BGS Karst Report Series: P1. Karst in the northern outcrop of Permian limestones

Environmental Change, Adaptation and Resilience Programme

Open Report OR/23/036

BRITISH GEOLOGICAL SURVEY

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Maurice, L.D., Cooper, A.H., Farrant, A.R., Mathewson, E., and Murphy, P.J.

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Front cover

Fissures in Permian limestones at Raisby Quarry. Photo by J. Rhodes, 1930. BGS photo archives P205184.

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
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email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
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Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House,
Upper Newtownards Road, Ballymiscaw,
Belfast, BT4 3SB
Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL
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Executive summary

This report documents the evidence for karst and rapid groundwater flow in the northern outcrop of the Permian dolomitic limestones and their associated gypsum sequences in County Durham and a small part of North Yorkshire, in northern England. It is part of the BGS karst report series on those karst aquifers in England in which cave development is limited – principally the Upper Cretaceous Chalk and the Jurassic and Permian limestones. The term “karst” applies to rocks that are soluble. In classic karst there are extensive caves and large-scale surface karst landforms such as dolines, shafts, stream/river sinks, and springs. In the past, the Chalk and the Jurassic and Permian limestones of England were not considered karstic because they have limited cave development, and because karst features are usually small and have not been well documented. The reports provide data and information on karst in each area.

There is clear evidence for karstic development in the Permian dolomitic limestones in the P1 area. Some short caves occur which appear to be fully or partially karstic in origin, and although they are now predominantly dry, they demonstrate that cave sized voids can develop in the limestones. Other caves and voids related to mass-movement are also present. There are also smaller karstic conduits, solutional fissures, dolines, dissolution pipes, stream sinks and springs present. However, there are no comprehensive datasets on these features and information on their frequency, distributions and characteristics is generally scarce. There is some further evidence that karstic networks of solutional fissures and conduits occur in the saturated zone, with some high transmissivities and yields, and large fissure inflows during construction. Both the unsaturated and saturated zones of the aquifer are impacted by karst, with a proportion of rapid recharge via surface karst features and solutional fissures, as well as some saturated zone networks of solutional conduits and fissures. These networks are likely to result in groundwater flow in unexpected directions and potentially over long distances. Considerable further work is needed to develop better datasets on karst features, and to assess the role of karst in the limestones in this area. There is more information on gypsum karst in the area, which is well-developed and poses significant engineering hazards and challenges, and also impacts on the limestones which collapse into the gypsum karst. The presence of sulphate-rich groundwater and springs indicate the interconnection of limestone and gypsum sequences in the Permian strata in the area, highlighting the complexity and connectivity between different geologies.

Acknowledgements

We thank Jenny Potts at the British Caving Library, the British Cave Research Association and the British Caving Association for help sourcing data on the caves and karst in the Permian limestone.

We thank Diane Steele at the Environment Agency for reviewing the report and providing hydrogeological/karst information on the area. At BGS we thank Bentje Brauns for reviewing the report; Vanessa Banks, who led much of the work on the BGS Karst Database; and Carole Sharratt for assistance with report formatting. This work was partially carried out under the Natural Environmental Research Council (NERC) Knowledge Exchange Fellowship Scheme, grant ref NE/N005635/1.

