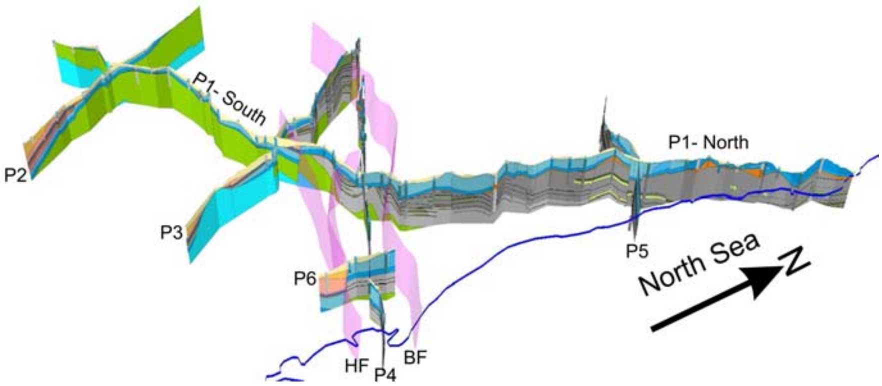
Environment Agency: Durham Permian Sections

Report prepared for the Environment Agency by the British Geological Survey

Internal Report CR/07/117



BRITISH GEOLOGICAL SURVEY

REPORT PREPARED FOR THE ENVIRONMENT AGENCY BY THE BRITISH GEOLOGICAL SURVEY
INTERNAL REPORT CR/07/117

Environment Agency: Durham Permian Sections

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3D Cross-sections through the Carboniferous and Permian of South Durham.

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Foreword

This report is the published product of a commissioned study by the British Geological Survey (BGS) Geology and Landscape North and Geology and Landscape South programmes on behalf of the Environment Agency North East Region.

Acknowledgements

Sally Gallagher of the Environment Agency is thanked for her help setting up the project and providing background information into which the project has to fit. Simon Price is thanked for project management and Richard Gillanders for help with borehole database matters. Helen Burke is thanked for help setting up many of the GIS aspects of the project.

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Summary

This report describes six sections constructed through the Permian and Carboniferous sequence in north-east England. The main north-south section (split into two parts) extends from near Sunderland in the north to near Darlington in the south. Four east-west sections are situated in the north, centre and southern parts of the area. In addition, a short north-south section is located just to the west of Hartlepool. The sections have been constructed to a depth of 300m and created from borehole and map information compiled using the GSI3D modelling software.

1 Introduction

The North East Region's Groundwater Modelling Strategy has identified the need for the development of a conceptual model for the Magnesian Limestone aquifer. In line with the Environment Agency R&D Technical Report W214 (Environment Agency Framework for Groundwater Resources Conceptual and Numerical Modelling), a scoping study was produced, that identified areas of uncertainty and work required for the development of the conceptual model.

The purpose of this project is to give the Environment Agency (EA) a regional understanding of the geology and hydrogeology of the Magnesian Limestone and overlying superficial deposits in the North East Region, using information presently held by the British Geological Survey (BGS). This report contributes to the conceptual model and understanding of the Magnesian Limestone aquifer.

There is uncertainty in the amount of recharge that the Magnesian Limestone receives from rainfall. The project is designed to gain a greater understanding of the geology of the superficial deposits and bedrock deposits and their hydrogeological properties. These are the key factors for the calculation of recharge to the Magnesian Limestone aquifer from rainfall. This element of the conceptual model is essential in understanding the potential water resource available within this aquifer.

1.1 SCOPE

The scope of this phase of the BGS project is to provide an interpretation of the geology of the Permian and adjoining strata of the Durham area.

The geological sequence of interest includes Carboniferous strata, comprising the Westphalian Coal Measures and the Namurian and Dinantian Yoredale Group and the basal Permian Yellow Sands Formation, which lie beneath the Permian sequence of magnesian limestones and marls, which include the main Magnesian Limestone aquifer. This project was to produce six geological cross-sections through the Permian and Carboniferous sequence. Two other phases detailing the superficial deposits and the hydrogeological domains within them have already been delivered.

2 Geological Summary

2.1 BEDROCK SUMMARY

The bedrock underlying the Darlington, Durham and Sunderland area comprises Permian rocks in the east, which unconformably overlie Carboniferous rocks to the west and at depth. The Carboniferous rocks comprise the Yoredale Group and the overlying the Pennine Coal Measures Group. They are unconformably overlain by the Permian Yellow Sands (Yellow Sands Formation of the Rotliegende Group) comprising weakly cemented, aeolian sandstones, distributed in ridges that represent sand dunes buried beneath the Zechstein Group. The sands are followed unconformably by a thin (less than 2 m) dark grey mudstone called the Marl Slate Formation which laps around them. This is in turn unconformably overlain by the interbedded magnesian limestones and marls of the Permian Zechstein Group. These magnesian limestones include the Raisby, Ford, Roker and Seaham formations, which are indivisible in most boreholes and comprise dolomitic limestones and dolostones that form the main aquifer bodies in the area, collectively referred to as the Magnesian Limestone aquifer. The limestones also include patch and shelf edge reef facies in the Ford Formation. The interbedded marls are commonly anhydritic or gypsiferous with significant sequences of evaporite in the south and south-east.

The generalized sequence of the Carboniferous rocks that underlie the area is shown in Figure 1, details of the Coal Measures in Figure 2 and the generalized geological sequence of Permian and Triassic rocks in Figure 3. The key of colours used for the sections and maps in the report are shown in Figure 8.

2.2 CARBONIFEROUS SEQUENCE

Details of the Carboniferous sequence in the study area are contained in the geological memoirs describing the 1:50,000 scale geological maps of the area (Smith and Francis, 1967 – Durham and Hartlepool; Mills and Hull, 1976 – Barnard Castle; Smith, 1994 - Sunderland). The Carboniferous sequence is summarised below:

CARBONIFEROUS	**Pennine Coal Measures Group**	**Pennine Upper Coal Measures Formation**, predominantly argillaceous strata with a few thin coals. Base at the Cambriense (Down Hill) Marine Band.	c.150m
		Pennine Middle Coal Measures Formation, mudstone, siltstone and sandstone with significant sandstone units and named coal seams. Base at the Vanderbeckeii (Harvey) Marine Band	c. 500m
		Pennine Lower Coal Measures Formation, mudstone siltstone and sandstone with significant sandstone units and named coals. Base at the Subcrenatum (Quarterburn) Marine Band.	c. 230m
	Yoredale Group	**Stainmore Formation** (Millstone Grit), mudstones and siltstone with significant coarse-grained sandstone units. Base at the top of the Great limestone.	c. 400m
		Alston Formation, sandstone, mudstone, siltstone and limestone (proved in Seal Sands/Harton boreholes).	c. 850m

Figure 1 The generalized Carboniferous sequence in the study area

The oldest strata in the district are the Yoredale Group deposits that are present mainly in the south and to the south-west of the study area. These strata include the Alston Formation a typical "Yoredale" facies sequence of limestones with mudstones and siltstones plus sandstones and minor coals in a cyclic sequence. In the Barnard Castle memoir (Mills and Hull, 1976) these units are included in the sequence that is Lower Carboniferous (Visean) in age and which forms part of the Carboniferous Limestone Series of strata. They are overlain by the Stainmore Formation previously referred to as the Upper Carboniferous Millstone Grit Series by Mills and Hull (1976). The lower part of this sequence is similar to the Yoredale facies rocks, but much of the upper two-thirds or so is typical of the "Millstone Grit" facies comprising coarse-grained sandstones with large-scale cross-bedding separated by thin argillaceous sequences that include seatearths and some thin coals. The details of these two formations are impossible to determine from the boreholes and they are left as undivided in the cross-sections produced for this report.

The Yoredale Group is overlain by the Pennine Coal Measures Group (formerly called the Coal Measures) comprising the Lower, Middle and Upper Coal Measures formations. The Upper Coal Measures are present only in the much-faulted Boldon Syncline on the western side of Sunderland. The Lower and Middle Coal Measures are the typical coalfield sequences of mudstones and siltstones in cyclic sequences with seatearths, coals and sandstones. They contain numerous named coals, many of which are locally cut out by erosive sandstone units. The details of the sequence are complex and a generalized succession is shown below in Figure 2 from the Sunderland area (reproduced after Smith 1994). From this figure it can be appreciated how irregular the sandstone units can be in the coal measures formations. Where there is good borehole evidence it has been possible to model the coals and sandstones present in this sequence, but the majority of the sections have been derived by considerable extrapolation of the units. Only selected coals, requested by the EA, have been shown on the sections and only then when there is good borehole evidence, consequently, not all of them have been shown across the complete area.

Pennine Middle Coal Measures Coals shown on sections:

Ryhope Five-Quarter

Ryhope Little

High Main

Five Quarter

Main

Maudlin

Hutton

Pennine Lower Coal Measures Coals shown on sections:

Harvey

Busty

Brockwell.

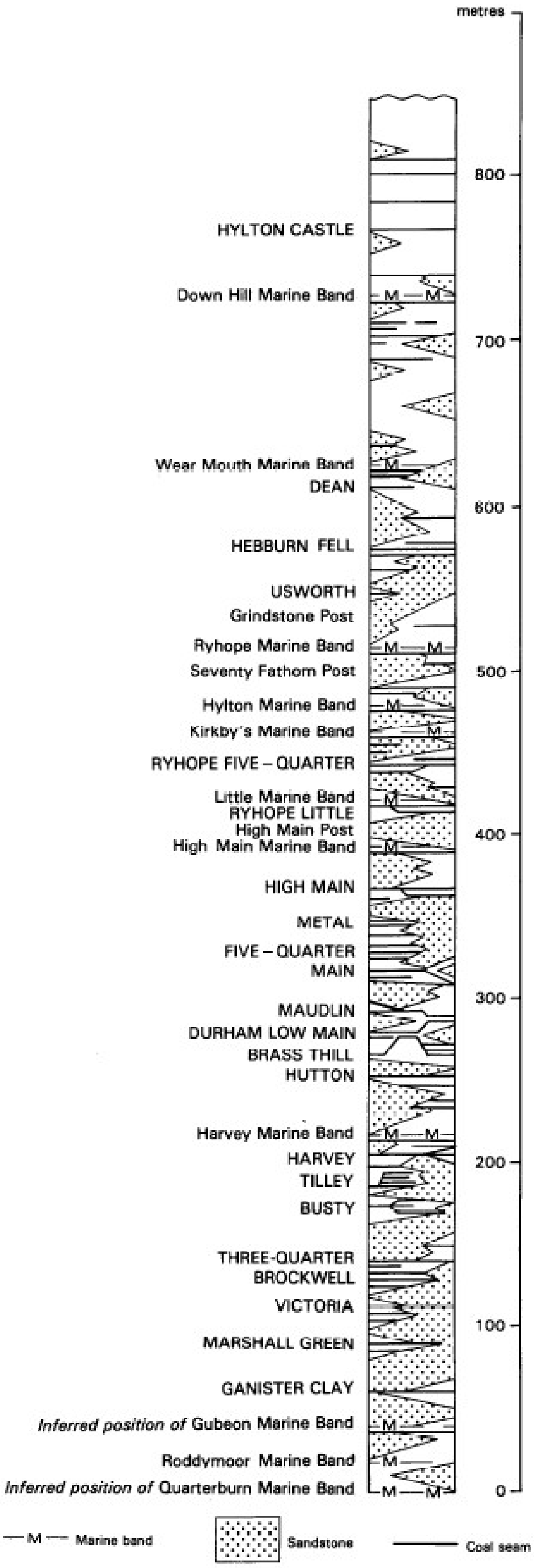

Figure 2 Sequence of the Pennine Coal Measures Group from Smith (1994).

2.3 PERMIAN SEQUENCE

2.3.1 The Early Permian erosion and Rotligende Group deposition

The Variscan earth movements at the end of Carboniferous times caused faulting and folding with associated uplift. By early Permian times, the land surface took the form of a major land-locked basin extending from eastern England across to Germany and Poland. The north-east of England lay near the western margin of this basin in tropical palaeolatitudes (Smith, 1989). The newly uplifted areas were subject to intense, mainly subaerial erosion in a desert environment. Some areas, such as the resistant Carboniferous sandstones and limestones formed subdued hills. However, the majority of the Permian basin, especially over the soft Westphalian rocks, was worn down to a rocky pediment plain on which thin deposits of basal, and channel deposits of breccia developed and across which sand dunes (the Yellow Sands Formation) were blown. In the district, these breccias and the overlying desert sand dunes form part of the early Permian Rotliegende Group. The Yellow Sands Formation comprises desert wind-blown sand preserved as lenticular sand dunes that were subsequently buried beneath the Zechstein Group. These sand dunes can be up to 70 m high and up to a kilometre or so across by several to tens of kilometres long. They are extensive towards the east and north beneath the Raisby Formation, and largely missing in the south of the study area. They were deposited as a series of south-west to north-east trending ridges. In boreholes the sands are a light bluish grey due to the oxidation state of the ferruginous grains and pellicles that coat the sand (Krinsley and Smith, 1981; Glennie, 1983; Smith, 1992), at outcrop they weather to an orange colour.

2.3.2 Late Permian Zechstein Group deposition

During the Late Permian the Zechstein Basin flooded and the sea inundated the early Permian desert landscape burying the hills, sand dunes and breccias. In the newly formed sea, the Marl Slate Formation a thin deposit of organic-rich argillaceous dolomite with fish remains was deposited in the deeper parts of the basin, but not so much at the basin margin. It fills in around the sand dunes and in places laps on to or over them. Subsequently, the depositional basin underwent a series of cycles of flooding and evaporation, possibly caused by glacioeustatic changes. These were interpreted as five evaporitic cycles (Smith 1989, 1995), but now they are accepted (Ruffell et al., 2006) as the seven Sequence-Stratigraphic Cycles ZS1-ZS7 proposed by Tucker (1991). Tucker (1991) interpreted the cycles as highstand (mainly carbonate) and lowstand (mainly evaporitic). The carbonate and sulphate phases are generally best developed near the margins of the basin, which approximate to the outcrop in the north-east England. However, the anhydrite is largely altered to gypsum or dissolved away at and near outcrop (Cooper, 1998) so that limestone or dolomite with calcareous mudstone form most of the Permian rocks seen at the surface. The anhydrite, halite and sylvinite deposits are present at depth towards the coast at Teesside and further east beneath the North Sea (Smith 1989; Smith and Taylor, 1992).

For the Permian strata, the study area effectively divides into two sub-areas. The northern one, north of the Hartlepool Fault, is dominated by dolomite and limestone sequences including the Roker Dolomite with very little interbedded mudstone or siltstone. To the east of this area there are thick evaporite deposits (Fordon Evaporites and Hartlepool Anhydrite) and only dissolution residues of these remain onshore. In the southern part of the study area – south of the Hartlepool Fault – the sequence is more typical of the Yorkshire sequence with the Roker Dolomite largely missing and its lateral equivalent largely included within the Edlington Formation sequence. The evaporites here are also thinner.

In both the north and south parts of the study area, the Raisby Formation was deposited on the Marl Slate Formation, directly on Yellow Sands Formation or the underlying Carboniferous bedrock. It comprises dolomite after limestone and represents the first highstand deposit that was deposited during this high water level phase. Subsequently, it was altered to dolomite (see below). It is extensive in the northern and western parts of the study area and takes the form of a carbonate ramp thickening towards the coast where it then thins dramatically into what was much deeper water at the time of deposition.

The following Ford Formation represents another highstand and also takes the form of a carbonate ramp, but with the inclusion of patch reefs and a major fringing reef complex that runs approximately parallel to the present coast. It is at this reef edge that the Ford Formation thins dramatically to the east and thick evaporite deposits come in, especially offshore. These are the succeeding Hartlepool Anhydrite Formation which formed during a lowstand. The Hartlepool Anhydrite is present as a very thick deposit offshore of Durham and is fairly thick in the Teeside to Darlington areas. Towards outcrop in the southern part of the study area it is changed to gypsum and largely dissolved leaving just the insoluble residues which combine with the calcareous mudstones of the overlying Edlington Formation to form part of that unit at outcrop in the southern part of the study area. North of the Hartlepool Fault, in the north of the study area, the Roker Dolomite Formation forms much of the outcrop. Offshore and just inland, this unit is sandwiched between the Hartlepool Anhydrite Formation below and the Fordon Evaporite Formation above. Chemical interactions of these evaporites (as solutions derived from them) with the dolomite have resulted in it changing into the Concretionary Limestone facies containing abundant sub-spherical secondary calcite concretions with internal radiating crystal structures.

