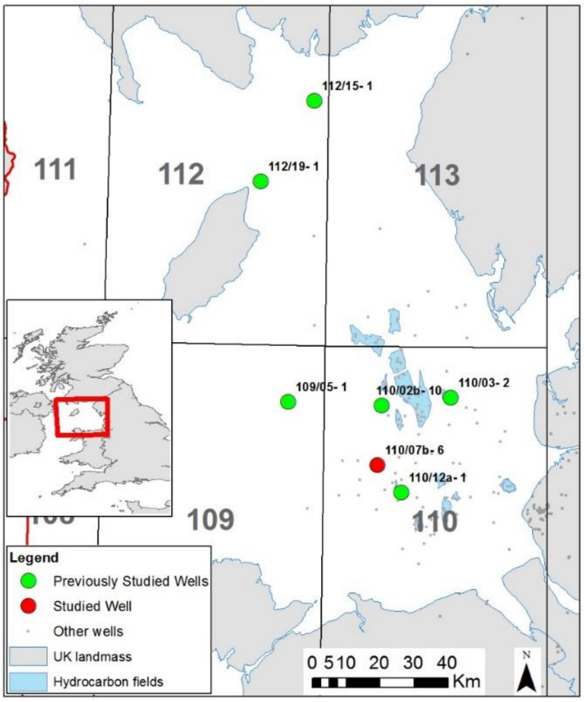


Figure 1 Map of well locations for the studied well and previously studied wells mentioned in this report.

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 110/7b- 6 in the East Irish Sea (EIS) area. The aim of the modelling was to confirm the Carboniferous source rocks have been mature and more critically the timing of burial and potential hydrocarbon generation. For the area studied, other reports have been extensively referenced to give a more complete understanding of the complexity when modelling the burial and thermal history of the EIS, than can be represented from study of one well. The well data and geochemical reports used for the modelling of this well have been extracted from CDA released reports.

The stratigraphy of the area is given in Wakefield et al. (2016; see also Figure 2, Figure 3), the source rock geochemistry data is shown in Vane et al. (2016), and the basin modelling work is incorporated into the petroleum systems analysis of Pharaoh et al. (2016b).

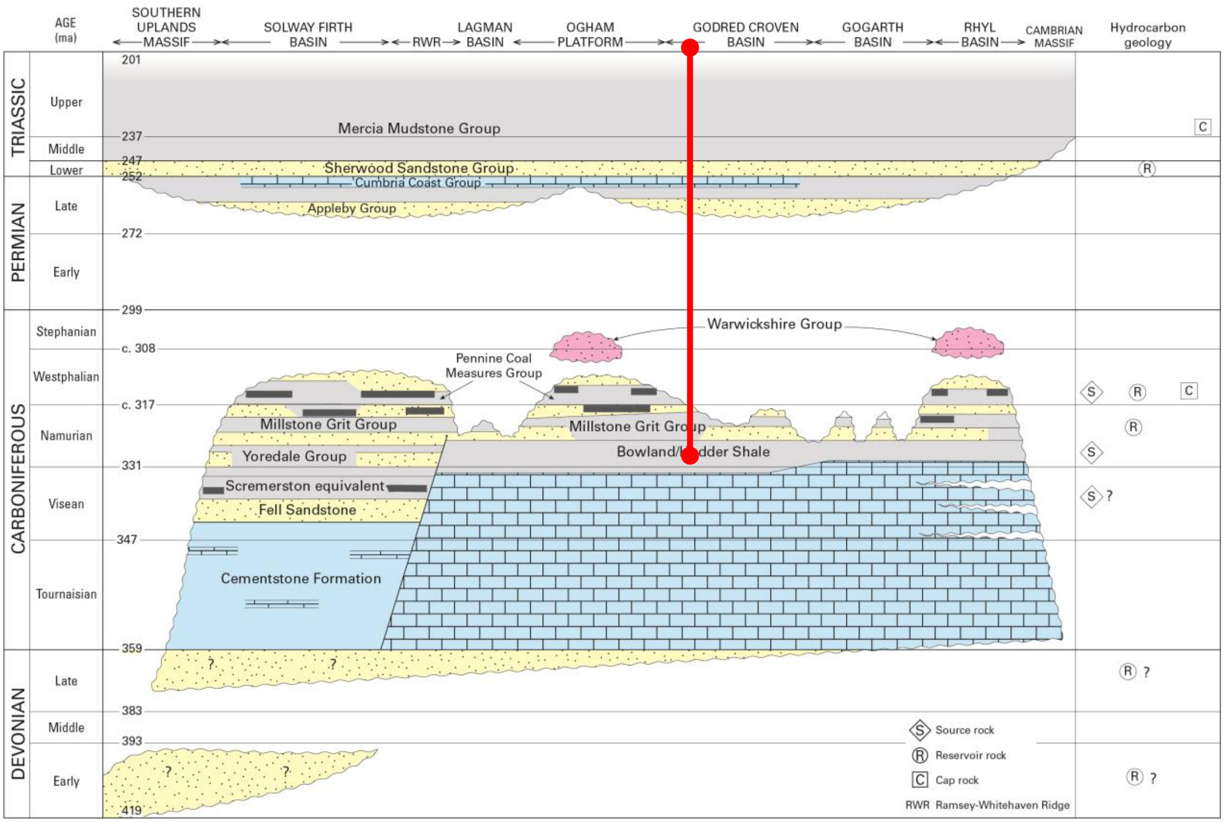


Figure 2 Synoptic diagram of the hydrocarbon system of the Irish Sea basins, showing principal source rocks, reservoirs and seals. Red line denotes approximate location of well 110/07b- 6.

