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Geological Framework Model and surface data for the area south of Ammanford

Geology & Regional Geophysics

Internal Report IR/15/007

BRITISH GEOLOGICAL SURVEY

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Geological Framework Model and surface data for the area south of Ammanford

C N Waters, R Kendall, and S Thorpe

Keywords

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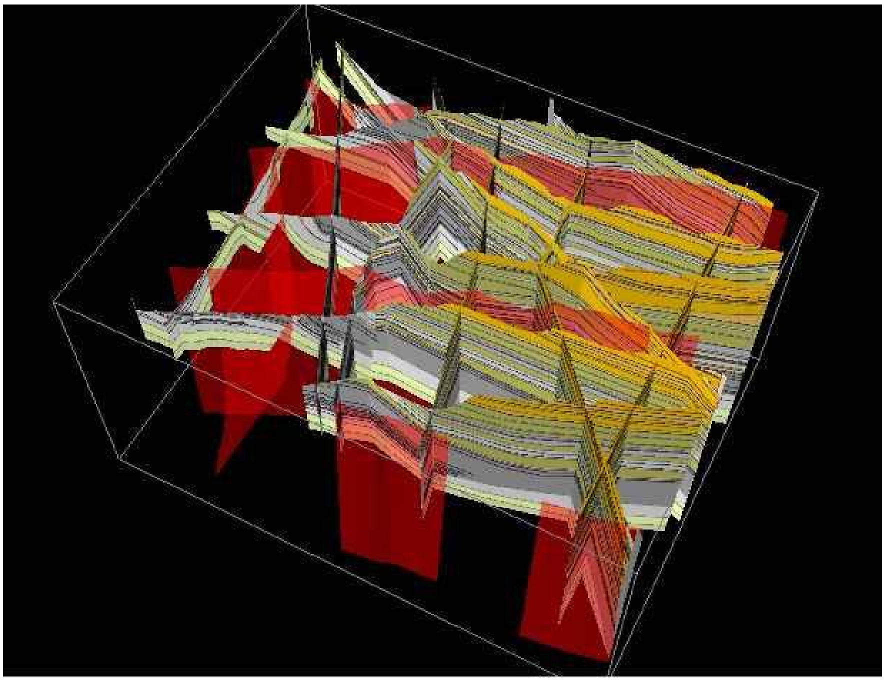
Frontispiece



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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on behalf of the SEREN project.

The report describes the process by which a 1:50 000 resolution Geological Framework Model for the area south of Ammanford, South Wales, was generated in order to aid visualisation of the 3D geology of the area. It describes the datasets required to generate the model, the distribution of component stratigraphical units and uses evidence from fieldwork to provide detailed descriptions of these units.

Notes

Figures in square brackets are National Grid references. For extracts from the project GIS and when referring to model coordinates, they are presented as six-figure numbers for eastings and northing, in which the letters have been replaced by a number [e.g. 300000 500000].

Borehole records referred to in the text are prefixed by the code of the National Grid 25 km^2 area and a number, e.g., SN60NE5. This provides a unique identifier (shown in this report enclosed by brackets) for the borehole data held within the BGS archives (National Geoscience Data Centre). There is direct online access to the collection of onshore scanned boreholes, shafts and well records at: http://www.bgs.ac.uk/data/boreholescans/home.html .

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Figure 2a. Vertical DTM of the study area derived from the Ordnance Survey Terrain-50 dataset sub-sampled to a 50 m grid. Ordnance Survey data © Crown Copyright and database right 2010.

Figure 2b. Perspective view of the DTM of the study area (looking to the north-east) derived from the Ordnance Survey Terrain-50 dataset sub-sampled to a 50 m grid. Ordnance Survey data © Crown Copyright and database right 2010.

Figure 3. Distribution of main boreholes and shaft records used for construction of the model.

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Figure 18. Geological map of the Superficial Deposits present at the ground surface across the study area, showing natural and artificial deposits and areas of landslide. The map is sourced from BGS v5 DiGMapGB datasets.

Tables

Table 1. Borehole/shaft records used in the study. Geologist coder of borehole data into BOGE used as the primary interpretation are: RHND1- Rhian Kendall; SDU- Steve Dumpleton; NWILL- Nathan Williams; GKL- Graham Lott and CNW- Colin Waters.

Table 2.Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram: a) Grovesend Formation; b) Swansea Member; c) Hughes Member; d) Brithdir Member; e) Rhondda Member; f) Llynfi Member; g) South Wales Upper & Middle Coal Measures formations; and h) South Wales Lower Coal Measures Formation and Marros Group.

Table 3 Summary of the stratigraphical units present within the Ammanford study area.

Plates

Plate 1 View of a mainly sandstone exposure, in Nant Pedol (CNW_53), looking south. Note the lowermost hard sandstone rests with apparent low-angle discordance on underlying siltstones.

Plate 2 View of a mainly sandstone exposure, in Nant Pedol (CNW_54), looking west. Note the lowermost soft mudstone of the Subcrenatum Marine Band is largely obscured by vegetation.

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Summary

Background

The original objective of this work was to assemble a 1:50 000 (50k) resolution 3D Geological Framework Model for an area south of Ammanford. The model was to have two main purposes:

1. To form the basis for a communication tool to present the 3D geological understanding of the area to a range of stakeholders; and
2. To support the reinterpretation of the geological succession mapped at surface.

This study specifically excludes the further development of the Framework Model to include hydrogeology, hydrochemistry or rock mechanics and does not include any consideration of potentially suitable resources such as Coal Bed Methane.

This report provides the explanation of the methodology and how this model was generated. Additional outputs of the study include:

1. An ArcGIS project containing the data used to compile the model; and
2. Surface observations of the geology collected following Sigma workflows, held in a GIS.

Development of a 3D geological framework model

A 1:50 000 resolution 3D geological framework model was successfully constructed for the study area using the *Geological Surveying and Investigation in 3D* (GSI3D) software package, developed partly in house at BGS, which can be used readily by geologists to construct a series of cross-sections that can more clearly display the geological succession. Models of this type have the potential to be accessible to members of the public and used by geologists to assess the potential location of resources, not evident from traditional 2D geological maps.

The approach followed was to construct a fence diagram of 12 cross-sections using GSI3D. These sections encompass the entire study area and using the geologists' expert knowledge to incorporate surface and subsurface data (24 deep boreholes and structural contour information from published geological maps) provide an interpretation of the geological succession at Bed, Member and Formation level, consistent with BGS 1:50 000-scale (50k) geological maps of the area.

1 Objectives and Scope

This report describes the development of a 1:50 000 (50K) resolution Geological Framework Model developed to test and document a generic methodology for producing such models in a complex coalfield area.

The criteria used to generate the Geological Framework Model are discussed, the information used to construct the model is outlined. Evidence provided from field assessment of the surface geology is presented to indicate the nature and characteristics of the rock units modelled in this study.

1.1 OBJECTIVES OF THIS STUDY

The original objective of this work was to assemble a 1:50 000 (50k) resolution 3D Geological Framework Model for an area south of Ammanford. The model was to have two main purposes:

1. To form the basis for a communication tool to present the 3D geological understanding of the area to a range of stakeholders; and
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1. An ArcGIS project containing the data used to compile the model; and
2. Surface observations of the geology collected following Sigma workflows, held in a GIS.

1.2 STUDY AREA

The study area (Figure 1) includes the town of Ammanford in the north-west, the outskirts of Glanaman in the north-east, Pontarddulais in the south-west and Clydach in the south-east. With the exception of the low ground in the north, following the valley of the River Loughor from Ammanford to Glanaman, much of the study area is defined by upland moors up to an elevation of 374 m.

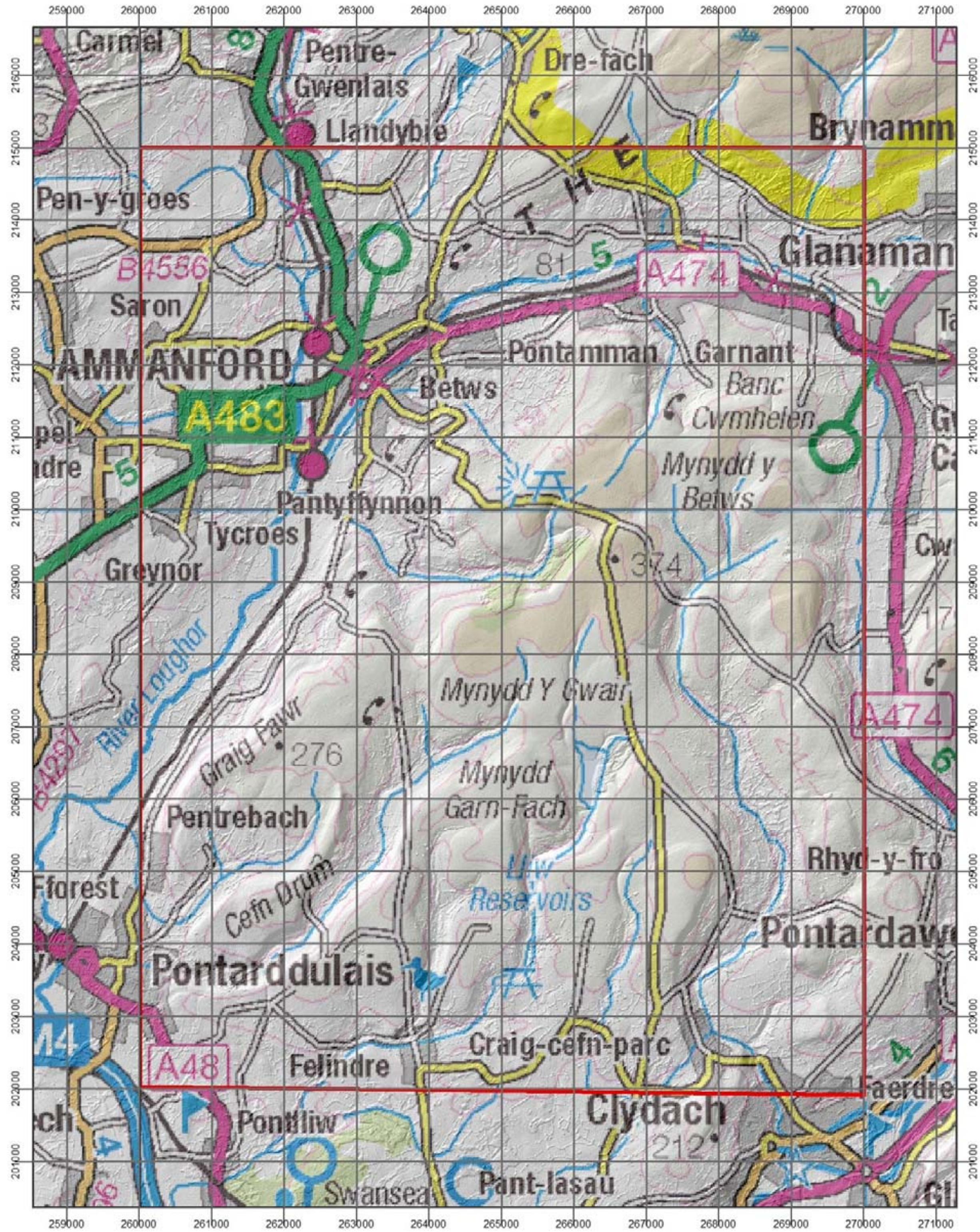

Figure 1. Extent of the study area (red box). The background is a digital elevation model showing the topography of the area using shaded relief illuminated from the NW. NEXTMap® Britain elevation data from Intermap Technologies.

The model presents the best representation of the 3D geology at a 1:50 000 resolution from surface to a maximum depth of 1 km, or to the base of the Twrch Sandstone Formation, whichever is shallower.

The model takes into account published geological map data and selected deep borehole logs. Existing seismic, gravity and magnetic data interpretations were considered to be of insufficient resolution to aid interpretation of the model and are not included.

Qualitative remarks are made throughout the account of the level of geological uncertainty across the area.

The *Geological Surveying and Investigation in 3D* (GSI3D) software package was used to construct a series of cross-sections that can more clearly display the geological succession and aid the infill of information missing in the legacy models. The structural framework of the model did not undergo rigorous integrity tests such as restoration/section balancing as part of this study.

2 Model datasets

This section describes the key datasets used to compile and augment the Ammanford 1:50 000 resolution GSI3D fence diagram.

2.1 DIGITAL TERRAIN MODEL

The DTM used in the study (Ammanford_OSOPEN_50m) is derived from the OS OpenData Terrain-50 model inside GSI3D at 50m cell resolution (Figure 2a and 2b).

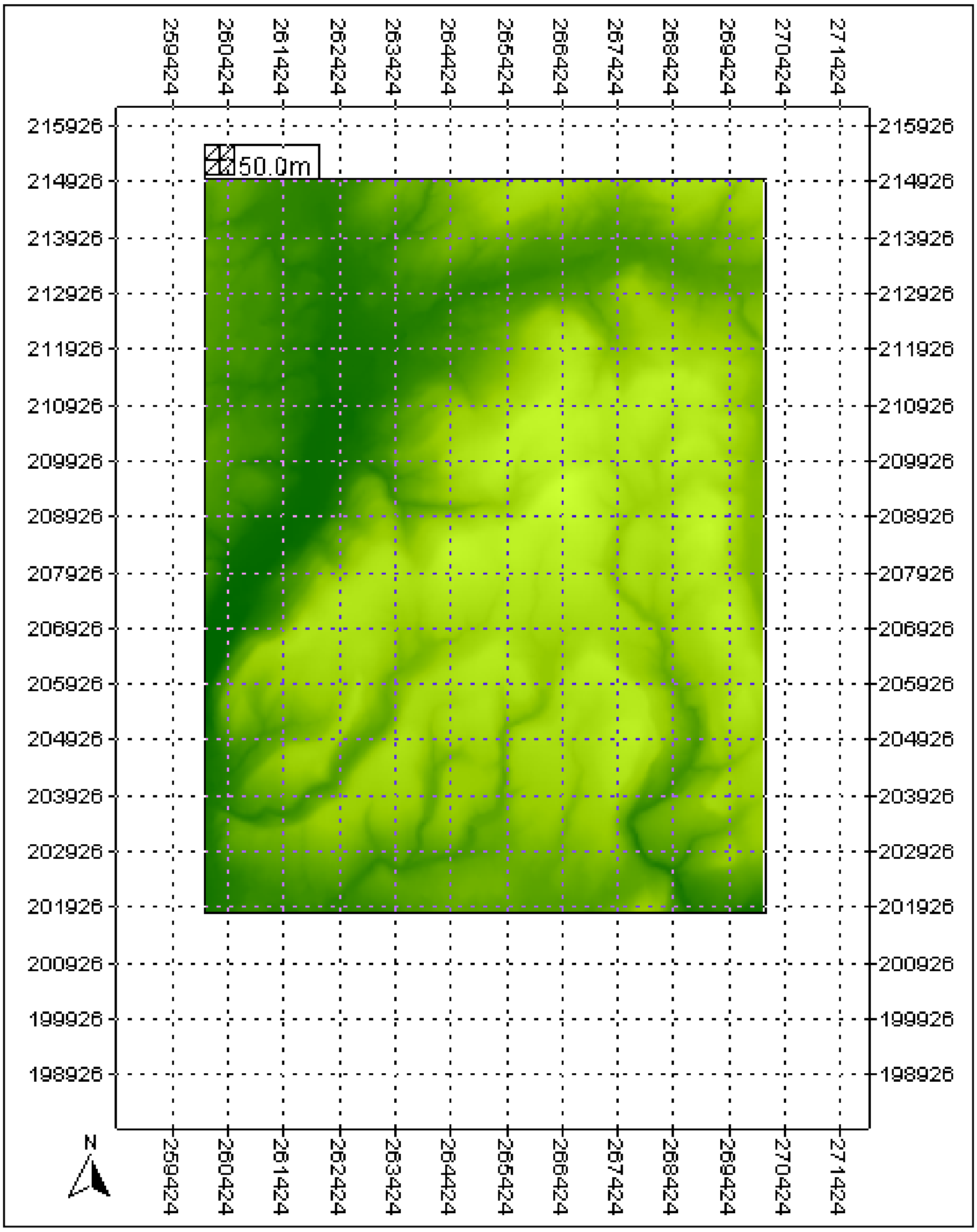

Figure 2a. Vertical DTM of the study area derived from the Ordnance Survey Terrain-50 dataset sub-sampled to a 50 m grid. Ordnance Survey data © Crown Copyright and database right 2010.

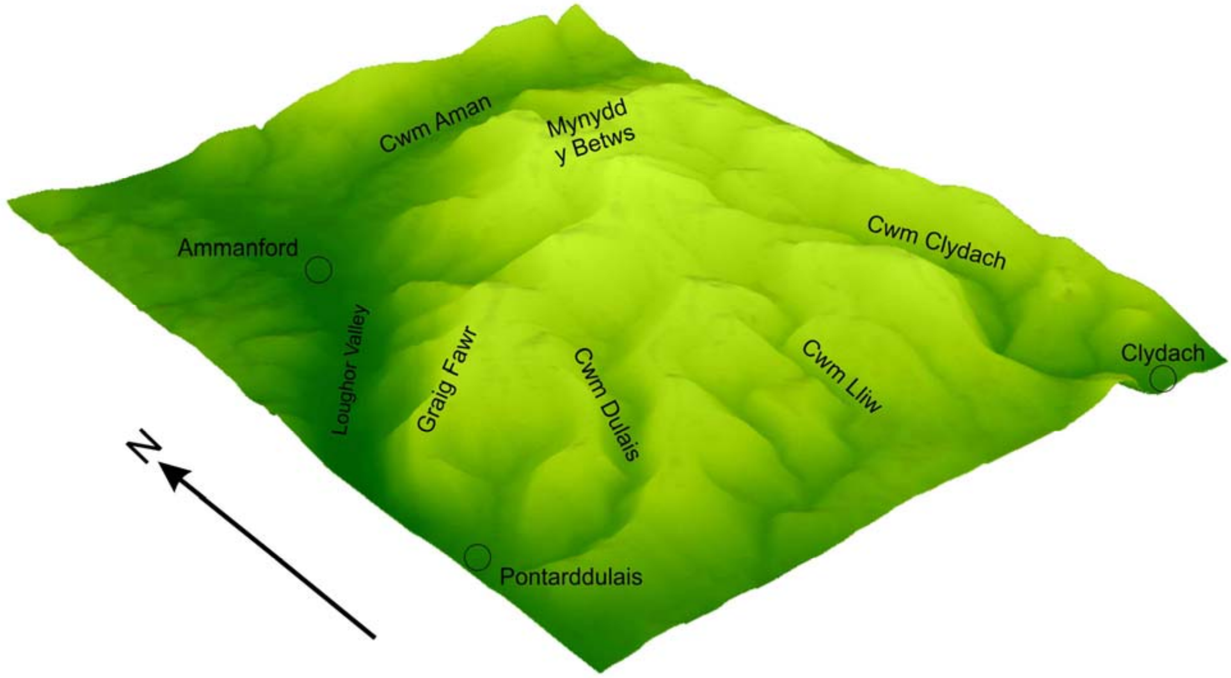

Figure 2b. Perspective view of the DTM of the study area (looking to the north-east) derived from the Ordnance Survey Terrain-50 dataset sub-sampled to a 50 m grid. Ordnance Survey data © Crown Copyright and database right 2010.