Onshore the Roker Dolomite Formation is overlain by thin evaporites that have largely dissolved away leaving the Seaham Residue. Offshore the thick Fordon Evaporite Formation is present overlain by the Seaham Formation a sequence of limestones and dolomites which represent yet another highstand. This formation is laterally extensive and a direct correlative of the Brotherton Formation (formerly called the Upper Magnesian Limestone) in Yorkshire (Figure 4). The overlying Billingham Anhydrite Formation is also altered to gypsum near outcrop and largely dissolved away so that the insoluble residues are included in the lower part of the largely insoluble Roxby Formation a sequence of calcareous mudstones from which the evaporites have been dissolved. The relationships are shown in and Figure 4.

			Thickness
TRIASSIC	**Sherwood Sandstone Group**	Red-brown fine- to medium-grained sandstone, (formerly Bunter Sandstone)	c. 250m
PERMIAN	**Zechstein Group**	**Roxby Formation,** (formerly Upper Marl): red-brown calcareous mudstone (marl) with subordinate gypsum beds and gypsum or anhydrite at its base	0 - 50m
		Sherburn Anhydrite Formation, anhydrite (gypsum near outcrop), becomes part of the Roxby Formation towards outcrop	0 – 3m
		Rotten Marl Formation, halitic mudstone (not shown on sections, becomes part of the Roxby Formation towards outcrop	0 – 7m
		Billingham Anhydrite Formation, Anhydrite (gypsum towards outcrop)	0 – 12m
		Seaham Formation, (formerly Upper Magnesian Limestone in south): pale grey calcitic dolostones mainly in thin beds	0 - 20m
		Seaham Residue, insoluble residues (mainly clay and silt) after the dissolution of the Fordon Evaporite Formation (mainly halite 0-75m) which is present offshore and at depth beneath Teesside.	1-2m
		Roker Dolomite Formation, (formerly Hartlepool and Roker Dolomite, and including the Concretionary Limestone Member; formerly part of Upper Magnesian limestone in north) dolomite and dolomitic limestone.	0 - 30m
		Edlington Formation, (formerly Middle Marl): red-brown calcareous mudstone (marl) with gypsum beds and gypsum or anhydrite at its base. Present in south of district includes thin distal parts of several formations and dissolution residues	0 - 53m
		Hartlepool Anhydrite Formation, Anhydrite (gypsum towards outcrop) present mainly in south of area, Hartlepool and offshore	0 – 200m
		Ford Formation, (formerly Middle Magnesian Limestone): pale grey and yellow dolomitic limestones and dolostones	0 - 70m
		Raisby Formation, (formerly Lower Magnesian Limestone): pale grey and yellow dolomitic limestones and dolostones	0 - 47m
		Marl Slate Formation, laminated calcareous bituminous mudstone	0 - c.2m
		Basal Permian Sands Formation, yellow fine to medium-grained sand of aeolian origin	0 - c.30m

Figure 3 The detailed Permian geological sequence in the study area.

	Groups	**Durham Formations at outcrop**	**Yorkshire Formations at outcrop**	**Yorkshire and Durham Formations and Members at depth**	English Zechstein Cycles (Smith, 1989)	Zechstein Sequences (Tucker 1991)
TRIASSIC	**Sherwood Sandstone Group**	Not divisible in area	Not divisible in area	Not divisible in area		
PERMIAN	**Zechstein Group**	**Roxby Formation**	**Roxby Formation**	**Littlebeck Anhydrite Formation**	**Z5**	**ZS7**
				Sleights Siltstone		
				Sneaton Potash Member (formerly upper Potash)	**Z4**	
				Sneaton (Halite) Formation		
				Sherburn Anhydrite Formation		**ZS6**
				Upgang Formation		
				Carnallitic Marl		
				Boulby Potash Member	**Z3**	**ZS5**
				Boulby Halite		
		Billingham Anhydrite Formation (gypsum or residue)		**Billingham Anhydrite Formation**		
		Seaham Formation	**Brotherton Formation**	**Brotherton Formation**		**ZS4**
		Seaham Residue (residue after the dissolution of the Grauer Salzton and Fordon evaporites)	**Edlington Formation**	**Grauer Salzton Formation**		
				Fordon Evaporite Formation	**Z2**	
		Roker Formation		**Kirkham Abbey Formation**		**ZS3**
		Hartlepool Anhydrite Formation (gypsum or residue)		**Hayton Anhydrite Formation**	**Z1**	
		Ford Formation	**Cadeby Formation** (Sprotbrough Member)	**Cadeby Formation**		**ZS2**
		Raisby Formation	**Cadeby Formation** (Wetherby Member)			**ZS1**
		Marl Slate Formation		**Marl Slate Formation**		
	Rotliegende Group	**Yellow Sands Formation** (with local breccia)	**Yellow Sands Formation** (with local breccia)	**Yellow Sands Formation** (with local breccia)		

Figure 4 Correlation of the Permian groups, formations and members after Smith (1989, 1995) and Tucker (1991) considerably updated with the formalised formation names where they exist.

3 Overview of sections

Six cross-sections have been constructed, but for convenience of printing them the main north-south section has been split in two, P1-North and P1-South that join at the intersection with section P3.

Figure 5 Location of Permian cross-sections P1 - P6 in north-east England

The area is crossed by two major basement bounding faults that have had a profound effect on the deposition and later structure of the area. These are the Butterknowle and Hartlepool faults shown in pink on the sections below. In addition, the Butterwick Fault is shown splaying of from the Hartlepool Fault and curving to the north-west. To the north of the Butterknowle Fault, the sequence is mainly Permian dolomites resting on Pennine Coal Measures Group. To the south the Permian sequence includes evaporites and rests on either Pennine Coal Measures Group or much older strata belonging to the Yoredale Group. As noted above, the Hartlepool Fault also marks the dividing line between the shelf dolomite-dominated Permian sequence to the north and the sequence with more interbedded mudstone and some evaporites to the south.

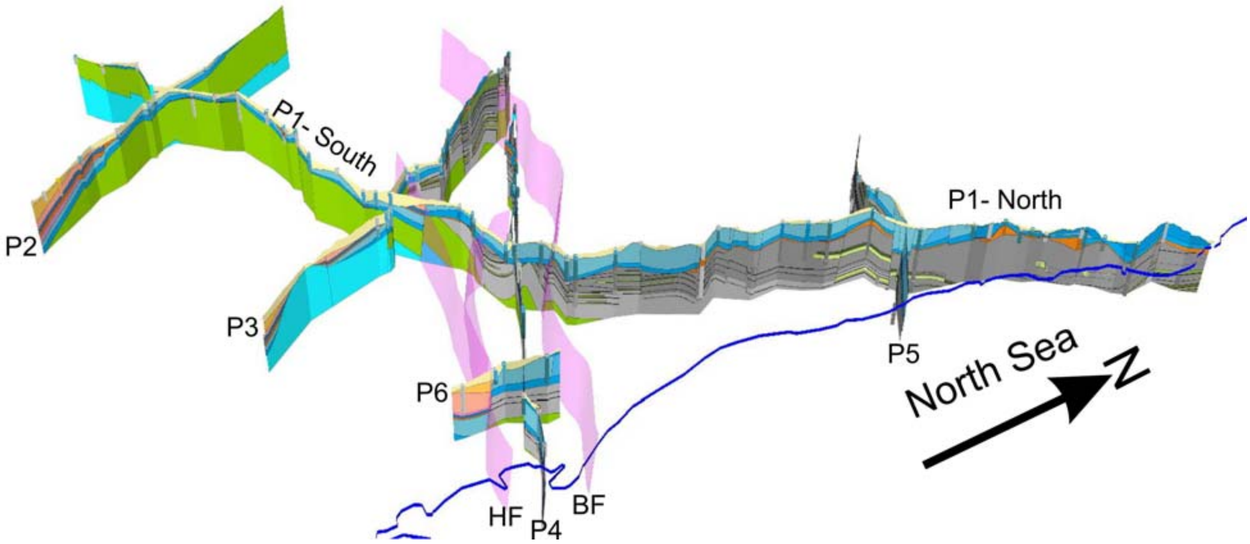

Figure 6 Relationships between section lines P1 - P6, major faults and the coastline of NE England (HF = Hartlepool Fault, BF = Butterknowle Fault)

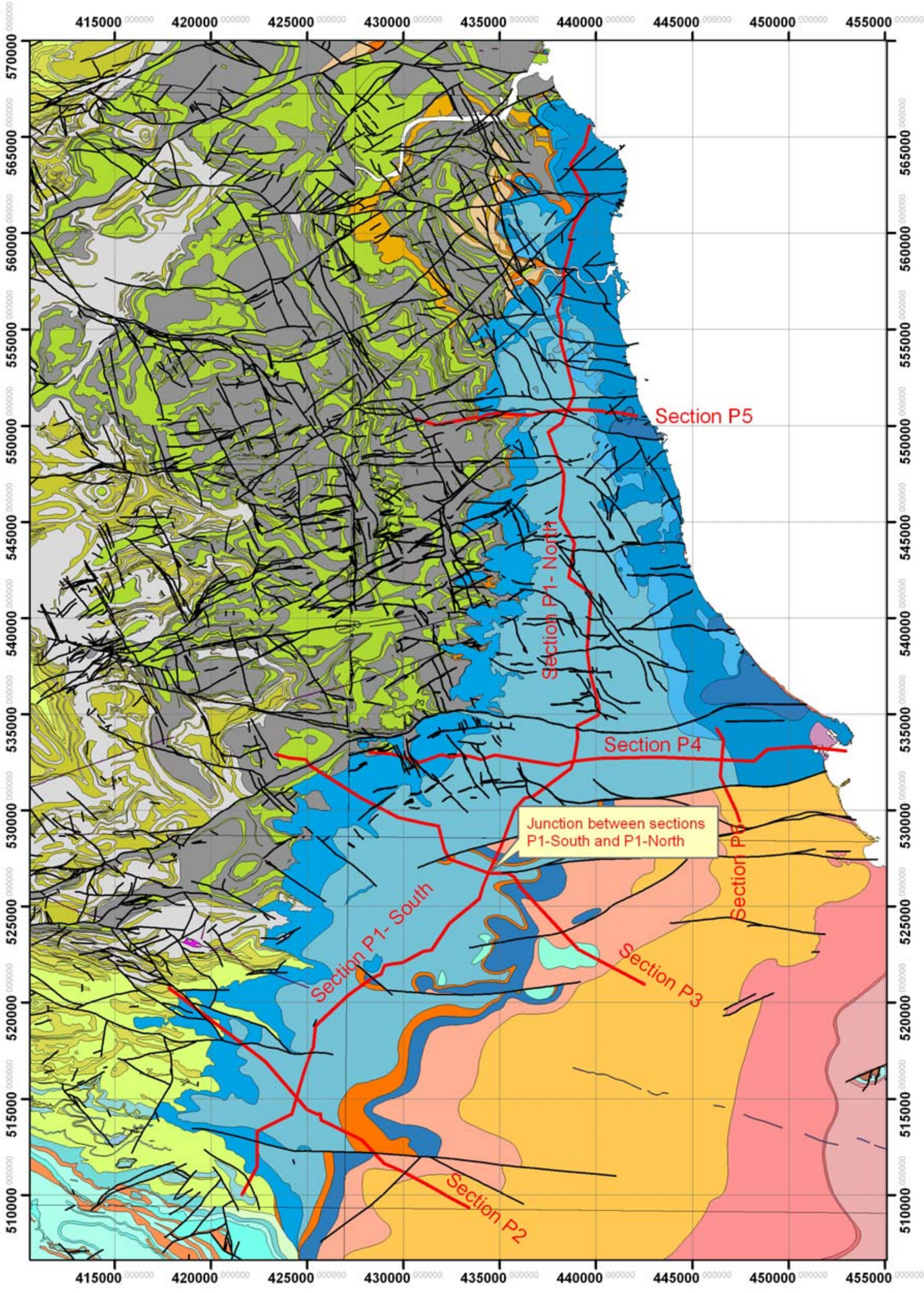

Figure 7 Location of sections P1 - P6 with respect to the local geology

Figure 8 Colours used for the sequence on the cross-sections and maps

4 Description of section P1 – North

4.1 LOCATION OF SECTION P1 – NORTH

Section P1-North is about 44km long and extends from near Marsden Bay in the north to the junction with section P3 near Sedgefield in the south, the boreholes used to construct the section are listed in Appendix 1.

Figure 9 Location of section P1-North and relationship to cross-cutting sections.

4.2 GEOLOGY AND INTERPRETATION OF SECTION P1 - NORTH

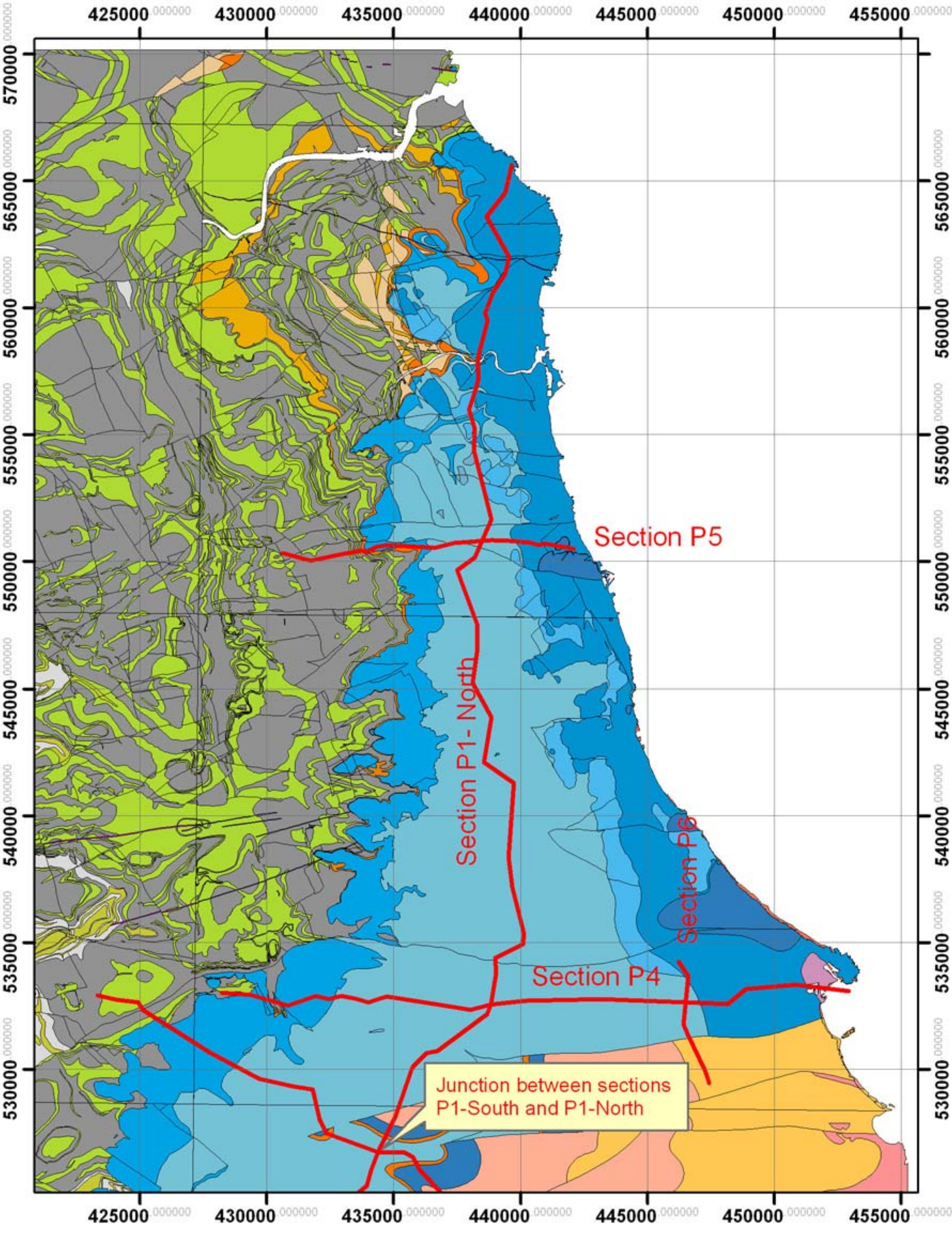

Figure 10 Geology of Section P1 – North

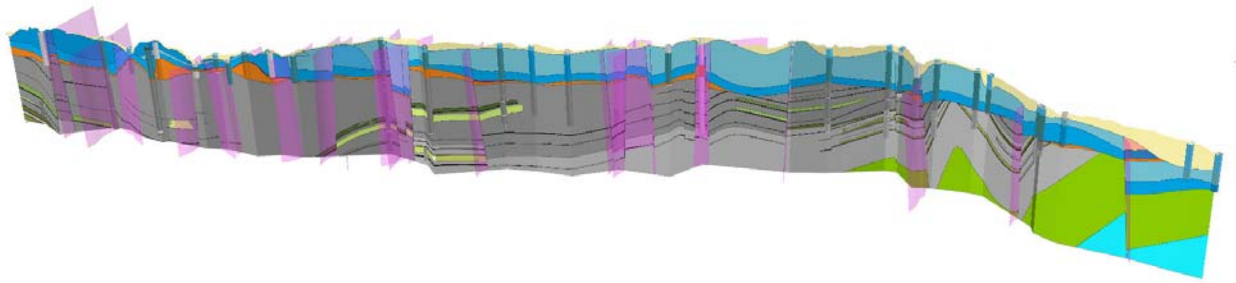

Figure 11 3D geology of section P1 - North showing faults in pink (south to right of section)

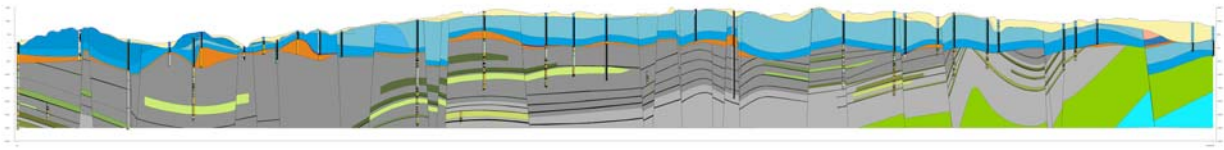

Figure 12 Geological cross-section P1 – North (south to right of section)

4.2.1 The Carboniferous sequence of Section P1 – North

The sections have been constructed to a depth of 300m. In the north of the district the Carboniferous sequence beneath the Permian strata is mainly Pennine Middle Coal Measures Formation with numerous coals and sandstones. The Pennine Lower Coal Measures are present in the south part of the sequence and these are underlain by the Stainmore and Alston formations of the Yoredale Group in the south. It must be stressed that there are very few boreholes that prove the thickness of the early Carboniferous sequence and the thicknesses taken for the Stainmore and Alston formations are extrapolated from the Barnard Castle area.

