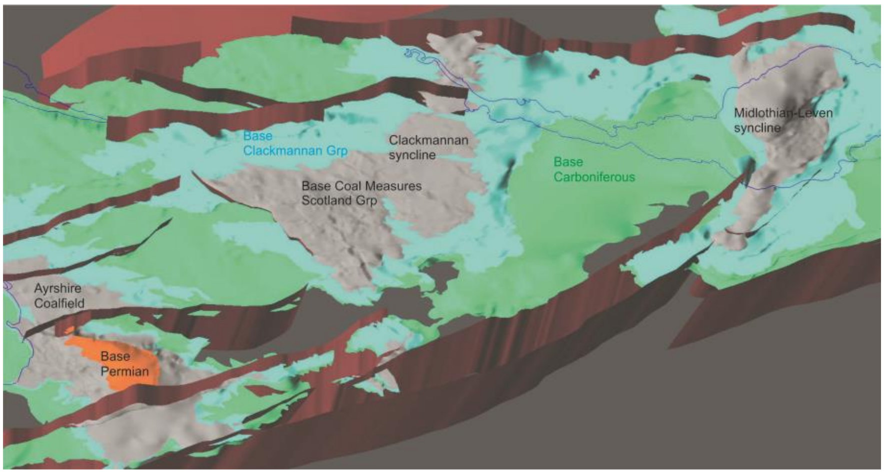
Model metadata report for the Midland Valley of Scotland Regional Model 2012/13

Geology and Landscape Programme

Open Report OR/13/032



BRITISH GEOLOGICAL SURVEY

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OPEN REPORT OR/13/032

Model metadata report for the Midland Valley of Scotland Regional Model 2012/13

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Keywords

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National Grid Reference

SW corner 171001,586010
NE corner 495900,844550

Front cover

Overview of model, looking north, 2 times vertical exaggeration

Bibliographical reference

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Forward

This report describes a 3D regional bedrock model of a selection of Carboniferous horizons covering the Midland Valley of Scotland. The report comprises a revised version of BGS internal report IR/13/013, to provide metadata documentation for the Midland Valley of Scotland Regional Model for external release.

Acknowledgements

A large number of individuals have contributed towards the model presented here – namely Tony Irving, Bill McLean, Sandy Henderson and David McInroy in data entry and interpretation, models worked on by Mike McCormac, David Millward, Tim Kearsey, Sarah Arkley, Andy Hulbert, Gaud Pouliquen and Mat Hardenberg, and geological overview and advice by Maxine Akhurst and Mike Browne.

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Summary

This report describes the revision of the Midland Valley of Scotland regional model in 2012/13 to integrate and unify models at a variety of higher resolutions that have been completed and approved between 2008 and 2012. The revised model contains a subset of only the largest faults and 4 key surfaces. It extends a significant way offshore in the east (Firth of Forth and Forth Approaches) and some way offshore in the west (Firth of Clyde). Geologist's judgement has been used in decision making for model integration. Model uncertainty is extremely variable, particularly at depth.

1 Modelled volume, purpose and scale

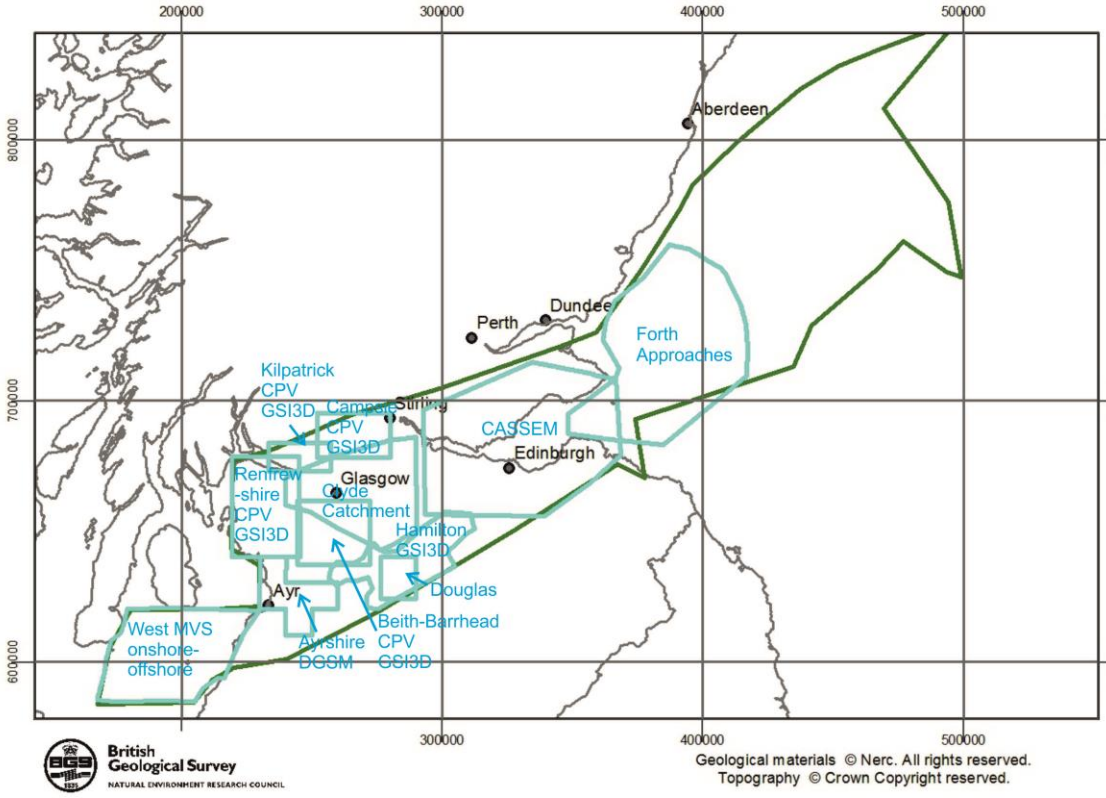

Figure 1 Map of the MVS 2012/13 regional model extent (in green) and approximate locations of the included higher resolution models (named in blue). For clarity, the boundary of the Lithoframe 250k (2008) model is not shown but was similar to the green MVS 2012/13 model

The model extends from the Firth of Clyde in the west to the Forth Approaches in the east with corner coordinates on the surface with the largest modelled extent SW corner 171001, 586010 to NE corner 495900, 844550 . Onshore borehole data recall was made between the bounding coordinates 190000, 580000 – 400000, 790000. The modelled surfaces extend from the ground or bathymetric surface (up to *c*.550m) to c. –6 km depth.

The model is appropriate for use at scales between 1:250 000 and 1:625 000. The purpose of the model is to give a regional picture of the depth and structure of key stratigraphic surfaces. These surfaces form a basis for regional resource estimation and tectonic understanding.

The Midland Valley regional model 2012/13 supersedes the Lithoframe 250k model (2008: see Monaghan and Pouliquen 2012) as it incorporates subsequent higher resolution models such as Clyde Catchment models (McCormac, 2012, 2013), CASSEM (Monaghan et al., 2008; Monaghan 2012a), Clyde Plateau Volcanic GSI3D models (Millward and Stephenson, 2011) and Forth Approaches model (Monaghan, Kearsey and McInroy, 2012). GB-3D (BGS, 2012) section lines were also integrated where appropriate. Revised borehole datasets and outcrop polygon (extents) were used to constrain the model.

The component and existing models integrated in this MVS2012/13 regional model are described by the metadata reports listed in Table 1.

Model	Report
Lithoframe 250k (2008)	Monaghan and Pouliquen, 2012
Clyde Catchment bedrock	McCormac 2012, 2013
CASSEM	Monaghan et al., 2008; Monaghan, 2012a
CPV GSI3D models	Millward and Stephenson, 2011
Douglas	Monaghan 2012b
Forth Approaches	Monaghan, Kearsey and McInroy, 2012
Hamilton GSI3D	Kearsey, 2012
West MVS onshore-offshore	Monaghan 2012c (and see also Ayrshire DGSM Monaghan and Arkley, 2012)

Table 1 Table summarising documentation of component models

2 Modelled surfaces/volumes

The model contains 4 key stratigraphic surfaces which are coloured up in Table 2 below, as well as a merged DTM/bathymetry capping surface.

Names of modelled surface (coloured) and intervening rock volumes (white)	**Lexicon Code or Surface Name**	**Equivalent names**
DTM/bathymetry	n/a	n/a
Base Permian (onshore only)	bPUND (PUND-SRLV)	Base Stewartry Group STEW, Base Mauchline Volcanic Formation MVL
Scottish Coal Measures Group	CMSC-CYCCM	Upper (UCMS), Middle (MCMS) and Lower (LCMS) Coal Measures Scotland
Base Scottish Coal Measures Group (onshore only)	bCMSC	Base Lower Coal Measures Scotland LCMS. Equivalent coals or marine bands= MUSF-SFMB-MEC-LDY-LOMB-RAIS-PORB
Passage and Upper Limestone Formations	PGP/PGV +ULGS -CYCC	
Limestone Coal Formation	LSC-CYCC	LSC and Top of limestone beds TOHO-URKI-DNLS-MCDL- MCLS
Lower Limestone Formation	LLGS-CYCC	
Base Lower Limestone Formation (onshore only)	bLLGS	Base Clackmannan Group CKN, Hurlet Limestone Member HUR and other equivalent limestone names HUR=BRLS=DMLS=UCRC=GILS=STMB=CHSL=WKL=HAWL=CBLS=PALS
Strathclyde and Inverclyde groups	SYG–CYCS + INV-SDSM	Strathclyde Group contains Lawmuir, Kirkwood, Clyde Plateau Volcanic, Pathhead, Sandy Craig, Pittenweem, Anstruther, Fife Ness, West Lothian Oil-Shale, Aberlady, Gullane, Arthur's Seat Volcanic and Garleton Hills Volcanic formations. Inverclyde Group contains Clyde Sandstone, Ballagan and Kinnesswood formations.
Base Carboniferous (onshore and offshore)	bCARB (CARB-SRLV)	Base Inverclyde Group (INV), Base Kinesswood Formation (KNW), and base Strathgryfe Lava (SGLA) and Largs Lava (LGLA) members in Renfrewshire CPV model where no Inverclyde Group is present

Table 2 MVS 2012/13 regional modelled surfaces (coloured) and intervening rock volumes (white). Volcanic formations which cut across the stratigraphy modelled are not shown (e.g. Bathgate Group, igneous intrusions)

Note that identification of the base Carboniferous can be problematic in certain situations/datasets (e.g. seismic data where the sandstone-dominated Kinesswood Formation overlies the sandstone-dominated Stratheden Group), see Browne et al. (1999) and Monaghan et al. (2008) for more details.