Contents

FIGURES

TABLES

Introduction to the BGS Karst Report Series

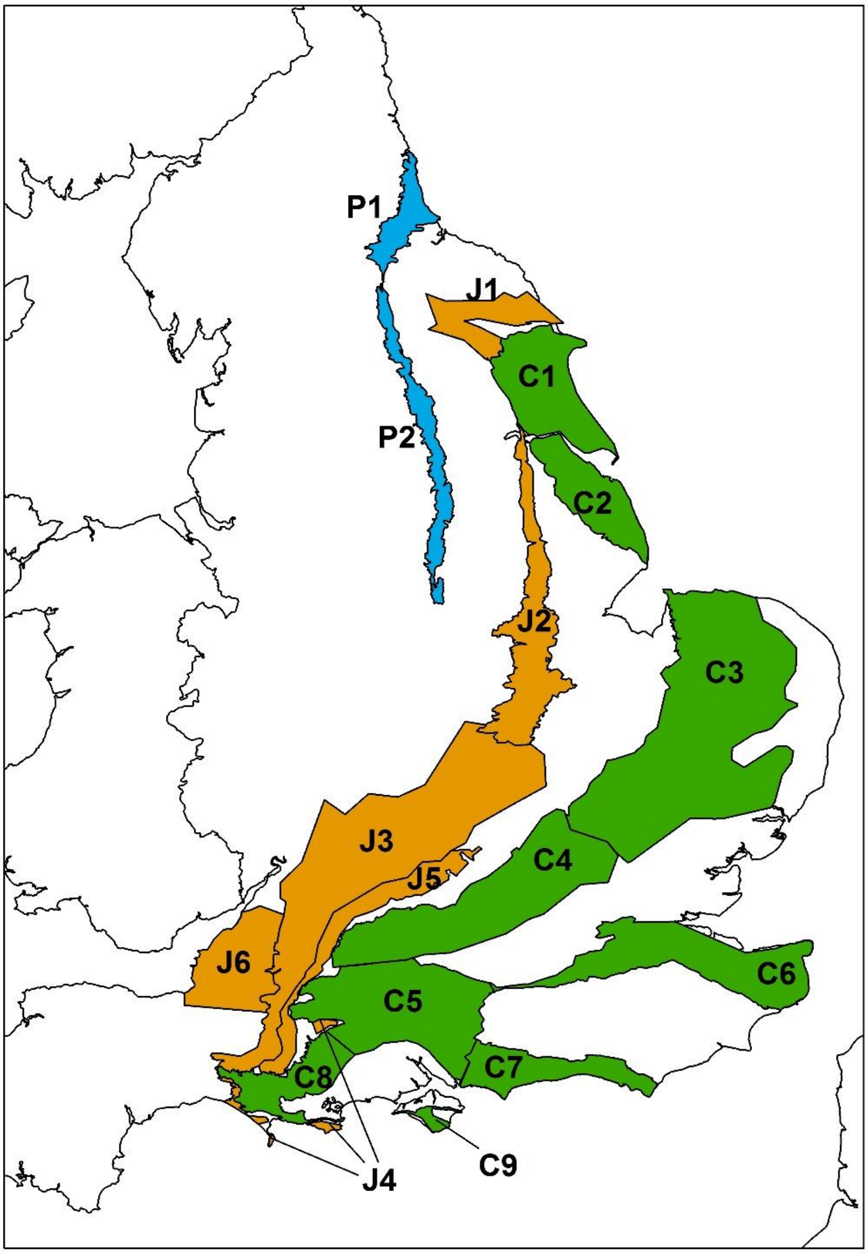
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – The Chalk and the Jurassic and Permian limestones. The series is derived from the NERC funded Knowledge Exchange fellowship "Karst knowledge exchange to improve protection of groundwater resources" undertaken between 2015 and 2022. This series is the first systematic review of karst features across these aquifers and provides a useful basis for future karst and hydrogeological studies.

The term "karst" applies to rocks that are soluble. In classical karst regions there are extensive caves; and there are large scale surface karst landforms such as dolines, shafts, river sinks, and springs. In the past the Chalk and the Jurassic and Permian limestones of England were not considered karstic because they have limited cave development, and because karst features are usually small and have not been well documented. However, permeability in these aquifers is determined by their soluble nature and groundwater flow is predominantly through small-scale karstic solutional features comprising small conduits ~ 5 to >30 cm diameter, and solutionally enlarged fractures (fissures) of ~0.5 to >2 cm aperture. There are some short caves in all three aquifers; they all have dolines, stream sinks and large springs; and rapid flow can occur over long distances. Karst is therefore an important feature of these aquifers.

The series will comprise 17 reports which provide an overview of the evidence for karst in different areas of England. The Chalk is divided into nine regions, primarily based on geomorphology and geography. The Permian limestones are divided into two areas, comprising a northern and southern outcrop. The Jurassic limestones have more variable geology and are divided into six areas. J1 covers the Corallian Group of Northern England. J2 covers the Lincolnshire Limestone Formation of central England. J3 covers the Great Oolite Group and Inferior Oolite Group of Southern England. J4 covers three small areas of the Portland and Purbeck limestones in Southern England. J5 covers the Corallian Group limestones of Southern England. J6 covers the Blue Lias limestones of south-west England and comprises several small outcrops within a large area.

Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; peer reviewed papers and reports; geological mapping; and through knowledge exchange between 2015 and 2022 with the Environment Agency, universities, water companies and consultants. The data are not complete and further research and knowledge exchange is needed to obtain a full picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports nonetheless provide an overview of the currently available evidence for karst and demonstrate that surface karst features are much more widespread in these aquifers than previously thought, and that rapid groundwater flow is common. Consideration of karst and rapid groundwater flow in these aquifers will improve understanding of how these aquifers function, and these reports highlight the need for further investigations of karst to enable improved management and protection of groundwater resources.

The reports are structured to introduce the area and geology, evidence of karst geomorphological features in the area (caves, conduits, stream sinks, dolines and springs), evidence of rapid flow from tracer testing, and other hydrogeological evidence of karst. Maps of the area show the distributions of karst features, and there is a quick reference bullet point summary.



Map of the locations of the Karst reports

C1) Karst in the Chalk of the Yorkshire Wolds
C2) Karst in the Chalk of Lincolnshire
C3) Karst in the Chalk of East Anglia
C4) Karst in the Chalk of the Chilterns and the Berkshire and Marlborough Downs
C5) Karst in the Wessex Chalk (Hampshire and Wiltshire)
C6) Karst in the Chalk of the North Downs
C7) Karst in the Chalk of the South Downs
C8) Karst in the Chalk of Dorset
C9) Karst in the Chalk of the Isle of Wight
J1) Karst in the Jurassic Corallian Group limestones of Northern England
J2) Karst in the Jurassic limestones of Central England
J3) Karst in the Jurassic Great and Inferior Oolite groups of Southern England
J4) Karst in the Jurassic Portland and Purbeck limestones in Southern England
J5) Karst in the Jurassic Corallian Group limestones of Southern England
J6) Karst in the Jurassic Blue Lias limestones of South-West England
P1) Karst in the northern outcrop of the Permian limestones
P2) Karst in the southern outcrop of the Permian limestones (and associated gypsum)

Introduction to karst data in the BGS karst report series

This section provides background on each type of evidence for karst, the data sources used, and any limitations in the data. This introduction is general to all the BGS karst reports and further specific information on data sources is provided within the individual reports where applicable. A glossary is provided at the end of the report.