4.2.2 The Permian sequence of Section P1 – North

The Permian sequence shows the effect of the buried sand dune ridges of the Yellow Sands Formation. These are aeolian sands that form approximately WSW to ENE trending ridges that vary from nothing to 60m thick. The yellow sands are described as being “millet-seed” sands (small rounded grains) in some of the boreholes. In the north of the district their regional thickness variation is shown by figure 37 in the Sunderland Memoir (Smith , 1994) and Figure 18 in the Durham Memoir (Smith and Francis, 1967) There are also localised pockets and valleys filled with breccia at this level in the sequence. The succeeding Marl Slate Formation is very thin and missing for many of the areas being considered; it is shown as a impersistent unit up to 4m thick. The Raisby Formation maps as relatively continuous across the area, thickening slightly to south and thinning slightly over highs in the Carboniferous basement, it is mainly 20-30m thick, but ranges from 15-60m. In contrast, the succeeding Ford Formation wedges out to the north of Sunderland so that the Roker Formation rests directly on the Raisby Formation. This relationship is shown in figure 34 of Smith (1994). The Ford Formation reaches a maximum thickness of about 100m towards the south of the section, but south of the Sedgefield fault where it is overlain by the Edlington Formation the thickness has reduced to around 56m. The formation includes patch reefs and shelf-edge reefs, which are shown on the published 1:10,000 and 1:50,000 scale maps. On section 1 the positions of the reefs is speculative because they are difficult to identify from borehole descriptions. Towards the very south of the section there is the Hartlepool Fault and south of this the Edlington and Roxby formations are present adjacent to the fault. This fault line represents the junction between the dominantly dolomite shelf sequence in the north and the mixed dolomite, calcareous mudstone and evaporitic sequence in the south.

4.2.3 The Carboniferous structure of Section P1 – North

The Carboniferous sequence is cut by numerous faults and some upright igneous dykes. The largest faults are in the south where the Butterknowle and Sedgefield to Hartlepool faults cut the sequence. These two southern faults appear on seismic sections to have been major basement structures that influenced the deposition of the Carboniferous sequence and subsequently became inverted (with associated folding) in late Carboniferous to earliest Permian times (Chadwick et al., 1995). Across the Butterknowle Fault the Carboniferous sequence shows a four-fold increase in thickness. The faults are shown as low angled and on the cross-sections have been given a dip of 45 degrees to the south compared with the more usual 66 degrees or so for the normal faults in the coalfield. There appears to have been reverse movement on these low-angled faults causing the formation of folds (Trimdon anticline and Fishburn syncline) along the line of the Butterknowle Fault that marks the boundary between the Alston Block to the north and the Stainmore Trough to the south. It is related to this movement that the Alston Formation (present beneath the Permian strata to the south) may have been uplifted against the Hartlepool Fault. The Butterknowle Fault is given a throw of 100-120m increasing eastwards to around 240m with a southerly dip of around 45 degrees (unpublished report by Dr D B Smith, 1985). However, this information was given before the fault was recognised as a major growth fault and it is probably only true for the upper parts of the sequence. The steeply dipping strata on the southern side of the fault form the northern limb of the Trimdon Anticline. The axis of this anticline in the Harvey seam lies between about 900 and 1100m south of the fault and the axial plane appears to dip south, parallel to the plane of the fault suggesting that the fault and anticline have a linked origin (Smith and Francis, 1967). Further south there is the Fishburn Syncline. Both the Trimdon Anticline and the Fishburn syncline form a series of en-echelon periclinal folds cut by numerous faults, the most significant of which is the Butterwick Fault.

Between the Butterknowle and Hartlepool Faults there is the NW-SE trending Butterwick Fault which connects eastwards with the West-Hartlepool Fault. This has been modelled with a more upright aspect. It is possible that like faults and periclinal en-echelon folds mapped further south the Butterknowle, Hartlepool and Butterwick faults and their associated folds could have a dextral lateral movement on them. This is the situation that occurs between the Craven Basin and Askrigg Block in the Skipton (Arthurton, 1984) and Harrogate areas (Cooper and Burgess, 1993) on the margins of the next block to the south. The folding and faulting of the Stainmore Trough sequence against the Alston Block may also have an element of lateral fault movement. This could have occurred both during deposition and during the subsequent folding and faulting.

In addition to faulting and folding, the Carboniferous sequence is also cut by several igneous dykes, which may compartmentalise the hydrogeology of the coal-bearing sequence. These dykes include the Hebburn Dyke which crosses section 1 running between Cleadon in the west and Whitburn in the east, passing just south of the Cleadon fault. (p122 in Sunderland Memoir, Smith 1994). The dyke is 4-15m wide, tholeiitic dolerite, subvertical in form, and known only from workings underground. It is not normally coincident with a fault but may follow Cleadon fault for a few hundred metres east of Cleadon. There is some speculation about the age of the dyke, but here it is modelled as pre-Permian and modelled up to the base of the Permian sequence. In the central part of Section P1-North there is also the Ludworth Dyke (Durham Memoir pp189-192, Smith and Francis, 1967). This dyke is probably related to the Whin Sill, it is doleritic up to about 20m thick and vertical. It is modelled as coincident with a minor fault that has a downthrow of between 5 and 10m to the south.

4.2.4 The Permian structure of Section P1 – North

The Durham Memoir (Smith and Francis, 1967) describes the Durham coalfield north and south of the Easington Fault as occurring in two situations. North of the Easington fault, the average dip of the coal measures exceeds that of the unconformity so that successively higher beds crop against the base of the Permian. South of the fault, the unconformity dips more steeply than the coal measures and this, together with the difference in strike between the Permian and Carboniferous strata, results in a closure of the coalfield towards the east. The memoir also notes that almost all faults of more than about 10ft (3m) displacement in the coal measures are reflected in the overlying Permian rocks cropping out along the coast; either as clean, relatively simple breaks having a dip of about 70 degrees, or as nearly vertical shatter belts up to 20 to 30ft (6-9m) wide. In both cases the displacement in the Permian strata generally appears to be considerably less than in the underlying coal workings. This situation is shown in the modelled cross-sections through the area. Much of the interpretation of the Permian structure has benefited from the contour maps in the Sunderland and Durham Memoirs (Smith and Francis, 1967; Smith, 1994), these were georegistered and used as a backdrop for the cross-section modelling. The base of the Permian in Section P1-North is irregular and offset by many faults. The section is approximately along strike so major thickness changes in the Permian strata are caused by primary effects – deposition on the irregular, eroded surface of the coal measures, and secondary faulting.

In addition to the reactivation of the faulting, the Tertiary earth movements caused renewed folding along pre-existing axes in the Carboniferous strata. The Permian strata were deformed into broad folds while the underlying folds in the Carboniferous strata were tightened. Consequently, the Trimdon Anticline is a broad fold in the Permian strata overlying a tighter fold in the Carboniferous.

5 Description of section P1 – South

5.1 LOCATION OF SECTION P1 – SOUTH

Section P1-South extends from the intersection of section P3 southwards between Newton Aycliffe and Darlington to about 12km due south of Piercebridge almost to Scotch Corner, the boreholes used are listed in Appendix 1.

Figure 13 Location of section P1 - South and its relationship to sections P2 and P3

5.2 GEOLOGY AND INTERPRETATION OF SECTION P1 - SOUTH

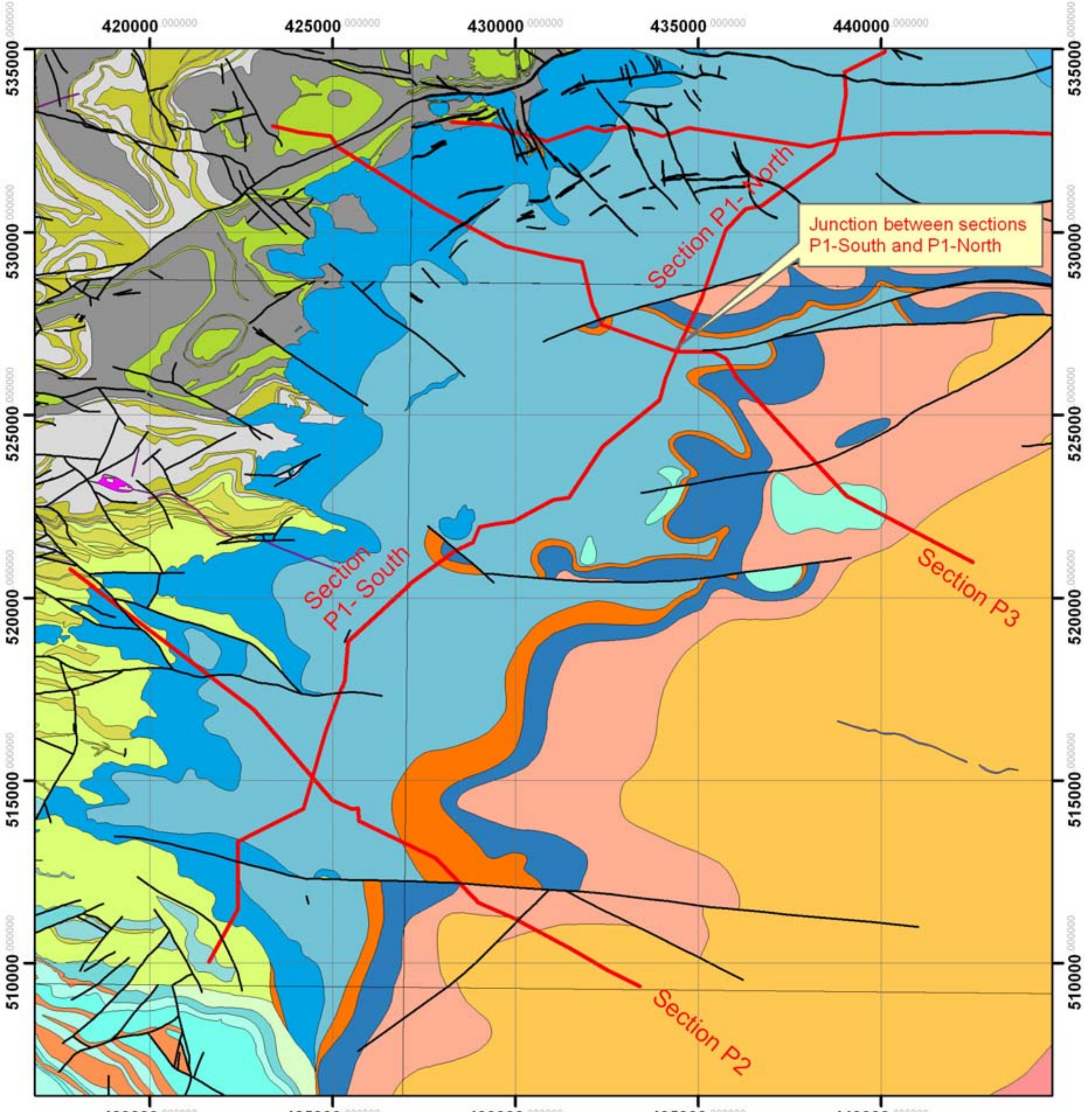

Figure 14 Geology of section P1 - South

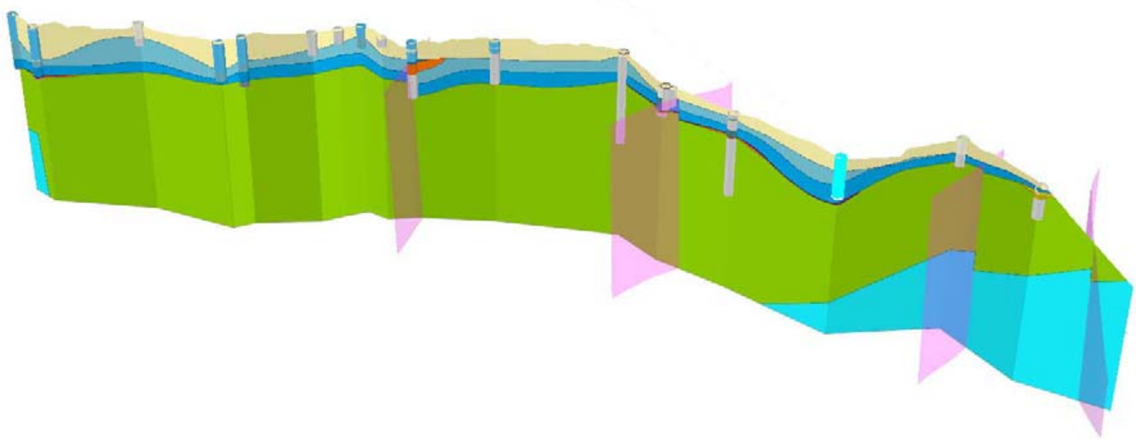

Figure 15 3D view of section P1 – South (south to right of section)

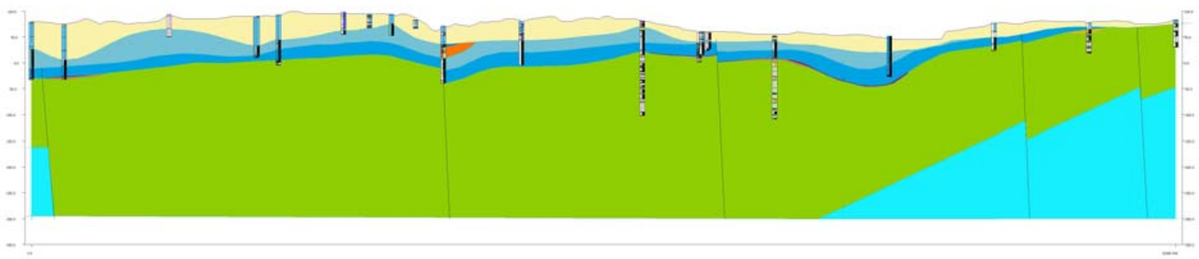

Figure 16 Section P1 - South (south to right of section)

5.2.1 The Carboniferous sequence of section P1 – South

The oldest rocks present within section P1-South occur at depths in excess of 150m, they are shown on the published Stockton (33) map as Alston Group of Dinantian age and on the Barnard Castle (32) map as the Carboniferous Limestone Series. This sequence is now referred to as the Alston Formation, a constituent part of the Yoredale Group. It comprises a sequence of limestones, mudstones and sandstones in a cyclic "Yoredale" facies. There are no boreholes on the section that penetrate this sequence the position of which is interpreted from extrapolation from the surrounding areas where it is exposed.

The Alston Formation is overlain by the Stainmore Formation (formerly group) that is the upper part of the Yoredale Group. This equates approximately with what was formerly called the Millstone Grit Group. It comprises up to 400 m of interbedded mudstones and siltstones with thick coarse-grained sandstone units. There are several boreholes that prove this part of the sequence showing it has a similar lithology to the sequence seen to the west on the Barnard Castle and Wolsingham areas (geological 1:50,000 scale sheets 26 and 32). The thickness and disposition of this part of the sequence is speculative, derived from the surrounding areas, but the seismic interpretation of Chadwick (1995 – map 9) suggests that the boundary between the Stainmore and Alston formations could be much deeper. If the interpretation of Chadwick (1995) is taken then the entire Carboniferous beneath this section will be part of the Stainmore Formation. This interpretation conflicts with the thicknesses published in the memoirs and casts doubt on the Alston Group inliers interpreted shown on the map (Figure 18) and on section P3.

