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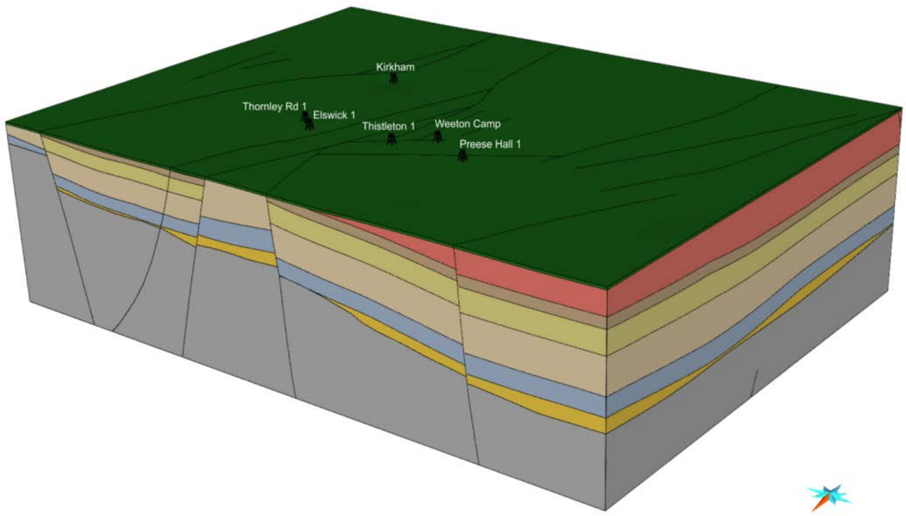
Groundwater Programme

Open Report OR/16/007



BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME

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A 3D geological model of post Carboniferous strata in the south Fylde area of the West Lancashire Basin, Blackpool, UK

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Foreword

The British Geological Survey (BGS), together with a number of partners is undertaking an independent environmental monitoring programme to characterise baseline conditions in the south Fylde east of Blackpool in an area proposed for shale-gas exploration and production. The monitoring will include measurement of: water quality (groundwater and surface water), seismicity, ground motion, air quality including radon, and soil gas. The programme aims to establish the environmental baseline before any shale-gas explorations begin.

This report presents the results of a desk study to develop an initial summary of the post-Carboniferous bedrock geology of the south Fylde. It is a component and specific deliverable of the environmental baseline project. The bedrock deposits form a number of shallow aquifers that are used locally for drinking water supply and agriculture. A separate report considers the superficial geology.

The geological information in this report will form the basis for identifying aquifer dimensions and configurations, groundwater flow paths and potential contaminant migration pathways, as well as determining optimum locations for sampling and monitoring. It will also provide information to support the locating of new borehole infrastructure (suitable for groundwater sampling and seismometers) and will underpin the interpretation of acquired hydrogeochemical data.

1 Introduction

1.1 GEOGRAPHICAL AND STRATIGRAPHICAL LIMITS OF THE MODEL

This report summarises the location, input data and methods used to produce a three-dimensional (3D) geological model of the south Fylde in Lancashire, England. The geological modelling exercise was undertaken in 5 days, with the bulk of this time being used in the compilation and organisation of input data. The model and any geological conclusions based upon it should therefore be regarded as preliminary and liable to change as additional work is undertaken and the model is refined or expanded geographically or stratigraphically.

The geographical extent of the geological model is covered by a rectangle approximately 20x14 km covering an area of 280 km^2 to the east of Blackpool between the River Ribble and the River Wyre (Figure 1). The boundaries of the area were set to provide a reasonable buffer around the main area of interest which falls between Kirkham and Elswick, in the vicinity of the Elswick gas field (DECC, 2013). Throughout the report the area indicated by the red rectangle in Figure 1 is referenced as the south Fylde.

The geological units included in the model only include those of Permian and Triassic age which rest unconformably on the Carboniferous. Superficial deposits of the south Fylde were not investigated beyond establishing a rockhead surface for the bedrock geological model, further information on the Quaternary geology of the south Fylde can be found in Ford (2016).

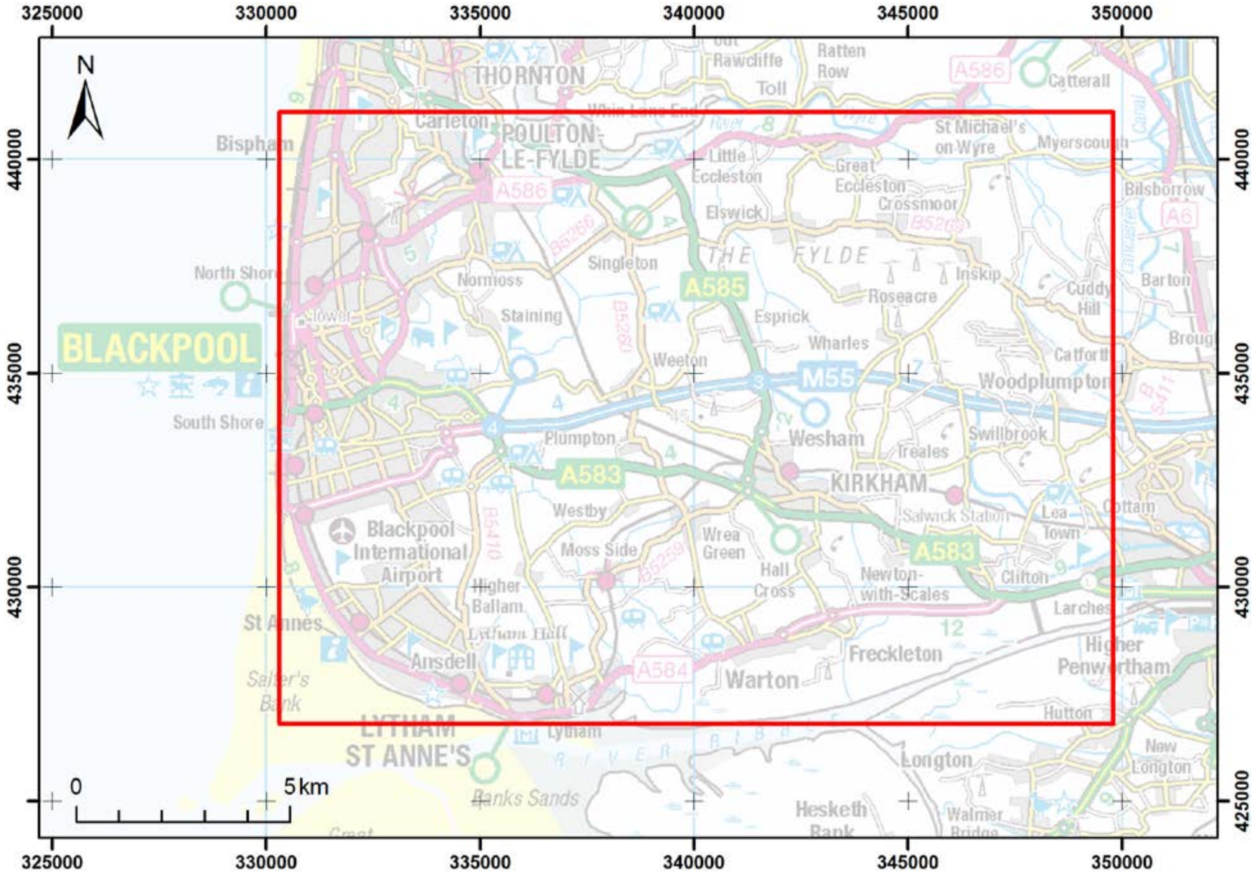

Figure 1 Boundary of the model shown by red rectangle

1.2 TOPOGRAPHY AND ROCKHEAD ELEVATION

The elevation of the south Fylde ranges from 0-47 mAOD with a mean of 14 mAOD (Figure 2). A low arcuate west-east trending ridge extends from the coastline through Kirkham and separates the valleys occupied by the rivers and estuaries of the Wyre and Ribble.

