



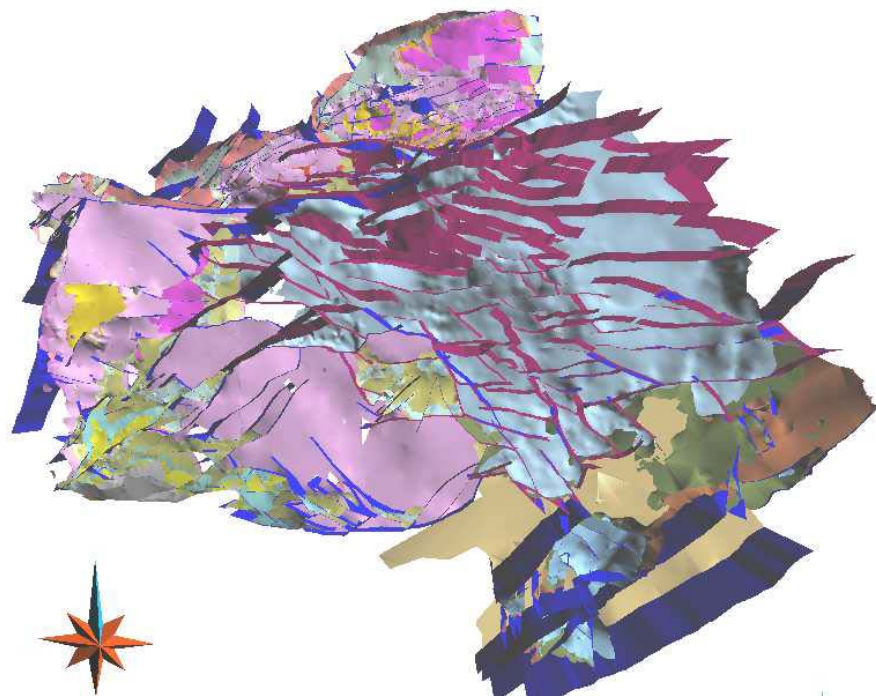
**British
Geological Survey**

NATURAL ENVIRONMENT RESEARCH COUNCIL

Bedrock GSI3D models from interpreted data in geologically complex Carboniferous terrains: A work in progress from the Clyde catchment area, Midland Valley of Scotland

Geology & Landscape Scotland

Internal Report IR/11/052



BRITISH GEOLOGICAL SURVEY

GEOLOGY & LANDSCAPE SCOTLAND

INTERNAL REPORT IR/11/052

Bedrock GSI3D models from interpreted data in geologically complex Carboniferous terrains: A work in progress from the Clyde catchment area, Midland Valley of Scotland

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Licence No: 100017897/2011.

Keywords

Report; GSI3D; geological model; Clyde Plateau Volcanic Formation.

Front cover

Clyde Plateau Volcanic Formation within whole catchment Geovisionary model (T Kearsey).

Bibliographical reference

MILLWARD, D, STEPHENSON, D. 2011. Bedrock GSI3D models from interpreted data in geologically complex Carboniferous terrains: A work in progress from the Clyde catchment area, Midland Valley of Scotland. *British Geological Survey Internal Report*, IR/11/052. 58pp.

Copyright in materials derived from the British Geological Survey's work is owned by the Natural Environment Research Council (NERC) and/or the authority that commissioned the work. You may not copy or adapt this publication without first obtaining permission. Contact the BGS Intellectual Property Rights Section, British Geological Survey, Keyworth, e-mail ipr@bgs.ac.uk. You may quote extracts of a reasonable length without prior permission, provided a full acknowledgement is given of the source of the extract.

Maps and diagrams in this book use topography based on Ordnance Survey mapping.

D Millward, D Stephenson

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgs london@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclea Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Foreword

This Internal Report describes the metadata and details of four 3D bedrock geological models of part of the northern, western and southern margins of the Clyde catchment and adjacent areas in the Midland Valley of Scotland. At the time of the work (January 2010 to April 2011) these represent the most complex faulted-bedrock models constructed in BGS using GSI3D version 2011 Bedrock. Also, these models differ from most GSI3D models because very few boreholes are available within the areas. Thus, the models have been constructed using surface data and interpreted cross-sections.

The bedrock modelling tools available as version 2011 Bedrock of GSI3D are still very much under development and an essential part of the modelling process has been to contribute to understanding the level of complexity that the software can cope with, and to provide feedback into the development programme.

This work formed part of the BGS Geology and Landscape Scotland's 3D modelling programme of the Clyde catchment, and is a contribution to the Clyde-Urban Super-Project (CUSP).

Acknowledgements

Our involvement in the modelling of the Clyde Plateau Volcanic Formation was instigated and supervised by Diarmad Campbell, whom we thank for his support and encouragement throughout the duration of the modelling.

We also thank Tim Kearsey for showing one of us (DM) how to use GSI3D and for many subsequent discussions on the processes of modelling.

The help and support of Ben Wood throughout the project is much appreciated, particularly for his ability to sort out modelling files that appear to have been corrupted by the 'L-plated' modeller. We have learned much through attempting to build models that are probably too complex for what GSI3D was originally designed.

We would also like to thank Hans-Georg Sobisch for his illuminating discussion on the possibility of modelling funnel-shaped intrusions, of which there are so many in the Midland Valley of Scotland.

Contents

Foreword	i
Acknowledgements.....	i
Contents.....	ii
Summary	v
1 Introduction	1
2 Summary of the geology	1
3 Model boundaries, scale and file locations.....	2
3.1 Campsie Fells block.....	3
3.2 Kilpatrick Hills block	3
3.3 Renfrewshire Hills block	3
3.4 Southern Hills block	3
3.5 Stratigraphical boundaries	4
3.6 Scale of the models.....	4
3.7 Project files	4
4 Data sources.....	5
4.1 DTM	5
4.2 Inputs from existing models	5
4.3 DigMapGB data: bedrock polygons and faults	5
4.4 Boreholes	7
4.5 Interpreted data: Cross-sections.....	8
5 Description of the models	9
5.1 Fault networks	9
5.2 Stratigraphical models	11
5.3 Surface calculation errors	15
5.4 Intrusions	16
6 Conclusions	17
Appendix 1 Workflow for funnel-shaped intrusions	19
References	20

FIGURES

Figure 1. Outline geological map and 3D view showing the outcrop of the Clyde Plateau Volcanic Formation (CPV).....	21
Figure 2. Campsie Fells block, topography and location.....	22
Figure 3. Kilpatrick Hills block, topography and location.....	22

Figure 4. Renfrewshire Hills block, topography and location.	23
Figure 5. Southern Hills block, topography and location.	23
Figure 6. Fence diagram construction for the Campsie Fells block.....	24
Figure 7. Campsie Fells block, fault network, looking north-east.	25
Figure 8. Base Kinnesswood Formation and Campsie East fault surfaces showing the duplex elements and weakly positive flower structure.....	25
Figure 9. Fault network for the Kilpatrick Hills block, looking north-east.	26
Figure 10. Renfrewshire Hills fault network, looking north-east.	26
Figure 11. 3D view of the Leap Moor Syncline, Loch Thom Anticline and Largs Fault system.....	27
Figure 12. Southern Hills block, fault network, looking north-east.....	27
Figure 13. Campsie Fells block, full model in map view, with calculated envelopes.	28
Figure 14. Campsie Fells, base Kinnesswood Formation, viewed from west-north-west.	28
Figure 15. Campsie Fells, base Ballagan Formation (BGN), viewed from west-north-west.	29
Figure 16. Campsie Fells, base Clyde Sandstone Formation (CYD), viewed from west-north- west.....	29
Figure 17. Campsie Fells, subcrop geological map beneath CPV.	30
Figure 18. Campsie Fells, base Slackdown Member (SLACKD), viewed from west-north-west.....	31
Figure 19. Campsie Fells, base Baston Burn Member (BAST), viewed from west-north-west...	31
Figure 20. Campsie Fells, base Slackgun Member (SLACKG), viewed from west-north-west. .	31
Figure 21. Base Drumnessie Member (DRUM), viewed from west-north-west.	32
Figure 22. Base Burnhouse Member (BURN), viewed from west-north-west.....	32
Figure 23. Base Campsie and Craigentimpin members (CAMPL, CRAIG, CAMPU), viewed from west-north-west.....	32
Figure 24. Base Shelloch Burn Member (SHEL; Fintry and Gargunnock hills), and Lower Lecket Hill and Meikle Bin members (LLECK; Kilsyth Hills), viewed from west-north-west.	33
Figure 25. Base Boyd's Burn Members (BOYD), viewed from west-north-west.....	33
Figure 26. Base Upper Lecket Hill Members (ULECK), viewed from west-north-west.	33
Figure 27. Kilsyth Member (KILS) and overlying units in the east of the block.	34
Figure 28. All overlying units and intrusions.....	34
Figure 29. Calculated envelopes for the Kilpatrick Hills block.....	35
Figure 30. Exploded 3D view of Kilpatrick Hills block, viewed from the north-west.....	35
Figure 31. Full Fence diagram of the Kilpatrick Hills block	36
Figure 32. Kilpatrick Hills block, envelopes for the base of the Burncrooks Pyroclastic Member (BCV in A) and the Greenside Volcaniclastic Member (GNSV in B).....	37
Figure 33. Calculated envelopes for the Renfrewshire Hills block.....	38
Figure 34. 3D exploded view of the Renfrewshire Hills model, looking south-south-west.....	39
Figure 35. View looking south-west of the Clackmannan and Scottish Coal Measures Groups in the southern part of the Renfrewshire Hills block.....	39
Figure 36. Full fence diagram for the Renfrewshire Hills block.	40

Figure 37. Calculated subcrop maps for the Renfrewshire Hills model.	41
Figure 38. 3D perspective of the Misty Law trachyte centre, viewed from the west.	42
Figure 39. Calculated envelopes for the Southern Hills block.....	43
Figure 40. Exploded 3D model of the Southern Hills block from the north-west.	43
Figure 41. Full fence diagram, Southern Hills block.	44
Figure 42 Surface artefacts adjacent to faults and resulting from calculation errors.	44
Figure 43. Intrusions: map view of the Campsie Fells block showing the envelopes (in bright red) of 9 funnel-shaped intrusions within the linear vent-systems.....	45
Figure 44. Cross-section A-B in Figure 33 showing relationship of intrusions to topography. Note the flared nature of these masses.	45
Figure 45. 3D view of intrusion 1 (Figure 33) from north-west.	46
Figure 46. 3D view from NW of the intrusions, selected stratigraphical surfaces and faults in the Campsie Fells block.....	46
Figure 47. Construction of faulted intrusions in the Campsie Fells block.	47
Figure 48. Calculation effects on the base Kinnesswood Formation surface when cut by intrusions; western Campsie Fells block.	48
Figure 49. 3D shape of simple intrusion constructed from 2 sections, Kilpatrick Hills block. ...	48
Figure 50. Constraining the base of an intrusion with an artificial stratigraphical surface.....	49

TABLES

Table 1. Summary of the units modelled within the CPV of the Campsie Fells block.....	12
Table 2. Summary of the units modelled within the CPV of the Kilpatrick Hills block.	13
Table 3. Summary of the units modelled within the CPV of the Renfrewshire Hills block.	14

Summary

This report describes the construction of 3D bedrock geological models of the Mississippian (Visean) Clyde Plateau Volcanic Formation (CPV), a succession of basaltic to trachytic lavas in the Midland Valley of Scotland using GSI3D version 2011 Bedrock. These lavas form a range of picturesque hills around the margin of the River Clyde catchment to the north, west and south of Glasgow. The modelling has formed part of the BGS Geology and Landscape Scotland's 3D modelling programme of the Clyde catchment, and is a contribution to the Clyde-Urban Super-Project (CUSP).

The horseshoe-shaped outcrop of the CPV was divided into 4 areas for modelling. To the north of Glasgow the Campsie Fells block comprises an area of c. 285 km² and the model consists of 23 geological units, 73 faults and 64 cross-sections. To the west of this the Kilpatrick Hills block model of an area of 145 km² has 9 geological units, 45 faults and 34 cross-sections. West of Glasgow is the Renfrewshire Hills block, an area of 650 km², with 18 geological units, 87 faults and 90 cross-sections. South of Glasgow is the Southern Hills block, some 530 km², with 8 geological units, 64 faults and 45 cross-sections. The scale for each of the models is nominally 1:50 000. Though the focus of the modelling was on selected divisions of the CPV, enveloping formations were also included. Most importantly here is the 3-fold division of the Inverclyde Group beneath the volcanic succession, and the overlying units within the Strathclyde, Clackmannan and Scottish Coal Measures groups, as appropriate.

There are few boreholes in the area and the models have been constructed mostly using outcrop data and published cross-sections as a starting point for constructing the fence-diagram. Also, a methodology was devised and tested successfully for the modelling of funnel-shaped intrusions which is appropriate for the multitude of small plugs, vents and necks that cut the sequence in the Midland Valley. Despite shortcomings in the quality of the calculated surfaces, the modelling has shown that GSI3D can cope with many aspects of complex Carboniferous geology as found in the Midland Valley of Scotland. However, as many of the stratigraphical surfaces in these models are marred by calculation errors, the models must not be regarded as finished products, which await improvements to the GSI3D engine, currently in progress.

The models show the following significant geological features:

The overstepping relationship of the base of the volcanic succession on the underlying Clyde Sandstone, Ballagan and Kinnesswood formations;

A transpressional 'pop-up' duplex structure developed within a restraining bend on the dextral strike-slip Campsie West Fault, provides a mechanism for formation of the unconformity at the base of the volcanic succession;

The localised distribution of lava and pyroclastic units and their spatial relationship with the linear vent-swarms.

1 Introduction

This report describes the four separate GSI3D version 2011 bedrock models of the Clyde Plateau Volcanic Formation (CPV) and enveloping sedimentary rock units that crop out to the north, west and south of Glasgow around the River Clyde catchment (Figure 1). In this report, model metadata, and the constraints on the data sources and methodology underpinning the models are set out first, and then the models are described. As the faulted-bedrock tools in GSI3D are still very much under development, some of the underlying issues that require either further work or that at present lie beyond the scope of the software are discussed in the final sections of the report. The modelling has been undertaken as part of the BGS Geology and Landscape Scotland's 3D modelling programme of the Clyde catchment, and is a contribution to the Clyde-Urban Super-Project.

These are bedrock-only models and all extend beyond the catchment boundary so that important information from these areas could be used to ensure the integrity of the catchment models. It is recognised that in parts of the area, such as that encompassing the Carron Valley Reservoir in the Campsie Fells, the bedrock geology is concealed by a significant thickness of superficial deposits. Nevertheless, apart from such local exceptions, at the model scale and thickness of the units, the effects of the superficial deposit cover are considered to be negligible and the deposits are omitted from these models. A separate catchment-scale model of the superficial deposits is available (Finlayson, 2011).

This work is an attempt to visualise the 3D bedrock geology of a succession mainly of basaltic lavas and associated pyroclastic rocks that form the lower Carboniferous (Mississippian: Visean) Clyde Plateau Volcanic Formation (Cameron and Stephenson, 1985). The relationships with the under- and overlying strata are also depicted. The numbers of bedrock geological units and faults included in the models (see section 2) made this exercise a critical test for the modelling software. An attempt is also made to assess if it is possible to model some of the many intrusions that were emplaced into the volcanic and adjacent units. This work differs from many of the other models in the Midland Valley of Scotland because there are few boreholes with which to constrain the models; thus, the modelling process uses interpreted data, including published cross-sections as the starting point for the construction of the fence diagrams.

2 Summary of the geology

The Clyde Plateau Volcanic Formation constitutes a major feature of the geology of the western part of the Midland Valley of Scotland. This was summarised by Cameron and Stephenson (1985), and Read et al. (2002). Detailed studies are presented on the BGS 1:50 000-scale geological maps for the area, including Stirling (S39W), Greenock (S30W), Glasgow (S30E), Airdrie (S31W), Irvine (S22W), Kilmarnock (S22E) and Hamilton (S23W) and in the accompanying memoir accounts (Forsyth et al., 1996; Francis et al., 1970; Hall et al., 1998; MacPherson et al., 2000; Monro, 1999; Paterson et al., 1990, 1998). For much of the Campsie Fells outcrop of the CPV, the modelling is based on the extremely detailed stratigraphical and structural interpretation of the Campsie Fells by Craig (1980).

The oldest rocks in the area encompassed by the models belong to the Upper Devonian Stratheden Group. These are overlain conformably by Carboniferous rocks of the Inverclyde Group, divided into the Kinnesswood, Ballagan and Clyde Sandstone formations (Waters et al., 2007). At outcrop along the northern flanks of the Renfrewshire, Kilpatrick, Fintry, Campsie and Gargunnock hills the Clyde Sandstone is succeeded, apparently conformably, by the CPV, the lowest unit within the Strathclyde Group. However, from borehole and outcrop evidence it is known that southwards across the Campsie Fells and Renfrewshire Hills, the base of the volcanic

succession progressively oversteps the Clyde Sandstone and Ballagan formations to rest directly on strata of the Kinnesswood Formation. This relationship is seen elsewhere in the Midland Valley of Scotland, reflecting an episode of deformation, uplift and erosion prior to the onset of volcanism (Read et al., 2002).

The CPV is the most extensive of a number of Mississippian volcanic successions to have been emplaced in the Midland Valley of Scotland. The formation comprises up to about 1000 m of basaltic to trachytic lavas and subordinate pyroclastic rocks (Read et al., 2002). A large number of localised lava successions have been identified in the Kilpatrick Hills and Campsie Fells blocks, with interpretations that reflect their eruption from the ENE-trending linear vent-swarms, now represented by mafic plugs and pipe-like bodies of pyroclastic rocks (Craig, 1980; Forsyth et al., 1996, fig.4). These include the North and South Campsie, Gonachan Glen and Dungleil linear vent-swarms. Also, in the centre of the Campsie Fells block is the Waterhead Central Volcanic Complex, a nested caldera structure. A positive gravity anomaly centred over the Waterhead area has been interpreted to be due to a subvolcanic mafic intrusion the top of which lies at a depth of 500 m and base at about 6 km (Cotton, 1968). Tephra deposits associated with caldera formation are preserved as the Meikle Bin Member.

Linear vent swarms are not known from the Renfrewshire Hills, nor from the Southern Hills. By contrast, the middle part of the succession in these areas is characterised by stacks of trachytic and trachyandesitic lavas, represented by the Misty Law Member in the Renfrewshire Hills, and by the Harelaw and Drumduff Hill members in the southern area. Whilst the stratigraphical relationships of these rocks are well known in the Renfrewshire Hills, the rather poorer exposure in the southern area precludes the construction of a detailed model.

The CPV is overlain by the volcanoclastic Kirkwood Formation which filled irregularities in the volcanic substrate, and by the dominantly sandstone succession of the Lawmuir Formation (Strathclyde Group). The interdigitating relationship between these two formations is not included in the models. The overlying Clackmannan Group and its constituent units of the Lower Limestone, Limestone Coal and Passage formations, are composed of a mixed succession of Yoredale and Millstone Grit facies (Waters et al., 2007). The Scottish Coal Measures Group forms the youngest rocks in the area. The sedimentary strata lying above the CPV are intruded by late-Carboniferous quartz-dolerite sills of the Midland Valley Sill-swarm.

Growth folds and fault displacement geometries controlled depositional thickness and facies, and influenced sediment dispersal patterns throughout the Midland Valley of Scotland during Carboniferous times; these structures were further tightened during end-Carboniferous deformation in the Variscan foreland (Read et al., 2002). Increasingly, evidence has been adduced to demonstrate the kinematic links between faulting and folding within a major dextral strike-slip regime, bound principally by the Highland Boundary and Southern Upland fault systems (e.g. Read, 1989; Rippon et al., 1996; Underhill et al., 2008). Elements of this complex history of deformation are evident within the modelled area, notably the effects of mid-Mississippian and end-Carboniferous deformation. The mid-Mississippian unconformity that is demonstrable along the southern margin of the Campsie Fells, adjacent to the Campsie Fault, has been attributed to magmatic doming prior to eruption of the CPV (Forsyth et al., 1996), though an origin associated with strike-slip faulting has been hinted at by Read (1989). This latter possibility is explored further in this report.

3 Model boundaries, scale and file locations

Considering its stratigraphy and structure, the large, horseshoe-shaped outcrop of the CPV was divided into four blocks for the purpose of modelling (Figure 1). The Campsie Fells, Kilpatrick Hills and Renfrewshire Hills blocks are joined across common faults, respectively the Campsie West and Clyde faults. The link between the Renfrewshire Hills block and the Southern Hills

block models is taken across a common north – south cross-section. Also, the Southern Hills block is linked through common faults at its south-eastern boundary with the GSI3D version 3 bedrock model of the Strathaven – Douglas Coalfield region of the Clyde catchment.

Brief descriptions of the aerial and stratigraphical extents of the four models are given below, along with the number of geological units and faults included, and the number of cross-sections constructed.

3.1 CAMPSIE FELS BLOCK

North west corner: 252 000 694 4000 South-east corner: 279 500 678 000
 Area 285 km²; 23 geological units; 73 faults; 64 cross-sections
 Model height determined by DTM; model depth cut-off 1500 m below OD

This picturesque area lies along the northern margin of the River Clyde catchment and includes the Gargunnock Hills, the Campsie Fells and Kilsyth Hills (Figure 2). The model is bound to the south by the Campsie Fault, a major strike-slip fault and duplex system. The western and northern boundaries were defined by the outcrop of the base of the Kinnesswood Formation. The eastern limit is taken just beyond the easternmost outcrop of the CPV and is defined by a single limiting cross-section.

3.2 KILPATRICK HILLS BLOCK

North west corner: 233 500 683 350 South-east corner: 258 250 673 000
 Area 145 km²; 9 geological units; 45 faults; 34 cross-sections
 Model height determined by DTM; model depth cut-off 1500 m below OD

The Kilpatrick Hills lie to west of the Campsie Fells and to the north of Dumbarton (Figure 3). To the west and north the model is bound by the outcrop of the Kinnesswood Formation; to the north-east it adjoins the Campsie Fells block along the Campsie West Fault and to the south it adjoins the Renfrewshire Hills block by the Clyde and Milngavie – Kilsyth faults.

3.3 RENFREWSHIRE HILLS BLOCK

North west corner: 219 240 678 500 South-east corner: 245 000 640 000
 Area 650 km²; 18 geological units; 87 faults; 90 cross-sections
 Model height determined by DTM; model depth cut-off 1500 m below OD

This area extends from the River Clyde south to the Ardrossan – Stevenston area and from the coast at Largs east to Johnstone (Figure 4). It includes the Renfrewshire Hills, and extends south to the northern part of the Ayrshire Coalfield at Irvine. The Renfrewshire Hills block is joined to the Kilpatrick Hills block by the Clyde and Milngavie – Kilsyth faults. The join to the Southern Hills block is by a north-south cross-section along Easting 245 000. A consequence of this artificial divide is that this model also includes the western part of the Beith–Barrhead Hills.

3.4 SOUTHERN HILLS BLOCK

North west corner: 244 500 661 600 South-east corner: 272 200 636 900
 Area 530 km²; 8 geological units; 64 faults; 45 cross-sections
 Model height determined by DTM; model depth cut-off 1500 m below OD

This large area covers the ground between Johnstone, East Kilbride, Strathaven and Kilmarnock (Figure 5). The northern limit of the model from Johnstone to the south side of Rutherglen is taken along the Gleniffer – Clarkston – Castlemilk West faults. The north-east and east boundary is the Dechmont Fault and the southern and south-western boundary the Inchgotrick – Strathaven faults.

3.5 STRATIGRAPHICAL BOUNDARIES

One of the important geological relationships seen in the area is the unconformity beneath the Clyde Plateau Volcanic Formation; the volcanic rocks progressively overstep the divisions of the Inverclyde Group to overlie the Stratheden Group locally in the south-west of the Renfrewshire Hills. As divisions of the Stratheden Group at subcrop beneath the Inverclyde Group are poorly known, the Kinnesswood Formation, at the base of the Inverclyde Group was selected as the lowest unit to be modelled in all of the blocks. Though the subsurface distribution of the Ballagan and Clyde Sandstone formations is not known in detail in parts, it is possible to interpolate the position of their subcrop boundaries from the sparse borehole and outcrop information and from regional geological knowledge.

The uppermost stratigraphical surface modelled in each of the blocks is determined by the geology of the geographical area encompassed. Those surfaces used typically range from just the uppermost unit of the Strathclyde Group in the Kilpatrick Hills block to various units within the Clackmannan Group; the Scottish Coal Measures Group is included in the south of the Renfrewshire Hills and Southern Hills blocks.

3.6 SCALE OF THE MODELS

All of the models utilise map and cross-section data at a scale of 1:50 000 and this is their nominal scale.

3.7 PROJECT FILES

Files associated with this project are stored in the following folder:

[W:\Teams\RSS\Clyde_Basin\Data\ClydePlateauVolcanic3Dmodel](#)

The latest GSIPR file at the time of writing this report is given below.