Stream sinks

Stream sinks provide direct evidence of subsurface karst and rapid groundwater flow because they are indicative of a network of solutional voids of sufficient size to transport the water away through the aquifer. Most stream sinks occur near to the boundary between the carbonate aquifer and adjacent lower permeability geologies, with surface runoff from the lower permeability geologies sinking into karstic voids in the carbonate aquifer at the boundary or through more permeable overlying deposits close to the boundary.

Data on stream sink locations in the Chalk and Jurassic and Permian limestones are variable and although there are many records, the dataset is incomplete, and further surveys are likely to identify additional stream sinks. Stream sink records are predominantly from the BGS Karst Database in which many were identified by desk study and geological mapping. Some additional records were obtained through knowledge exchange.

Most streams that sink have multiple sink points over distances of 10s to 1000s of metres. The sink point varies depending on flow conditions and also as some holes become blocked with detritus and others open up. Each individual sink point provides recharge into a solutional void in the underlying carbonate aquifer, and their locations therefore provide direct evidence of the locations of subsurface solutional features enabling rapid recharge. The sink points range from seepages through alluvial sediments in the stream bed and small holes in stream beds, to sink points located in karstic depressions of more than 10 m in depth and/or diameter. Some data sources report many/all individual sink points associated with a stream; whilst others report a single point for an individual stream irrespective of whether there are multiple sink points. The data presented here comprise all the sink point records that the studies report, but there are likely to be many more sink points in streambeds which have not yet been identified. Further information on the discharge and nature of the stream sinks is generally sparse, but where available, information from reports and papers are summarised.

Some streams and rivers flowing over carbonate geologies have reaches with substantial losses or which dry up in the middle of their course. These are also a type of karst stream sink providing recharge to solutional voids in the subsurface. Whilst some that sink into obvious holes in the riverbed have been identified, and there are some studies that provide evidence of river losses/drying, there has been no systematic study of the occurrence of karstic recharge through riverbeds in the Chalk, or Jurassic or Permian limestones. River flow data were not reviewed for these reports. The data presented are from a brief literature review, and there may be many other streams and rivers that provide point recharge into subsurface karstic features.

Caves and smaller conduits

Karstic caves (conduits large enough for humans to enter) occur in the Chalk and Jurassic and Permian limestones, providing clear evidence of the importance of karst in these aquifers. Caves were identified from literature review, predominantly from publications of the British Cave Research Association, and local and regional caving societies.

Smaller conduits are observed in quarry walls and natural cliff outcrops, and in images of borehole walls. Conduits (~5 to >30 cm in diameter) and solutional fissures (apertures of ~ 0.5 to > 2 cm) are commonly observed. However, there is no dataset on conduits, and they have generally not been studied or investigated, so it is not possible to assess their frequency or patterns in their distributions. Information on conduits from knowledge exchange and literature review is included, but the data are very limited in extent.

Dolines

Dolines provide direct evidence of karst and may be indicative of rapid groundwater flow in the subsurface. They occur in the Chalk, the Jurassic and Permian limestones, and gypsum. However, their identification can be challenging as surface depressions of anthropogenic origin (e.g. dug pits, subsidence features associated with the collapse of old mines, dewponds) can appear similar to karst dolines. This is especially the case in the Chalk. The reports review the evidence for surface depressions in the area, and discuss whether these are likely to be karstic or anthropogenic in origin.

Data on surface depression locations come from the BGS Karst Database in which they were identified by either desk study or during geological mapping. Other records of surface depressions were obtained through knowledge exchange and literature review, and studies of dolines in the area are summarised. In some areas there may be surface depressions/dolines that have not yet been identified.

Dissolution pipes

Dissolution pipes (a form of buried doline) only occur in karstic soluble rocks, and their presence is therefore evidence of karst. Their role in providing recharge into subsurface karstic features is poorly understood. Many of them appear to contain low permeability material and may be formed by in-situ bedrock dissolution and therefore may not be linked to larger dissolutional voids in the subsurface, but some may be associated with open solutional fissures and cavities.

Dissolution pipes occur at very high spatial densities in some areas and are commonly encountered in civil engineering projects. Some data on dissolution pipes come from the Natural Cavities database. This is a legacy dataset held by the British Geological Survey and Stantec (formerly Peter Brett Associates). It comprises data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). Information from reports and papers with information on dissolution pipes in the area are summarised.