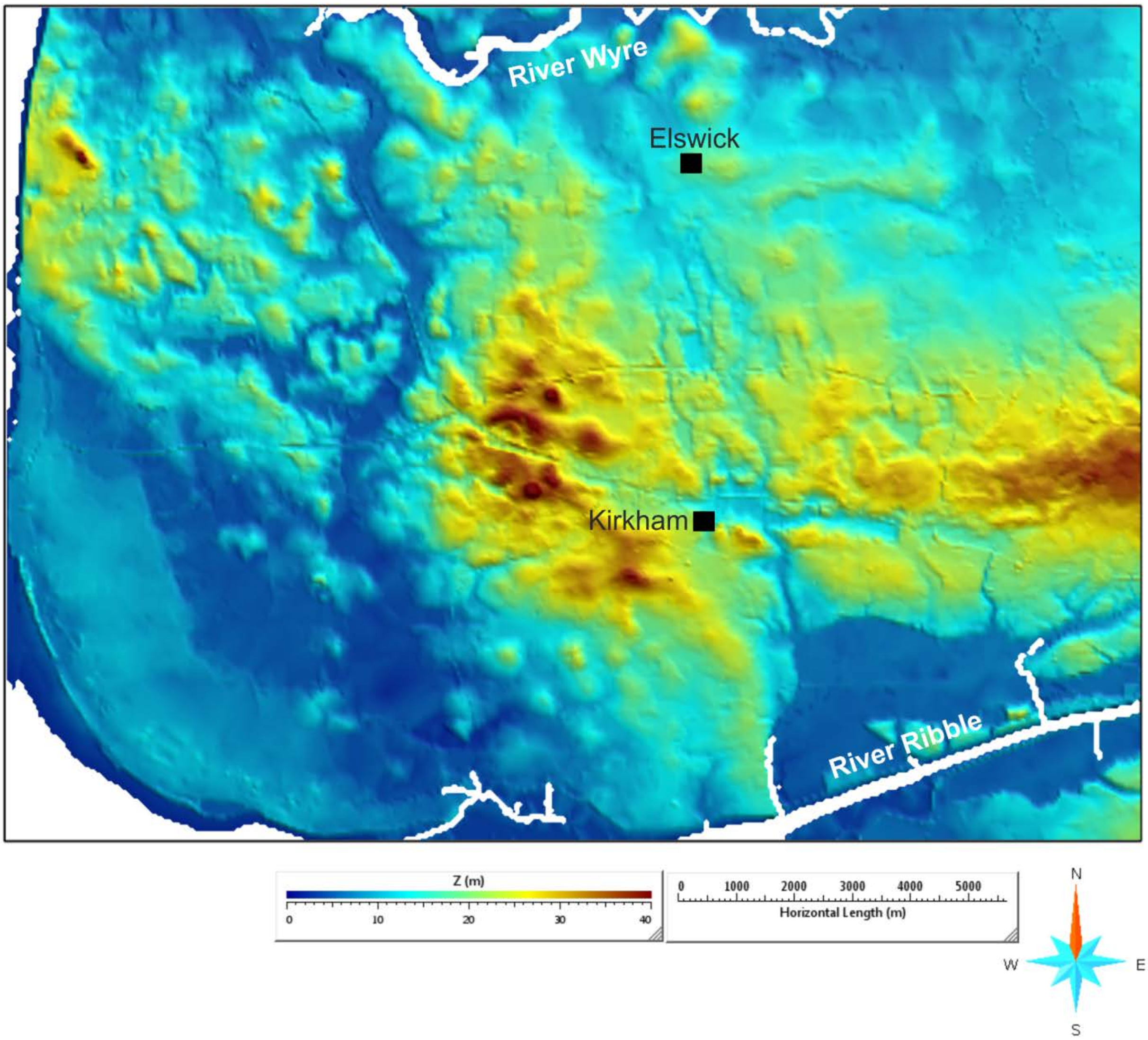

Figure 2 Topography of the south Fylde. Digital terrain model based on Ordnance Survey OSTerrain50 (OpenData).

The low-relief terrain of the south Fylde is underlain by a continuous sheet of superficial deposits dominated by Quaternary glacial tills and glaciofluvial sands and gravels (Aitkenhead et al., 1992; Ford, 2016; Wilson and Evans, 1990). According to the BGS National Superficial Deposit Thickness Model (Version 5) and its Rockhead T50 derivative (Lawley and Garcia-Bajo, 2009) the base of these superficial deposits (which defines a surface known as 'rockhead') lies at an elevation of 8 to -60 mAOD with a mean elevation of -17 mAOD (Figure 3). Rockhead elevation has an irregular pattern, which to some extent reflects clustered borehole control, but in general it falls from east to west with a marked local thickening around Blackpool and under the River Wyre to the northwest of Elswick. This rockhead surface was used as the upper boundary to the bedrock geological model.

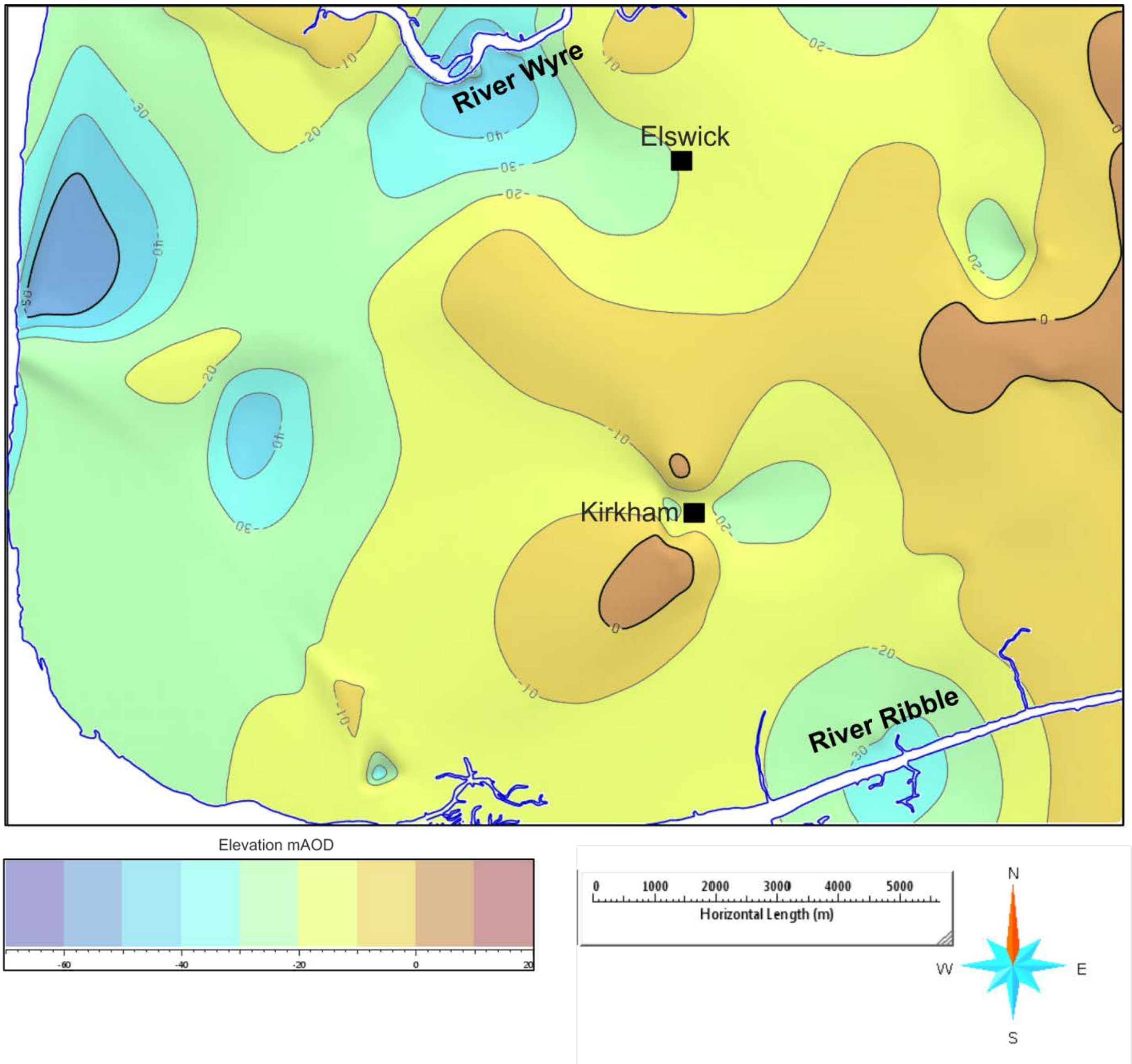

Figure 3 Map showing elevation of rockhead in the south Fylde. Based on BGS Rockhead T50 model (http://www.bgs.ac.uk/products/onshore/superficialThickness.html).

1.3 BEDROCK GEOLOGY AND BASEMENT STRUCTURE

Bedrock geology is concealed entirely by superficial deposits in the south Fylde. Boreholes and seismic data show, however, that the area is underlain by a several kilometre thick Permo-Triassic succession comprising the Appleby Group, Cumbrian Coast Group, Sherwood Sandstone Group and Mercia Mudstone Group (Aitkenhead et al., 1992; Wilson and Evans, 1990). Permo-Triassic strata rest unconformably on Carboniferous rocks, whose eroded top defines the Variscan Unconformity (Figure 4). BGS geological mapping of the south Fylde shows that the Triassic Sherwood Sandstone Formation occurs at rockhead to the east of the SW-NE trending Woodsfold Fault, a major down-to-the-west normal fault along the eastern margin of the West Lancashire Basin (Figure 6). To the west of the Woodsfold Fault, BGS geological mapping indicates that Mercia Mudstone occurs at rockhead although, as discussed below, the modelling undertaken for this study suggests that this distribution requires amendment in the area to the north of the Thistleton 1 borehole.