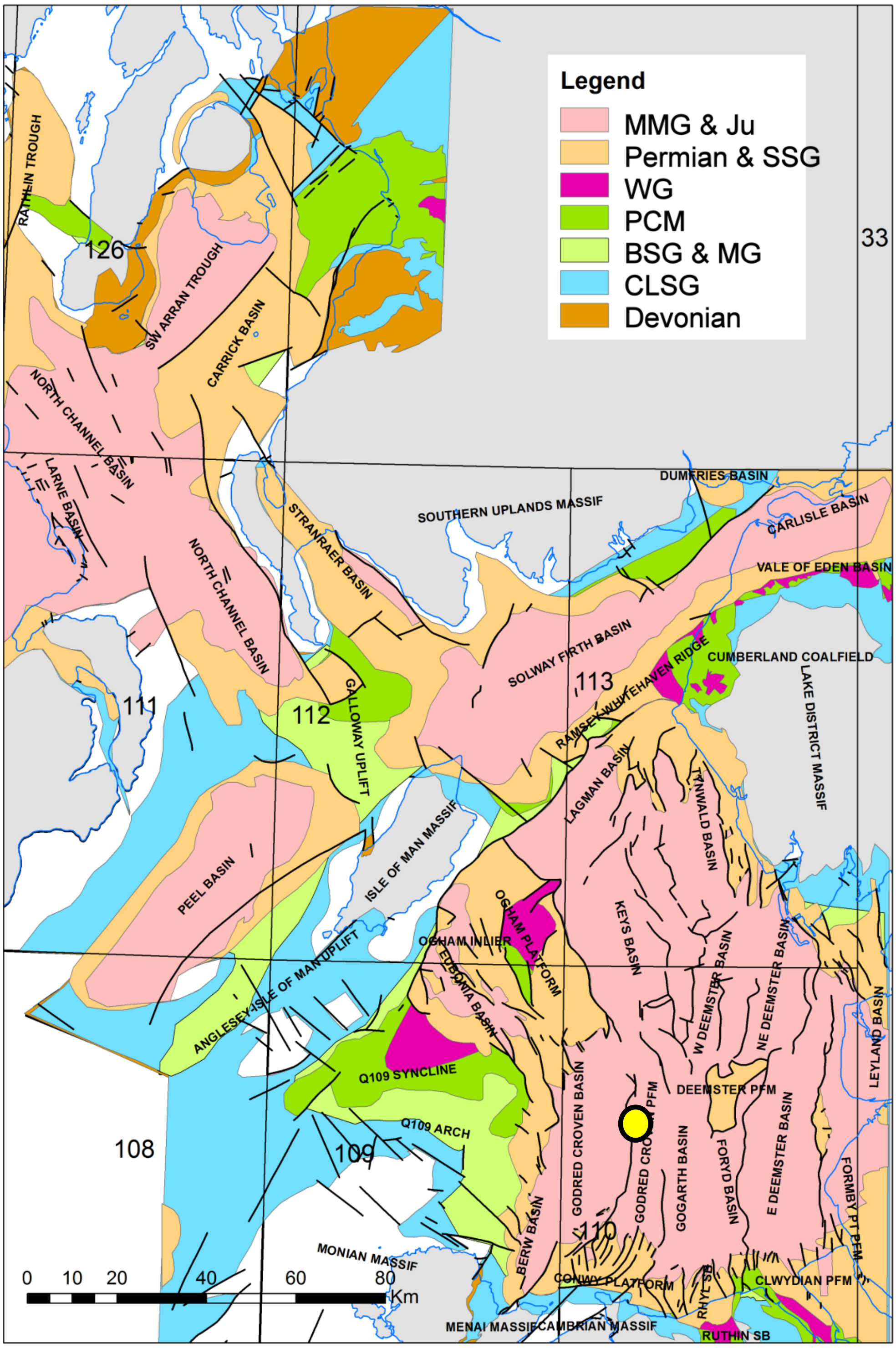


Figure 3 Pre-Quaternary subcrop map with named tectonic elements. Yellow marker is location of well 110/07b- 6. Key to geology: Ju, Jurassic; MMG, Mercia Mudstone Group; SSG, Sherwood Sandstone Group; WG, Warwickshire Group; PCM, Pennine Coal Measures; MG, Millstone Grit Group; BSG, Bowland Shale Formation; CLSG, Carboniferous Limestone Supergroup.

2 Methodology

Source rock organic geochemical data available for the Irish Sea study area was limited, consequentially there was a small selection of wells with suitable data sets to undertake thermal and burial/uplift modelling. Well 110/07b- 6 had the most comprehensive coverage of Rock-Eval, total organic carbon (TOC) and maturity (Vitrinite Reflectance=VR) data over the Carboniferous interval of interest.

The overall aims of this modelling were:

- To model thermal and burial/uplift history of a well for which no previous published results have been found.
- To predict when the onset of oil and gas generation occurred
- To compare the well history to other 1D models in the EIS

The 1D model was calculated using BasinMod™ (Platte River Associates software). Well stratigraphy and rock properties were entered to model compaction and temperature through time. Estimations of thickness, properties of eroded units, the amount of erosion and palaeo-heat flow all influence the modelled maturity and are used to calibrate the model to best match the measured VR values. Vitrinite reflectance data was derived from both measured values and converted from RockEval-derived T_{max}, all of which were sourced from the wells' geochemical report (Geochem Laboratories Limited, 1988). There are limitations in using VR_{calc} from T_{max} for non-Type II kerogens (discussed further in Vane et al., 2015) such that measured VR is used preferentially.

Plots of maturity vs depth and vs time were produced as well as a plot of heat flow vs time. The maturity windows follow commonly used vitrinite reflectance ranges (Kubala et al., 2003) (Table 1)

Maturity window	**Vitrinite Reflectance Range (VR, %)**
Early Oil	0.5 - 0.7
Mid Oil	0.7 - 1.0
Late Oil	1.0 - 1.3
Main Gas	1.3 - 3.0

Table 1: Typical maturity windows used for basin modelling.

A number of supporting reports produced by the 21CXRM Palaeozoic project team provided additional input to the modelling:

- Timing of Carboniferous deposition and Carboniferous onshore history overview provided by stratigraphers (Wakefield et al., 2016)
- Seismic interpretations to assess erosional unconformities indicating the thickness of material removed (Pharaoh et al., 2016a)
- Tectonic history of the Irish Sea to assess if uplift amounts are reasonable (Pharaoh et al., 2016a, T. Pharaoh *pers. comm.*)

3 Previous modelling work in this region

Defining the post-Triassic geological history of the EIS is complicated by the almost complete lack of a post-Triassic succession. Apatite fission track analysis (ATFA) can be used to determine the thermal history of a rock. However there are temperature limitations which means above 125^{o}C the thermal indicator is completely reset (Giles and Indrelid, 1998). In the EIS this usually means the AFTA only records the Cenozoic to recent history (Green et al., 1997). There have been many studies to try to constrain the complex basin history of the Irish Sea area, especially the significant amount of Cenozoic uplift and change in paleo-heat flow associated with the uplift event (Cowan et al., 1999; Quirk et al., 1999) (Figure 4) (Table 2).

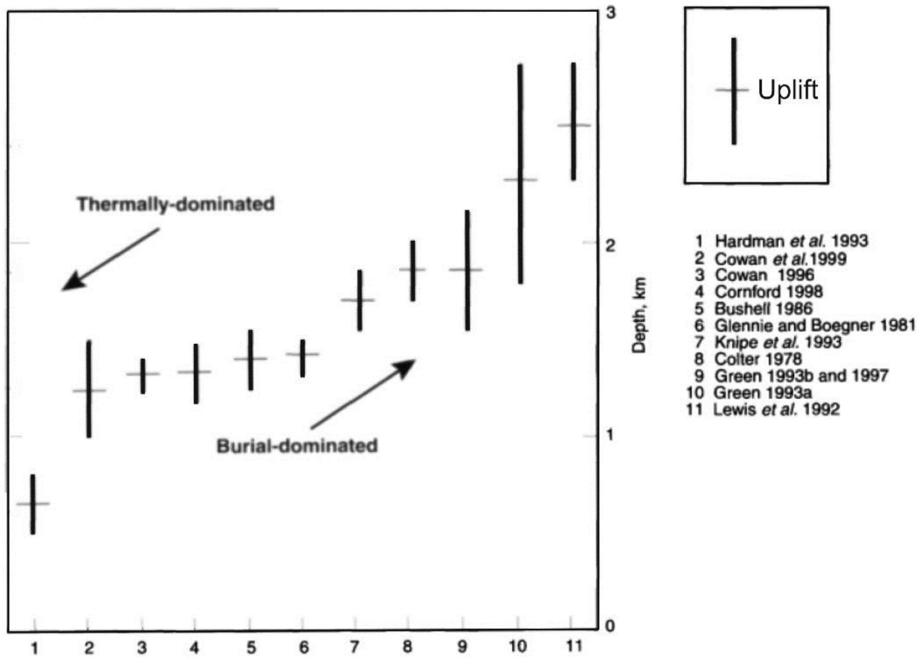


Figure 4 Estimates of Cenozoic uplift in the East Irish Sea from published literature, ranging from <1 km to between 2 – 3 km. (From Cowan et al., 1999).

An uplift-dominated hypothesis is favoured with studies citing the onshore evidence (Chadwick et al., 1993), extension amounts (Rowley and White, 1998), density logs (Colter, 1978; Bushell, 1986) or using AFTA with a constant geothermal gradient (Green et al., 1993a, 1993b, 1997; Lewis et al., 1992). Conversely, increased palaeo-heat flow and more minor uplift can also explain the Cenozoic hydrocarbon production (Hardman et al., 1993; Cowan, 1996; Cowan et al., 1999). Some authors have postulated a mixed system with raised palaeo-heat flow and uplift (Knipe et al., 1993).

Most authors postulate a Cimmerian uplift event, despite a lack of any evidence as all AFTA data has been reset (>125^{o}C) in the Cenozoic (Giles and Indrelid, 1998). Reconstructing the post-Triassic sequence relies heavily on interpretation from the adjacent Jurassic onshore in the Carlisle and Cheshire basins, and Early Jurassic sedimentation of the Keys Basin (Jackson and Mullholland, 1993, see Figure 3). The post-Cimmerian Cretaceous sedimentation is also unknown, however, it has been strongly suggested that the Chalk Group was deposited across the much of the British Isles including the EIS. Remnant chalk and flints are also preserved underneath the nearby onshore Northern Irish Cenozoic volcanic rocks (Wilson, 1981; Ziegler, 1990; Jackson et al., 1995).

The other unknown when modelling the EIS is the amount of Carboniferous stratigraphy removed by the Variscan Orogeny. Seismic interpretation has suggested up to 5 km of deposition and therefore significant burial has occurred in some of the sub-basins (Pharaoh et al., 2016a). For these sub-basins, burial to this depth with a typical geothermal gradient would have produced hydrocarbons before Variscan Orogeny, if suitable source rocks were present. On highs and slopes the Carboniferous succession may have reached much lower maturities before the regional uplift and erosion.