Springs

Large springs are indicative of connected networks of karstic voids that provide flow to sustain their discharges. Data on spring locations were collated from the BGS karst and springs databases, and Environment Agency spring datasets. Further information on springs was obtained through knowledge exchange and literature review. The springs dataset presented in this report series is not complete, and there are likely to be more springs than have been identified. In England there are very few data on spring discharges and for most recorded springs the discharge is unknown. However, in most areas some springs with large reported discharges of > 10 or > 100 $l.s^{-1}$, have been identified. There remains much work to be done to develop a useful dataset on the discharges and characteristics of springs in the Chalk and Jurassic and Permian limestones, but the data presented here provide an initial overview, and suggest that large springs are common in these aquifers.

Tracer tests

Tracer tests provide direct evidence of subsurface karstic flowpaths in which groundwater flow is rapid. The development of cave-sized conduits is not a pre-requisite for rapid groundwater flow, and in aquifers where cave development is limited, the karstic flowpaths may comprise connected networks of smaller conduits and solutional fissures.

Tracer test data were compiled from literature review and knowledge exchange. It is probable that most of the successful tests that have been carried out in these aquifers have been identified.

Other evidence of karst and rapid groundwater flow

This section provides an overview of other evidence of karst from literature review and knowledge exchange; and includes evidence from borehole monitoring or other hydrogeological studies.

There is substantial evidence of karst from groundwater abstractions from these aquifers. Whilst all successful abstractions are likely to be supplied by connected networks of solutional voids, the higher the transmissivity, the more widespread and well developed the karstic networks are likely to be. Transmissivity data from the national aquifer properties manual (Allen et al., 1997; MacDonald & Allen, 2001) are presented.

Knowledge exchange with water companies highlighted that in many areas water supply abstractions and springs have some characteristics that are indicative of karst. In some areas abstractions have indicators of groundwater with low residence time and/or connectivity with surface water, for example coliforms, turbidity, detection of rapidly degrading pesticides, evidence of connectivity with the sea or surface rivers over long distances. To protect site confidentiality these data are not presented specifically, but a general overview is provided where appropriate.

1 Introduction: The northern outcrop of Permian limestones

1.1 AREA AND GEOLOGY/GENERAL HYDROGEOLOGY

The P1 karst area covers the northern outcrop of the Permian limestones and gypsum extending from South Shields in County Durham to Scotch Corner in North Yorkshire (Figure 1, Figure 2). Major rivers in the area include the River Tees in the south of the area, and its major tributary the Skerne. The Tees drains eastward to the North Sea. The River Wear in the north of the area also drains eastward into the North Sea at Sunderland.

Figure 1. The P1 northern outcrop area

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The Permian Zechstein Group forms the bedrock geology of the P1 area (Figure 2). The bedrock geology in the figures in this report is from the British Geological Survey 1:50,000 scale geological mapping. The strata dip gently towards the east or south-east (Allen et al., 1997). The Zechstein Group is underlain by the Yellow Sands Formation of the Rotliegend Group which unconformably overlies strata of Carboniferous age (the Pennine Coal Measures Group in the north and Yoredale Group in the south), and these older strata outcrop to the west of the Zechstein Group. To the south-east of the Zechstein Group the bedrock geology comprises the overlying younger Permian and Triassic strata (predominantly sandstones). These older and younger rocks are not included on Figure 2 or other figures in this report for clarity.

The geological units of the Zechstein Group in this area are outlined in Table 1 which shows the sequence given for the Durham geological sheet area (British Geological Survey, 2008) and from Cooper et al. (2007). The geology of this area is based on the work of Smith (1989,1994,1995); Smith et al. (1967) and Smith et al. (1986), and reported in Cooper et al. (2007). The Zechstein Group is dominated by the dolomitic limestones which form a karst aquifer and are the main focus of this report. In the lower parts of the Zechstein Group the Raisby and overlying Ford Formations are dolomitic limestones which outcrop over much of the P1 area. The Hartlepool Anhydrite Formation occurs in a small area near Hartlepool and is covered by superficial deposits. In the north of the P1 area, the Ford Formation is overlain by the dolomitic limestones of the Roker and Seaham formations. In the north of the area anhydrite and gypsum were once present, especially between the Ford Formation and the overlying sequences. Past dissolution of the gypsum and anhydrite has produced a heavily palaeokarstified sequence with abundant breccia pipes. Breccia pipes and dissolution residues can be seen especially along the coast around Marsden Bay where they perforate the Seaham Formation (Smith, 1972, 1994; Smith et al., 1967), see Section 2.3. Some of the breccia pipes are cemented breccias, others poorly cemented and more susceptible to erosion. Dissolution residues and breccias after the dissolution of the evaporites (mainly gypsum and anhydrite) are present in the sequence. Offshore, dissolution becomes less eastwards, and thick gypsum and anhydrite units are present.