2.2 BOREHOLES

The distribution of principal deep boreholes (24 in total) contributing to the Ammanford 1:50 000 resolution model is shown in Figure 3. The borehole details presented in Table 1 were used to create a GSI3D BID (borehole id) file and the GSI3D BLG (borehole log file) was extracted from the corporate BOGE database. Where multiple entries of data on BOGE were available, the interpretation of the geologist shown in Table 1 was adopted. During the construction of the fence diagram an update of changes to these interpretations was maintained to facilitate update of the BOGE database.

BGS_ID	EASTING	NORTHING	START HEIGHT	TD	BGS NO	BH NAME	GEOLOGIST
256100	266521	0208883	341	837.16	SN60NE5.	Betws 2	RHND1
256101	268880	0207190	256	1135.76	SN60NE6.	Baran (Abernant 6)	RHND1
256102	269890	0206360	287	168.25	SN60NE7.	Hardings BH (Abernant 3)	RHND1
256105	269442	0207400	292.13	1031.75	SN60NE10.	Abernant 9 (Nantygwyn)	RHND1
256106	267873	0209348	225.52	819.91	SN60NE11.	Betws 12 (Hafod)	SDU
256107	266170	0206910	228.42	855.24	SN60NE12.	Betws 10	NWILL
256108	268981	0209722	270.34	716.00	SN60NE13.	Betws 14	NWILL
256110	260952	0207477	26	1041.20	SN60NW1.	Llanedi	SDU
256115	260538	0209694	82	46.02	SN60NW5.	Wernos Colliery	RHND1
256117	262900	0209760	68	405.50	SN60NW7.	Betws 8 (Tan y Garn)	RHND1
256357	267863	0210494	298.9	644.74	SN61SE27.	Betws 13 (Henrhyd)	RHND1
256398	264874	0210453	235	416.51	SN61SW16.	Butchers	SDU
256405	264660	0212230	80	307.24	SN61SW23.	Ammanford 1	RHND1
256407	262600	0210110	31	202.08	SN61SW25.	Yristowlog	RHND1
256408	262000	0210960	31	123.75	SN61SW26.	Balance Pit	RHND1
256409	260208	0210055	104	209.40	SN61SW27.	Wernos Shaft	NWILL
256434	264073	0210775	153.97	249.51	SN61SW52.	Betws 11	RHND1
256435	262920	0210650	44.75	241.28	SN61SW53.	Betws 7	GKL
257031	270020	0208500	163	701.04	SN70NW25.	Cwmgorse 1	RHND1
18106551	266997	0207058	246.4	892.87	SN60NE16.	Betws 5	
18106556	264339	0209347	189.63	525.35	SN60NW12.	Betws 6	
18109854	265364	0206939	253.2	934.10	SN60NE17.	Betws 4	
18109855	266365	0207642	284.84	848.84	SN60NE18.	Betws 9	
18622939	267434	0207024	234	1278.10	SN60NE19.	Pontardawe 1	CNW

Table 1. Borehole/shaft records used in the study. Geologist coder of borehole data into BOGE used as the primary interpretation are: RHND1- Rhian Kendall; SDU- Steve Dumpleton; NWILL- Nathan Williams; GKL- Graham Lott and CNW- Colin Waters. Conditions apply to the release of data for those boreholes shown in red.

There is a strong concentration of boreholes in the central part of the area, reflecting exploration for coal within the Upper Carboniferous strata. 10 of the boreholes terminate at depths less than 500 m below ground surface (Table 1). 4 of the boreholes terminate at depths greater than 1000 m below ground surface.

The borehole data presented in this report include both boreholes designated commercial-in-confidence and those in the public domain; there is direct online access to the latter via: http://www.bgs.ac.uk/data/boreholescans/home.html. The vintage and quality of the borehole records are highly variable and the interpretation of the position of some stratigraphical boundaries in older colliery records can be conjectural. This is particularly the case when trying to differentiate between, for example, the extent of sandstones, which are not recorded in some logs, and the interpretation of the coal, which in some cases is provided a name in modern Coal

Authority logs. However, the boreholes typically provide sufficient description to allow the distinction of the major units, broadly at member level. Many of the modern deep boreholes give very detailed lithological descriptions and provide excellent control at bed level. In this study 8 confidential borehole records were also used to compile the fence diagram (Table 1). In the event that a model of this type is required for external use, there is a procedure by which confidential boreholes could be requested to be released. However, there is a risk that such a request would be unsuccessful. The procedure is outlined below:

Where boreholes are listed as confidential in the BGS Single Onshore Borehole Index (SOBI) they may be released by the SOBI Data Manager under certain circumstances. The Data Manager will take all reasonable steps to contact owners/suppliers using suitable available research evidence including using online resources such as Companies House, Directories and databases indicating commercial activity.

- Where ownership can be established then the Data Manager will take all reasonable steps to make contact and obtain release.
- If the information has been held for longer than 4 years and has been donated on a voluntary basis then the owners/suppliers have the right to ask for continued confidentiality provided they can produce a valid reason. This is set out in the Environmental Information Regulations 2004.
- If records are deposited under statute then the Data Manager is obliged to follow the relevant legislation, but will follow the same procedures as for voluntary data. Where government statutes are involved there will be a greater presumption towards release.
- If the record is over 4 years old and there is no evidence of who donated the record or who has ownership of the record then the borehole can be released by the Data Manager under the terms of the announcement in the London Gazette 22nd May 2009 (Notice: 825421).
- Confidential records which are less than 4 years old or which are still within a longer agreed period of confidentiality will not be released without agreement of the owner/supplier.

Additional information about the policies and release of confidential boreholes can be found at http://www.bgs.ac.uk/services/ngdc/records/policy.html

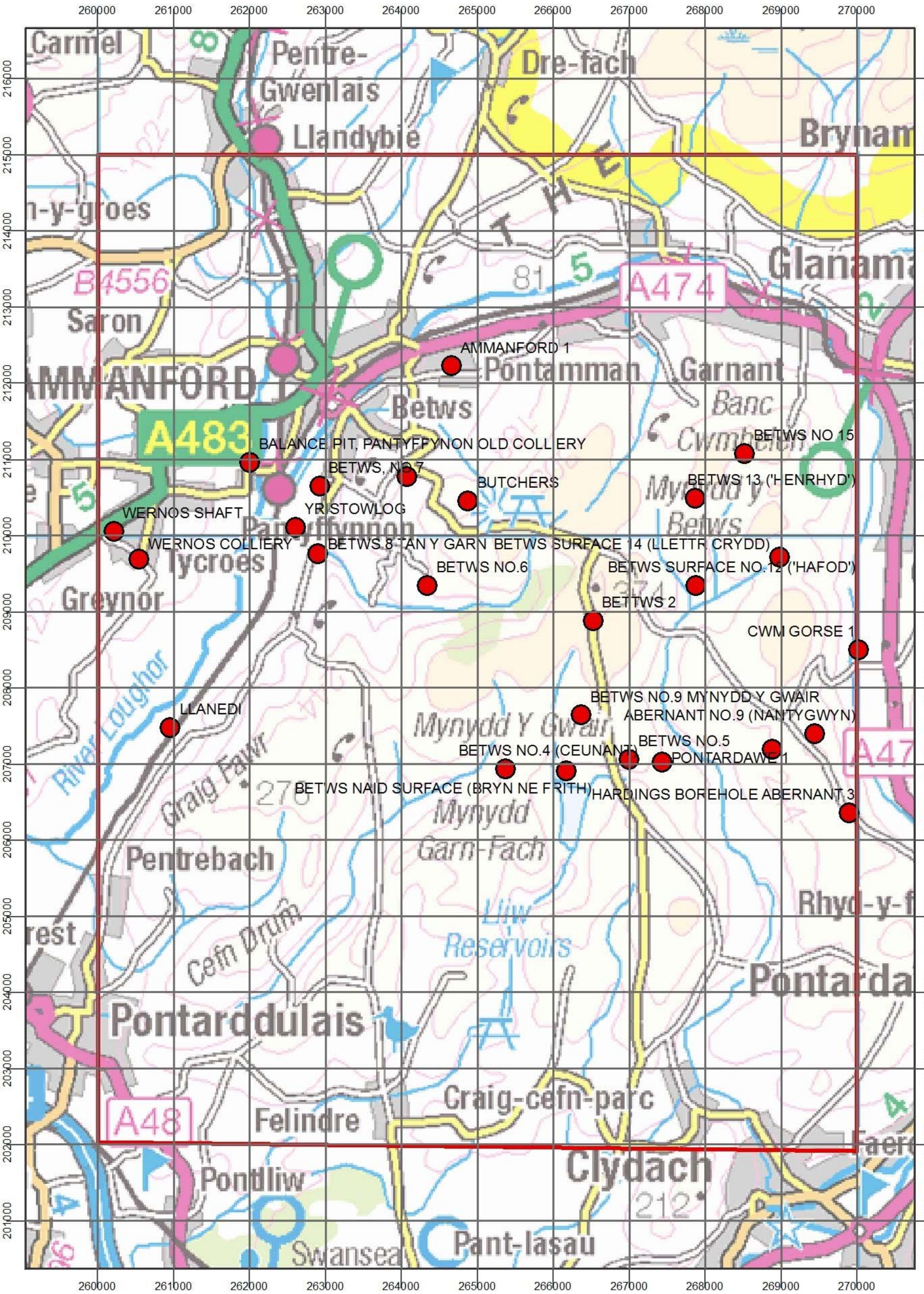

Figure 3. Distribution of main boreholes and shaft records used for construction of the model and extent of 1:10,560-scale geological maps.

2.3 SURFACE GEOLOGICAL MAPS

The surface geological maps used in this study are sourced from the openly accessible BGS v5 DiGMapGB datasets available as GIS line and polygon data (in ESRI and MapInfo platforms) http://mobile.bgs.ac.uk/products/digitalmaps/DiGMapGB.html. These *digital* geological maps are derived from the different series of published *analogue* BGS geological maps. Many paper-only maps have been digitised retrospectively though the nomenclature has often been updated to conform to current usage. Where necessary, additional interpretations have been incorporated, in particular to ensure edge-matching of map tiles of different vintages. The study used the "Bedrock geology" (lithological units) and "Linear features" (faults) themes of the DiGMapGB-50 dataset at 1:50 000-scale, which are based upon analogue 1:50 000-scale geological map (BGS, 1977).

To locally facilitate greater resolution of the geology, individual 1:10,000- and 1:10,560-scale geological maps were consulted (Figure 3). In addition to displaying coal seam names and splits in sandstones, they provide important subsurface information, including structural contours on named coal seams and the direction of hade (angle between the fault plane and the vertical measured perpendicular to the strike of the fault) and throw (vertical offset) direction and amount on faults. Ideally, these maps should be georectified and available as a raster backdrop on the GSI3D map view to facilitate digitisation. For this study approximate positions for the contours were estimated from the map. The published map provides a Generalized Vertical Section (GVS) which was used to estimate local thicknesses of units in areas where borehole data was unavailable. The GVS was compiled into a master succession used to construct the GSI3D GLEG (geological legend) file. The study area incorporates the following 1:10,560-scale geological maps (publication date in brackets): SN60NW (1965); SN60NE (1969); SN60SW (1966); SN60SE (1972); SN61SW (1969); and SN61SE (1972).

3 GSI3D Fence Diagram Construction

This phase of work resulted in the generation of a dense framework of cross-sections that provide a strong visual 3D appraisal of the distribution of the geology beneath the study area. The sections extend to an average depth of 2 km and were generated from either the existing BGS National Geological Model, or created as part of this study. The workflow in the generation of the GSI3D fence diagram is outlined below at Figure 4.

3.1 NATIONAL GEOLOGICAL MODEL

Since 2011 BGS have been compiling a National Geological Model (NGM), a component of which is a bedrock model comprising a network of 121 cross-sections (Mathers et al., 2012). The fence diagrams are built in the Geological Surveying and Investigation in 3D (GSI3D) software (Kessler and Mathers, 2004; Kessler et al., 2009). The fence diagram honours existing 3D geological framework models, based mainly upon seismic reflection interpretation and well data, including those that coincide with the study area (Figure 4).

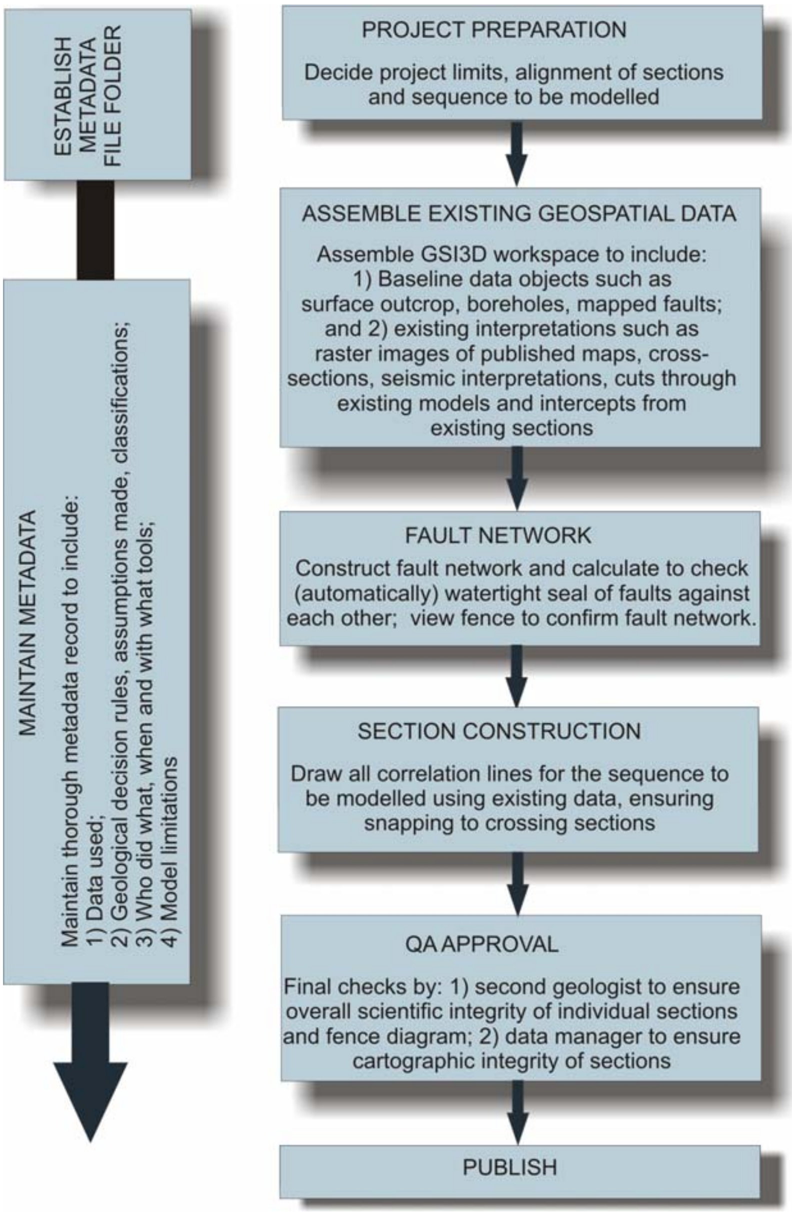

Figure 4 GSI3D Fence diagram construction workflow

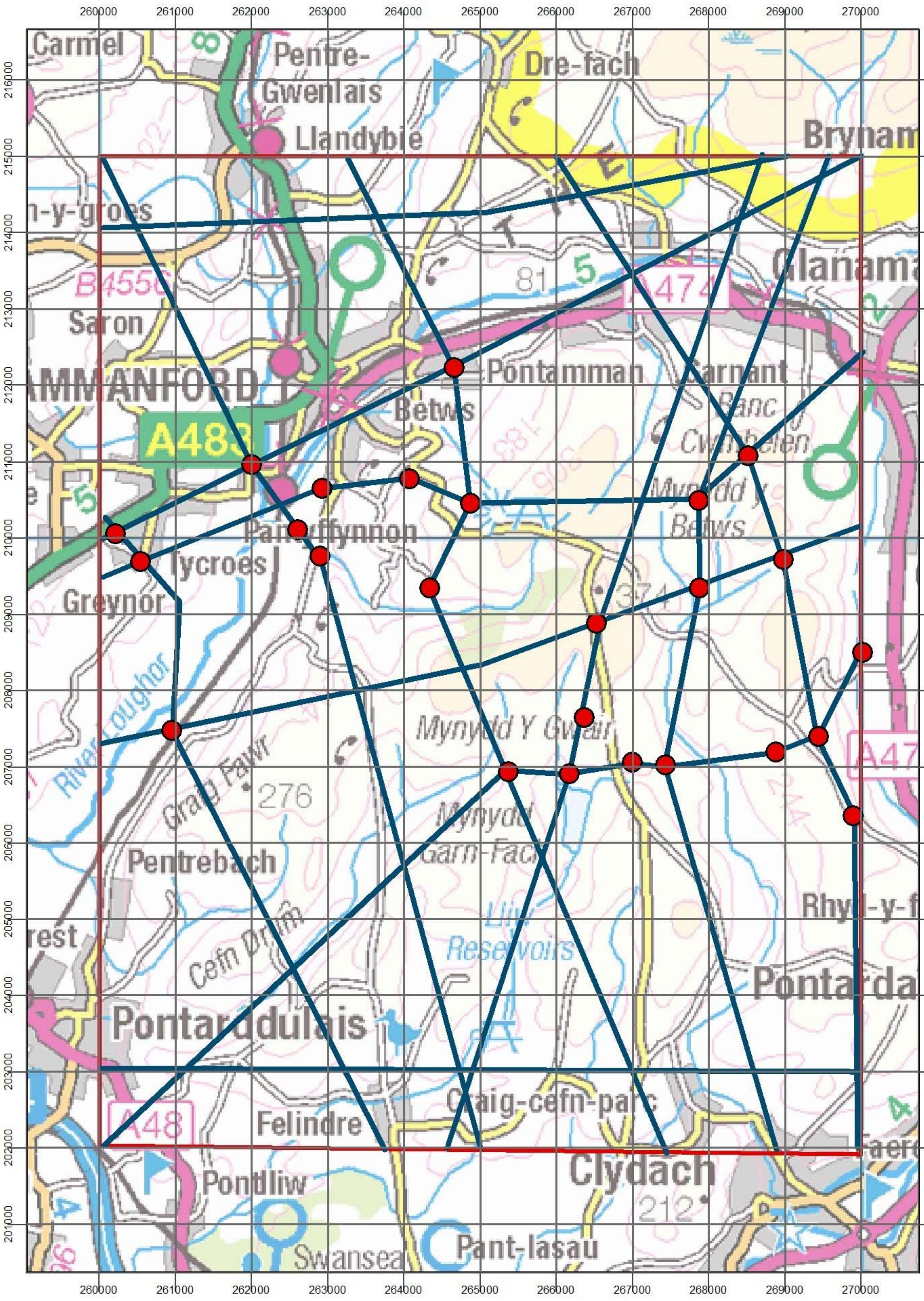

Figure 5. Distribution of sections (blue lines) used to create the 1:50,000 resolution fence diagram within the study area.