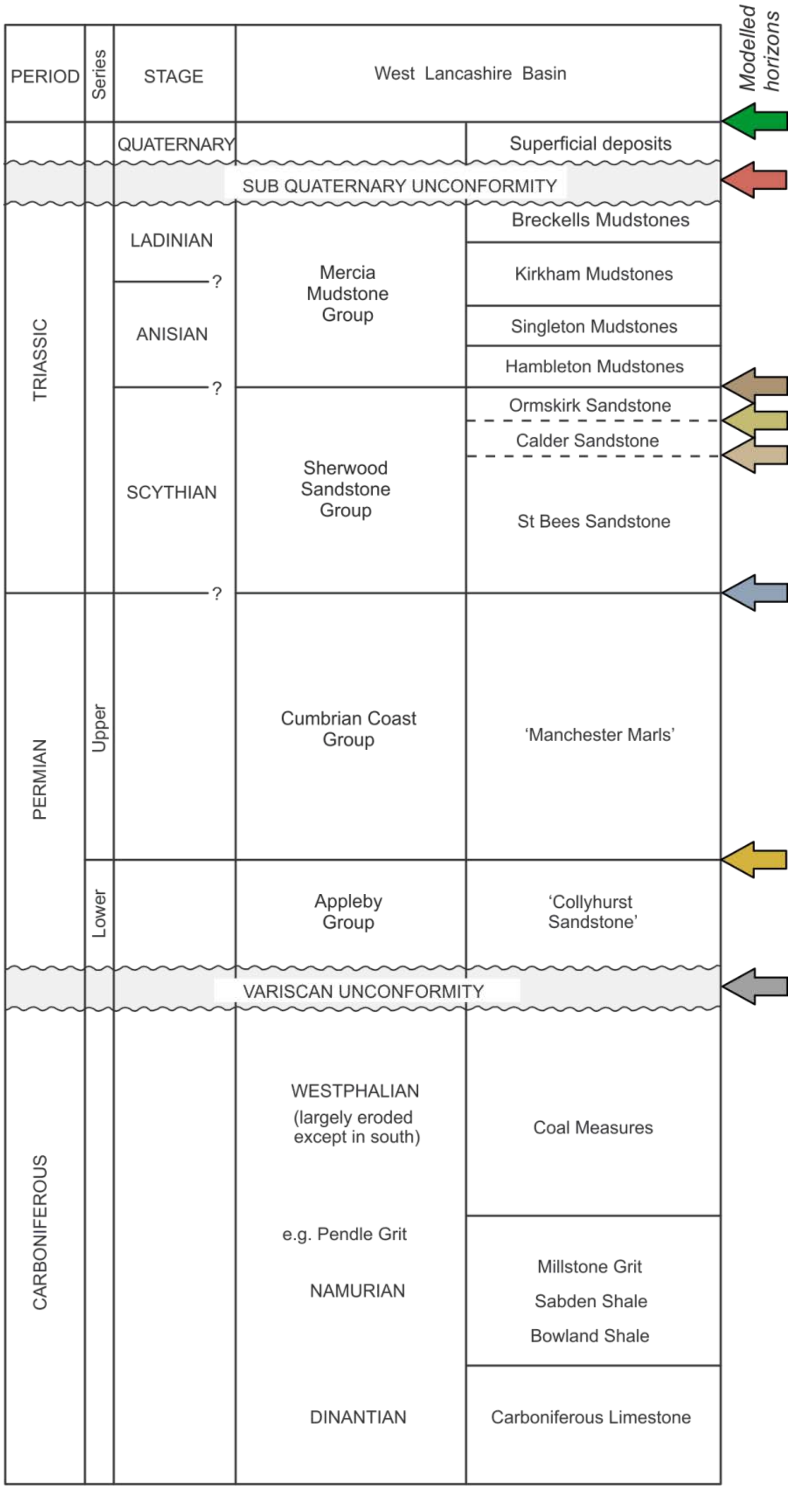

Figure 4 Chronostratigraphy and lithostratigraphy of Carboniferous to Triassic bedrock units in the West Lancashire Basin, modified from DECC (2013). Thick arrows on the right of the table show the stratigraphic position of the eight horizons that have been included in the model.

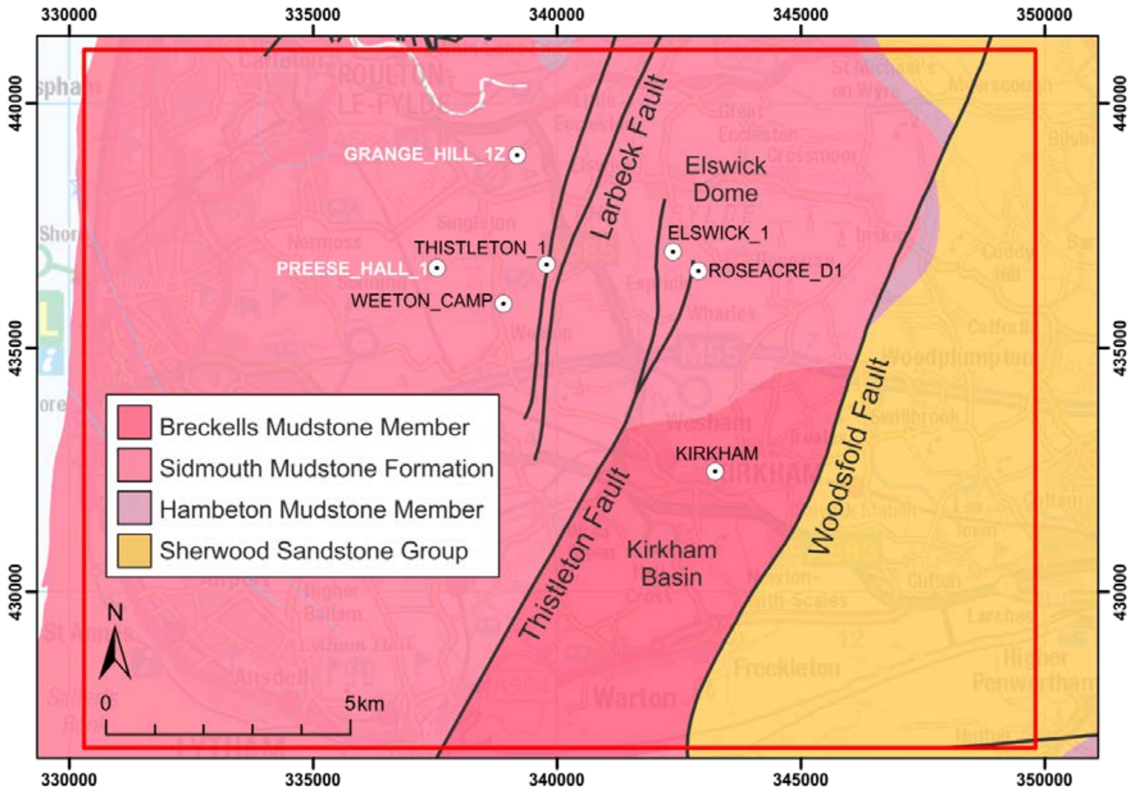

Figure 5 Bedrock geology of the south Fylde. Map based on BGS DiGMapGB-50. Note that bedrock geology is entirely concealed beneath a layer of superficial deposits.

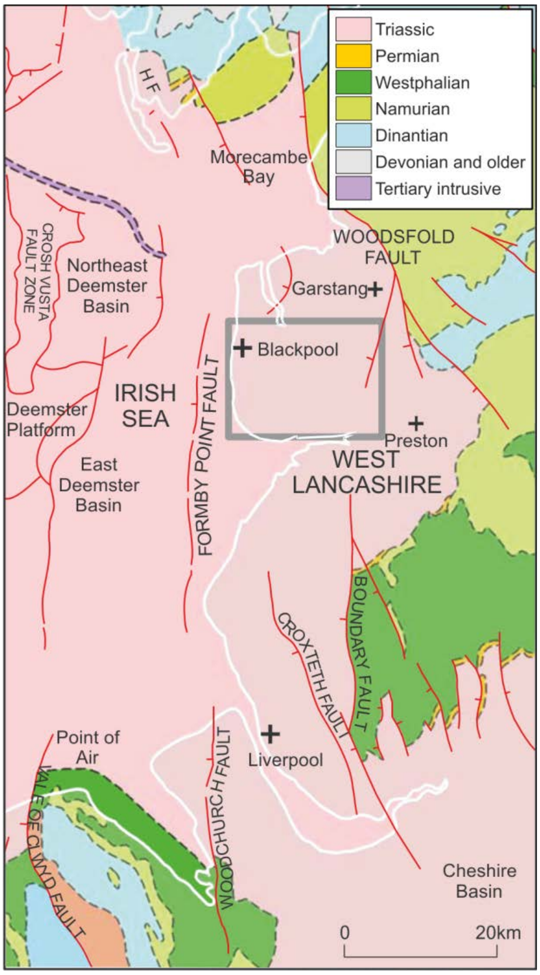

Figure 6 The south Fylde area (shown as grey outlined box) in its regional tectonic setting on the eastern flank of the East Irish Sea Basin. Map modified from DECC (2013)

Beneath the Permo-Triassic cover, the top of the Carboniferous has considerable relief created by differential movement of fault-bounded blocks. To the west of the Woodsfold Fault is the Kirkham Basin, a deep graben-like structure (Figure 7). This is bounded to the west by a faulted structural high (including the Elswick Dome) where the deep hydrocarbon exploration boreholes Elswick 1 and Thistleton 1 were drilled (Figure 8). Westwards from this high the top Carboniferous surface dips toward the west under Blackpool and toward the Formby Point Fault which forms the boundary of the East Irish Sea Basin (Figure 6).

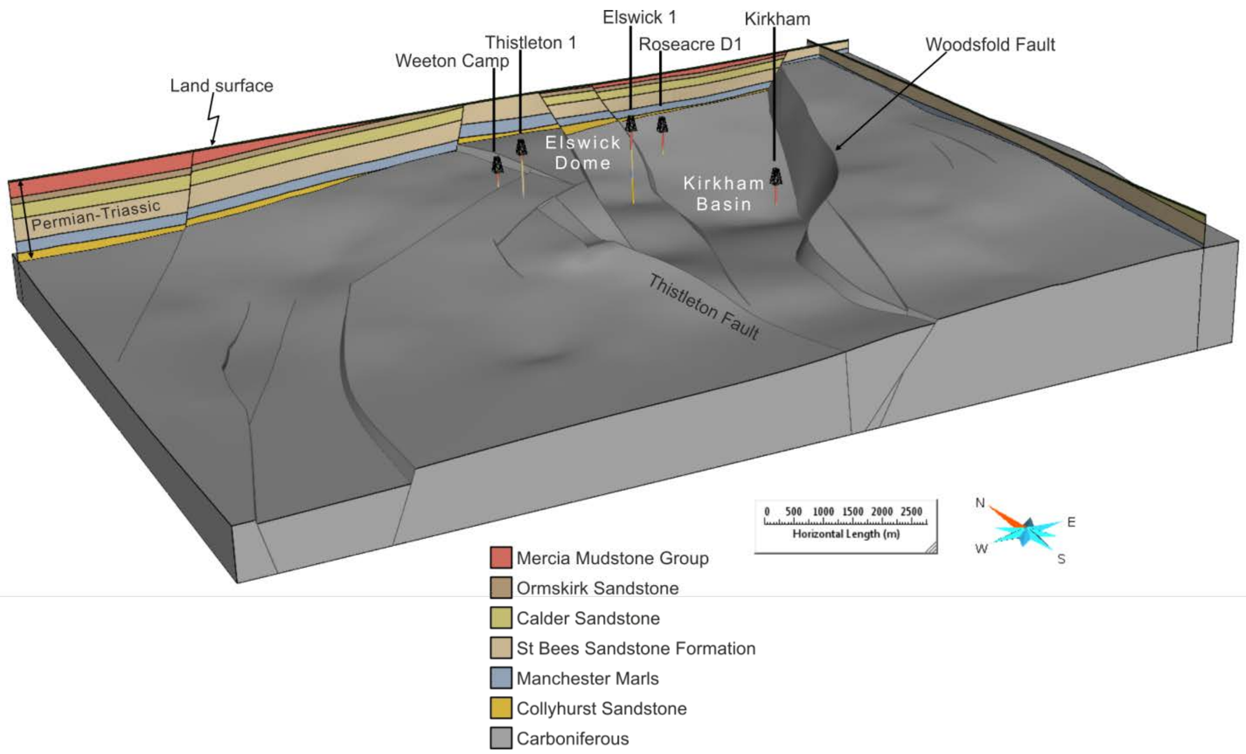

Figure 7 Perspective view on the top of the Carboniferous with the Permo-Triassic cover shown as two cross-sections

