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Thermal Modelling of the Cheshire Basin using BasinMod™

DGSM Cheshire Basin

Internal Report IR/03/092

BRITISH GEOLOGICAL SURVEY

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Thermal Modelling of the Cheshire Basin using BasinMod™

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Foreword

This report is the published product of a study by the British Geological Survey (BGS). It is built on earlier studies, in particular previous modelling of the Cheshire Basin using Earthvision and HotPot (Plant et al 1999). This study forms part of a multidisciplinary study of the Cheshire Basin to contribute to the Digital Geoscientific Spatial Model (DGSM), created to hold the data that reflects the current understanding of the 3D structure and composition of the UK.

This report details the development of 1-D models and integration to produce a 2-D model of the Cheshire Basin.

Acknowledgements

The authors wish to thank W. J. Rowley and A. Carr for their contribution to this report.

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Summary

The Cheshire Basin is a half-graben formed as one of a series of sedimentary basins during Permo-Triassic rifting. The Permo-Triassic infill of this basin may have been up to four or five kilometres thick prior to geologically recent erosion. The basin is flanked to the East and West by Carboniferous and older rocks. The succession in this region displays widespread uplift and erosion resulting from northward encroachment of the Variscan Front at the end of the Carboniferous.

This report details the development of 1-D thermal models and integration to a 2-D model of the Cheshire Basin. BasinMod™ (Platte River Software) has been used to model compaction and temperature through burial over geological time using a variety of datasets. The report considers the Cheshire Basin area through the Carboniferous to the present day, concentrating on the late Carboniferous Coal Measures where maturity data are available.

Heat flow in this region was assumed to be generally high during the latest Carboniferous to early Permian. Modelled isotherms and maturity plots imply that the greatest temperatures attained in the productive Coal Measures occurred during Permian to Cretaceous burial in the basin centre, and during late Carboniferous to Permian time outside of the basin.

The 1-D models imply that some Carboniferous Coal Measures reached the oil generation window. Minor oil stains and shows were found in some Cheshire Basin boreholes. However there does not appear to be a suitable trap to create a commercially viable reservoir.

The BasinMod model results and this best practice report with accompanying checklist and guidelines are stored electronically for the DGSM.

1 Introduction

The Cheshire Basin has been the subject of numerous geological models using a variety of software packages (Plant *et al*., 1999 and references therein). As part of the development of the DGSM, three 1-D models have been integrated to produce a two-dimensional (2-D) model of thermal maturity across the Cheshire Basin. The 1-D models and 2-D model presented here were produced using Platte River Associates Software BasinMod 1-D version 7.61 and BasinMod 2-D version 4.61. The final 1-D models may be used alongside geological assessments of the basin to consider the geological history of the eastern Midland Valley from the Carboniferous to the present day.

BasinMod is a modelling software package distributed by Platte River Software. Borehole stratigraphy and rock properties were used to model compaction and temperature through burial over geological time. The modelled maturity and maturity data were then compared graphically and used to develop the model until the model fit the available data. Plots of the maturity, temperature, x vs. depth and x vs. time were produced.

The 2-D model draws a cross-section between 1-D models based on three selected boreholes. (Figure 1 - Pie Rough [BNG 382915 343990], Knutsford [370269 0377851] and Up Holland [350440 402900]). These three boreholes were chosen on the basis of their detailed stratigraphy and maturity data. A summary of the stratigraphy of the basin is given in Figure 2. Pie Rough is located on the eastern side of the basin, on the upthrown side of the Red Rock Fault. It cuts through Carboniferous Coal Measures and Warwickshire Group. Up Holland is located near to the western feather-edge of the basin and cuts though Middle Coal Measures to the underlying Namurian sandstones. Knutsford, in the centre of the basin, cuts through the Mercia Mudstone Group to basal Permian sandstones and Upper Coal Measures. The three boreholes all show the Variscan unconformity caused by uplift which removed up to several hundred metres of Carboniferous strata before deposition resumed during the Permian. A smaller erosional unconformity synchronous with the Hardegsen Unconformity (above the Triassic Bulkeley Sandstone Formation) is also observed in Knutsford.

The Little Ness Borehole drilled on the Wem Fault was found to contain hydrocarbons, and minor oil stains were reported in the Ashton and Ellesmere Port boreholes (Plant *et al*., 1999). Hydrocarbon shows were also present in the Blacon East and Churton boreholes. In the adjacent Coalbrookdale, Lancashire and North Staffordshire coalfields, Carboniferous rocks were found to contain oil. Some coal seams also produced small amounts of gas when mined.

Currently the Cheshire basin has a low average heat flow (52 mWm^{-2}; Plant *et al*., 1999). High Late Palaeozoic vitrinite reflectance (VR) values over the whole region imply that heat flow was high over an area much larger than the Cheshire Basin. The palaeo-heat flow used to model Pie Rough Borehole was the best constrained by maturity data and so was used as a basis for the palaeo-heat flow curves for Knutsford and Up Holland. Knutsford also had a few porosity measurements from the Sherwood Sandstone (Plant et al, 1999). The basin history and palaeo-heat flow were somewhat simplified in order to run the 2-D model.

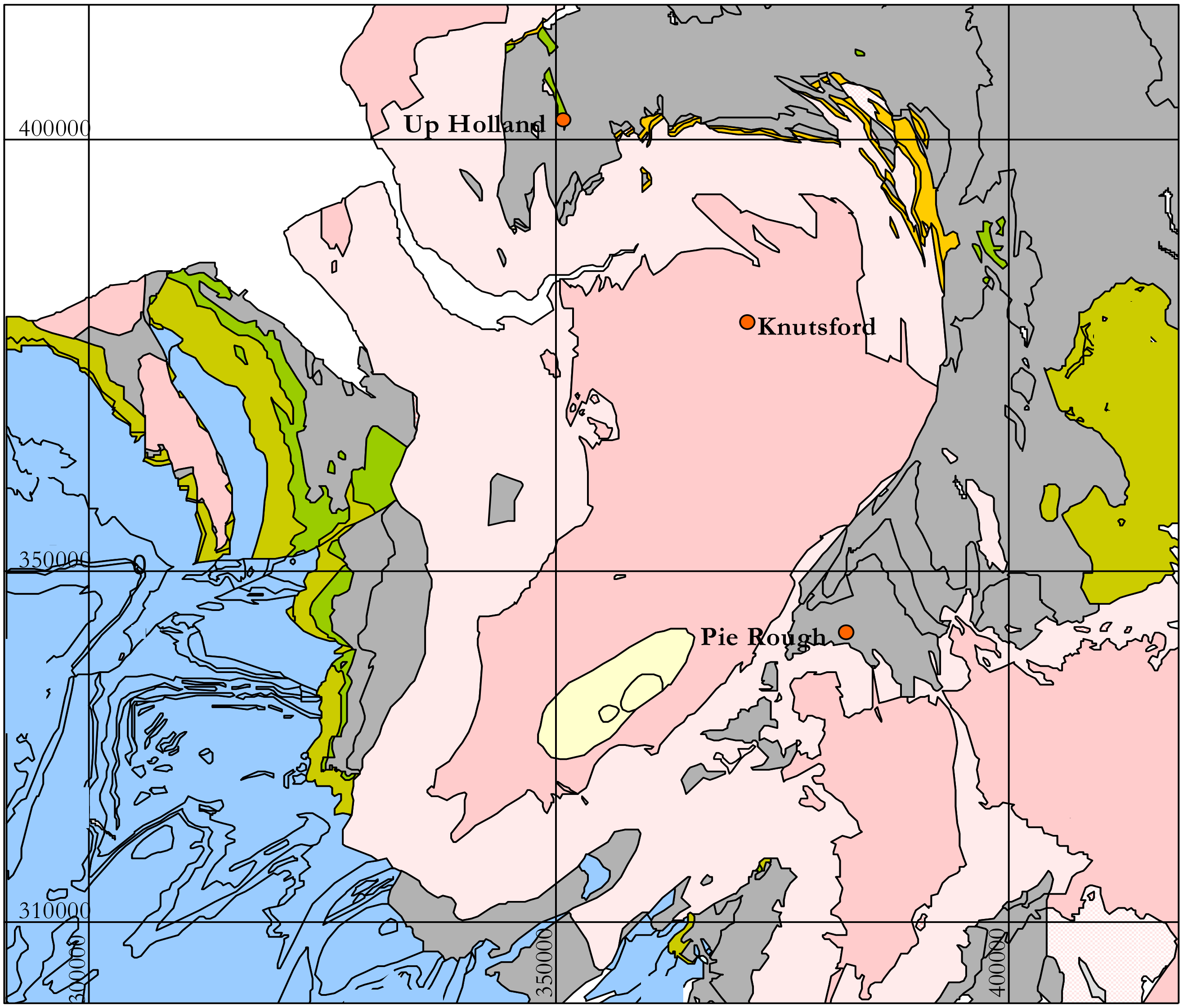
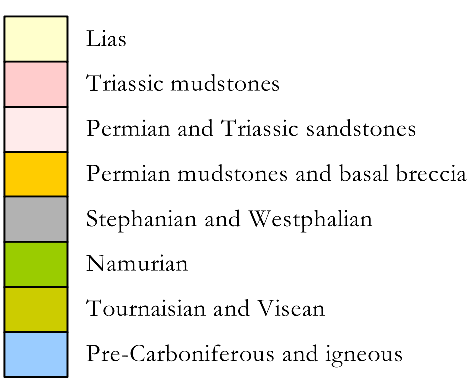