5.2.2 The Permian sequence of section P1 - South

Small areas of breccia are proved locally at the base of the Permian sequence, but the Yellow Sands Formation is largely missing in the south of the study area. The limestone and dolomite sequence on Section P1-South is thin as the Raisby and Ford formations thin westwards on to the Pennines and southwards on to the flank of the Middleton Tyas Anticline where they are missing altogether (Richmond sheet 33). The thickest part of the sequence preserved is in the middle of the Darlington Syncline that approximates to the intersection of sections P1-South with section P2. A small area of the Edlington and Seaham formations is caught against the westerly continuation of the Hartlepool Fault line. At this locality the borehole proves a thin sequence of mudstone representing the Edlington Formation. This far west the evaporites were either not deposited, or they have been dissolved away.

5.2.3 The Carboniferous structure of section P1 - South

The section does not have much evidence for the detailed structure of the Carboniferous rocks. The overall dip for the southern part of the sequence is northerly, but there is a possibility of periclinal folds adjacent to the continuation of the Hartlepool Fault. From the interpretation of the Stockton area and the strata proved in the Billingham Mine (Raymond, 1960) it is possible that Alston Formation could be present in folds not shown on the section.

5.2.4 The Permian structure of section P1 – South

The main structure of the Permian strata is a gentle easterly dip with the easterly plunging Darlington Syncline. This is an important structure for the hydrogeology beneath Darlington as it concentrates the groundwater flow into the axial regions of the syncline and helps to control both the preservation and subsequent dissolution of the anhydrite and gypsum of the Hartlepool Anhydrite Formation beneath Darlington (Cooper and Gordon, 2000).

6 Description of section P2

6.1 LOCATION OF SECTION P2

Section P2 extends from near Killerby in the north-west, passing just to the south of Darlington and terminating in the south-east near Neasham, the boreholes used to construct the section are listed in Appendix 1.

Figure 17 Location of section P2 and its relationship to sections P1- South and P3

6.2 GEOLOGY AND INTERPRETATION OF SECTION P2

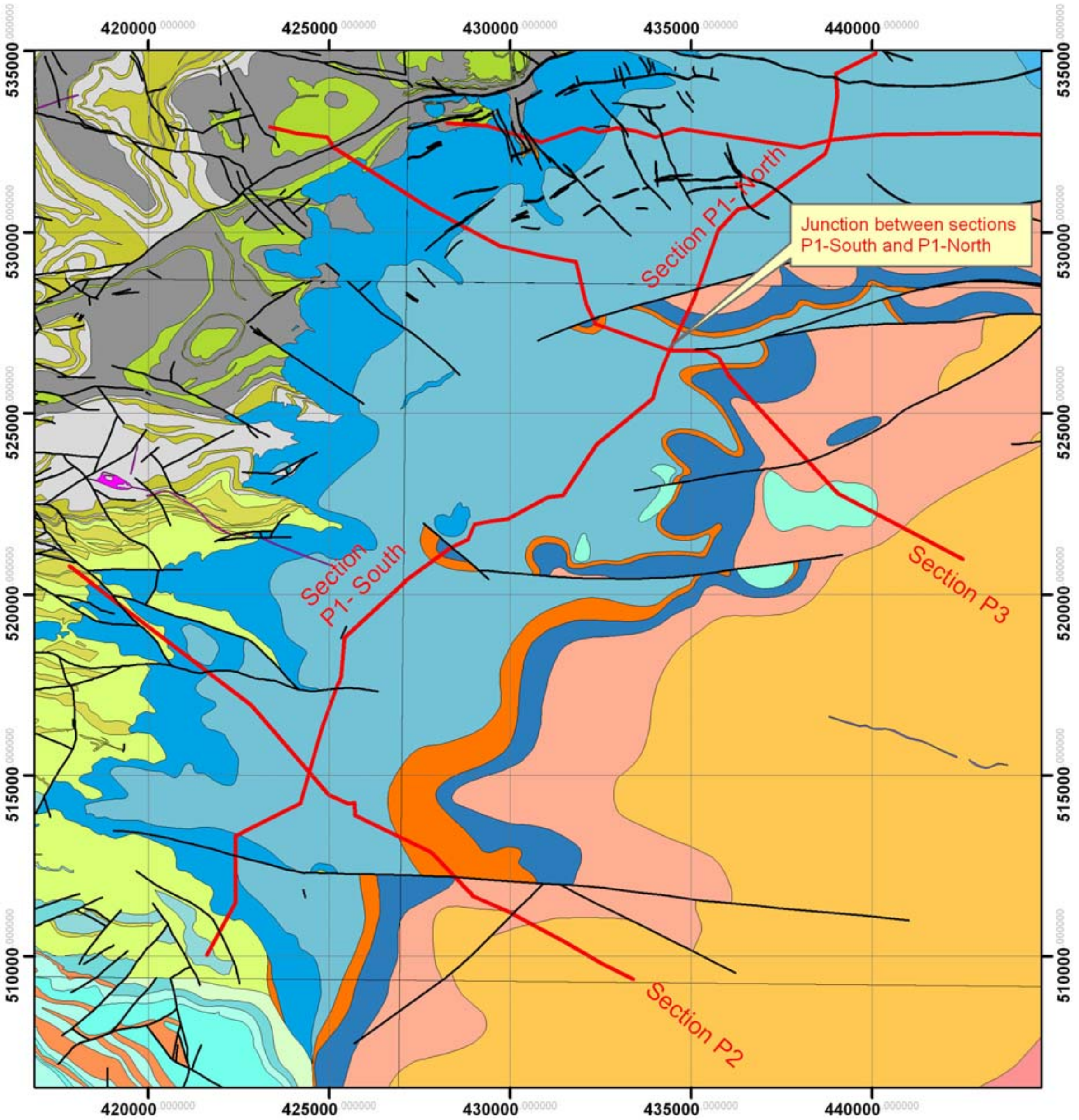

Figure 18 Geology of section P2

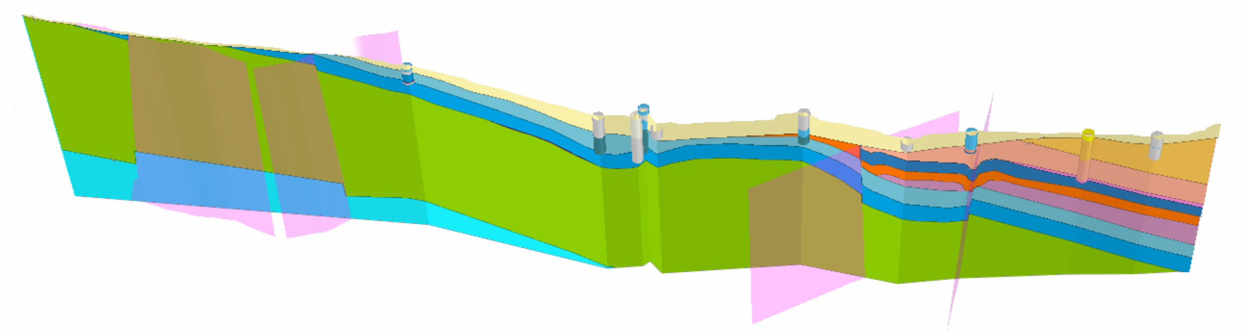

Figure 19 3D view of section P2 (east to right of section)

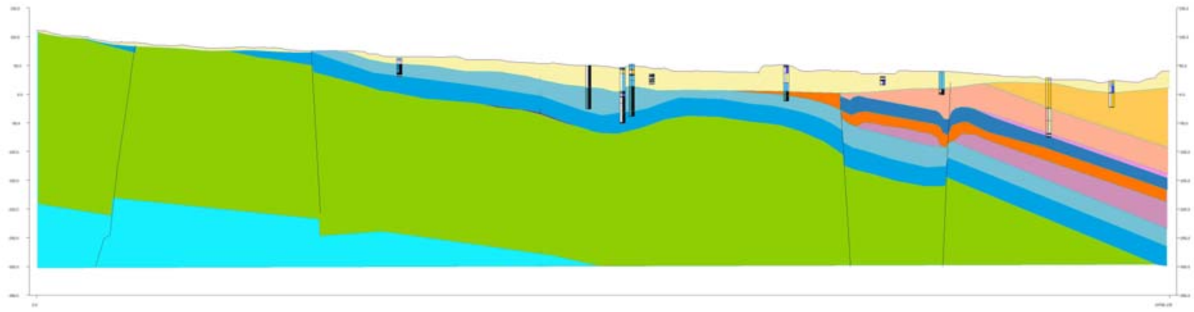

Figure 20 Section P2 (east to right of section)

6.2.1 The Carboniferous sequence of section P2

The oldest rocks present within section P2 at depths of about 300m are shown on the published Stockton (33) map as Alston Group of Dinantian age and on the Barnard Castle (32) map as the Carboniferous Limestone Series. This sequence is now referred to as the Alston Formation, a constituent part of the Yoredale Group. It comprises a sequence of limestones, mudstones and sandstones in a cyclic “Yoredale” facies. There are no boreholes on the section that penetrate this sequence the position of which is interpreted from extrapolation from the surrounding areas where it is exposed.

The Alston Formation is overlain by the Stainmore Formation (formerly group) that is the upper part of the Yoredale Group. This equates approximately with what was formerly called the Millstone Grit Group. It comprises up to 400 m of interbedded mudstones and siltstones with thick coarse-grained sandstone units. These will be of similar lithology to the sequence seen to the west on the Barnard Castle and Wolsingham areas (geological 1:50,000 scale sheets 26 and 32). Like the Alston Formation, the thickness and disposition of this part of the sequence is speculative, derived from the surrounding areas. However, it must be noted that the seismic interpretation of Chadwick (1995 – map 9) suggests that the boundary between the Stainmore and Alston formations could be much deeper. This interpretation conflicts with the thicknesses published in the memoirs and casts doubt on the Alston Group inliers interpreted shown on the map (Figure 18) and on section P3. If the interpretation of Chadwick (1995) is taken then the entire Carboniferous beneath this section will be part of the Stainmore Formation.

6.2.2 The Permian sequence of section P2

The Permian sequence on section P2 is typical of the Permian south of the Hartlepool Fault and through the Teesside area. Within this part of the study area the Yellow Sands Formation is largely missing and there is evidence of buried hills of Carboniferous strata similar to those seen further to the south. In the south on the Richmond (41) sheet the Middleton Tyas Anticline in the Carboniferous sequence sticks up into the Permian strata causing it to thin over the fold. The borehole evidence suggests that the Raisby and Ford Formations are relatively thin across this area when compared with further north. This thinning is also shown on section P3 (Figure 24) and to the southern end of section P1-South (Figure 16).

6.2.3 The Carboniferous structure of section P2

Very little structure is delineated on the section; as noted above, the exact position of the contact between the Alston and Stainmore formations is speculative. At the western end of section P2 the exposed Stainmore Formation strata are dipping to the NNE and the Pennine Lower Coal Measures Formation comes in just to the north of the section. At the southern end of the section the strata could be on the northern flank of the Middleton Tyas Anticline mapped on the Richmond (41) sheet.

6.2.4 The Permian structure of section P2

The Permian structure on this section is relatively simple. It generally has a gentle easterly dip, but through Darlington there is an open east-west trending syncline plunging to the east and flanked to the south by a significant normal fault that juxtaposes the Roxby Formation against the Edlington Formation. To complicate matters, the structure is interpreted as being more complicated where the Hartlepool and Billingham anhydrite formations come near outcrop or approach faults at relatively shallow depths. In these situations the anhydrite hydrates to gypsum and dissolves causing foundering of the overlying strata. This can produce monoclinal structures which reverse the regional easterly dip to a westerly direction. This situation has been recorded in the Darlington district and the Ripon area much further to the south (Cooper, 1998). Within the dissolution areas up to about 40m of the Hartlepool Anhydrite Formation (as gypsum) and up to 6m of the Billingham Anhydrite Formation (as gypsum) have been dissolved. Where the evaporites have dissolved the overlying strata (especially the Seaham Formation) is commonly brecciated due to foundering. Sulphate-rich groundwater and active dissolution are common in this sequence in this area (Lamont-Black et al., 2002 and 2005).

7 Description of section P3

7.1 LOCATION OF SECTION 3

Section 3 extends from just south of Spennymoor to the north-west of Stockton, the boreholes used are listed in Appendix 1.

Figure 21 Location of section P3 and its relationship to section P1 – South and P2

7.2 GEOLOGY AND INTERPRETATION OF SECTION P3

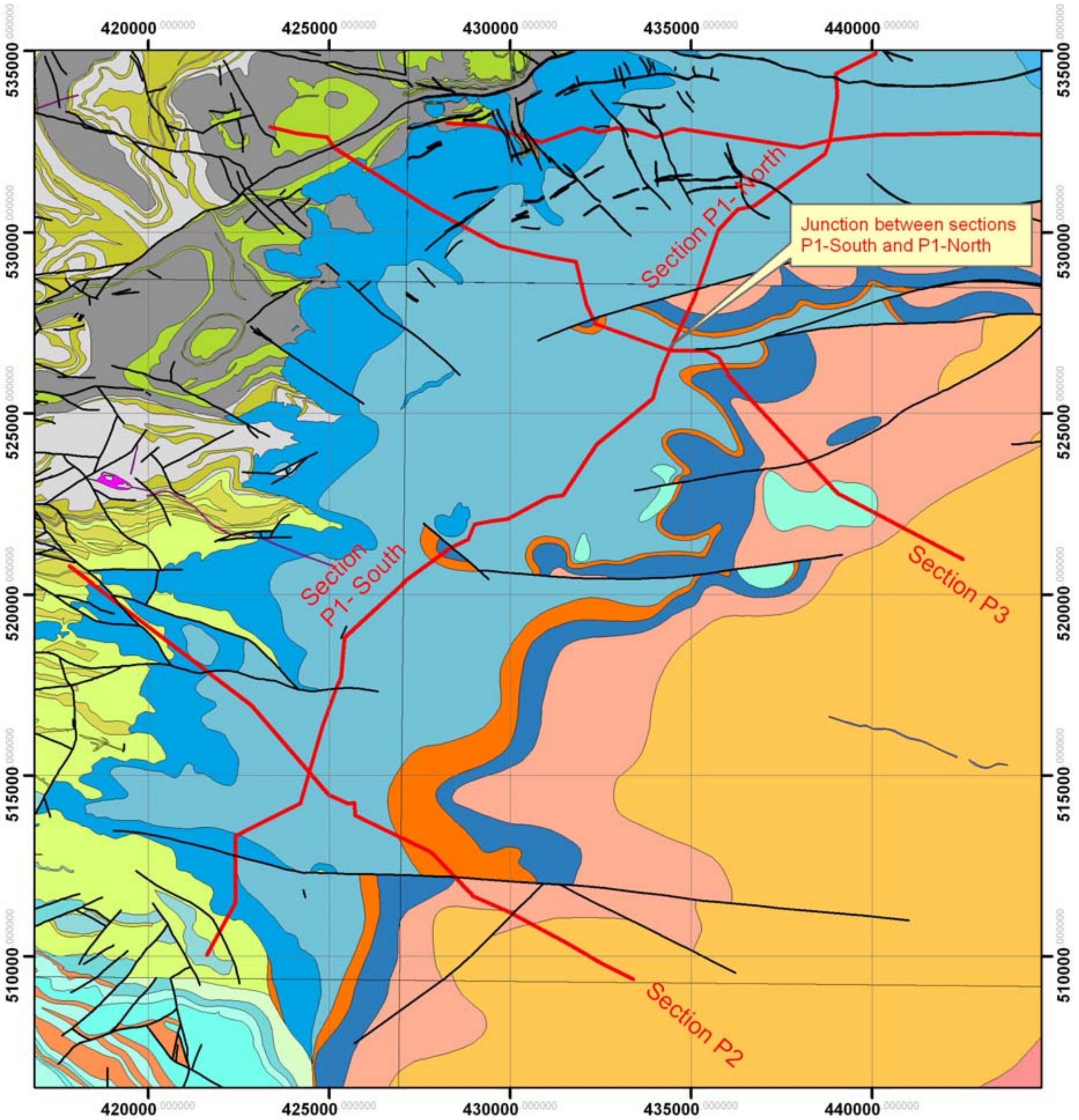

Figure 22 Geological map of the study area showing the location of Section P3 and its relationship with Section P1 – South and P2

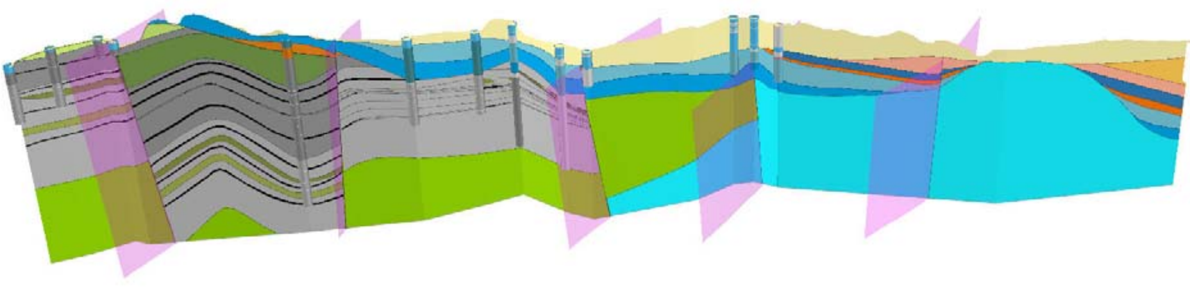

Figure 23 3-D view of Section P3 showing the faults in pink and the bedrock geology, (north-west to left, south-east to right).