Table 2 Thickness of eroded section based on published 1D burial and thermal history plots. (See Appendix 2 for schematic plots)

Well	Variscan Uplift	Cimmerian Uplift	Palaeocene Uplift	Eocene – Recent Uplift	Deepest Burial	Comments	Ref
109/05- 1	4700m	2000m	1000m	500m	Late Carboniferous		Geotrack International, 1997
110/02b- 10	800m	-	700m	600m	Early Cenozoic	Cenozoic uplift rate linear	Vincent and Andrews, 2013
110/03- 2	500m	1200m	800m	600m	Mid-Cretaceous	Eocene-Miocene 600m subsidence	Integrated Geochemical Interpretation, [unknown]
110/07b- 6	700m	150m	650m	450m	Early Cenozoic		This study
110/12a- 1	600m	200m	900m	100m	Early Cenozoic		Floodpage et al., 2001
112/15- 1	3000m	1000m	1500m	500m	Early Cenozoic		Geotrack International, 1997
112/19- 1	1000m	500m	400m	850m	Early Cretaceous	Cenozoic uplift rate linear	Newman, 1999

4 Previous geochemical work for well 110/07b- 6

The original well geochemical report (Geochem Laboratories Limited, 1988) evaluated 975 m of the Carboniferous section with sample sources including 63 ditch cuttings, 30 sidewall core and 2 formation water samples. No whole rock core was collected in the Palaeozoic interval. Analysis undertaken on the samples included:

- 133 total organic carbon tests (TOC)
- 31 pyrolysis datasets
- 9 vitrinite reflectance measurements
- 12 kerogen type and spore colouration determinations

The report splits the 1510 m – 2485 m interval into four zones based on changes in geochemical characteristics (Table 3).

Zone	Depth (m)	Strat	Lithology	TOC (wt %)	Maturity (see Table 1)	Kerogen Type	Pyrolysate (mg/g)	Shows
A	1510-1675	Millstone Grit Group	Red mudstone/sandstone overlaying black mudstone	0-3.66	Mid-Late Mature for oil	I – 0% II – 5% III – 25% IV– 70%	3.16-6.06	Waxy crude oil (1585-1600m) [Common oil source to shows in 110/07-2, 110/08-3 and Formby]
B	1675-1950		Black/dark grey mudstone	0.9-5.26	Mid-Late Mature for oil		<3	Weak shows of light oil (1645-1860m)
C	1950-2100		Mudstone, shales, evaporates and limestones	1.16-2.98	Late Mature for oil	I – 2% II – 10% III – 28% IV– 60%	<1.95	None noted
D	2100-2485	Bowland Shale Formation	Interbedded grey mudstone and grey limestone	1.85-7.24	Late Mature for oil / Main Gas		<1.1	Weak shows of light oil (2103-2118m) Intermittent traces of condensate (2225-2484m)

Table 3 A summary of well 110/07b- 6 geochemical report for the 4 zones in the drilled Carboniferous section. (Geochem Laboratories Limited, 1988).

There was no maturity data available for the post Carboniferous sequence, this means there is no geochemical control points to help constrain the Mesozoic and Cenozoic uplift events.

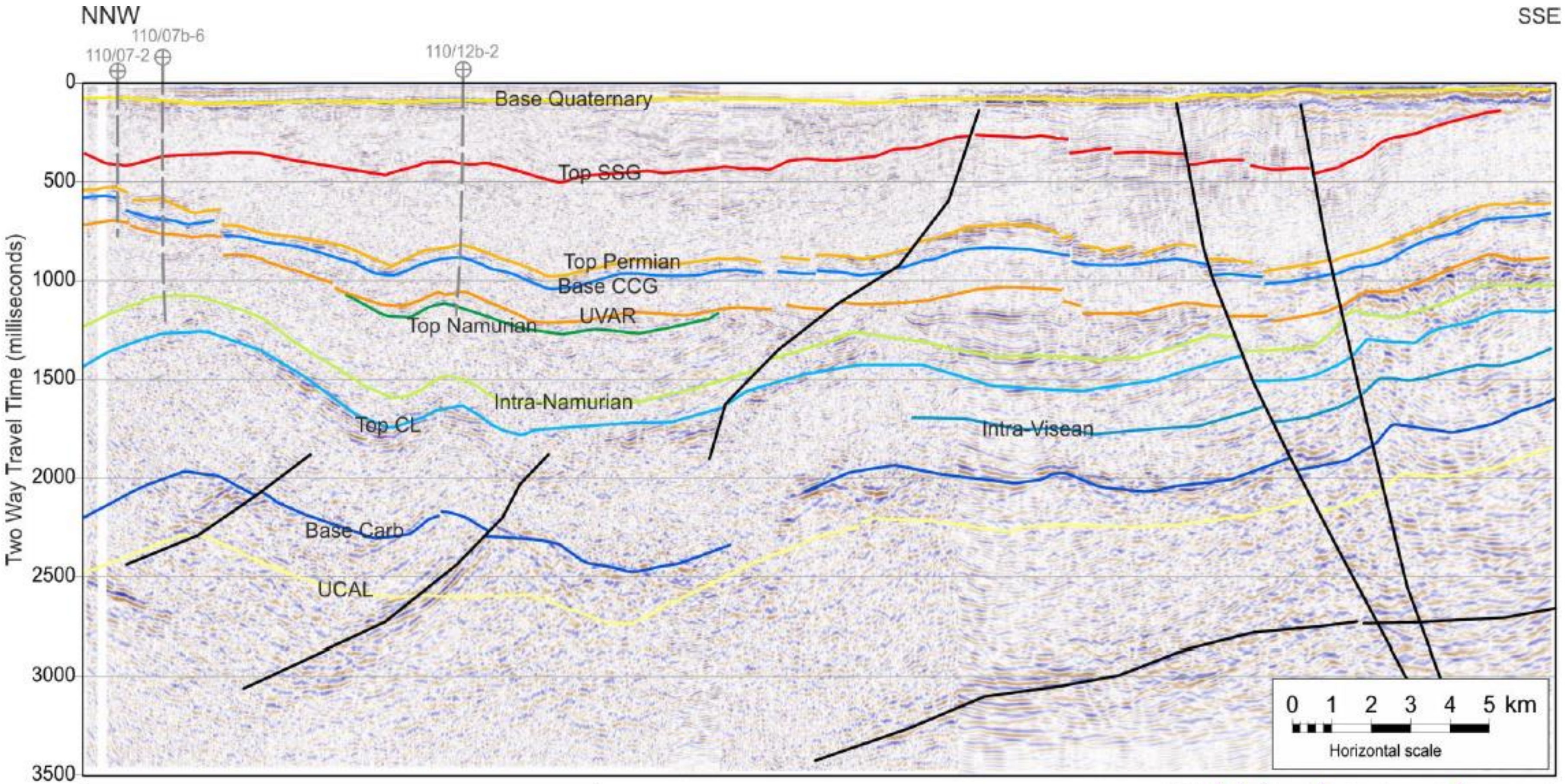
5 1D BasinMod modelling of 110/07b- 6

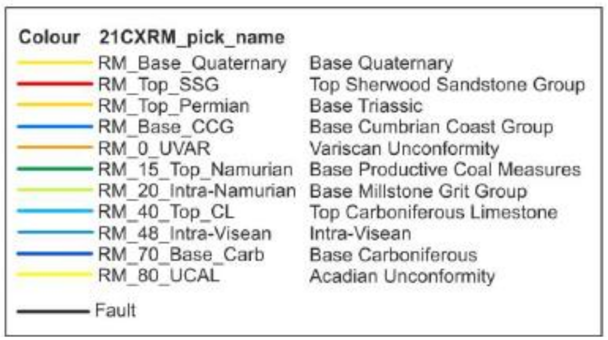
The geochemical data described above was used in the 1D BasinMod modelling, this gave a data spread over the whole of the Carboniferous interval. The calculated maturity profile was then matched with the measured VR values.

The model was not very sensitive to variations in the Carboniferous deposition and uplift amounts, however, a total of 1100 m of uplift was modelled for the Variscan Orogeny. Looking at the seismic data which passes close to the well, it has been estimated that 100 m of Millstone Grit Group was removed (Pharaoh et al., 2016a) (Figure 5). A total of 700 m of Pennine Coal Measures was estimated to have been removed from this location as well as 50 m of Warwickshire Group (Pharaoh et al., 2016a; Wakefield et al., 2016).