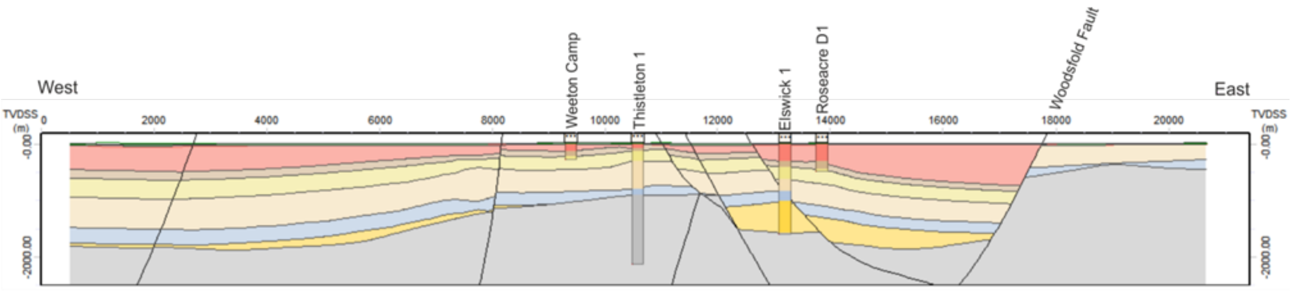

Figure 8 West-East cross section across the south Fylde, see Figure 7 for borehole locations. No vertical exaggeration.

1.4 PERMO-TRIASSIC STRATIGRAPHY

The Permo-Triassic succession in the south Fylde extends from the Permian Appleby Group ('Collyhurst Sandstone') to the lower parts of the Triassic Mercia Mudstone Group (Figure 4). Table 1 summarises the key characteristics of various Permo-Triassic formations and Table 2 shows their thickness based on interpretation of the Thistleton 1 and Elswick 1boreholes. The lithostratigraphical nomenclature of the Permo-Triassic of the UK is in a state a flux and a full discussion of the various stratigraphic units and their correlatives can be found in Ambrose et al. (2014), Howard et al. (2008) and via the BGS lexicon of named rock units (http://www.bgs.ac.uk/lexicon/home.html).

Table 1 General characteristics of Permo-Triassic stratigraphic units in NW England

Stratigraphical Unit	**Subdivisions and key characteristics**	
Mercia Mudstone Group	Brechells Mudstones	Reddish brown structureless mudstones
	Kirkham Mudstones	Reddish brown and grey mudstones and siltstones, includes salt toward the west
	Singleton Mudstones	Reddish brown structureless mudstones, includes salt toward the west
	Hambleton Mudstones	Grey interlaminated mudstones and siltstones
Ormskirk Sandstone Formation	Fine- to coarse-grained sandstone, cross-bedded, friable, probably mostly aeolian, marked by a rapid upward decrease in gamma-ray value and an increase in sonic interval travel time. Sharply overlain by the Mercia Mudstone Group.	
Calder Sandstone Formation	Red brown, medium- to coarse-grained, generally poorly sorted, cross bedded sandstone. The lower boundary on the underlying St Bees Sandstone Formation is sharp and is taken at the upward change to typical aeolian sandstones from typical fluvial sandstones, which are finer grained and better cemented. Geophysically the boundary is sharp, marked by an increase in sonic interval transit time and an increase in gamma-ray values.	
St Bees Sandstone Formation	Red-brown, very fine- to medium-grained, commonly micaceous sandstones, generally cross bedded, some parallel lamination; mudstone clasts locally common, subordinate thin beds of greenish grey sandstone. Well cemented with relatively high gamma ray response and low sonic transit times.	
Cumbrian Coast Group (Manchester Marls Formation)	Red marl (calcareous mudstone and siltstone) with thin beds of fossiliferous marine limestone and dolomite; locally green; sandy in places especially in top part; local breccias and pebbly beds. Units of halite and anhydrite.	
Appleby Group (Collyhurst Sandstone Formation)	In the south Fylde area, conglomerates and pebbly sandstones with limestone and igneous clasts, sandy mudstones and muddy sandstones. Thickness and facies highly variable. Elsewhere clean aeolian sandstones.	

The Permian Appleby Group (which includes the Collyhurst Sandstone) is unconformable on the Carboniferous and typically shows large variations in thickness over short distances. The Elswick 1 borehole proved 554 m of basal Permian strata, which on the British Gas composite log were assigned to the Collyhurst Sandstone, although the lithologies differ substantially from the soft red aeolian sandstones which are characteristic of this formation in its type area in Manchester (Tonks et al., 1931). In the Elswick 1 borehole the Appleby Group comprises an alternation of limestone-clast conglomerates, pebbly sandstones, sandstones and sandy mudstones. On geophysical logs the conglomerates form 'blocky' intervals with low gamma-ray values and low sonic transit times (Figure 9). The Appleby Group is absent in the Thistleton 1 borehole, which was drilled on a basement high (Figure 8), but present in the Preese Hall 1 further to the west (De Pater and Baisch, 2011). The coarse-grained character and variable thickness distribution controlled by fault-bounded basins probably indicates an alluvial fan setting for the Appleby Group in the south Fylde area.

Table 2 Thickness of Permo-Triassic units in Thistleton 1 and Elswick 1.

WellName	X	Y	Z	MD	MarkerName	Thickness	Notes
THISTLETON_1	339780	436700	-1.836000085	24.6959991	TopMerciaMudstoneGroup	75.8	Eroded top
THISTLETON_1	339780	436700	-77.61787415	100.477867	TopOrmskirkSandstoneFormation	46.9	
THISTLETON_1	339780	436700	-124.543541	147.403534	TopCalderSandstoneFormation	177.0	
THISTLETON_1	339780	436700	-301.5750427	324.435028	TopStBeesSandstoneFormation	495.0	
THISTLETON_1	339780	436700	-796.5795288	819.439453	TopManchesterMarlsGroup	106.6	
THISTLETON_1	339780	436700	-903.2215576	926.081482	TopVariscanUnconformity		
ELSWICK_1	342380	436965	-5.290100098	25.2901001	TopMerciaMudstoneGroup	295.0	Eroded top
ELSWICK_1	342380	436965	-300.332428	320.332428	TopOrmskirkSandstoneFormation	103.0	
ELSWICK_1	342380	436965	-403.3232727	423.323273	TopCalderSandstoneFormation	217.0	
ELSWICK_1	342380	436965	-620.3144531	640.314453	TopStBeesSandstoneFormation	206.1	Around 300 m faulted out
ELSWICK_1	342380	436965	-826.3912964	846.391296	TopManchesterMarlsGroup	192.2	
ELSWICK_1	342380	436965	-1018.612305	1038.6123	TopCollyhurstSandstoneFormation	554.5	
ELSWICK_1	342380	436965	-1573.114746	1593.11475	TopVariscanUnconformity		

The Cumbrian Coast Group, or Manchester Marls as shown on most composite logs, is 192 m thick in Elswick 1 and 106 m in Thistleton 1, where it rests directly on Carboniferous basement. In Elswick 1 the Cumbrian Coast Group comprises three broadly equal parts with green and brown mudstones and dolomitic siltstones at the base, interbedded mudstones and evaporites with characteristically low gamma-ray responses (Figure 9) in the middle and reddish brown mudstones and dolomitic siltstones at the top.

The St Bees Sandstone forms the lowermost unit in the Triassic Sherwood Sandstone Group (Barnes et al., 1994). It is 495 m thick in the Thistleton 1 borehole, but only 206 m in the Elswick 1 borehole, where around 300 m of the formation is cut out by normal faulting. The St Bees Sandstone is a thick sequence of generally fine-grained, well-cemented sandstones with occasional thin intercalated mudstones. The predominance of trough cross-bedding and other structures indicates a predominantly fluvial origin (Barnes et al., 1994).

The top of the St Bees Sandstone is marked by an abrupt shift toward the relatively poorly consolidated and generally coarser-grained sandstones of the Calder Sandstone Formation, a lateral correlative of the Wilmslow Sandstone Formation (Ambrose et al., 2014). The Calder Sandstone is clearly distinguished in geophysical logs from the underlying St Bees Sandstone by an abrupt decrease in gamma-ray value and an increase in sonic transit time (Figure 9). A cross-plot of gamma-ray value against sonic transit time highlights the contrasting properties of the two formations, and also with the overlying Ormskirk Sandstone (Figure 10). The Calder Sandstone is 177 m thick in Thistleton 1 and 217 m thick in Elswick 1. The common presence of well-rounded, wind-blown quartz grains indicates a shift towards a more aeolian-influenced depositional environment, particularly in the lower half of the formation. In the upper half of the formation gamma-ray values increase, possibly associated with a shift toward finer-grained sandstones and fluvially-dominated depositional environments (Figure 11) (Wilson and Evans, 1990).

The Ormskirk Sandstone forms the uppermost part of the Sherwood Sandstone and in many respects resembles the lower parts of the Calder Sandstone in comprising mostly fine- to coarse-grained, weakly cemented sandstones with common well-rounded aeolian grains (Wilson and Evans, 1990). The Ormskirk Sandstone has some of the lowest gamma-ray values in the Sherwood Sandstone (Figure 11), but also shows a number of conspicuous gamma-ray spikes which indicate the presence of thin mudstones (Figure 11). The Ormskirk Sandstone was fully cored in the Weeton Camp borehole and details can be found in Wilson and Evans (1990).