3 Modelled faults

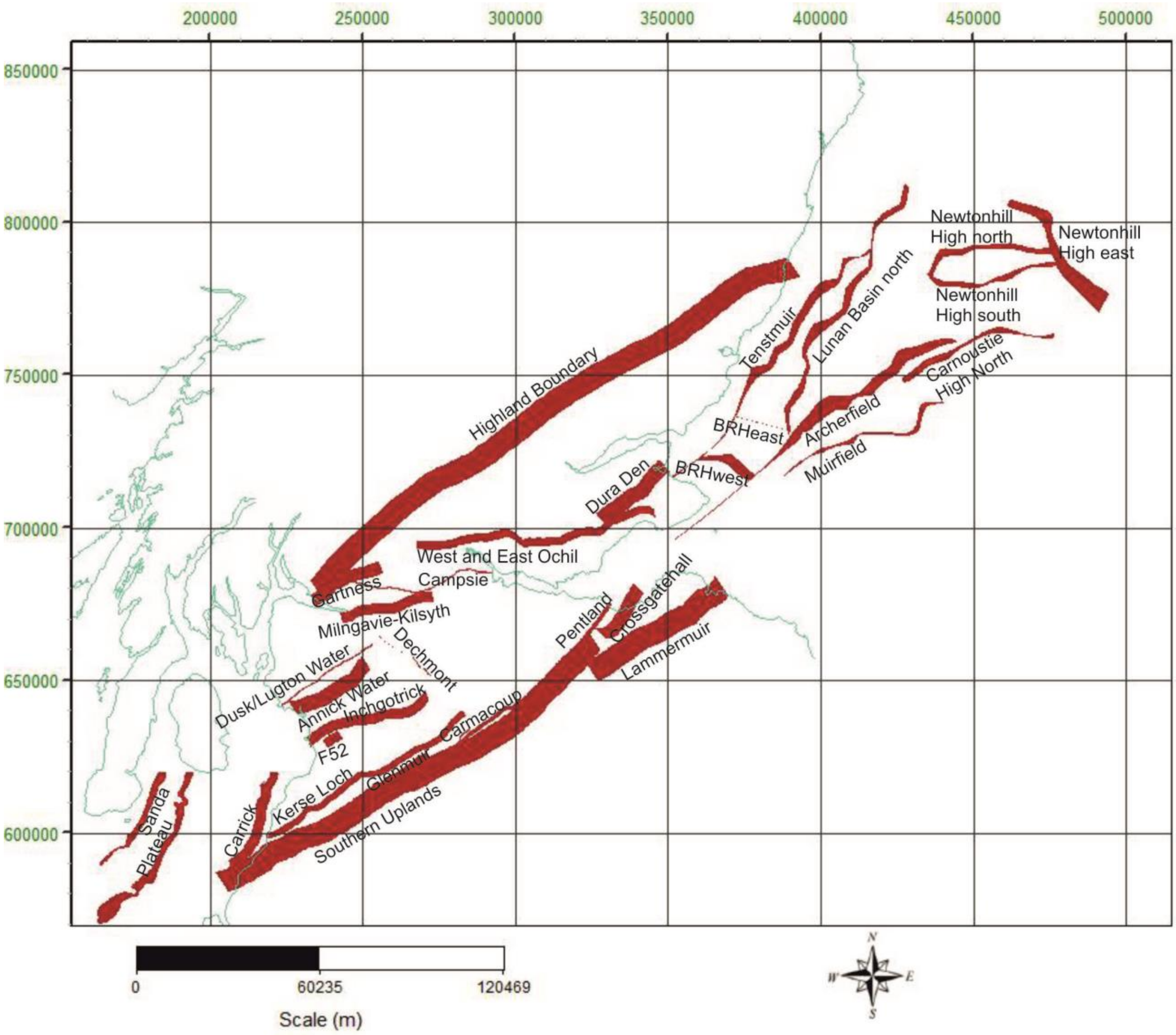

Figure 2 Named map of the modelled faults included in the MVS regional model 2012/13

Only the 31 faults with the largest lengths of tens of kilometres and/or the largest displacements of hundreds of metres, or which have in significant changes in geology across them were included in the MVS regional model 2012/13 (Figure 2). Ideally more faults of similar or slightly smaller size/throw would be incorporated in this regional model to better represent the geology of this complex area. This is particularly true in the central parts of the model (Clackmannan Syncline, West Lothian and to the east of Glasgow). Figure 3 shows some structural elements of the Midland Valley of Scotland, as discussed in the text.

Section 4.6.1 below describes in detail the source, dip and depth of the modelled faults

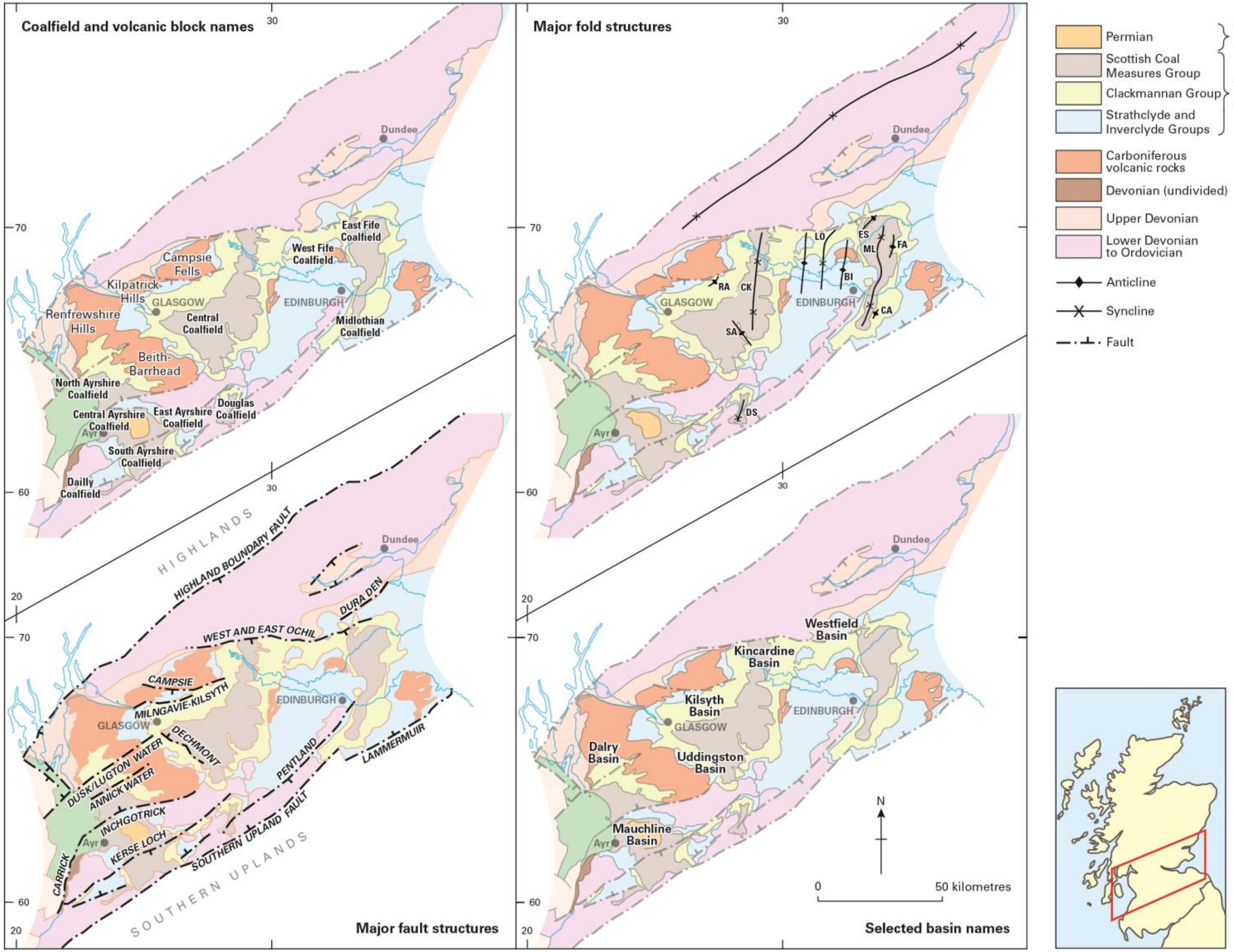

Figure 3 Structural elements of the Midland Valley of Scotland, as discussed in the text. CA Cousland – D'Arcy Anticline, ML Midlothian – Leven Syncline, ES Earl's Seat Anticline, BI Burntisland Anticline, LO Lochore Syncline, CK Clackmannan Syncline, RA Riggin Anticline, SA Salsburgh Anticline, DS Douglas Syncline, FA Forth Anticline.

4 Model datasets

4.1 DTM/BATHYMETRY

A combined 500 m resolution DTM and bathymetry surface derived for the Lithoframe 250k 2008 (Monaghan and Pouliquen, 2012) model was used as the capping surface to the MVS 2012/13 regional model. For a model at this scale, improvements to the DTM/bathymetry since 2008 should make negligible difference. This surface comprises an interpolated BGS DIGBATH 250k dataset offshore merged with a sub-sampled CEH DTM onshore. The DTM/bathymetry is used as an approximation to the rockhead surface. In some areas of the Midland Valley with a thick covering of superficial deposits covering (e.g. the Kelvin Valley) this approximation is not ideal and future work should use a rockhead surface which incorporates recent superficial deposits modelling in the Clyde Catchment and beyond.

4.2 BOREHOLE DATA

Borehole data were recalled from the BGS.Borehole_Geology database in 2012 and 2013 and edited manually to include records reaching only the base of the stratigraphic horizons and using the stratigraphic codes given in Table 1. Initially the BGS Intranet form (http://bgsintranet/projects/dgsm/dataaccess/sddbsst_start.htm) was used for the recall, and latterly the 'Magpie' system being developed was tested and used. During the recall, interpreters were prioritised in the order AAMI, other interpreters entering 'DV' or 'OV' content codes, TMCM, DJLO.

Detailed comments on borehole data are given in Appendix 1, including some data points added from well data (where wells=boreholes with geophysical logs drilled for hydrocarbon exploration). Some well data have been entered to BGS.Borehole_Geology (e.g. Firth of Forth 25/26-1) but other well data have not (e.g. Inch of Ferryton). Well data are particularly important as the wells are normally deep, with associated property information, and sometimes with core samples. Subject to confidentiality constraints, future work is required to ensure all well data interpretations are included in BGS.Borehole_Geology and/or models.