The Mesozoic events have more of an influence on the final modelled maturity profile than events in the Palaeozoic. Four hundred and twenty five meters (425 m) of Triassic strata and 625 m of Jurassic strata are predicted to have been removed. Estimations on the amount of Mesozoic strata deposited were based on published values whilst also matching the VR profile (Giles and Indrelid 1998, Jackson et al., 1995).

The Cimmerian uplift event, which has been postulated by several authors was included in the model as an uplift of 150 m (e.g. Hardman et al., 1993; Giles and Indrelid, 1998). Subsequently late Cretaceous deposition of 200 m of Chalk Group was estimated. The Cenozoic uplift event was split into a rapid uplift event of 650 m in the Palaeocene, and a slower uplift of 450 m based on the AFTA profiles (Green et al., 1997; Quirk and Kimbell, 1997). This gives a total Cenozoic uplift of 1100 m which is in the lower end of the published 1-3 km uplift estimates (Figure 4 and Table 2).





Arbitrary NNW-SSE line through the following 3D migrated seismic reflection data: **TerraCube**[REGRID] 3D data courtesy of CGG.

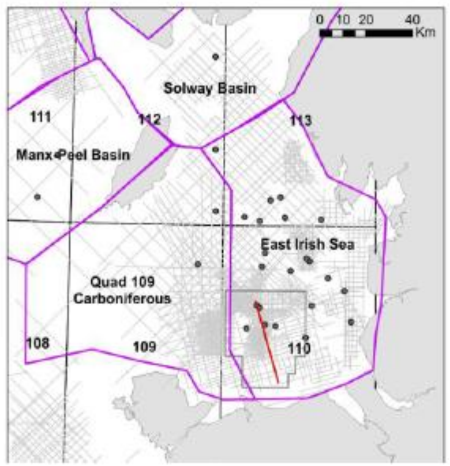


Figure 5: An interpreted seismic profile from NNW to SSE including well 110/07b- 6. The well is located on a minor Variscan inversion high. Variscan orogeny (UVAR) can be seen to erode the top Millstone Grit Group (Top-Namurian). From Pharaoh et al., 2016a.

Heat flow has changed throughout geological time, increasing in times of tectonic and volcanic activity. Current heat flow for the EISB has been estimated to be 50 mWm^{-2} (Cowan et al., 1999). Peaks in heat flow correspond to the uplift events at the Variscan Orogeny, Cimmerian uplift and Cenozoic uplift, with the highest heat flow predicted in the Cenozoic, at 70 mWm^{-2} (Figure 6). The significant increased heatflow in the Cenozoic can be attributed to the onset of rifting in the North Atlantic. The increased heat flow is less than predicted by Cowan et al. (1996) who suggested up to 80% increase in heat flow with a 1 km uplift Cenozoic event. If the figures suggested by Cowan et al. (1996) were used, then the modelled maturity would be

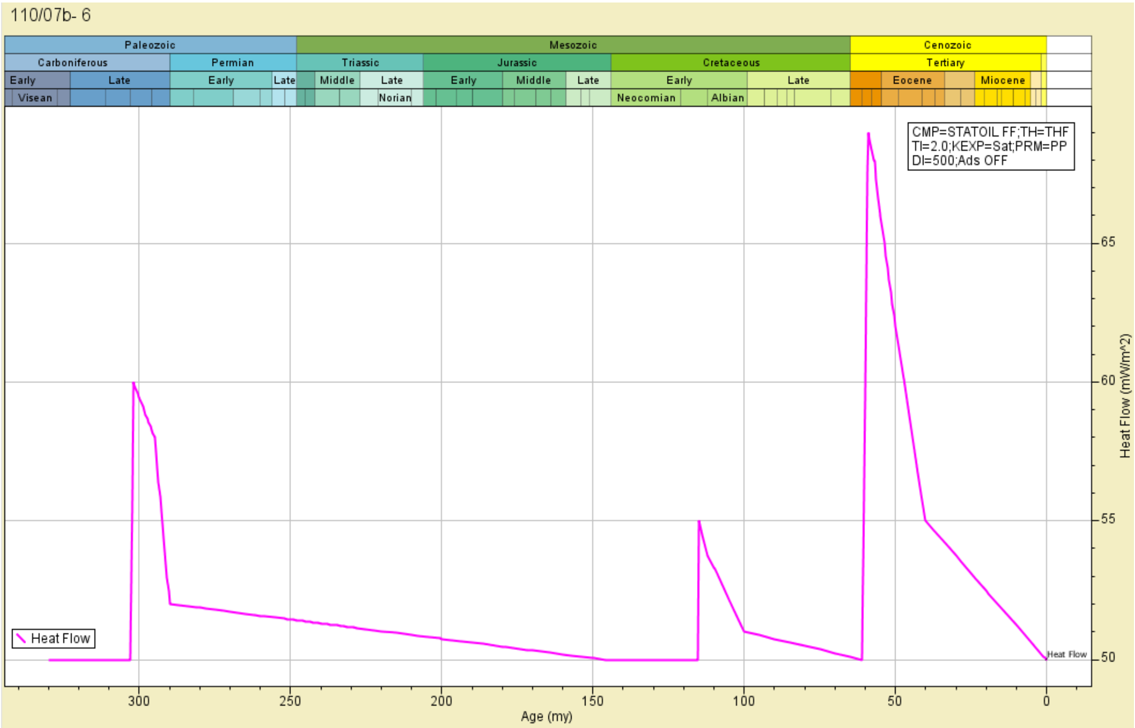


Figure 7 Modelled palaeo-heat flow curve for 110/07b- 6.

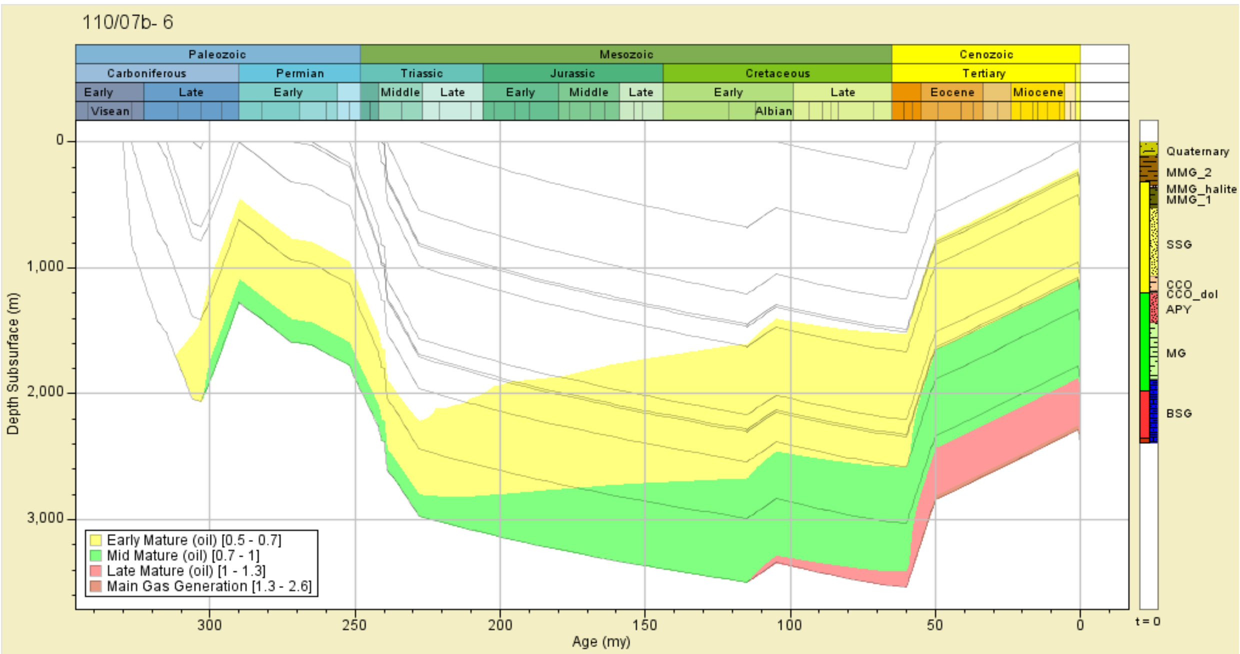


Figure 6 Modelled burial history. The well terminates in the Bowland Shale Formation, the base of which is not reached.

significantly greater than the measured VR profile.

The relatively minor predicted uplift could be attributed to the location of the well on a minor Variscan Orogenic high. This would result in a more condensed post-Carboniferous sequence, a shallower burial depth and lower maximum formation temperature (Pharaoh et al., 2016a; Pharaoh *pers comm*).