The Ormskirk Sandstone has a sharp contact with the overlying Mercia Mudstone which is divided into a number of formations based primarily on colour and other features such as the inclusion of thin sandstones and evaporites (see Table 1). An exhaustive description of the

Mercia Mudstone of south Fylde can be found in Wilson and Evans (1990). Note that the thick salt deposits which are found at Preesall and under Blackpool (Wilson and Evans, 1990) are not present in the Kirkham area which occurs toward the eastern margin of the West Lancashire Basin.

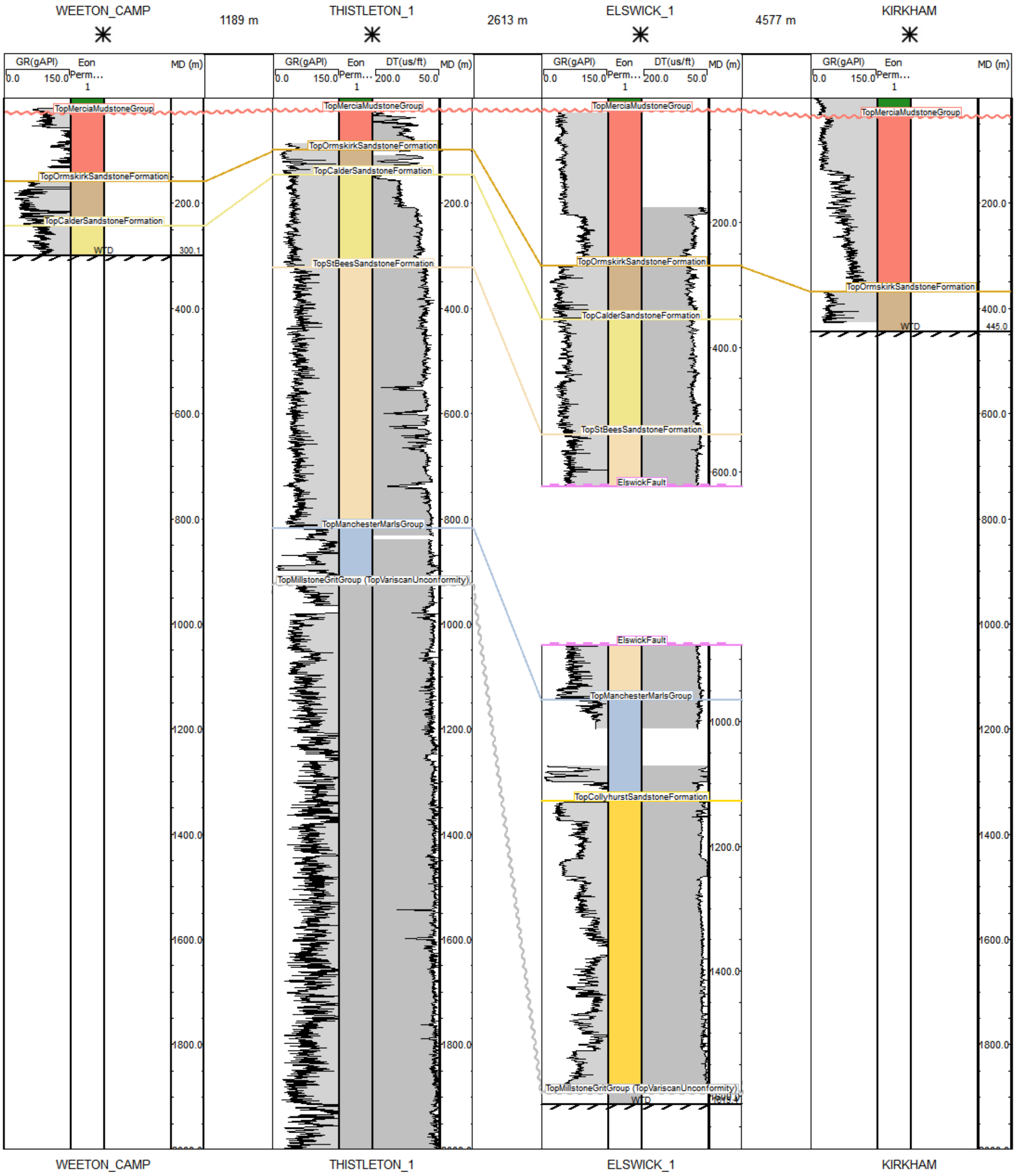

Figure 9 Geophysical log correlation of Permo-Triassic strata in the south Fylde.

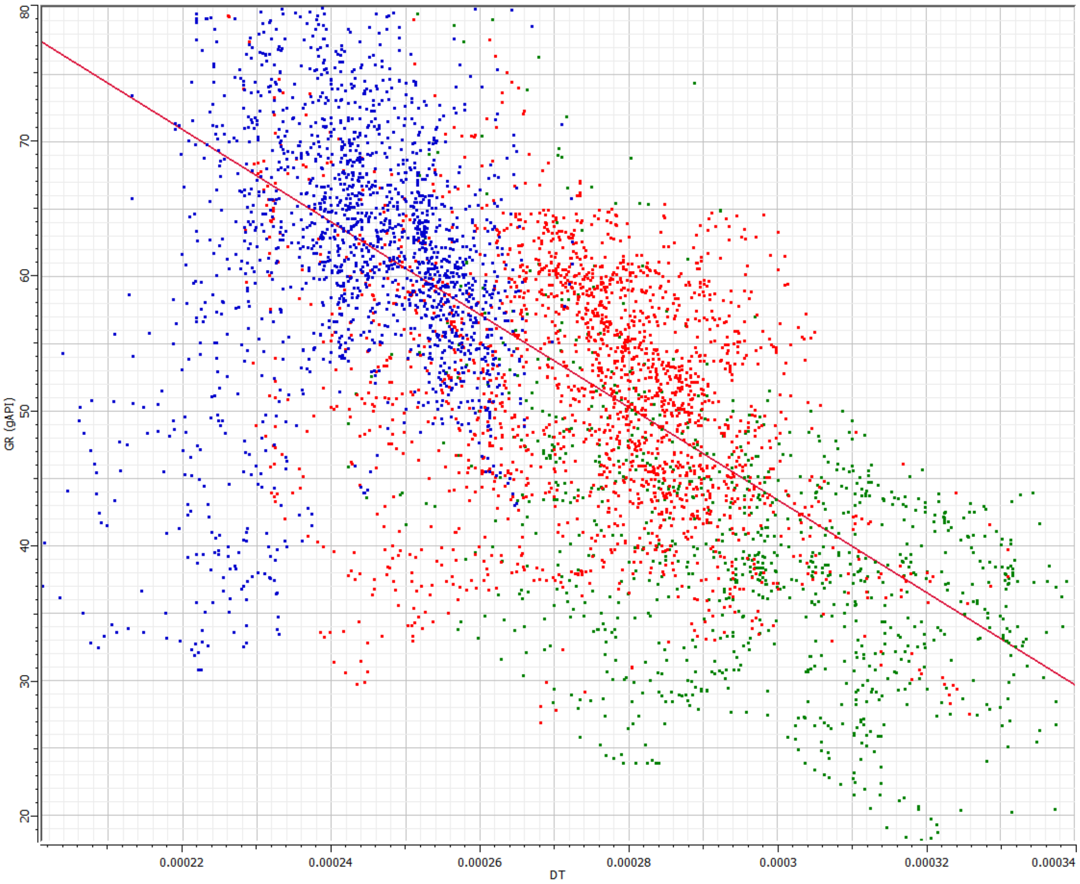

Figure 10 Cross-plot of gamma-ray (GR) values in API units against sonic transit time (DT) in seconds per metre for the Sherwood Sandstone interval of the Elswick borehole. Note the differentiation of the St Bees Sandstone (blue points), Calder Sandstone (red points) and Ormskirk Sandstone (green points).

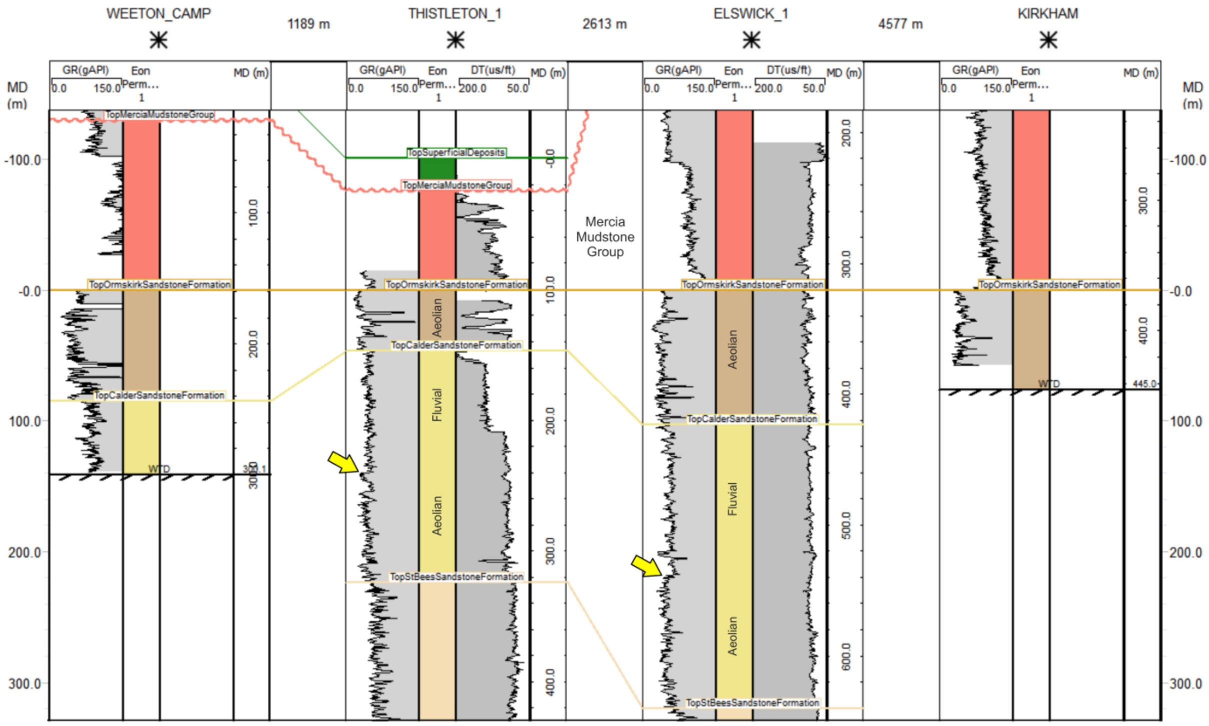

Figure 11 Logs flattened on top of the Ormskirk Sandstone. Thick yellow arrows indicate a positive shift in gamma-ray values at a midpoint in the Calder Sandstone.