The current released GB3D_v2012 dataset was produced to complement the existing 1:625 000 scale map sheet published by BGS (2007) using the same colour schema and geological classification http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/gb3d.html.

None of the 625K resolution cross-sections constructed for the GB3D_v2012 model coincide with the study area. In a subsequent update of the model, released in 2014, additional sections were constructed at the same resolution but incorporating several master boreholes. Again, none of these sections cross the study area.

If such legacy sections had been available, such 1:625k resolution sections are considered to be of insufficient resolution and lacking adequate detail to be incorporated into the fence diagram constructed as part of the current study.

Typically, the interpretation of the geology to depths of up to 200 m below ground surface was more strongly influenced by the surface geology, whereas at greater depths boundaries generated from intercepts with borehole records or structural contours on coal seams were given priority.

3.2 AMMANFORD 50K RESOLUTION GSI3D FENCE DIAGRAM: CONSTRUCTION METHODOLOGY

No existing cross-section was available from the published 1:50 000-scale geological map for Ammanford (BGS, 1977) that crossed the study area. Therefore, all sections included in the fence diagram represent novel interpretations. The distribution of these 12 sections is shown in Figure 5 and the names of these sections (in italics above) are used in Section 4 of this report when describing the distribution of the geological units.

The sections were interpreted to include the stratigraphy relevant to the 1:50 000-resolution model (Table 2) and where necessary interpretations were extended to at least 2 km depth below OD. The section lines were constructed to ensure that all 25 boreholes fell along a section line to aid interpretation.

Construction of coal seams is particularly difficult using GSI3D, which colours up the lithostratigraphy based upon the named lower boundary. The software is unable to allow the digitisation of units such as coals or marine bands just as lines. Consequently, all coals have been digitised with a base and top and an arbitrary thickness of 1 m. This was done by digitising the basal boundary and copying the line with an assumed 1 m thickness. However, when changes to lines were required, as a consequence of fitting crossing sections, the modification of the coal lines was particularly problematical and time consuming.

Name id	**STRATIGRAPHY**	**LITHOLOGY**	**PARENT**
SUPD-IMPERM	SUPERFICIAL DEPOSITS	UNDIFFERENTIATED	
GDB1-MDSS	GROVESEND FORMATION	MUDSTONE, SILTSTONE & SANDSTONE	WAWK
GELI1-COAL	GELI-COAL GELLI COAL	COAL	WAWK
GDB2-MDSS	GROVESEND FORMATION	MUDSTONE, SILTSTONE & SANDSTONE	WAWK
GDB3-SDST	GROVESEND FORMATION	SANDSTONE	WAWK
GELI2-COAL	GELLI COAL	COAL	WAWK
GDB4-MDSS	GROVESEND FORMATION	MUDSTONE, SILTSTONE & SANDSTONE	WAWK
GDB5-SDST	GROVESEND FORMATION	SANDSTONE	WAWK
GDB6-MDSS	GROVESEND FORMATION	MUDSTONE, SILTSTONE & SANDSTONE	WAWK
PENC-COAL	PENYSCALLEN COAL	COAL	WAWK
GDB7-MDSS	GROVESEND FORMATION	MUDSTONE, SILTSTONE & SANDSTONE	WAWK
S4FC1-COAL	SWANSEA FOUR FEET COAL	COAL	WAWK
GDB8-MDSS	GROVESEND FORMATION	MUDSTONE, SILTSTONE & SANDSTONE	WAWK
S4FC2-COAL	SWANSEA FOUR FEET COAL	COAL	WAWK

Table 2a) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the Grovesend Formation.

SW1-MDSS	SWANSEA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
BW2F-COAL	BRYNWHILACH TWO-FEET COAL	COAL	PES
SW2-MDSS	SWANSEA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
SW3-SDST	SWANSEA MEMBER	SANDSTONE	PES
SSFC-COAL	SWANSEA FIVE FEET COAL	COAL	PES
SW4-MDSS	SWANSEA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
SW5-SDST	SWANSEA MEMBER	SANDSTONE	PES
GRAC-COAL	GRAICOLA COAL	COAL	PES

Table 2b) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the Swansea Member (Pennant Sandstone Formation).

H1-MDSS	HUGHES MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
S2FC-COAL	SWANSEA TWO FEET COAL	COAL	PES
H2-MDSS	HUGHES MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
H3-SDST	HUGHES MEMBER	SANDSTONE	PES
H4-MDSS	HUGHES MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
H5-SDST	HUGHES MEMBER	SANDSTONE	PES
CE1C-COAL	CILLE No.1 COAL	COAL	PES
H6-MDSS	HUGHES MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
H7-SDST	HUGHES MEMBER	SANDSTONE	PES
H8-MDSS	HUGHES MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
HUGC-COAL	HUGHES COAL	COAL	PES

Table 2c) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the Hughes Member (Pennant Sandstone Formation).

BD1-MDSS	BRITHDIR MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
GGMC-COAL	GLYNGWYLIM COAL	COAL	PES
BD2-MDSS	BRITHDIR MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
BD3-SDST	BRITHDIR MEMBER	SANDSTONE	PES
BD4-MDSS	BRITHDIR MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
BD5-SDST	BRITHDIR MEMBER	SANDSTONE	PES
BDRC-COAL	BRITHDIR COAL	COAL	PES

Table 2d) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the Brithdir Member (Pennant Sandstone Formation).

RA1-MDSS	RHONDDA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
RA2-SDST	RHONDDA MEMBER	SANDSTONE	PES
RA3-MDSS	RHONDDA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
RA4-SDST	RHONDDA MEMBER	SANDSTONE	PES
RA5-MDSS	RHONDDA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
DUKC-COAL	DUKE COAL	COAL	PES
RA6-MDSS	RHONDDA MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
RA7-SDST	RHONDDA MEMBER	SANDSTONE	PES
N2RC-COAL	No.2 RHONDDA COAL	COAL	PES

Table 2e) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the Rhondda Member (Pennant Sandstone Formation).

LLFB-MDSS	LLYNFI MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
UPIC-COAL	UPPER PINCHIN COAL	COAL	PES
LLFB1-MDSS	LLYNFI MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
LLFB2-SDST	LLYNFI MEMBER	SANDSTONE	PES
LLFB3-MDSS	LLYNFI MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
LLFB4-SDST	LLYNFI MEMBER	SANDSTONE	PES
LLFB5-MDSS	LLYNFI MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
UWCO-COAL	UPPER WELSH COAL	COAL	PES
LLFB6-MDSS	LLYNFI MEMBER	MUDSTONE, SILTSTONE & SANDSTONE	PES
LLFB7-SDST	LLYNFI MEMBER	SANDSTONE	PES
LPIC-COAL	LOWER PINCHIN	COAL	PES

Table 2f) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the Lynfi Member (Pennant Sandstone Formation).

SWUCM-MDSS	S. WALES UPPER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWMCM1-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
LWCO-COAL	LOWER WELSH COAL	COAL	SWCM
SWMCM2-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
REDCO-COAL	RED COAL	COAL	SWCM
SWMCM3-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWMCM4-SDST	S. WALES MIDDLE CM	SANDSTONE	SWCM
SWMCM5-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
GNTC-COAL	GARNANT COAL	COAL	SWCM
SWMCM6-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWMCM7-SDST	S. WALES MIDDLE CM	SANDSTONE	SWCM
SWMCM8-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWMCM9-SDST	S. WALES MIDDLE CM	SANDSTONE	SWCM
SWMCM10-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWMCM11-SDST	S. WALES MIDDLE CM	SANDSTONE	SWCM
SWMCM12-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWMCM13-SDST	S. WALES MIDDLE CM	SANDSTONE	SWCM
SWMCM14-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
STWR-COAL	STWRIN COAL	COAL	SWCM
SWMCM15-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
RCKC-COAL	ROCK COAL	COAL	SWCM
SWMCM16-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
HARC-COAL	HARNLO COAL	COAL	SWCM
SWMCM17-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SLCO-COAL	STANLLYD COAL	COAL	SWCM
SWMCM18-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
BLYD-COAL	BRASLYD COAL	COAL	SWCM
SWMCM19-MDSS	S. WALES MIDDLE CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM

Table 2g) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the South Wales Upper & Middle Coal Measures formations.

SWLCM1-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
GWCO-COAL	GWENDRAETH COAL	COAL	SWCM
SWLCM2-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
STKC-COAL	STINKING COAL	COAL	SWCM
SWLCM3-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
TWCO-COAL	TRICHWART COAL	COAL	SWCM
SWLCM4-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
PQCO-COAL	PUMPQUART COAL	COAL	SWCM
SWLCM5-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
RFCO-COAL	RHASFACH COAL	COAL	SWCM
SWLCM6-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWLCM7-SDST	S. WALES LOWER CM	SANDSTONE	SWCM
SWLCM8-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWLCM9-SDST	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWLCM10-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
SWLCM11-SDST	S. WALES LOWER CM	SANDSTONE	SWCM
SWLCM12-MDSS	S. WALES LOWER CM	MUDSTONE, SILTSTONE & SANDSTONE	SWCM
BISHM-MDSS	BISHOPSTON MUDSTONE FM	MUDSTONE, SILTSTONE & SANDSTONE	MARR
TWR-SCON	TWRCH SANDSTONE FM	CONG + SDST	MARR

Table 2h) Stratigraphical nomenclatures used in the 1:50 000 resolution GSI3D fence diagram for the South Wales Lower Coal Measures Formation and Marros Group.

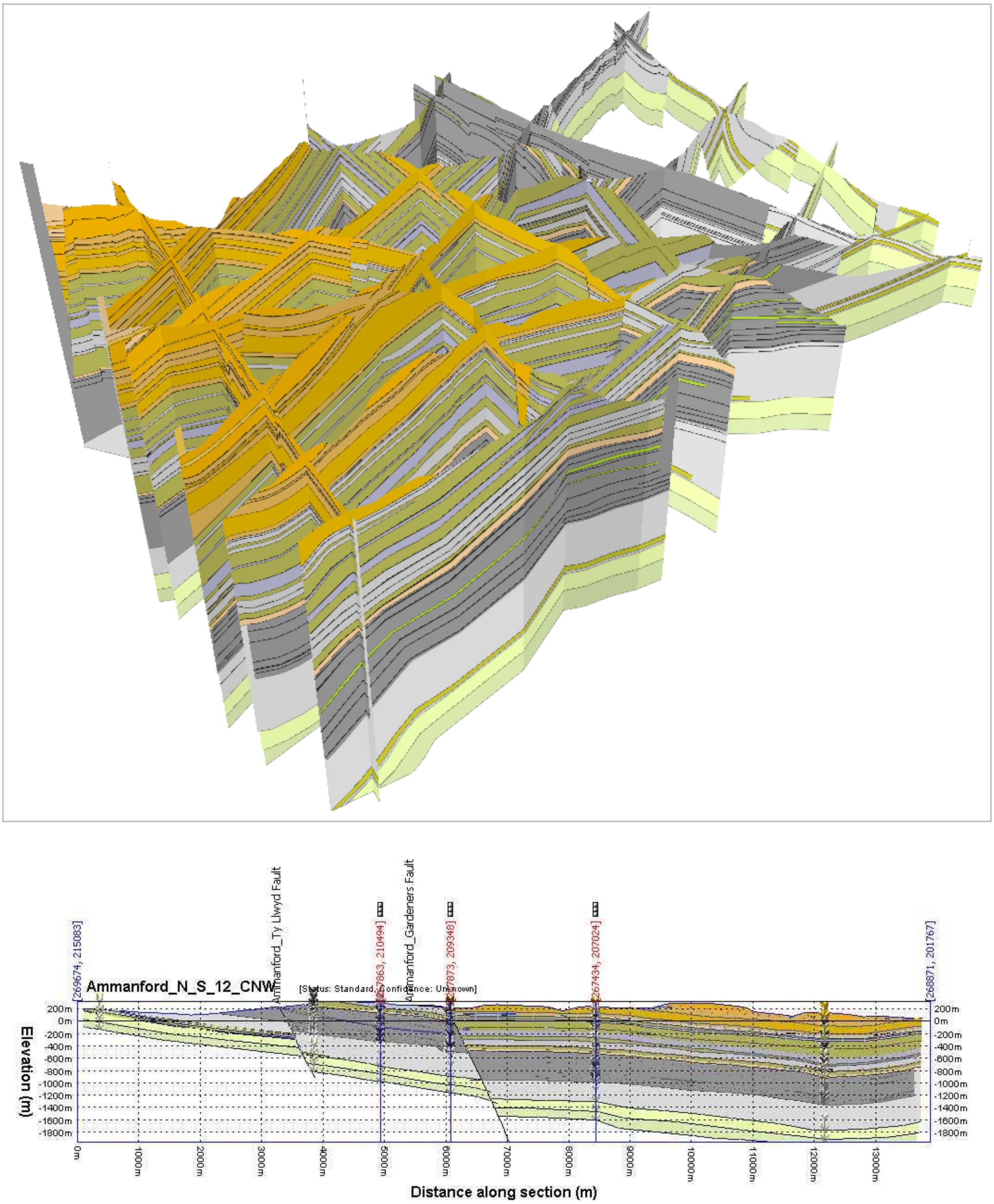

Figure 6. a) View of 1:50,000 resolution cross-section network for fence diagram, viewed looking towards the west. This is an unmodified screen grab from the GSI3D viewer. The fault and individual coal seams are shown in black. The stratigraphical succession, in descending order is: Orange- Swansea Member; Dirty orange- Hughes Member; Green- Brithdir Member (component mudstones shown in pale grey); Green- Rhondda Member (component mudstones shown in medium grey); Pale grey- Llynfi Member (component sandstones shown in green); Pink- South Wales Upper Coal Measures Formation; Dark grey- South Wales Middle Coal Measures Formation (component sandstones shown in green); Pale grey- South Wales Lower Coal Measures Formation (component sandstones shown in green); Yellow- Bishopston

Mudstone Formation; Lime green- Twrch Sandstone Formation. There is no vertical exaggeration and horizontal scale varies with perspective. b) Example section (Ammanford_N_S_12_CNW) as constructed in GSI3D, showing position of boreholes (NGR given in red) and intercepts from crossing sections shown as coloured arrows.

3.3 FAULT NETWORK

The geometry of 6 key faults has been constructed in GSI3D to provide a framework for the Ammanford 1:50 000 resolution fence diagram. The fault network used in the fence diagram is shown in Figure 7. In addition to the modelled structures, the presence of many less significant faults within Carboniferous strata (shown in Figure 8) is indicated in the cross sections by a stepping of the affected geological contacts.

Faults dipping steeper than 70° are easy to construct in GSI3D. Shallower angle reverse faults and thrusts may be difficult to construct as older units sit above younger and GSI3D colours up units based on a normal upward-younging geological succession. This is a GSI3D drawing issue only, that can be rectified by creating additional structural entities in the stratigraphical succession such that they are in the order present in the section. Furthermore, the truncation of one fault against another at depth is not determined in the fault modelling process, but happens when cross-sections are drawn and the model automatically calculated. No calculation is possible for Y-shaped faults, the fault network calculation does not revise the display in sections, and the faults appear in the sections as digitized. No attempt was made to calculate the model and therefore “tails” of redundant fault segments can be seen in the sections of the fence diagram.

Details on the structure of the study area are provided in section 4.2.