The BasinMod model suggests that source rocks reached oil and then gas window maturity levels during three burial phases (Figure 7). Firstly, immediately preceding the Variscan Orogeny, the Bowland Shale Formation reached 0.7% Ro. Secondly, immediately prior to the Cimmerian uplift event, 1.0% Ro was briefly reached. The deepest burial and main gas generation was reached before the Cenozoic uplift event (Figure 8). This deepest burial reaching the main gas generation 1.3% Ro which matches the geochemical report where trace gas condensate was noted at the base 30 m of the drilled Bowland Shale Formation. The BasinMod model results support theories (Hardman et al., 1993; Green et al., 1997; Quirk et al., 1999) that the Carboniferous sources for some EIS structures were mature and could have filled in the Jurassic, breached and then be re-filled by hydrocarbons in the late Cretaceous/early Cenozoic. After the early Cenozoic uplift event, generation ceased. The BasinMod results indicate oil generation due to the mixed type II and III kerogens and maturity level input to the model. The basin modelling is suggestive of oil generation, which is compatible with decreasing hydrogen index/increasing production index with increasing maturity (see Vane et al., 2016), and the presence of the Conwy and Douglas oil fields to the south

The kerogen information provided by the geochemical report suggests that for both the Millstone Grit Group and the Bowland Shale Formation there is a current day high percentage of Type IV inertinite (Table 3). The Millstone Grit Group had equal amounts of generation in the Carboniferous and the Cenozoic (Figure 9). The Bowland Shale Formation had the majority of generation in the Mesozoic and Cenozoic, with minor generation in the Carboniferous (Figure 10).

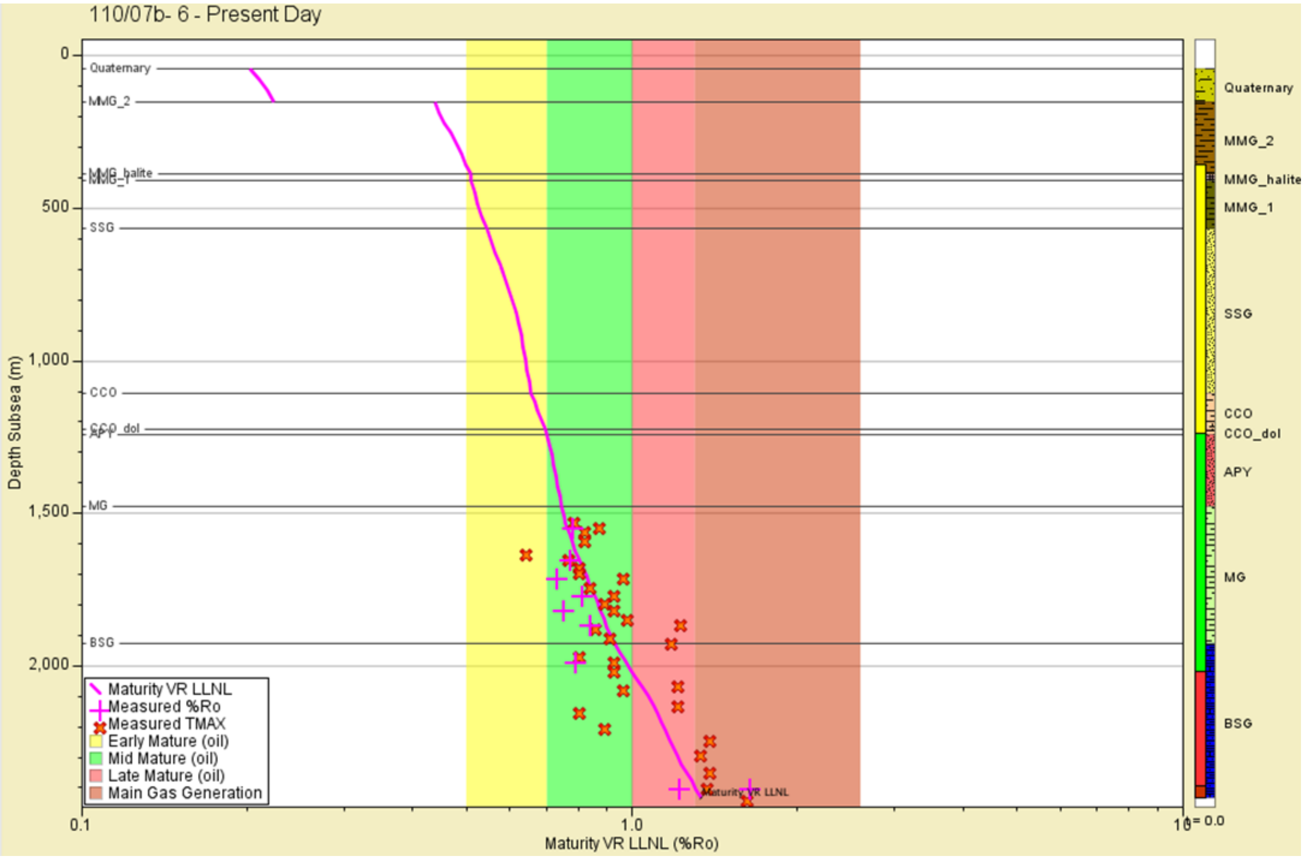


Figure 8 Depth plot showing model results, maturity data and maturity windows.

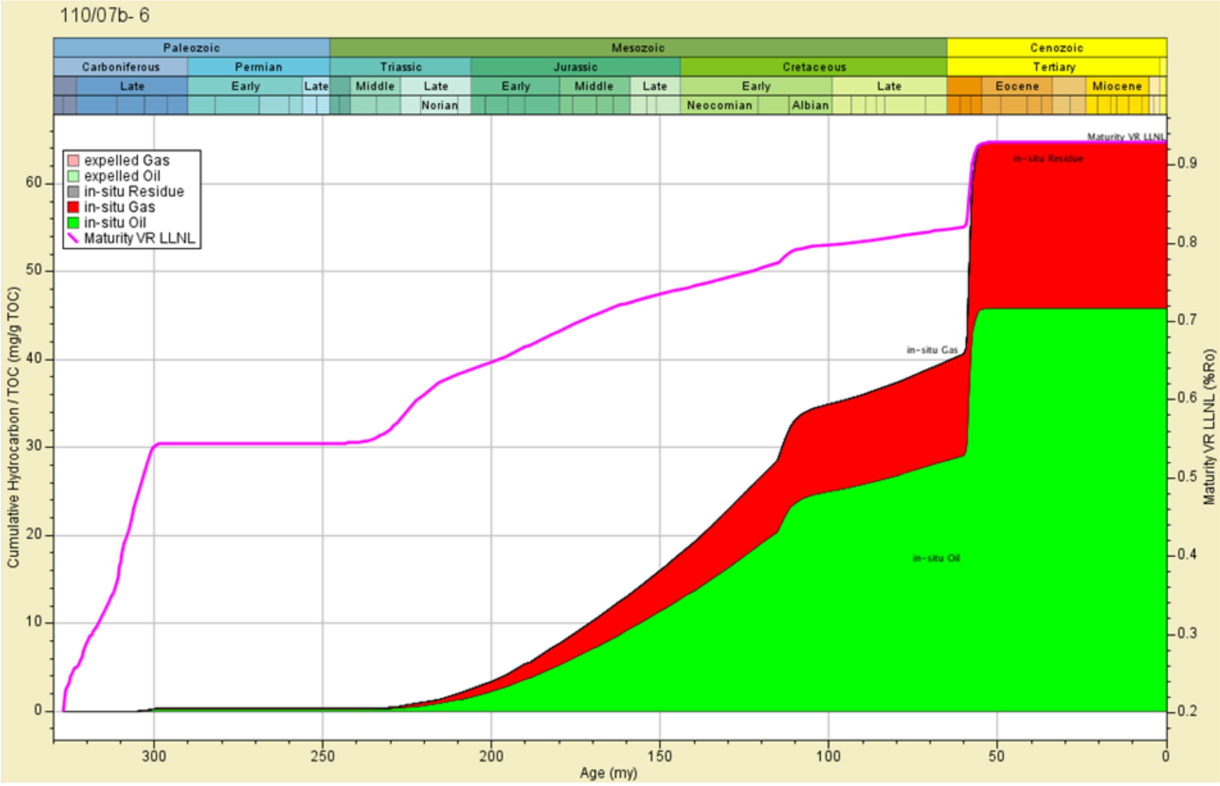


Figure 9 Time plot showing the time of generation for the Millstone Grit Group. The current model suggests main generation occurred equally in the Jurassic and early Cretaceous and early Cenozoic.