2 Development of a Subsurface Geological model

2.1 SOFTWARE AND OVERVIEW OF METHOD

The geological model was produced using Paradigm® SKUA-GOCAD™ 15.5 which provides a unified environment for well analysis, cross-section construction and 3D geological modelling (Paradigm, 2015). The modelling followed conventional methods starting with the analysis of individual wells and the identification of stratigraphic markers, followed by the construction of well-sections and cross-sections to check stratigraphic correlations and build structural constraints for the modelling process. Most of the structural control comes from depth-converted 2D seismic lines which were interpreted as part of a previous study on the Craven Basin and adjacent areas (Kirby et al., 2000). No new seismic interpretation was undertaken as part of this work.

The model was built using the Structure and Stratigraphy workflow in SKUA-GOCAD™ 15.5 which provides structured semi-automatic routines which allow the construction of consistent models with pre-defined steps. This introduces a new 3D modelling technology which combines a fully volume-based implicit modelling approach. Geological surface modelling can be broadly categorized in explicit or implicit surface modelling approaches. Explicit modelling approaches are probably the most familiar and involve fitting a surface mesh to given geological constraints using direct triangulation, parametric polynomial functions, spline functions or an iterative process of minimising the weighted sum of distances between constraints and the mesh and surface roughness using the discrete smooth interpolation (DSI) algorithm. In implicit modelling the surface is extracted by tracing an isovalue that defines the geological interface in a 3D scalar field computed on a grid or tetrahedral mesh. which in SKUA-GOCAD™ 15.5 uses implicit geological modelling methods which consider geological interfaces as equipotential surfaces of a 3-D scalar field

the method is very close to classical geological thinking in the sense that it attempts to reproduce the natural drawing of a geologist simultaneously guided by some observed contact points and by the knowledge of orientation field mentally inferred from structural data.

discontinuities in the tetrahedralized model—introduced by dissociated nodes—enable parallel, bounded and discontinuous surfaces (e.g. faulted geological surfaces).

The algorithm used in SKUA-GOCAD™ 15.5 can be broken down into three phases:

1. The creation of a 3D tetrahedral mesh of user-defined resolution. Mesh may contain discontinuities which represent unconformities and faults which later define breaks of the reconstructed surface.
2. Interpolation of a volumetric implicit function over the tetrahedral mesh using discrete smooth interpolation. The volumetric implicit function is calculated from all available model input data including well markers, manually digitised curves and surfaces. The interpolation of the implicit function is performed using the DSI method (Mallet, 1992 and Mallet, 2002).
3. Surface reconstruction from the implicit function. Optionally the triangulation of the reconstructed surface can be improved.

Surfaces extracted from the implicit volumetric function may be further refined by precisely fitted to well markers by local or regional deformation. The final part of the workflow involves the creation of solid geological models comprising 3D irregular grids of user-specified resolution.

The solid based implicit modelling approach, which has many advantages in comparison to the surface modeling approach of gOcad:

1. The model consists always of consistent bodies;
2. Each element takes into account the location and extension of other elements (editing one
3. fault will update the whole fault network);
4. Artificial fault throw can be avoided;
5. Modeling of thin beds is possible without horizon crossings;
6. The 3D model can dynamically be edited and updated.

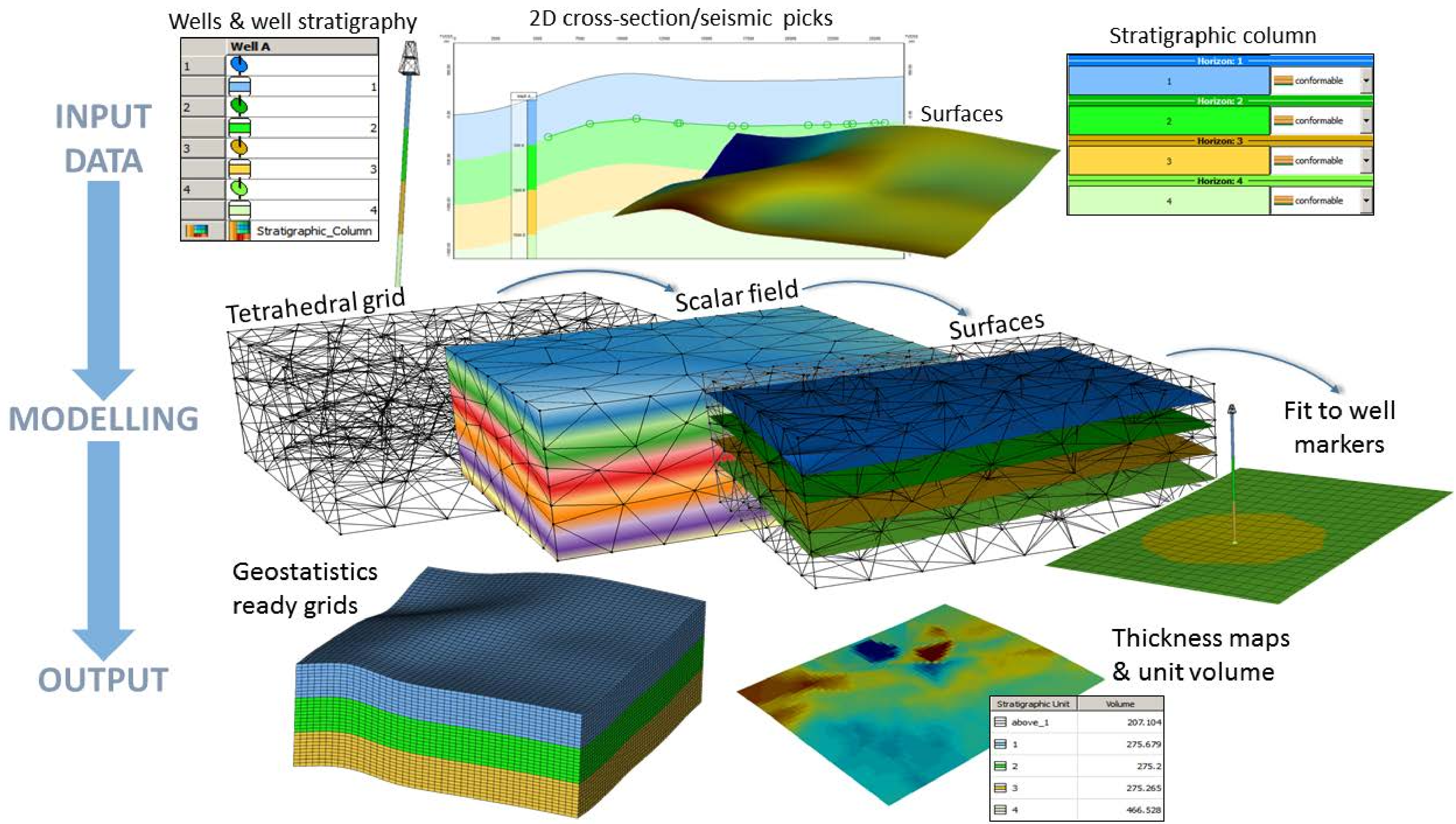

Figure 12 Overview of the SKUA-GOCAD 15.5 structure and stratigraphy modelling workflow for a simple volume without discontinuities (faults or unconformities).

2.2 MODELLED HORIZONS AND CONFIGURATION OF THE STRATIGRAPHIC COLUMN

Eight horizons were modelled with the base horizon located at the top of the Carboniferous, often referred to as the Variscan Unconformity (DECC, 2013). Figure 13 shows the configuration of the SKUA-GOCAD stratigraphic column used in the modelling process. All horizons were modelled as conformable with the exception of Top Variscan and Top Mercia Mudstone Group, which represents the sub-Quaternary erosion surface or rockhead.

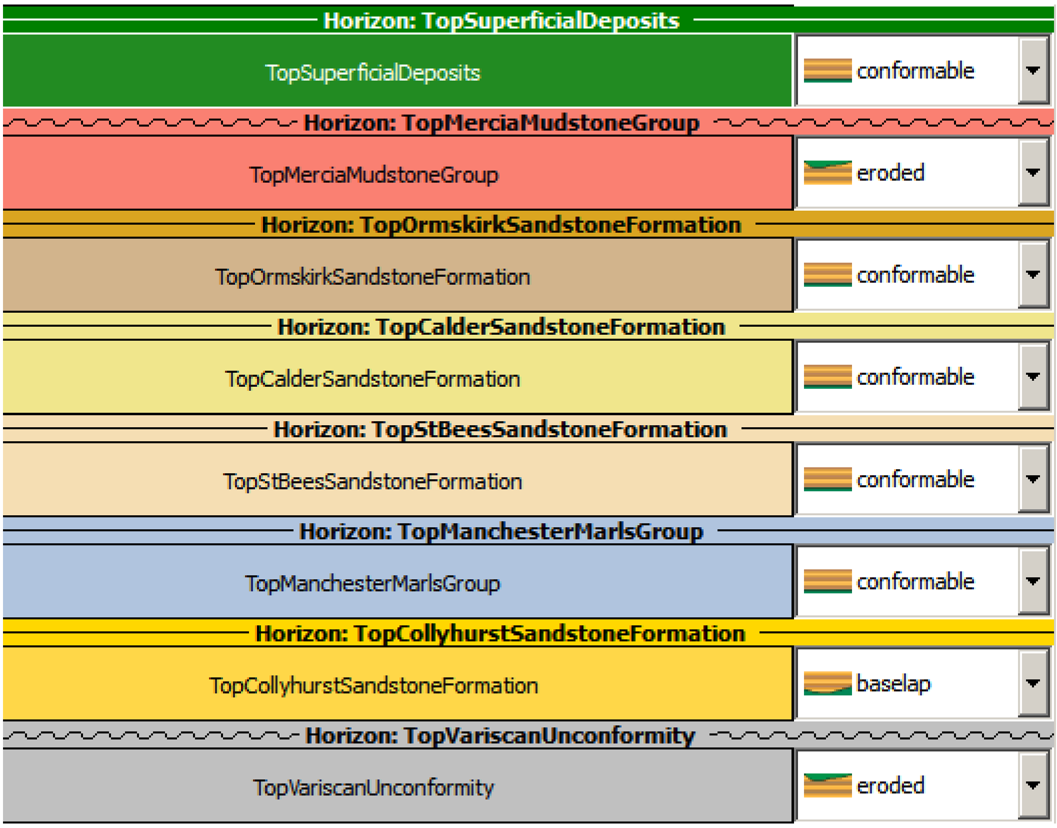

Figure 13 Configuration of the SKUA-GOCAD stratigraphic column used in the modelling showing modelled horizons, geological units and stratigraphic contacts. Stratigraphic nomenclature follows that commonly shown on composite logs in the area.