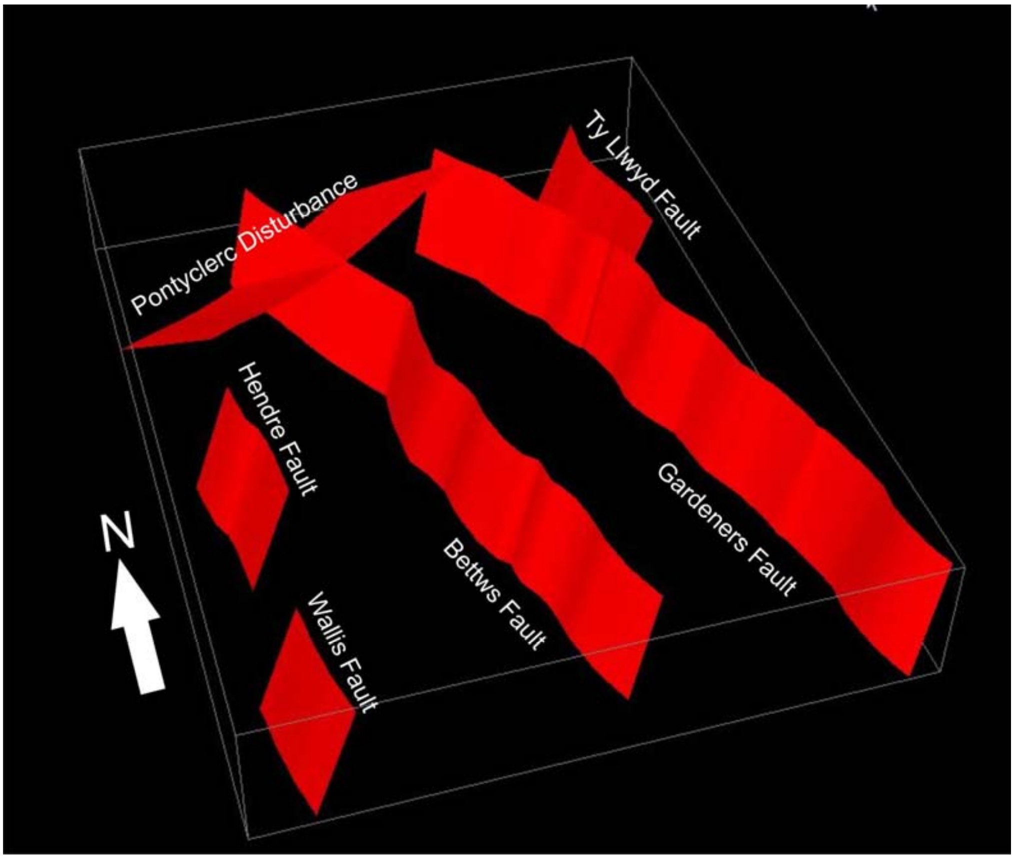

Figure 7. View of fault network for the fence diagram of the entire study area, viewed looking towards the north. This is an unmodified screen grab from the GSI3D viewer. There is no vertical exaggeration.

4 Overview of the geology of the study area

This section provides an overview of the geology of the Ammanford study area. Details on the subsurface distribution of units as determined by the new Ammanford 1:50 000 resolution 3D model, indicating the source information, are also provided.

4.1 GEOLOGICAL SUCCESSION

The geological units found in the study area are described briefly below, from the oldest to the youngest, and are summarised in Table 3.

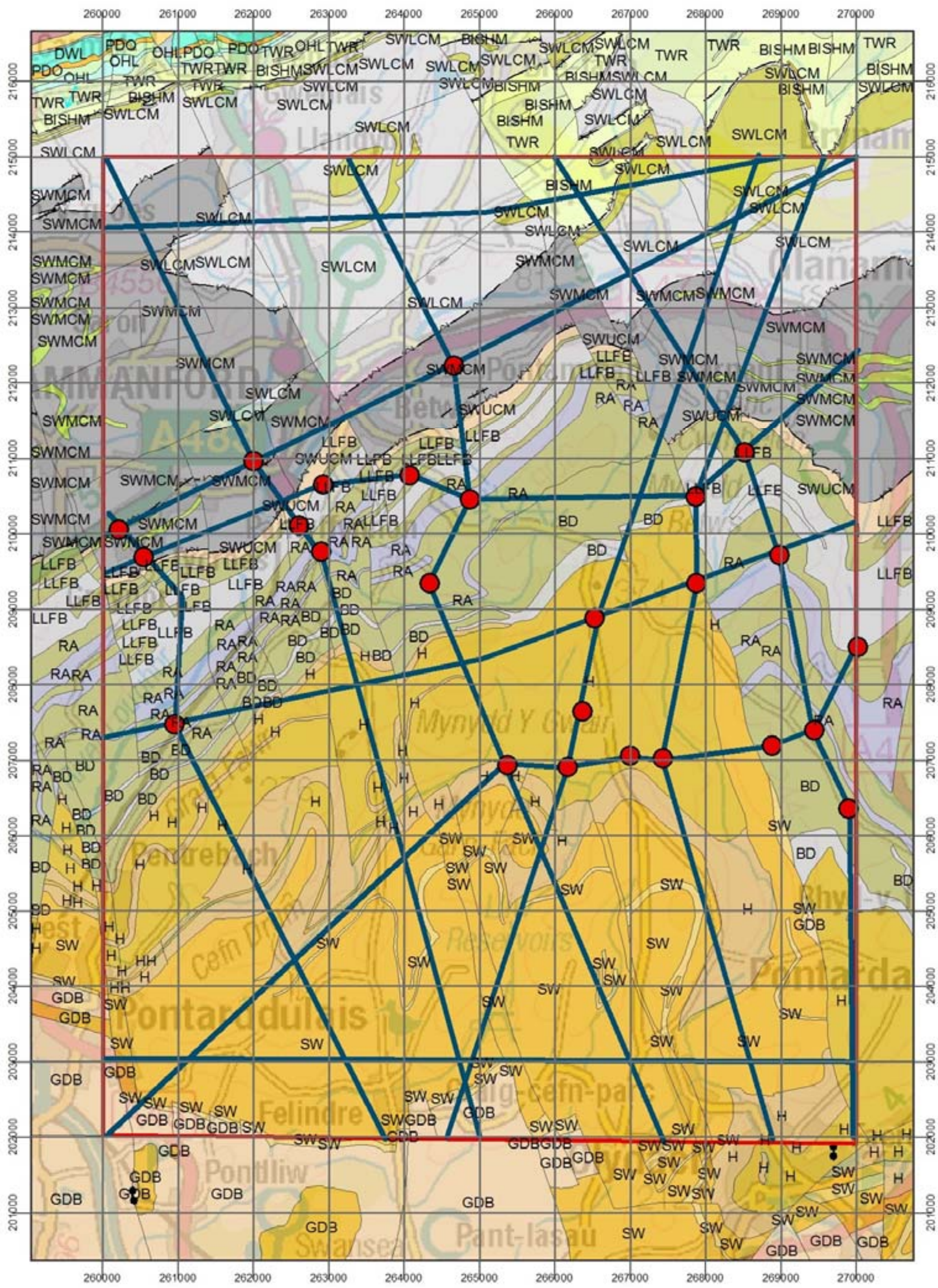

Figure 8. Geological map of the bedrock succession present at the ground surface across the study area, showing the main lithostratigraphical units and geological faults. The map is sourced from BGS v5 DiGMapGB datasets.

Age	Group	Formation	Member	Rock characteristics	Thickness
Quaternary superficial deposits				Stony and sandy clay (till); thin beds of sand and gravel; thin peat and clay	Generally thin (<10m)
ASTURIAN	**WARWICKSHIRE**	Grovesend		Mainly mudstones and siltstones with coals, typically thinner than in the Pennant Sandstone Formation. Lithic sandstones are subordinate, but locally thick.	Up to 45m seen
		Pennant Sandstone	Swansea	Green-grey lithic sandstones with thin mudstone/siltstones and seatearths and thin coals	Up to 290m
			Hughes		310m
			Brithdir		200m
			Rhondda		240-300m
BOLSOVIAN			Llynfi	Green-grey and blue-grey, feldspathic, micaceous lithic sandstones with thin mudstone/siltstones and seatearths and thin coals	180-230m
	SOUTH WALES COAL MEASURES	South Wales Upper Coal Measures		Grey coal-bearing mudstones/ siltstones with seatearths and minor quartzose sandstones	50-55m
DUCK.		South Wales Middle Coal Measures		Grey mudstones dominate, thick coals with seatearths and ironstones, subordinate thin quartzitic sandstones, marine bands common in upper part	440-560m; thins to N
LANGSET.		South Wales Lower Coal Measures		Grey mudstones dominate: below Rhasfach Coal, coals thin, several thick quartzitic sandstones and marine bands common; upper part thick coals with seatearths	200-415m; thins to N & W
NAMURIAN	**MARROS**	Bishopston Mudstone		Medium to dark grey mudstones with some beds of grey siltstone and minor quartzitic sandstone and rare thin coals	c. 135m
		Twrch Sandstone		Quartzose pebbly and conglomeratic sandstone with thin mudstone/siltstone interbeds	c. 110-170m

Table 3 Summary of the stratigraphical units present within the Ammanford study area, describing main lithologies and approximate thicknesses. Langset.- Langsettian; Duck- Duckmantian

4.1.1 Marros Group

4.1.1.1 Twrch Sandstone Formation

The Twrch Sandstone Formation has been mapped at crop in a small area in the extreme north of the study area at Pant-y-bryn [2655 2149], but everywhere else extends beneath younger South Wales Coal Measures and Warwickshire groups across the remainder of the area. In the southern part of the study area the base of the unit may extend to depths in excess of 2 km. During the previous resurvey of the area this unit was mapped as the Basal Grit of the Millstone Grit (BGS, 1977). The unit was renamed as the Twrch Sandstone Formation and formally defined by Waters et al. (2009). The unit was not seen during the current study, but is described as dominated by quartzose sandstone with thin mudstone/siltstone interbeds (Waters et al. 2009). The sandstone is commonly pebbly and conglomeratic and may occur in upward coarsening cycles or with channelled bases and upward fining cycles. The unit is of no economic importance associated with coal resources and as such the deep boreholes do not penetrate this unit.

4.1.1.2 Bishopston Mudstone Formation

The Bishopston Mudstone Formation has been mapped at crop in small areas in the extreme north of the study area around Twynmynydd and north of Bryn Pedol, but everywhere extends beneath younger South Wales Coal Measures and Warwickshire groups across the remainder of the area. In the southern part of the study area the base of the unit may extend to depths in excess of 2 km (Figure 6b). During the previous resurvey of the area this unit was mapped as the Millstone Grit Series (BGS, 1977). The unit was renamed as the Bishopston Mudstone Formation and formally defined by Waters et al. (2009). The unit was seen during the current study locally exposed in the Nant Coch (CNW_57) and Nant Pedol (CNW_53 and 54) stream sections in with isolated exposure of mudstone and quartzitic sandstone. The formation is described as dominated by medium to dark grey mudstones, commonly fossiliferous, with some beds of medium grey siltstones and beds of interbedded siltstone and mudstone (Waters et al. 2009). Sporadic, minor pale grey quartzitic sandstones and rare thin coals may also be present. The uppermost mainly sandstone beds are mapped as part of the Bishopston Mudstone Formation, but may represent part of the Telpyn Point Sandstone Formation (former Farewell Rock) that is recognised in SW Wales (Waters et al. 2009) but not mapped in the Ammanford area. The sandstone may equate to the Cumbriense Quartzite of George (2000), the latter known to have an incised base, as suggested in the plate for locality CNW_53. The unit is of no economic importance associated with coal resources and as such the deep boreholes do not penetrate this unit.

Key localities:

CNW_53 [269540 215001]: Succession, youngest at top, is:

Siltstone, yellowish grey, very thinly planar laminated and bedded, sharp base 0.45m

Sandstone, hard, medium grey, sharp base 0.2m

Sandstone, soft, pale yellowish grey, fine-grained, thinly planar bedded, possibly bioturbated, sharp base (level of hammer in plate) 1.9m

Sandstone, hard, pale buff, quartzitic, very fine-grained, comprising three planar, slightly wedged beds, sharp base 0.3m

Siltstone, dark grey, very thinly bedded with possibly slightly discordant top 1.2m

Plate 1 View of a mainly sandstone exposure, in Nant Pedol (CNW_53), looking south. Note the lowermost hard sandstone rests with apparent low-angle discordance on underlying siltstones.

CNW_54 [269515 214931]: The very top of the succession, starting 1m below the Subcrenatum Marine Band and representing the transgressive system developed below the fully marine mudstones, comprises:

Siltstone, dark and pale grey laminae, very thinly planar laminated, ripple cross-laminated, gradational base 0.8m

Sandstone, very hard, medium grey, very fine-grained, siliceous, very thinly planar laminated, ripple cross-laminated with common in situ *Lingula* 2.0m

CNW_57 [266669 214521]: Section towards top of succession, youngest at top, is:

Siltstone, medium grey, very thinly bedded, sharp base 1.2m

Sandstone, very hard, medium grey, fine-grained, quartzitic, single bed with sharp base 0.35m

Mudstone, soft, brown-weathered 0.03m

Sandstone, very hard, medium grey, fine-grained, quartzitic, medium bed 0.2m

4.1.2 South Wales Coal Measures Group

4.1.2.1 SOUTH WALES LOWER COAL MEASURES FORMATION

The South Wales Lower Coal Measures Formation has been mapped at crop within the northern part of the study area and everywhere extends beneath younger Pennant Sandstone Formation and the Grovesend Formation in the central and southern parts of the area (Figure 9). In the southern part of the study area the base of the unit may extend to depths in excess of 1.7 km below OD (Figure 6b). During the previous resurvey of the area this unit was mapped as the Lower Coal Measures (BGS, 1977). The unit was renamed and formally defined by Waters et al. (2009). The unit is locally mainly obscured by Superficial Deposits. The lower part of the formation is well exposed in Nant Pedol (CNW_54, 55 and 56). The formation is described as dominated by grey mudstones, with the base defined as the base of the Subcrenatum Marine Band (Waters et al. 2009). Within the lower part of the formation, below the Rhasfach Coal, coals are thin, there are several thick quartzitic sandstones present (collectively known as the Farewell Rock during the previous resurvey) and marine bands are common. The upper part of the formation has few sandstones and no marine bands, but includes several thick coals with seatearths. The coals modelled during this study, in ascending order are: Rhasfach, Pumpquart, Trichwart, Stinking and Gwendraeth coals.

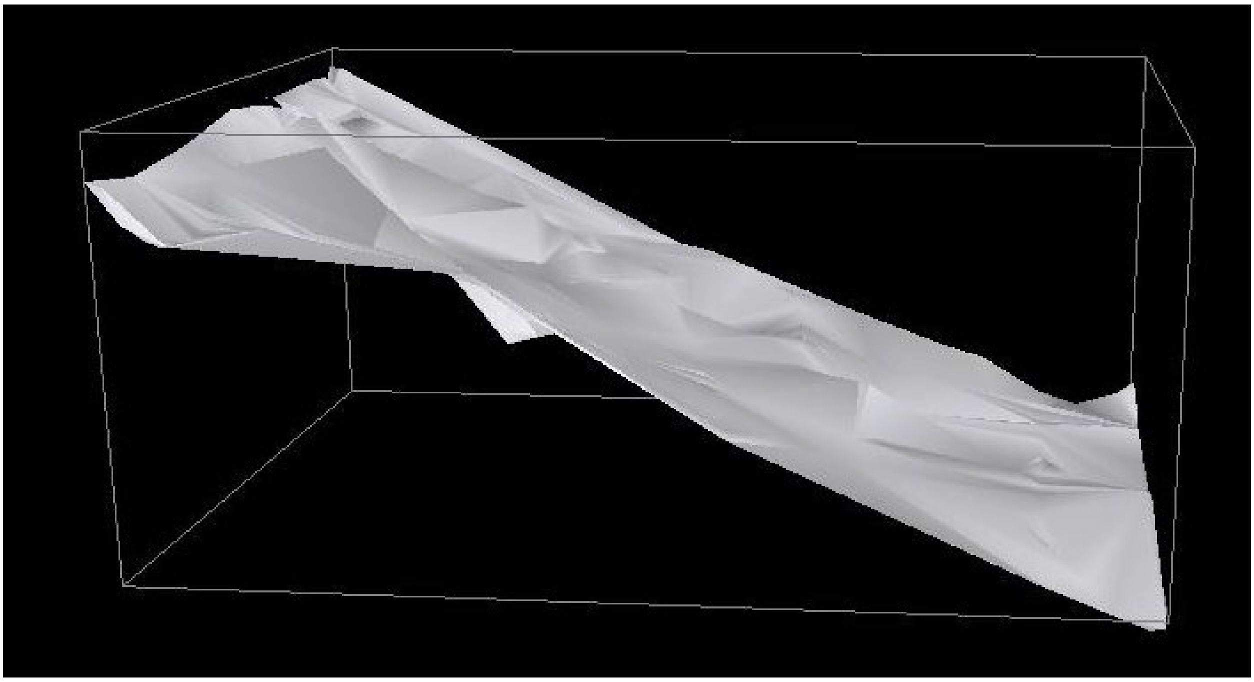

Figure 9 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the South Wales Lower Coal Measures Formation.Key localities:

CNW_54 [269515 214931]: The very base of the formation, including SWLCM11-SDST of the model and the underlying Subcrenatum Marine Band (SWLCM12-MDSS) comprises:

Sandstone, very hard, pale to medium grey, fine-grained, thickly irregular bedded (up to 0.45m) with lower bedding planes more laterally continuous, sharp planar base 4.0m

Sandstone, yellowish grey, very fine-grained, micaceous, very thinly planar laminated and bedded 0.5m

Mudstone, dark grey, very carbonaceous, very thinly planar bedded c. 1m

The 4m thick sandstone described in this section, locally known as the Farewell Rock, is exposed for some 200m downstream in a narrow gorge in Nant Pedol, as far as CNW_55 [269477

214743], where it is also fine-grained with 0.4m-thick beds. The sandstone may be up to 30m thick in this section.

Plate 2 View of a mainly sandstone exposure, in Nant Pedol (CNW_54), looking west. Note the lowermost soft mudstone of the Subcrenatum Marine Band is largely obscured by vegetation.