4.3 MAP DATA

Outline and outcrop curves existed from the previous version of the regional model (Monaghan and Pouliquen, 2012) for bCMSC and bLLGS surfaces based on 1:50 000 scale map data. The curves were updated to match more recent mapping and modelling work in the CASSEM, Douglas (1:10 000 scale maps) and Ayr sheet areas.

The bCMSC was further edited in the vicinity of the Salsburgh Anticline. The bCMSC curve for Ayrshire, Douglas and Midlothian-Leven Syncline was filtered at 100 m and densified to 500 m. The Central Coalfield/Clackmannan Syncline curve was filtered to 150 m and decimated to 500 m (slightly coarser because of the data distribution/reliability).

The bLLGS curve was filtered to 150 m for the central/eastern main extent polygon and 100 m for the Dailly, Douglas and Ayrshire coalfields, all were also densified to 500 m.

The bCARB outline was created by selecting and merging all Carboniferous strata onshore from DiGMapGB at 1:50 000 scale (BGS, 2010). Base Carboniferous outlines were extracted from offshore models (CASSEM, Forth Approaches, West MVS onshore-offshore) and merged with the onshore data. Carboniferous outcrops were calculated in GIS by 'erasing' where the outline polygon intersected 1:50 000 DiGMap faults and by manually editing out igneous contacts or irregularities caused by dykes. The outline curve was filtered to 250 m, densified to 1000 m and edited manually where necessary at faulted boundaries.

Outline 'extent' polygons mainly represent the true extent of a stratigraphic unit, terminating at a faulted boundary or outcrop. However, in a few places the extent represents the edge of the seismic survey, offshore model, or the coastline. These boundaries are highlighted on the contour maps of the modelled surfaces (Figures 12 – 14) for clarity.

Note also that only the major extent polygons have been included for any modelled stratigraphic horizons and that smaller, isolated extent mapped at 1:50 000 scale are missing. One notable exclusion is the base Carboniferous between Perth and Dundee (excluded at this stage due to lack of data).

4.4 MINE PLAN DATA

No mine plan data were used directly in the MVS regional model 2012/13, but they have been incorporated in many of the component models that are integrated within it.

4.5 SEISMIC DATA

No seismic data interpretation was used directly in the MVS regional model 2012/13 but seismic data were a key data source constraining the CASSEM model from the highest quality MVS dataset in the Firth of Forth (Midlothian-Leven Syncline and Forth Anticline), to lower quality onshore seismic data around the Earls Seat Anticline (Milton of Balgonie) and the Burntisland Anticline (Monaghan et al., 2008). The CASSEM model has been integrated into the MVS regional model 2012/13 (see section 4.6.2 below).

BGS has also undertaken interpretation of lower quality, widely spaced seismic data in the vicinity of the Clackmannan Syncline and Salsburgh Anticline down to base LLGS level. This seismic interpretation was incorporated into the Lithoframe 250k (2008) model resulting in a 'lumpy' modelled surface for bCMSC and bLLGS. The seismic data interpretation was re-examined for the MVS 2012/13 regional model and was difficult to reconcile in places with the sparse borehole data and mapped outcrops. In general, the seismic data interpretation appears too deep with respect to borehole data points. Thus in the area of the northern Clackmannan syncline where no higher resolution modelling has been undertaken (see 4.6.2 below), the seismic data interpretation within the previous modelled surface was smoothed and better fitted to borehole data points.

Offshore in the outer Firth of Forth/Forth Approaches (east) and Firth of Clyde (west), seismic data are the only data source constraining the existing models. Horizons within the Carboniferous have not been interpreted, or are not correlated with onshore stratigraphy and so only the base Carboniferous surface has been included offshore.

4.6 PREVIOUS MODELS INTEGRATED INTO THIS MODEL

One of the main reasons for revising the MVS regional model was to integrate and unify the higher resolution models completed in recent years. The sections below describe how this was done. The methodology followed is similar to that described by Terrington et al. (2010) for unifying and integrating legacy models in the Thames Basin.

4.6.1 Modelled Fault Planes

Some modelled fault planes were imported directly from existing higher resolution component models, others were re-modelled taking into account a number of factors as described in Table 3 below. The result is that the fault model set is not internally consistent in terms of fault dip and depth.

Fault name	Source	Dip (degrees)	Depth
Southern Uplands Fault,	Lithoframe 250k (2008) is too far south near Girvan. West MVS onshore-offshore (2004) one is very slightly different position than GB-3D. So, for this model re-digitised using Digmap 1:625 000 linework (BGS, 2008)	50 to NW	8 km
Lammermuir Fault,	Lithoframe 250k (2008) same as CASSEM, used as is	50 to NW	8 km
Crossgatehall Fault	Lithoframe 250k (2008) dipping in the wrong direction - use CASSEM fault	60 to NW	8 km
Pentland Fault,	Re_digitised from 1:50 000 scale Digmap to get full extent and consistent with CASSEM, GB-3D and Douglas (1:10 000 scale linework: known locally as Kennox fault) models	77 to NW	5 km
Plateau Fault	From west MVS onshore-offshore model (2004). Fault plane is 'bendy' but leave as is to be consistent with seismic interpretation and existing model	~70 to NW	5 km
Carrick Fault	From west MVS onshore-offshore model (2004). Fault plane is 'bendy' but leave as is to be consistent with seismic interpretation and existing model	~55 to NW	5 km
Sanda Fault	From west MVS onshore-offshore model (2004)	~70 to SE	5 km
Kerse Loch Fault,	Re-digitised from DiGMap 1:50 000 but taking into account previous modelled interpretation south of Mauchline Basin. Difficult to pick trace between Glenbuck and Dalquandy as several possible segments.	70 to SE	5 km
Annick Water Fault,	Re-digitised trace at 1:50 000 using CPV GSI3D models as a guide (note CPV GSI3D modelled faults are vertical)	50 to NW	5 km
Dusk Water (Lugton Water) Fault,	Re-digitised trace at 1:50 000 using CPV GSI3D models as a guide. Does not now include Clarkston Fault (as in Lithoframe 250k). Given steep dip to SE as throw sense varies along length	85 to SE	5 km
Dechmont Fault,	Merged segments from Clyde Catchment models, following the 1:50 000 map. To the NW the Dechmont is cut by the Blythswood , the two faults have not been joined together	75 to west in south, 89 in north	1.5 km
Campsie Fault	Re-digitised using 1:50 000 map to cover full extent with some differences from high resolution models in picked location using 1:50 000 map at western and eastern end. CPV model report has low hade (i.e. high dip) to north (though maps imply dip to south)	85 to north to fit CPV model	5 km
Ochil Fault (west and east)	East and West Ochil fault segments re-digitised as one structure using 1:50 000 map trace, though join around Powmill/Cleish area is uncertain. Eastern end extended to include Branxton Fault, so more compatible with CASSEM version of Ochil fault	65 from Rippon et al (1996) to south	5 km
Dura Den Fault	Re-digitised using 1:50 000 map trace to extend	50 to SW	5 km

	to NE towards coast		
Tentsmuir, Lunan Basin north, Brockheadeast, Brockheadwest, Archerfield, Muirfield, Carnoustie High North, Newtonhill High south, Newtonhill High east, Newtonhill High north faults	Faults imported directly from Forth Approaches model	Variable – from seismic interpretation 45 to 85	10 km
Highland Boundary Fault.	Re-digitised using Digmap 1:625 000 linework (BGS, 2008)	50 to SE	8 km
Carmacoup Fault	Imported from Douglas model	75 to SE	1.5 km
Glenmuir Fault	Kennox fault from Lithoframe 250k (2008) renamed and trimmed at c.273 622	50 to NW	5 km
f52	Bounding northern end Mauchline Basin – from West MVS onshore-offshore model	70 to S	8 km
Milngavie-Kilsyth Fault	Re-digitise trace following Clyde Catchment model	60 to SE	5 km
Gartness Fault	Re-named from Lithoframe 250k (2008) and clipped spike at base	65 to SE	8 km
Inchgotrick Fault	Re-digitised using Digmap 1:50 000 linework	60 to NW	5 km

Table 3 Definition of faults integrated in the MVS 2012/13 regional model

4.6.2 Modelled surfaces – decision making for the integrated model

Figure 1 shows the location of models that were integrated into the MVS 2012/13 regional model. In addition 16 section lines which crossed the MVS were exported from the first released version of GB-3D (GB3D_Master_Project_V6_0.gsipr: BGS, 2012) and imported as curves into GOCAD®. Combined curves for each stratigraphic unit were made (e.g. All_GB3D_CKN). However, note in drawing the GB-3D sections the Lithoframe 250k, CASSEM and Clyde Catchment models were consulted, such that they do not give much 'new' interpretation apart from on the base Carboniferous of the Clackmannan Syncline (as described in Table 4 below).

Cross-section shapefiles from 1:50 000 scale maps were also imported for three areas which were lacking in data/higher resolution models – Sheet 14E South Ayrshire, Sheet 15 W East Ayrshire and Sheet 39E northern Clackmannan Syncline, and curves for the appropriate horizons extracted as necessary.

The Table 4 below aims to summarise the higher resolution models which were incorporated into the MVS 2012/13 regional model and the associated decision making process. The accompanying Figures 4 – 6 also illustrate this. Note that for all surfaces, horizon outcrops and boreholes were also used to constrain the modelled surface (see sections 6, 7 below).