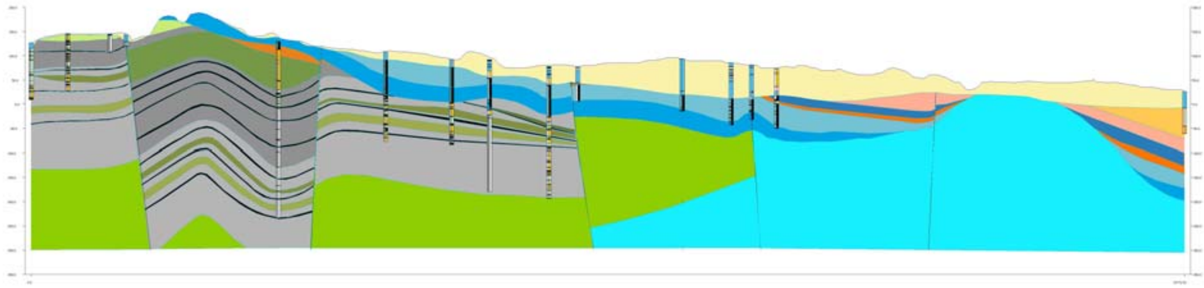

Figure 24 Section P3 showing the bedrock geology to a depth of 300m below OD, north-west to left, south-east to right, the section is 24km long (south-east to the right).

7.2.1 The Carboniferous sequence of section P3

The whole of the area is underlain by Carboniferous rocks at depth, these are concealed by Permian rocks in the east (Figure 24) which are heavily blanketed by superficial deposits that reach a maximum thickness of approximately 75 m. Most of the information about the Carboniferous rocks has come from borehole interpretations with a little, fairly old, seismic interpretation.

The oldest rocks present within the area are shown on the published Stockton (33) map as Alston Group of Dinantian age. This sequence is now referred to as the Alston Formation, a constituent part of the Yoredale Group. It comprises a sequence of limestones, mudstones and sandstones in a cyclic "Yoredale" facies. These rocks outcrop as inliers, surrounded by Permian strata (Figure 22) and intersect section P3 near Whitton [GR 4383 5228]. The published map notes that *"The upper part of the Alston Group crops out in four inliers, but data is lacking to give details"*. There are no boreholes in the area in the BGS collection that penetrate these inliers, but they do lie on or near the lines of seismic investigation routes. It is likely that the inliers have been interpreted from commercial in confidence seismic information that was available at the time the map was compiled. The very deep Seal Sands borehole on Teesside proves about 3000m of the Yoredale Group sequence, but there is no indication of the exact thickness in the study area. Strata of the Alston Formation were also found beneath a thinned Permian sequence below Billingham Anhydrite Mine (Raymond, 1960).

The Alston Formation is overlain by the Stainmore Formation (formerly group) that is the upper part of the Yoredale Group. This equates approximately to the Millstone Grit sequence (Figure 1). It comprises up to 400 m of interbedded mudstones and siltstones with thick coarse-grained sandstone units. These will be similar to the sequence seen to the west on the Barnard Castle and Wolsingham areas (geological 1:50,000 scale sheets 26 and 32). The thickness and structure of this part of the sequence is speculative, derived from the surrounding areas, but the seismic interpretation of Chadwick (1995 – map 9) suggests that the boundary between the Stainmore and Alston formations could be deeper. This interpretation conflicts with the thicknesses published in the memoirs and casts doubt on the Alston Group inliers interpreted on section P3.

Above the Alston Formation there is the Pennine Coal Measures Group which within the study area comprise the Pennine Lower Coal Measures Formation, about 230 m thick, overlain by the Pennine Middle Coal Measures Formation, which is approximately 600 m thick. The boundary between these formations occurs at the Harvey (Vanderbeckei) Marine band and both formations comprise mainly mudstone and siltstone with numerous named coals and numerous thick sandstone units. The individual coal seams are variable in thickness and may be absent in regions defined as wash-outs. In these areas sandstone-filled channels and thicker, more extensive sandstone units may have eroded the coals and associated deposits. The generalized sequence for this part of northern England is shown in Figure 1 . On Section P3 not all the coal seams are shown, but the following coal seams requested by the EA and their associated significant sandstones are modelled:

- Sandstone at outcrop east of the Butterknowle Fault and below the Ryhope Five-Quarter Coal
- Sandstone above the 5 Quarter Coal
- Five-Quarter Coal
- Main Coal
- Maudlin Coal
- Sandstone above the Hutton Coal in the west of the area
- Hutton Coal
- Harvey Coal
- Sandstone above the Busty Coal
- Busty Coal
- Sandstone above the Brockwell Coal
- Brockwell Coal

7.2.2 The Permian sequence of section P3

On Section P3, the Permian sequence is shown to lap on to the Carboniferous rocks of the Pennines to the west and on to the elevated Yoredale Group rocks that protrude as buried hills resulting in inliers on the published map. The relationship has been modelled as an onlap situation since this is what has been mapped on the Middleton Tyas Anticline (Richmond Sheet 41) and around the Harrogate Anticline (Harrogate Sheet 62 and Cooper and Burgess, 1993) further to the south. The buried hills of Carboniferous strata give rise to numerous inliers, both shown on the published Stockton (33) map and proved in the workings of the Billingham Anhydrite Mine (Raymond, 1960) where Alston Formation strata have been proved and where the lower part of the Permian Zechstein Group (Raisby to base of Seaham formations) is largely missing.

The Edlington and Roxby formations on Section P3 possibly include evaporites in the form of the Hartlepool Anhydrite (as gypsum) at the base of the Edlington Formation and the Billingham Anhydrite (as gypsum) at the base of the Roxby Formation. These two evaporite formations are difficult to map and no boreholes prove their existence on the line of Section 3, consequently only the Edlington and Roxby formations have been shown.

7.2.3 The Carboniferous structure of section P3

The borehole data is variable and in some fault blocks there is reasonable certainty about the correlations, in others the model must be considered as extrapolative. In the west of the district the modelling has some surface geological control while to the east it has very little. In the west the Butterknowle Fault (shown on the Barnard Castle, Wolsingham and Durham maps – sheets 26, 27 and 32) is a major tectonic structure that appears to be a reactivation of an Acadian/Caledonian basement fault which passes across the country from the Lake District. This deep basement line partly bounds the Stainmore Trough (Darlington area) which is present between the Alston Block (Northumberland, Tyne and Wear and northern county Durham) to the north and the Askrigg Block (North Yorkshire) to the south. To the south of this line the inference from the inliers of Yoredale Group rocks in the Stockton area (east end of Section P3) is that the sequence has been folded, faulted and possibly reverse faulted by basin inversion against the block sequence present to the north during the end Carboniferous Variscan deformation events. This is the situation that occurs well to the south at the junction between the Craven Basin and the Askrigg Block along the Craven Faults seen on the Settle and Harrogate districts (sheets 60 and 62; Arthurton, 1984; Cooper and Burgess, 1993). On Section P3 (Figure 24) the faulting between the Pennine Coal Measures Group and the Yoredale Group is inferred to be a pre-Permian reverse fault that was reactivated as a normal fault in post Permian times. East of this there is another fault which could also be a reverse fault in the Carboniferous reactivated as a normal fault/fold after the Permian. This is a continuation of the structures mapped as the Seaton Carew/Newton Hanzard/Greatham faults on the Stockton area (sheet 33), which both have a post-Permian downthrow to the south.

7.2.4 The Permian structure of section P3

The Permian rocks are faulted by several normal faults which preserve small areas of the higher parts of the sequence. It appears that these faults are largely reactivation structures over reverse and normal faults in the underlying Carboniferous sequence. The faulted east-north-east trending anticline present south of Sedgefield has been modelled as a reactivation structure over a reverse fault. This structure passes eastwards into the Seaton Carew/Newton Hanzard/Greatham faults, which all have a normal downthrow to the south (inset map on Sheet 33, Stockton).

8 Description of section P4

8.1 LOCATION OF SECTION P4

Section P4 extends from Spennymoor in the west to Hartlepool in the east, the boreholes used are listed in Appendix 1.

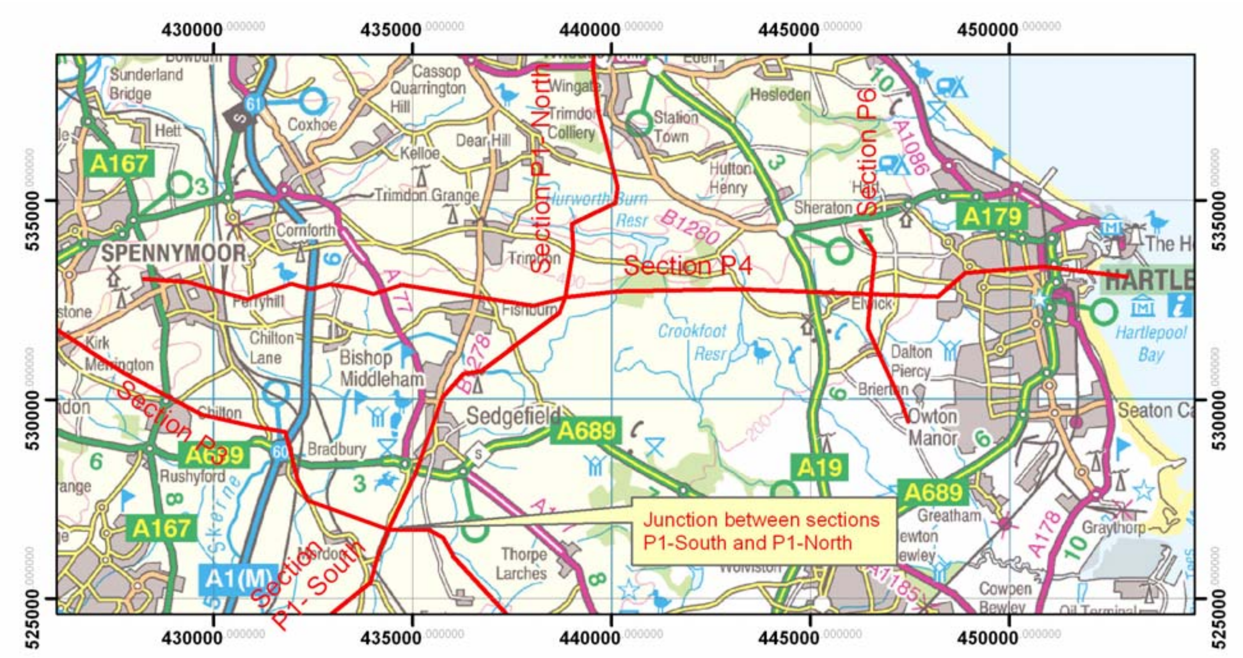

Figure 25 Location of section P4 and its relationship to sections P1-North and P6

8.2 GEOLOGY AND INTERPRETATION OF SECTION P4

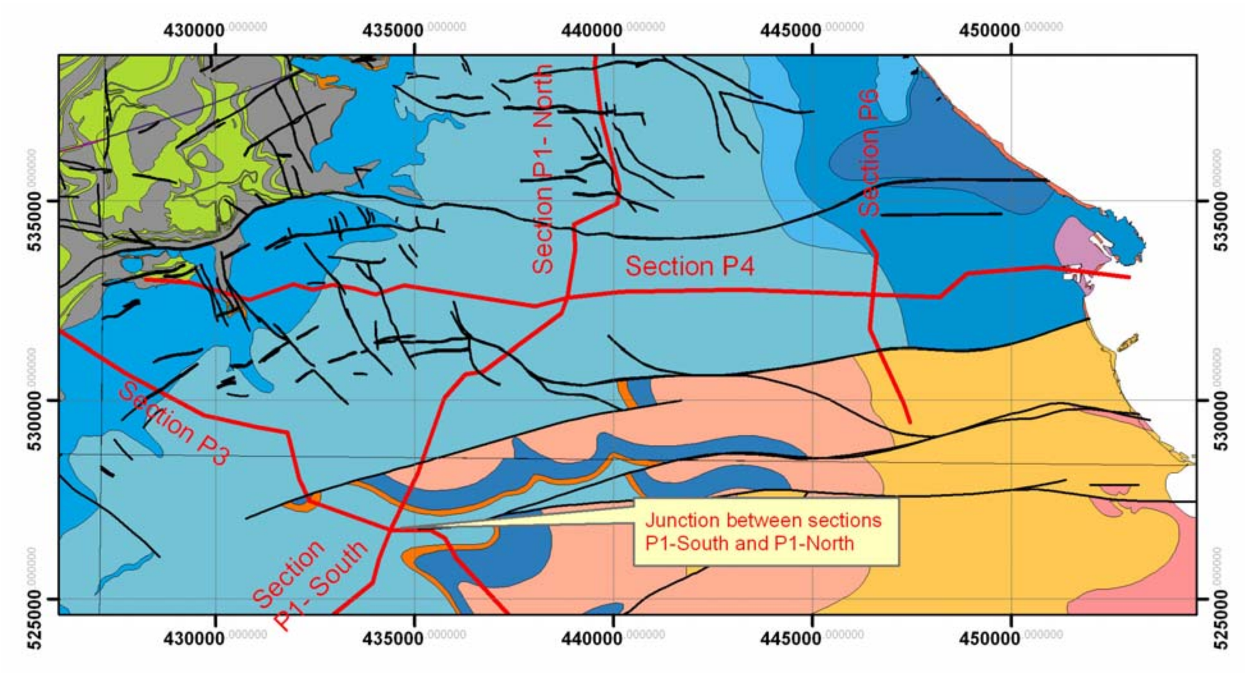

Figure 26 Geology of section P4

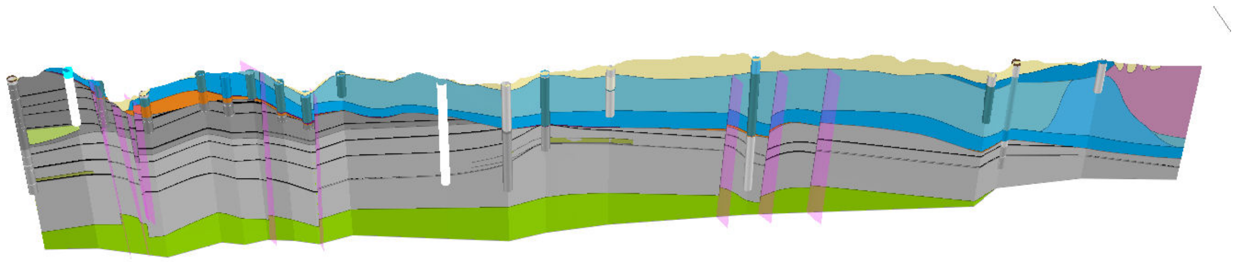

Figure 27 3D view of section P4, (east to right of section)

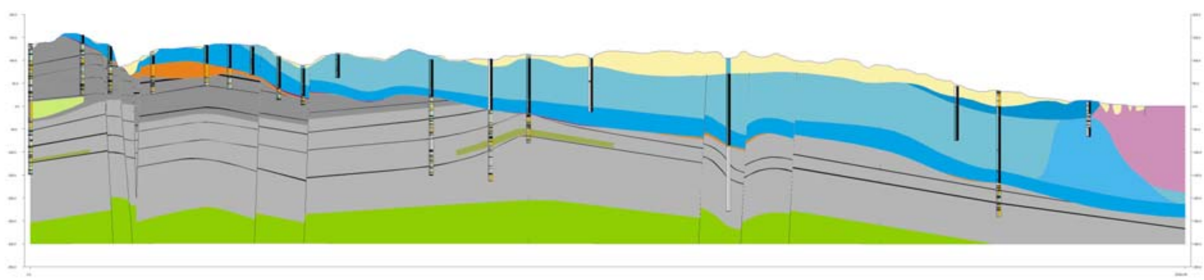

Figure 28 Section P4 (east to right of section)

8.2.1 The Carboniferous sequence of section P4

The Middle and Lower Coal Measures formations along the line of section 4 are fairly well delineated at least to the base of the Brockwell Seam. The sequence of coal seams shown in Figure 2 is present with significant sandstone units mapped beneath the Hutton Seam in the west of the section and above the Brockwell seam in the west and centre of the section, this later occurrence is near to the base of the Permian sequence at the junction of sections P1-North/P1-South.