In the south of the area, south of the Hartlepool Fault, the upper part of the Zechstein Group includes the Edlington and Roxby formations (separated by the Seaham Formation dolomitic limestones). The Roxby Formation extends to the east beyond the main P1 area. The southern area is significantly different to that in the north and the line of the Hartlepool Fault appears to have had a strong influence on the changes in sedimentation and sequence. In the south, the Edlington and Roxby formations comprise calcareous mudstones and include evaporite strata (gypsum and anhydrite). The geology south of the Hartlepool Fault is very similar to the geology of the P2 area (Maurice et al., 2024) with which it is continuous at depth. However, some of the formation names south of the Middleton Tyas anticline, where the Permian strata at outcrop thin, are different for historical reasons (Smith et al., 1986). The Ford and Raisby formations in the P1 area equate respectively to the Wetherby and Sprotbrough members of the Cadeby Formation in the P2 area. The Seaham Formation of the P1 area equates to the Brotherton Formation of the P2 area.

The evaporite karst of the Edlington and Roxby formations is well documented with many features including karstic depressions and some caves (e.g. Cooper, 1986, Cooper, 1996; Cooper, 1998; Cooper and Saunders, 1999; Cooper et al., 2011; Cooper et al., 2013; Cooper, 2020). This evaporite karst poses a substantial subsidence hazard with frequent collapse dolines. Most of the documented features occur further south around Ripon which is in the area covered by the P2 karst report (Maurice et al., 2024). However, evaporite karst is present in the northern Permian outcrop and subsidence related to gypsum occurs in the Darlington area (e.g. Cooper, 1996; Cooper, 1998; Cooper and Gordon, 2000; Lamont-Black et al., 2002; Lamont-Black et al., 2005; Cooper et al., 2011; Cooper et al., 2013; Cooper, 2020). The frequency and scale of karst features in the evaporites demonstrate the strongly karstic nature of these rocks.

Although the main focus of this report is the karst of the Permian dolomitic limestones, the limestones are impacted by the evaporite karst. For example, the limestones of the Roker and Seaham formations are foundered and brecciated due to the dissolution of the underlying evaporites (Smith, 1972, 1994, Smith et al., 1967). The presence of breccia pipes can act as conduits for groundwater (Davis and Horswill, 2002) with flow from the superficial deposits above, or from below depending on the local hydrogeological situation. In the southern part of the P1 area there can be some connectivity between the units, caused by the presence of breccia pipes perforating the Edlington, Seaham/Brotherton and Roxby formations. The Edlington Formation, for example, is reported to function as a "leaky" aquitard in some places (Allen et al., 1997; Kortas and Younger, 2013). This will mainly occur at outcrop or at depths of less than about 100-120m, which is the gypsum/anhydrite transition zone and limit of karstification in the Edlington and Roxby formations (Cooper, 1986 and 2020).

The limestones of the Zechstein group are dolomitic in nature, (comprising calcium magnesium carbonate), and were previously known as the 'Magnesian Limestones'. The non-gypsum related karst in the Zechstein group is developed in limestones, dolomitic limestones and dolomites. The limestones and dolomites are well cemented, with fractures and faults enabling solutional development of permeability. However, the solubility of dolomitic rocks is lower than that of pure limestones, so the karstic features are less well developed than in the limestones of Carboniferous age (Farrant and Cooper, 2008). In an assessment of the scale of karstification in UK karst aquifers, Atkinson and Smart (1981) considered that the Permian limestones lie between the Chalk which has the lowest level of karstification, and the Jurassic limestones; with the Carboniferous and older limestones having the highest degree of cave and karst development.

Recharge occurs around the western edge of the outcrop, with groundwater flow east towards the North Sea (Allen et al., 1997). The lower limestone units in the Zechstein Formation are hydraulically connected to the underlying Yellow Sands Formation although the intervening Marl Slate Formation can act as an aquitard (Bearcock and Smedley, 2009). In some places in the west of the area, the Marl Slate Formation and the Yellow Sands Formation are absent, and the Permian limestones lie unconformably on the Carboniferous aged Pennine Coal Measures Group and older strata, and there are instances of mine water pollution of the overlying limestone aquifers (Neymeyer et al., 2007).

Most of the P1 area is covered by superficial deposits, predominantly glacial till (Figure 3). Buried channels, cut into the bedrock, are infilled with glacial deposits, particularly in the south-east of the area, to the north-west of Hartlepool (Price et al., 2007a). The course of the River Tees is heavily incised, and this helps to control water flow and the local hydrogeological gradient and gypsum karstification in the south (Lamont-Black et al., 2005). Thick glacial deposits, alluvium, and river terrace deposits are present around the Tees in the south. There are also some glacial sand and gravel and lacustrine deposits in the centre of the area and near the coast. Raised marine deposits are present in the southern coastal areas, near Hartlepool. The thickness and extent of the superficial deposits has a significant influence on the presence and distribution of karst features in the Permian limestones. Surface and groundwater flow are interconnected where drift is thin or absent (Allen et al., 1997; Price et al., 2007a, b). The superficial geology in Figure 3 is from the BGS 1:625,000 geological mapping. Figure 4 shows the superficial thickness from the BGS BSTM (Basic Superficial Thickness Model). Whilst this model gives a rough approximation of the thickness of the superficial deposits, it should be used with caution as the data are interpolated from borehole records. The model suggests that over much of the area the superficial cover is thin (< 10 m), with an increase in the thickness towards the south-east. Allen et al. (1997) report that to the east of the River Skerne the thickness of the glacial deposits is > 30 m, with a maximum of 84.5 m; whilst to the west of the River Skerne, it is much thinner, and often < 3 m.