Campsie Fells block

[W:\Teams\RSS\Clyde_Basin\Data\ClydePlateauVolcanic3Dmodel\ClydePlateauVolcanicsNorth\CPVmodelvers5MinusFault.gsipr](#)

The *.GVS and *.GLEG for the model are:

[3D_Campsie_bedrock_modified.GVS](#)

[3D_Campsie_bedrock.GLEG](#)

Borehole interpretation file: [CPVCampsieBlgfile.blg](#)

Kilpatrick Hills block

[W:\Teams\RSS\Clyde_Basin\Data\ClydePlateauVolcanic3Dmodel\ClydePlateauVolcanicsKilpatricks\CPVKilpatrickHills3intrusions.gsipr](#)

The *.GVS and *.GLEG for the model are:

[KilpatrickHillsGvs.GVS](#)

[KilpatrickHillsGleg.GLEG](#)

Borehole interpretation file: [KilpatrickHillsBLGfile.blg](#)

Renfrewshire Hills block

[W:\Teams\RSS\Clyde_Basin\Data\ClydePlateauVolcanic3Dmodel\ClydePlateauVolcanicsWest\ClydePlateauVolcanicsWest5e.gsipr](#)

The *.GVS and *.GLEG for the model are:

[Clyde_catchment.GVS](#)

[Clyde_catchment.GLEG](#)

Borehole interpretation file: [FinalRenfrewshireHillsBLGfile.blg](#)

Southern Hills block

W:\Teams\RSS\Clyde_Basin\Data\ClydePlateauVolcanic3Dmodel\ClydePlateauVolcanicsSouth\ClydePlateauSouth vers2e.gsi pr

The *.GVS and *.GLEG for the model are:

CPVsouthArea.GVS
CPVsouthArea.GLEG

Borehole interpretation file: CPVsouthAreaBlgfile.blg

4 Data sources

4.1 DTM

The DTM used in each of the models has been sub-sampled from NextMap® DSM dataset via the data portal in GSI3D, with a resolution of 100 m.

NextMap data were preferred over the Rockhead Elevation Model (RHEM) because at the scale of the models the thickness of the cover of superficial deposits overall was considered to be negligible. Further, the areas modelled have a very low density of boreholes, and in such areas a nominal 1 m drift thickness is assumed in calculation of the RHEM, thus introducing another source of uncertainty.

4.2 INPUTS FROM EXISTING MODELS

The lithostratigraphical and fault surfaces from the GoCad® *Midland Valley Lithoframe 250k Model* imported into GSI3D and used as a guide in the construction of the surfaces are detailed below. No existing data were relevant to the *Campsie Fells block*.

Kilpatrick Hills block

The following fault surfaces were incorporated:
Campsie, Milngavie – Kilsyth

Renfrewshire Hills block

Base Hurlet Limestone (base Lower Limestone Formation)
Base Lower Coal Measures Scotland Formation

The following fault surfaces were incorporated:

Annick Water, Barrhead, Blythswood, Dusk Water, Gleniffer, Gleniffer2, Milngavie – Kilsyth, Milngavie – Kilsyth2, Paisley Ruck, and Walkinshaw

Southern Hills block

Base Hurlet Limestone (base Lower Limestone Formation)

The following fault surfaces were incorporated:

Annick Water, Barrhead, Castlemilk West, Clarkston, Dechmont, Dusk Water, Gleniffer2 to 7 and Paisley Ruck

In addition this model also used fault surfaces constructed in the adjacent Clyde Region Model (T Kearsey) to the east.

4.3 DIGMAPGB DATA: BEDROCK POLYGONS AND FAULTS

Geology polygons for the sedimentary formations and fault lines were extracted from the DigMapGB-50 database. Though ArcGIS shape-files for these are available directly from the database, they are too data-rich for direct inclusion in GSI3D. Thus, the bases of all geological units were digitised in GSI3D. This has been done with considerable simplification, a necessary process given the complexity of the models.

Currently, the DigMapGB-50 dataset depicts a wide range of lithological units within the CPV, rather than component members which are preferred in this case for modelling. For the Campsie Fells, Kilpatrick Hills and Renfrewshire Hills blocks, a large number of members (or units with implied member status) is described in the memoirs (e.g. Craig, 1980; Forsyth et al., 1996; Hall et al., 1998; Paterson et al., 1990, 1998) and illustrated in simplified form in both the memoirs and in the map marginalia. Recently, these units have been formalised within the Lexicon of Named Rock Units, and the polygons marked up at the 1:50 000-scale by one of us (DS) in preparation for digitisation and entry into the DigMapGB50 database. These manuscript maps were used to construct outcrop lines for the members selected for modelling.

Codes for the lithostratigraphical units used in the model GVS files are the Lex-codes from the BGS *Lexicon of Named Rock Units*. An explanation of the units within the Clyde Plateau Volcanic Formation where this is subdivided is given in Section 5.2 of this report. In the Campsie Fells block, the intrusions are given the codes VENT for the funnel-shapes volcanic necks and CALD for the Waterhead Central Volcanic Complex.

4.3.1 Faults

The fault networks are greatly simplified from those extracted from the DigMapGB50 dataset. The faults used in each of the blocks were selected on the basis of having significant displacements and those that are required to maintain the integrity of the fault network. Thus, the huge number of faults with minor displacements depicted in the northern part of the Renfrewshire Hills block, for example, has been largely excluded. Modelling of fault tips (0 displacement) is cumbersome in GSI3D at present and the selection of such faults was kept only to those considered to be essential. As with the bedrock lines, ArcGIS shape-files from the DigMap50-GB were not used directly; the faults were re-digitised in GSI3D with simplification.

In the Campsie Fells block, an intricate network of faults with their estimated throws is given by Craig (1980) and these faults were incorporated into the BGS maps of the area. Here, the model includes all faults from Craig's map with throws greater than, or equal to 30 m; some other faults with smaller throws are included only where these are essential to the integrity of the model.

The hade and movement history of many of the faults in the region is poorly known and no research has been carried out as part of this modelling exercise to understand the structure better. For the Campsie Fells, Craig (1980) considered the faults to be vertical or near-vertical. However, the cross-sections on the BGS 1:50 000 scale maps show many of the faults with hade of 45 to 60°, implying in many cases that the faults are simple extensional structures (Forsyth et al., 1996). This has been proved for some faults within the coalfields (Penn et al., 1984) where there is also evidence from underground working. However, some of the larger structures, such as the Largs Fault and Campsie East Fault, affecting the volcanic formation have a fault-trace geometry that is complex, multi-stranded with variable but probably low hade, and a demonstrable strike-slip component (Read, 1989; Rippon et al., 1996).

A further consideration here concerned the current functionality of GSI3D. Faults with low hade will generally calculate well. However, hade of more than about 30° and low intersection angles between adjoining faults will produce poorly calculated surfaces. Moreover, in sections, 'Y'-shaped fault intersections that occur within the depth range of the stratigraphy that is being modelled will not currently draw correctly in the section window and hence cannot be calculated. This problem is particularly acute with the 'keel'-shaped intersections that are a common feature of strike-slip duplex structures.

For all these reasons most of the faults in these models are considered to be simple planar structures with a nominal hade of 5-15°. Adopting this method enables the fault networks to be built very quickly, though they may not be entirely geologically realistic. Exceptions to this are noted in later sections of this report.

4.4 BOREHOLES

There are only a very small number of boreholes within the model areas that provide detailed information on the CPV. A few more provide information in the peripheral areas on either the underlying Inverclyde Group or the overlying Clackmannan Group; many of these also give depths to either the base or top of the CPV. The boreholes used to constrain surfaces within the models are listed below: all were instigated by BGS (formerly IGS).

Campsie Fells block

<i>BGS Bore No</i>	<i>Bore name</i>	<i>easting</i>	<i>northing</i>	<i>elevation</i>	<i>drilled length (m)</i>
NS78SW5	Tak-ma-doon	272910	680530	260	268
NS68SW1	Clachie Bridge	264470	683680	269	300

The Clachie Bridge Borehole was drilled into the Waterhead Central Volcanic Complex (Craig, 1980; IGS Report 76/10) and though it confirms the complicated nature of the caldera fill, it does not provide information critical to the modelling. Tak-ma-doon proved the lower part of the volcanic succession and details of the underlying Inverclyde Group (IGS report 79/12).

Kilpatrick Hills block

<i>BGS Bore No</i>	<i>Bore name</i>	<i>easting</i>	<i>northing</i>	<i>elevation (m)</i>	<i>drilled length (m)</i>
NS37NE20	Kipperoch	237270	677420	85	300
NS47NW2	Barnhill	242690	675710	100	356
NS47NE1	Loch Humphrey	245820	675550	320	423

The Loch Humphrey Borehole is important in that it established the presence of a volcanoclastic unit within the CPV separate from, and younger than, the pyroclastic rocks at the base of the formation (IGS report 79/12). The other boreholes provide information on the divisions of the Inverclyde Group (IGS Report 78/10).

Renfrewshire Hills block

<i>BGS Bore No</i>	<i>Bore name</i>	<i>easting</i>	<i>northing</i>	<i>elevation (m)</i>	<i>drilled length (m)</i>
NS24NW20	Coalhill No 2	224320	646530	130	130
NS24NE95	Muirlaught	226040	646140	96	100
NS24SW57	Ardrossan	223080	641910	3	78
NS24SE249	Hullerhirst	227300	642600	30	70
NS24SE250	Ardeer	227630	640090	8	164
NS24SE263	Diddup	226510	644060	47	174
NS25NW5	Largs	221580	659360	109	395
NS27SW5	Everton	221450	671030	99	143
NS34NE11	Kirkwood	238850	647160	60	77
NS34NE12	Montgreenan	235030	645230	70	161
NS34SE150	Kilmaurs	239550	641240	50	84
NS35NW51	Lora Burn	233360	658410	107	45
NS35SE80	Oldmill	238970	652390	110	66
NS37SW10	Knocknairshill	230560	674380	124	398
NS43SW98	Harelaw 1	241660	633000	98	69
NS43SE81	Deaconhill	248930	631530	105	323
NS45SW39	Dunniflat	420300	653140	138	58

Most of these boreholes provide data on the Clackmannan Group and uppermost clastic units of the Strathclyde Group (IGS reports 77/10, 78/21, 79/12). Only the Largs and Knocknairshill boreholes provide significant detail on the basal 150 and 90 m respectively of the CPV; these and the Everton borehole (IGS reports 78/21, 79/12) also supply detail on the underlying Inverclyde Group. Harelaw 1 and Deaconhill boreholes are located to the south of the Annick

Water Fault and thus outside of the modelled area. However, these boreholes proved that the Lawmuir Formation overlies the Ballagan Formation and demonstrates the absence at subcrop of the CPV, south of the Inchgotrick Fault (IGS Report 77/10, 81/11).

Southern Hills block

<i>BGS Bore No</i>	<i>Bore name</i>	<i>easting</i>	<i>northing</i>	<i>elevation (m)</i>	<i>drilled length (m)</i>
NS63NW83	Fore Hairshaw	261370	639880	259	74
NS46SE164	Glenburn	247830	660660	91	467

The Fore Hairshaw Borehole (also spelt Hareshaw) provides local detail of the Lower Limestone and Kirkwood formations, and depth to the top of the CPV in the south of the model area (Paterson et al., 1998). The Glenburn Borehole (IGS Report 81/11) provides important information on the basal units of the CPV and on the underlying Inverclyde Group at the north-eastern part of the Beith–Barrhead Hills. The Harelaw 1 and Deaconhill boreholes are also relevant here, lying just to the south of the Inchgotrick Fault.

4.5 INTERPRETED DATA: CROSS-SECTIONS

Cross-sections from the published 1:50 000-scale maps formed the starting point for each of the models. These scaled cross-sections were scanned, imported as backdrops in the GSI3D section window and digitised. By working outwards from these iteratively, the remaining parts of the fence diagrams were then constructed (Figure 6). This process was aided by a wealth of outcrop data on the maps, from Craig's thesis (1980) on the Campsie Fells and the various memoirs for the districts (Francis et al., 1970; Forsyth et al., 1996; Hall et al., 1998; Monro, 1999; Paterson et al., 1990, 1998).

Published cross-sections used in this way are as follows.

Campsie Fells block

1. Stirling (S39W) section line A-A, Gargunnock Hills – North Third Reservoir;
2. Stirling memoir, Plate VI, Fintry, Gargunnock and Touch hills;
3. Glasgow (S30E) section line C-D, northern part Corrie of Balglass to Clachan of Campsie;
4. Airdrie (S31W) section A-B, northern part Lennoxton to Endrick Water;
5. Section from Craig (1980), Dunmore to Corrie Burn.

Kilpatrick Hills block

1. Glasgow (S30E) section AB, Dumbarton Muir to Edinbarnet

Renfrewshire Hills block

1. Greenock (S30W) section line A-A', Lunderston Bay to Coalhouse Hill;
2. Greenock (S30W) section line C-C', Wemyss Point to Walls Hill
3. Irvine (S22W) section line 1, Portencross to Stewarton
4. Irvine (S22W) section line 2, Glenside to Irvine

Southern Hills block

1. Kilmarnock (S22E) section, east Kilbride to Newmilns
2. Hamilton (S23W) section A-A', Mains castle to Earnock
3. Hamilton (S23W) section B-B', Meadowfoot

5 Description of the models

In common with GSI3D modelling ‘best practice’, the fault networks were built and calculated first, followed by construction and calculation of the stratigraphical surfaces. Significant iteration of the process occurred. An assessment of the degree of confidence in the geological model constructed is recommended by best practice and a method was developed by Clarke (2004) specifically for models where interpreted data form the main source of data. However, no assessment of confidence has yet been made for these CPV models.

5.1 FAULT NETWORKS

5.1.1 Campsie Fells block

Part of the network of 73 faults is illustrated in Figure 7. Craig (1980) interpreted most of the faults as near vertical, a feature that is carried through the model. Further, downthrow values for most of the faults are given by Craig (1980) and these have been honoured within the modelling as far as has been practicable. Specific issues are described below as being relevant to the construction and interpretation of the model.

The structure of the area is dominated by the Campsie West and East faults, forming a sinuous, multi-stranded structure with a large throw down to the south (Forsyth et al., 1996). On the published BGS 1:50 000-scale geological map this structure is shown as a simple extensional structure with a substantial hade to the south. However, the presence of lozenge-shaped fault-blocks on the inside of its greatest curvature just to the north of Kilsyth, and abrupt changes in stratigraphy and structure between these adjacent blocks, suggests that the Campsie East Fault is a strike-slip fault with duplexes developed within a restraining bend (cf. Read, 1989). Furthermore, the modelled surfaces of the sedimentary formations beneath the CPV show the fault zone to be a weakly positive flower structure (e.g. Figure 8). The low hade to the north shown here for the Campsie East Fault is more in keeping with such an interpretation. Clearly, this has implications for fault evolution in this area. Whilst most of the vertical displacement on the Campsie East Fault was probably late Carboniferous, it may be inferred that transpressive re-activation of an earlier, underlying deep-seated structure during the early Carboniferous, prior to the CPV eruptions, was the cause of the unconformable relationship that now exists between the CPV and underlying formations. The presence and orientation of the linear vent-swarms within the block may also be accounted for by the inferred strike-slip tectonic regime.

A notable feature of the geology of this block as depicted on the BGS 1:50 000-scale maps is the significantly greater number of faults shown in the south of the area compared with that in the north. In part, this probably reflects the very detailed mapping by Craig (1980) in the south compared with that for the Stirling district to the north. A few faults were inserted or extended in order to effect a join between the north and south parts. However, an increasing fault density southwards across the block towards the Campsie East Fault might also be expected with proximity to the flower structure.

Craig’s (1980) geological map depicts the margin of the Waterhead Central Volcanic Complex as a single structure, the Waterhead Ring Fault (Figure 7). It is not possible to model such an enclosed structure in GSI3D and for the purposes of modelling, this fault was divided into an arcuate fault cut by a second, through-going fault on its eastern side.

5.1.2 Kilpatrick Hills block

The fault network for the Kilpatrick Hills is illustrated in Figure 9. The Campsie West, Auchineden and Milngavie–Kilsyth faults with large downthrows more or less bound the Kilpatrick Hills, the sigmoidal shape of the block suggesting that the volcanic rocks are contained within a strike-slip fault duplex. In support of this is the fact that the Milngavie –

Kilsyth Fault truncates folds with north-east-trending axial plane traces that seem to be a north-eastward continuation of the Paisley Ruck (Hall et al., 1998, fig. 16).

Downthrow values for many of the major faults are given in Hall et al. (1998, fig.16). In the absence of data on fault geometry in the Kilpatrick Hills block, the faults are modelled as steep planar structures. Many of the faults with short lengths and small throws have been omitted from the DigMapGB-50 dataset.

5.1.3 Renfrewshire Hills block

The fault network for the Renfrewshire Hills block is illustrated in Figure 10. The framework comprises a number of fault orientations and includes major structures that extend beyond the model area. The Paisley Ruck, and the Dusk Water and Annick Water faults have a north-easterly trend, parallel to the Highland Boundary and Southern Upland fault zones. Complex zones of fractures are associated with these faults and evidence has been adduced for multiple phases of movement with both vertical and strike-slip components (Monro, 1999). A lateral displacement vector for these faults is perhaps best demonstrated by the presence along the trace of the Dusk Water Fault of sigmoidal fault blocks with abruptly changing throws forming graben and horst structures in adjacent blocks.

The wide fault zone known in the Glasgow area as the Paisley Ruck (Hall et al., 1998) crops out in the eastern side of the Renfrewshire Hills block, but south-west of Lochwinnoch it extends to the Ayrshire coast north of Ardrossan as a set of en echelon faults and anastomosing fault lozenges. A variable vertical displacement up to 550 m down to the north-west is recorded from the Glasgow area.

Though of similar trend to the Paisley Ruck, the Dusk Water Fault apparently has a relatively high hade to the south-east, implied from seismic data across it (Hall, 1974). It also has a large reverse component juxtaposing, at its maximum south of Dalry, Passage Formation strata in the footwall block against CPV in the hanging-wall block, a throw of more than 200 m.

The north-north-east trending Largs Fault zone, including the Inverkip faults to the north-east, contains a sinusoidal network of generally very steep faults, associated with an almost northerly trending syncline – anticline pair, the Leap Moor Syncline and Loch Thom Anticline (Figure 11). Paterson et al. (1990) inferred that these folds were formed and their crests eroded, associated with movement on the Largs Fault prior to the onset of CPV eruptions. This accords with the reverse re-activation of the Campsie Fault discussed in section 5.1.1.

In the north of the block, the approximately east–west curved traces of the Cloch and Clyde Faults place these alongside the Milngavie–Kilsyth and Campsie faults that bound the Kilpatrick Hills and Campsie Fells blocks to the north-east. The offset of the Renfrewshire Hills outcrop of the CPV relative to the Kilpatrick Hills and Campsie Fells, could indicate that all these faults have a large right-lateral strike-slip component. If this were the case then the intriguing question arises as to how far eastward is the Glasgow Central Coalfield underlain by the CPV?

With the exception noted above, the geometry of most of the faults is not known, but for the purpose of modelling their hade are considered to be near vertical. Downthrows are mostly not recorded and have been inferred during section drawing.

5.1.4 Southern Hills block

The fault network for the Southern Hills block is illustrated in Figure 12. The northern boundary of the block is marked by the sinuous, Gleniffer, Clarkston and Castlemilk West faults. Though these are shown on BGS 1:50 000-scale maps as dipping moderately to the north, their surface trace geometry is more compatible with a steep hade. The Dusk Water Fault extends into this area from the Renfrewshire Hills block, laterally displacing the Beith – Barrhead Hills CPV outcrop by 2.5 km; the sense of displacement is dextral.

The geometry of the Dechmont Fault in the east of the block is taken from the main Clyde Basin model. Similarly, some of the faults in the south-eastern extent are taken directly from the GSI3D model of the Strathaven – Douglas Coalfield part of the Clyde catchment.

With the exception noted above, the geometry of most of the faults is not known, but for the purpose of modelling their hade are considered to be near vertical. Downthrows are mostly not recorded and have been inferred during section drawing. Most faults within the outcrop of the CPV have been omitted because of the lack of a coherent detailed stratigraphy (see below).

5.1.5 Comments on the fault networks

Every fault has been modelled as a simple dipping surface and hence has been grossly simplified. Though probably not geologically correct, adopting this methodology has meant that construction of the fault networks has been achieved quickly and by using consistently steep dips for the faults calculation errors have been reduced to a minimum. However, within a strike-slip fault-system in particular, complex changes in dip and strike of the faults are to be expected, as are curved profiles for the faults. Shallow-plunging, Y-shaped intersections of faults, a major feature where there are fault duplexes, cause particular problems in model calculation. Where such truncations occur within the stratigraphical depth of the model, parts of the section will not colour correctly and hence will not calculate. However, where such intersections are steep and occur beneath the lowest stratigraphical surface, fewer problems arise. This issue will require resolution before more realistic fault networks can be built.

5.2 STRATIGRAPHICAL MODELS

5.2.1 Campsie Fells block (Figure 13)

Three basal surfaces have been modelled within the Inverclyde Group: Kinnesswood (KNW), Ballagan (BGN) and Clyde Sandstone (CYD) formations (Figures 6, 14-16). The shape of these reflects both the changing thickness of these units, as demonstrated along the northern and western outcrop of the formations, and the progressive overstep of the CPV southwards across the Clyde Sandstone and Ballagan formations to rest on Kinnesswood Formation locally, adjacent to the Campsie Fault (Forthsyth et al., 1996, fig. 3) (Figures 16, 17). A check on this is provided by a thickness of about 200 m for the Ballagan Formation at outcrop along the northern scarp and the Tak-ma-doon Bore in the south of the block which proved only 20 m; 2 km to the west in the Bachille Burn [NS 707 793] the CPV appears to rest directly on Kinnesswood Formation.

For the purpose of the GSI3D model, the large number of local units within the CPV has been grouped into the 15 members listed in Table 1. Some of these units are directly the members with that name, but most comprise several members considered to be spatially and lithologically related. The consequence of dividing the volcanic succession wholly into subunits has meant that no base-CPV surface has been constructed within the model.

Figures 18-28 show views of the modelled basal surfaces of most of the volcanic units. Of the 15 CPV units modelled only the Campsie (CAMPL, CAMPU) and Kilsyth lava members are distributed throughout the block (Figures 23, 27). All other units are locally distributed at outcrop, and their subcrop extents are interpolated from the outcrop data. Thus, their extents only reflect the distribution of the units in general terms. Nevertheless, the models neatly show the concentration of the various units along the northern and southern flanks of the block, probably associated with the ENE-trending linear vent-swarms (Craig, 1980). Internal unconformities are present in the sequence: note how the Upper Lecket Hill Lava Member is seen to overstep the Lower Lecket Hill and Boyd's Burn lava members westwards on to the Campsie Lava Member (Figures 24-26).

The Campsie Lava Member poses a technical problem in the GSI3D methodology, because it wholly envelopes the Craigentimpin Lava Member and its correlated units. Therefore, the

Campsie Member has been divided artificially into lower and upper (CAMPL, CAMPU) units solely for the purpose of modelling. The two divisions are given the same colour to minimise the attention drawn to them.

Table 1. Summary of the units modelled within the CPV of the Campsie Fells block.

Model Code	Modelled member	Other lava members/ previous names included for modelling	Description	Maximum thickness (m)
GARV	Garvald	Knowehead, Corrie, Craig-douffie	Basalt, hawaiite & mugearite lavas	50+
KILS	Kilsyth Hills	Holehead, Denny Muir	Plagioclase-macrophyrlic basalt and trachybasalt lavas	200+
ULECK	Upper Lecket Hill	Fin Glen	Trachyte, mugearite, hawaiite lavas and pyroclastic rocks	110+
BOYD	Boyd's Burn		Hawaiite lavas	50
MEIK	Meikle Bin		Pyroclastic rocks	130 (see text)
LLECK	Lower Lecket Hill	Langhill	Hawaiite, mugearite, benmoreite lavas	50
SHEL	Shelloch Burn		Trachybasalt, mugearite, basalt lavas	65
CAMPU	Campsie, upper		Basalt and hawaiite lavas	215
CRAIG	Craigentimpin	Loup of Fintry, Laird's Hill, Overton	Plagioclase macrophyric basalt, hawaiite lavas	35
CAMPL	Campsite, lower	Faughlin, Tappetknowe	Basalt and hawaiite lavas	135
BURN	Burnhouse	Laird's Loup, Carron Bridge	Hawaiite lavas	65
DRUM	Drumnessie		Basalt lavas and pyroclastic rocks	60
SLACKG	Slackgun	Slackgun Interbasaltic Beds	Volcaniclastic rocks	85
BAST	Baston Burn	Skiddaw	Basalt lavas	70
SLACKD	Slackdown	Basal group	Hawaiite lavas	50

Data from Craig (1980) and Forsyth et al. (1996).

Though the very localised Meikle Bin Member was considered to be an explosive deposit from the Waterhead Central Volcanic Complex by Craig (1980) and Forsyth et al. (1996), it was not described by them as a stratigraphical unit. However, as it overlies the Lower Lecket Hill Member it may be considered as such; the thickness of 130 m given in Table 1 has been derived from the cross-sections and is a minimum because the top of the member is nowhere preserved.

Units modelled above the CPV include the Kirkwood, Lawmuir and Lower Limestone formations. This part of the succession is intruded by quartz-dolerite sill(s) of the Midland Valley Sill-swarm. However, as these sills occur only at the eastern limit of the model, are outside the Clyde catchment and transgress the stratigraphy, they are omitted from the model at this stage.

5.2.2 Kilpatrick Hills block

The calculated envelopes and a 3D exploded view of the model are shown in Figures 29 and 30 respectively. The full fence diagram is shown as Figure 31.

A full succession of Inverclyde Group strata is present at outcrop along the west and north of the Kilpatrick Hills and data are proved in boreholes in the west. However, there is no information on the stratigraphy at subcrop in the eastern part of the area. Across the Kilpatrick Hills there is no evidence to suggest that the component formations of the Inverclyde Group thin or become absent at subcrop to the south-east. The relationship between these formations and the overlying

CPV is apparent conformity. Therefore, it is assumed that these formations continue to depth at similar thicknesses to that seen at outcrop.