8.2.2 The Permian sequence of section P4

The Permian strata include thick Yellow Sands Formation (up to about 40m) in the lower part of the succession towards the western end of the section. Thin breccias are also present in the middle and east of the section. The boreholes and preserved sequence suggest an undulating unconformity and a more undulating top to the Yellow Sands Formation. The Marl Slate Formation is recognised mainly towards the west and middle of the section where it only reaches a metre or so in thickness and where it fills hollows or fills in around the Yellow Sands Formation. In boreholes, the succeeding Raisby Formation is difficult to separate from the overlying Ford Formation, however some holes logged by Dr D B Smith help to separate them. The Raisby Formation where it crops out in the west is interpreted to be around 50-60m thick. It thins eastwards to a minimum of around 30m at the coast. The overlying Ford Formation is modelled as being of fairly constant thickness across the area along the line of section P4 and reaches about 125m in thickness. By comparison with the good exposures to the north (Smith and Francis, 1967; Smith 1994) the Ford Formation is interpreted to be bounded on the east by a reef that marks an abrupt boundary with the overlying Hartlepool Anhydrite Formation. The Ford Formation complex is interpreted as a reef-bounded carbonate ramp. Offshore at the eastern end of section P4 the Hartlepool Anhydrite Formation is inferred to be about 190m thick and beneath Hartlepool the former anhydrite mine worked levels over an 80m thickness of the formation. The Hartlepool Anhydrite Formation disappears onshore and the relics of it that went over the reef top have been dissolved so that the overlying Roker Formation (including the Concretionary Limestone Member) rest directly on the underlying Ford Formation. The relationships of the formations are shown by Smith, (1989 and 1994 – Figure 35).

The West Hartlepool Fault that occurs just to the south of section P4 and on section P6 is interpreted to be an important structure that influenced Permian deposition during the Rotliegede and Zechstein Group times. It marks the place where the pre-Permian hills that are present to the south die out and the Yellow Sands Formation sand dunes come in. It also marks the southern limit of the thick carbonate/dolomite sequences and the fringing reefs, which do not come back in until south and east of the Middleton Tyas area.

8.2.3 The Carboniferous structure of section P4

Section P4 runs east-west through the fault block that is bounded by the Butterknowle Fault to the north and the West Hartlepool fault to the south. The structure of this belt is illustrated by the structure contour map in the Durham memoir (Plate XIV, Smith and Francis, 1967). It shows that the coal-bearing sequence is folded into a series of periclines including the Trimdon Anticline and the Fishburn Syncline. However, because section 4 effectively runs along strike the folding is not very apparent. Section P1-North (Figure 12) shows the structure as the section cuts perpendicularly through it.

8.2.4 The Permian structure of section P4

The Permian structure along section P4 shows a gentle easterly dip cut by numerous minor faults that mainly represent reactivation of the underlying faults affecting the Carboniferous sequence.

9 Description of section P5

9.1 LOCATION OF SECTION P5

Section P5 extends from near Colliery Row and the A1M in the west eastwards to the coast just to the north of Seaham, the boreholes used are listed in Appendix 1. The line of the section has been chosen to go near Houghton Quarry.

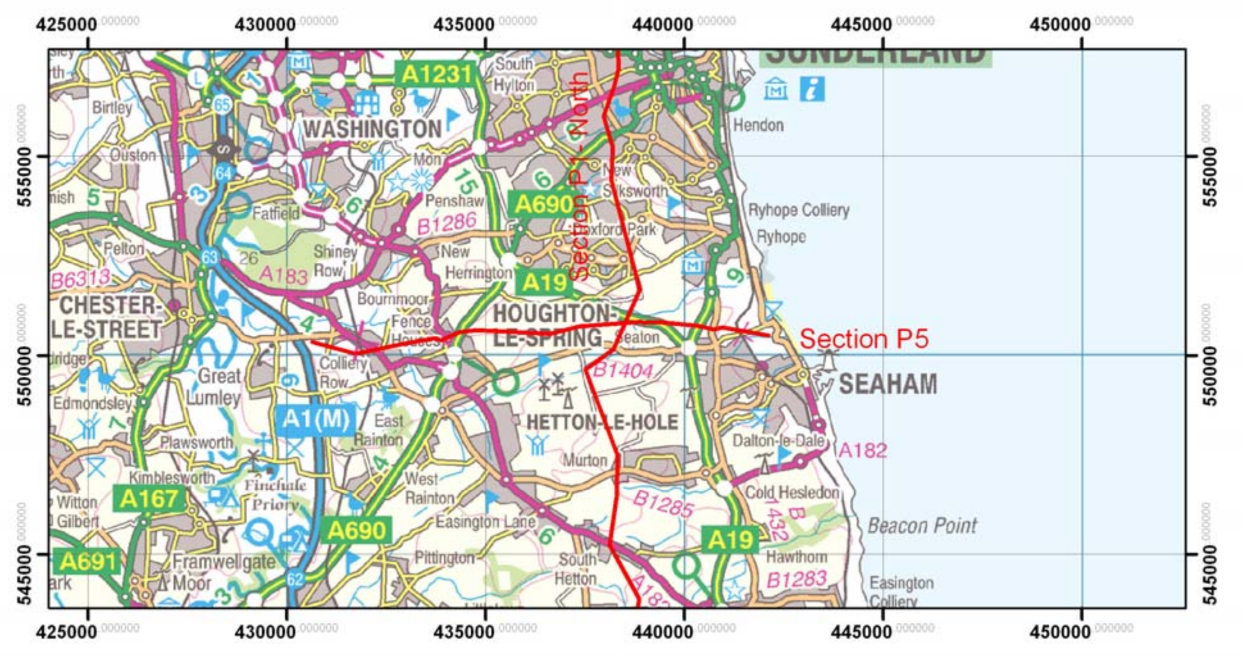

Figure 29 Location of section P5

9.2 GEOLOGY AND INTERPRETATION OF SECTION

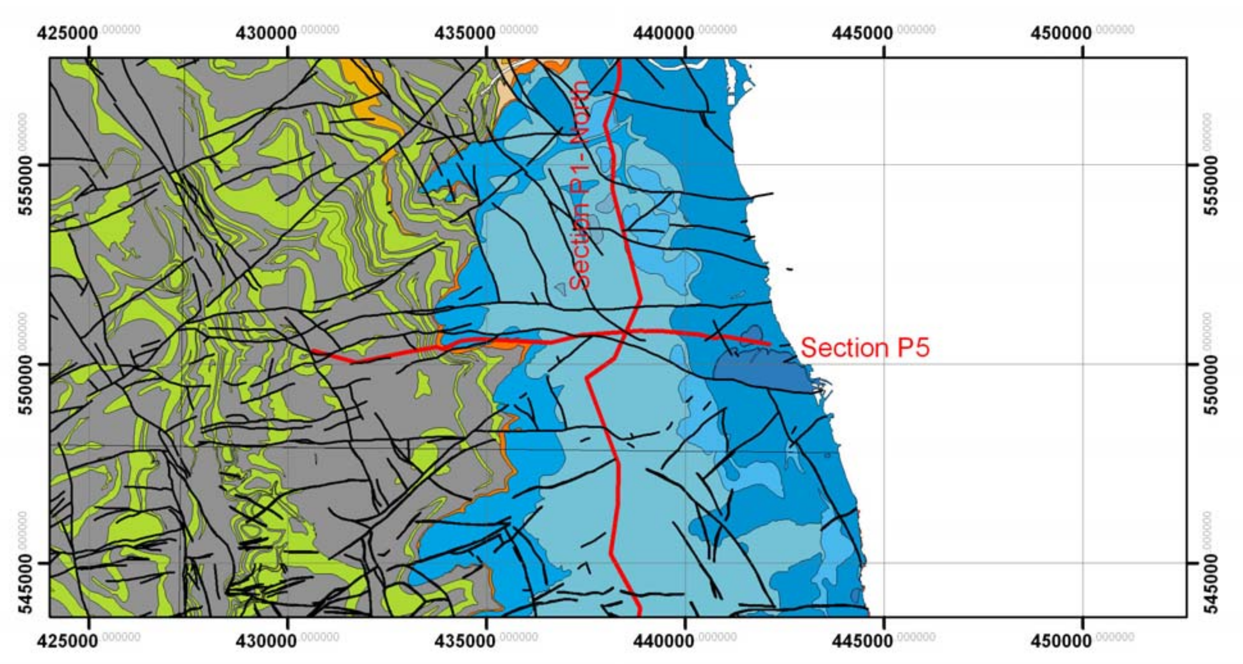

Figure 30 Geology of section P5

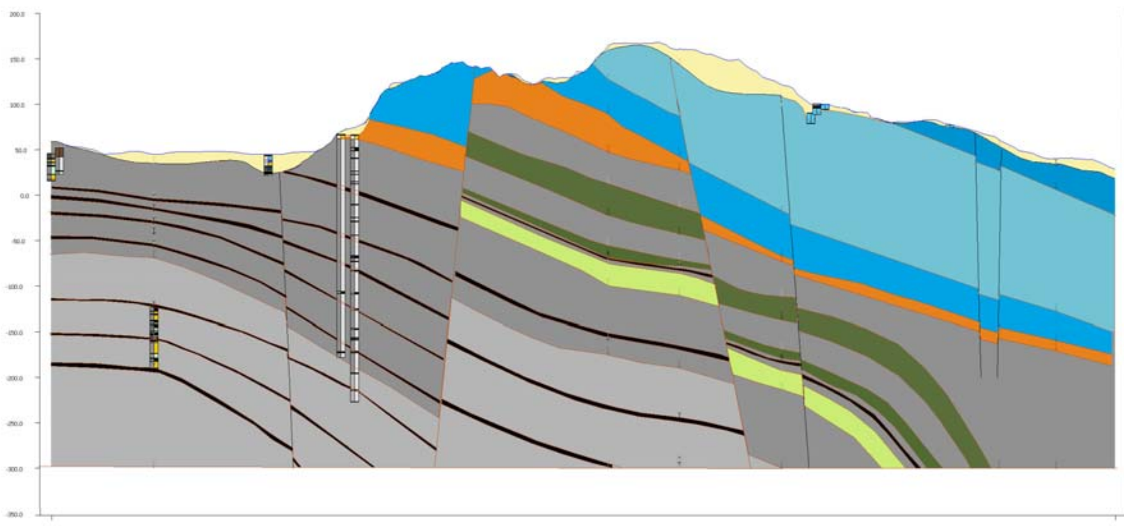

Figure 31 Section P5 (east to right of section)

9.2.1 The Carboniferous sequence of section P5

The Carboniferous sequence of section P5 is interpreted from the exposed Pennine Coal Measures seen at outcrop on the Sunderland sheet (21) and the boreholes further east. The Ryhope Little Coal is present at outcrop and in a borehole a little to the east, its presence is fairly well constrained. The Harvey, Busty and Brockwell seams in the Pennine Lower Coal Measures are proved underground in coal workings and by underground boreholes. The sequence between these two sets of data is poorly constrained but one borehole suggests that at about the level of the Hutton Seam, some of the seams are washed out and replaced with sandstone. This has been modelled as being terminated in the west at a fault; we have no evidence as to how extensive this sandstone and the adjacent sandstone units are, because they are not indicated in the boreholes near outcrop. The distribution of good boreholes in the area is such that there is little reliable evidence of the coal seams to the east of the area, consequently, the sequence in the east of the section is not well constrained.

9.2.2 The Permian sequence of section P5

The Permian sequence shows the presence of thick lenticular Yellow Sands Formation at the unconformity between the Permian and Carboniferous strata. These sandstones reach at least 25 m, possibly 35 m thick in the vicinity of Houghton Quarry, the outcrop pattern here suggesting the crest of a buried sand dune. Along most of this cross-section, the Raisby Formation is interpreted to be around 25-40 m thick which is similar to its thickness along much of the outcrop, but it may thicken on the flanks of the buried sand dune and thin over the top of it. The overlying Ford Formation is much thicker and interpreted to have patch reefs developed within it. The disposition of the strata in the vicinity of Houghton Quarry is reinforced by borehole evidence, but there may be some folding or thickening of the sequence towards the fault that runs approximately parallel to section P5, consequently the Raisby Formation hereabouts appears thicker than it does a little to the east and is shown up to about 70m thick. Alternatively, there may be some unrecognised Ford Formation to the south of the quarry adjacent to the fault.

9.2.3 The Carboniferous structure of section P5

The Carboniferous structure shows a general easterly dip which increases considerably towards the coast and the intersection with section P1-North. The faults downthrow to the north and the coast.

9.2.4 The Permian structure of section P5

The Permian structure shows a gentle easterly dip with faults that are along the same lines as the faults affecting the Carboniferous, but with generally smaller amounts of throw on them.

10 Description of section P6

10.1 LOCATION OF SECTION P6

Section P6 extends for about 5km in a north-south direction passing through Elwick just to the west of Hartlepool, the boreholes used are listed in Appendix 1.