The British Geological Survey undertook work to determine the impact of superficial deposits on recharge to the Permian limestones, creating a series of superficial geology domains for two areas that cover the north and south of the P1 karst report area (Price et al., 2007a, b). Boreholes were used to determine superficial deposit thicknesses and classify the deposits as aquifers or aquitards. New maps were created which show the thicknesses of the superficial deposit aquifers and aquitards. Eleven superficial deposit hydrogeological domains were created, with maps showing their distributions, reproduced here in Figure 5 and Figure 6, with the domain descriptions from Price et al. (2007a, b) in Table 2. In Figure 5 (the south of the P1 area) domain 10 (< 5 m of superficial deposits) is dominant in the west and north-east, with domains 1 and 2 (> 30 m and 10-30 m of aquitard) and 11 (channel deposits) dominating the east. These domains are also the most extensive in Figure 6 (the north of the P1 area area). Large parts of this area are classified as domain 10 (< 5 m of superficial deposits), with some areas of domains 1 and 2 and 11, especially in the central southern parts of the area (Figure 6).

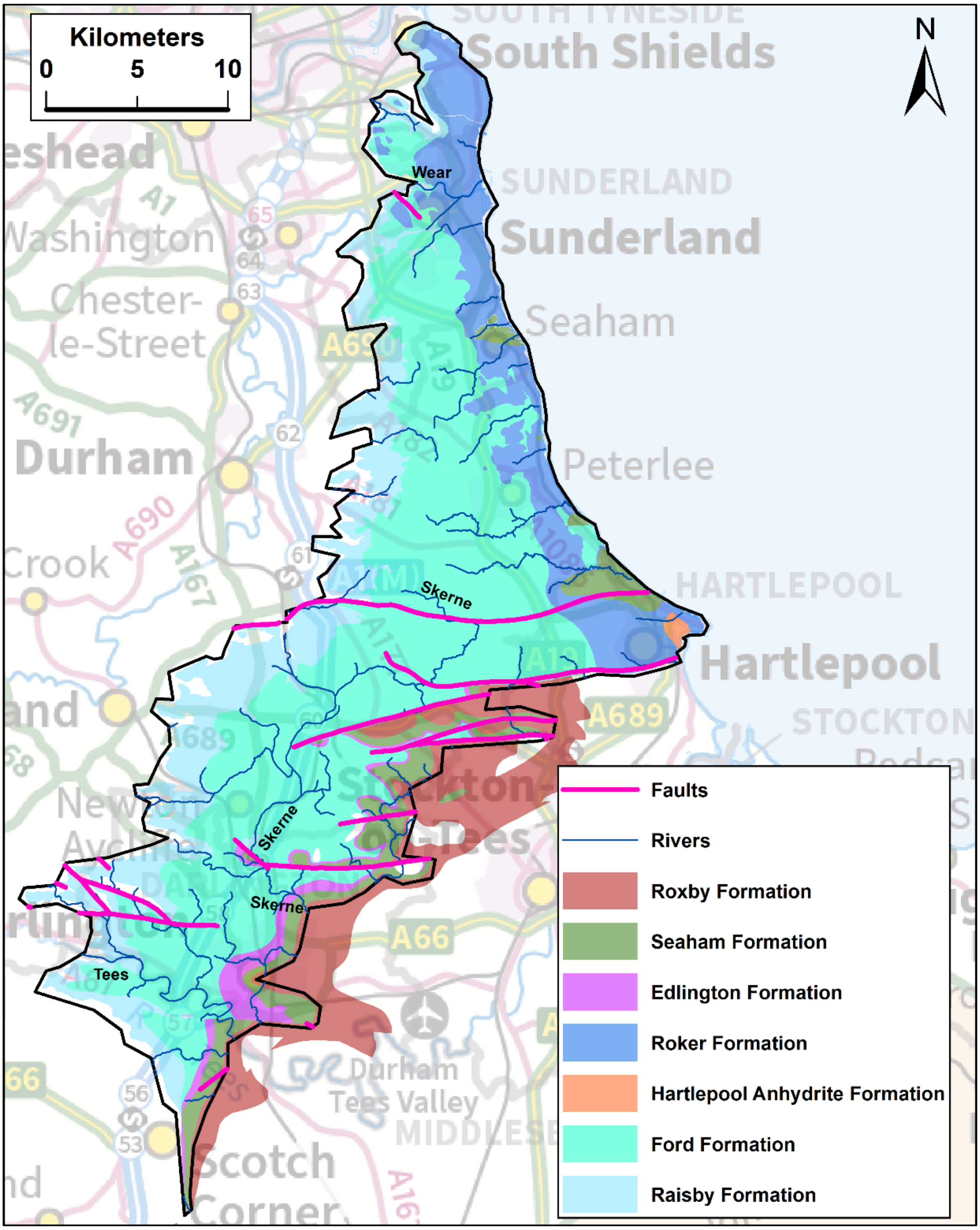

Figure 2. The Zechstein Group in the P1 area

Table 1. The Zechstein Group and underlying geologies in the P1 area

Sequence given for the Durham geological sheet area (British Geological Survey, 2008):