Figure 1: Simplified geological map of the Cheshire Basin showing the location of modelled 1-D wells.



Period	Group	Stratigraphic unit	Equivalents
		→ Eastern Basin Margin	
Jurassic	Lias		
Triassic	Penarth		Prev. Rhaetic
	Mercia Mudstone (MMG)	Blue Anchor	Prev. Tea Green Marl
		Brooks Mill Mudstone	Prev. U. Keuper Saliferous Beds
		Wilkesley Halite	
		Wych Mudstone	Prev. M. Keuper Marlstone
	Mercia Mudstone (MMG)	Byley Mudstone	Prev. M. Keuper Marlstone
		Northwich Halite	Prev. L. Keuper Saliferous Beds
		Bollin Mudstone	Prev. L. Keuper Marl
		Tarporley Siltstone	Prev. Keuper Waterstones
		Diachronous but conformable	
	Sherwood Sandstone (SSG)	Tarporley → Helsby Sandstone	
		Hardegsen Unconformity	
		Bulkeley Hill Sandstone	
		Wilmslow Sandstone	Wildmoor Prev. U. Mottled Sandstone
		Chester Pebble Beds	Hawksmoor, Kidderminster Prev. Bunter pebble beds
		Kinnerton Sandstone	Prev. L. Mottled Sandstone
Permian	Sherwood Sandstone (SSG)	Bold → Manchester Marl	
		Collyhurst Sandstone	
		Variscan Unconformity	
Carboniferous (Stephanian)	Warwickshire Group	Salop	Prev. Barren Measures Prev. Radwood and Keele
Westphalian D		Halesowen	Prev. Keele Locally passes into Newcastle Diachronous Prev. Barren Measures Prev. Newcastle
Westphalian C		Etruria	
	Coal Measures	Upper Coal Measures (UCM)	
Westphalian B		Middle Coal Measures (MCM)	
Westphalian A		Lower Coal Measures (LCM)	
Namurian	Millstone Grit (MG)		
Visean			

Figure 2: Simplified stratigraphic succession in the Cheshire Basin and adjacent areas.

2 Data Requirements

BasinMod is used to model compaction based on the stratigraphy. However, to constrain the model, the model results need to be compared to an equivalent dataset. The process of comparing the model results to the data and refining the model is known as 'calibration'. The three boreholes selected for this project have Volatile Matter, (VM) Vitrinite Reflectance (VR) data or Apatite Fission Track data (AFTA).

Sufficient data to calibrate a 1-D model is rarely available. For example, Knutsford could not be calibrated by the VR data alone, due to its scarcity and distribution, and a larger AFTA dataset was also necessary. Pie Rough had the most complete VR dataset, and was therefore the most suitable candidate to develop the initial heat flow model. This was then used as the basis for similar models at Knutsford and Up Holland, and finally for the 2-D model.

3 1-D Models

BasinMod 1-D calculates heat flow curves based on the finite rifting model of Jarvis & McKenzie (1980). This assumes that in an extensional environment there is rapid initial subsidence due to crustal thinning associated with a thermal anomaly i.e., high heat flow. Unlike McKenzie's earlier model, this one recognises that continental basin formation by extension takes a finite time. 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. For modelling heat flow in basins with limited extension (stretching factor $\beta \leq 2$), the Jarvis & McKenzie (1980) model assumes that the thermal anomaly develops and decays within about 60 Ma.

The three wells were modelled and calibrated separately, then the results combined in the 2-D section. Pie Rough had the most complete volatile matter dataset (Millott *et al*., 1946) which was converted to VR (Stach *et al*., 1982, Table 4) and used to make minor modifications to the Jarvis & McKenzie palaeo-heat flow curves to improve the fit of the model to the data. The modelled maturity was calibrated graphically against the maturity data for the borehole. The slope of the modelled maturity plot is influenced by the palaeo-heat flow and the actual model maturity values are most affected by the thickness of sediments deposited subsequently.

The eroded sediment thickness was estimated using vitrinite reflectance (VR), apatite fission track analysis (AFTA) and porosity data. Palaeozoic stratigraphical ages were taken from Lippolt et al (1984) and Besly & Kelling (1988). Lithology mixes to best approximate the stratigraphy were constructed from borehole records held by BGS in the NGRC, and borehole data in Plant *et al*. (1999) and Rees & Wilson (1998). Millott *et al*. (1946) provided tables of Westphalian coal properties in the Pie Rough borehole, including volatile matter. The latter were converted to vitrinite reflectance using Stach *et al*., (1982, table 4), and entered into BasinMod for comparison with the model heat flow. Rees and Wilson (1998) produced isopach maps of the Westphalian strata in the Stoke-on-Trent district, which were used to approximate eroded sediment thickness up to and including the Etruria Formation. Cross sections through other boreholes on the Stoke-on-Trent Sheet were used to estimate eroded sediment thickness up to the end of the Carboniferous. Permo-Triassic deposits are not well preserved in this region and therefore it was difficult to evaluate their missing thickness. Finally, estimates of water depth and palaeo-sea level were included. The vitrinite reflectance data were then used for final calibration to produce a best-fit, geologically reasonable model.

3.1 PIE ROUGH

The comparison of model maturity and maturity data is shown in Figure 3. Figure 3a shows the model burial history with isotherms every 10ºC. Figure 3b shows the palaeo-heat flow and Figure 3c shows a comparison of model maturity (solid red line) and maturity data (black crosses). The thickness of eroded Carboniferous strata indicated by the model is seen on the left hand side of Figure 3a, where a layer is deposited then eroded (cut off by the near-horizontal line representing the surface) at the end of the Carboniferous.

Initial rock thickness estimates of eroded thickness based on surrounding boreholes were entered into the 'stratigraphy' table in the model, and these values were then altered to fit the model results to the maturity data. The final Pie Rough model suggests that approximately 650m of Carboniferous strata were removed during the Variscan erosional event. After this erosion, further deposition in the Permian is shown, followed by the removal of an estimated 200m of strata during the Hardegsen event. The model layers seen to reach the 'surface' in Figure 3a represent rock layers eroded before the present day. Estimated water depth was then added from