In this model the CPV is divided into component units (Table 2), utilising the presence of volcanoclastic units at the base and in the central part of the succession. The calculated envelopes for the units, the Burncrooks Pyroclastic Member at the base and the Greenside Volcanoclastic Member within the formation, are illustrated in Figure 32. Both members are proved at outcrop and in the Loch Humphrey Borehole, but their subcrop extent is not known. The interpolated subcrop extents shown come from the inference that these deposits were erupted from the linear vent swarms as with the Slackgun Member in the Campsie Hills.

Table 2. Summary of the units modelled within the CPV of the Kilpatrick Hills block.

Model Code	Member	Other lava members/ previous names included for modelling	Description	Maximum thickness (m)
KILPH2	Clyde Plateau Volcanic Formation, upper division undivided	Tambowie, Mugdock, Cochno	Mostly lava flows of macroporphyrific basalt and mugearite	Up to 450
GNSV	Greenside Volcanoclastic Member		Tuff, agglomerate and volcanoclastic sedimentary strata	5-55
KILPH1	Clyde Plateau Volcanic Formation, lower division undivided	Carbeth, Saughen Braes, Aucheneden	Lava flows of macro- and microporphyrific basalt and mugearite	Up to 250
BCV	Burncrooks Pyroclastic Member		Tuff, agglomerate and volcanoclastic sedimentary strata	Up to 80

The lava members between the two volcanoclastic units are combined into a single unit, as are those above the higher of the volcanoclastic units. A consequence of wholly dividing the CPV is that no base-CPV surface has been constructed.

The only unit modelled above the CPV is the combined Kirkwood and Lawmuir formations.

5.2.3 Renfrewshire Hills block

The calculated envelopes for the stratigraphical units and exploded 3D views of the full Renfrewshire Hills block model are illustrated in Figures 33-35 and the fence diagram in Figure 36.

Outcrop and borehole evidence in and adjacent to the block indicates that the CPV oversteps the constituent formations of the Inverclyde Group southwards to overlie the Upper Devonian formations south of Largs (BGS Scotland 1:50 000-scale sheet S22W, Irvine). However, the detail of this is poorly constrained. In the north, all three formations crop out and are proved in the Knocknairshill and Everton boreholes. The southern limit of the Clyde Sandstone Formation is constrained only by its outcrop just to the north of the Muirshiel Fault. The southward limit of the Ballagan Formation is constrained only by its southernmost exposures just to the north of the Muirshiel Fault and its absence from the Largs and Glenburn boreholes, the latter a little to the east of the block and just to the south of the Gleniffer Fault (Figure 37A). The Kinnesswood Formation is absent for only a short distance south of Largs before it reappears south of the south-west continuation of the Paisley Ruck. The complete removal of the Kinnesswood Formation is taken to be a local feature that does not extend very far eastwards, though this cannot be proved.

A substantial thickness of Ballagan Formation is recorded in the Harelaw and Deaconhill boreholes to the south of the block. The reappearance of the Ballagan Formation is taken to occur across the Annick Water and Inchgotrick faults.

On the south bank of the River Clyde the area between the Cloch Fault and Fault 65 is shown modelled as Kinnesswood Formation, but this represents an area in the DigMapGB-50 dataset where the Inverclyde Group is not divided into constituent formations. Evidence from adjacent areas, both north and south of the river suggest that all three formations are probably present.

Stratigraphical information on the CPV across the block is variable. A detailed stratigraphy is available for the well exposed area of the Renfrewshire Hills (Paterson et al., 1990, table 6). The number of units in this scheme is reduced for the purposes of modelling (Table 3) and is applied to the area to the north-west of the Paisley Ruck and its extension south-west towards Ardrossan. A consequence of dividing the volcanic succession wholly into subunits in this part of the block is that no base-CPV surface has been constructed for this area.

Table 3. Summary of the units modelled within the CPV of the Renfrewshire Hills block.

Model Code	Member	Other lava members/ previous names included for modelling	Description	Thickness (m)
KBLA	Kilbarchan	Marshall Moor	Macro and microporphyritic basalt	Up to 150
SGLA2	Strathgryfe, (upper)		Hawaiite and mugearite lavas	Up to 500
MLLA	Misty Law		Trachyte and rhyolite, with intercalated pyroclastic rocks	Up to 300
SGLA1	Strathgryfe (lower)		Hawaiite and mugearite lavas	Up to 250
LGLA	Largs	Greeto	Microporphyritic basalt	Up to 240
NODV	Noddsdale Volcaniclastic		Basaltic pyroclastic rocks	Up to 200

South-east of the Paisley Ruck the CPV is shown undivided (Figure 37B). In much of this area the CPV lies beneath later strata and information is limited to a few small outcrops and several boreholes locating the top of the CPV. Though a volcanic stratigraphy for the Beith – Barrhead Hills has been proposed by Hall et al. (1998), the CPV is not divided in this relatively small part of the model. However, the substantial change in thickness of the CPV across the Paisley Ruck, from about 900 m in the northern Renfrewshire Hills to about 300 m in the Beith – Barrhead Hills (Paterson et al., 1990; Hall et al., 1998) is reflected in the model. The CPV is known to be absent from the succession in the Deaconhill and Harelaw 1 boreholes to the south-east of the Inchgotrick Fault. In the absence of detailed subsurface information between this structure and the Renfrewshire Hills, the thickness of the CPV is taken to be 300 m or less.

The Noddsdale Volcaniclastic and Largs members at the base of the CPV are only seen at outcrop in the west of the district and their eastward subcrop extent is not known. In the model they are assumed to have an elongate extent along the Largs Fault zone (Figure 37C, D).

The main thickness of the CPV, up to 750 m in the northern part of the Renfrewshire Hills, is taken up by the Strathgryfe Member. On the south side of the Muirshiel Fault the member is split into an upper and lower part by the Misty Law Member, a stack of trachytic and rhyolitic lavas and pyroclastic rocks. The form of the Misty Law Member is shown in Figure 38. The abrupt eastward thinning out of the member at subcrop is predicted from field observation by one of us (DS) and is incorporated into the model. Where the Misty Law Member pinches out, the base of the upper subunit of the Strathgryffe Member is continued in the sections for modelling purposes. North of the Muirshiel Fault, where the Misty Law Member is missing, model unit

SGLA2 is used for the undivided Strathgryffe Member. The subunits of the Strathgryffe Member are given the same colour, to indicate that, when superimposed, this boundary is not significant. The Kilbarchan Member is modelled to the north-west of the Paisley Ruck.

The uppermost units of the Strathclyde Group and the overlying Clackmannan and Scottish Coal Measures groups are modelled in the north-east and south of the block (Figures 33-36). The Kirkwood and Lawmuir formations are grouped together for modelling purposes and the Passage Formation is not divided into its component members. The large reverse throw on the Dusk Water Fault is emphasised by the model (Figure 35).

5.2.4 Southern Hills block

The calculated envelopes for this block, an exploded 3D image of the model and the fence diagram are shown in Figures 39-41.

In this block information on the nature of the strata that underlie the CPV is sparse. The only direct information comes from the northern flank of the Beith–Barrhead Hills, where the Glenburn Borehole proved the CPV to overlie the Kinnesswood Formation directly. Regional considerations show that east of the area modelled and about 2 km east of the Strathaven – Inchgotrick fault system, a small outcrop of CPV overlies Devonian strata directly. Further, to the south of the Inchgotrick Fault at the western extent of the model, the CPV is absent with Clackmannan Group strata overlying Ballagan Formation. Thus, in the Southern Hills model the Kinnesswood Formation is taken to underlie the CPV over the entire block, north and west of the Inchgotrick and Strathaven faults. The overlying Ballagan and Clyde Sandstone formations are considered to be entirely absent here.

In the model, the CPV is not divided across this large area. In general, the covering of superficial deposits is more extensive in this area than over the other blocks and the exposure is typically poor. Furthermore, the stratigraphy and thicknesses of the lava units is understood less well, though a crude stratigraphy is depicted on the BGS 1:50 000 Kilmarnock sheet. Estimates of the thickness of the CPV across the model area range from about 300 m for the Beith – Barrhead Hills (Hall et al., 1998), and from 500 m (MacPherson et al., 2000) to more than 900 m (Hall, 1974) for the Southern Hills.

Strata overlying the CPV are present in two basins, in the north-east at East Kilbride and in the south near Kilmarnock. The Kirkwood and Lawmuir formations are combined for modelling, but surfaces for the Lower Limestone, Limestone Coal, Upper Limestone, Passage and Lower Coal Measures Scotland formations are given (Figure 40).

5.3 SURFACE CALCULATION ERRORS

5.3.1 Non-calculation of surface polygons

Despite best efforts at ensuring that formation bases are ‘snapped’ to crossing sections and nodes applied correctly at faults, some surfaces stubbornly refuse to calculate within some polygons defined by intersecting cross-sections. In some cases this is limited to a single surface, for example in the Burncrooks Pyroclastic Member envelope shown in Figure 32A, whereas in other places all surfaces within a polygon may fail to calculate, for example in the south-east of Figure 33. The occurrence of these does not seem to be readily predictable. Whilst some of these issues have been resolved by adding extra nodes, adjusting linework or by adding extra sections, this process has proved time-consuming and, in some cases, no resolution has been possible.

5.3.2 Surface artefacts

In places, the modelled stratigraphical surfaces are adorned with unintentional spikes that often protrude through higher surfaces, including the DTM. These are artefacts of the calculation algorithm and mar the overall effect of the model surface. Typically these are seen at the

intersection of the bedrock surface with fault surfaces (Figure 42). The presence of these does not seem to be removed by changing node position and number; however, inserting extra cross-sections can in some cases reduce the effects.

5.4 INTRUSIONS

Significant features of the Clyde Plateau Volcanic Formation within the Campsie Fells and Kilpatrick Hills blocks are the presence of a putative small caldera and the transgressive Midland Valley Sill in the former, and swarms of linear vents in both. As all these features crop out and cross-cut other units, and some are cut by faults they cannot be modelled as ‘lenses’, a tool within the superficial version of the GSI3D software. Sills that remain within the bounds of a single lithostratigraphical unit can be modelled as simple stratigraphical units, though the enveloping unit would have to be modelled as upper and lower divisions (as with the Craigentimpin Member within the Campsie Lower and Campsie Upper members in the Campsie Fells block). However, it is not yet possible to model the transgressive sills such as the Midland Valley Sill, outward dipping plutons nor dykes.

The caldera is modelled as a simple structure bound by faults. A single unit (CALD) is given an artificial base located well below the base of the lowest formation (Figure 28).

In the Midland Valley of Scotland there are many hundreds of relict volcanic vents, necks and narrow diameter, near-cylindrical plugs (for BGS usage see Gillespie et al., 2008). Groups of these may be aligned as linear vent swarms. In some of these a relict vent or neck filled with pyroclastic rocks is intruded by a basaltic plug. In the immediate palaeo-subsurface, the vents might reasonably be interpreted to have a flared or trumpet-like shape. They are thus a type of funnel-shaped intrusion, a distinct class of intrusion. A possible approach to modelling these funnel-shaped intrusions was suggested by H-G Sobich. From the modelling perspective, these bodies could be considered to be the youngest ‘stratigraphical unit’ having an ‘unconformable’ relationship with the units they cut. A methodology has been developed and tested (Appendix 1). For simplicity, any compound vent or neck with central plug is modelled as a single structure. Furthermore, for this methodology to work, it is assumed that the surface dips inwards, as steeply as possible.

Within the Campsie Fells and Kilpatrick Hills blocks, a number of funnel-shaped intrusions within the linear vent-swarms of Craig (1980) have been modelled in the western part of the block (Figure 43). There is a clear relationship between topography and the intrusions (Figure 44) and the 3D shape of one of the intrusions is illustrated in Figure 45. Though non-faulted masses are the easiest to construct, the methodology is robust enough to enable full calculation of those cut by faults (Figures 46 and 47).

5.4.1 Comments

Bearing in mind that GSI3D was not designed to model intrusions specifically, this attempt at modelling funnel-shaped intrusions has produced good initial results (e.g. Figure 45). With careful location of cross-sections, acceptable results can also be achieved for examples where an intrusion is faulted or has been emplaced along a fault (Figures 46, 47).

However, two important technical issues arise that are outwith the control of the modeller: firstly, the calculated bedrock surfaces adjacent to the intrusion are typically disrupted by spiky artefacts, and secondly, the shape of the lowest part of the intrusion is poorly constrained with the methodology so far developed. These require attention to improve the overall appearance of the model.

All of the bedrock surfaces around the intrusions are disrupted to some extent and this is illustrated in Figure 48. The spikes extend up, or down, the side of the intrusion surface and some penetrate adjacent bedrock surfaces. This effect seems similar to that reported below between bedrock surfaces and faults.

In all of the intrusions modelled, the deepest extent of the intrusion was constrained only by the cross-sections. Upon calculation of the surface this produces a cross-shaped cross-section to the lower part of the intrusion, rather than the smooth oval shapes of the subcrop envelopes that constrain the intrusion shape where it passes through bedrock surfaces at shallower levels (Figure 49). An artificial bedrock surface (IntBase) was inserted near to the base of an intrusion in the Kilpatrick Hills model with the aim of constraining the shape of the intrusion at its base better. However, as Figure 50 shows this has not resolved the matter because of calculation errors.

6 Conclusions

The Clyde catchment contains many geological elements that are typical of Upper Palaeozoic regions of the UK, including coalfields, and thus these models provide a good test of GSI3D capability.

- Its huge benefit is the intuitive, geological way of working. Both primary and interpreted data can be easily used to construct models.
- The methodology is ideally suited to the construction of models in areas where borehole data are few and where there is a reliance on the use of expert judgement in the preparation of interpreted data such as cross-sections.
- Fault networks can be constructed quickly, but need to be simplified hugely from reality:
 - Copes well with faults with low hade, but less well where the hade is above 30°;
 - Copes well where fault intersections are steep, but shallow intersections and 'keel' structures (including many elements of strike-slip duplexes) will not model;
 - Fault '0'-displacement construction needs to be made easier.

The method has been applied successfully to a volcanic succession and associated intrusions:

- Calculated surfaces are, however, locally crude, with some spiky artefacts which resist removal, particularly adjacent to faults:
 - holes in calculated layers are common (5-10%) and some whole blocks between cross-sections/faults refuse thus far to calculate despite all efforts to ensure snapping etc.
- Unconformities are readily constructed from sections and subcrop line work.
 - Workflow-solutions are possible for lenticular units.
- Intrusions – funnel-shaped intrusions (as applicable to the multitude of vents and necks of the Midland Valley of Scotland) may be modelled as lithostratigraphical units, cutting all others;
 - Concordant sills may be modelled as stratigraphical units (however, intrusions may be at more than one level in the stratigraphy, increasing the number of surfaces to be modelled);
 - Theoretically, plugs with inward-dipping sides up to 89.9° can be modelled using this method, though in practice the steepest angle is constrained by the closeness the subcrop line work can be digitised;
 - Though essential to any modelling system, the following intrusion types cannot be modelled currently: outward-dipping plutons and plugs; transgressive and faulted sills, dykes.

The main geological outcomes of this work are as follows:

- The localised distribution of the lava and volcanoclastic units has been visualised along with their spatial relationship with the linear vent systems in the Campsie Fells and Kilpatrick Hills;
- The overstepping relationship of the base of the volcanic succession on the underlying formations within the Inverclyde Group has been demonstrated;
- A transpressional ‘pop-up’ duplex structure developed within a restraining bend on the dextral strike-slip Campsie East Fault, provides a mechanism for formation of the unconformity below the base of the volcanic succession.

Appendix 1 Workflow for funnel-shaped intrusions

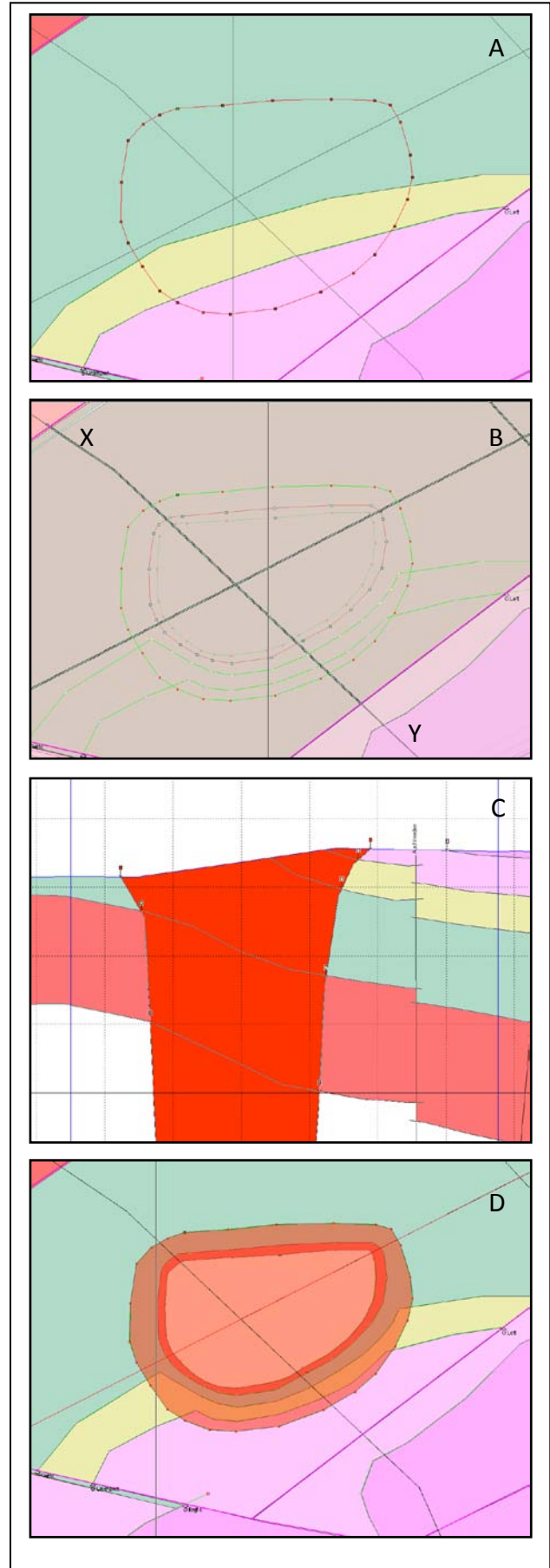
1. ***This method will only work for intrusions that have inward-dipping sides.***
2. Make entries for the intrusive units in the GVS and GLEG files, as the youngest "stratigraphical" unit.
3. Complete construction of sections with fault and lithostratigraphical/lithological units, ignoring the presence of the intrusions.
4. Calculate model and debug as far as possible.
5. Assume a nominal base level for the intrusion, well beneath the lowest stratigraphical layer.
6. Construct intrusions as follows:

In map view:

7. Draw outcrop of intrusion (Figure A)
8. Draw concentric subcrop lines for each of the units that are cut by the intrusion. Where unit bases at outcrop are cut by the intrusion, adjust their position as subcrop lines (Figure B).
9. Nodes for each unit base should be arranged in a concentric pattern from the centre point of the mass. This will ensure that there are no overlaps where the subcrop lines are close together to give a very steep surface that does not extend beyond the vertical.

In sections:

10. A minimum of 2 orthogonal sections are required, crossing through the centre of the mass (Figure C, X-Y).
11. Draw intrusion, snapping to outcrop arrows (Figure C).
12. Adjust the shape of the intrusion sides so that 'subcrop' arrows for the unit bases have the correct z value.
13. Slice out the segments of unit bases that cut through the intrusion and snap to the sidewall ('base') of the intrusion.
14. Re-calculate model and check envelopes (Figure D – intrusion envelope has transparency to show other envelopes).



References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: <http://geolib.bgs.ac.uk>.

CAMERON, I B, and STEPHENSON, D. 1985. British Regional Geology: The Midland Valley of Scotland, 3rd edition. London: HMSO.

CLARKE, S M, 2004. Confidence in geological interpretation: a methodology for evaluating uncertainty in common two and three-dimensional representations of subsurface geology. *British Geological Survey Internal Report* IR/04/164.

COTTON, W R. 1968. *A geophysical survey of the Campsie and Kilpatrick Hills*. Unpublished PhD thesis, University of Glasgow.

CRAIG, P M. 1980. *The volcanic geology of the Campsie Fells area, Stirlingshire*. Unpublished PhD thesis, University of Lancaster.

FINLAYSON, A. 2011. A three-dimensional Quaternary geology model of the Clyde catchment. British Geological Survey Internal Report, OR/XX/XXX. 16 pp.

FORSYTH, I H, HALL, I H S, and McMILLAN, A A. 1996. Geology of the Airdrie district. *Memoir of the British Geological Survey*, Sheet 31W (Scotland). ISBN 0 11 884508 X.

FRANCIS, E H, FORSYTH, I H, READ, W A, and ARMSTRONG, M A. 1970. Geology of the Stirling district. *Memoir of the British Geological Survey*, Sheet 39 (Scotland).

GILLESPIE, M R., STEPHENSON, D. and MILLWARD, D. 2008. Proposals for classifying lithodemic units of intrusive rock. *British Geological Survey Research Report* RR/08/05.

HALL, I H S, BROWNE, M A E, and FORSYTH, I H. 1998. Geology of the Glasgow district. *Memoir of the British Geological Survey*, Sheet 30E (Scotland). ISBN 0 11 884534 9.

HALL, J. 1974. A seismic reflection survey of the Clyde Plateau Lavas in North Ayrshire and Renfrewshire. *Scottish Journal of Geology* 9, 253-279.

MACPHERSON, K A T, SMITH, R A, AKHURST, MC. 2000. Geology of the Kilmarnock district. *Sheet description of the British Geological Survey*, 1:50 000 Series Sheet 22E Kilmarnock (Scotland). 30pp.

MONRO, S K. 1999. Geology of the Irvine district. *Memoir of the British Geological Survey*, Sheet 22W and part of Sheet 21E (Scotland).

PATERSON, I B, HALL, I H S, and STEPHENSON, D. 1990. Geology of the Greenock district. *Memoir of the British Geological Survey* Sheet 30W and part of 29E Scotland.

PATERSON, I B, MCADAM, A D, and MACPHERSON, K A T. 1998. Geology of the Hamilton district. *Memoir of the British Geological Survey* Sheet 23W Scotland.

PENN, I E, SMITH, I F, and HOLLOWAY, S. 1984. Interpretation of a deep seismic profile in the Glasgow area. *Investigation of the geothermal potential of the UK. British Geological Survey*.

READ, W A. 1989. Sedimentological evidence for a major subsurface fracture system linking the eastern Campsie and the eastern Ochil faults. *Scottish Journal of Geology* Vol. 25(2), 187-200.

READ, W A, BROWNE, M A E, STEPHENSON, D, and UPTON, B G J. 2002. Carboniferous. 251-299 in: TREWIN, N H (editor) *The Geology of Scotland*. Fourth edition. (London: The Geological Society.)

RIPPON, J, READ, W A, and PARK, R G. 1996. The Ochil Fault and the Kincardine basin: key structures in the tectonic evolution of the Midland Valley of Scotland. *Journal of the Geological Society of London* Vol. 153, 573-587.

UNDERHILL, J R, MONAGHAN, A A, and BROWNE, M A E. 2008. Controls on structural styles, basin development and petroleum prospectivity in the Midland Valley of Scotland. *Marine and Petroleum Geology* Vol. 25, 1000-1022.

WATERS, C N, BROWNE, M A E, DEAN, M T, and POWELL, J H. 2007. Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore). *British Geological Survey Research Report* RR/07/01.

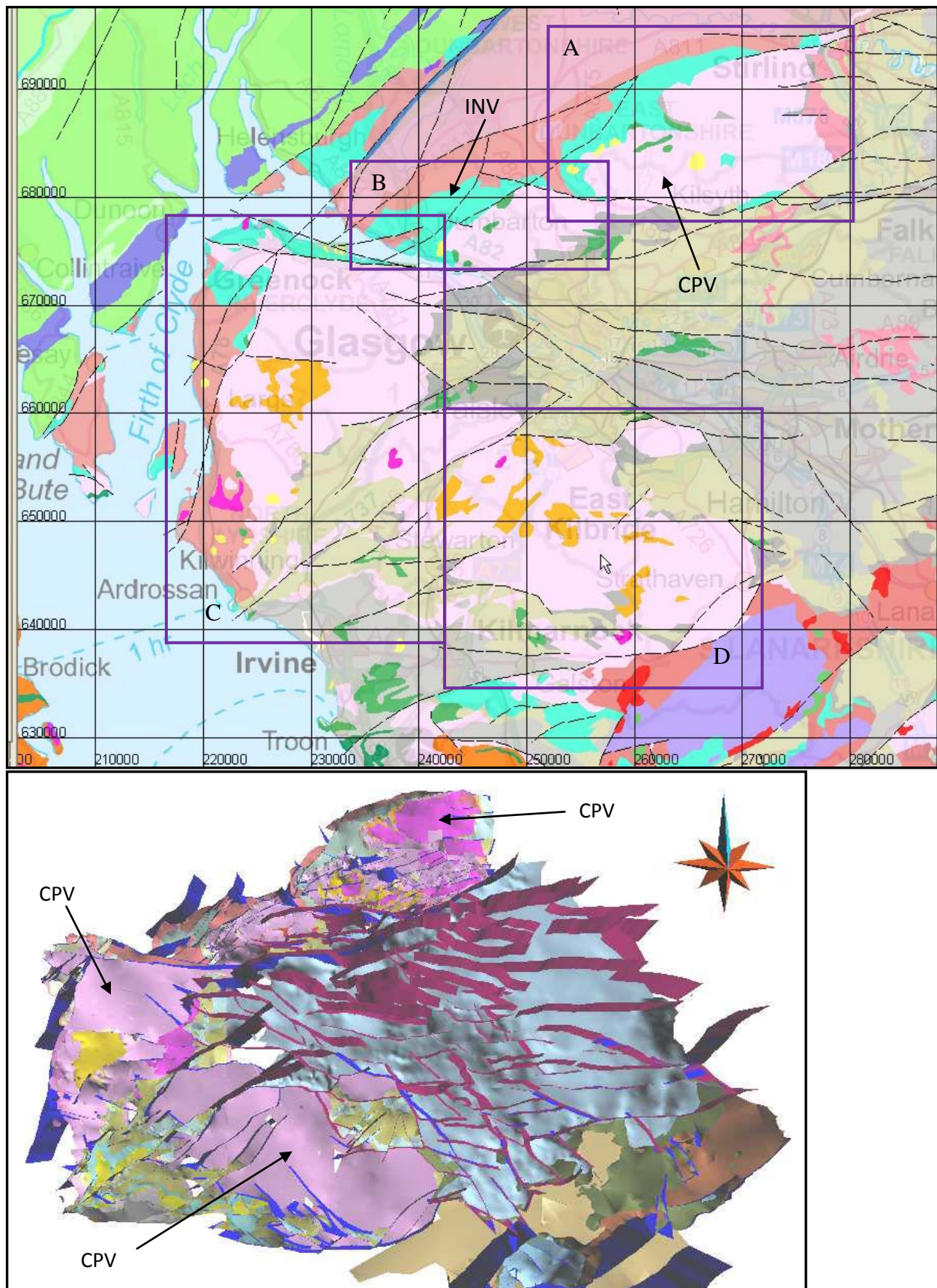


Figure 1. Outline geological map and 3D view showing the outcrop of the Clyde Plateau Volcanic Formation (CPV).