Key localities:

CNW_56 [269143 213980 to 269135 213900]: section below the Rhasfach Coal, including SWLCM6-MDSS of the model, with youngest at top, is:

Carbonate nodule, hard, pale to medium grey, ochreous-weathered with goniatite debris 0.1m

Mudstone, medium grey, fissile, very thin bedded 1.2m

Mudstone, dark grey, fissile, very clayey, very thinly planar bedded c. 3m

Mudstone, dark grey, fissile, carbonaceous, finely micaceous, gradational base c. 3m

Mudstone, medium to dark grey, slightly greenish, very clayey, very thinly planar bedded c. 3m

Gap c. 2m

Sandstone, hard, medium to dark grey, quartzitic, thin planar bedded (0.2m-thick beds) with dark grey siltstone partings up to 0.05m thick 0.8m

CNW_58 [261904 211583], section from uppermost part of formation (SWLCM1-MDSS in model), above the Gwendraeth Coal, with youngest at top, is:

Sandstone, hard, medium grey, fine-grained, sharp base with ironstone pebbles with pyrite mineralisation and coal clasts 5-6m

Mudstone, soft, dark grey, possibly rooted, poorly exposed c. 2m

4.1.2.2 SOUTH WALES MIDDLE COAL MEASURES FORMATION

The South Wales Middle Coal Measures Formation has been mapped at crop within the northern part of the study area and everywhere extends beneath younger Pennant Sandstone Formation and the Grovesend Formation in the central and southern parts of the area (Figure 10). In the southern part of the study area the base of the unit may extend to depths in excess of 1.6 km below OD (e.g. section Ammanford_N_S_8_CNW). During the previous resurvey of the area this unit was mapped as the Middle Coal Measures (BGS, 1977). The unit was renamed and formally defined by Waters et al. (2009). The unit is locally mainly obscured by Superficial Deposits. The formation is described as dominated by grey mudstones, with the base defined as the base of the Vanderbeckei (Amman) Marine Band (Waters et al. 2009, Waters et al. 2011). Grey mudstones dominate with thick coals with seatearths and ironstones, subordinate thin quartzitic sandstones, and marine bands common in the upper part. Named coal seams are shown in Table 2c. The coals in the lower part of the succession are particularly thick and in comparison with other parts of the Coal Measures are separated by relatively thin mudstones. This makes this interval of significant economic importance and many of the deep boreholes extend to this interval. The coal seams split and join over short distances and correlation of the seams is difficult and borehole logs often show many different nomenclatures. The recognition and correlation of individual seams in this interval is problematic, especially because of the absence of marine bands. Above the Stwrin Coal the seams are separated by greater thicknesses of mudstone/siltstone, but also with common sandstone beds. Marine bands are also common in this upper interval, are often described in borehole records and aids identification and correlation of named coals.

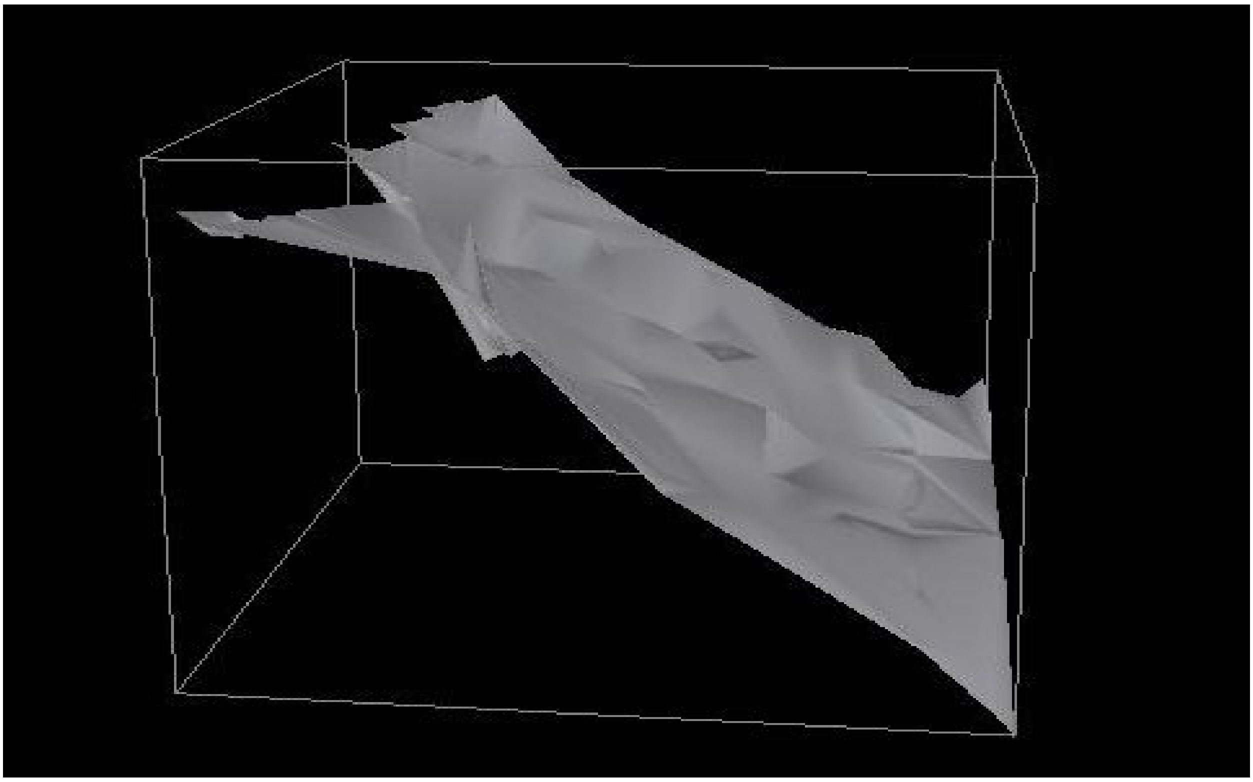

Figure 10 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the exploded distribution of the bases of modelled units (see Table 2g for key) for the South Wales Middle Coal Measures Formation.

Key localities:

CNW_52 [268026 213159]: disused quarry at Glanaman from succession between the Harnlo and Ddugaled Rider coals (SWMCM16-MDSS in model). The top of the overgrown quarry face in the southwest comprises 1.2m of poorly exposed black, very thinly planar bedded mudstone. The eastern side of the quarry, representing the lowermost part of the succession in the quarry, comprises poorly exposed sandstone, including a 0.15m thick bed of hard, pale grey, fine-grained, quartzitic sandstone.

CNW_49 [267837 212013], small roadside exposure at Troed Y Rhiw in an unnamed sandstone succession in the upper part of the formation (SWMCM14-MDSS in model), with youngest at top, is:

Sandstone, pale grey, very fine-grained, coarsely micaceous with planty material, sharp base c.2m

Mudstone, dark grey, thin bedded, abundant ironstone nodules, very finely micaceous c.3m

4.1.2.3 SOUTH WALES UPPER COAL MEASURES FORMATION

The South Wales Upper Coal Measures Formation has been mapped at crop within the central part of the study area and everywhere extends beneath younger Pennant Sandstone Formation and the Grovesend Formation in the central and southern parts of the area (Figure 11). In the southern part of the study area the base of the unit may extend to depths in excess of 1.1 km below OD (e.g. section Ammanford_N_S_8_CNW). During the previous resurvey of the area this unit was mapped as part of the Llynfi Beds (BGS, 1977). The unit was renamed and formally defined as the South Wales Upper Coal Measures Formation by Waters et al. (2009). The unit was seen at two localities along the Grenig Road, north of Banc Cwmhelen (CNW_50 and 51) during the current study and is locally mainly obscured by Superficial Deposits. The formation is described as mainly grey coal-bearing mudstones/ siltstones with seatearths and minor quartzose sandstones (Waters et al. 2009). The base of the formation is defined as the top of the Cambriense (Upper Cwmgorse) Marine Band (Waters et al. 2009, Waters et al. 2011), the youngest marine band recognised in the succession. The top is taken at the base of the first incoming thick lithic arenite of the Llynfi Member, which in this area typically occurs immediately above the Lower Pinchin Coal.

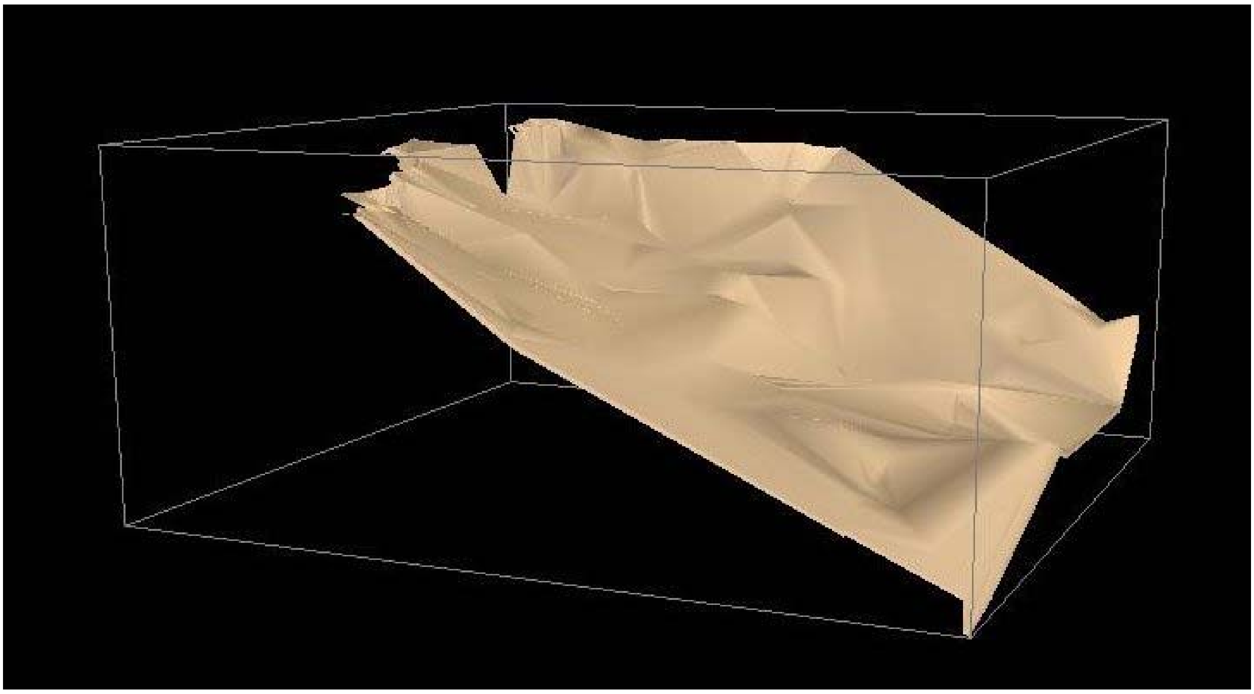

Figure 11 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the South Wales Upper Coal Measures Formation.

Key localities:

CNW_50 [268306 211584], section in drain adjacent to road at Trum-yr-hwch, with youngest at top, is:

Sandstone, pale to medium grey, very fine- to fine-grained, very micaceous, very thinly planar bedded, planar and cross-laminated, sharp base 1.5m

Siltstone, medium grey, finely micaceous, very thinly planar laminated, planty 0.9m

Gap c.1m

Mudstone, dark grey with ironstone nodules near base c. 4m

CNW_51 [268358 211551], small excavation above the section exposed at CNW_50, comprises 2.5m of mudstone, very clayey, medium to dark grey with very fine pale planar laminae, very thinly planar bedded, minor ironstone development, with a 0.1m-thick siltstone bed with both gradational top and base present near the top of the section.

4.1.3 Warwickshire Group

4.1.3.1 LLYNFI MEMBER (PENNANT SANDSTONE FORMATION)

The Llynfi Member has been mapped at crop within the central part of the study area and everywhere extends beneath younger members of the Pennant Sandstone Formation and the Grovesend Formation in the south of the area (Figure 12). In the southern part of the study area the base of the unit may extend to depths in excess of 1.1 km below OD (e.g. section Ammanford_N_S_8_CNW). During the previous resurvey of the area this unit was mapped as part of the Llynfi Beds (BGS, 1977). The unit was renamed and formally defined as the Llynfi Member by Waters et al. (2009). The member was seen in a single section at Cwmamman (CNW_43) from a level above the Upper Pinchin Coal (LLFB_MDSS in model). The member comprises green-grey and blue-grey, feldspathic, micaceous lithic sandstones with thin mudstone/siltstones and seatearths and thin coals (Waters et al. 2009). The base is taken at the base of the first incoming thick lithic arenite of the Llynfi Member, which in this area typically occurs immediately above the Lower Pinchin Coal. The Upper Welsh and Upper Pinchin coals have been modelled in this study.

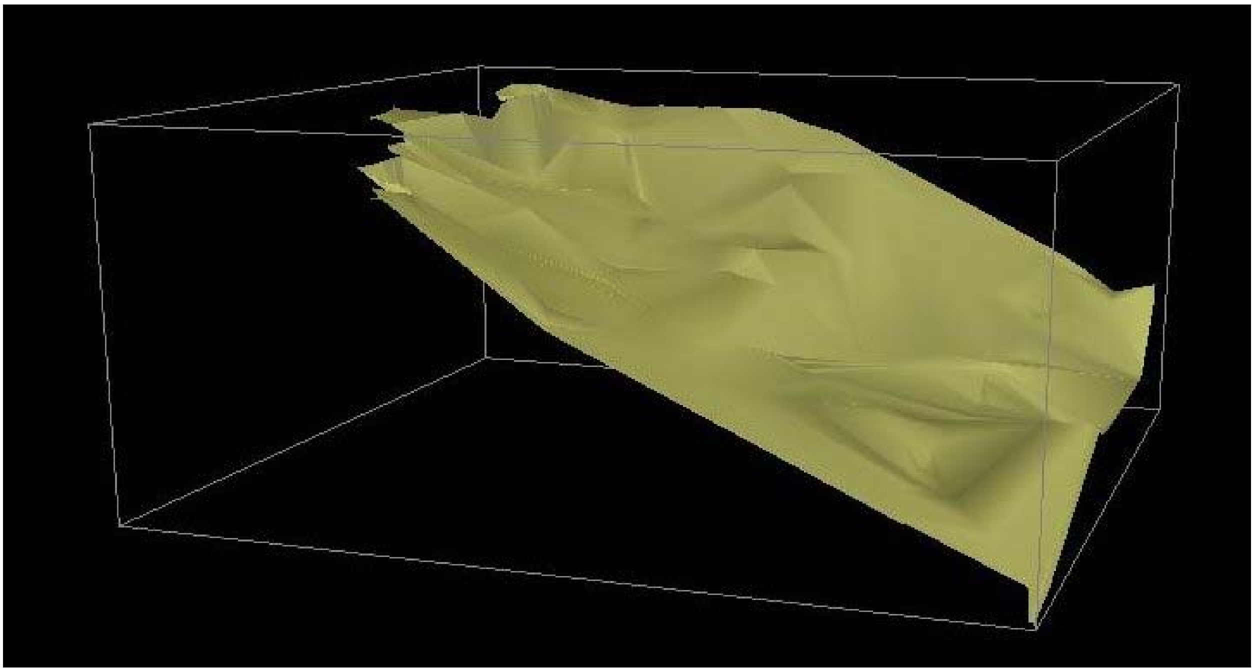

Figure 12 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the for the Lynfi Member.

Key locality:

CNW_43 [267015 212180], small excavation, the succession with youngest at top, is:

Sandstone, medium grey, very fine- and fine-grained, micaceous and carbonaceous, abundant plant material and leaf impressions, very thinly planar bedded and laminated, with lower 0.45m including some cross-lamination, with basal bed 0.2m thick with sharp base 2.5m

Mudstone, medium to dark grey, very thin (cm-scale) planar bedding, passing down to medium grey with very thin pale grey planar laminae 4m

Plate 3 View of Lynfi Member with harder sandstone (left) resting upon comparatively softer mudstone (right), looking north. Hammer head marks boundary between sandstone and mudstone.

4.1.3.2 Rhondda Member (Pennant Sandstone Formation)

The Rhondda Member has been mapped at crop within the central part of the study area and everywhere extends beneath younger members of the Pennant Sandstone Formation and the Grovesend Formation in the south of the area (Figure 13). In the southern part of the study area the base of the unit may extend to depths in excess of 0.9 km below OD (e.g. section Ammanford_N_S_9_CNW). During the previous resurvey of the area this unit was mapped as the Rhondda Beds (BGS, 1977). The unit was renamed and formally defined as the Rhondda Member by Waters et al. (2009). The member comprises green-grey lithic sandstones with thin mudstone/siltstones and seatearths and thin coals (Waters et al. 2009). The base is taken at the base of the No.2 Rhondda Coal. The Duke Coal is a prominent marker in the succession. The sandstones range from pale to dark grey and are typically medium-grained or fine- to medium-grained. Bed bases are typically sharp. Beds range from massive, planar bedded or cross-bedded.