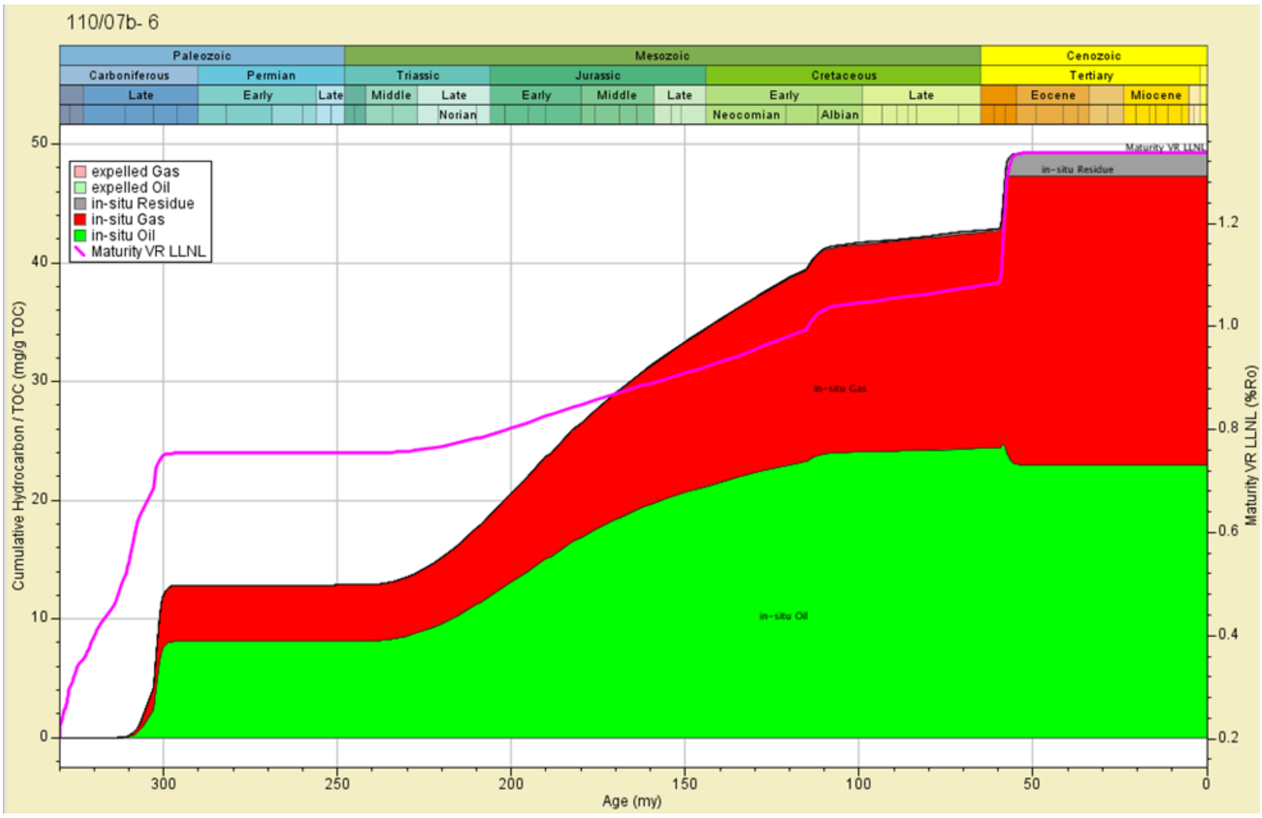


Figure 10 Time plot showing the time of generation for the Bowland Shale Formation. The current model suggests minor generation occurred in the Carboniferous, with the majority of generation in the Mesozoic and early Cenozoic.

6 Conclusions

The removal of most post-Triassic strata in the East Irish Sea and a complex uplift history makes basin history modelling a challenge. Well 110/07b- 6 had the most comprehensive geochemical data set available and no previous published thermal and burial history model, and was subsequently modelled to help understand the timings of hydrocarbon generation in a typical well on the margin of the hydrocarbon province of the EIS.

For the well modelled the key results are summarised as follows:

- Cenozoic uplift of 1.1 km is associated with a 20 mWm^{-2} increase in heat flow to 70 mWm^{-2}
- Carboniferous sediments reached the 0.7% Ro before a 700 m Variscan uplift.
- The maturity reached in the late Carboniferous was not exceeded until the early Jurassic with thermal maturity increasing until the early Cenozoic.
- Deepest burial, and maximum thermal maturity, was reached in the early Cenozoic when the Bowland Shale Formation was sufficiently thermally mature to generate gas.
- Approximately equal volumes of hydrocarbons were generated in the Millstone Grit Group during the Jurassic, the Cretaceous and the early Cenozoic
- Minor oil generation for the Bowland Shale Formation occurred in the late Carboniferous, with the majority of generation in the Mesozoic and early Cenozoic.

There are obvious limitations with using one well to make statements on the whole Irish Sea. On seismic data and in source rock datasets, well 110/7b- 6 can be said to be fairly representative of the hydrocarbon province, however, if more data was available for the peripheral wells they would be of great interest when understanding the hydrocarbon system more widely. Given the producing oil and gas fields of the EIS, sourced from the Carboniferous, it has clearly reached maturity at optimal time intervals. However, with the current dataset it is difficult to extrapolate the source rock maturity and timing of generation outside of the East Irish Sea. More comprehensive studies of well data in the Manx-Peel, Solway and Quadrant 109 basins would be beneficial.

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Appendix 1: Additional 1D burial and thermal history plots

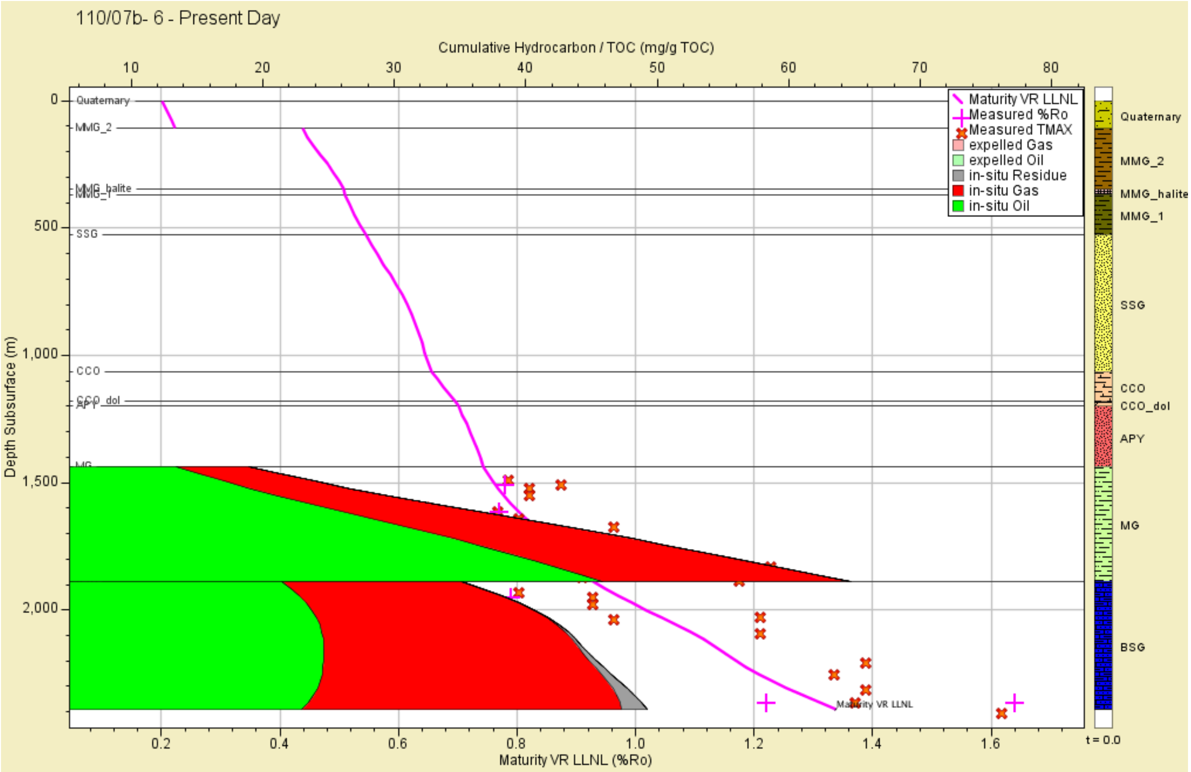

Figure 11 Depth plot showing the generation potential for the Millstone Grit Group and the Bowland Shale Formation.