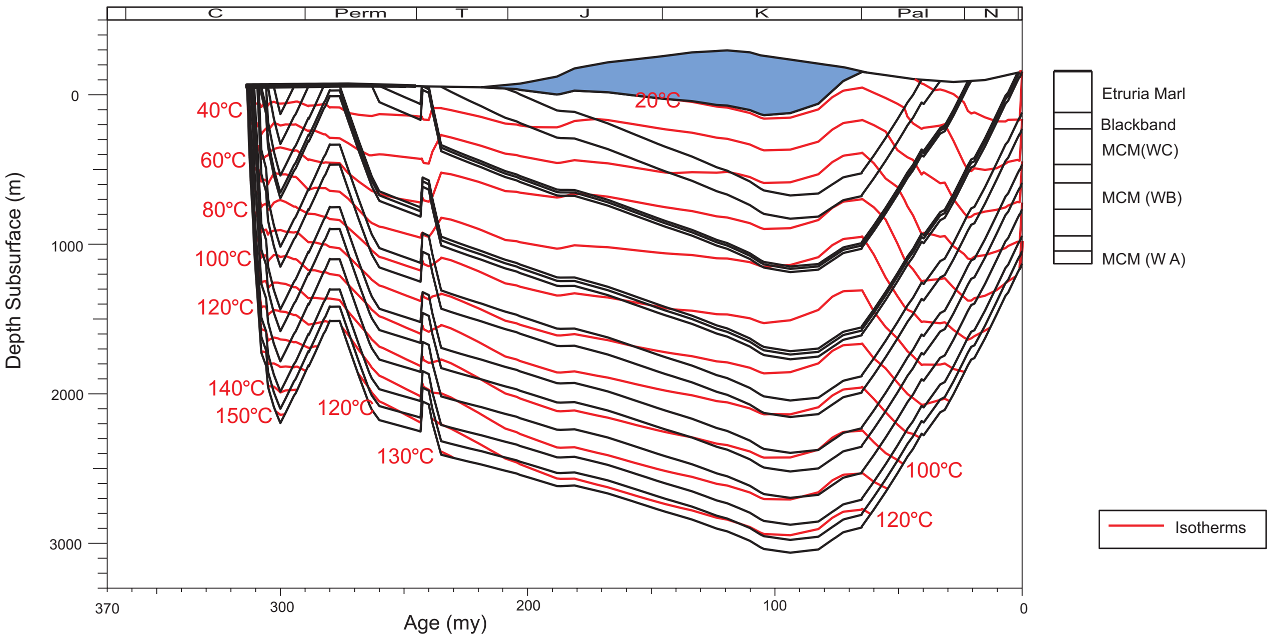


Figure 3a; Modelled burial history and isotherms in Pie Rough borehole.

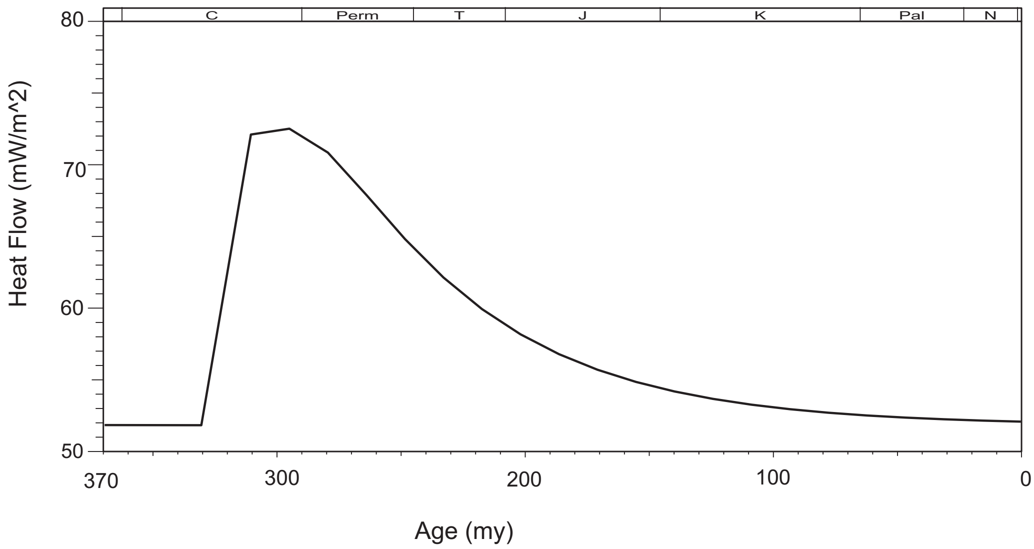


Figure 3b;Modelled heat flow history in Pie Rough borehole.

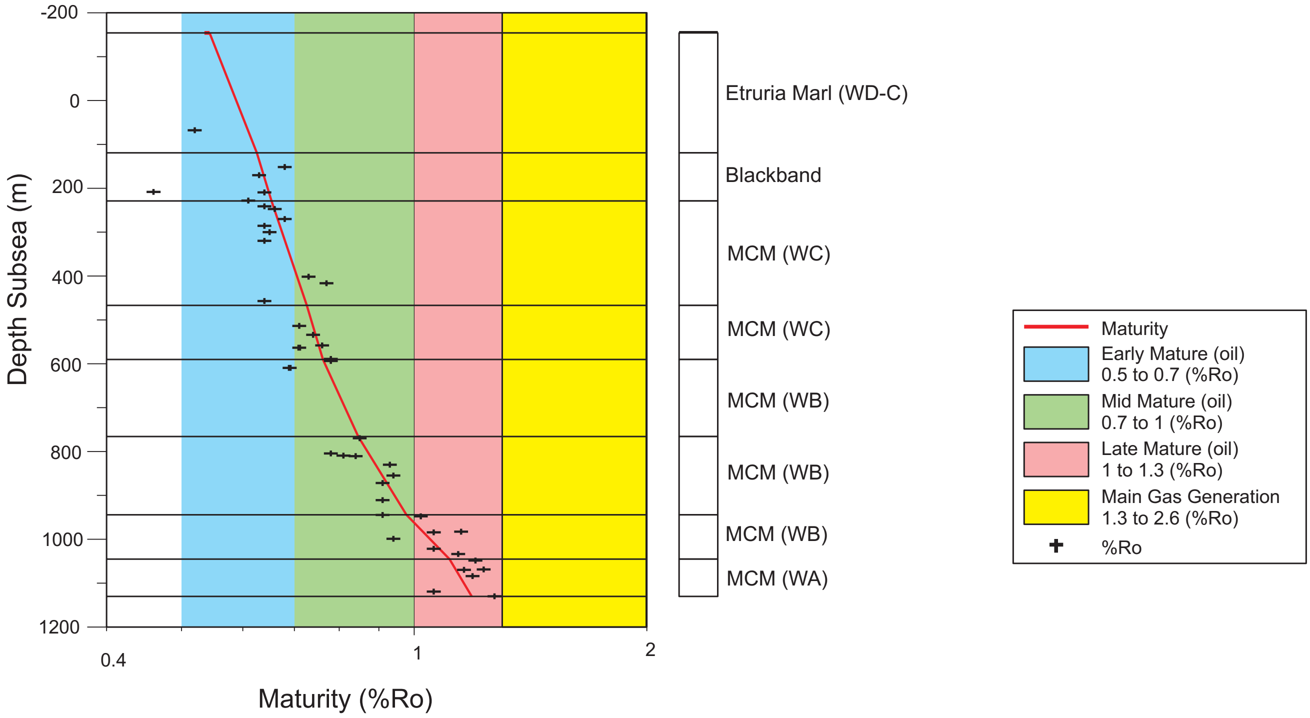


Figure 3c; Modelled maturity (VR) in Pie Rough borehole.

the literature search, (blue lozenge at top of Figure 3a). Water depth is not well constrained by the model. The heat flow model (Figure 3b) is well constrained by the slope of the VR data curve (Figure 3c). Heat flow appears to have reached $72mWm^{-2}$ during the late Carboniferous, resulting in temperatures of around 150ºC in the deepest Westphalian A strata. The Permo-Trias cover indicated by this model attained a thickness of about 1km, with a further 500m added during the Jurassic-Cretaceous. This model implies that the Westphalian A coals achieved a depth of burial of around 3km during the Cretaceous, although temperatures did not reach those experienced during the late Carboniferous. Figure 3c indicates that the Carboniferous Coal Measures reached the oil generation window. However, due to the lack of a suitable trap structure the oil has migrated out of the basin.

3.2 UP HOLLAND

The palaeo-heat flow from Pie Rough was then used as a basis for the other two 1-D models where the vitrinite reflectance data is less complete. Pearson & Russell provided VR data for Westphalian A to Pendleian age strata from Up Holland Borehole. Stratigraphical data from Plant *et al*. (1999) were used to model the eroded stratigraphy. The VR data were then used to calibrate the model and the heat flow history was assumed to follow a similar pattern to that of Pie Rough. Coal Measures in the Westphalian are algal-rich, which may have caused suppression of the VR data and therefore account for the slight difference between the model maturity curve and maturity data points in the Carboniferous coals of Up Holland (Figure 4c). Pie Rough VR data was converted from volatile matter data, and so does not show suppression.