INV Inverclyde Group. Outlines of the model blocks are shown: A Campsie Fells, B Kilpatrick Hills, C Renfrewshire Hills, D Southern Hills. Geological map from DigMap-625; 3D view is a Geovisionary compilation of Clyde catchment models



Figure 2. Campsie Fells block, topography and location

Figures 2-5 are oblique aerial views from ArcScene.

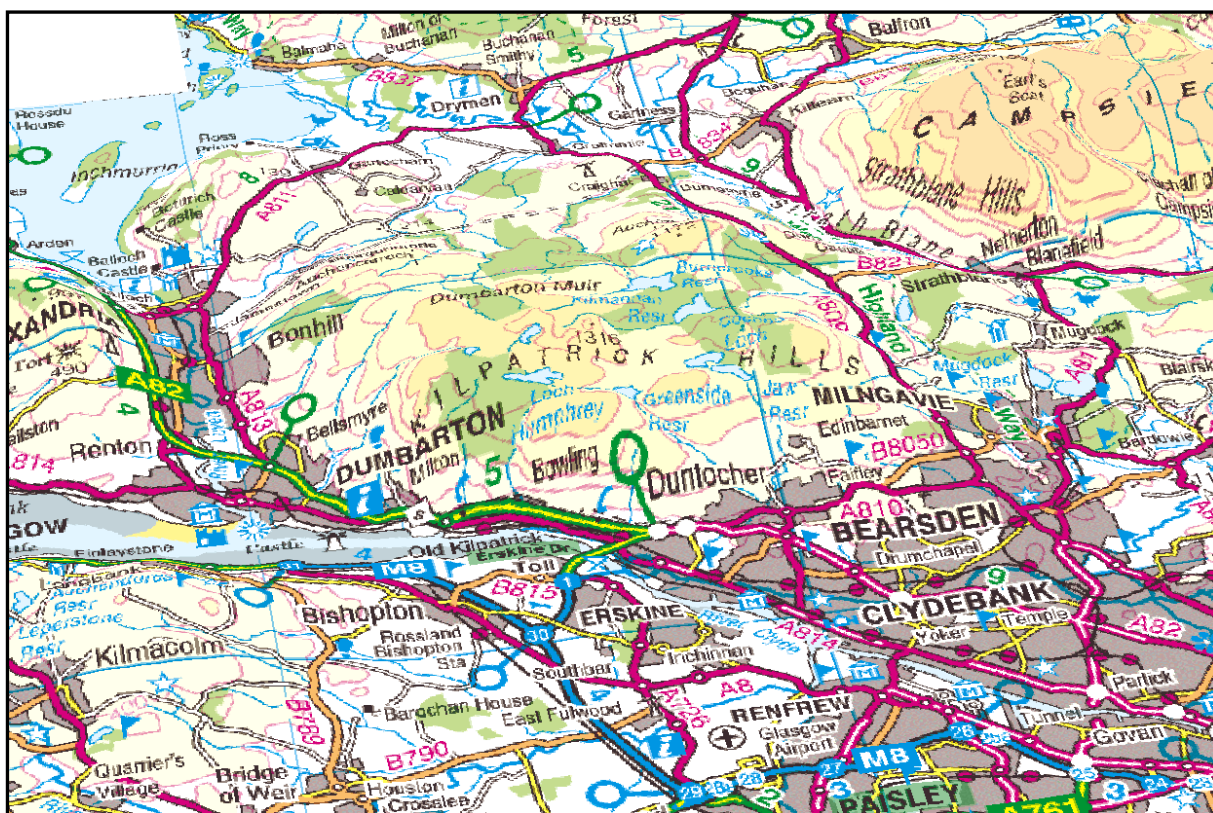


Figure 3. Kilpatrick Hills block, topography and location



Figure 4. Renfrewshire Hills block, topography and location.



Figure 5. Southern Hills block, topography and location.

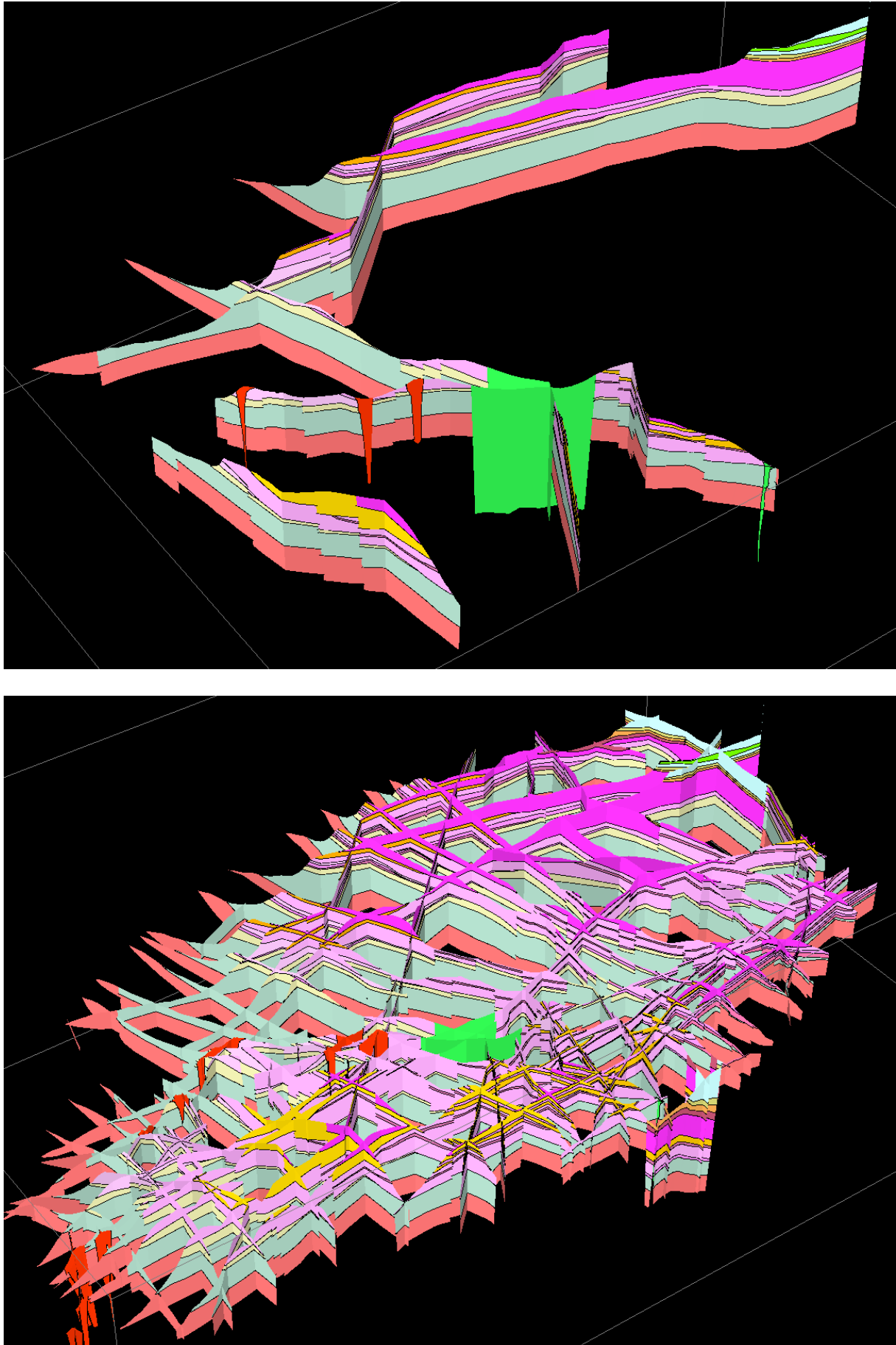


Figure 6. Fence diagram construction for the Campsie Fells block.

- A. Published cross-sections, drawn first; view looking north-east.
- B. Full fence diagram built up by working out from the published data.

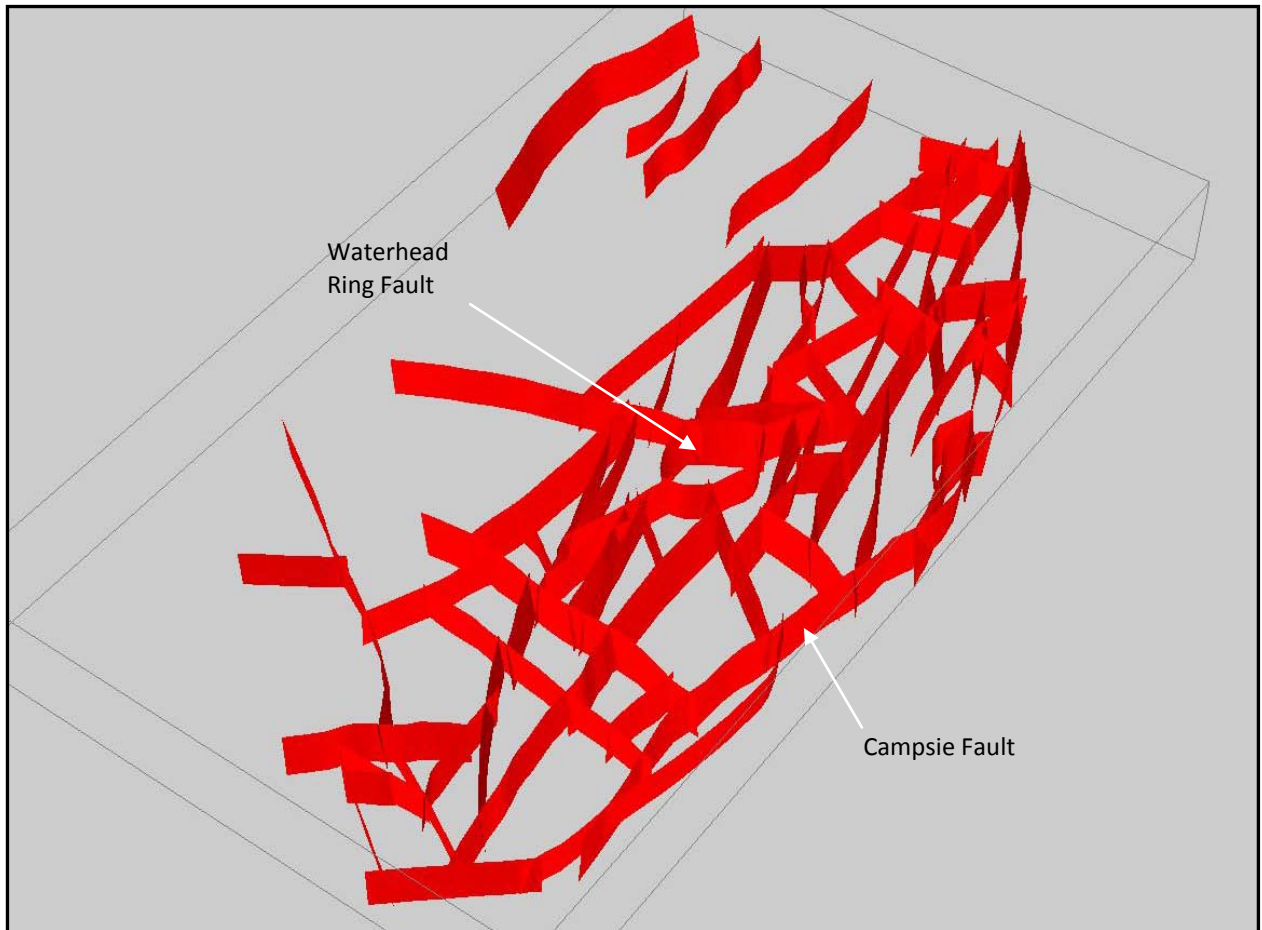


Figure 7. Campsie Fells block, fault network, looking north-east.

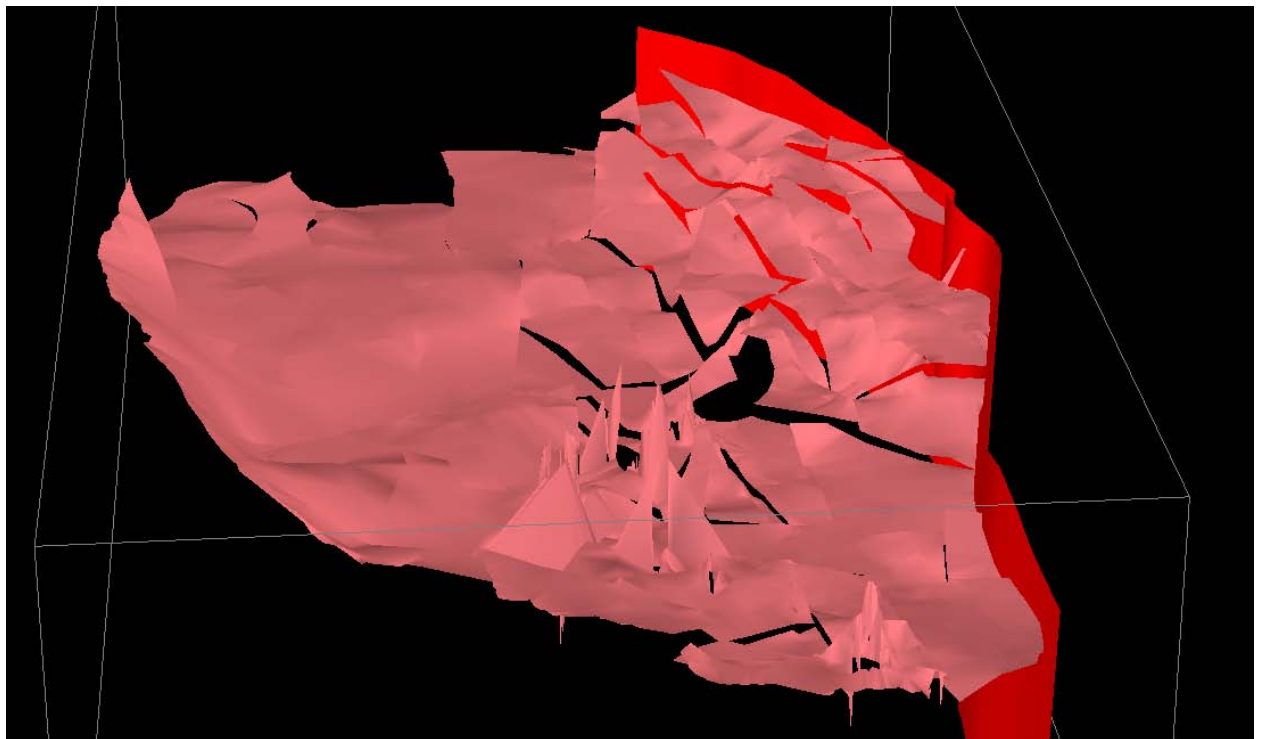


Figure 8. Base Kinnesswood Formation and Campsie East fault surfaces showing the duplex elements and weakly positive flower structure.

Note: there is a 3x vertical exaggeration to emphasise the structure



Figure 9. Fault network for the Kilpatrick Hills block, looking north-east.

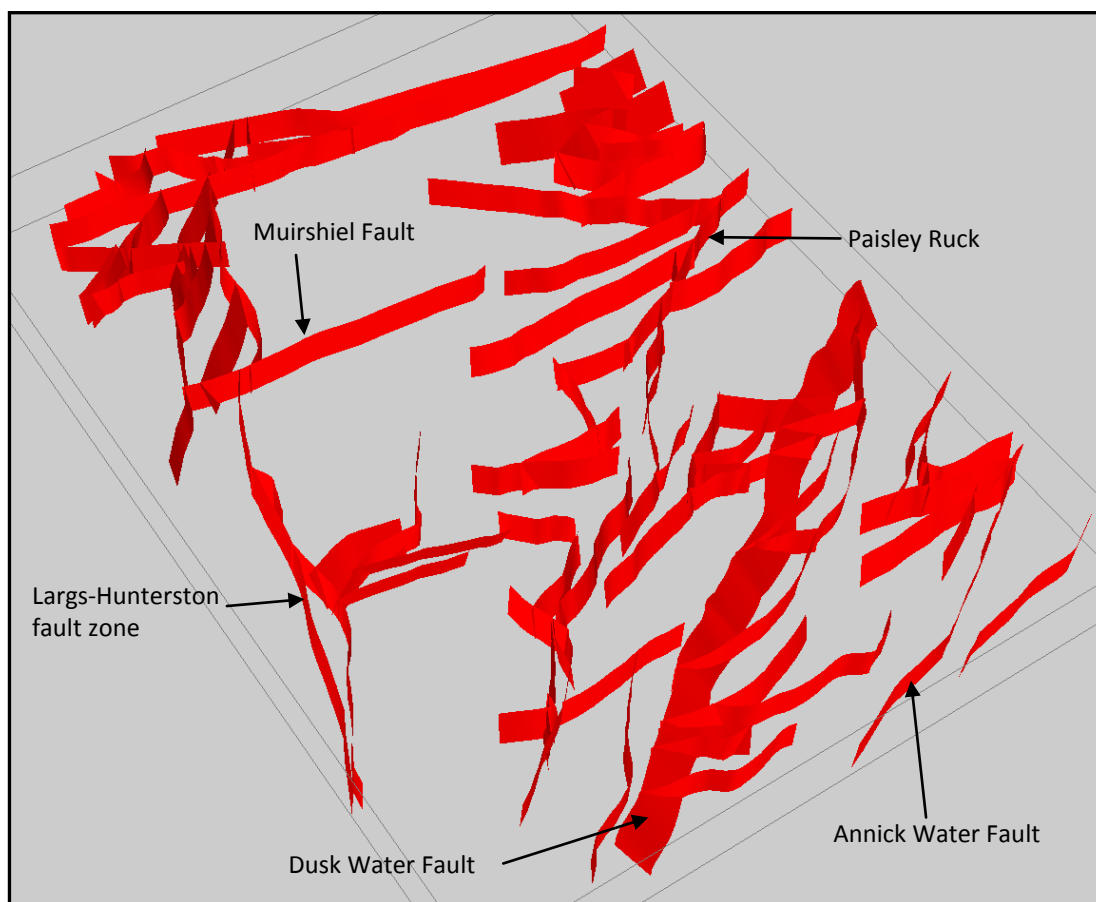


Figure 10. Renfrewshire Hills fault network, looking north-east.

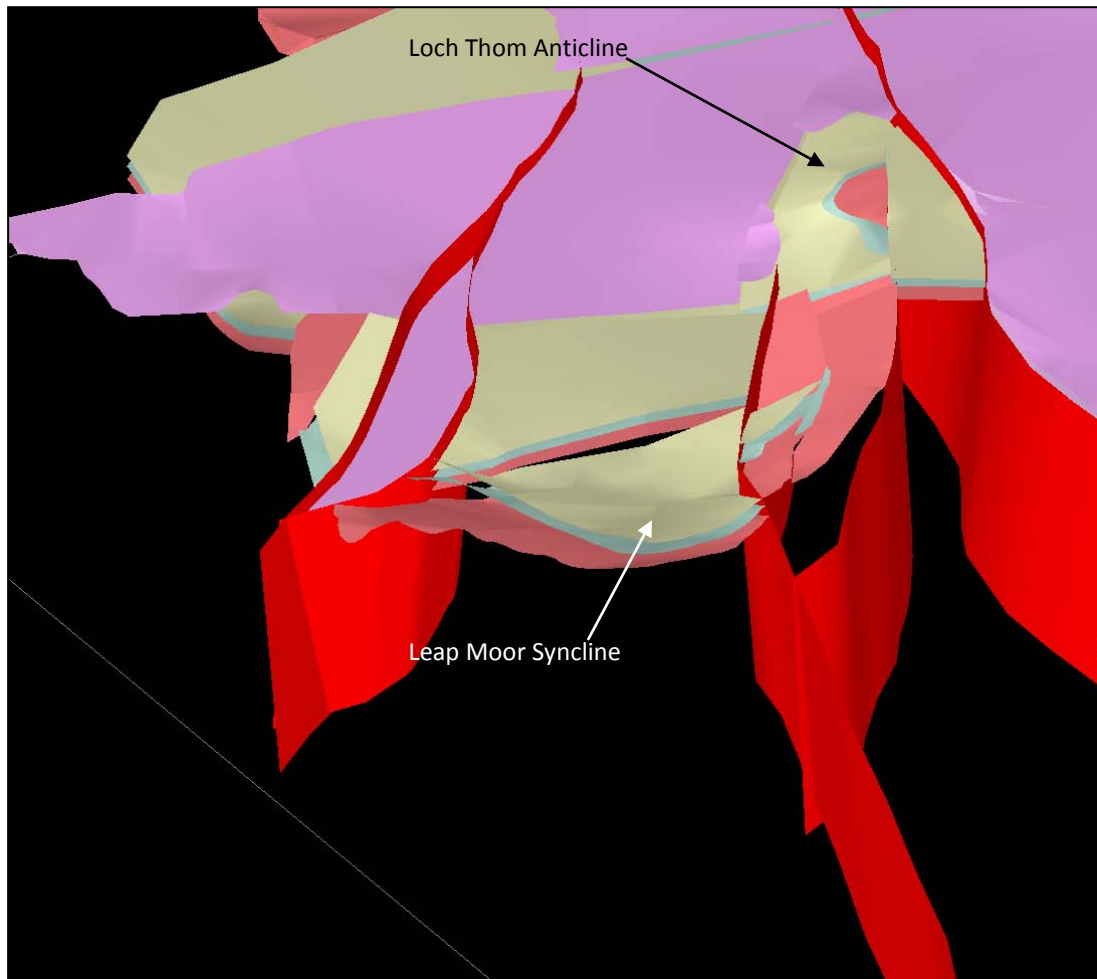


Figure 11. 3D view of the Leap Moor Syncline, Loch Thom Anticline and Largs Fault system.

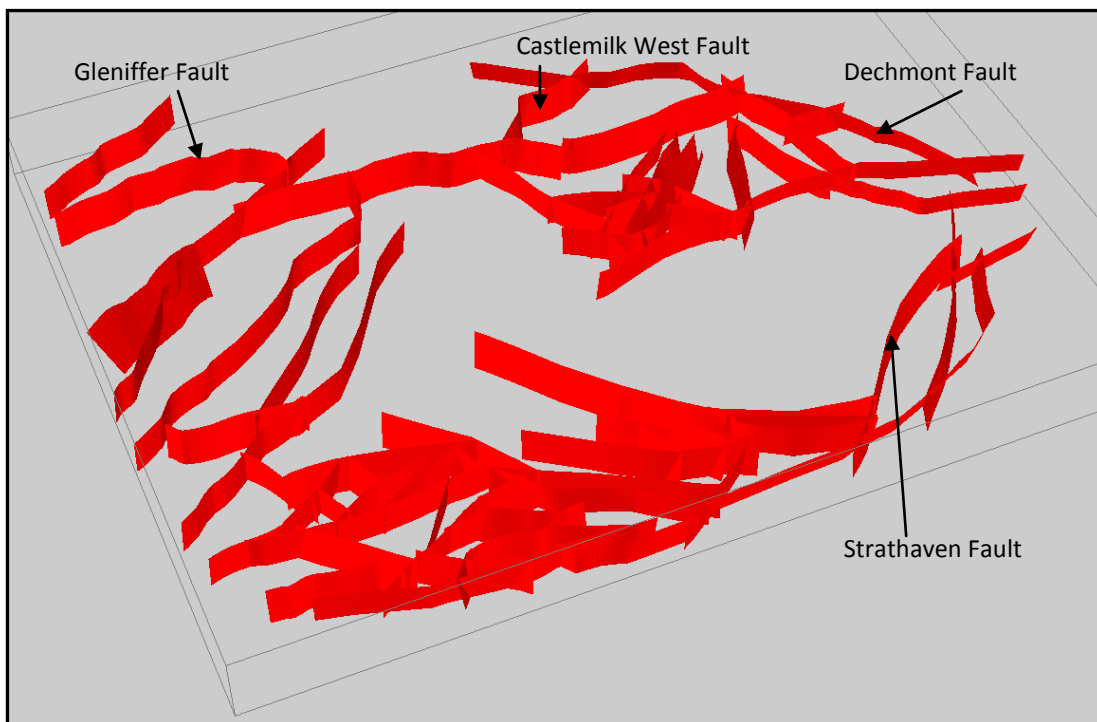


Figure 12. Southern Hills block, fault network, looking north-east.