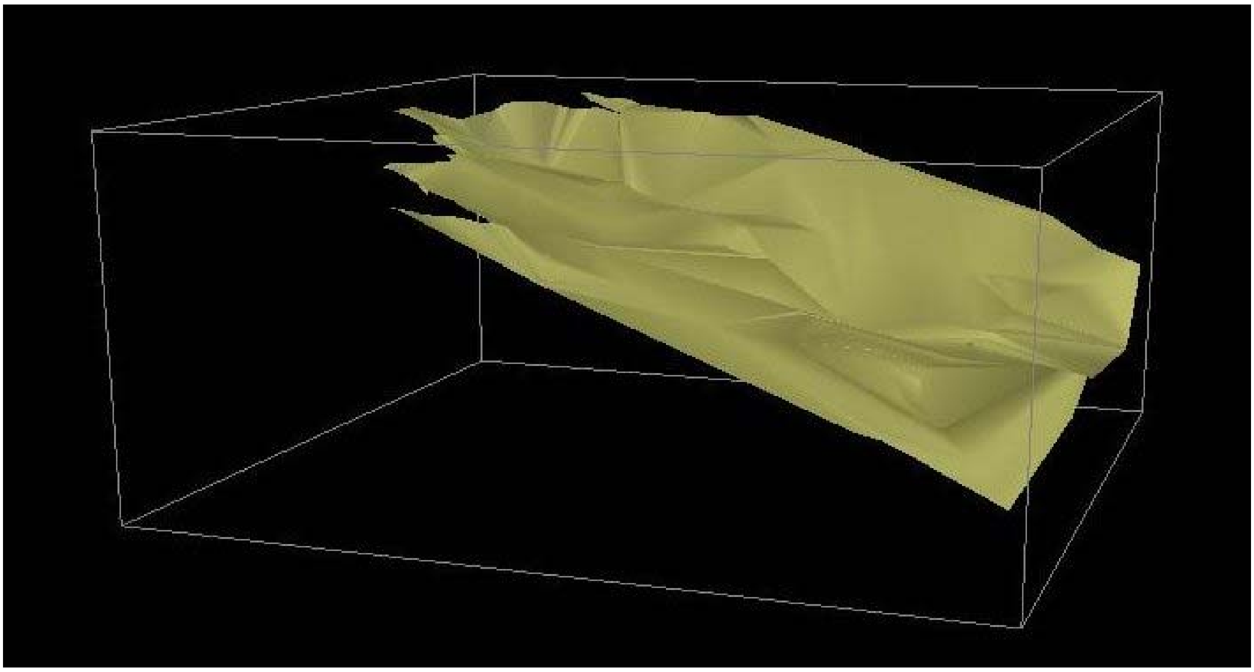

Figure 13 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the for the Rhondda Member.

Key localities:

CNW_17 [263677 209700] located in RA6-MDSS of model- c. 2 m of sandstone, medium to dark grey, medium-grained, cross-bedded with foresets to 152SE16, joints striking 005-185°.

CNW_16 [263650 209166] cascades above footbridge, located stratigraphically above CNW_17 in RA2-SDST of model- c. 3 m of sandstone, medium grey, fine- to medium-grained, cross-bedded with foresets to 254WE17, sub-vertical joints striking 075-255°.

CNW_18 [269485 208181] disused quarry in basal part of RA4-SDST, stratigraphical level as CNW_17. Succession, youngest at top, is:

Sandstone, medium brown, medium-grained, massive with sharp base	1.5m
Sandstone, pale brown, medium-grained, thins northwards	up to 0.48m
Sandstone, medium greenish grey, medium-grained, cross-bedded with tabular foresets and some scours	1.1m
Sandstone, pale to medium grey, medium-grained, massive with sharp base, thickens northwards	1.1-2.3m
Sandstone, pale grey, fine- to medium-grained, planar bedded, beds up to 0.35m thick, mainly medium bedded with thin softer, more micaceous, very thinly bedded sandstone	2.2m

The sections shows sub-vertical fractures trending 020-200 with small displacements down to East.

Plate 4 View of disused quarry in sandstone of Rhondda Member, locality CNW_18 near Pwllfawatkin, looking west.

CNW_19 [269489 208077] disused quarry in RA4-SDST at higher stratigraphical level than CNW_18. Succession, youngest at top, is:

Sandstone, medium greenish grey, medium-grained, coarsely micaceous and carbonaceous above sharp planar base, upward-fining to fine- to medium-grained, thinly planar bedded 1.4m

Siltstone, medium grey, locally iron-rich, micaceous, planar and cross-laminated, sharp base 0.9m

Sandstone, pale grey, fine- to medium-grained, thin planar bedded with some low-angle cross-bedding 1.9m

CNW_44 [266830 211867], stream section in interbedded sandstone and mudstone (part of RA6-MDSS in model, located below the Duke Coal) with basal sandstone (equivalent to RA7-SDST in model) forming a prominent dip slope. Succession, youngest at top, is:

Mudstone, very weathered, dark grey, very planty with abundant stems, sharp base 2m

Sandstone, hard, medium greenish grey, fine-grained, interbedded with softer siltstone, medium grey, micaceous, very thinly bedded with sandstone beds up to 0.2m thick 3m

Sandstone, pale grey, fine-grained, very thinly planar bedded, sharp undulose base 2m

Mudstone, medium to dark grey with very thin pale laminae, very thinly planar bedded, gradational base 2.0m

Gap c.1m

Sandstone, medium greenish grey, fine- to medium-grained, feldspathic, cross-laminated with sharp top 0.6m

Plate 5 View of Rhondda Member at Banwen, Cwmamman (CNW_44), looking south. Geologist inspecting the uppermost mudstone of the section.

CNW_47 [266810 211775], backscarp to a landslide, comprises c. 3m of greenish grey, orange-weathered, medium- to coarse-grained sandstone, some mica, trough cross-bedded. This sandstone equates to RA4-SDST in model, occurring above the Duke Coal.

Plate 6 Rhondda Member cross-bedded sandstone in landslide backscarp above Cwm Garenig, Cwmamman (CNW_47), looking west.

4.1.3.3 Brithdir Member (Pennant Sandstone Formation)

The Brithdir Member has been mapped at crop within the central part of the study area and everywhere extends beneath younger members of the Pennant Sandstone Formation and the Grovesend Formation in the south of the area (Figure 14). In the southern part of the study area the base of the unit may extend to depths in excess of 0.6 km below OD (e.g. section Ammanford_N_S_9_CNW). During the previous resurvey of the area this unit was mapped as the Brithdir Beds (BGS, 1977). The unit was renamed and formally defined as the Brithdir Member by Waters et al. (2009). The member comprises green-grey lithic sandstones with thin mudstone/siltstones and seatearths and thin coals (Waters et al. 2009). The base is taken at the base of the Brithdir Coal.

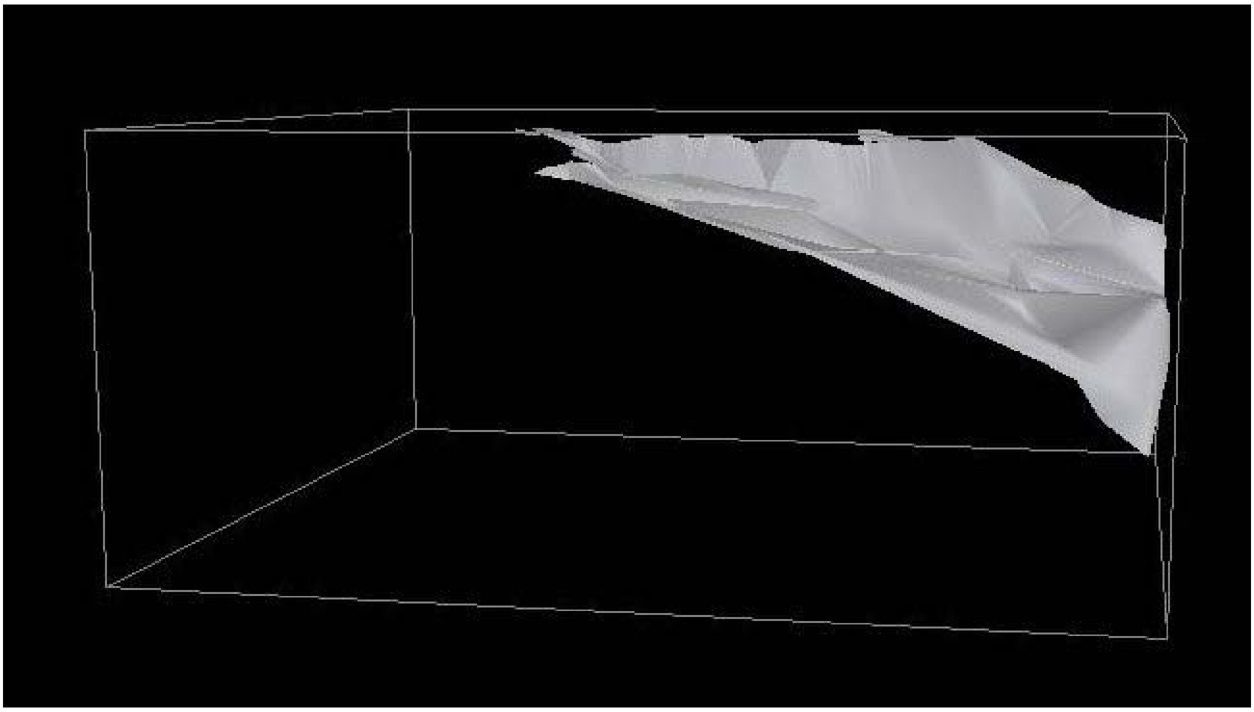

Figure 14 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the for the Brithdir Member.

Key localities:

CNW_1 [270083 206344] Roadside exposure in base of lowermost sandstone unit (BD5-SDST) resting upon the Brithdir Coal (BDRC-COAL). Succession beneath sandstone, youngest at top, is:

Siltstone, thin bedded	1m
Coal	0.05m
Claystone, dark brownish grey, listric surfaces	0.2m
Coal, smutty with irregular clay partings toward top	>0.55m

The section is cut by a fault trending 030-210 with a throw down to the southeast. The section is faulted against a medium grey, medium- to coarse-grained massive sandstone, 1.5m thick.

Within the overlying argillaceous succession at around the level of the Glyngwylim Coal, the following sections were recorded by the road junction north of Penlle'r Castell:

CNW_4 [266451 209709]

Sandstone, pale greenish brown, fine-grained, locally micaceous with ironstone nodules, medium planar bedded (0.1-0.15m thick), locally with shallow channel scours, gradational base	1.9m
Sandstone, soft, greenish grey, very fine-grained, clayey top, very weathered	c. 1.5m
Siltstone/mudstone, soft, greenish grey, very poorly exposed.	

Plate 7 View of sandstone-dominated succession in upper part of the Brithdir Member at locality CNW_4, north of Penlle'rcastell, with 2m thick sandstone forming prominent hard bed. Looking southeast.

CNW_5 [266481 209756] 6m gap from top of section relative to base of CNW_4

Coal, very weathered and disturbed	0.1m
Seatearth, greyish brown, very rooted, sharp base	0.4m
Mudstone, silty, greenish grey, orange-weathered with common ironstone nodules, finely micaceous, sharp base	2m
Mudstone, black, shaly with very thin coal laminae, sharp base	0.8m
Coal, vitreous, striated, spectral colours	0.25m
Claystone, soft, medium to dark grey, listric surfaces	0.45m
Coal	0.05m
Seatearth, clay, dark brownish grey, abundant roots, gradational base	0.9m
Sandstone, hard, very fine-grained, iron-rich with ironstone nodules at top, gradational base	0.5m
Mudstone, dark grey, orange ferruginous weathering	0.3m
Sandstone, orange weathered, fine-grained, coarsely micaceous, very thin bedded passes eastward to hard, pale brown, medium-grained	

sandstone in c. 0.1m beds with burrows/resting traces on bases, small scours and cross-bedding	c. 2m
Mudstone, dark grey, silty, planar laminated, flaggy, finely micaceous	0.6m

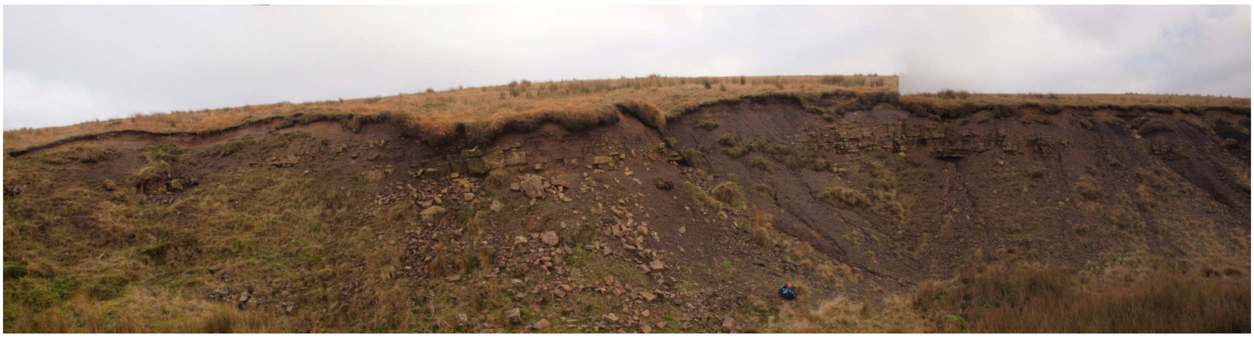

Plate 8 View of mudstone-dominated succession in upper part of the Brithdir Member at locality CNW_5, north of Penlle'r Castell, with 2m thick sandstone forming prominent hard bed. Looking south.

4.1.3.4 Hughes Member (Pennant Sandstone Formation)

The Hughes Member has been mapped at crop within the central part of the study area and everywhere extends beneath younger members of the Pennant Sandstone Formation and the Grovesend Formation in the south of the area (Figure 15). In the southern part of the study area the base of the unit may extend to depths in excess of 0.4 km below OD (e.g. section Ammanford_N_S_9_CNW). During the previous resurvey of the area this unit was mapped as the Hughes Beds (BGS, 1977). The unit was renamed and formally defined as the Hughes Member by Waters et al. (2009). The member comprises green-grey lithic sandstones with thin mudstone/siltstones and seatearths and thin coals (Waters et al., 2009). The base is taken at the base of the Hughes Coal.

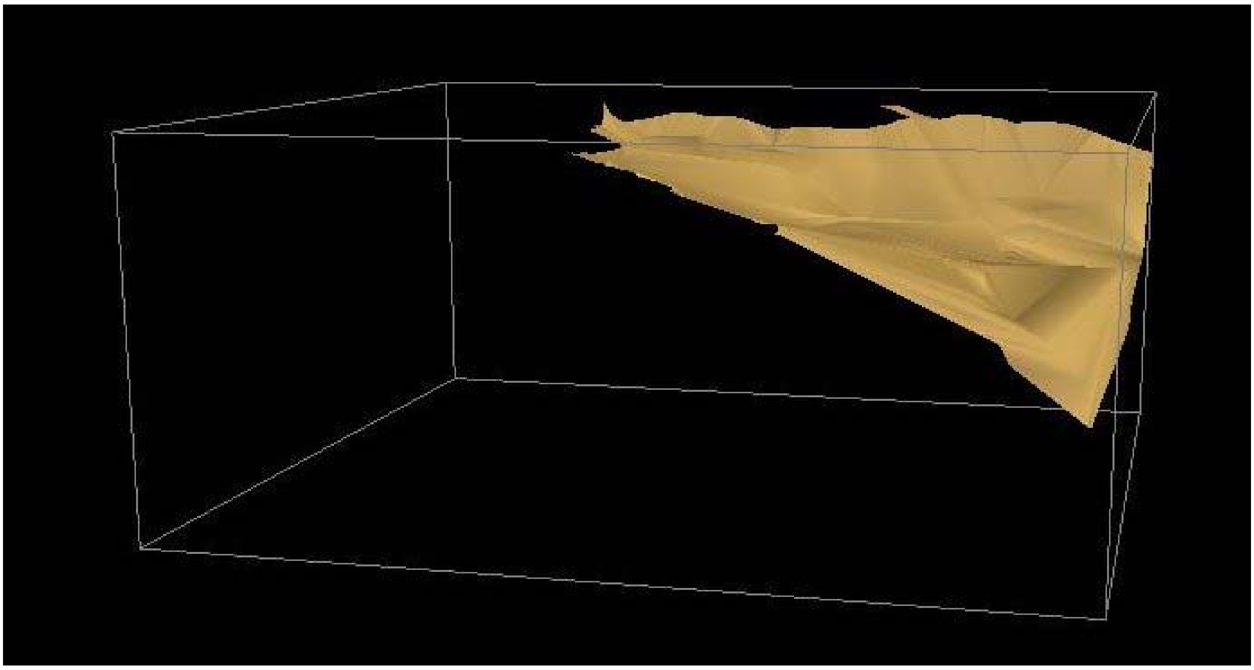

Figure 15 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the for the Hughes Member.Key localities:

The Hughes Coal is inferred to be exposed at the following locality.

CNW_3 [266914 209666]

Mudstone/coal, dark grey, carbonaceous	0.05m
Claystone, soft, medium grey, fissile with abundant plant material including roots and leaf material	0.9m
Coal, soft and very weathered, masked by shale debris	0.4m
Seatearth, claystone, pale grey and orange mottled, abundant roots	0.4m

The basal part of the overlying sandstone of the Hughes Member (H7-SDST) is recorded at:

CNW_15 [263364 208382]

Sandstone, greenish grey, medium- to coarse-grained, carbonaceous laminae, thin planar bedded with cross-lamination and cross-bedding toward top	1.8m
Gap	1.1m
Sandstone, slightly harder, greenish grey, medium-grained, low-angle cross-bedding	0.4m
Sandstone, pale greenish grey, medium- to medium to coarse-grained, thin-bedded with possible low-angle foresets, sharp base	1.0m
Sandstone, greenish brown, medium-grained, thin to medium bedded (up to 0.7m) locally with scoured bases, possibly passing southwards to coal shale	0.4m

The upper part of the H7-SDST is recorded at a dry waterfall at two localities:

CNW_9 [266461 206873]

Sandstone, medium grey, medium-grained, planar bedded (0.1m beds) passing down to greenish grey, coarse-grained sandstone with plant stems	3m
Sandstone, hard, medium grey, fine- to medium-grained, thickly cross-bedded, with micaceous and carbonaceous foresets, sharp base	1.5m
Siltstone, medium grey with some orange mottling, poorly exposed	1.7m

and CNW_8 [266373 206696]

Sandstone, medium grey, medium-grained, micaceous toward top, cross-bedded with troughs up to 0.3m thick at top	c. 6m

Above the H7-SDST is a dominantly argillaceous succession in which several coals are recorded. The lowermost part of the succession can include up to 5 thin seams, unnamed on the published map SN60NE. Two seams were exposed during the current survey. The lowermost coal, seen at **CNW_12** [267022 206874], is not shown at this position on the published map, being inferred at a higher level:

Coal, soft, very weathered	0.1m

Seatearth, clay, medium grey and ochreous mottled with roots and coaly films	0.65m
Siltstone, medium greenish grey with dark carbonaceous roots	0.2m

About 10m up the slope is the following composite section at **CNW_13** [267038 206793] and **CNW_14** [266967 206796], with various coal leaves considered to be the Cille No.1 Coal:

Clay, orange-weathered and fragmented; very weathered mudstone	0.9m
Coal, very weathered, fissile in 3 leaves, sharp base with clay partings, locally pipes down into seatearth	0.3m
Seatclay, pale brown to pale grey, very weathered	0.8m
Mudstone, dark grey, shaly with ironstone nodules	0.6m
Coal	0.03m
Clay, orange-brown, some roots	0.2m
Coal	0.12m
Clay, orange-brown	0.1m
Gap, metre-scale	
Siltstone, greenish grey with root traces, gradational base	0.6m
Sandstone, medium greenish grey, very fine-grained, very thinly planar laminated, becoming siltier towards the base and top, cross-laminated toward top	2.2m

The uppermost part of the mapped argillaceous succession does include unmapped sandstones, such as in the roadside exposure at **CNW_10** [267181 206422]:

Sandstone, pale greenish grey, very fine-grained passing to siltstone, thin bedded with distinct harder beds up to 5cm thick with sharp bases, common ironstone nodules; some lenticular bedding, small scours and small-scale cross-lamination	1.8m

4.1.3.5 SWANSEA MEMBER (PENNANT SANDSTONE FORMATION)

The Swansea Member has been mapped at crop within the southern part of the study area and locally extends beneath the Grovesend Formation in the extreme south of the area (Figure 15). In the southwestern part of the study area (west of the Wallis Fault) the base of the unit may extend to depths in excess of 150 m below OD (e.g. section Ammanford_W_E_6_CNW). During the previous resurvey of the area this unit was mapped as the Swansea Beds (BGS, 1977). The unit was renamed and formally defined as the Swansea Member by Waters et al. (2009). The member comprises green-grey lithic sandstones with thin mudstone/siltstones and seatearths and thin coals (Waters et al. 2009). The base is taken at the base of the Graicola Coal, which is extensively worked by lines of shallow excavations east of Upper Lliw Reservoir.