Previous model	**Description of decision making**
Base Permian	
West MVS onshore-offshore	Surface imported directly from this model. Minor spike and overlap with DTM/bathymetry removed.
Base CMSC	
Lithoframe 250k	Used as basis in the northern Clackmannan Syncline, but smoothed and manipulated to fit borehole data better. Used as a basis in north-east and south Ayrshire Coalfield apart from in the vicinity of cross-sections noted below.
CASSEM	Midlothian-Leven syncline taken as is. Not used at western edge Clackmannan Syncline
Clyde Catchment	Used as is, version supplied by MMCC 30/01/13
Douglas	Used as is. Note outcrop from most recent 10 000 maps used in this model differs from

	much older linework on Digmap1:50 000
CPV GSI3D models	Renfrewshire CPV model used
GB-3D section interpretation	Appears well fitted to existing models – already assessed. Not used.
1:50,000 scale map section interpretation	Lithoframe 250k model not well fitted to map cross-sections which are taken in preference in south and east Ayrshire, and northern Clackmannan Syncline
Base LLGS	
Lithoframe 250k	Used as basis in the northern-western Clackmannan Syncline, but smoothed and manipulated to fit borehole data better. Used as a basis in north-east and south Ayrshire Coalfield apart from in the vicinity of cross-sections noted below. Used for the Dailly Coalfield.
CASSEM	Used majority of modelled surface apart from in the southern Clackmannan Syncline where took Clyde Catchment in preference. In the northern-eastern Clackmannan Syncline used as a basis but smoothed and manipulated to fit borehole data better.
Clyde Catchment	Used as is, version supplied by MMCC early Feb 2013.
Douglas	Used as is
CPV GSI3D models	Used Renfrewshire and Beith-Barrhead CPV GSI3D models apart from where took Clyde Catchment in preference in East Kilbride, Kilsyth and Johnstone area the GOCAD® model is neater with smaller triangle resolution and the interpretation is similar. Used Campsie Fells CPV GSI3D model
GB-3D section interpretation	Appears well fitted to existing models (though smoother) – already assessed. Not used.
1:50,000 scale map section interpretation	Lithoframe 250k model not well fitted to map cross-sections which are taken in preference in south and east Ayrshire. Cross-section in Clackmannan Syncline does not reach these depths.
Base Carboniferous	
Lithoframe 250k	Used as basis in north-east and south Ayrshire apart from in the vicinity of cross-sections noted below, around and SE of Glasgow and at the southern end of the Midlothian Coalfield. Not used in Clackmannan Syncline as overlaps with bLLGS surface and not consistent geometry with overlying strata – GB-3D section lines used in preference here.
CASSEM	Taken as is in eastern MVS, apart from in the far east in the Firth of Forth where unconstrained by data, where the Forth Approaches dataset is taken in preference
Forth Approaches	Taken as is over most of the area but did not include far west of surface where poorly data constrained as used CASSEM surface here in preference.
Hamilton	Taken as is, though surface smoothed in northern part
CPV models	Extracted base Kinnesswood Fm surface from all 4 GSI3d models apart from a small area of Renfrewshire CPV GSI3D where the base of lava units LGLA and SGLA2 form the base Carboniferous
GB-3D section interpretation	Used in the Clackmannan Syncline where no Clyde Catchment model (only reaches bLLGS surface) and Lithoframe 250k model does not appear consistent with overlying surfaces. Also used in east Fife between the CASSEM and Forth Approaches datasets, where there is no other data.
1:50,000 scale map section interpretation	Lithoframe 250k model not well fitted to map cross-sections which are taken in preference in south and east Ayrshire. Cross-section in Clackmannan Syncline does not reach these depths.

Table 4 Description of the models integrated for each modelled surface and the logic used in decision making

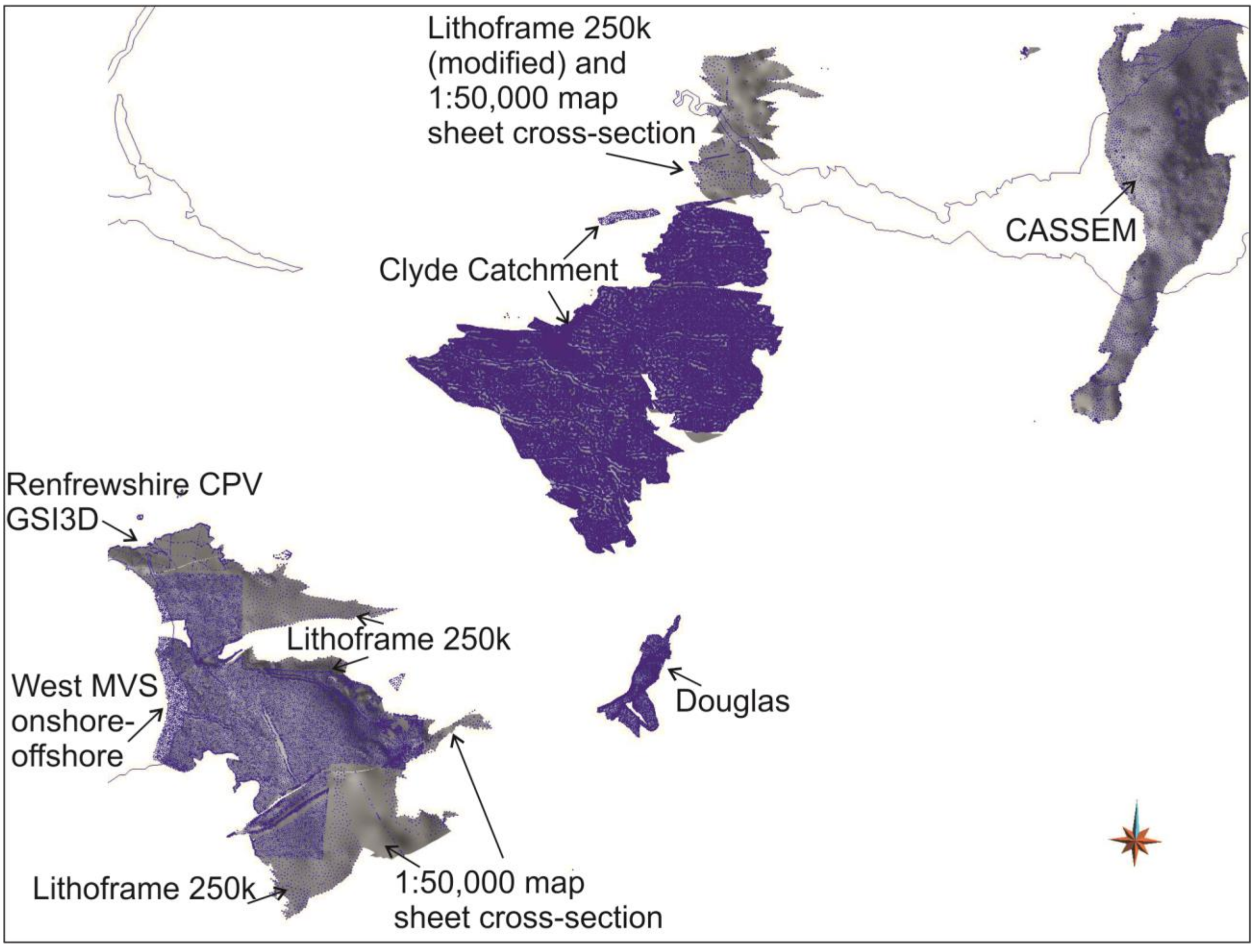

Figure 4 Map view showing the location and data density of previous models integrated (via extract of pointsets) for the base Scottish Coal Measures Group modelled surface.

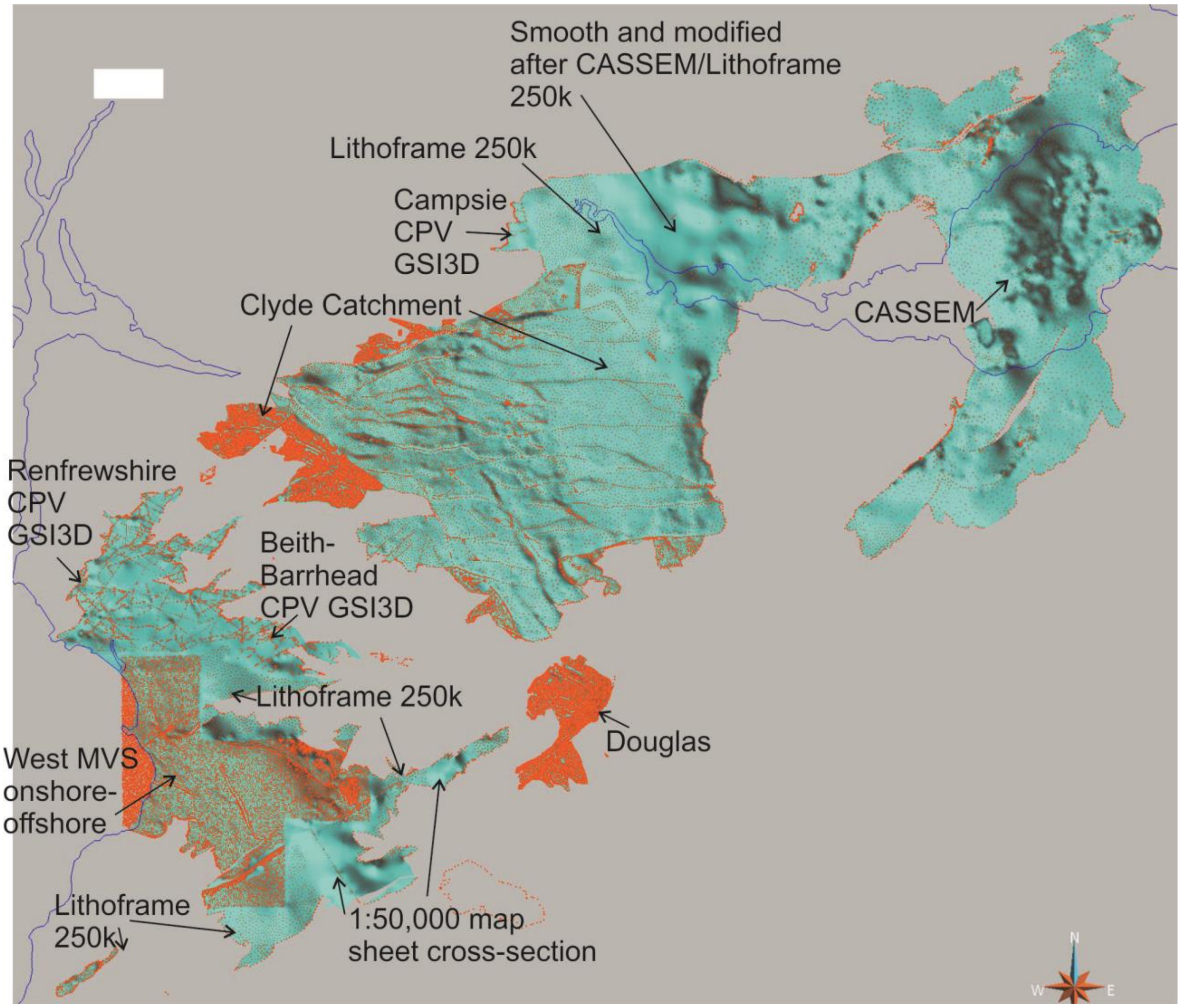

Figure 5 Map view showing the location and data density of previous models integrated (via extract of pointsets) for the base Lower Limestone Formation (base Clackmannan Group) modelled surface.