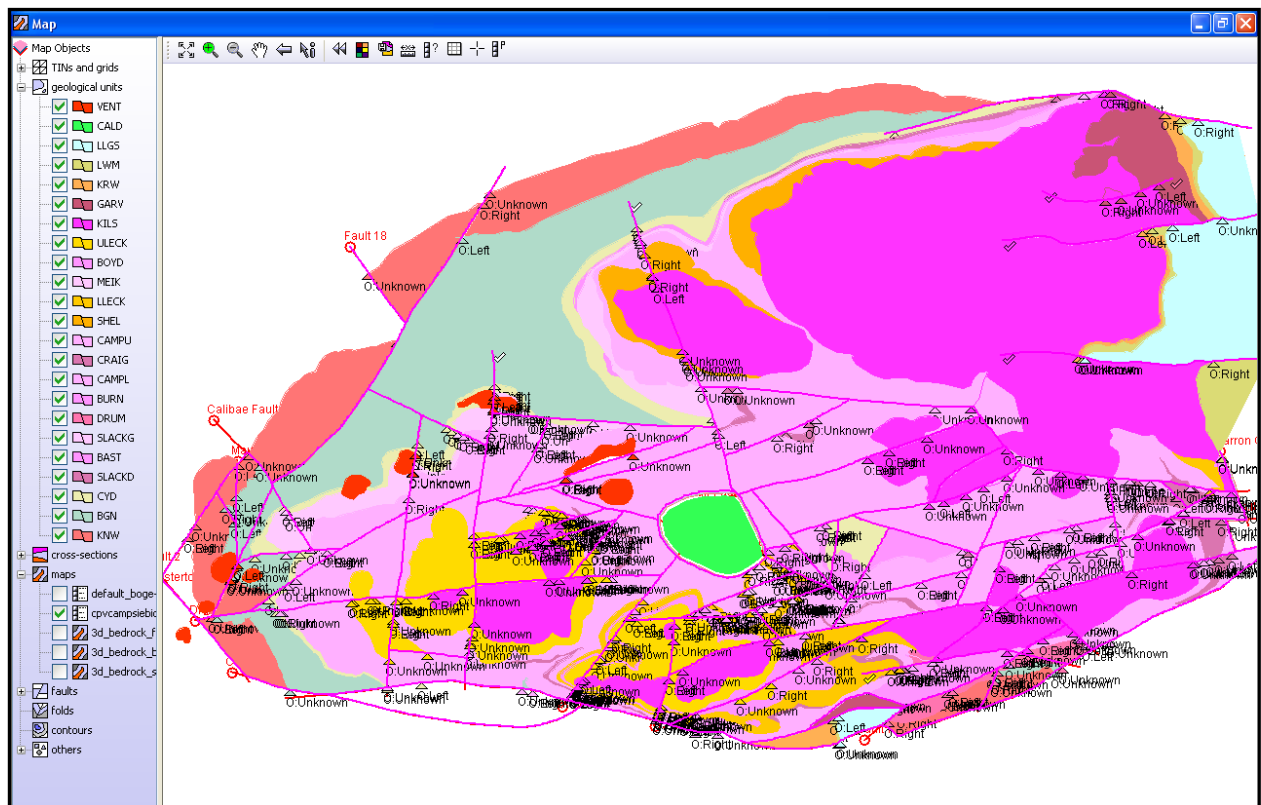


Figure 13. Campsie Fells block, full model in map view, with calculated envelopes.

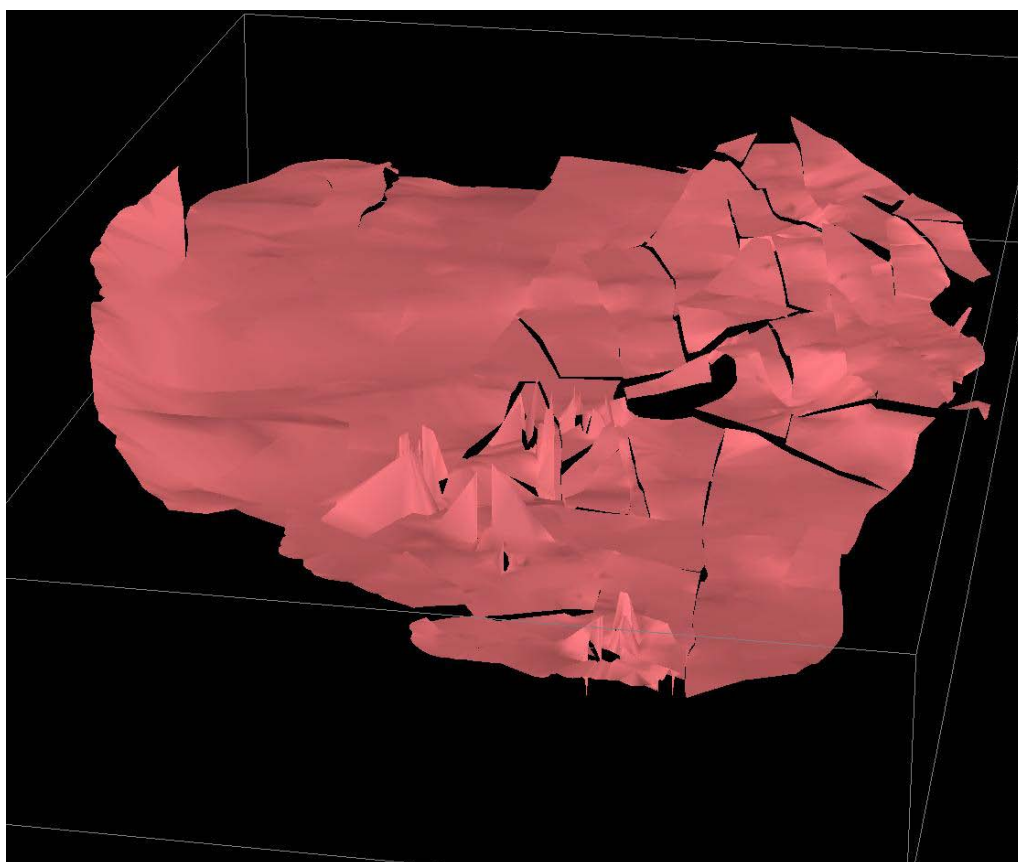


Figure 14. Campsie Fells, base Kinnesswood Formation, viewed from west-north-west.

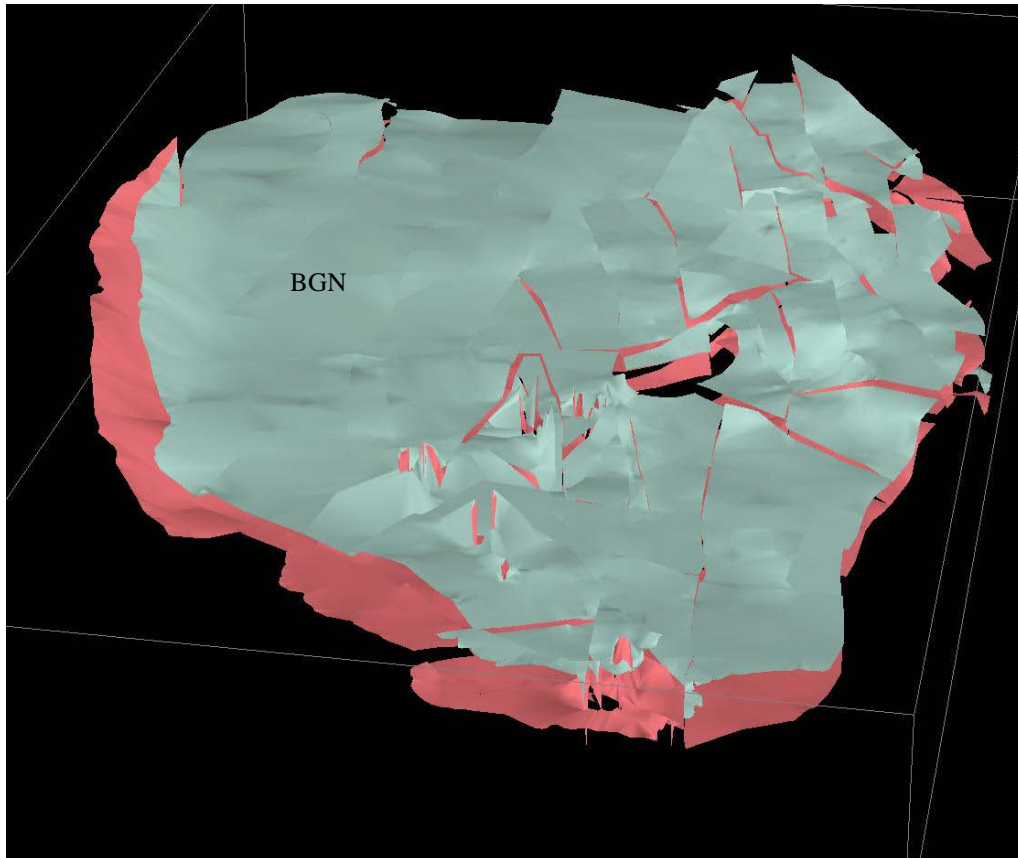


Figure 15. Campsie Fells, base Ballagan Formation (BGN), viewed from west-north-west.

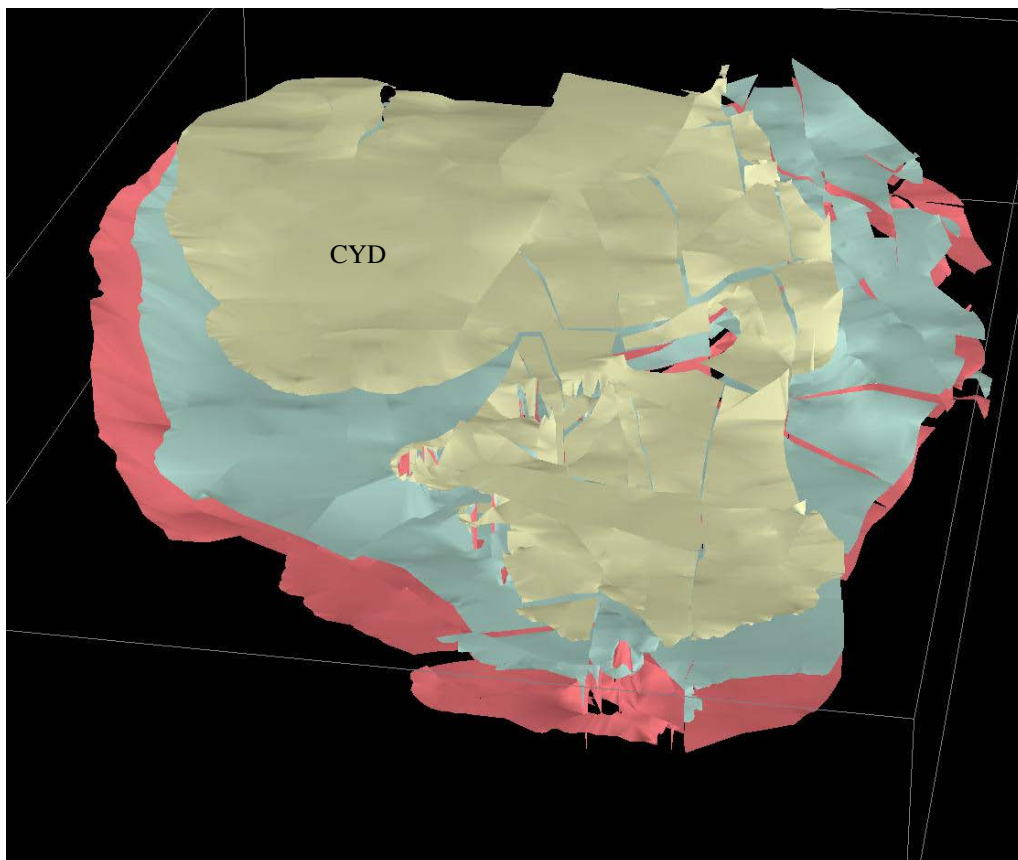


Figure 16. Campsie Fells, base Clyde Sandstone Formation (CYD), viewed from west-north-west.

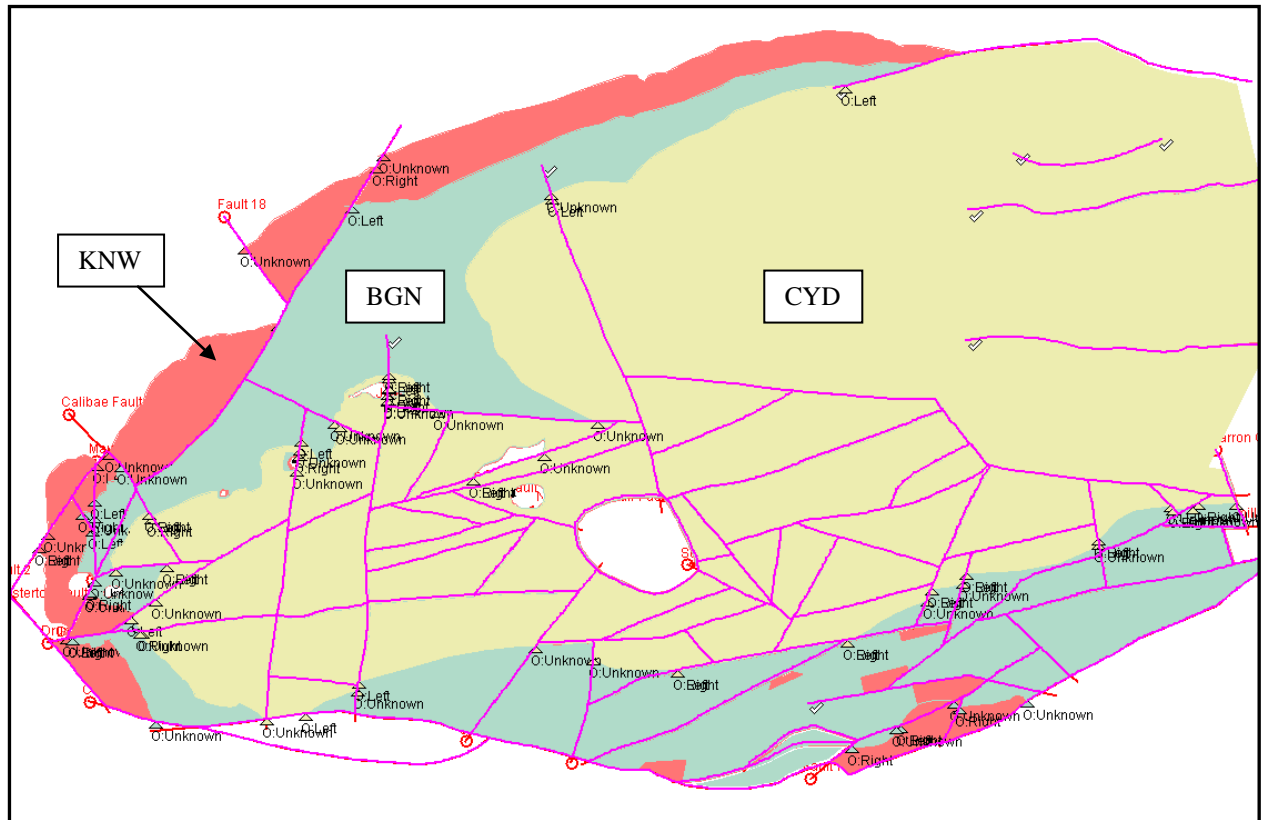


Figure 17. Campsie Fells, subcrop geological map beneath CPV.

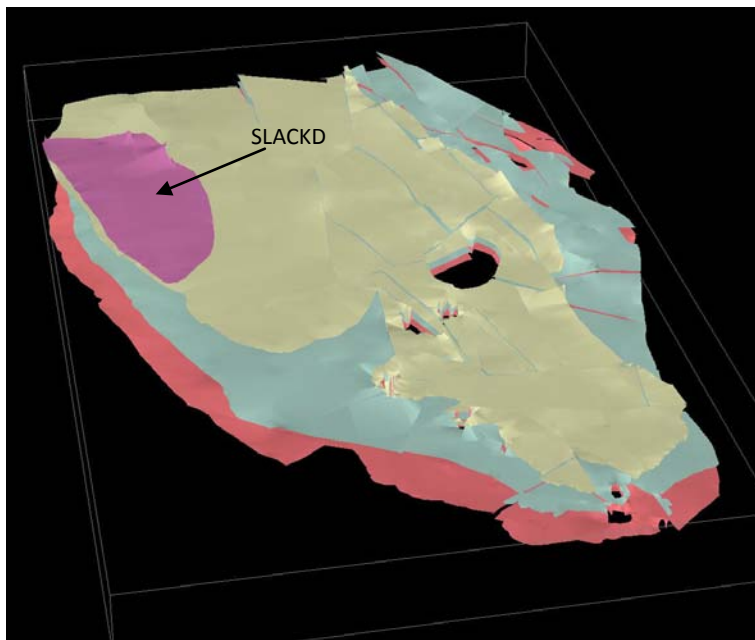


Figure 18. Campsie Fells, base Slackdown Member (SLACKD), viewed from west-north-west.

At outcrop along the northern scarp of the block, this member is confined to the Gargunnock – Touch hills, The subcrop extent is conjectural.

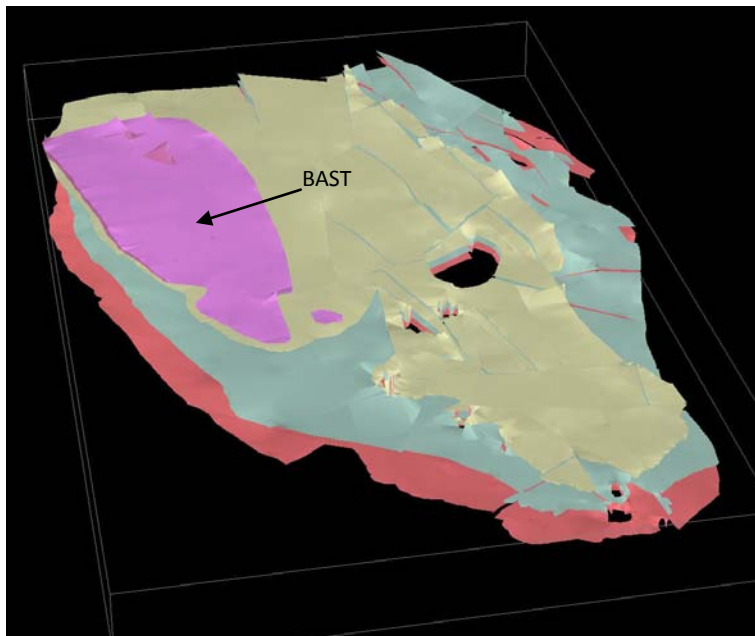


Figure 19. Campsie Fells, base Baston Burn Member (BAST), viewed from west-north-west.

This member extends further west into the Fintry Hills, compared with the underlying Slackdown Member. The largely conjectural subcrop of the Baston Burn Member is shown as being more extensive than the underlying unit.

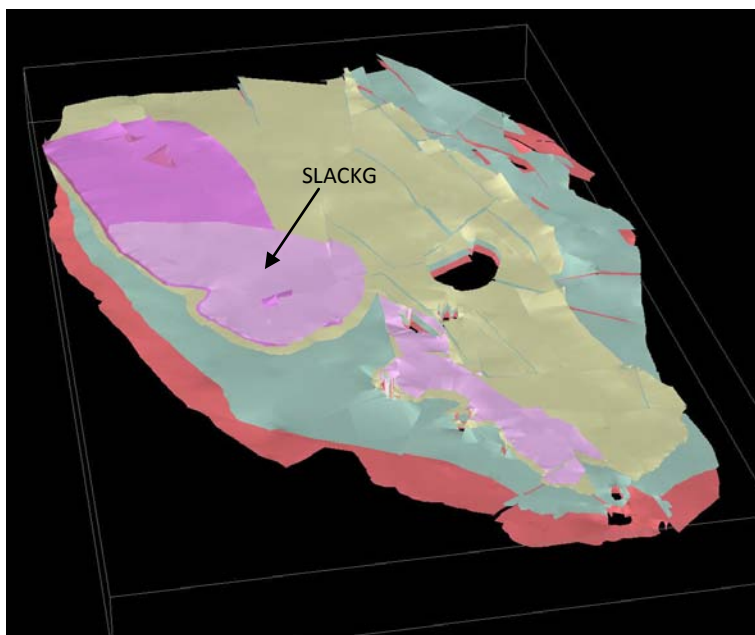


Figure 20. Campsie Fells, base Slackgun Member (SLACKG), viewed from west-north-west.

The Slackgun Member crops out along the northern margin of the Campsie Fells and extends eastwards through the Fintry and Gargunnock hills. These rocks are overstepped southwards in the Campsie Fells and, as they are inferred to be related to the North Campsie Linear Vent System their subcrop southwards is restricted.

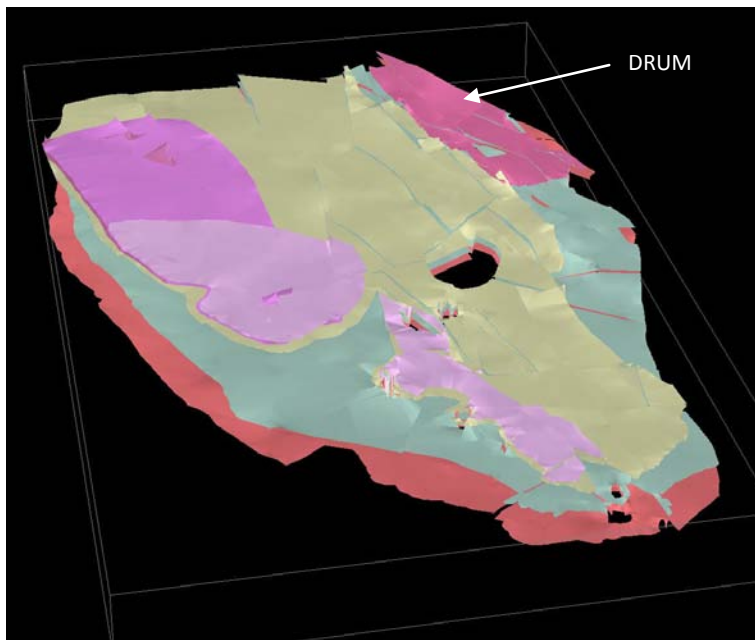


Figure 21. Base Drumnessie Member (DRUM), viewed from west-north-west.

The Drumnessie Member crops out within fault duplexes adjacent to the South Campsie Fault in the south-east of the block. Since the member does not crop out in the Carron valley, this limits its northern extent.

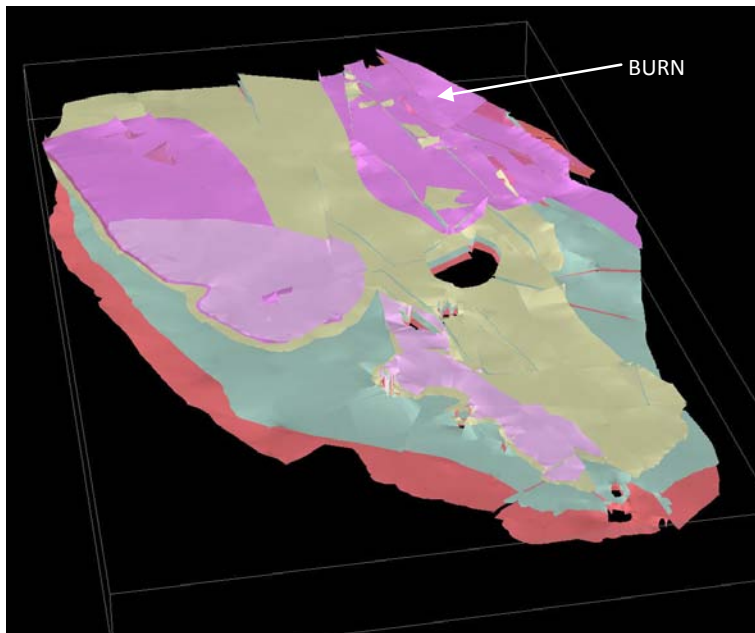


Figure 22. Base Burnhouse Member (BURN), viewed from west-north-west.

This member has a similar, but more extensive distribution to the underlying Drumnessie Member. The furthest north that the Burnhouse Member is seen is in the Carron valley.

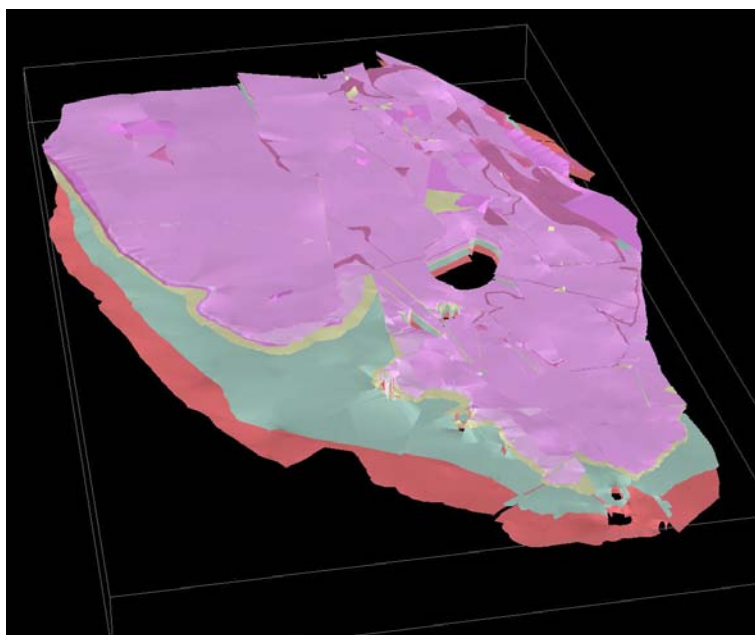


Figure 23. Base Campsie and Craigentimpin members (CAMPL, CRAIG, CAMPU), viewed from west-north-west.