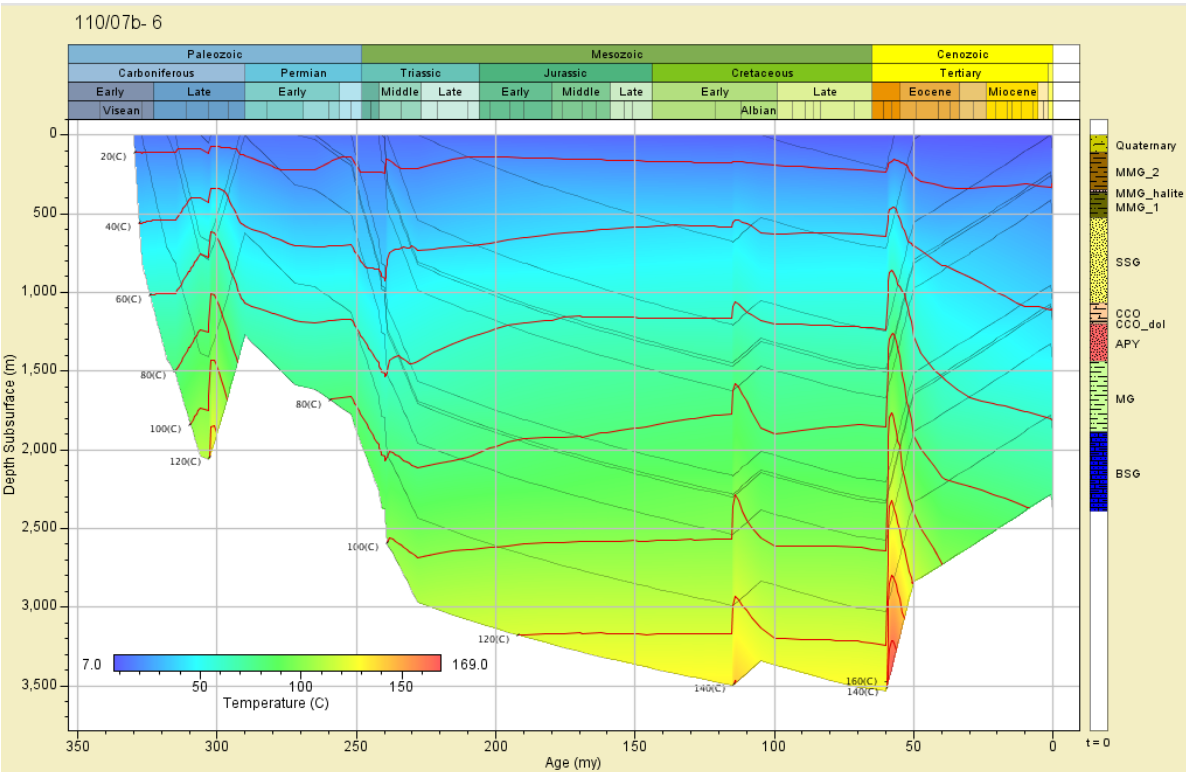

Figure 12 Burial history with palaeo-temperature profile overlay. Isotherms at 20°C intervals.

Appendix 2: Schematics of selected previous studies

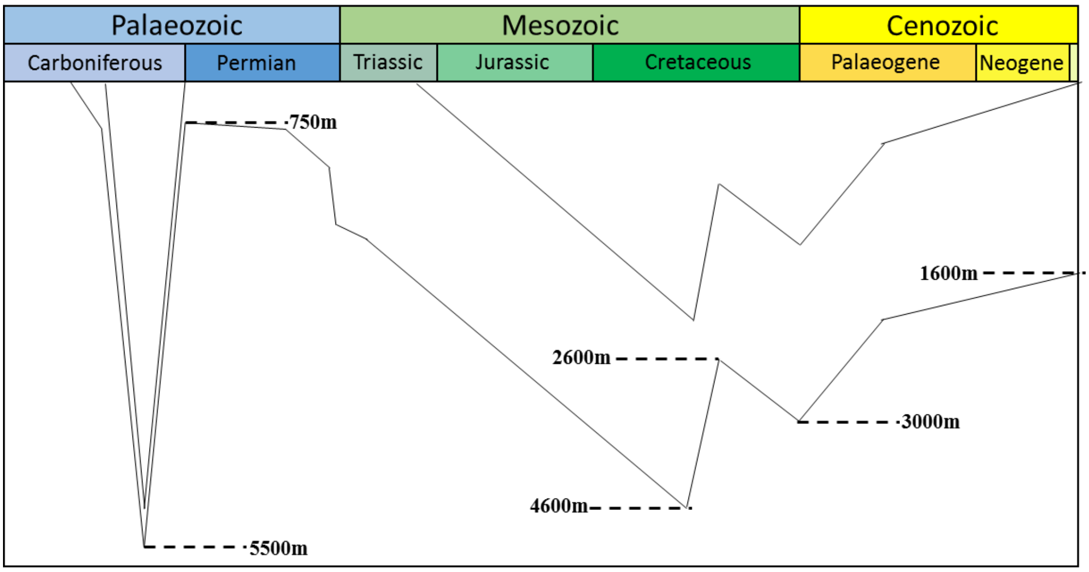

Figure 13 Schematic time vs depth plot for well 109/05-1 (Geotrack International, 1997). Not to scale.

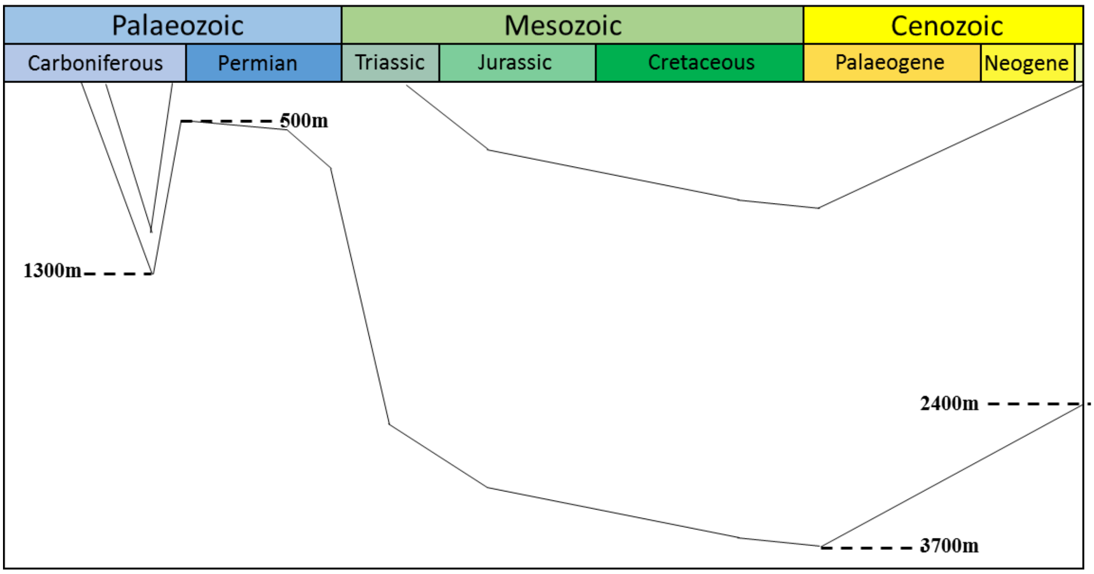

Figure 14 Schematic time vs depth plot for well 110/02b-10 (Vincent and Andrews, 2013). Not to scale.