2.3 MODEL INPUT DATA

2.3.1 Well data

The south Fylde area has a long history of hydrocarbon exploration (DECC, 2013) which provides two released deep wells, Thistleton 1 (completed 15 Feb 1988) and Elswick 1(completed 2 June 1990) and a number of shallower wells drilled by BGS including Weeton Camp, Kirkham and the recently (2015) drilled 500 m deep borehole at Roseacre D1 (see Figure 5 for borehole locations). De Pater and Baisch (2011) provide published detailed on the Preese Hall 1 borehole (completed 16 Aug 2010) and there are unreleased deep boreholes at Grange Hill 1 (completed 15 April 2011), Grange Hill 1Z (completed 15 April 2012) and Anna’s Road 1 (completed 21 Nov 2012) (OGA, 2016). Only released well data were used in the model. Figure 14 shows the location of wells used in the model relative to the faulted top Carboniferous surface.

2.3.2 Seismic data

Structural interpretation of the south Fylde is based largely on 2D seismic reflection data of varying age and quality that was interpreted by Kirby et al. (2000). Depth-converted seismic picks were used to constrain the structure of the top Carboniferous surface. Figure 14 shows the distribution of seismic lines relative to the modelled surface. There were insufficient interpreted seismic picks to constrain the position of younger horizons within the Permo-Triassic cover, which could be an area for future work. The fault network was constructed to honour vertical offsets in the depth-converted seismic picks. With 2D seismic lines, there is clearly much uncertainty regarding the lateral and vertical extension of many of the faults and how they connect and branch in the subsurface. The model illustrates only one solution for the hard data and many other fault networks are possible.

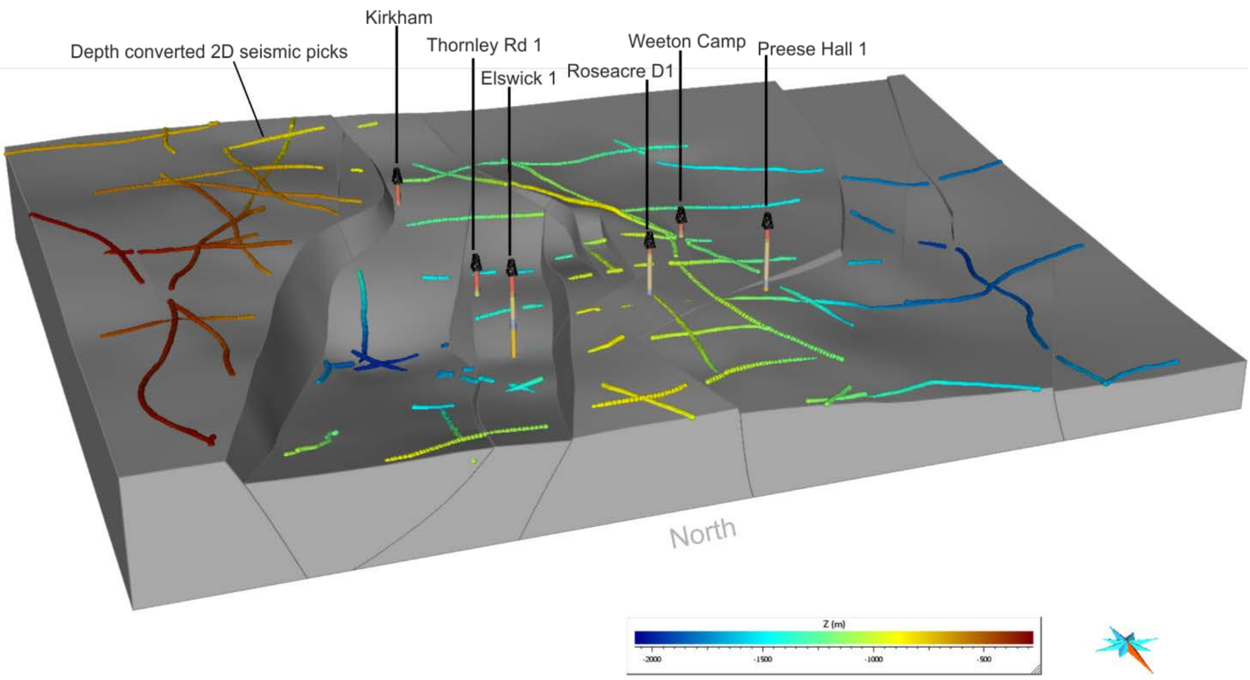

Figure 14 Borehole and seismic control data (coloured for elevation) for the south Fylde model plotted on the top Carboniferous surface viewed from the north.

2.3.3 Geological map linework

BGS DiGMapGB-50 bedrock geological linework (Figure 5) was not used as modelling input data since all of it is based on the interpretation of sparse borehole evidence in the superficial-covered south Fylde (Aitkenhead et al., 1992). There are thus some differences in the distribution of bedrock geological units between the model and existing geological maps, most notably in the area to the north of Thistleton 1 borehole. Here the model showed erosion of the Mercia Mudstone across a basement high (Figure 15) where the existing geological map (Figure 5) indicated that Mercia Mudstone should be present. Information subsequently gained from the unreleased Grange Hill 1Z well, which was not used in the modelling process, shows that in this case the model is correct.

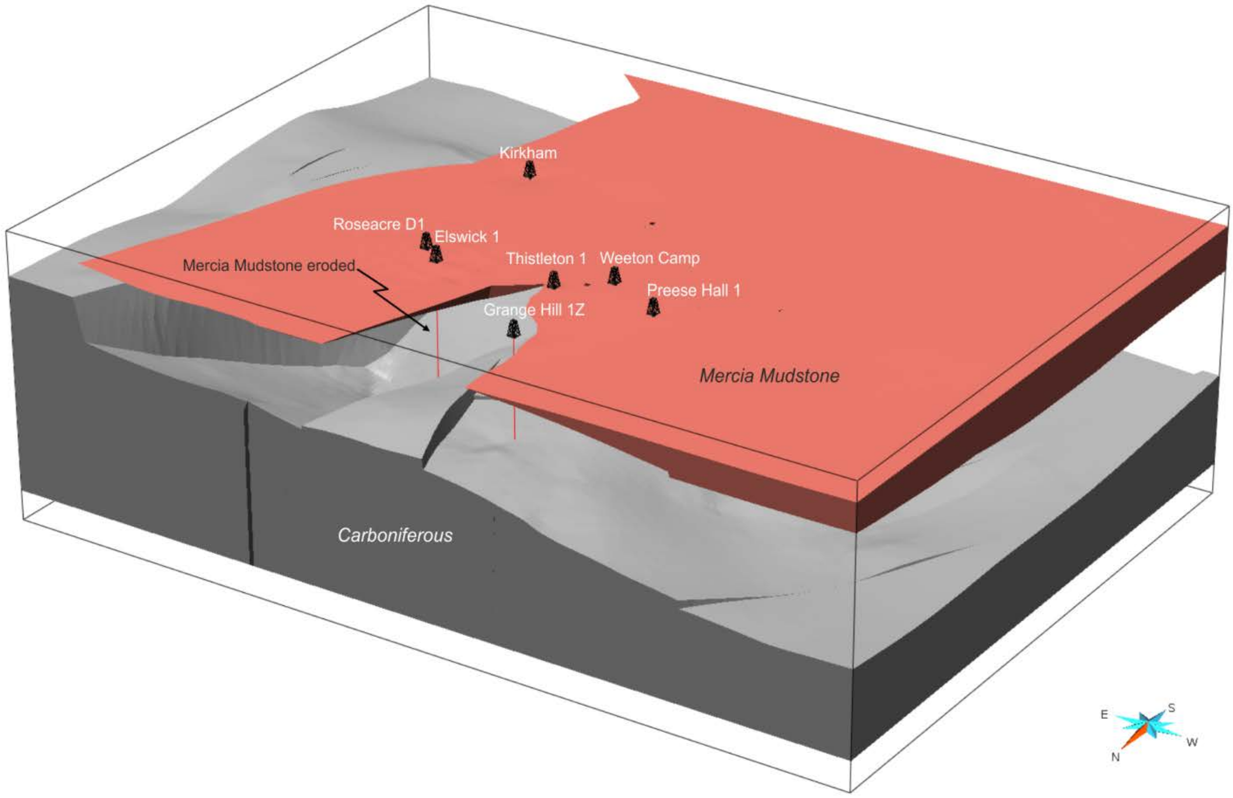

Figure 15 Model showing the Carboniferous and Mercia Mudstone rock volumes. Note erosion of the Mercia Mudstone in an area to the north of the Thistleton 1 borehole.

2.3.4 Manually-digitised picks

Four west-east cross-sections were constructed across the south Fylde area (Figure 16) and these were used to create additional input data for modelling the Permo-Triassic cover sequence. Note that cross-sections 1 and 4 did not intersect any wells and polylines representing horizon tops were generated solely on the basis of regional thickness trends. The positioning of the conjectural polylines was an iterative process with each new generation of the model being displayed within the cross-section window and used to refine and modify the position of the digitised horizon picks.