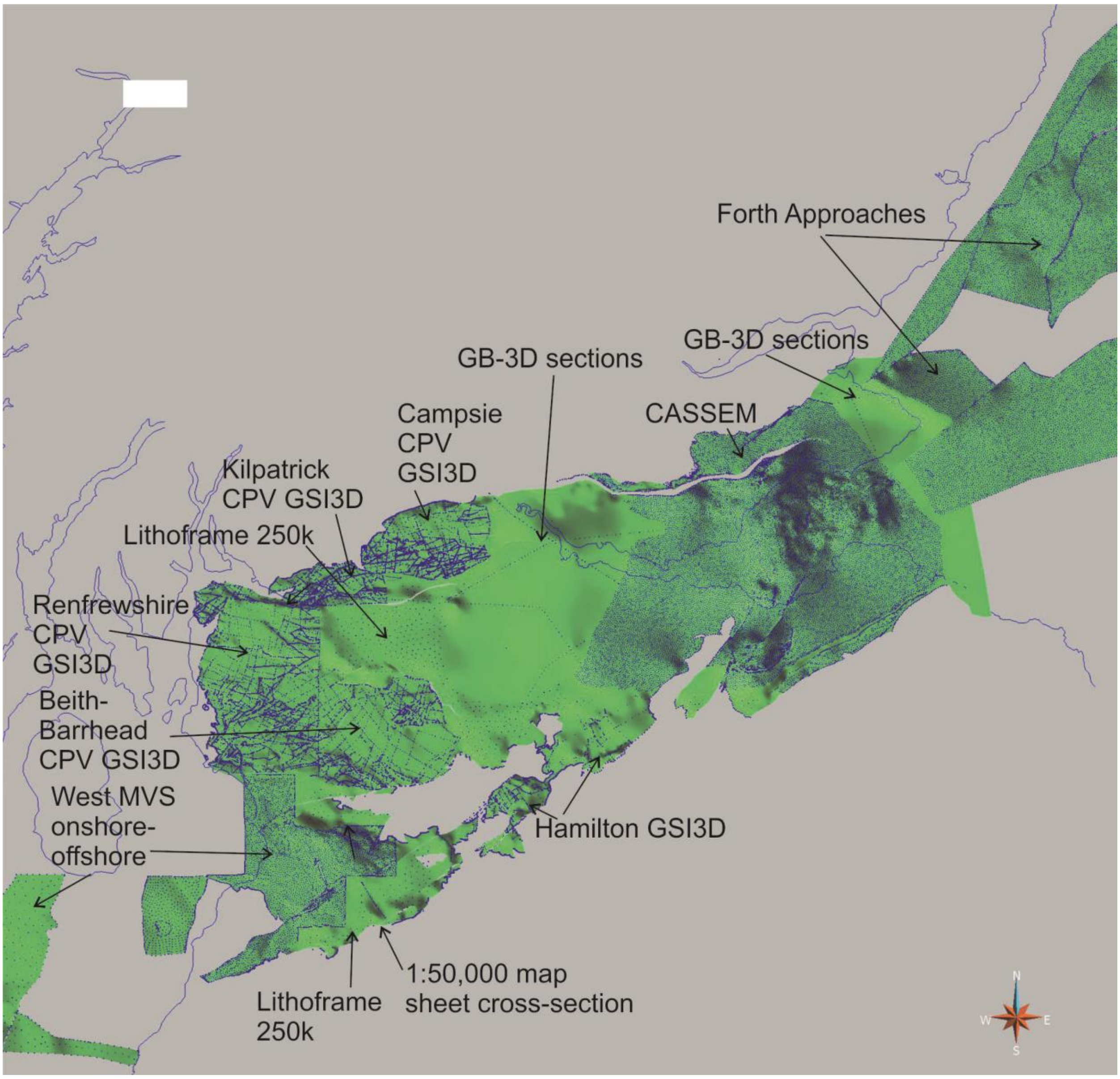

Figure 6 Map view showing the location and data density of previous models integrated (via extract of pointsets) for the base Carboniferous modelled surface.

In summary, the decision making process for incorporating previous models as described above evaluated a number of factors, very similar to those described in Terrington et al (2010) including

- Knowledge of data density, type and completeness used to constrain the original model
- Knowledge of original modelling software, modeller experience, methodology
- Relative age of modelling
- Geological consistency of models

4.6.2.1 Exclusions

Models that were excluded from the MVS 2012/13 regional model include models deemed superseded and not included for consideration in the NGM (e.g. Fife onshore-offshore models pre-dating CASSEM) and much higher resolution or commercial-in-confidence models e.g. Central Glasgow, Ravenscraig. Individual models from the Glasgow area such as Larkhall, Motherwell etc had already been incorporated into the Clyde Catchment model.

4.7 INTERPRETED DATA

Cross-section interpretations from GB-3D and 1:50 000 maps are used in places, as described above (Table 4).

5 Dataset integration

For each modelled horizon, pointsets derived from boreholes reaching the unit base and outcrops projected onto the DTM/bathymetry surface were combined with pointsets extracted from the higher resolution models described in Table 4 and Figures 4 – 6 above.

6 Model development log

All modelling was done by Alison Monaghan between August 2012 and March 2013. In summary the steps involved:

- Data preparation project for each modelled unit
- Creation of fault model project
- Creation of initial and then refined surfaces for each modelled horizon, working downwards from base CMSC
- Model cleaning, checking, refinements

7 Model workflow

The overall principle for data was to use newly-recalled borehole sets defining the base of the stratigraphic units, with outcrop data/extent envelopes and combined with pointsets extracted from previously completed higher resolution models across the Midland Valley (see Table 4 and Figure 4 – 6 above). Where no higher resolution models existed, the Lithoframe 250k (2008) model was used as a guide and replaced by GB-3D or 1:50 000 scale cross-section data in local areas as appropriate (see Table 4 above).

The GOCAD® structural workflow manager (GOCAD® version 2009.4) was used as standard to create a faulted model and faulted horizon surfaces.

During the faulted horizon modelling, points within a tolerance of faults were excluded. The tolerance varied from 100 – 500 m dependent on the dataset. The larger values were generally used in the areas of GSI3D-derived data where the faults had previously been modelled as vertical and so were not coincident with the faults in this model.

Manual editing of fault-horizon contacts was necessary in a few cases, often where spikes occurred in the vicinity of smaller faults from the higher resolution models that were not included in MVS 2012/13 regional model.

Some additional manual editing was performed at the discretion of the geologist/modeller. These included:

- Smoothing of regions – mainly from areas of GSI3D-derived data which had numerous faults in the original model
- Manual editing of spikes – mainly relating to vents or faults modelled in GSI3D-derived data that were not included in this model.

- Remove crossovers –between horizons towards the basin margins where the succession is thin, and between the modelled base unit and the DTM/bathymetry
- Fit surface to pointsets of borehole data in areas where these are not fitting particularly well (e.g. northern Clackmannan Syncline). A slightly convoluted method was used because doing a simple 'fit to pointset' created undesirable edge effects a long way across the modelled surface and there was not the function to set an influence distance from 'fit to pointset'. Using 'well markers fit' via the workflow would allow an influence distance to be used. This was tried, but the project setup with several parts of surface for each horizon and the naming conventions used meant that it was difficult to create the stratigraphic column necessary for this function to work. Also, working with over 600 'well markers' for the bLCMS caused the project to run extremely slowly. So, fitting the surface to problem borehole data points was done by:
    - Create region of points to set control nodes on away from problem borehole fits, leaving a good gap to smooth the interpolation
    - Set control nodes on that region only
    - Run 'fit to pointset' do not 'insert points' (as this splits mesh and created new control nodes in all areas) but do insert control nodes. Check fit etc.
    - Unset the control nodes on the region defined previously
    - Re-add control nodes to fault borders, where these existed before (set control node, on border)
    - Unset control nodes on the pointset used
- Boreholes proving the modelled stratigraphic units but not reaching their base (e.g. total depth (TD) *within* LCMS) were used to create an unfaulted surface. The modelled surface of the base of the unit (e.g. bCMSC) should be *deeper than* this surface. Areas where the modelled base unit surface was above the 'deeper than' surface and constrained by borehole data on the 'deeper than' surface were manually selected as a region. Using 'remove crossovers' the base unit modelled surface was pushed down beneath the 'deeper than' surface. This operation was only necessary in fairly small, patchy areas, generally around the basin margins.

Thus, in summary, the higher resolution models across the Midland Valley were integrated and unified by (i) decision making as to model to be used (ii) extraction of pointsets from previous models, combination with borehole and outcrop data and re-interpolation (iii) various manipulation and smoothing steps as described above.

8 Model assumptions, geological rules used

It was assumed that the borehole data proving the base of a unit was a correct interpretation at the correct depth from BGS.Borehole_Geology and that this dataset has the highest confidence to fit the modelled surface. Obviously visible inconsistencies were checked and removed as part of the modelling process.

The data selection and workflow (sections 4 and 7) in the MVS 2012/13 regional model were a process of integrating and summarising previous higher resolution models via re-interpolation and geologist judgement. That is, the MVS 2012/13 regional model does not fit the component models exactly, and it is usually of a consistent and coarser TIN resolution. It provides a single unified summary of the component models appropriate for use at scales between 1:250 000 and 1:625 000.

Unit thicknesses are extremely variable within and between sub-basins of the Midland Valley and so it is not possible to have a set of rules of unit thicknesses to be maintained.

9 Model limitations

There are a number of areas where the modelled surfaces do not fit well to the controlling pointsets extracted from higher resolution models. This is intentional and a result of the judgement of the geologist/modeller in choosing the datasets and in modelling operations performed. The areas that do not fit well the controlling pointsets are:

- Along datasets defining the footwall and hangingwall intersections of units with fault planes previously modelled in higher resolution GSI3D models but where faults are not included in the MVS2012/12 regional model. Because the GSI3D faults were modelled as vertical features there are two data points with the same XY location but different Z values (Figure 7). The GOCAD® interpolation smooths between the two Z data points but fits neither, rather giving a smoothed version of the fault plane (Figure 7). In some areas (e.g. Campsie and Kilpatrick CPV GSI3D models on bCARB) there are almost more fault planes with two Z values than section line points to constrain the surface. It was considered whether to include only the cross-section and outcrop line points to give a smoother, better fitted result, but this would result in no representation of the modelled faults and so this method was not used.