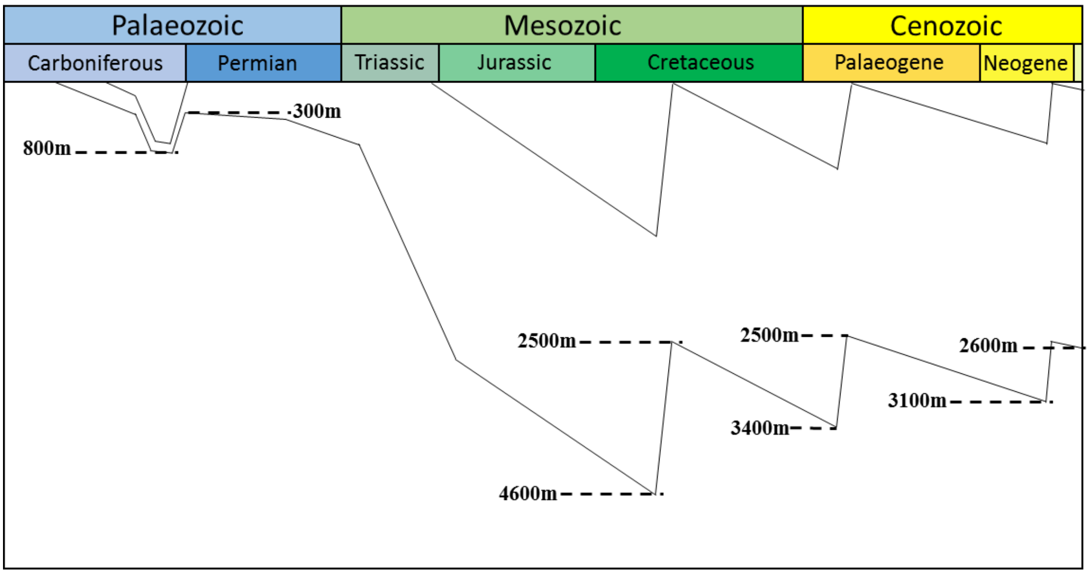

Figure 15 Schematic time vs depth plot for well 110/03-2 (Integrated Geochemical Interpretation Ltd, unknown). Not to scale.

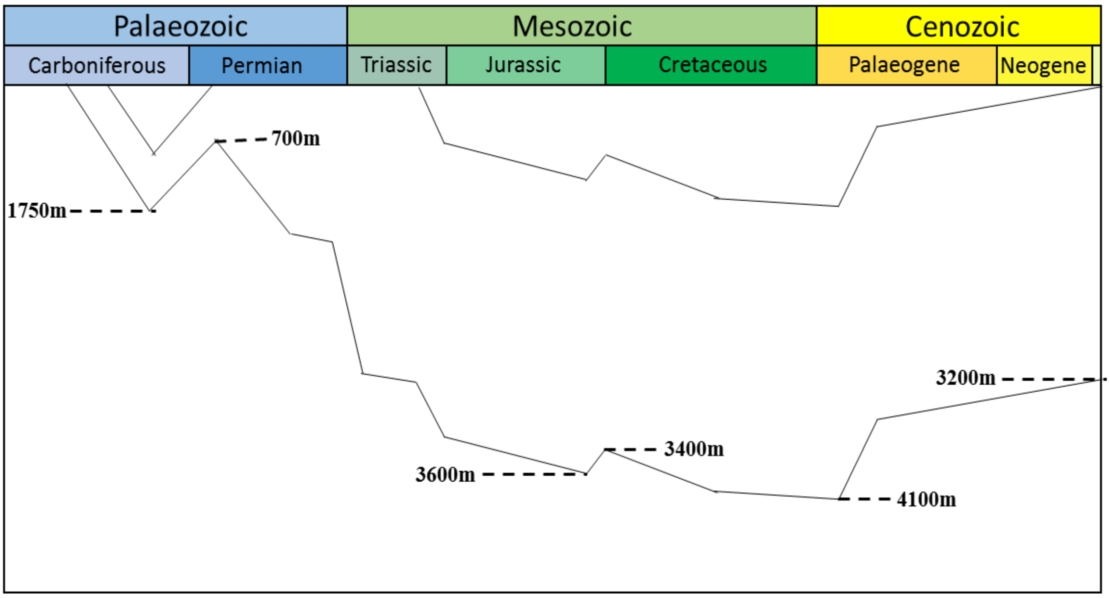

Figure 16 Schematic time vs depth plot for well 110/12a-1 (Floodpage et al., 2001). Not to scale.

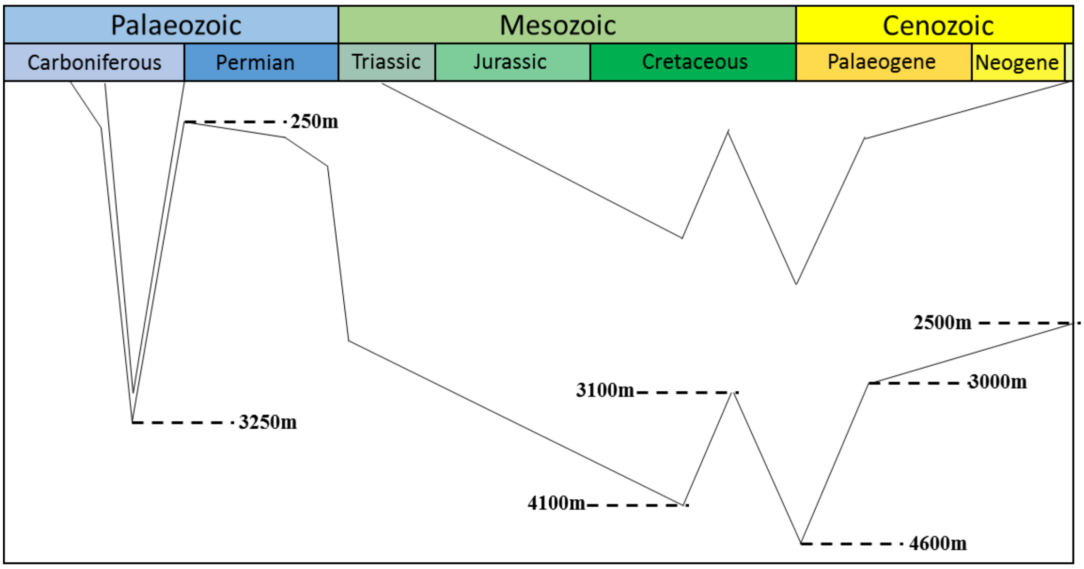

Figure 17 Schematic time vs depth plot for well 112/15-1 (Geotrack International, 1997). Not to scale.

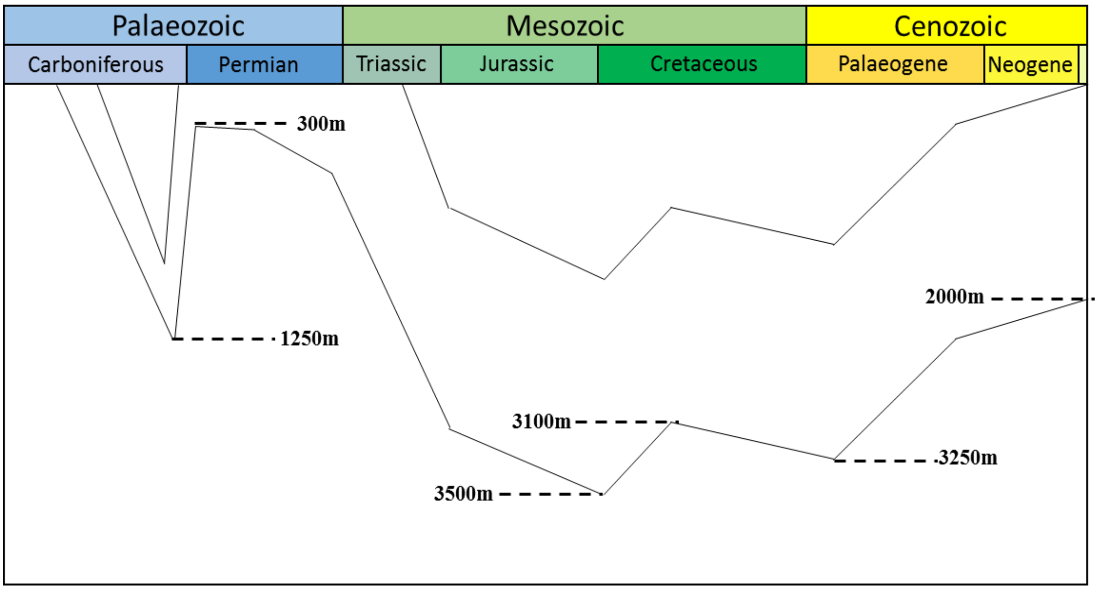

Figure 18 Schematic time vs depth plot for well 112/19-1 (Newman, 1999). Not to scale.