The Up Holland 1-D model shows a similar stratigraphical history to that of Pie Rough, with approximately 700m of sediment removed during the Variscan uplift and 150m during the Hardegsen event (Figure 4a). Permo-Triassic cover was calculated to be around 530m, with a further 400m deposited during the Jurassic and Cretaceous. However, the heat flow and temperatures reached are slightly lower; this model shows heat flow of up to $68mWm^{-2}$ during the late Carboniferous, with temperatures of around 130ºC in the Westphalian A coals, and slightly lower temperatures achieved on reaching a depth of about 2km during the Cretaceous (Figure 4a). These results are fairly well constrained by the VR data. Figure 4c indicates that the Coal Measures reached the oil generation window, however there was no suitable trap structure and the oil migrated out of the basin.

3.3 KNUTSFORD

Limited vitrinite reflectance data are available in Pearson & Russell (2000) for Knutsford Borehole. Borehole temperature data is also available in Burley *et al*. (1984). Lewis *et al*. (1992) provided AFTA data from the Westphalian, Permian and Triassic. Following the findings in Plant *et al*. (1999), fluid circulation in the basin was included in the model, using the '2-D fluid flow' and 'delta heat' options in BasinMod. ‘2-D fluid flow’ assumes fluid flows through the borehole and surrounding area rather than a closed system with fluid circulation contained within the borehole. It was assumed that most circulation occurred in the porous Permo-Triassic sandstones during the Palaeogene. Borehole data were taken from records held in the NGRC at BGS Keyworth, and the eroded stratigraphy was estimated using information in Plant *et al*. (1999). These data were then used to develop a best-fit model.

The Knutsford 1-D model (Figure 5) shows a different burial history from that of Pie Rough and Up Holland, with highest temperatures achieved during the Cretaceous. The model implies removal of approximately 900m of Carboniferous sediment during Variscan uplift, with deposition recommencing with the Sherwood Sandstone (Figure 5a). An estimated 50m of

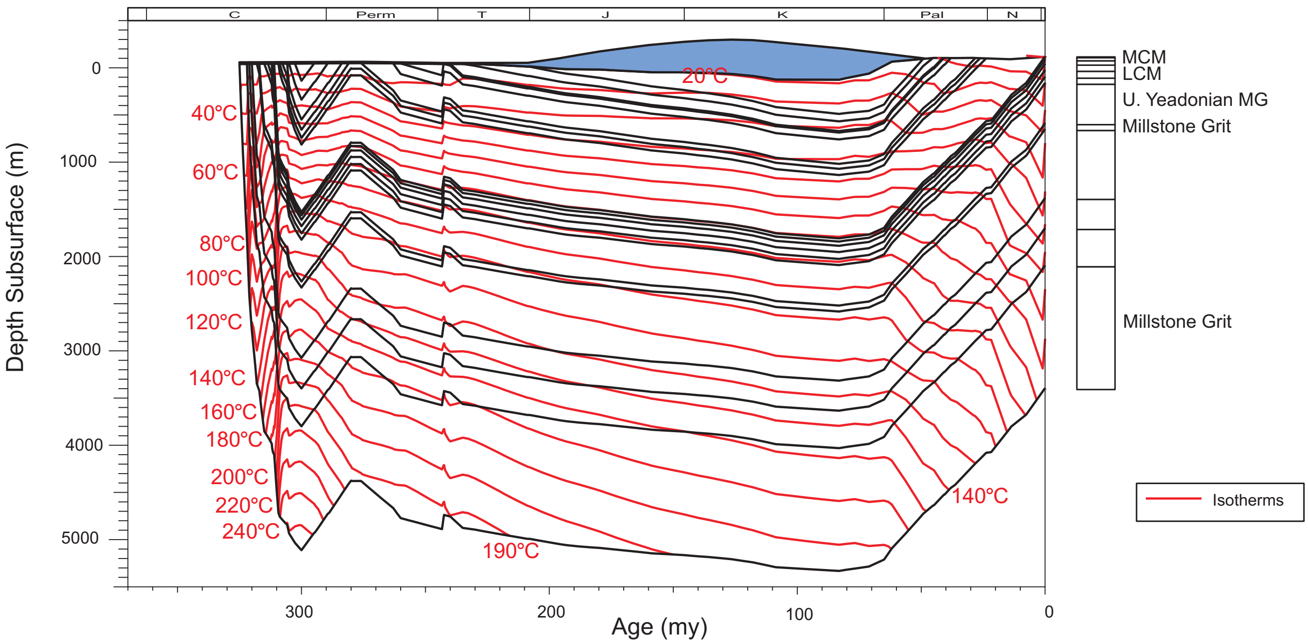


Figure 4a; Modelled burial history and isotherms in Up Holland borehole.

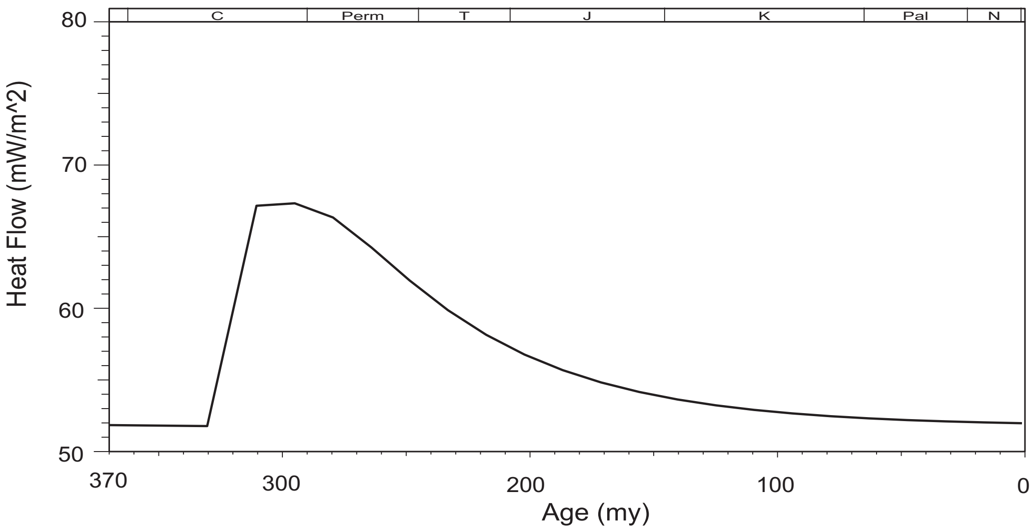


Figure 4b;Modelled heat flow history in Up Holland borehole.