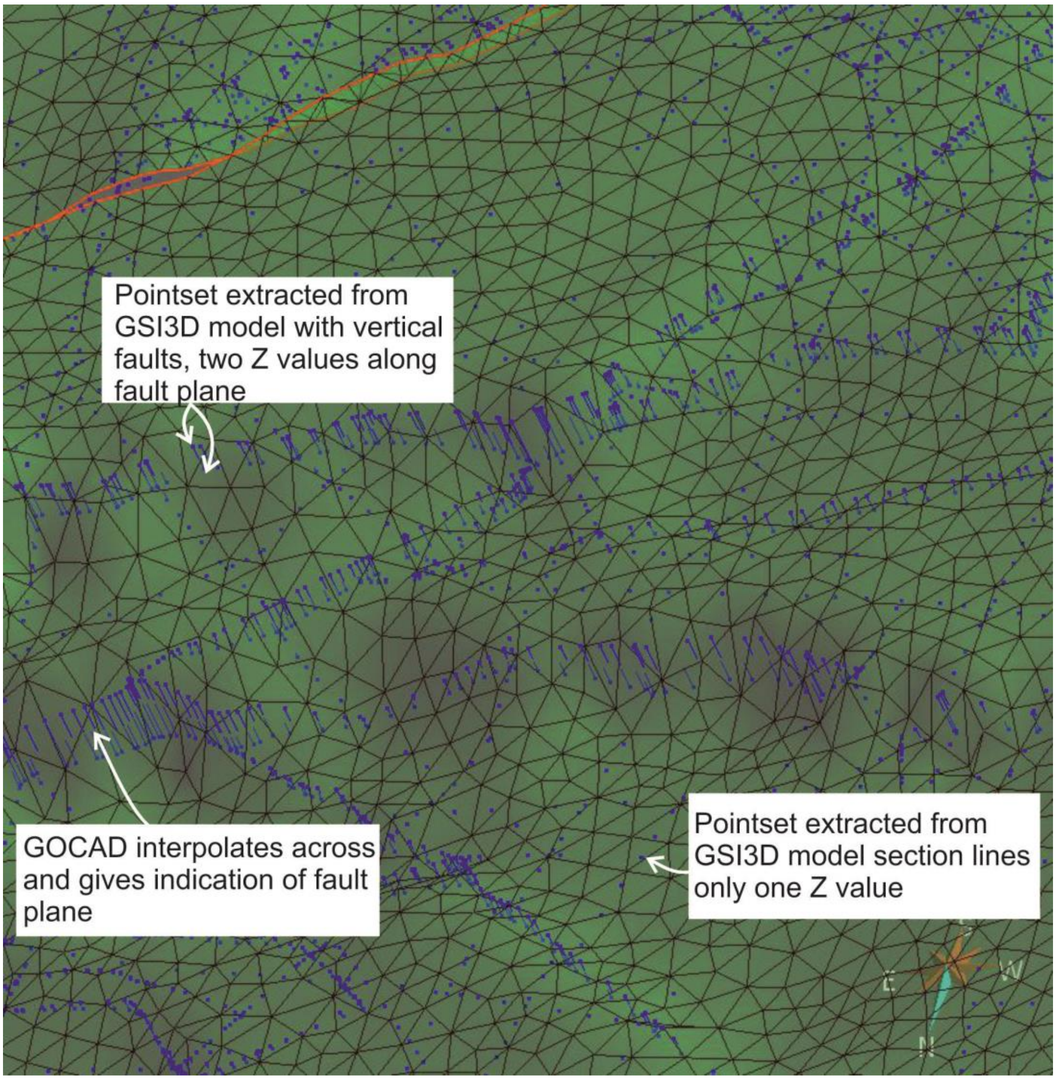

Figure 7 Image showing fit of GOCAD® interpolation to a pointset extracted from a GSI3D model containing numerous vertical faults.

- Smoothing – regions were created for some very ‘lumpy’ parts of the surface (with derivation from seismic or GSI3D section line data) and were re-interpolated with a smoothing applied.
- Regions were identified (e.g. northern Clackmannan Syncline) where the fit of the incorporated model pointset (from a seismic interpretation) to borehole data was poor. Fit to boreholes was performed (see Section 7) but this results in the modelled surface not fitting the control data pointset from a legacy model.
- Excluding erroneous data along fault planes etc - for example along the western part of the Ochil faults on bCARB points have been erroneously included in the data file, but these have been excluded from the fault-horizon modelling by using a tolerance distance.
- Given the shallower depths in surrounding higher resolution models, the bLLGS (base Clackmannan Group) surface in the northern Clackmannan Syncline is likely to be modelled too deeply. The few deep borehole points available are honoured but there are none in central and eastern parts of the syncline where the model is based on the Lithoframe 250k (2008) interpretation which incorporated seismic interpretation. Additional borehole/well data plus higher resolution modelling is recommended for this uncertain area of the model.
- Future work should include an updated rockhead model onshore-offshore and include all well data not currently available in BGS.Borehole_Geology.
- Igneous rocks have not been modelled specifically, though large parts of the region are cut by igneous intrusions and vents. Extrusive igneous rocks have been modelled within the rock volumes constrained by the base stratigraphic surfaces, apart from the Bathgate Group (Bathgate Hills, Kinghorn and Salsburgh volcanic formations) which in places span the base Lower Limestone Formation/Clackmannan Group boundary.
- Only a small subset of the faults identified across the MVS have been used. The faults used, their dips and depths result from a variety of geological and previous modelling sources (Table 3). The throw sense along some faults is quite variable. In some cases, this reflects the mapped offsets and in others it relates to previous modelled interpretations or issues including/excluding data points around fault planes that were previously modelled in a slightly different location or with a differing dip.
- Small outcrops (outliers) of the modelled unit are excluded from the MVS 2012/13 surfaces modelled at regional scale. Small holes (inliers) have also been excluded.

10 Model images and basin structure

The integrated MVS2012/13 regional model clearly shows the main structural elements of the Midland Valley basin (Figures 8 – 14). The model defines in the subsurface the position of key stratigraphic horizons and should be a valuable tool for regional evaluation for resources such as unconventional hydrocarbons, geothermal energy etc, subject to the limitations and uncertainty described in sections 9 and 11.

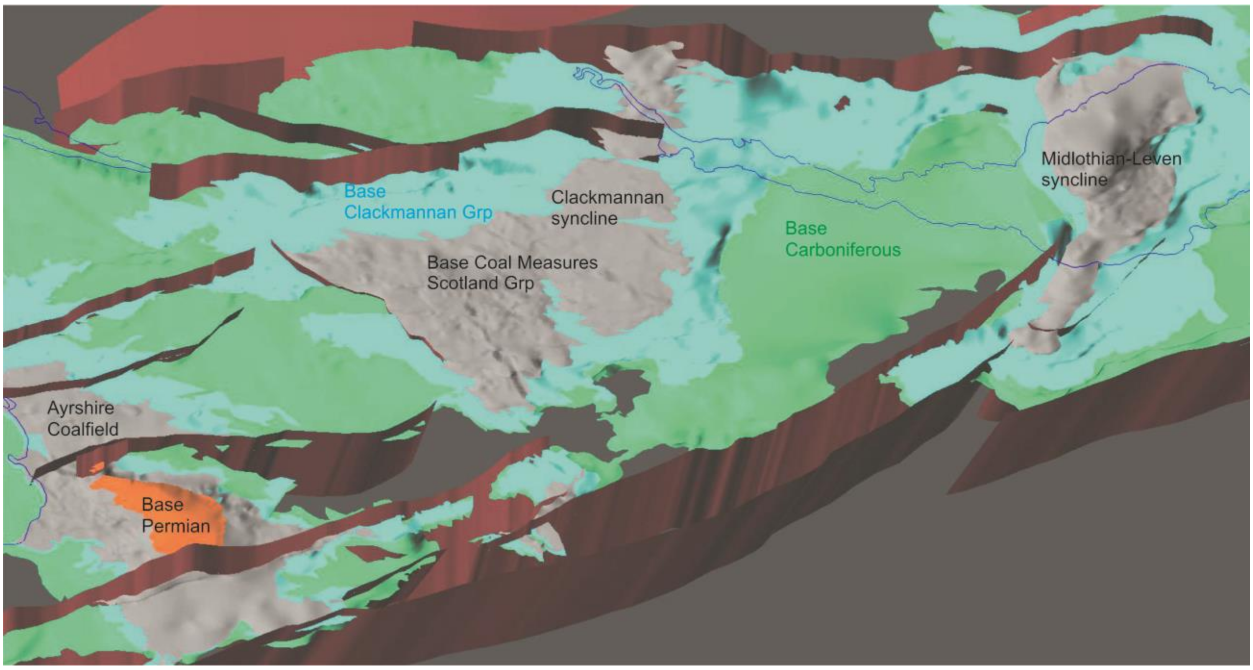

Figure 8 Image showing overview of the modelled surfaces and fault, looking north, two times vertical exaggeration, for the onshore area of the model.

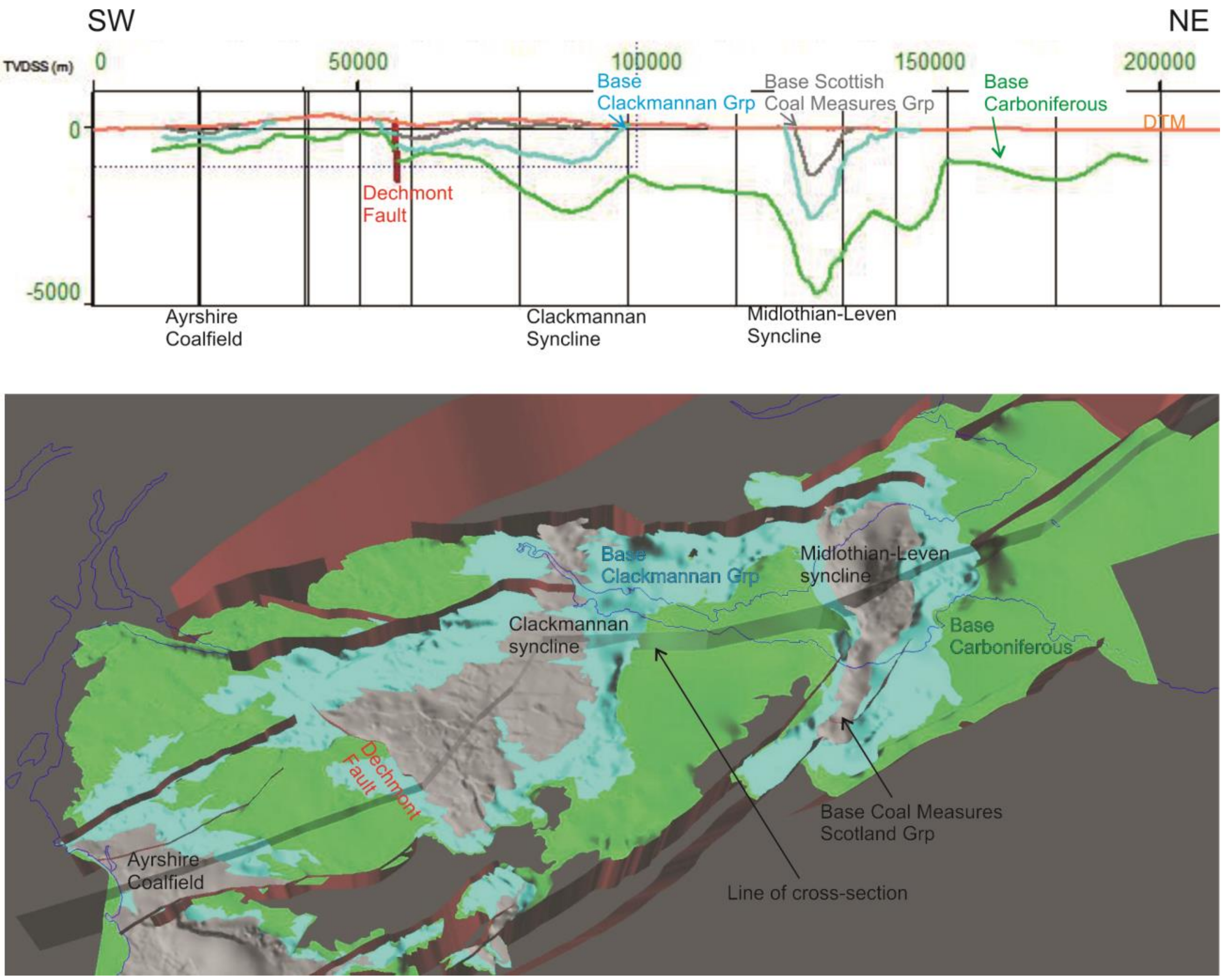

Figure 9 Images of SW to NE cross-section of the model showing some of the main structural features. Note that the cross-section is significantly vertically exaggerated, with both axes labelled in metres.