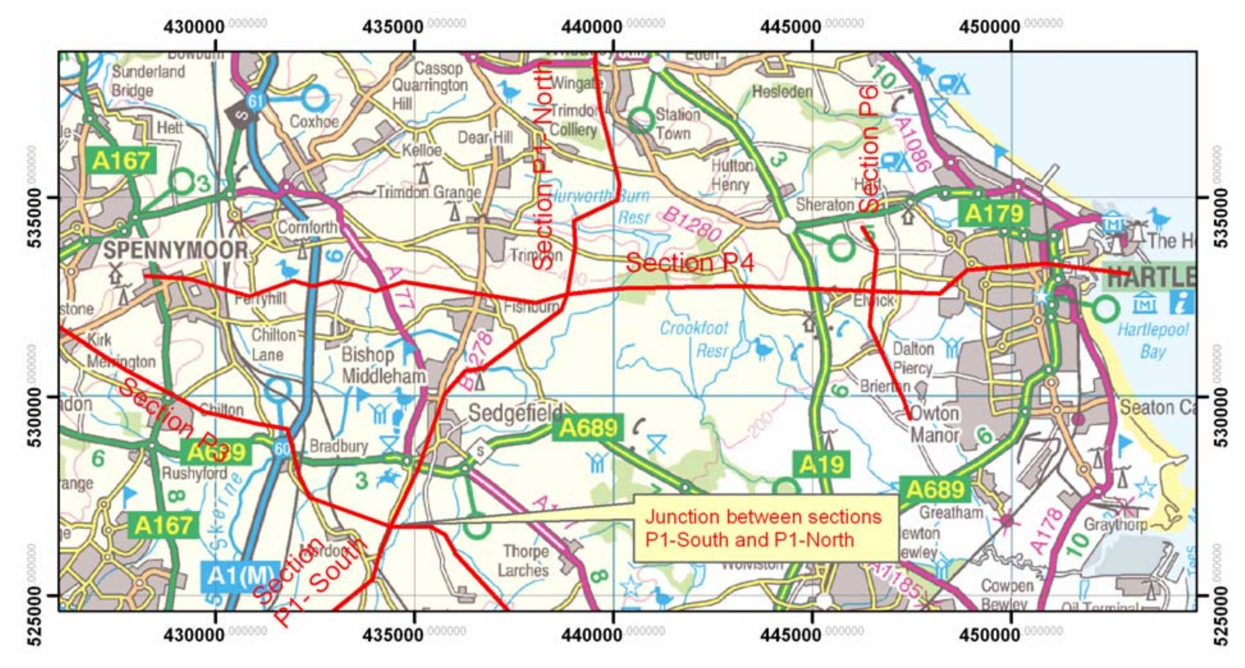

Figure 32 Location of section P6 and its relationship to section P4

10.2 GEOLOGY AND INTERPRETATION OF SECTION

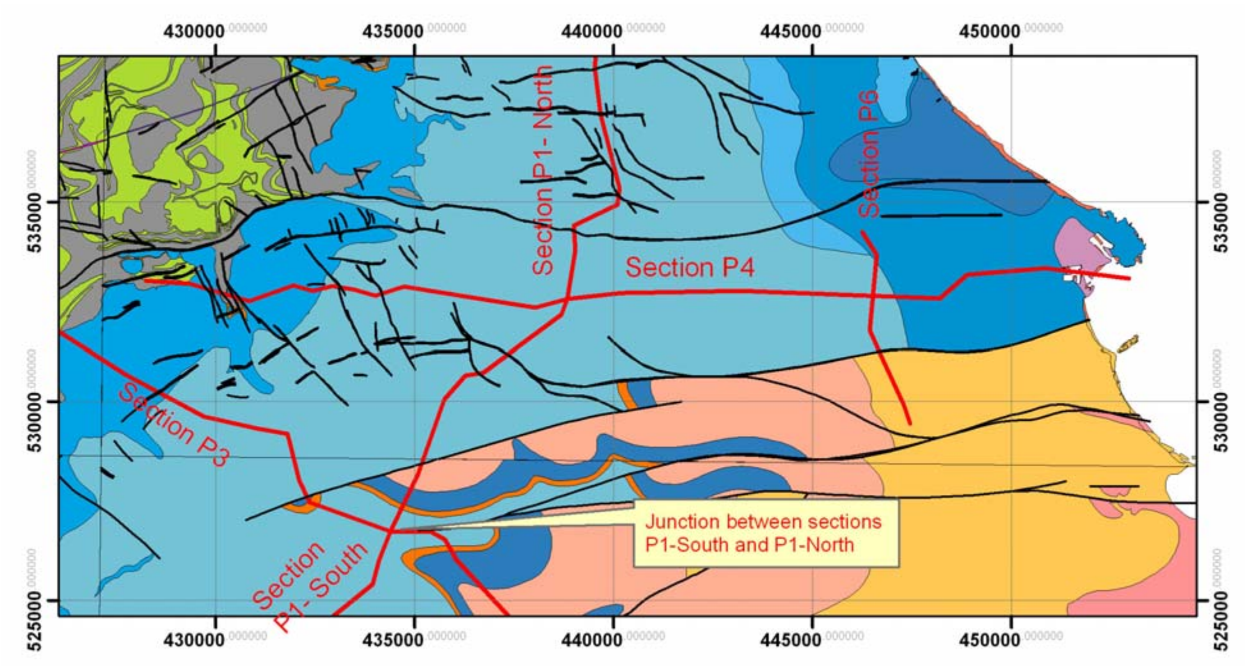

Figure 33 Geology of section P6

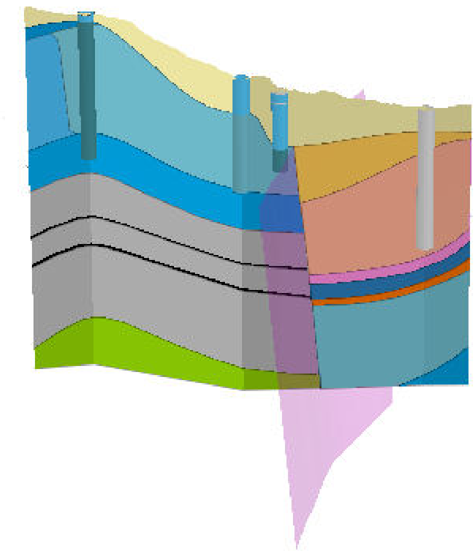

Figure 34 3D view of section P6 (south to right of section)

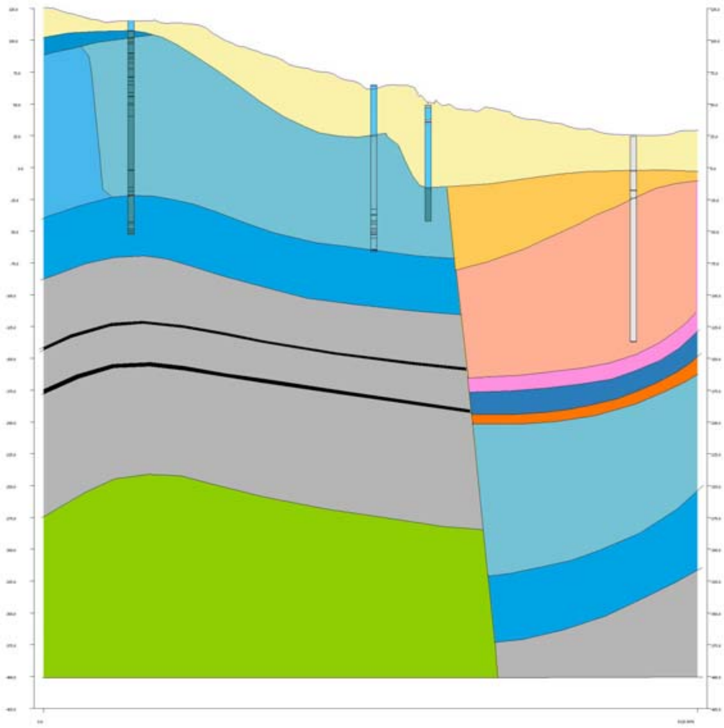

Figure 35 Section P6 (south to right of section)

10.2.1 The Carboniferous sequence of section P6

The Carboniferous sequence on section P6 is not proved by any boreholes on the line of the section, but is inferred by extrapolation from section P4 which should be referred to for details.

10.2.2 The Permian sequence of section P6

The Permian sequence is preserved as a thick sequence to the south of the West Hartlepool Fault. As noted in the Permian structure description for Section 4, this fault marks the boundary between the thick reef-flanked deposits to the north which contrast with the more evaporitic deposits present to the south. There is no good borehole evidence in this area and the problem in interpreting this sequence is whether to stop the limestones and dolomite exactly at the fault or to take them further south. By comparison with the area to the north (Smith, 1989; 1994; Smith and Francis, 1967), the Ford and Raisby formations thin dramatically at the edge of the platform, which may also be fault controlled. This is what we have modelled for the area to the west of Hartlepool, but there is no borehole control on what occurs here. What is obvious is that to the south of the fault the more evaporitic and mudstone rich sequences come in. It may be that the Hartlepool Anhydrite should be included as a thicker unit on this section at the base of the Edlington Formation. The Billingham Anhydrite Formation is shown at the base of a very thick Roxby Formation.

10.2.3 The Carboniferous structure of section P6

The only major Carboniferous structure shown on this section is the West Hartlepool Fault which is a basin bounding fault modelled with a dip of about 45 degrees. This fault is likely to have controlled considerable thickness variations in the Alston and Stainmore Formations.

10.2.4 The Permian structure of section P6

The West Hartlepool Fault is the structure that affects the Permian sequence both from a likely sedimentological point of view and from a subsequent structural viewpoint. The fault marks the abrupt junction between the Raisby and Roker formations to the north with Edlington, Seaham and Roxby formations along with the Triassic Sherwood Sandstone Group to the south. Smith and Francis (1967 – Plate XV) suggest a downthrow to the south of around 600 feet (about 200m) on this fault.

Appendix 1 List of boreholes used to construct sections

Note, coordinates are given where sections start, terminate or turn at a location without a borehole.

Section P1 – South

Borehole No	NGR E	NGR N
NZ32NW13.	434105.0	526017.0
NZ32NW14.	433945.0	525407.0
NZ32SW83.	432380.0	524130.0
NZ32SW93.	431460.0	522730.0
NZ32SW19.	431435.0	522720.0
NZ32SW13.	431029.0	522661.0
NZ22SE6.	429923.0	522067.0
NZ22SE13A	429429.0	522003.0
NZ22SE119.	429010.0	521920.0
NZ22SE11M	428829.0	521493.0
NZ22SE17.	428341.0	521271.0
NZ22SE15.	427128.0	520380.0
NZ21NE1.	425419.0	518795.0
NZ21NE21.	425316.0	517707.0
NZ21NE85.	425290.0	517660.0
NZ21NE84.	425260.0	517570.0
NZ21NE90.	425240.0	517540.0
NZ21NW1.	424801.0	516347.0
NZ21SW15.	424192.0	514219.0
NZ21SW1.	422391.0	513315.0
NZ21SW5.	422399.0	511486.0
NZ21SW6.	421606.0	510011.0

Section P1 – North

Borehole No	NGR E	NGR N
NZ36NE80.	439660.0	565620.0
NZ36SE24.	439400.0	564540.0
NZ36SE106.	438670.0	563590.0
NZ36SE59.	439560.0	562010.0
Coordinate	439398.8	561357.3
NZ36SE32.	438920.0	560620.0
NZ35NE6.	438613.0	559772.0
NZ35NE471.	438720.0	559510.0
NZ35NE82.	438310.0	557960.0
NZ35NE84.	438350.0	557220.0
NZ35NE142.	438221.0	556740.0
NZ35NE173.	437963.0	556000.0
NZ35NE461.	438200.0	555220.0
NZ35SE14.	438152.0	554401.0
NZ35SE191.	438868.0	551647.0
NZ35SE31B	438209.0	550145.0
NZ34NE74.	437505.0	549643.0
NZ34NE75.	438315.0	547470.0
NZ34NE97.	438290.0	546434.0
NZ34NE107.	438110.0	545230.0
NZ34SE5.	438861.0	543869.0
NZ34SE15.	438573.0	542100.0
NZ34SE103.	439740.0	541280.0
NZ33NE153.	439530.0	538350.0
NZ33NE16.	439677.0	537177.0
NZ43NW49.	440154.0	535331.0
NZ43SW15.	440097.0	534926.0
NZ33SE64.	439000.0	534393.0
NZ33SE26.	439039.0	533784.0
NZ33SE51.	438837.0	532551.0
NZ33SE39.	438691.0	532164.0
NZ33SE57.	436719.0	530715.0
NZ33SE43.	436281.0	530640.0
NZ33SE2.	435741.0	530053.0
Coordinate	435078.1	528163.9
NZ32NW10.	434396.0	526734.0
NZ32NW13.	434105.0	526017.0

Section P2

Borehole No	NGR E	NGR N
Coordinate	417809.5	520763.7
NZ21NW2.	422832.0	516936.0
NZ21SW11.	424981.0	514453.0
NZ21SE146.	425520.0	514200.0
NZ21SE29.	425679.0	514231.0
NZ21SE32.	425714.0	513885.0
NZ21SE82.	427816.0	512861.0
NZ21SE51D	428978.0	511650.0
NZ21SE40.	429915.0	511235.0
NZ31SW9.	431554.0	510359.0
NZ30NW35.	432500.0	509800.0
Coordinate	433398.1	509347.1

Section P3

Borehole No	NGR E	NGR N
NZ23SW105.	423348.0	532910.0
NZ23SW70.	424082.0	532732.0
NZ23SW34.	424942.0	532629.0
NZ23SE50.	425109.0	532337.0
NZ23SE134.	427760.0	530660.0
NZ22NE39.	429712.0	529614.0
NZ32NW4.	431038.0	529323.0
NZ32NW2.	431809.0	529187.0
NZ32NW84.	432100.0	528000.0
NZ32NW12.	432359.0	527464.0
Hopper House	434396.0	526734.0
NZ32NE10.	435392.0	526733.0
NZ32NE66.	435760.0	526530.0
NZ32NE4.	436016.0	526083.0
Coordinate	436003.4	526065.1
Coordinate	439053.2	522768.0
NZ42SW99.	442500.0	520950.0

Section P4

Borehole No	NGR E	NGR N
NZ23SE22.	428240.0	533015.0
NZ23SE39.	429369.0	532936.0
NZ23SE44.	429954.0	532759.0
NZ33SW149.	430845.0	532496.0
NZ33SW157.	431953.0	532886.0
NZ33SW163.	432444.0	532758.0
NZ33SW216.	432930.0	532880.0
NZ33SW180.	433499.0	532787.0
NZ33SW179.	434009.0	532629.0
NZ33SW259.	434730.0	532860.0
NZ33SE23.	436751.0	532540.0

NZ33SE34.	438033.0	532342.0
NZ33SE51.	438837.0	532551.0
NZ43SW54.	440193.0	532700.0
NZ43SW4.	443201.0	532755.0
NZ43SE35.	448186.0	532561.0
NZ43SE11.	448887.0	533159.0
NZ53SW142.	450850.0	533320.0
Coordinate	452950.1	533073.5

Section P5

Borehole No	NGR E	NGR N
NZ35SW278.	430638.0	550327.0
NZ35SW296.	430727.0	550305.0
NZ35SW42.	431730.0	550029.0
NZ35SW39.	432960.0	550286.0
NZ35SW50.	433746.0	550430.0
NZ35SW98.	433883.0	550366.0
Coordinate	434342.0	550572.0
Coordinate	434764.0	550633.0
Coordinate	436615.0	550528.4
NZ35SE190.	437376.0	550721.0
NZ35SE162/110	438819.0	550829.0
NZ35SE162/108	438882.0	550841.0
NZ35SE162/107	438971.0	550823.0
NZ35SE180.	439328.0	550835.0
NZ45SW192/F	440336.0	550739.0
Coordinate	440743.0	550643.9
Coordinate	440949.5	550702.7
Coordinate	442115.3	550487.1

Section P6

Borehole No	NGR E	NGR N
Coordinate	446240.7	534237.5
NZ43SE84.	446610.0	533660.0
NZ43SE8.	446431.0	531765.0
NZ43SE2.	446603.0	531376.0
NZ42NE56.	447285.0	529918.0
Coordinate	447449.1	529443.4

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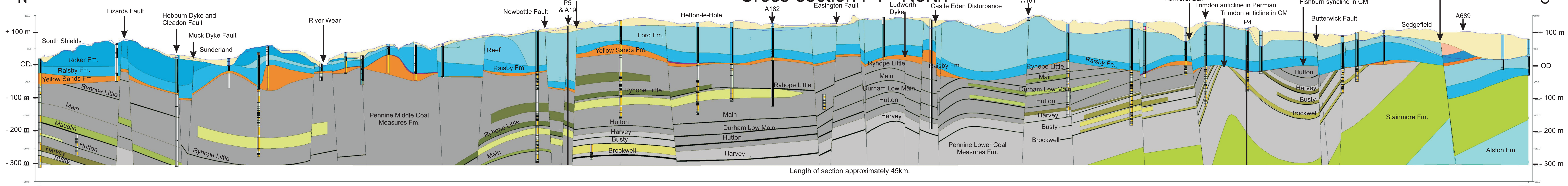
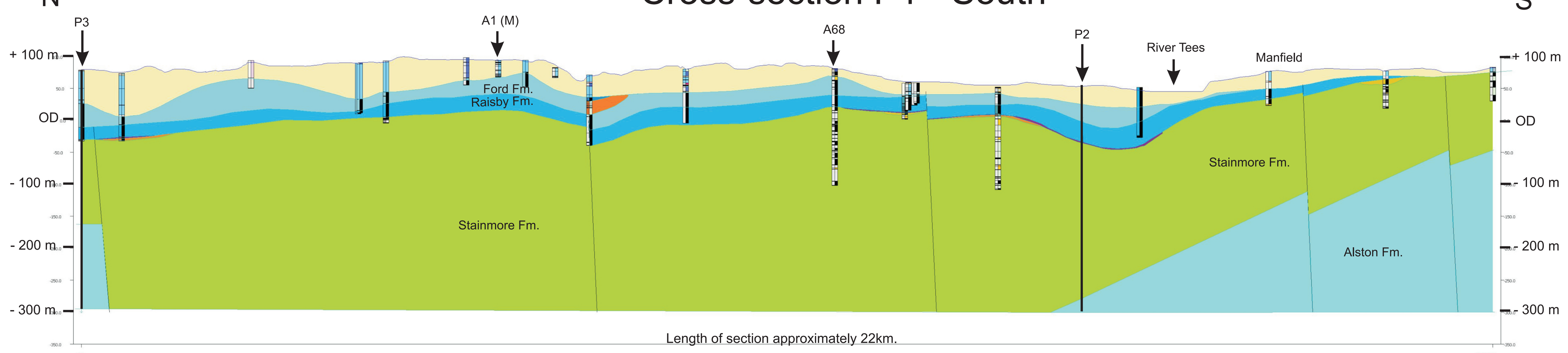
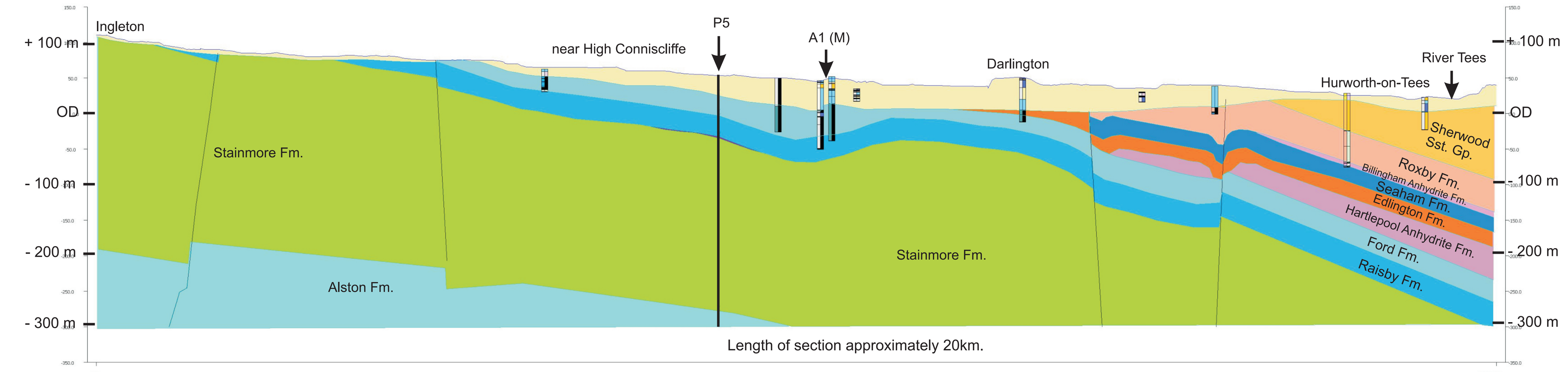
Cross-section P1 - North