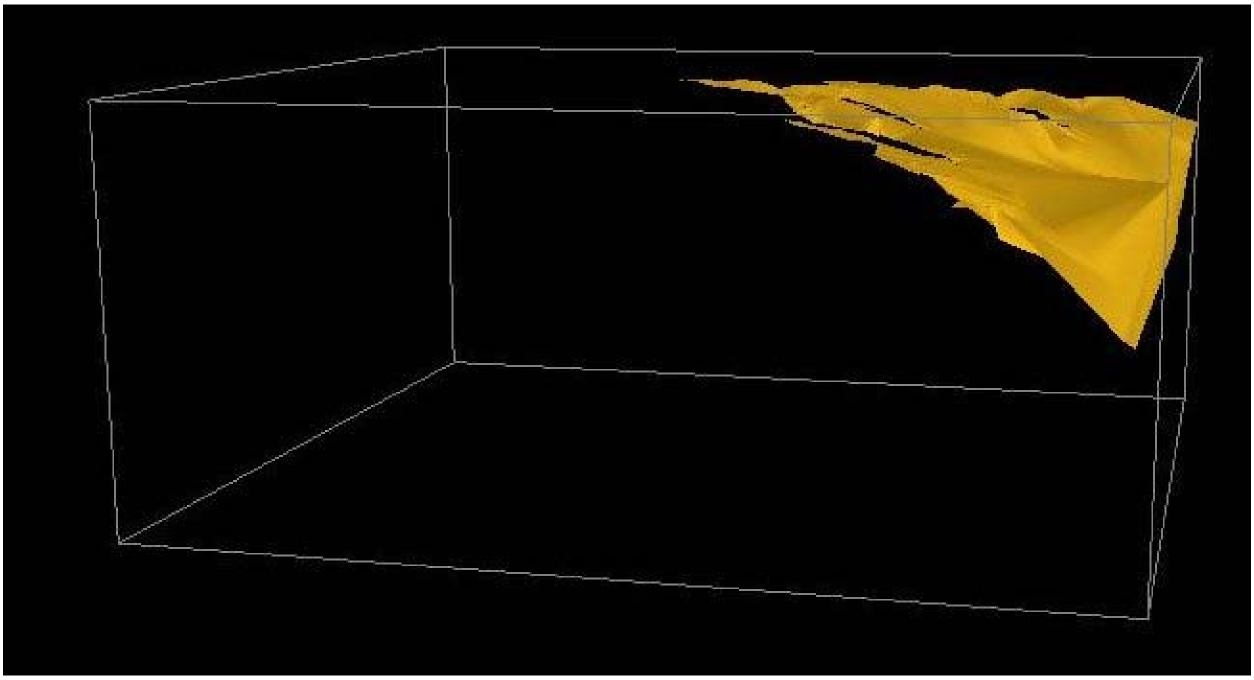

Figure 16 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the for the Swansea Member.

Key localities:

The basal sandstone of the member SW5-SDST forms an extensive dip slope on Tor Clawdd. The basal part of the sandstone is exposed above Graicola Coal workings at:

CNW_6 [266920 206497] above possible adit

Sandstone, pale to medium grey, medium-grained, carbonaceous surfaces, thinly planar bedded with sets of tabular cross-beds up to 0.1m	2.5m

CNW_7 [266635 206182] adit and sandstone section visible:

Sandstone, medium grey, orange-weathered, fine- to medium-grained, locally micaceous and carbonaceous, flaggy, low-angle foresets in sets up to 0.45m with scours up to 0.1m cross-bedded with troughs up to 0.3m thick at top	1.4m

Plate 9 a) view of shaft in uppermost part of Hughes Member at the level of the Graicola Coal; b) cross-bedded sandstone. Locality CNW_7, east of Upper Lliw Reservoir.

The same basal sandstone of the Swansea Member (SW5-SDST) is exposed along the gorge of the Lower Clydach River, north of Clydach.

CNW_21 [268168 202664 to 268056 202665], path side exposure:

Sandstone, medium grey, fine-grained, carbonaceous and micaceous, cross-laminated, beds with rippled tops, thin to medium planar bedded c.6m

Sandstone, medium grey, medium-grained, thick bedded c.4m

Sandstone (not accessible), very thinly planar bedded, thins and fails westward 0-c.1m

Sandstone, medium greenish grey, ochreous-weathered, medium-grained, medium planar bedded in 0.3m-thick beds, small mudstone lithoclasts, base not seen 3.2m

Short gap, obscured by wall

Siltstone, medium grey, very thinly planar laminated, very thin bedded, micaceous and carbonaceous c.4m.

Plate 10 View of the upper 10m of a section of the Swansea Member basal sandstone along the gorge of the Lower Clydach River, north of Clydach (CNW_21), looking west. Bed thickness decreases upwards.

Further to the north, within the same valley, this basal sandstone is also exposed at Pen y ban as a partly worked natural crag.

CNW_23 [267852 205834]:

Sandstone, pale buff, fine-grained, very micaceous, very thin to medium planar bedded, cross-bedded, sharp base c.4.5m

Sandstone, ochreous, fine- to medium-grained, carbonaceous and micaceous laminae, low-angle cross-bedding 0.75m

Sandstone, ochreous-weathered, medium-grained, massive with spheroidal weathering 0.6m

Sandstone, pale grey, medium-grained, cross-bedded, sharp base 0.8m

Sandstone, pale to medium grey, fine- to medium-grained, abundant carbonaceous debris on bed bases, medium and thick planar beds up to 0.4m thick 2.4m

Plate 11 View of the basal sandstone of the Swansea Member, Cwm Clydach (CNW_23), looking north.

The basal sandstone (SW5-SDST in model) is also exposed in a disused railway cutting near Pontarddulais, with a more argillaceous component observed at CNW_42 [260412 203662]:

Siltstone, dark grey, finely micaceous, very thinly planar bedded passing down gradationally to medium to dark, very thinly laminated, trough cross-bedded siltstone with sharp planar base ~2.5m

Sandstone, medium greenish grey, fine-grained, carbonaceous and micaceous 1.4m

In Afon Lliw, north of the Lower Lliw Reservoir, a significant thickness of the Swansea Member is exposed in a series of exposures. The basal sandstone above the Graicola Coal (SW5-SDST in model) is exposed in CNW_38, 39 and 40 and overlying sandstone above the Swansea Five Feet Coal in CNW_26 and 27 (SW3-SDST in model).

CNW_40 [265524 205199]: Basal part of lower sandstone

Sandstone, dark grey, fine-grained, micaceous, very carbonaceous, very thin planar bedding and planar lamination, with some low-angle cross-bed foresets, sharp base 4m

Beneath the overhang at the base of the section is debris of coal and sandstone.

Plate 12 View to south of basal sandstone of the Swansea Member immediately above Graicola Coal, Afon Lliw (CNW_40); hammer head marks base of sandstone with marked overhang possibly representing position of the Graicola Coal.

CNW_38 [265497 205141]: Darren Serth quarry- Lower sandstone above section in CNW_40 in lower quarry level

Sandstone, orange-weathered, dark grey, fine-grained, carbonaceous, very thick bedded, upward thinning, sharp channelled base 3−4m

Sandstone, medium grey, medium-grained, with carbonaceous debris and ironstone clasts, cross-bedded, sharp base 1−3m

Sandstone balls, very fine-grained, carbonaceous with oval ironstone pebbles and log impressions, with some mud and coal around the balls, in a matrix of dark grey, fine- to medium-grained, contorted sandstone with carbonaceous layers 0−1.4m

Sandstone, medium greenish grey, medium-grained, low-angle trough cross-bedding, upward thinning sets, sharp base 2−3m

Sandstone, medium grey, fine- to medium-grained, medium to thick planar bedded, upward thinning (0.2−0.45m thick), sharp channelled base 0.85m

Plate 13 View to east of lower sandstone of the Swansea Member in Darren Serth quarry (CNW_38); right hand of scale marking level of sandstone balls (detailed view below).

Plate 14 Details of sandstone ball structures in section CNW_38, Darren Serth quarry.

CNW_39 [265500 205130]: Lower sandstone above section in CNW_38 in upper level, Darren Serth quarry.

Sandstone, medium grey, fine- to medium-grained, very thick bedded, very few ironstone clasts near base 8m

Sandstone, soft, medium grey, medium- to coarse-grained, coaly with abundant ochreous ironstone clasts, sharp grooved base 0−1m

Sandstone, medium grey, fine-grained, carbonaceous and micaceous laminae, thin bedded, locally with shallow scours and cross-bedding ~4m

Plate 15 View to north of lower sandstone of the Swansea Member in upper part of Darren Serth quarry (CNW_39). Detail of shallow scour and cross-bedding, with abundant pebbles of ochreous ironstone.

CNW_26 [265481 204578]: Stream section above Lower Lliw Reservoir, in upper sandstone above section in CNW_27.

Sandstone, medium greenish grey, fine- and fine- to medium-grained, thickly cross-bedded 3−5m

Sandstone, very hard, medium greenish grey, fine-grained, thick to very thick bedded, upward thinning, lowermost bed 1.4m thick 2.4m

Gap ~3m

Sandstone, pale greenish grey, medium-grained, micaceous and carbonaceous films, medium planar bedded 1.7m

Gap ~1m

Sandstone, medium to dark greenish grey, fine- to medium-grained, coarsely micaceous, medium bedded ~1m

Gap ~1m

Sandstone, medium greenish grey, medium-grained, carbonaceous, thin bedded, sharp base 0.7m

Sandstone, very hard, pale greenish grey, fine-grained, single massive bed 0.6m

CNW_27 [265434 204575]: Stream section above Lower Lliw Reservoir, in upper sandstone continuation below in CNW_26, occupying a small syncline.

Sandstone, pale pinkish grey, fine- and fine- to medium-grained, thinly planar bedded 0.8m

Gap ~4m

Sandstone, medium grey, medium-grained, feldspathic, coal clasts, thin to thick planar bedded 1.8m

Gap 1.2m

Sandstone, medium greenish grey, fine- to medium-grained, thin to thick planar bedded 1.4m

Gap ~1m

Sandstone, medium greenish grey, pinkish weathered, fine- to medium-grained, thin bedded ~5m

The sandstone above the Swansea Five Feet Coal (SW3-SDST in model) is also observed in two small sections on Bryn-bach Common.

CNW_24 [261735 203406]:

Sandstone, pale grey, medium-grained, feldspathic, thick bedded, sharp base ~4m

Sandstone, medium greenish grey, medium-grained, thin to thick bedded, finer and more micaceous at top, planar and lenticular bedded 1.4m

CNW_25 [261774 203447]:

Sandstone, greenish grey, medium- and medium- to coarse-grained, feldspathic with ironstone clasts, tabular cross-bedded 1.6m

Sandstone, medium- and medium- to coarse-grained, thinly planar bedded with low-angle foresets and troughs, beds up to 0.15m thick 1.0m

4.1.3.6 Grovesend Formation

The Grovesend Formation has been mapped at crop within the extreme south-western part of the study area and is only present on the southern part of the following sections: Ammanford_N_S_5_CNW, Ammanford_N_S_8_CNW, Ammanford_N_S_11_CNW and western part of Ammanford_W_E_6_CNW. It does not extend below sea level within the study area (Figure 17). During the previous resurvey of the area this unit was mapped as the Grovesend Beds (BGS, 1977). The unit was renamed and formally defined as the Grovesend Formation by Waters et al. (2009). In contrast with the underlying Pennant Sandstone Formation, the Grovesend Formation comprises mainly mudstones and siltstones with coals, typically thinner than in the Pennant Sandstone Formation. Lithic sandstones are subordinate, but locally thick. The base is taken at the base of the Swansea Four Feet Coal.

The mudstone-dominated succession forms comparatively low ground with few exposures and no section was observed during this study.

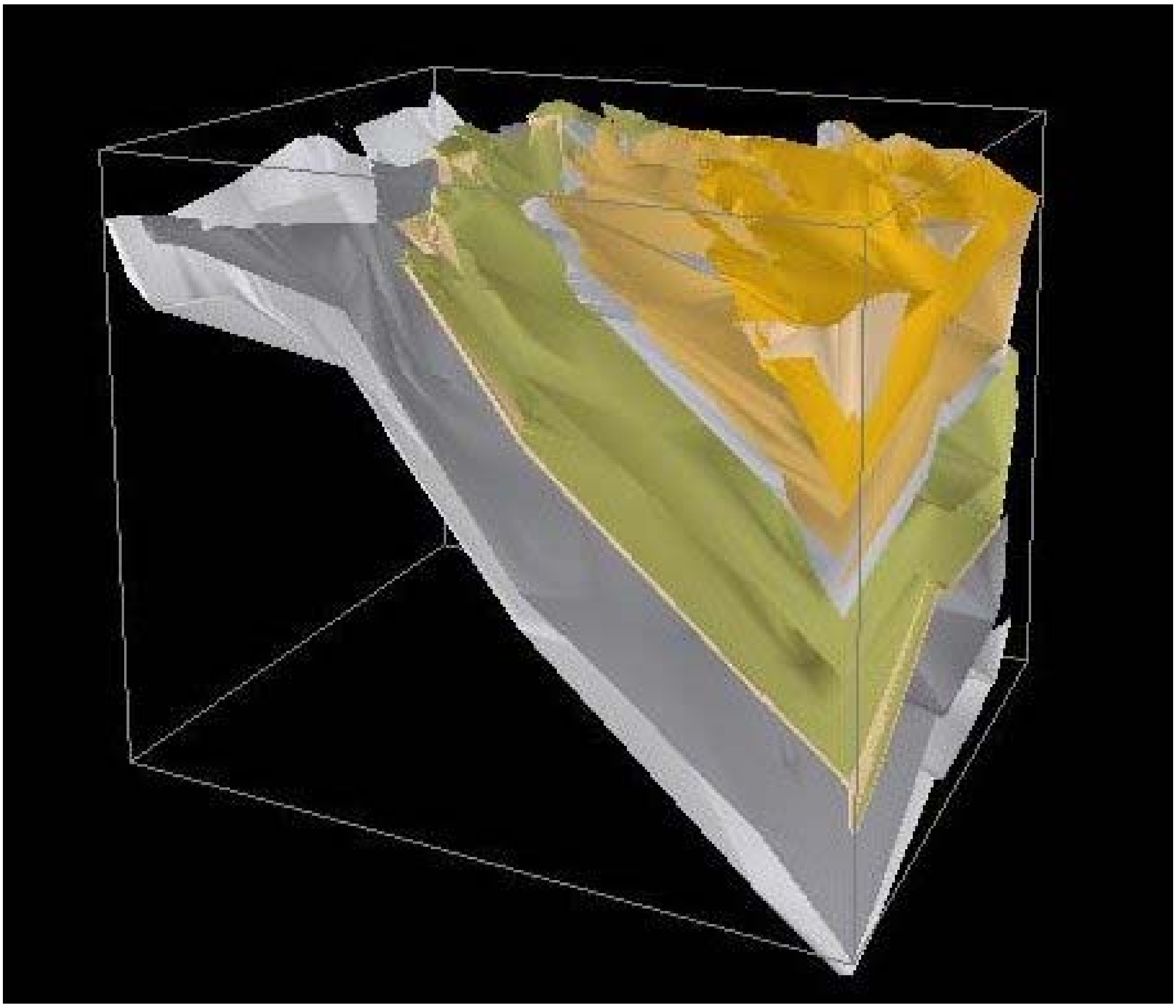

Figure 17 View of Ammanford 1:50 000 resolution GSI3D model, looking ENE, showing the modelled base for the for all units shown in figures 9-16, with Grovesend Formation at top of succession.

4.2 STRUCTURE

The Carboniferous strata in the study area dip southwards (Figure 6b), consistent with a position on the northern limb of the South Wales Coalfield syncline. Dips in the north of the study area are typically steeper and more variable (e.g., Ammanford_N_S_8_CNW), commonly from 10 to 27 degrees to the S or SSE, but tightly folded in proximity to a series of "disturbances" described below. In the south dips are typically between 3 and 10 degrees to the SSE or SE, though locally are steeper in proximity to the NNW-trending set of faults.