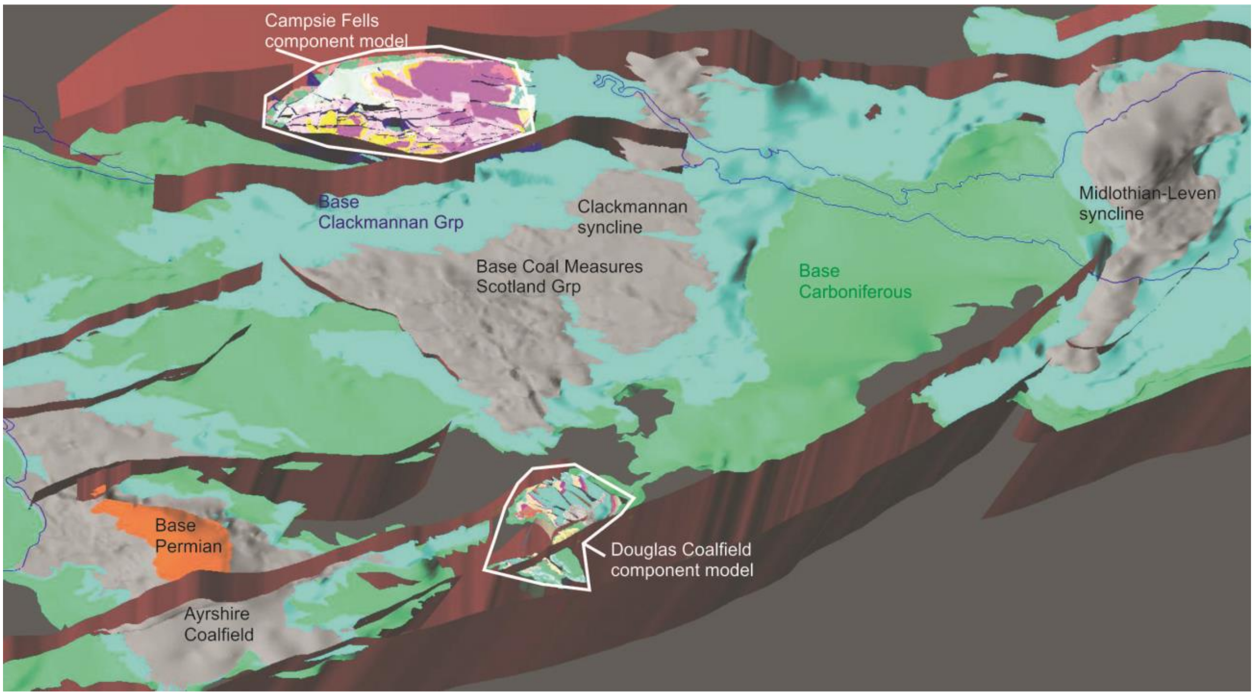

Figure 10 Image giving an example of two higher resolution models (Campsie Fells and Douglas Coalfield) to give an example of the construction of the MVS regional model 2012/13 integrated from multiscalar component models.

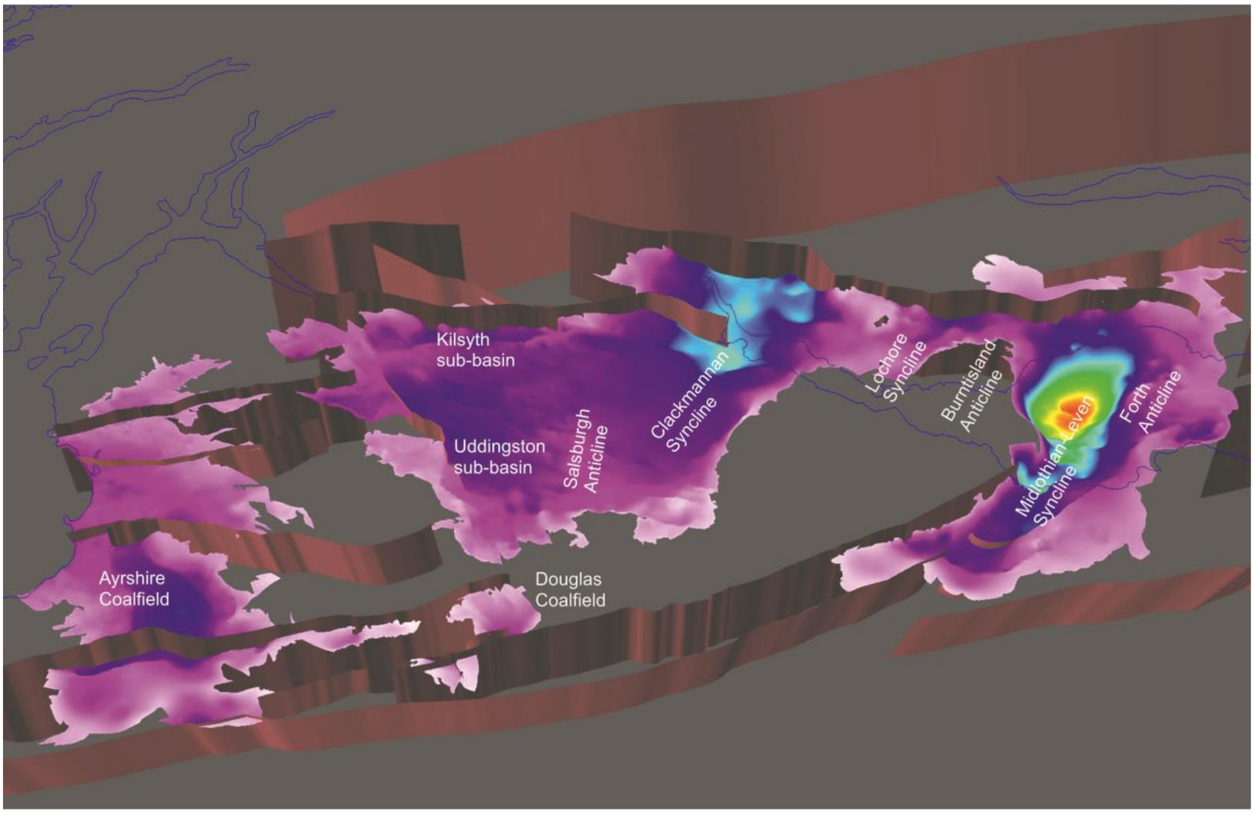

Figure 11 Looking north on the bLLGS modelled surface with faults shown and main structural elements labelled, vertical exaggeration x2

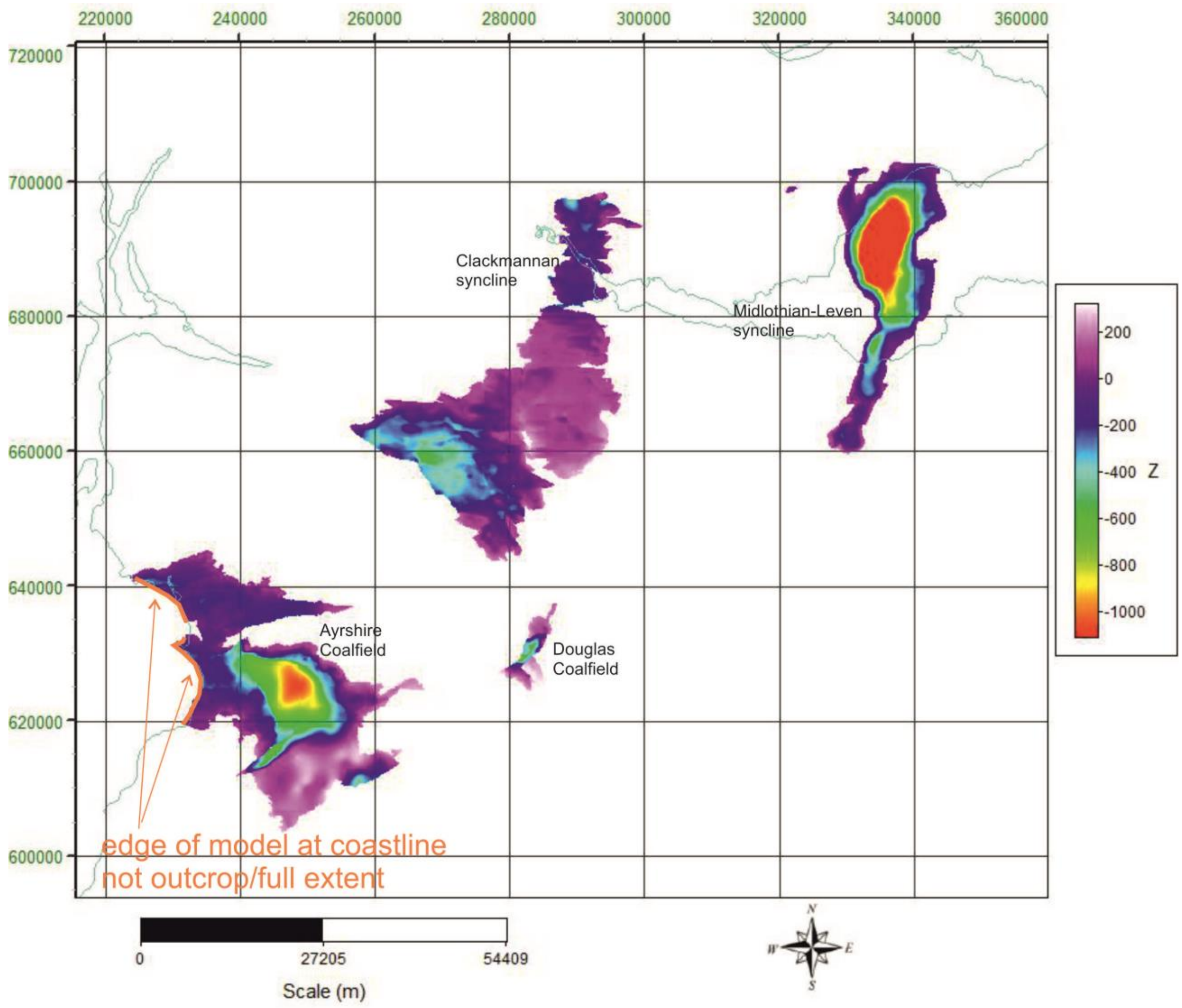

Figure 12 Contour map on Base Scottish Coal Measures Group (minor outcrops are not modelled)