Cross-section P1 - South



Cross-section P2



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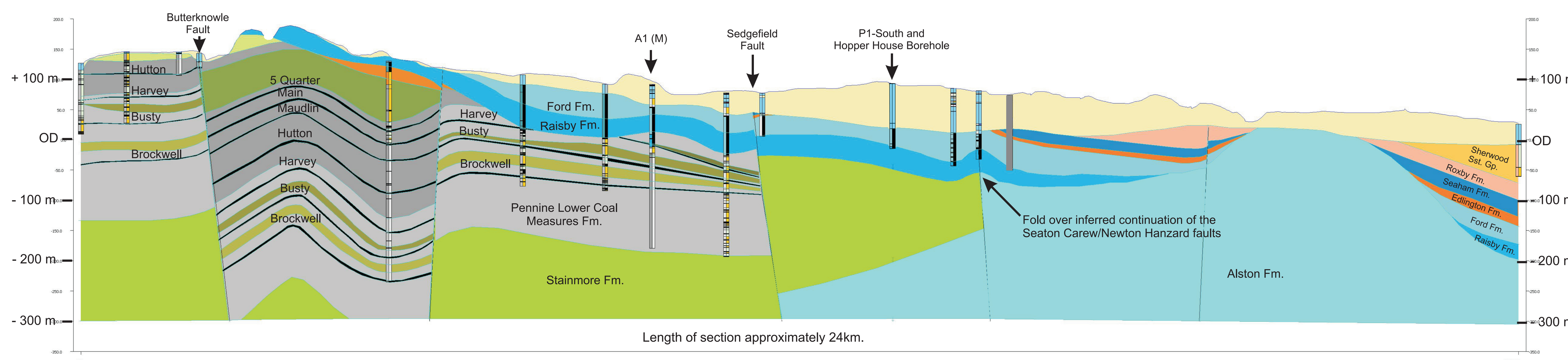
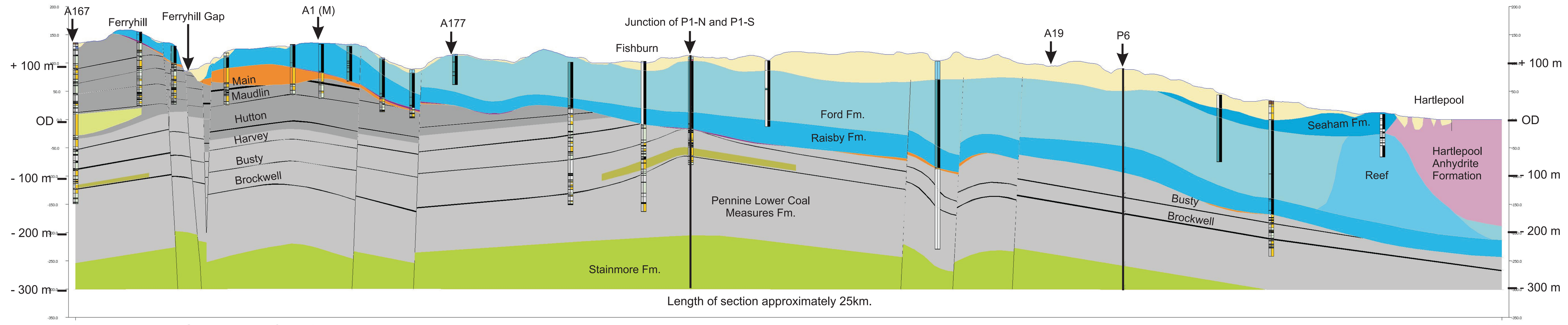
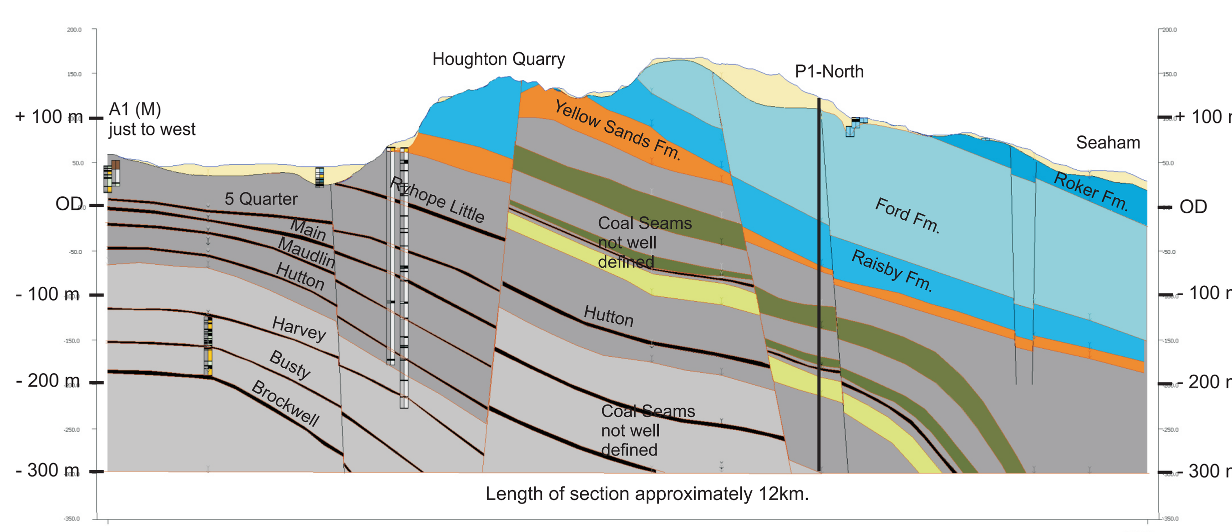


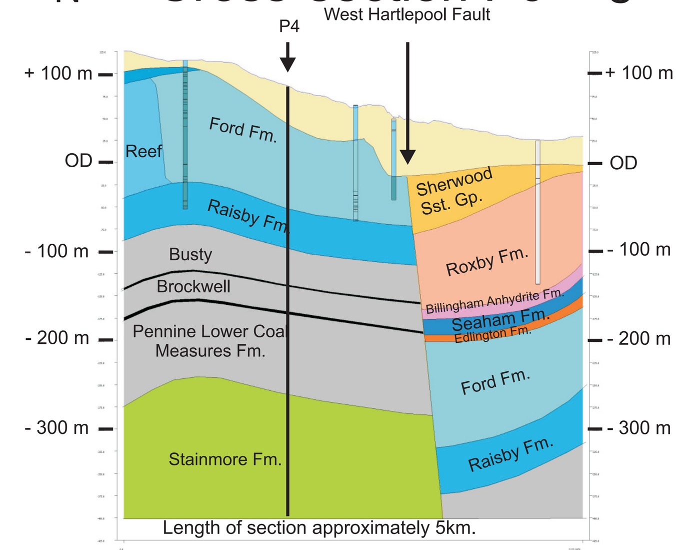
Cross-section P4



Cross-section P5



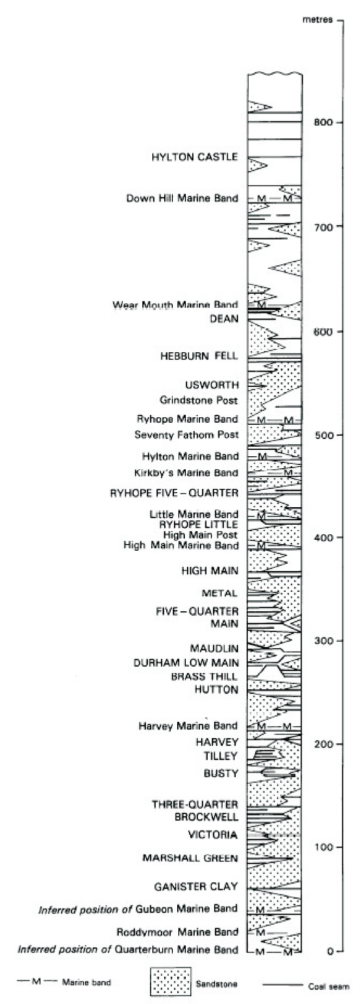
Cross-section P6

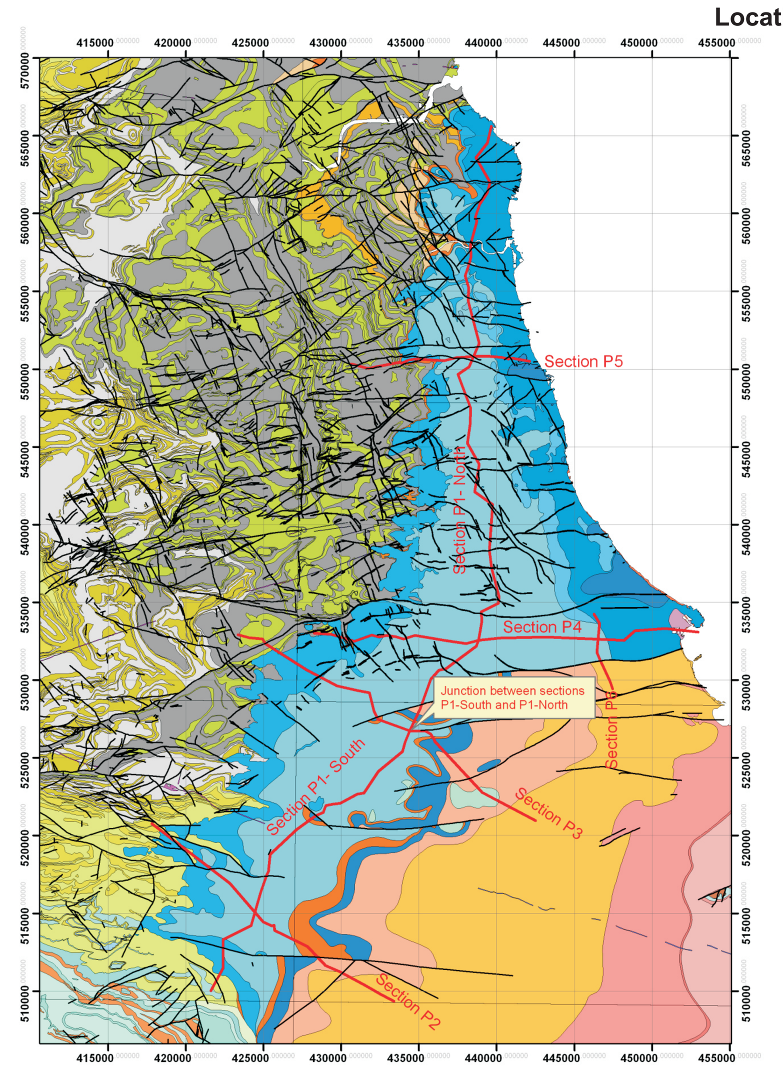


Scale 1 km

Vertical Exaggeration x 10 Vertical scale 50 m

Sequence of coal seams in the Durham area





Location of cross-sections

SUPERFICIAL
- Superficial Deposits

TRIASSIC
- Sherwood Sandstone Group

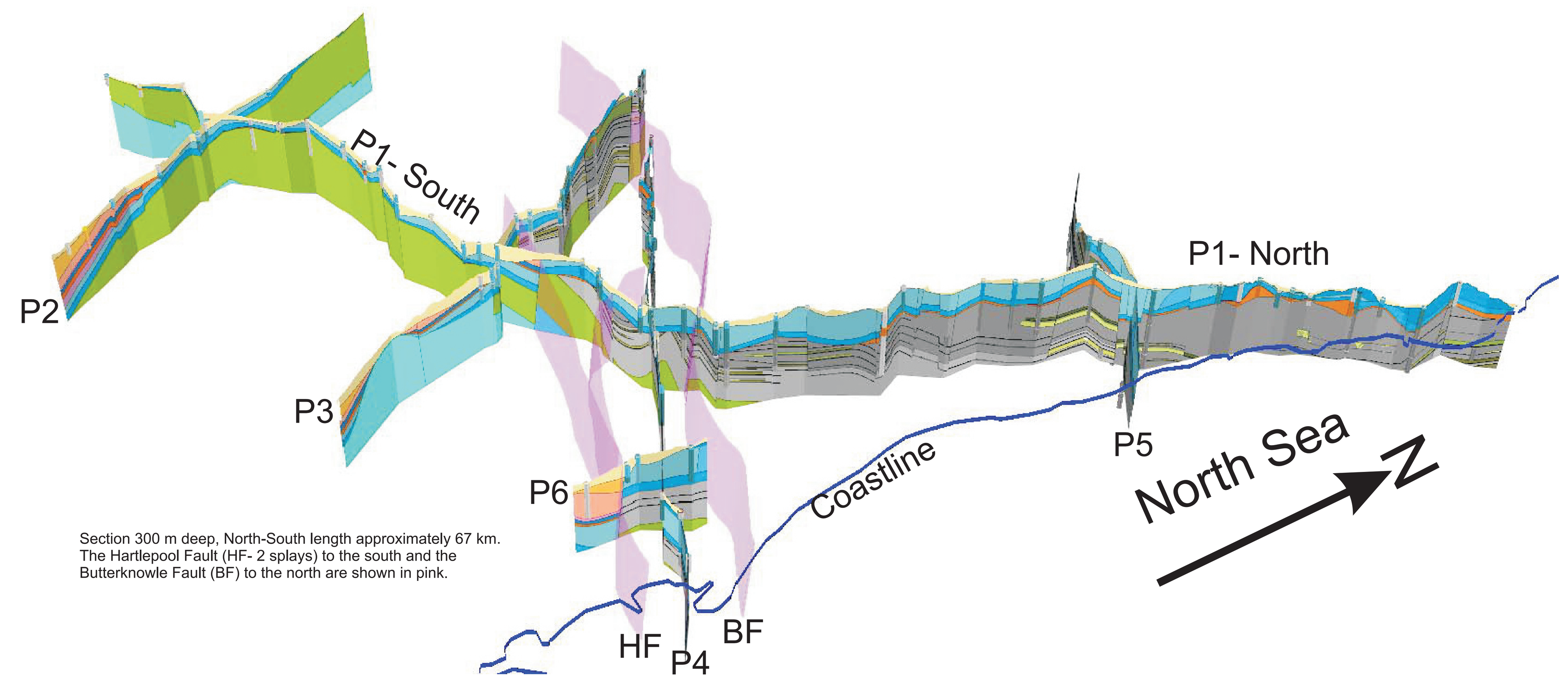
PERMIAN
- Roxby Formation
- Billingham Anhydrite Formation
- Seaham Formation
- Roker Formation
- Concretionary Limestone Member
- Edlington Formation
- Hartlepool Anhydrite Formation
- Ford Formation (Reef)
- Ford Formation
- Raisby Formation
- Marl Slate Formation
- Yellow Sands Formation

CARBONIFEROUS

Pennine Middle Coal Measures Formation
- Mudstone
- Coal seams (named)
- Sandstone (undivided)
- Sandstone above 5 Quarter Coal

Pennine Lower Coal Measures Formation
- Mudstone
- Coal seams (named)
- Sandstone above Harvey Coal
- Sandstone above Busty Coal
- Sandstone above Brockwell Coal

Yoredale Group
- Stainmore Formation
- Alston Formation



Section 300 m deep, North-South length approximately 67 km. The Hartlepool Fault (HF- 2 splays) to the south and the Butterknowle Fault (BF) to the north are shown in pink.

The boreholes shown on the cross-sections are coloured with two columns. Confidential boreholes are represented by a grey column.

The left-hand column is stratigraphical and coloured the same as the legend on the map where information is certain. Where there is uncertainty, the column is coloured pale grey.

The right-hand column is coloured for lithology. The colours used are yellow for sandstone, pale green for siltstone and mudstone, black for coal (note at this scale not all black lines are coals, some may be thin units of other deposits and the bounding lines are showing instead). The Permian lithology shown as black means that lithological information is poor.

The cross-sections are compiled from borehole information that varies considerably in distribution, age, quality, depth and content. The geological information has been compiled from these boreholes and digital map data at a scale of 1: 50 000. Use of the cross-section interpretations at scales larger than 1:50 000 is not recommended. The varied distribution of the borehole data means that in some places the sections are well constrained and in others the geological lines are considerably extrapolated. The cross-sections are the best interpretation that the geologist has been able to make from the existing information and new boreholes may require this interpretation to be modified.

Durham, Permian Geological Cross-sections

Produced by the British Geological Survey using GSI3D

for the Environment Agency by K.Whitbread, A.H.Cooper and A.Irving

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Environment Agency