The Campsie Member is the most extensive unit on the block. It envelopes the Craigentimpin Member entirely in the area mapped by Craig (1980). This unit is not separated in the Stirling district.

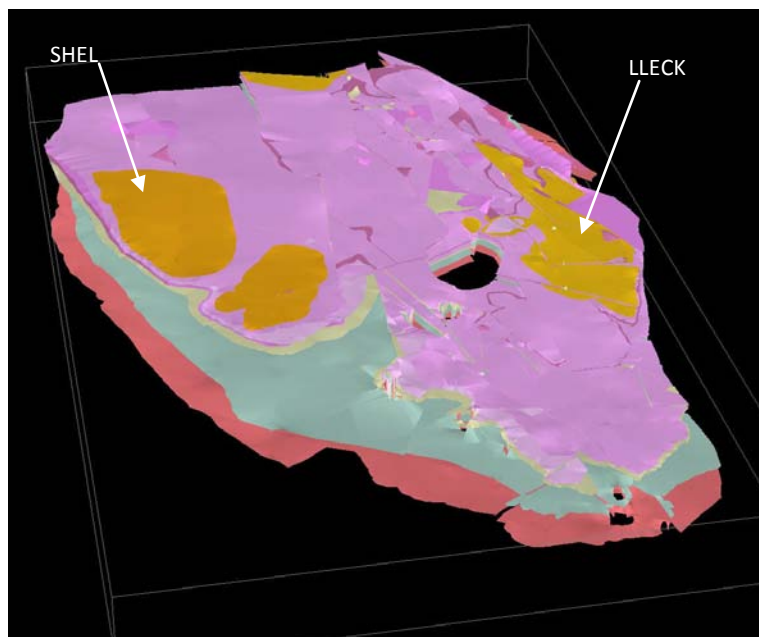


Figure 24. Base Shelloch Burn Member (SHEL; Fintry and Gargunnoch hills), and Lower Lecket Hill and Meikle Bin members (LLECK; Kilsyth Hills), viewed from west-north-west.

These two discrete units overlie the Campsie Member.

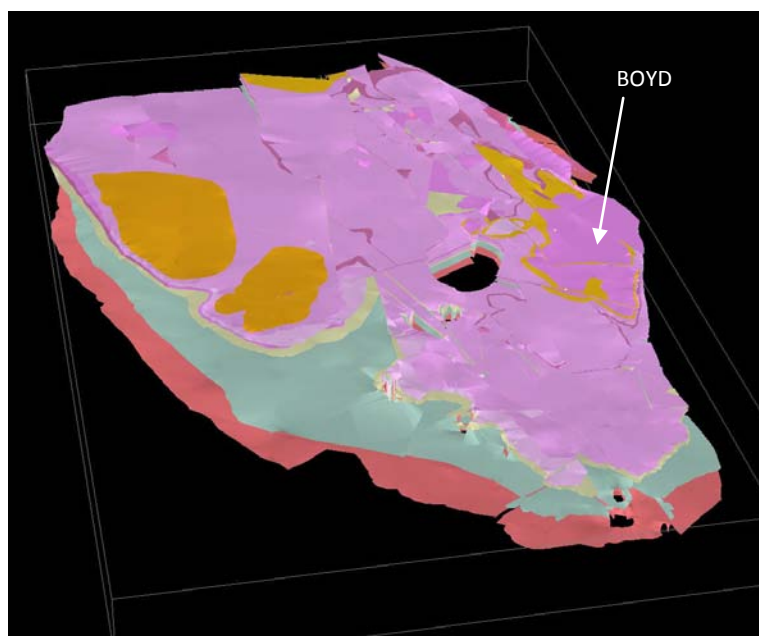


Figure 25. Base Boyd's Burn Members (BOYD), viewed from west-north-west.

This member is very locally distributed in the Kilsyth Hills, separating the Lower and Upper Lecket Hill members.

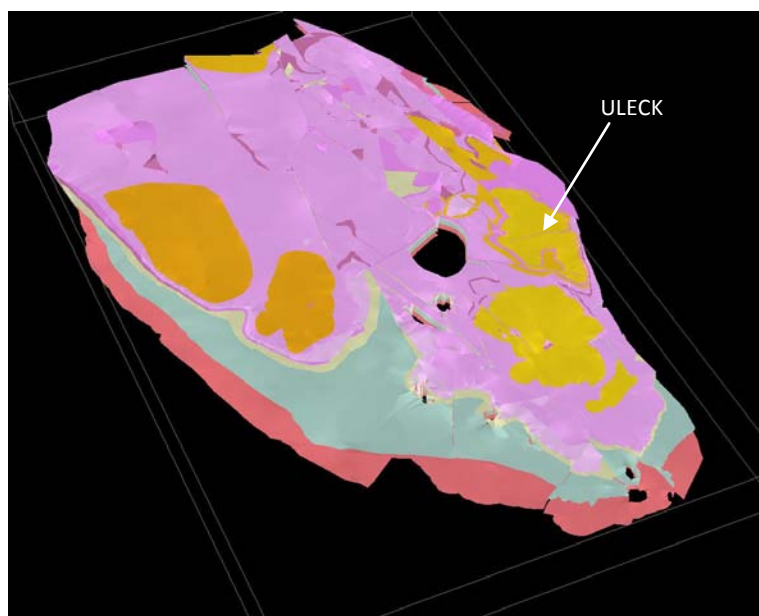


Figure 26. Base Upper Lecket Hill Members (ULECK), viewed from west-north-west.

This member oversteps the Boyd's Burn and Lower Lecket Hill Member westwards to overlie the Campsie Member.

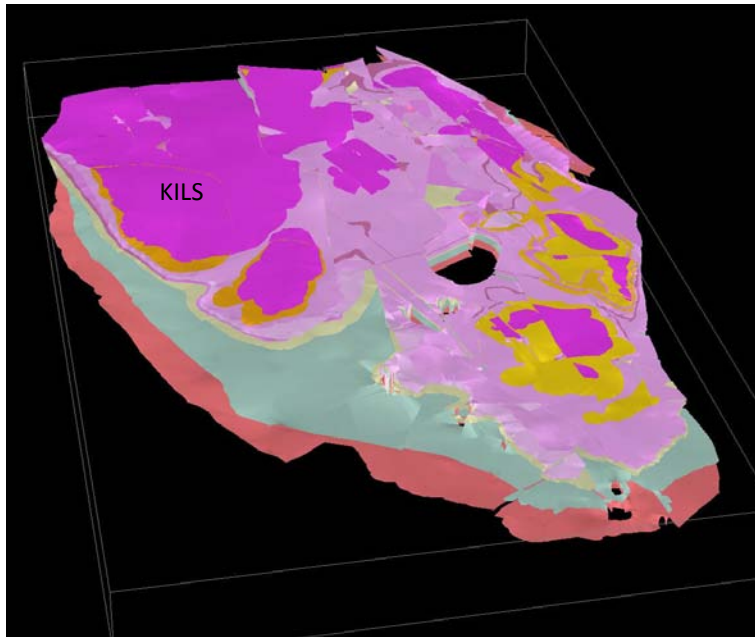


Figure 27. Kilsyth Member (KILS) and overlying units in the east of the block.

The Kilsyth member occurs throughout the block.

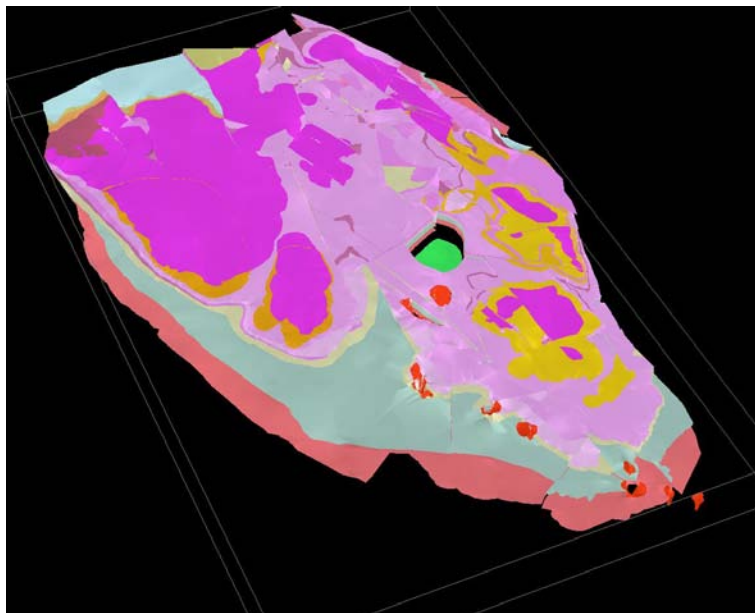


Figure 28. All overlying units and intrusions.

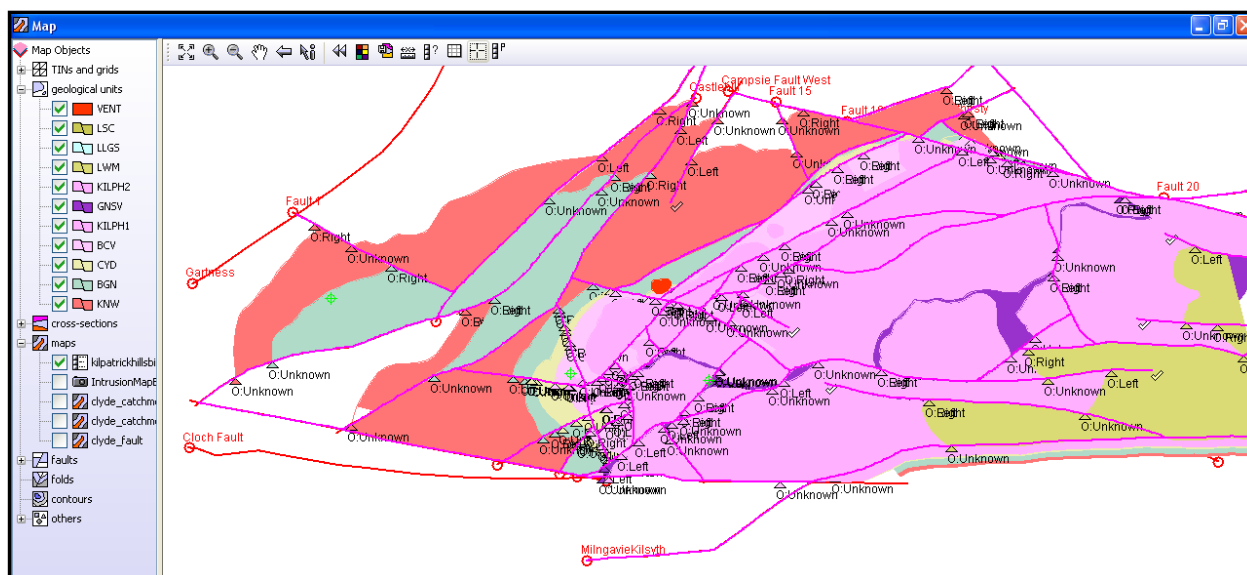


Figure 29. Calculated envelopes for the Kilpatrick Hills block.

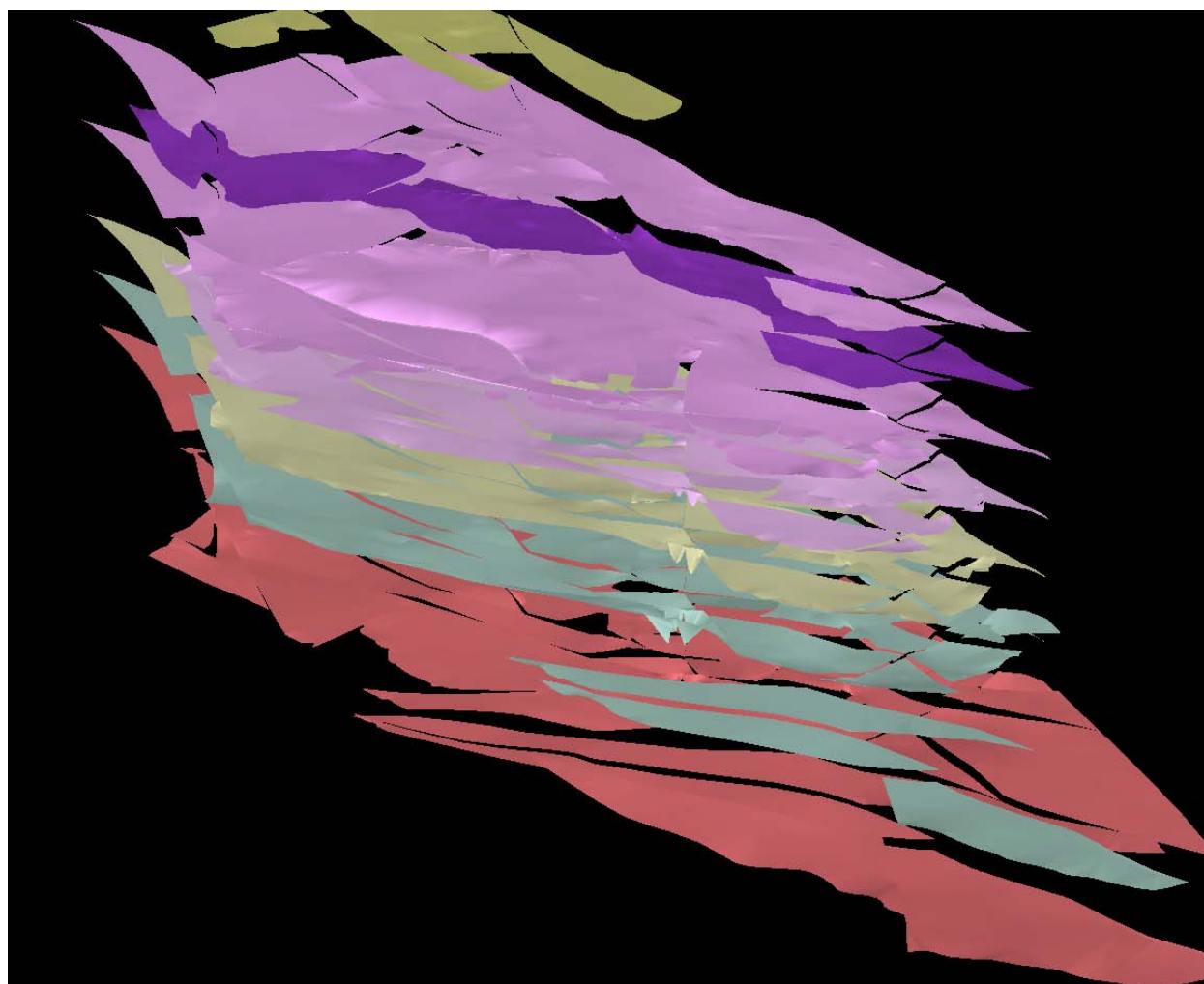


Figure 30. Exploded 3D view of Kilpatrick Hills block, viewed from the north-west.

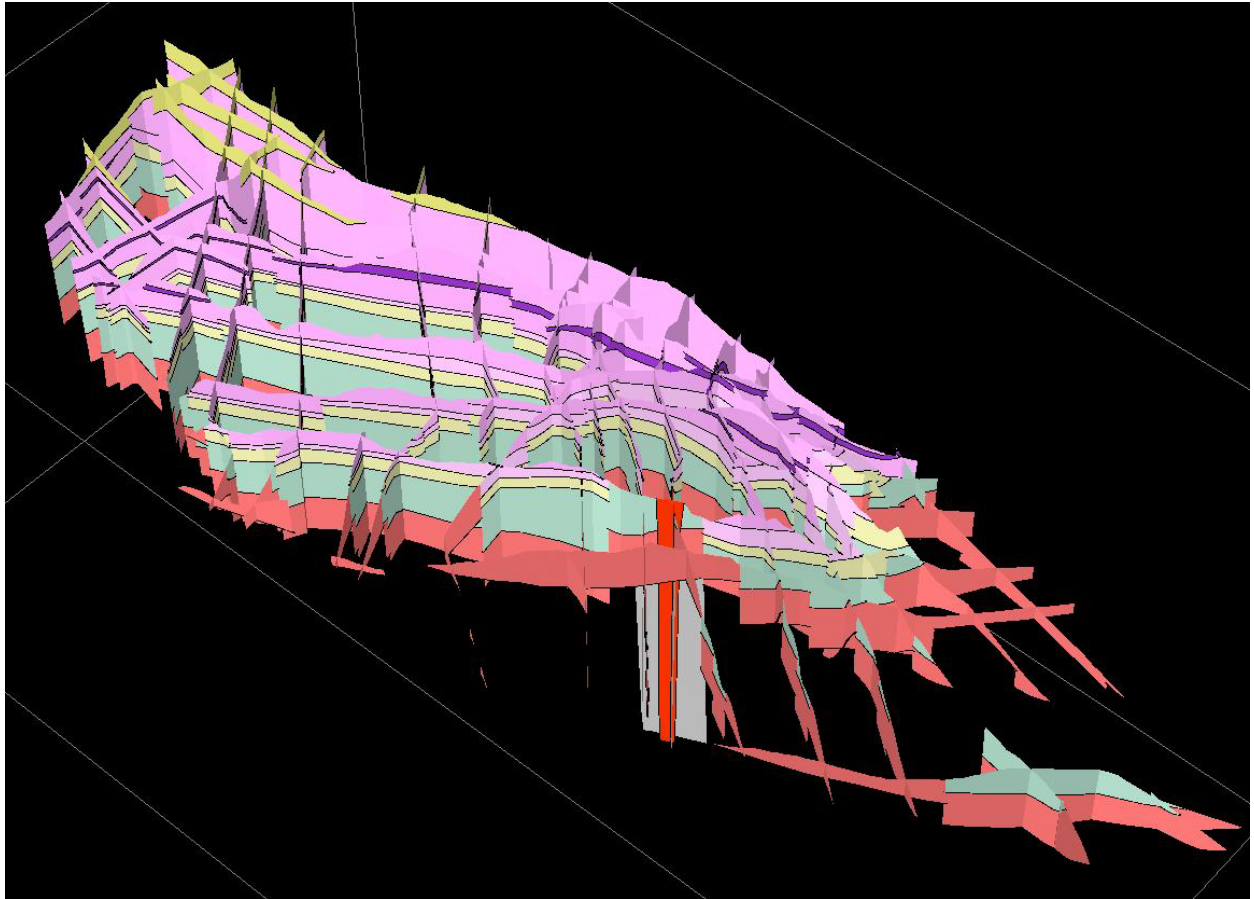


Figure 31. Full Fence diagram of the Kilpatrick Hills block

Oblique view from the north-west.

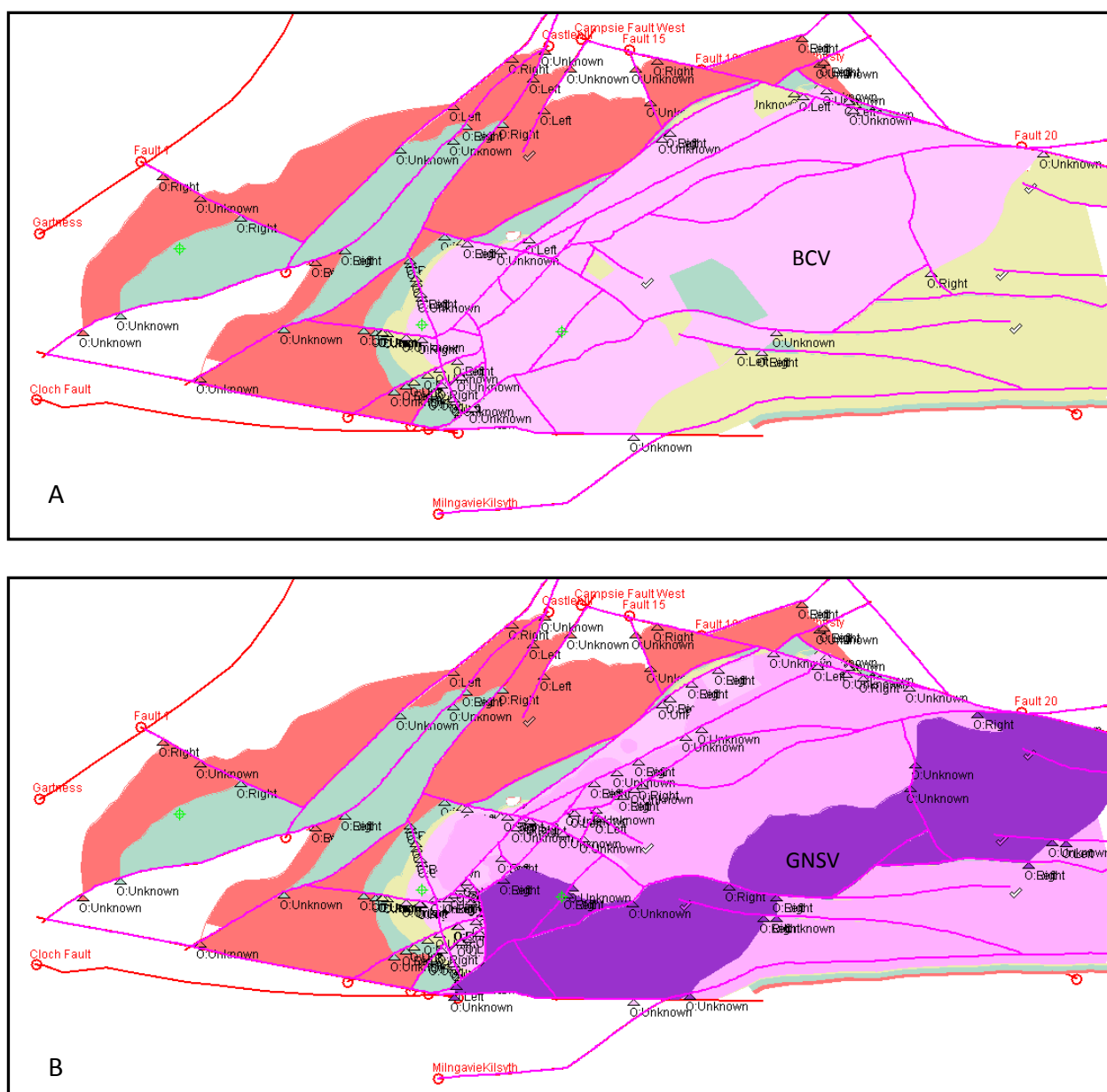
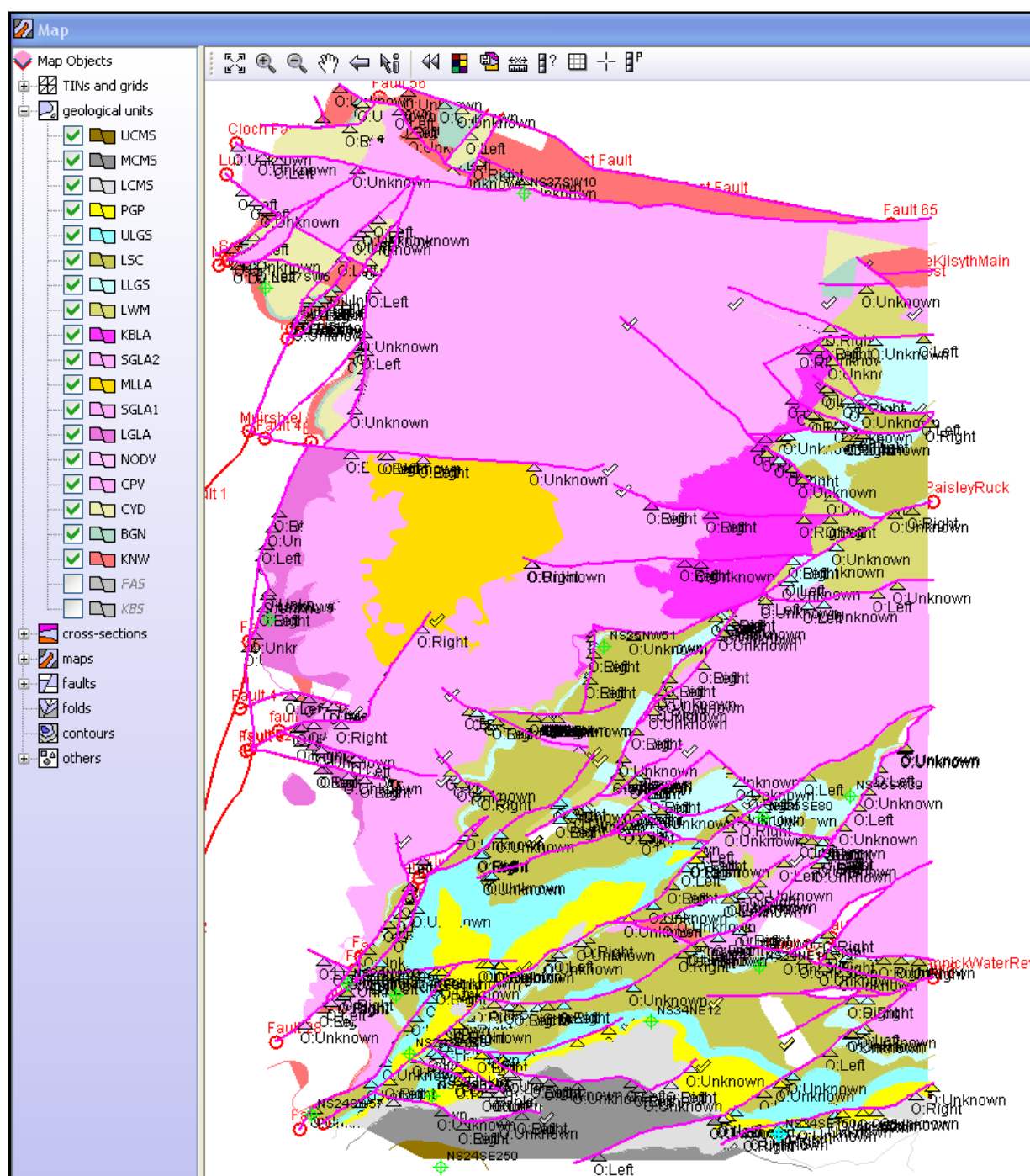


Figure 32. Kilpatrick Hills block, envelopes for the base of the Burncrooks Pyroclastic Member (BCV in A) and the Greenside Volcaniclastic Member (GNSV in B).