Group	Formation	Lithology	Thickness
Zechstein Group	Roxby Formation	Calcareous mudstone/gypsum	65-110 m
	Seaham Formation	Dolomitic limestone	5-20 m
	Edlington Formation	Calcareous mudstone/gypsum	0-10 m
	Roker Formation	Dolomitic limestone	25-75 m
	Hartlepool Anhydrite Formation	Anhydrite	0-12 m
	Ford Formation	Dolomitic limestone	20-80 m
	Raisby Formation	Dolomitic limestone	35-80 m
	Marl Slate Formation	Dolomitic/calcareous siltstone	<1 to 5 m
Rotliegend Group	Yellow Sands Formation	Sand	0 to 40 m
Pennine Coal Measures Group	Pennine Middle Coal Measures Formation	Mudstone, siltstone and sandstone	Up to 360 m

Sequence at outcrop and down-dip in the south of the area and offshore, with details of units that are mainly subsumed into the Roxby Formation at outcrop (from Cooper et al., 2007):

Group	Formation	Lithology	Thickness
Zechstein Group	Roxby Formation	Calcareous mudstone/gypsum	0-50 m
	Sherburn Anhydrite Formation	Anhydrite (and gypsum)	0-3 m
	Rotten Marl Formation	Halitic mudstone	0-7m
	Billingham Anhydrite Formation	Anhydrite (and gypsum)	0-12 m
	Seaham Formation	Dolomitic limestone	0-20 m
	Seaham Residue	Insoluble residues (mainly clay and silt	1-2m
	Roker Formation	Dolomitic limestone	0-30 m
	Edlington Formation	Calcareous mudstone/gypsum	0-53 m
	Hartlepool Anhydrite Formation	Anhydrite (and gypsum)	0-200 m
	Ford Formation	Dolomitic limestone	0-70 m
	Raisby Formation	Dolomitic limestone	0-47 m
	Marl Slate Formation	Dolomitic/calcareous siltstone	0-2 m
Rotliegend Group	Yellow Sands Formation	Sand	0 to 30 m
Pennine Coal Measures Group	Pennine Middle Coal Measures Formation	Mudstone, siltstone and sandstone	Up to 360 m