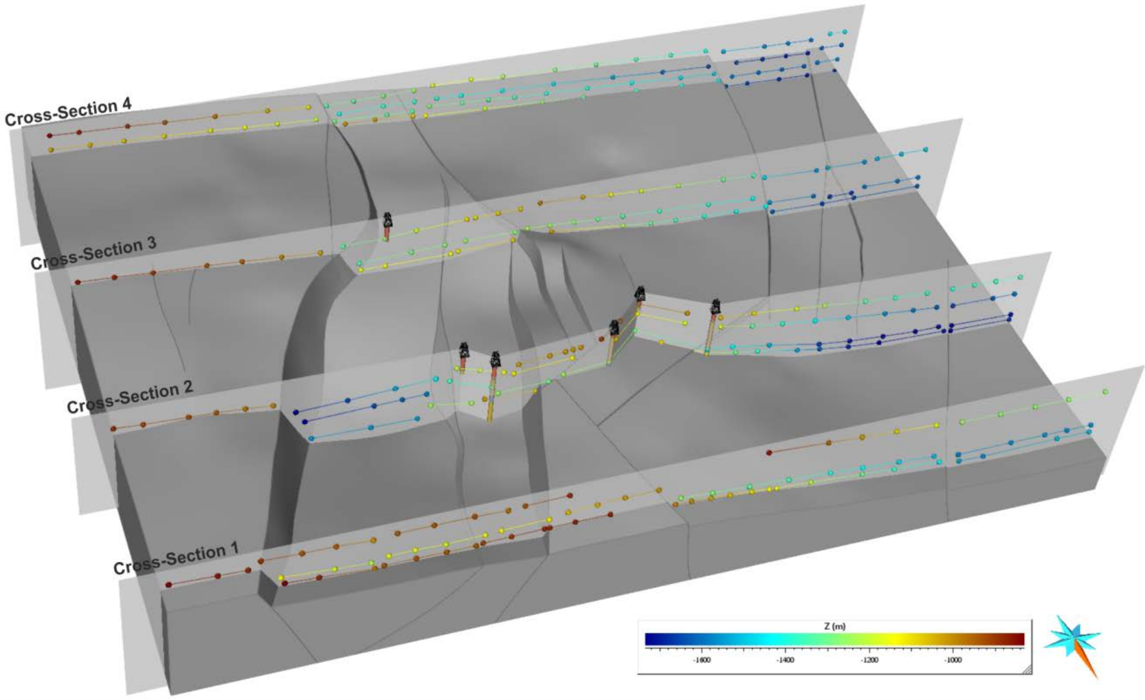

Figure 16 Cross-sections and location of additional picks used to constrain the geological model. Nodes and lines and coloured for elevation.

2.4 GEOLOGICAL MODELLING PROCESS AND OUTPUT

Geological modelling was undertaken using Paradigm's SKUA-GOCAD™ 15.5 Integrated Earth Modelling application. This uses an implicit modelling approach which automates all fault network and stratigraphic horizon construction (Paradigm, 2015). The resulting geological model (Figure 17) honours horizon well markers precisely and provides a user-specified fit to other 'soft' input data, such as manually-digitised polylines created on cross-sections. All horizons and geological units within a model are built simultaneously and follow the stratigraphic rules defined within the geological column (Figure 13) which specify where horizons are conformable, unconformable, eroded or onlapping. The position of horizons is constrained largely by thickness models constructed from well information and other inputs. It is important to note that the resultant model represents only one of an infinite number of solutions to the sparse array of hard input data. All of the input data and parameter settings used in the modelling run are provided in an accompanying document (model metadata).

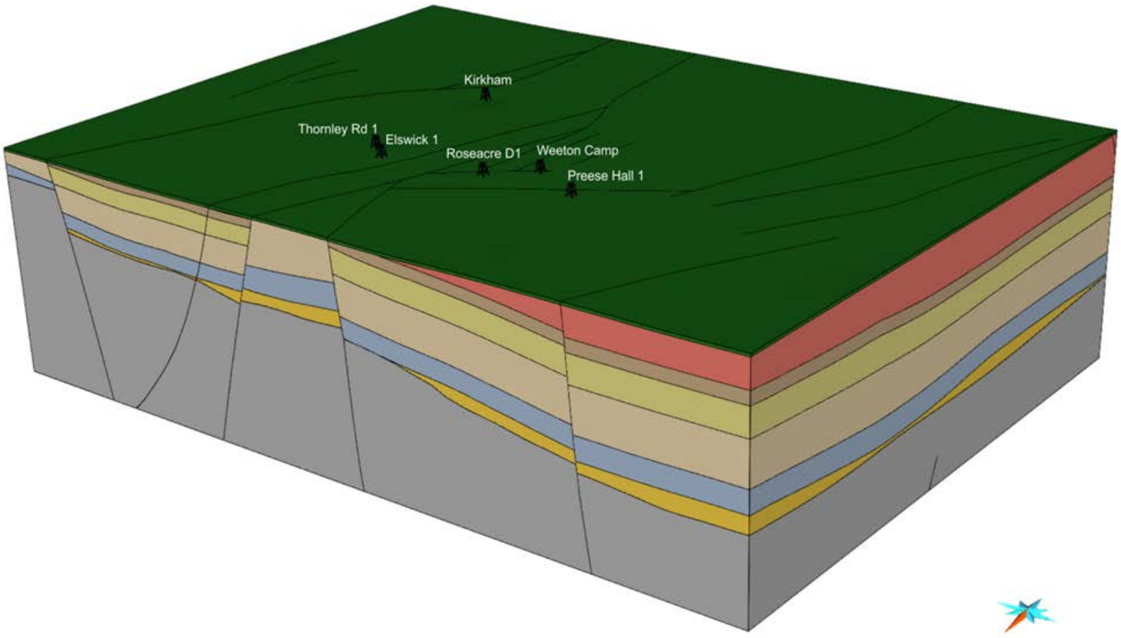

Figure 17 Geological model shown with two times vertical exaggeration. Vertical dimension covers approximately 2.5 km. See Figure 7 for key to geological units.

The SKUA-GOCAD geological model is a 3D grid with stratigraphically-aligned cells which are truncated at faults and unconformities (Figure 18). Cells (of any user-specified dimensions) can be attributed with properties such as rock type, porosity or hydraulic conductivity allowing refinement of the model beyond the current broad formation-level subdivisions. Grids can be exported in many formats suitable for flow modelling and other dynamic simulations.

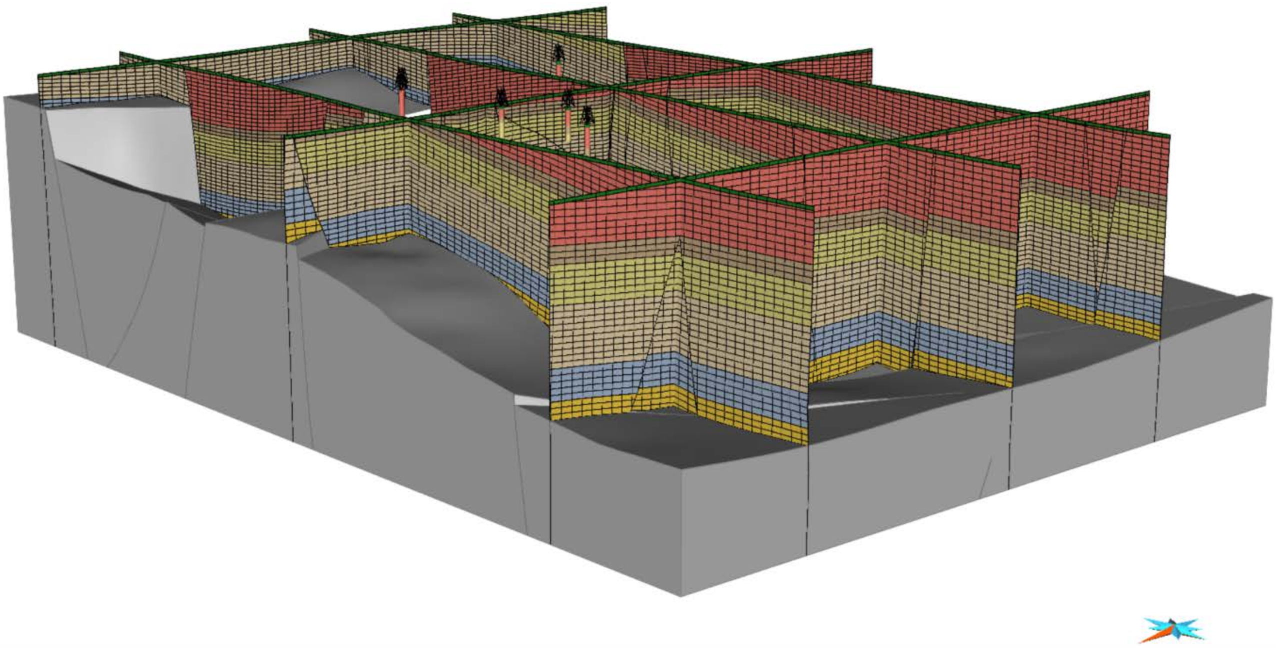

Figure 18 Sections through the model showing internal grid structure.

3 Conclusions and further work

This study has shown that, while subsurface data in the south Fylde are sparse, it is nonetheless sufficient to build a geological model that increases our understanding of the stratigraphy and structure and is capable of making accurate predictions on the distribution of concealed rock units. The present model was built in a relatively short time and requires refinement and further checking by the insertion of additional borehole control and seismic sections. Geological units are currently modelled as groups or formations which in reality comprise a large number of rock types which interbed and change laterally. There are sufficient geophysical logs and other well data such as core to capture some of this heterogeneity in the model by applying stochastic geostatistical techniques on the 3D geological grids. There is considerable scope for refining the model through the reinterpretation of 2D seismic lines and in particular by building in new information from 3D seismic surveys.

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

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