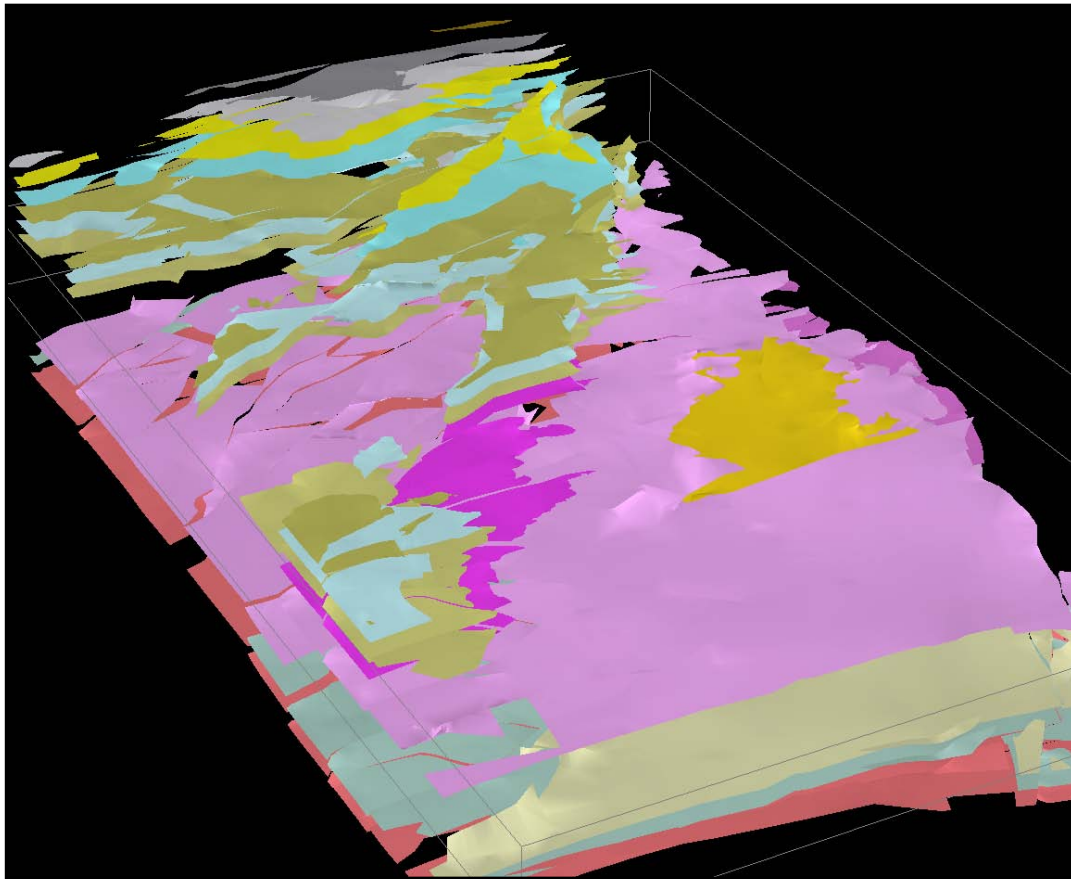


Figure 34. 3D exploded view of the Renfrewshire Hills model, looking south-south-west.

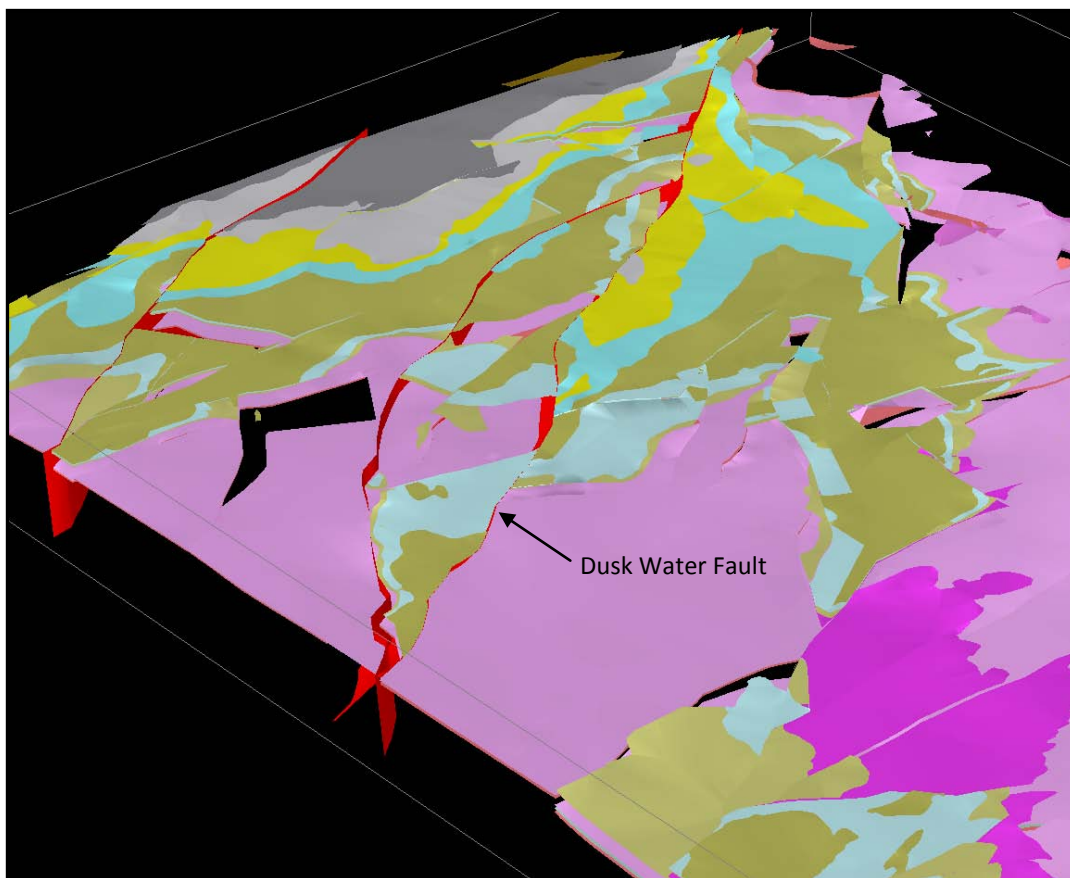


Figure 35. View looking south-west of the Clackmannan and Scottish Coal Measures Groups in the southern part of the Renfrewshire Hills block.

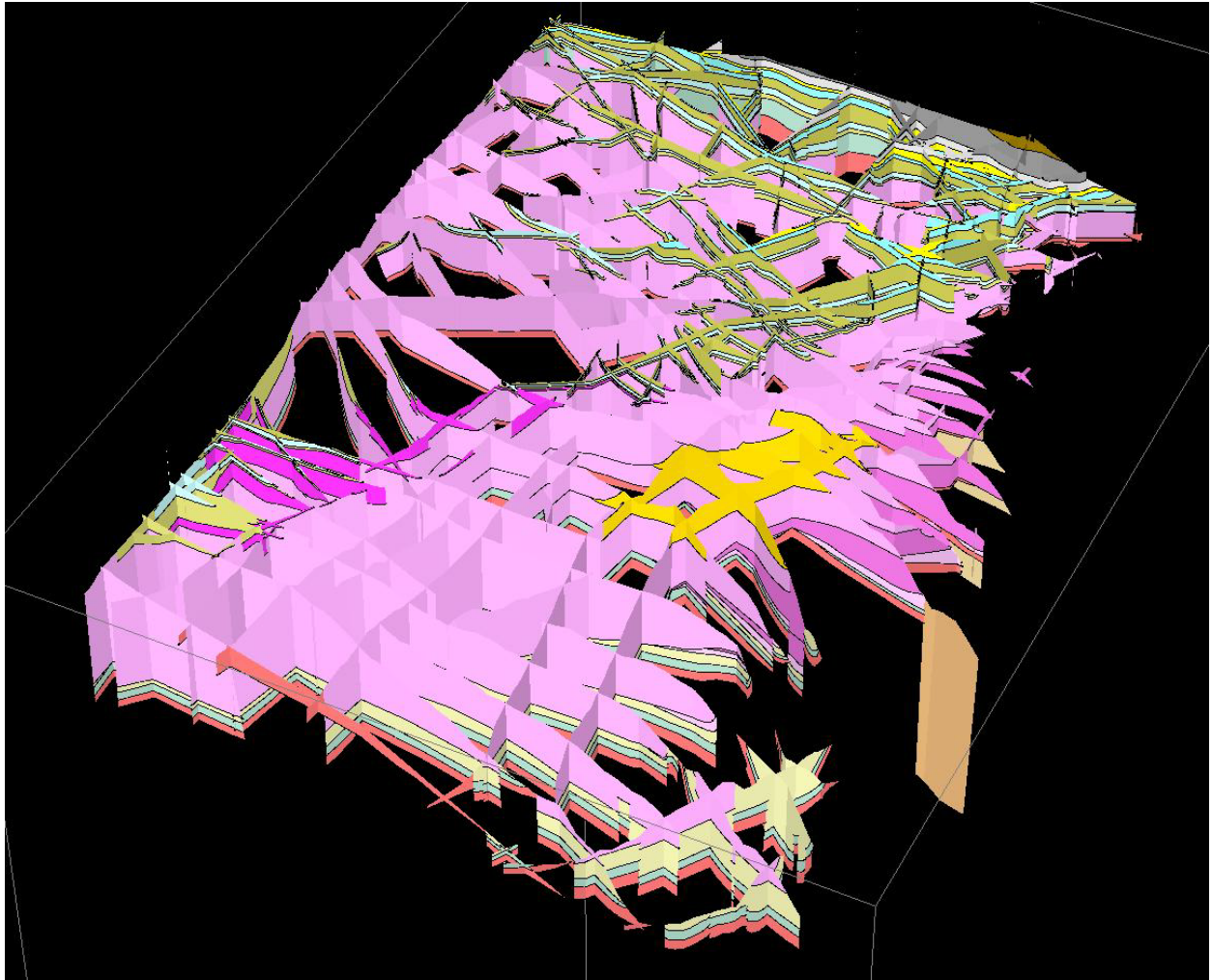


Figure 36. Full fence diagram for the Renfrewshire Hills block.

Oblique view from north-west



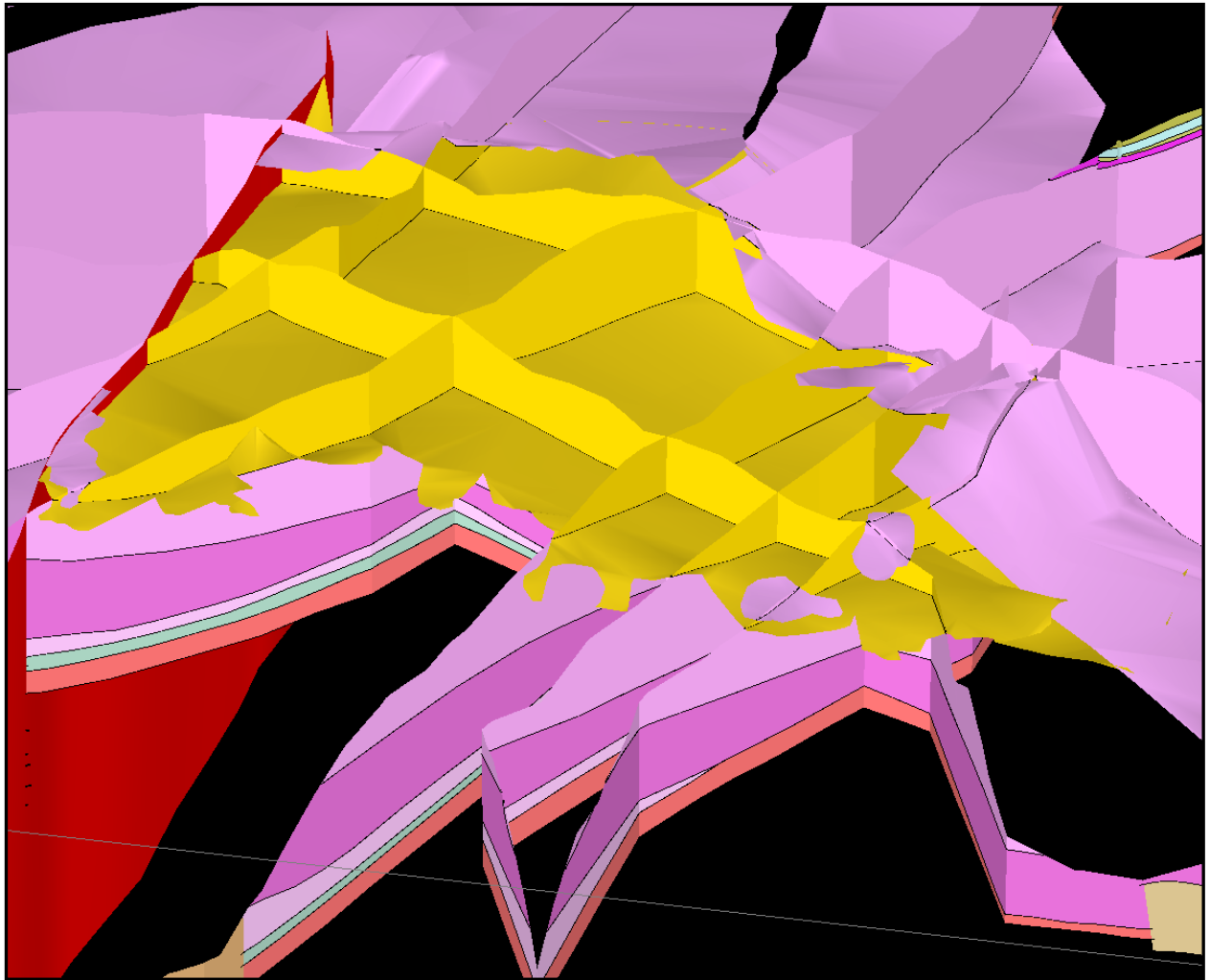


Figure 38. 3D perspective of the Misty Law trachyte centre, viewed from the west.

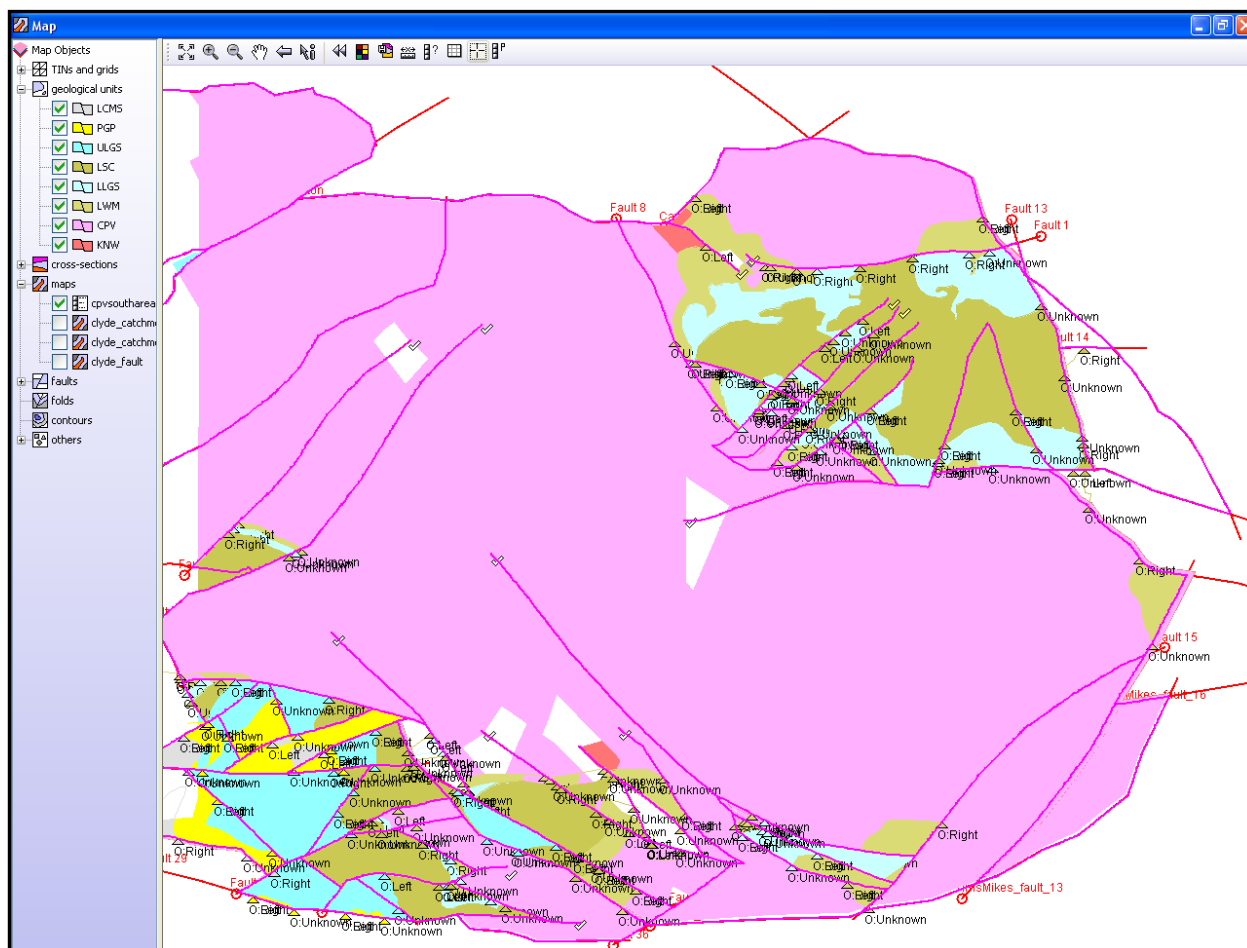


Figure 39. Calculated envelopes for the Southern Hills block.

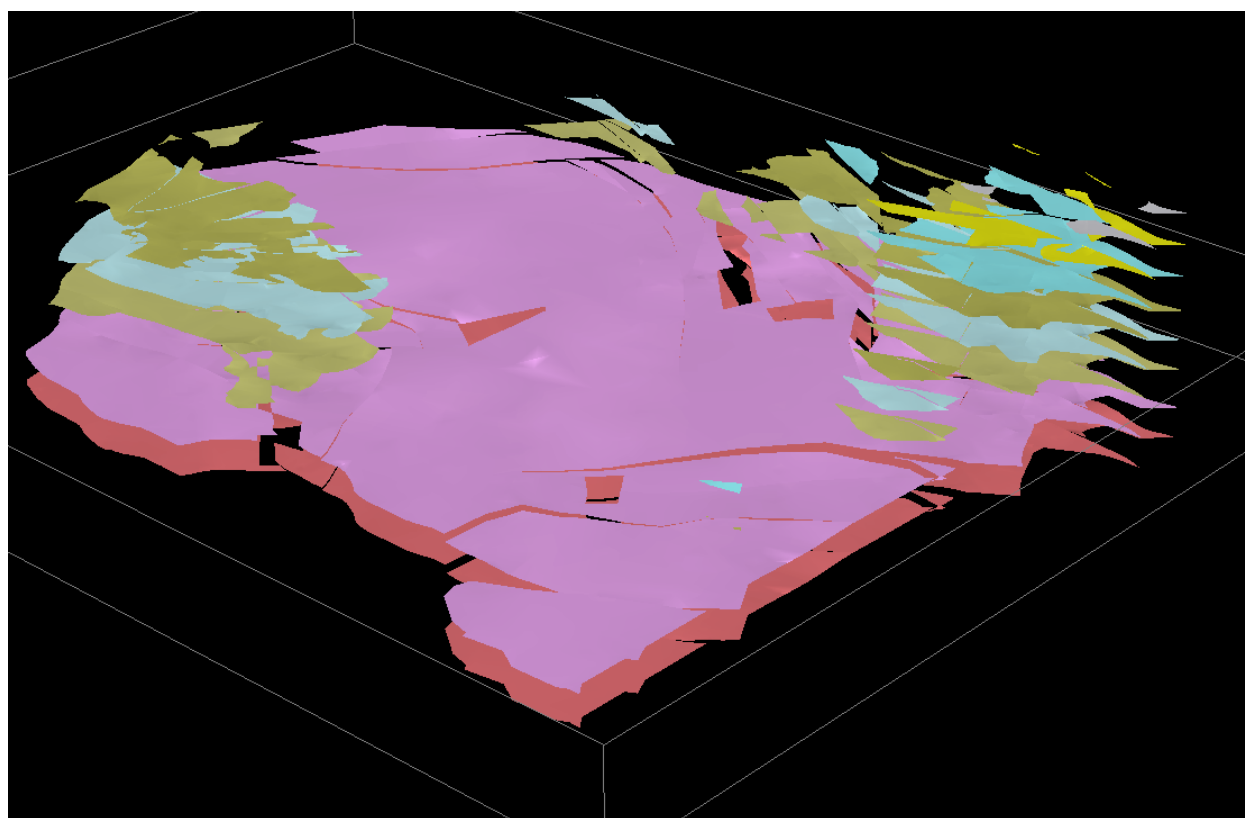


Figure 40. Exploded 3D model of the Southern Hills block from the north-west.

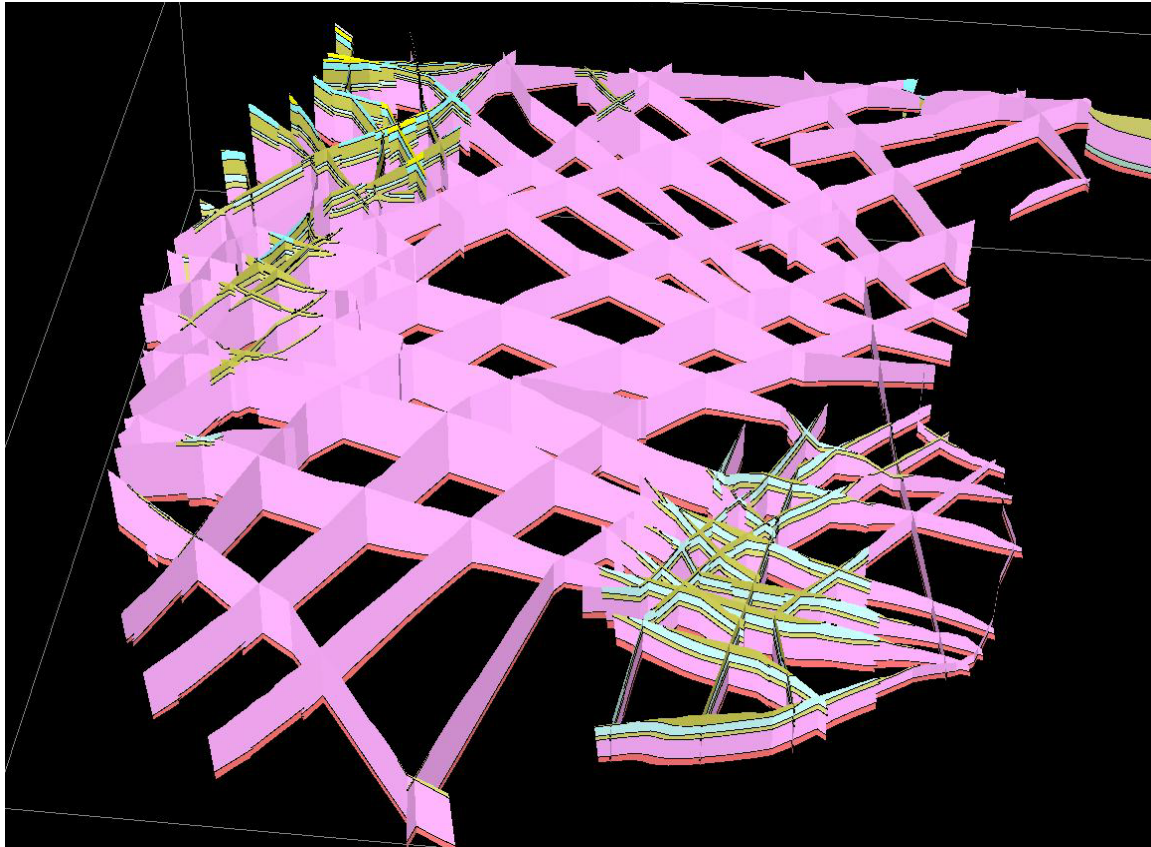


Figure 41. Full fence diagram, Southern Hills block.