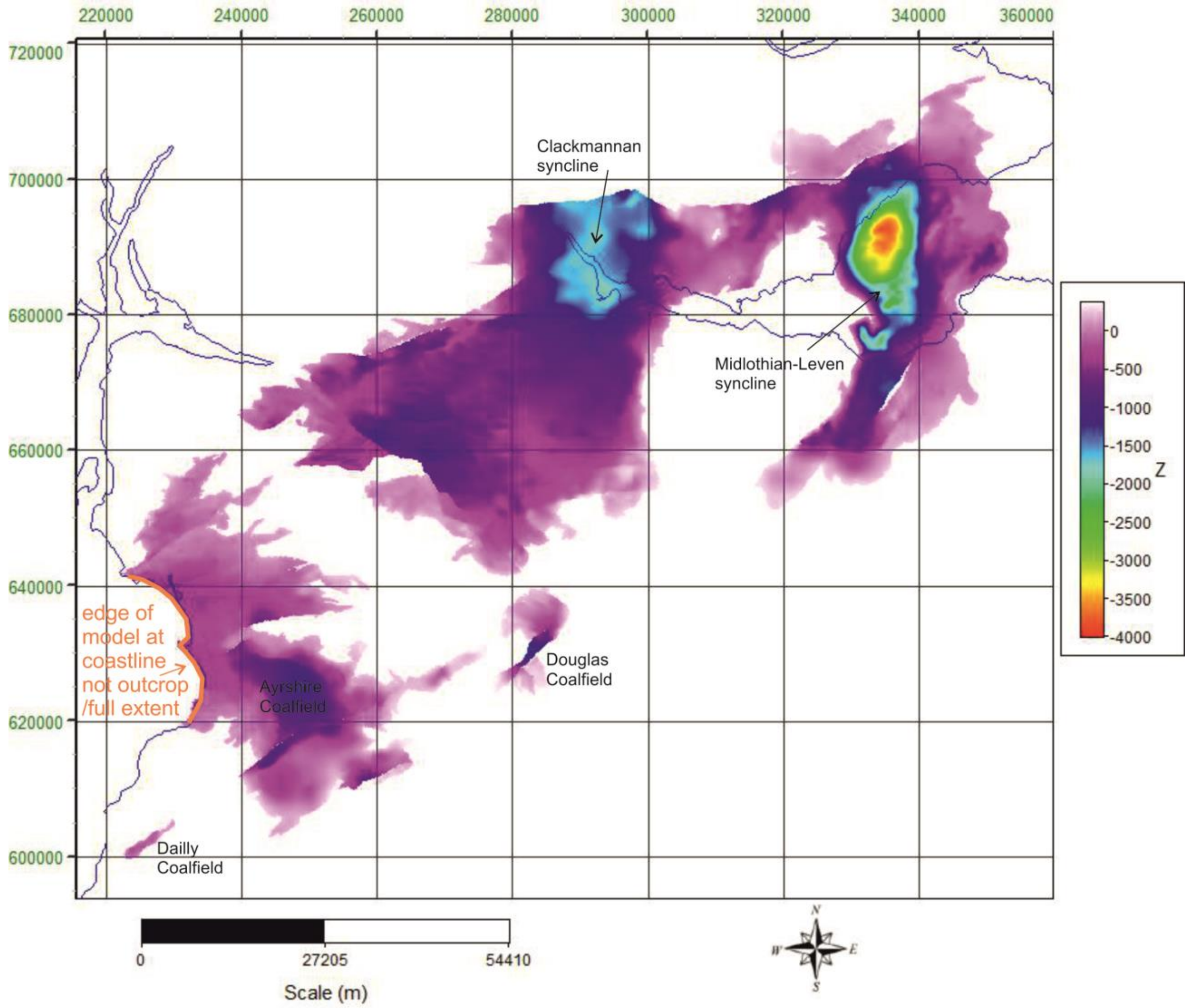

Figure 13 Contour map on Base Lower Limestone Formation/Clackmannan Group (minor outcrops are not modelled)

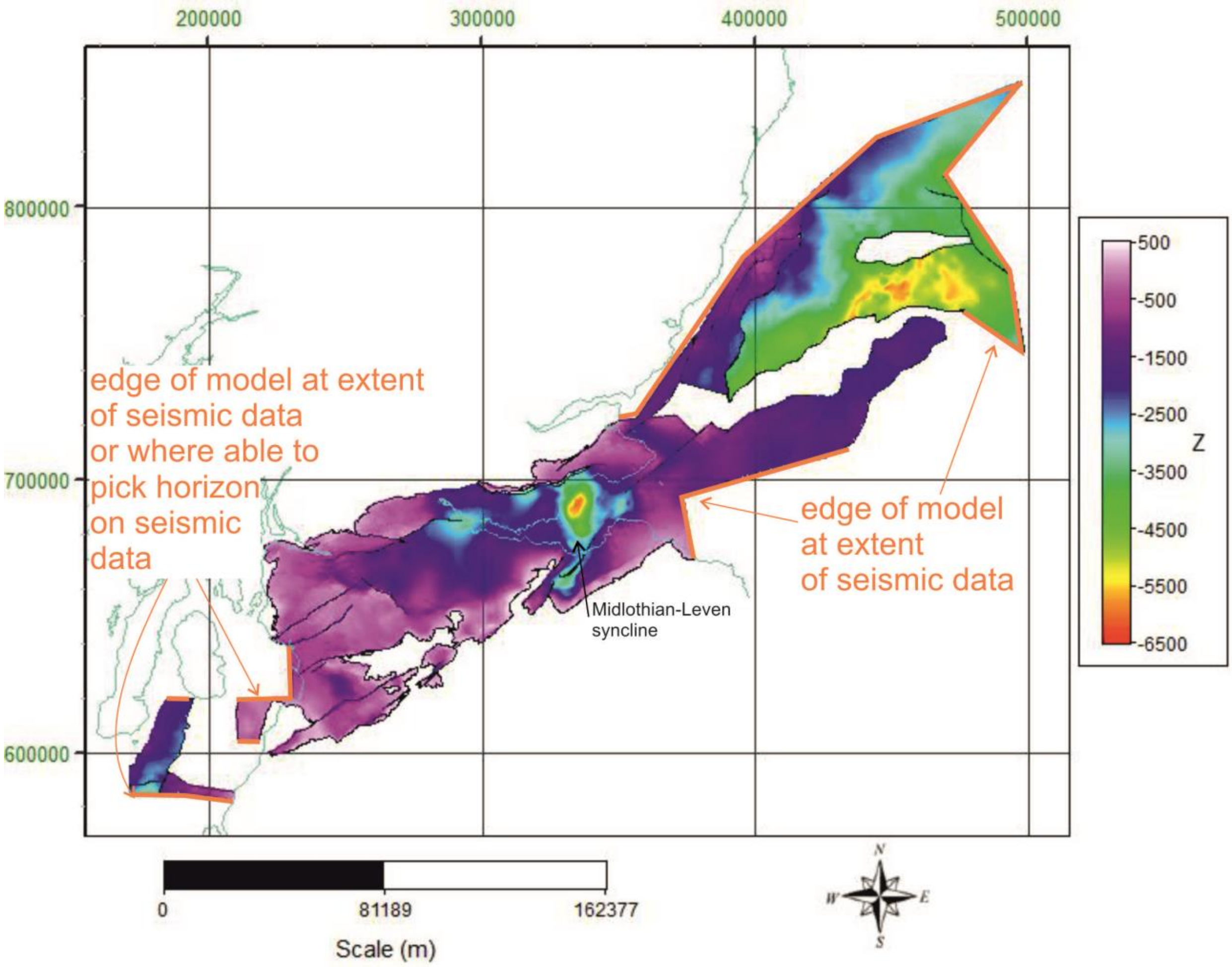

Figure 14 Contour map on Base Carboniferous (minor outcrops are not modelled)

11 Model uncertainty

No detailed or quantitative uncertainty has been undertaken due to the difficulty of assigning values to the numerous different datasets and models incorporated within this integrated model. A summary of the model uncertainty as judged by the geologist/modeller is:

bPUND – fairly certain, maximum uncertainty of a few tens of metres.

bCMSC- fairly certain, maximum uncertainty of up to about 100 m, most uncertain in areas not covered by higher resolution modelling (e.g. south and east Ayrshire, northern Clackmannan syncline, southern Midlothian syncline).

bLLGS –moderately certain to uncertain, quite variable, maximum uncertainty of a few hundred metres, most uncertain areas in deepest parts not constrained by borehole data and areas lacking in higher resolution models.

bCARB – mainly uncertain apart from locally close to outcrop, maximum uncertainty of up to around 500 m or possibly more. Uncertain over many deeply buried parts, especially those with no higher resolution modelling or seismic data (e.g. Central Coalfield/Clackmannan Syncline).

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Appendix 1 Detail of edits to borehole data

Base LLGS data file – two deep boreholes Rashiehill and Valleyfield go into volcanic rocks and having looked at the records these are probably very near the base LLGS so have been kept in the data file.

NT39NW 334 recalled record was edited by hand as this underground borehole has an erroneous start height in SOBI, it should be at -543m.

Added to base LLGS to the dataset from the Inch of Ferryton borehole (290777, 690150) – from M Browne unpublished report at 5663ft drill depth, start height 9.78 so Z=-1715 m. Base INV was also added at 6520 ft = -1978 m. This well record is not currently in BGS.Borehole_Geology as it is a ‘DTI’ well.

Added interpretation record of Salsburgh 1A well (WLO to UEXD by AAMI at -941.71) into Base Carboniferous dataset, though this it is possible that the igneous rocks could be CPV?