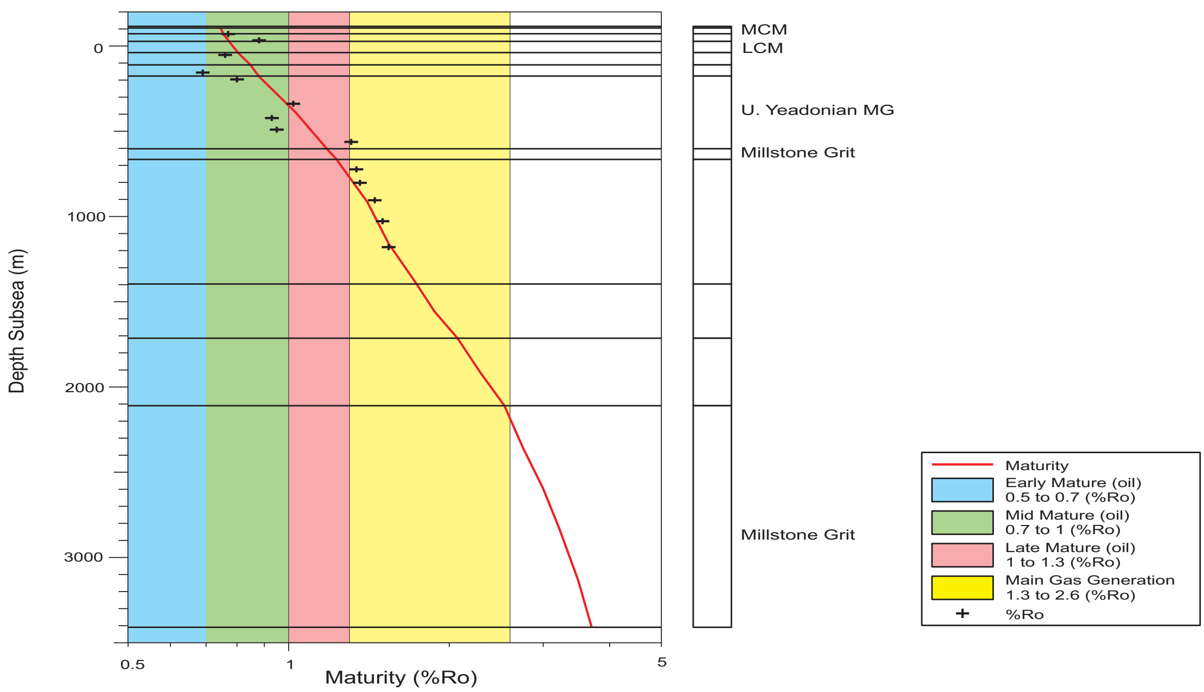


Figure 4c; Modelled maturity (VR) in Up Holland borehole.

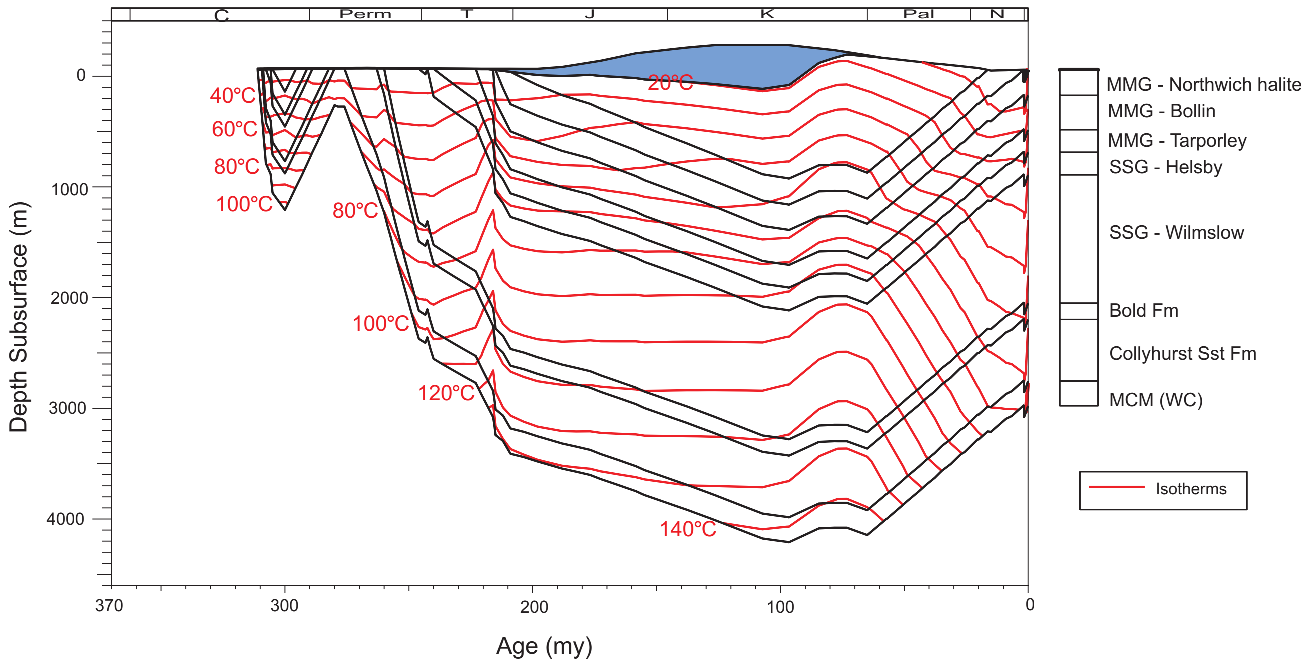


Figure 5a; Modelled burial history and isotherms in Knutsford borehole.

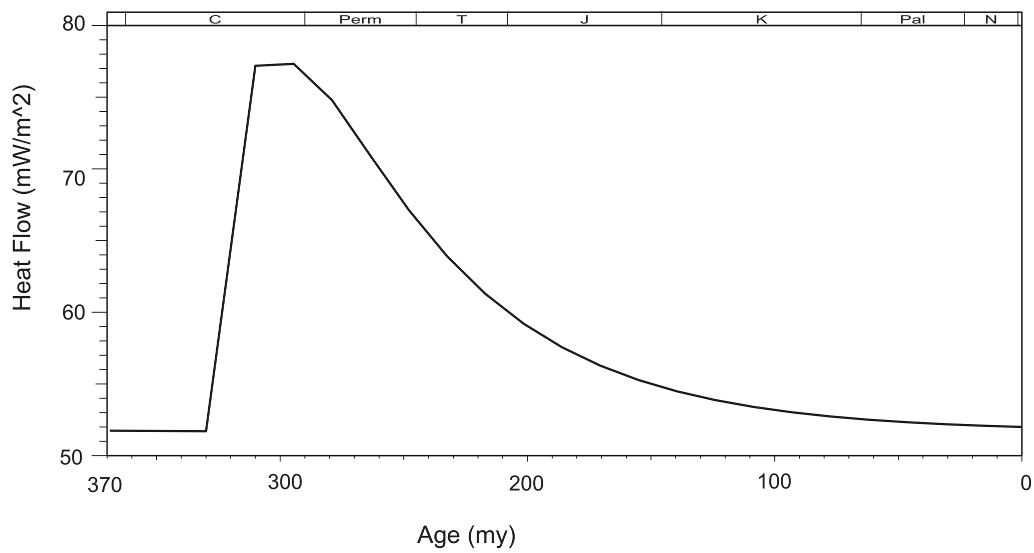


Figure 5b;Modelled heat flow history in Knutsford borehole.

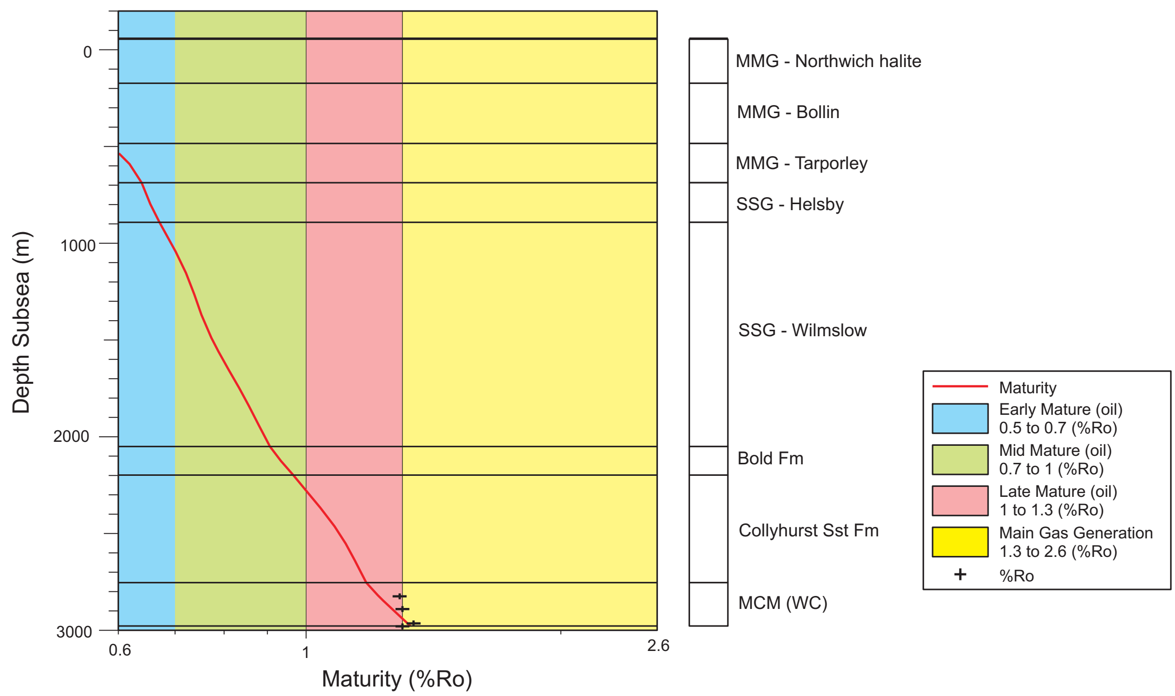


Figure 5c; Modelled maturity (VR) in Knutsford borehole.