Oblique view from the east.

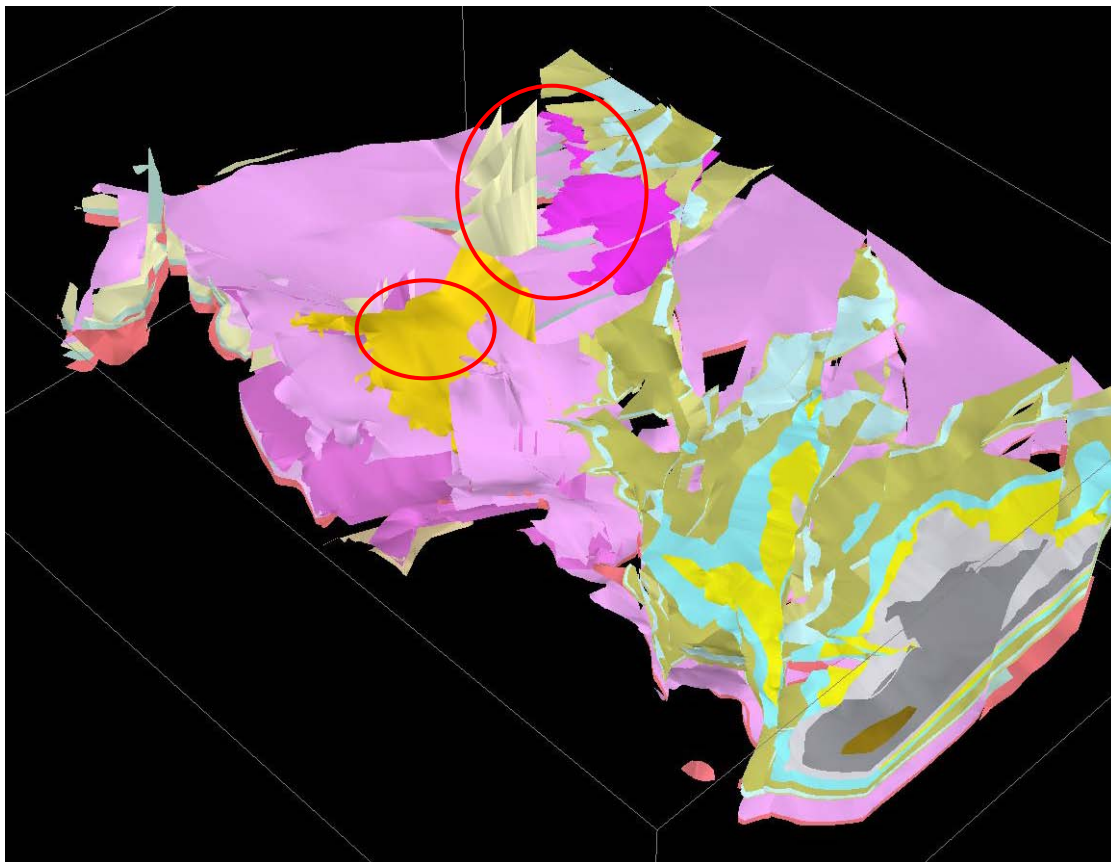


Figure 42 Surface artefacts adjacent to faults and resulting from calculation errors.

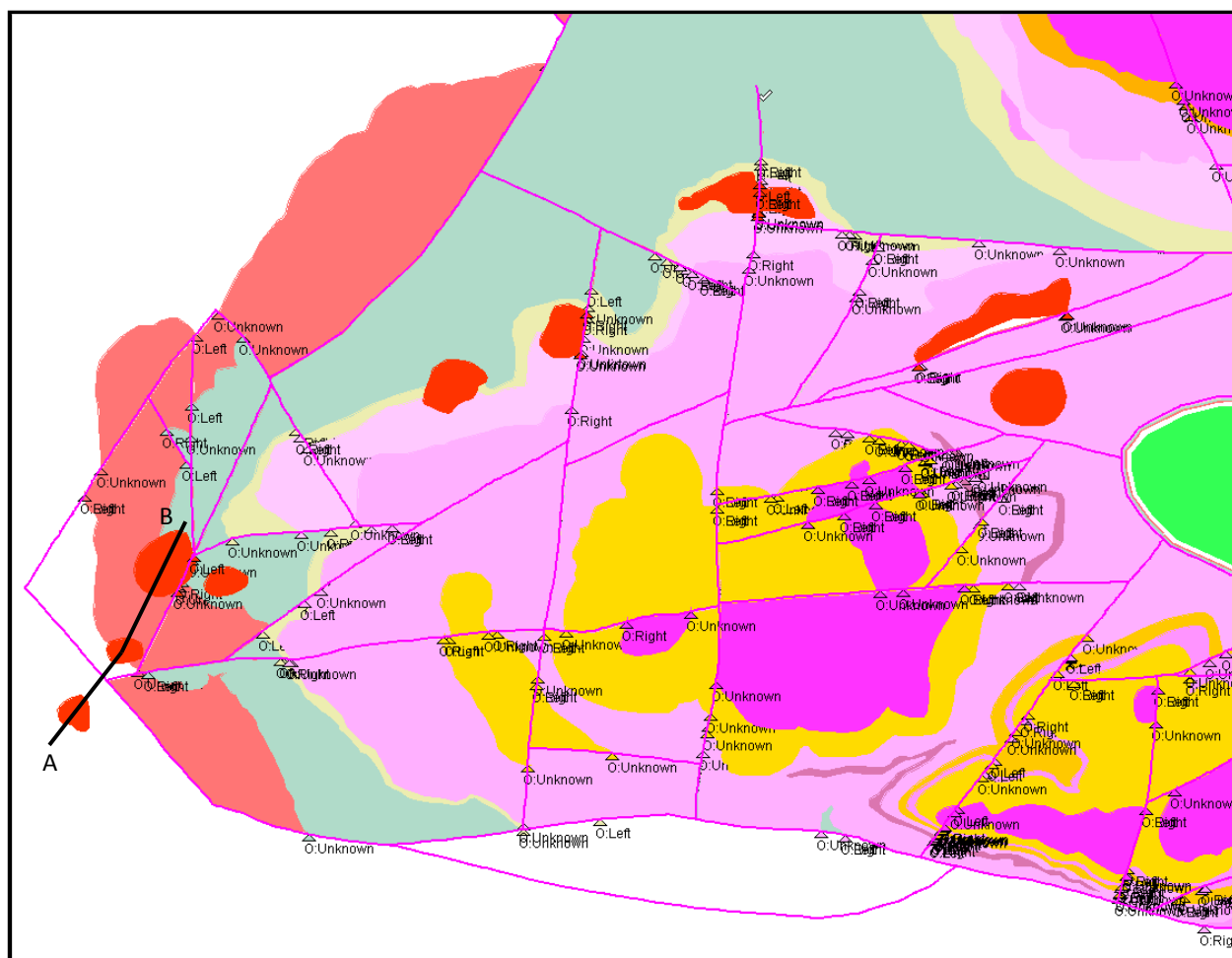


Figure 43. Intrusions: map view of the Campsie Fells block showing the envelopes (in bright red) of 9 funnel-shaped intrusions within the linear vent-systems.

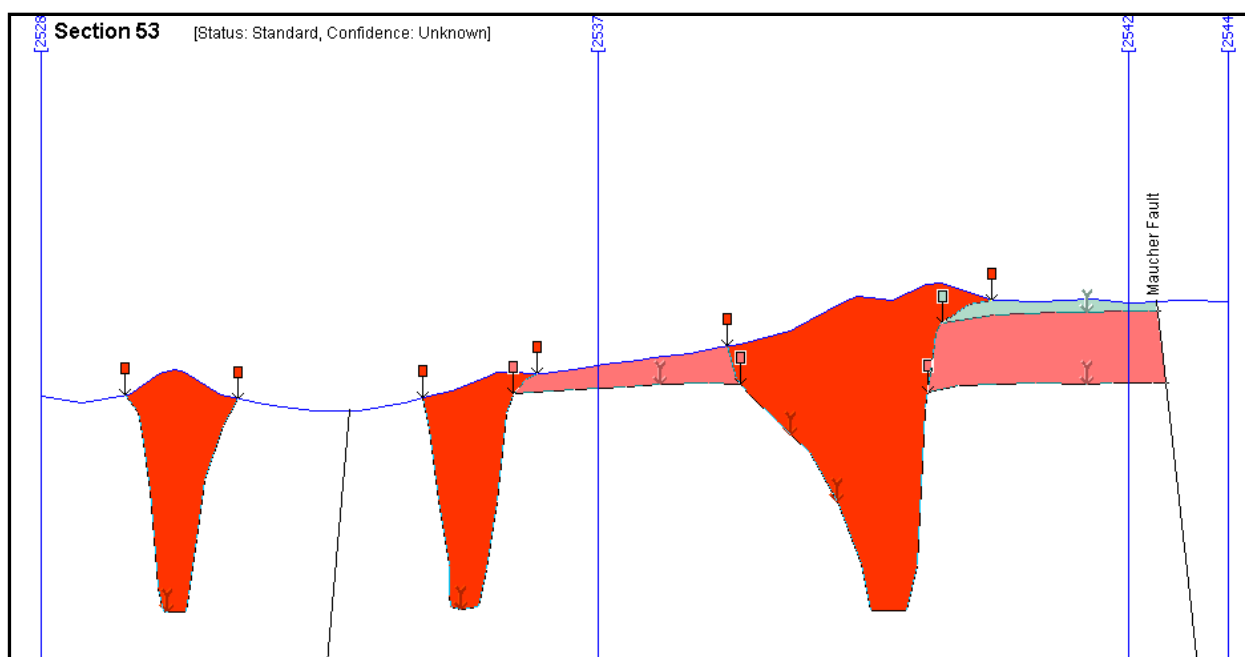


Figure 44. Cross-section A-B in Figure 33 showing relationship of intrusions to topography. Note the flared nature of these masses.

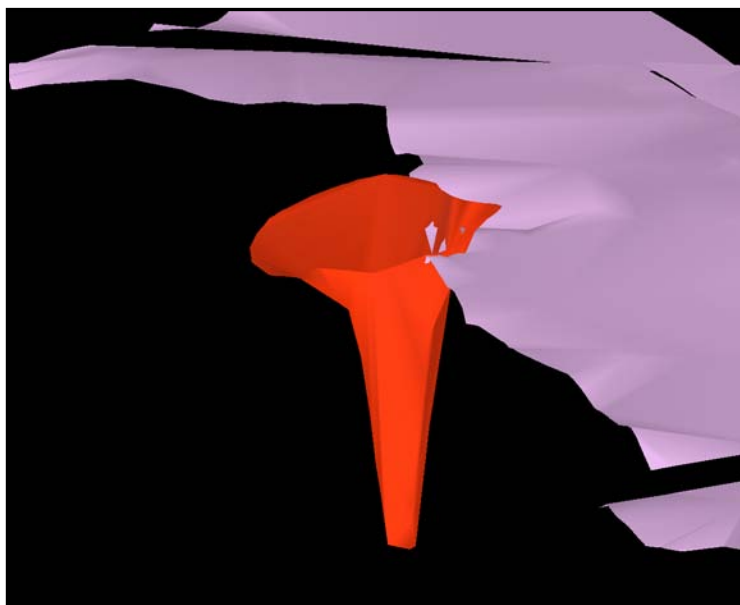


Figure 45. 3D view of intrusion 1 (Figure 33) from north-west.

The lilac-coloured stratigraphical surface is the Slack Gun Member (SLACKG in Table 1).

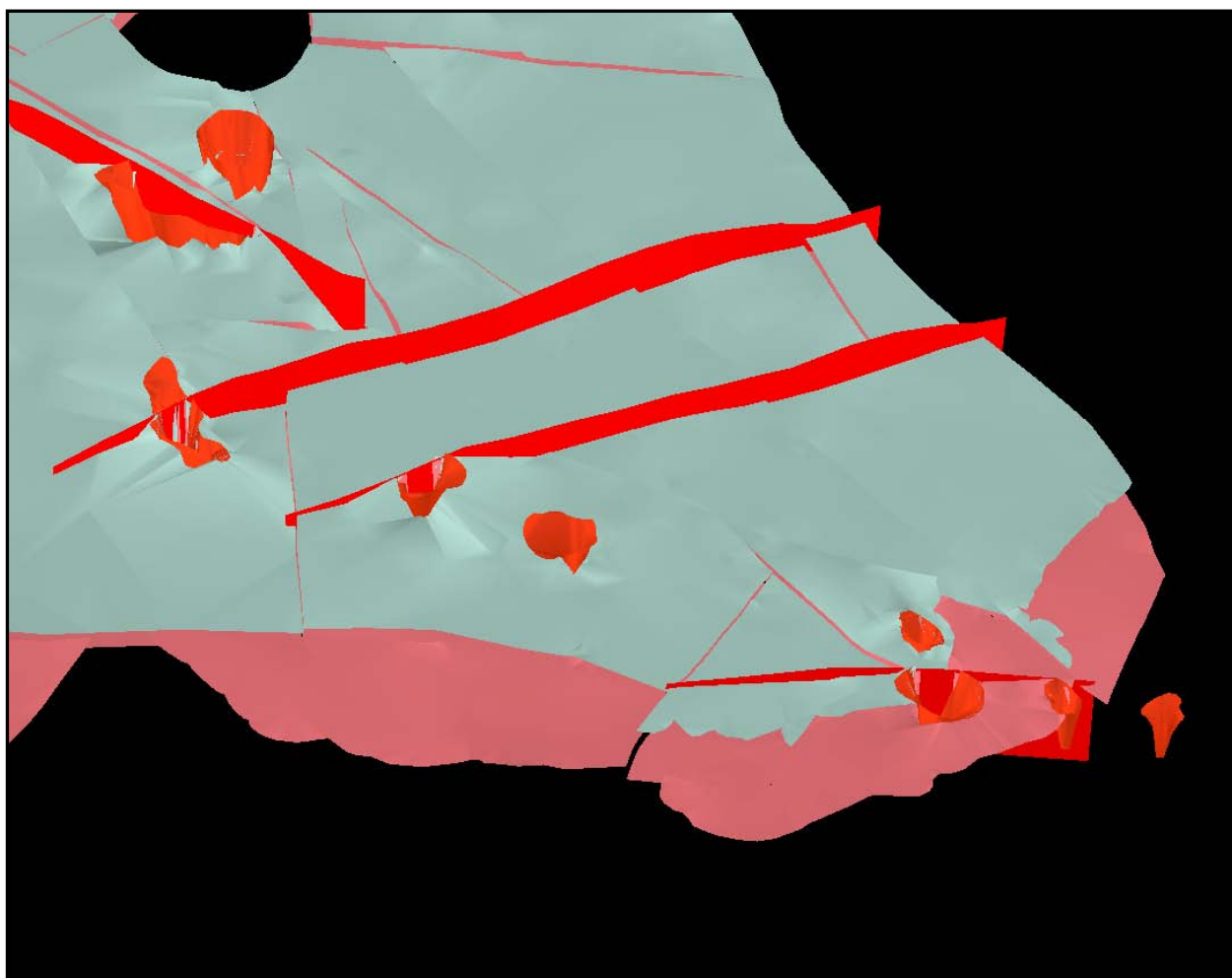


Figure 46. 3D view from NW of the intrusions, selected stratigraphical surfaces and faults in the Campsie Fells block.

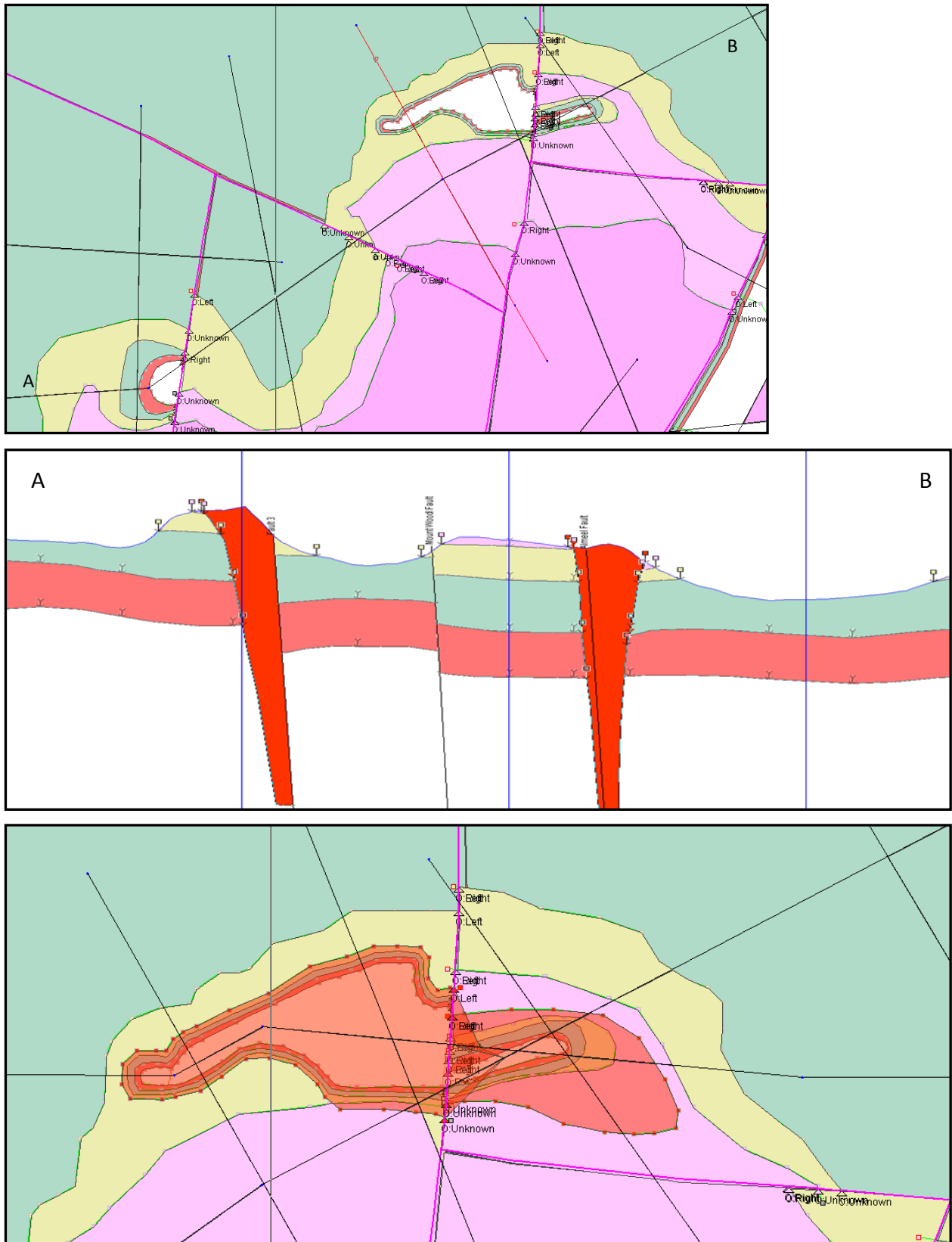


Figure 47. Construction of faulted intrusions in the Campsie Fells block.

- A. Calculated envelopes for two faulted intrusions
- B. Section
- C. Northern of the intrusions with the addition of an extra section through the axis of the intrusion.

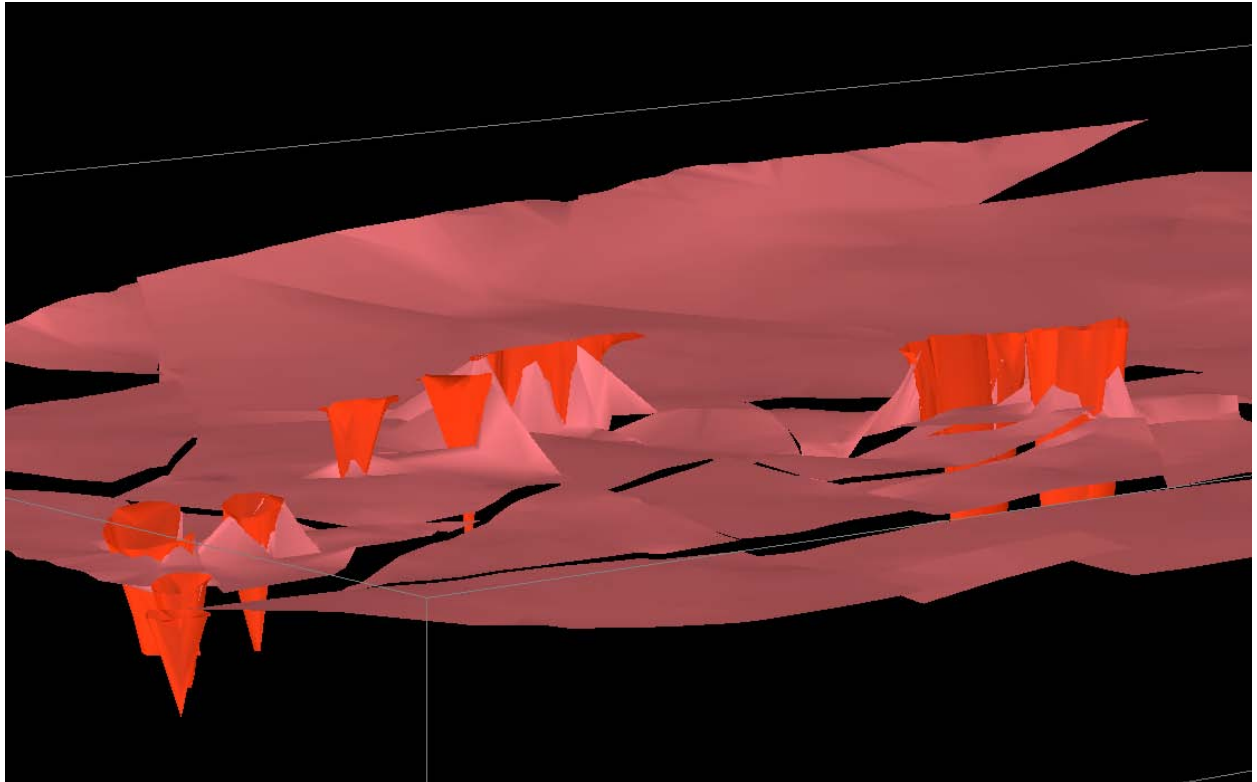


Figure 48. Calculation effects on the base Kinnesswood Formation surface when cut by intrusions; western Campsie Fells block.

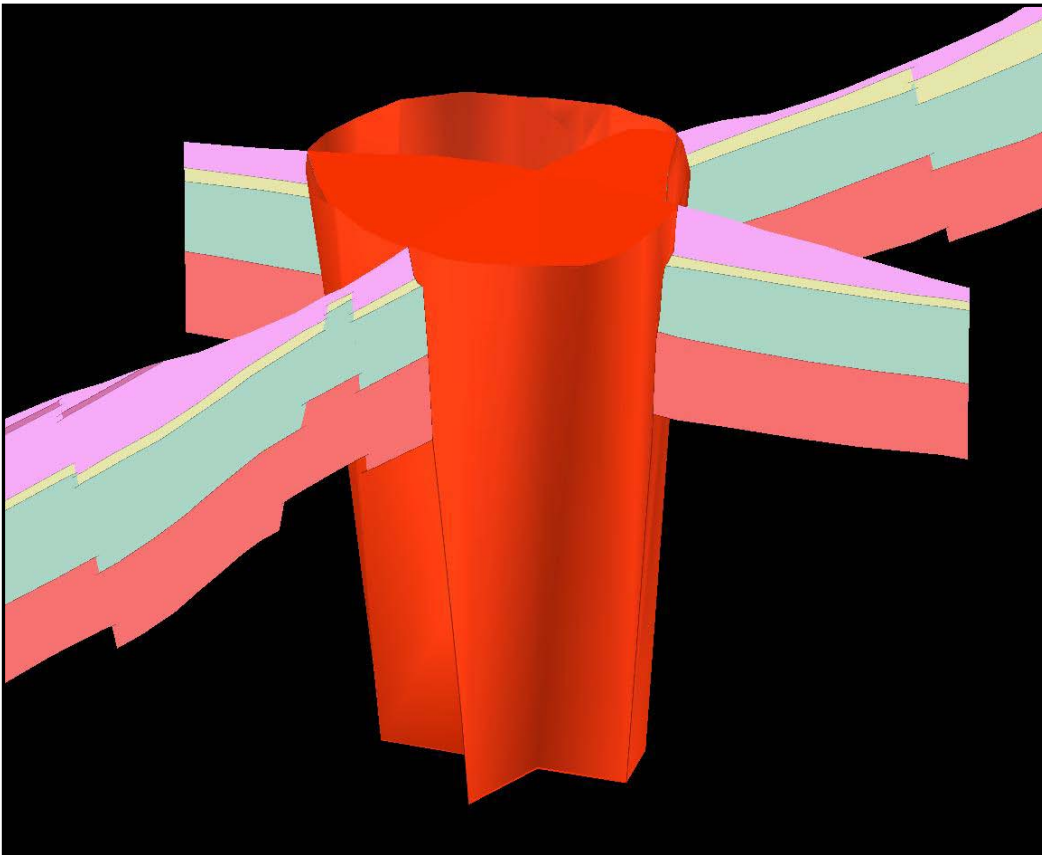


Figure 49. 3D shape of simple intrusion constructed from 2 sections, Kilpatrick Hills block. Note that the shape of the deepest part of the intrusion is controlled only by the sections.



Figure 50. Constraining the base of an intrusion with an artificial stratigraphical surface