The fault network constructed for the model is illustrated in section 3.3 and Figure 7. The dominant pattern is of a series of NNW-trending normal faults with throws down to the west. The location of these faults, where they cut sandstones of the Pennant Sandstone Formation, are typically well-constrained through feature mapping and observed offsets in sandstone features, e.g. Plate 16. Locally, the fault positions are also constrained at depth where they have been recorded in coal workings, the position being recorded on the published geological maps. It is then possible to estimate the dip of faults between their position at crop and in the coal seam. For example workings in the Graicola Coal show that the Bettws Fault, in the southern part of the study area [~264 204] dips about 57 degrees to the west with a throw down to the west of about 15m. The Gardeners Fault at about [268 207] has a dip of about 68 degrees to the west. The Ty Llwyd Fault is dipping about 51 degrees to the west around [268 212] and throw down to the west of about 100m, based upon workings in the Pumpquart Coal. An example of an unnamed NNW-trending fault was seen at locality CNW_46 (Plate 17). Note that the sandstone strata in the footwall are undisturbed, whereas the mudstone in the hangingwall is steeply dipping and fractured.

Plate 16 View to northeast of features in the Llynfi and Rhondda members (middle distance) truncated by a NNW-trending fault evident at locality (CNW_46), evident in hollow in centre-right of image, with Rhondda Member strata present in the foreground and right).

Plate 17 View to north of NNW-trending fault at locality (CNW_46) with basal sandstone of the Rhondda Member (equivalent to RA7-SDST in model) in footwall (right) and younger mudstone of the Rhondda Member (RA5-MDSS in model) in the hangingwall (left). Detail of steeply dipping weathered mudstone present just beneath regolith.

A further set of structures, recognised only in strata of the South Wales Coal Measures Group in the northwest of the study area, have a broad ENE−WSW trend. They include, ordered from north to south, the Glyn-hir crush belt, the Caerbryn disturbance, the Saron disturbance and Pontyclerc disturbance. The nature of these "disturbances" is somewhat uncertain, other than they reflect broad zones of fracturing and folding, much more complex than is denoted by the position of a single fault on the published maps. No exposures of the disturbances were seen during the study. They probably include low-angle reverse fault zones of uncertain orientation. However, where unnamed faults of this trend are proved in coal works, the faults have a low dip to the south, e.g. in the Pumpquart Coal around [260 214], which dips about 25 degrees to the south. This would be consistent with the observation of South Wales Lower Coal Measures to the south of the Pontyclerc Disturbance at locality CNW_58, in what is interpreted as the hangingwall, thrust above South Wales Middle Coal Measures in the footwall to the north. The disturbances are shown truncating the NNW-trending faults, suggesting that the former post-date the latter.

5 Confidence in the Ammanford 50k Resolution Model

In this section the issue of confidence, both generically, and in the context of the Ammanford 50k Resolution Model produced during this study, will be discussed. It will cover factors such as the accuracy of the geological map data and provide a qualitative description of the confidence of the model based on the availability and types of data.

5.1 OVERVIEW

Three-dimensional geological models are produced, in general, by geologists applying expert judgment to interpret available data. This makes the assessment of uncertainty in the resulting models less straightforward than for comparable spatial information produced by purely statistical prediction. Modellers make judgments about the relative quality of different types of available data and the extent to which simple trends in the units of interest (e.g. a gentle dip) allow their structure to be extrapolated with confidence away from observations. Confidence decays with increasing distance from a hard observation, such as a field exposure, an interpreted borehole, or a "softer" observation such as a geophysical measurement.

The qualitative approach provides an appraisal of the extent, amount and quality of the data used to constrain the boundaries presented within the model. When constructing the 3D geological model in such a coalfield area, the geologist uses a combination of surface geological map data (see Section 2.3), projected to depth, borehole records (see Section 2.2) and surfaces derived from mining data displayed on the published geological maps.

In this project, models based on expert interpretation are used, aided by computer software, so direct statistical measures of uncertainty are not available.

5.2 QUALITATIVE ASSESSMENT OF CONFIDENCE IN THE AMMANFORD 50K FENCE DIAGRAM

The study area can be subdivided into three domains, marked by different levels in the confidence of the interpretation of the geological model through factors such as availability of deep borehole data, surface exposure and the complexity of the structure within the bedrock geology. An important factor is the extent to which the bedrock at surface is obscured by Superficial Deposits. The extent and nature of these deposits is shown in Figure 18. These domains are discussed separately below.

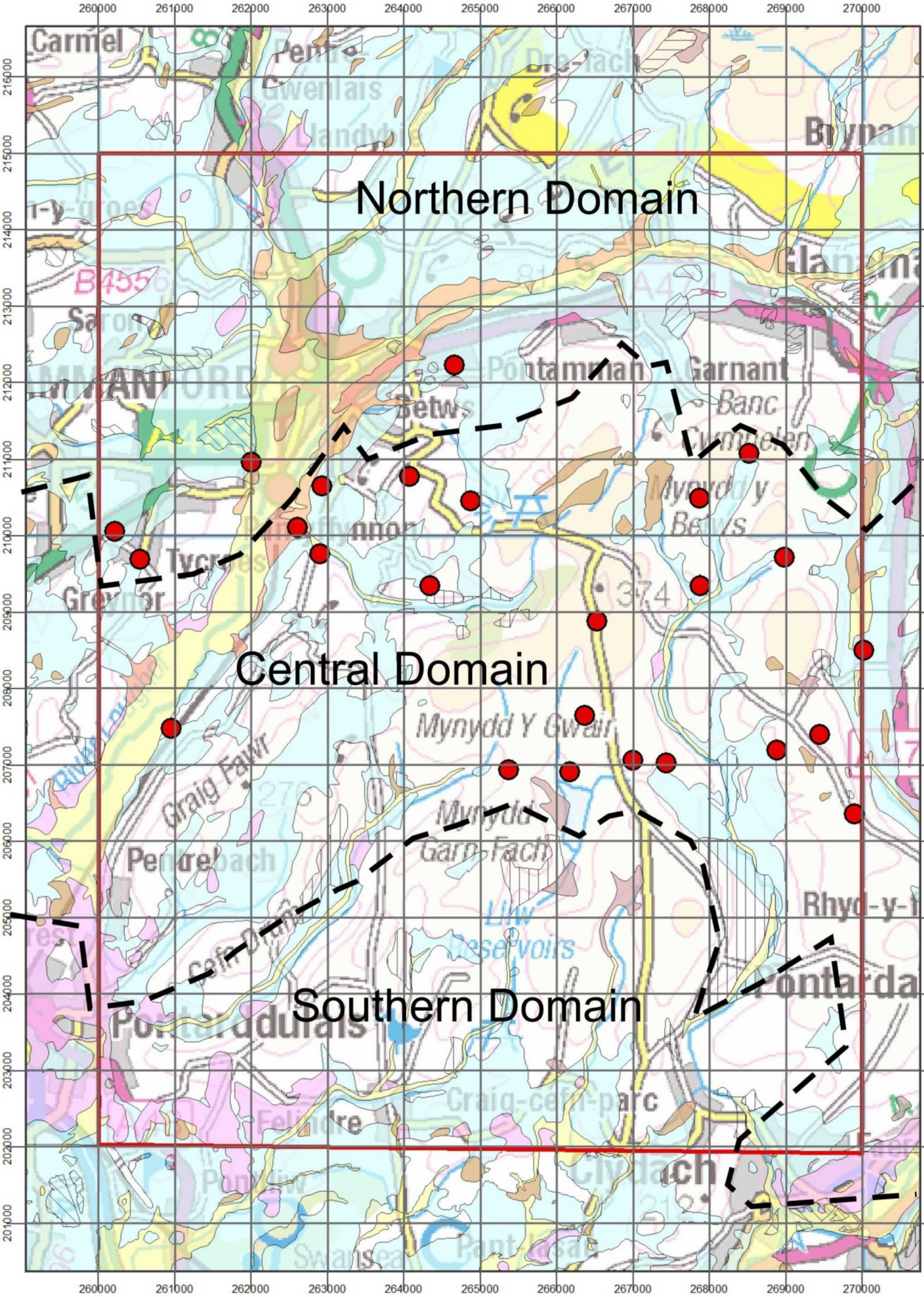

Figure 18. Geological map of the Superficial Deposits present at the ground surface across the study area, showing natural and artificial deposits and areas of landslide. The map is sourced from BGS v5 DiGMapGB datasets.

5.2.1 Domain 1: Northern area

This area broadly coincides with the area of outcrop of the South Wales Coal Measures and Marros groups. Interpretation into the subsurface is largely based upon surface crop of geological units and projection of units based upon dip and some structural contour data for certain coal seams. There are few sandstones in this interval and as such the domain is poorly featured, which limits the ability to infer the structure. There are only four deep boreholes in this domain (Figure 3) to base the thickness and depths of units. There is also a poorly constrained surface geology with few natural exposures of the bedrock. The bedrock is extensively obscured by superficial deposits and consequently the position of coal seams in particular is conjectural in many cases. There is also a complex deformation including tight folding and development of low-angle thrusts which cannot be adequately modelled in the fence-diagram. Uncertainty in the regional dip hinders prediction of where coals are present at crop, if unproven, but also limits the extent boundaries can be projected to any depth. These all lead to there being significant uncertainty in the distribution of boundaries at depth within this domain.

5.2.2 Domain 2: Central area

This domain broadly coincides with the area of crop of the Pennant Sandstone Formation, excluding the uppermost Swansea Member. Interpretation of the subsurface lithostratigraphical boundaries is based upon mainly well constrained surface bedrock geology, with common exposure of sandstones and the position of coals commonly evident from surface workings. The domain has a marked topography in which the sandstones form marked scarp and dip slopes; features that permit accurate recognition of the boundaries and position of faults. The bedrock is, structurally simple with relatively constant dips and no thrusting. The domain is associated with little cover by superficial deposits (Figure 18). There is good coverage of deep borehole data (21 in total), although comparatively few of these are in the west of the study area (Figure 3). Some structural contour data for certain coal seams is shown on published geological maps. In summary, the extrapolation of units to depth is well constrained in this domain.

5.2.3 Domain 3: Southern area

This domain broadly coincides with the area of outcrop of the Swansea Member and Grovesend Formation. Interpretation of the subsurface geology is here based upon mainly surface geology observations, largely mapped as a series of long dip slopes, and the surface units only project to shallow depths. There is little cover by superficial deposits (Figure 18) to obscure the nature of the bedrock geology. The succession is structurally simple with relatively constant dips and no thrusting. However, there are few boreholes to help constrain the distribution of units at depth. In summary, the subsurface distribution of units in this domain is moderately well constrained at shallow levels but is increasingly uncertain with depth.

5.3 UNCERTAINTY BASED UPON SURFACE DATA

This section describes the process by which uncertainty in an area where the 3D model is largely constrained from surface data, as is the case in the northern and southern parts of the study area. This section introduces the concepts of accuracy of the geological map data, including the types of geological boundaries, the precision of field capture of boundaries and subsequent reduction in that precision in response to rescaling the data. Where subsurface structure is inferred by projection from surface observations, in this study we identify three principal sources of uncertainty:

- The degree of exposure of surface structure;
- The heterogeneity of the dip direction (azimuth) observed at the surface, where this is small the surface observations provide consistent information which the modeller may use to infer subsurface information; and

- The heterogeneity of the dip angle (magnitude) itself.

The study proposes possible methodologies for quantifying confidence in the surface data described above. We do not attempt to quantify these uncertainties in this study.

5.3.1 Accuracy of geological map data

Geological mapping is based on the evidence and data available at the time of survey and in particular the experience of the surveyor and his knowledge of the survey area. Whereas all maps are representations, geological maps are often also largely interpretations (Smith, 2009).

Four main factors determine the overall positional 'accuracy' or reliability of geological map data, representing a combination of geological and cartographic factors (Smith, 2009). These are described in turn below.

5.3.1.1 OBSERVED BOUNDARIES

Observed boundaries between bedrock units are used where the contact is visible at outcrop and there is no doubt about its position. However, a junction that is not directly visible may have been regarded as 'observed' by one geologist (because of a distinct and sharp change of slope) whilst another would have regarded it as 'inferred' (because the rock junction was covered by grass and soil).

Even where a lithostratigraphical boundary is observed, uncertainty may result through the definition of geological units and differences in their understanding and recognition. Geological boundaries are defined in various ways, though are shown using the same linestyle on the geological map. Some are closely constrained as sharp planar boundaries. Others may have sharp non-planar (or irregular) boundaries and although the boundary is easily recognisable, it may not be possible to map the irregularities at 1:10 000-scale and the map will be a simplification. A further category is gradational boundaries. The base of the unit may be defined, somewhat arbitrarily, as the bottom of the first bed of a specific lithology, or by the change from being dominantly one lithology to being dominantly another; in some cases one lithology attaining a specific percentage within another may be used to define the boundary. The mapped geological line here is again an approximation and represents a zone of poorly defined width within which one unit passes into another.

Definitions may change with time and place and the historical practice of BGS mapping distinct 1:50 000-scale tiles may result in different areas using distinct definitions for the same unit, or use completely different means to subdivide the succession into groups, formations and members. Furthermore, different geologists may have different understandings of what has been mapped previously, what they have mapped, and how the boundaries were recognised in practice.

5.3.1.2 INFERRED BOUNDARIES

Inferred boundaries are less reliable and regarded as approximate. They are used in areas where surface exposure is absent or uncommon because of soil cover, extensive vegetation or urban development. Geological maps, nevertheless have to be complete and so will represent interpretations based on a limited amount of direct observation combined with other available data. Without direct observation of geological boundaries, the geologist will rely upon inferring the position of a boundary, using criteria such as landform geometry, changes in soil, vegetation or drainage and loose fragments of bedrock (brash) present on a slope. The geologist can also use trigonometrical projection of boundaries based upon known dips and thicknesses of geological units, but such techniques may have a high level of uncertainty. An additional category of conjectural boundaries is sometimes used on BGS maps, particularly where the bedrock geology is obscured by thick superficial deposits. These are the least reliable boundaries and may in part be little more than educated guesses.

5.3.1.3 CAPTURE OF GEOLOGICAL LINEWORK

There are aspects of ‘precision’ which indicate how precisely the data have been created in a technical or absolute sense. There is the precision by which the geological boundary has been captured by the geologist. GPS provides an accuracy of 5 to 10 m. However, GPS has only been used routinely during fieldwork since 2000 and many of the map sheets covering the study area were surveyed prior to that date. In many cases, traditional surveying techniques would allow accuracies of about 10 m (1 mm on a 1:10 000-scale map). However, in open moorland or mountain areas or woods, where there may be sparse cultural information to allow precise location, the errors may be greater. In the study area, the geological survey was carried out during the period 1957−64 on a 1:10,560 field base map, but with a National Grid scale permitting accurate transfer of map data. During the field visits carried out during this study GPS was used, but apparent

The digital 1:50 000 data used in this study were obtained by digitising older published 1:50 000 sheets and these may not be a fully accurate copy of the detail shown on the printed map, as errors may have been introduced during the digitisation process. The specification for the digitisation of the analogue geological linework required that the digital lines did not deviate from the centre of the mapped line by more than 0.2 mm. This is equivalent to 10 m on the ground at a scale of 1:50 000. ‘Precision’ factors also apply to the Ordnance Survey topographical base map, and may relate for example to the scale and type of surveying.

5.3.1.4 SCALING FACTORS

Cartographic aspects of map-making include the selections, representations and generalisations made in producing maps at progressively smaller scales with decreasing detail. The Ammanford 50K resolution model output from this study is produced at 1:50 000-scale and utilises surface map data acquired from DiGMapGB at this same scale. The 1:10 000-scale data that BGS collects during surveying and which represents the fundamental geological map dataset, is too complex for this scale of modelling.

The compilation of geological maps onto 1:50 000 scale maps can lead to an error of +/- 50 m on the ground; 1.0 mm either side of a line on the map (Smith, 2009). This is partly as a result of the generalisation of the geological lines mapped at a scale of 1:10 000 (or 1:10 560), to fit the 1:50 000 (or earlier 1:63 360) topographical maps. In some parts of the study area, it is also partly because of the errors in conversion from the projection systems used on the earlier County Series maps to the British National Grid.

In summary, geological maps should not be regarded as depictions of fact and taking expert advice on the reliability of the map from either the original surveyor or a similarly experienced individual is highly desirable.

5.3.2 Quantifying the amount of bedrock at crop

The greater cover of superficial deposits greatly obscures the certainty of the position of bedrock boundaries at crop.

In order to assess the percentage outcrop of bedrock across the study area it is necessary to use DigMap50k to identify the distribution of successions that obscure the bedrock (Figure 22). These deposits include: a) natural superficial deposits; b) landslide deposits; c) artificial deposits.

6 Conclusions

6.1 OBJECTIVES AND BACKGROUND

The methodology documented in this report provides a robust, generic and replicable method that could be applied widely across the UK in areas of complex coalfields.

The objectives of this study were:

- To test and document a generic methodology for producing a 3D Geological Framework Model of a complex coalfield area; and
- Model the depths coal seams which may have importance as potential sources of energy through non-conventional extraction processes.

A 1:50 000 resolution 3D geological framework model was successfully constructed for the study area using the Geological Surveying and Investigation in 3D (GSI3D) package, developed partly in house at BGS, which can be used more readily by geologists to construct a series of cross-sections that can more clearly display the geological succession.

6.2 METHODOLOGY FOR BUILDING A MODEL

The 3D geological model was constructed in GSI3D, to develop a robust model that incorporates surface and subsurface data. This approach uses the strengths of this software package as a communication tool to aid visualisation of the geology in the form of simple cross-sections.

Appendix 1 Abbreviations commonly used in report

50k	1:50 000-scale or –resolution
BGS	British Geological Survey
BOD	Below Ordnance Datum
DiGMapGB	Digital Geological Map of Great Britain
DTM	Digital Terrain Model
GB3D	3D geological model for Great Britain
GSI3D	Geological Surveying and Investigation in 3D
K	Thousand
NGM	National Geological Model

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