overburden was also removed during the Hardegsen event. The model palaeo-heat flow peaked at $78mWm^{-2}$ during the late Carboniferous (Figure 5b), with the Westphalian C coals reaching temperatures of around 100ºC. Model calculations imply that late Cretaceous burial beneath 2.8km of Permo-Triassic strata, with a further 1km of Jurassic and Cretaceous strata, resulted in these coals experiencing burial of around 4km and temperatures of 140ºC. Figure 5c indicates that the Middle Coal Measures reached the gas generation window. However, due to the lack of a suitable trap structure, the hydrocarbons migrated out of the basin.

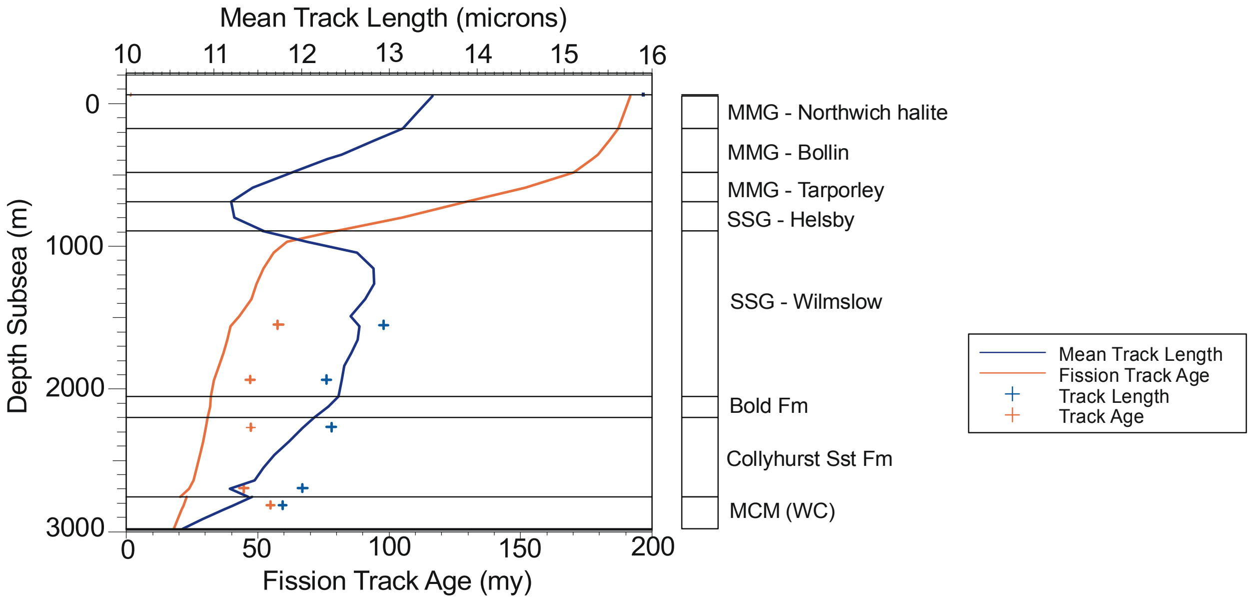


Figure 5d; Apatite Fission Track data and model from Knutsford Borehole.

3.4 SUMMARY OF 1-D MODELS

It is unlikely that heat flow remained constant through basin deformation, uplift and erosion. The general shape of the heat flow verses time curve used showed high Carboniferous heat flow decreasing to the present day low levels over geological time. For all the 1-D models, peaks in the heat flow are present around the time of the Variscan event. All 1-D models indicate some hydrocarbon generation, however due to the lack of a suitable trap structure the hydrocarbons migrated out of the basin.

The Pie Rough model from outside the basin and the Up Holland model on the edge of the basin show similar burial histories, with 650-700m Carboniferous sediment removed during the Variscan erosion and 200-150m sediment removed during the Hardegsen event. The highest heat flow of $72\text{-}68mWm^{-2}$ during the late Carboniferous caused the highest maturity coals such as the Westphalian A coals which reached temperatures of 150-130ºC. During the Permian-Cretaceous burial of the Westphalian coals of around 3km for Pie Rough and 2km for Up Holland, the model temperatures are not as high as during the Carboniferous, indicating the high heat flow had more effect on the maturity.

The Knutsford model from the basin centre shows a different burial history, with the highest model temperatures for this borehole (140ºC in the deepest layer – the Westphalian C Middle Coal Measures) achieved during deep burial (around 4km) during the Cretaceous. The model indicates around 900m of Carboniferous sediment removed during the Variscan erosion and only 50m during the Hardegsen event.

4 2-D Model

The 2-D thermal model was generated by combining results from the calibrated 1-D models. A seismic/stratigraphical cross-section based on the Earthvision model provided by J. Rowley (pers.comm.) was entered into BasinMod 2-D. Major faults were added using unpublished BGS internal interpretation maps. For simplicity, the Red Rock and Alderley Edge faults were included as one major basin-bounding fault, and only the Bridgemere and King Street faults within the basin were included (Figure 6a). Only faults that cut more than one horizon affect calculated model results. Porosity data for Knutsford borehole are provided in Plant *et al*. (1999), the VR and AFTA data used in the 1-D models were also used. The wells were added to the cross section as 'pseudo-wells', i.e. instead of constructing the cross section from the wells, the cross section was constructed from the seismic data and then constrained using the modelled wells.

For simplicity the 2-D model the lithologies were assumed to be uniform across the basin. Initially the model was constructed using only the current sediment thickness. The model was ‘coupled’, (i.e. the lines separating model layers were joined correctly such that the correct rock properties were contained within the appropriate model layers) and successfully run. This initial model was then modified to include the Variscan unconformity and erosional surface. A simplified heat flow based on those developed for the three 1-D models was used, with a high heat flow in the Carboniferous decreasing to present day levels (Figure 6c). Two 'end member' models were then produced, one with all deposition and erosion occurring at the Variscan unconformity, the other with all deposition and erosion occurring at the surface Permian-recent. The model could fit the data with 1.5km of deposition and erosion during the Jurassic and Cretaceous, but would have required more than 5km of deposition between the stratigraphy seen at the top of the boreholes and the Variscan uplift, to achieve the maturity and porosity indicated by the well data.

Finally, the 2-D model was constructed using the 1-D models as a guide to the eroded stratigraphy (Figure 6a). The broken line above the Variscan unconformity indicates the eroded Carboniferous sediment, and can be seen to terminate near to Up Holland where the Variscan unconformity intersects the surface (Figure 6a). The Sclater & Christie (1980) or exponential method of compaction was chosen. This method was developed from wells on the North Sea Central Graben, which may show some overpressuring; correcting for this tends to result in undercompaction, which may have affected the fit of the model. BasinMod 2-D software does not allow inclusion of the Variscan unconformity above the present surface in the Pie Rough borehole, which slightly degrades the fit of the VR data compared to the more satisfactory fit of the 1-D Pie Rough model. Figure 6b shows the overall calculated maturity in the basin. The ellipses represent measured VR data from the boreholes, and illustrate that the model fits the data well.

Figure 6d, e and f show the fit of the 2-D model to the data at three points selected along the 2-D section selected to coincide with the 1-D boreholes and allow comparison of the 2-D model maturity and VR data. Figure 6e shows modelled maturity only for shallow stratigraphy due to the model layers selected for the 2-D model, the deepest of which was the Upper Coal Measures. The deeper coal measures were regarded as ‘basement’ beneath the modelled layers due to availability of data.

In general, the models fit the data well and are geologically reasonable. Using the more sophisticated and detailed 1-D models to produce a 2-D cross section was a successful approach. There is still potential to refine the 2-D model, for example, varying lithology across the basin.

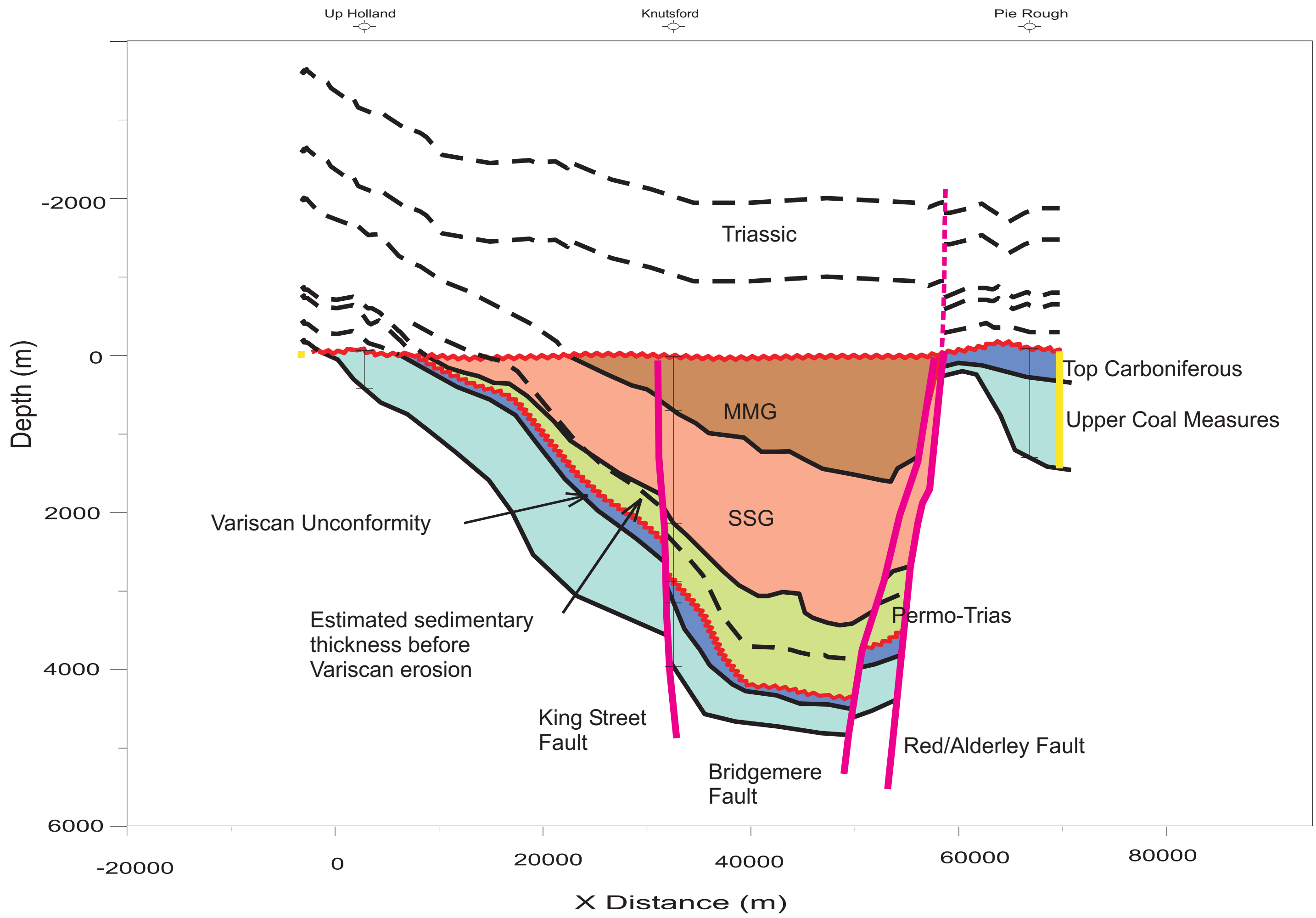


Figure 6a; Modelled 2-D Cross Section at the present day

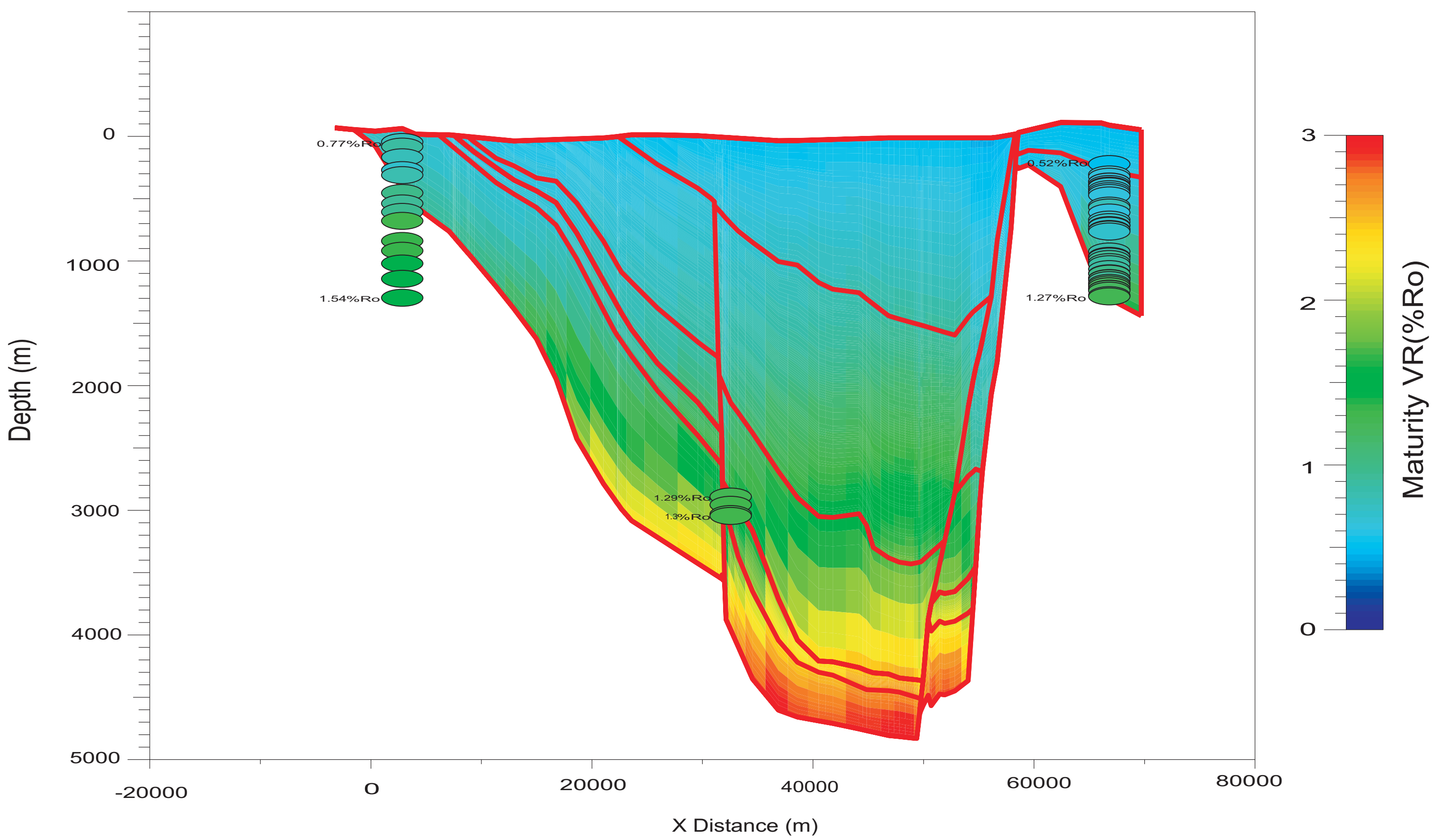


Figure 6b; Modelled maturity (VR) Cross Section at the present day

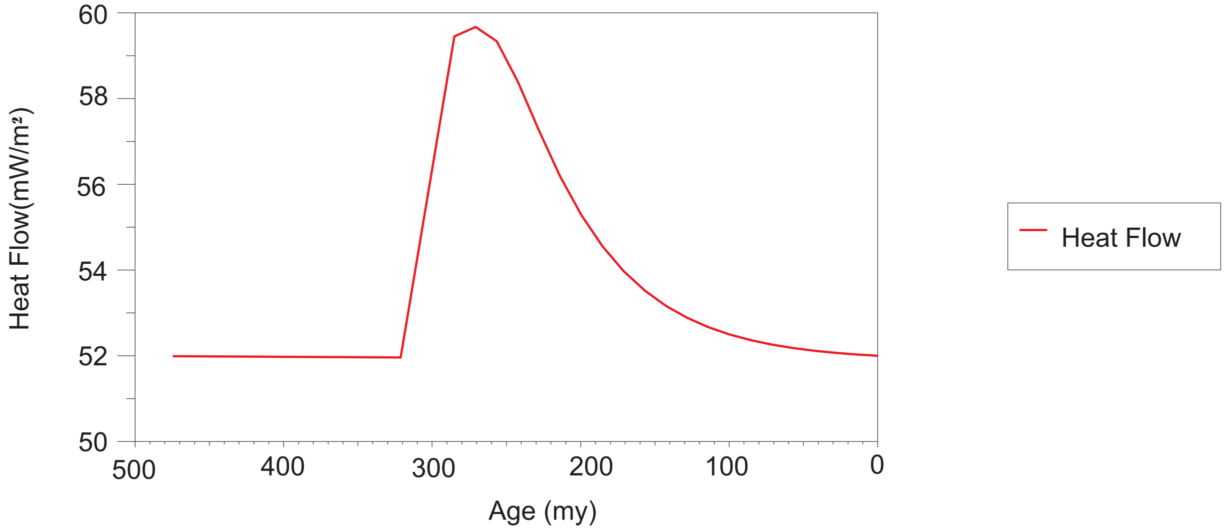


Figure 6c; Modelled heat flow across the Cheshire Basin

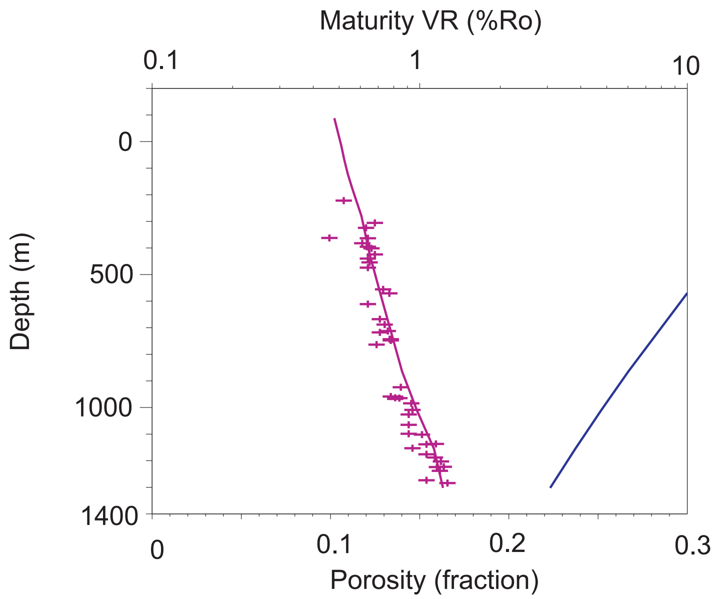


Figure 6d; Present day maturity in Pie Rough Borehole

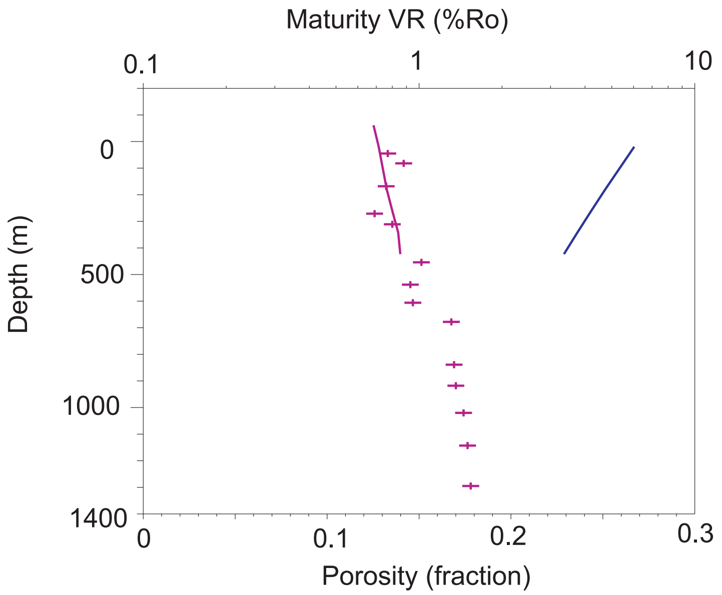


Figure 6e; Present day maturity in Up Holland Borehole

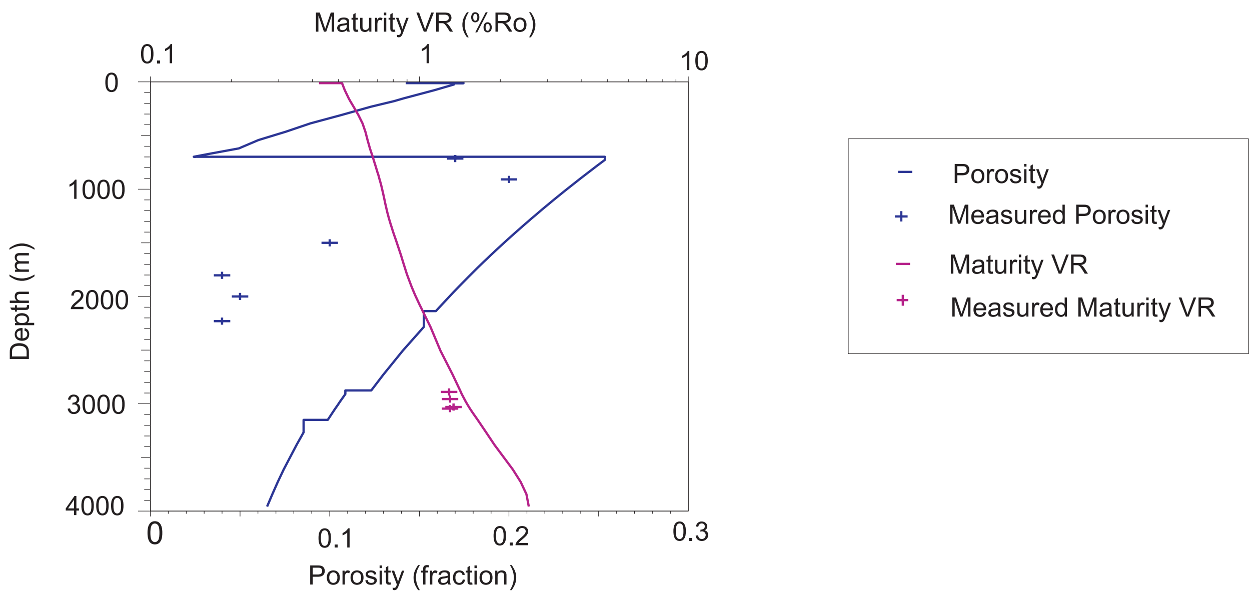


Figure 6f; Present day maturity and porosity in Knutsford Borehole

5 Input to the DGSM

BasinMod plots can be output in a variety of formats, including CGM, then imported into PowerPoint or CorelDraw, amongst other packages. The input stratigraphy and calibration data may also be output as a text file. BasinMod files may also be exported as Microsoft Word files to display the input data and chosen parameters. This file would allow reconstruction of the model, using BasinMod or another package.

The GLOS (Geological Large Object Store) is held on the BGS UNIX server kwsn. Models are stored within an individual subdirectory in the GLOS. All the models produced for this report are held within the Cheshire Basin subdirectory with 'discovery' and 'technical' metadata files which give details of the format of the files, abstract, model location, scale and detail. The model files and metadata can be retrieved through the DGSM data portal via the BGS intranet.

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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