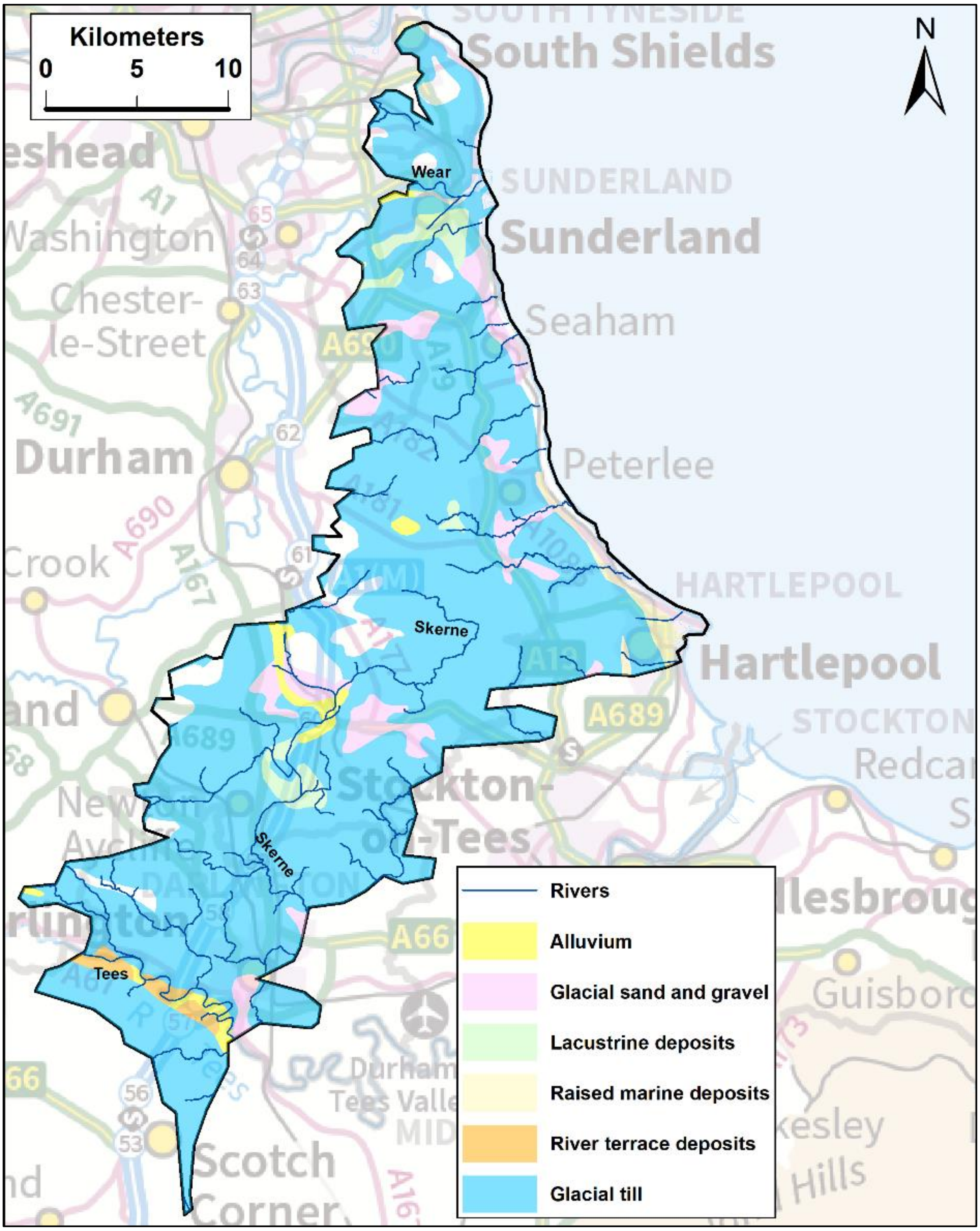

Figure 3. Superficial geology

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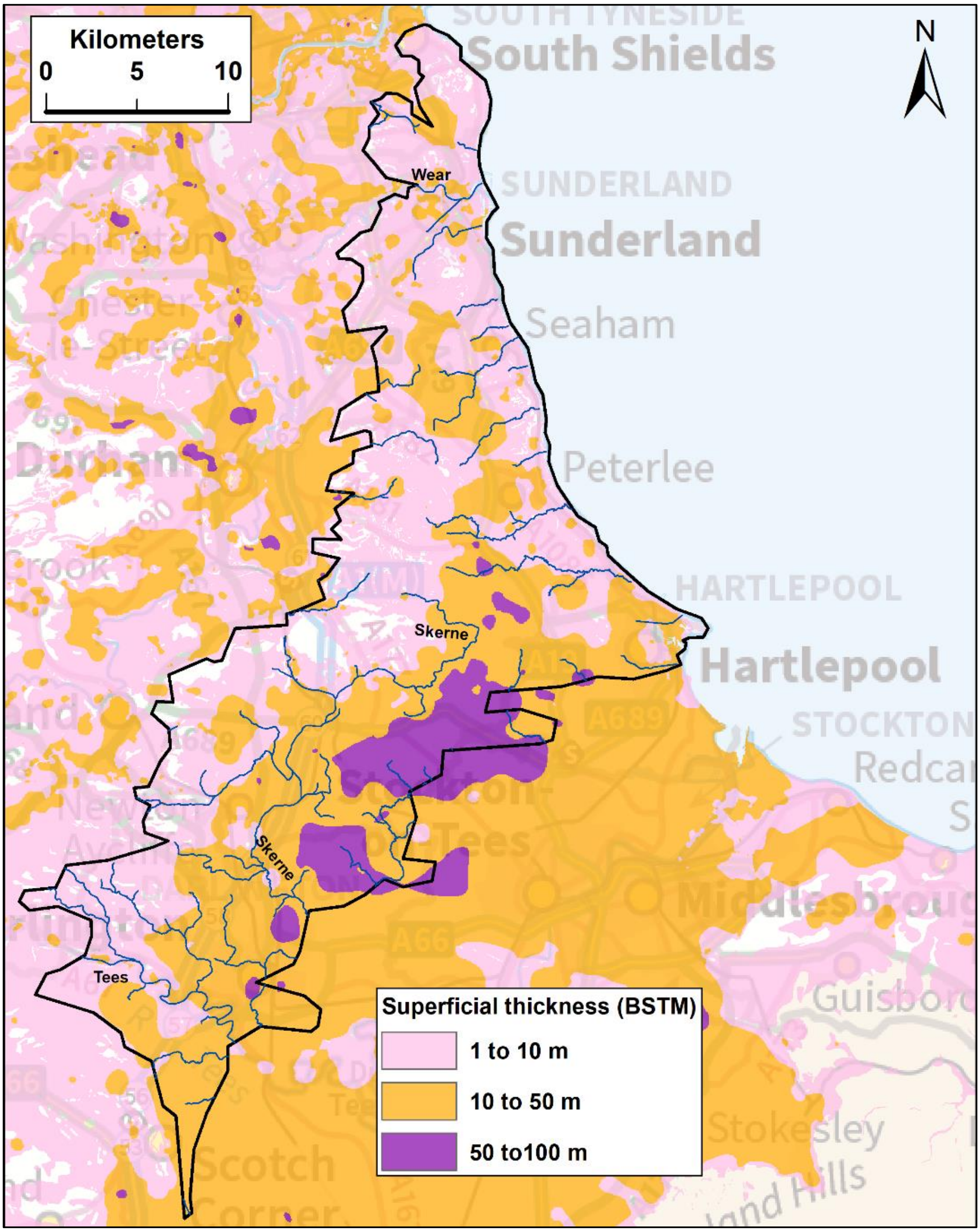

Figure 4. The BGS BSTM model of superficial thickness

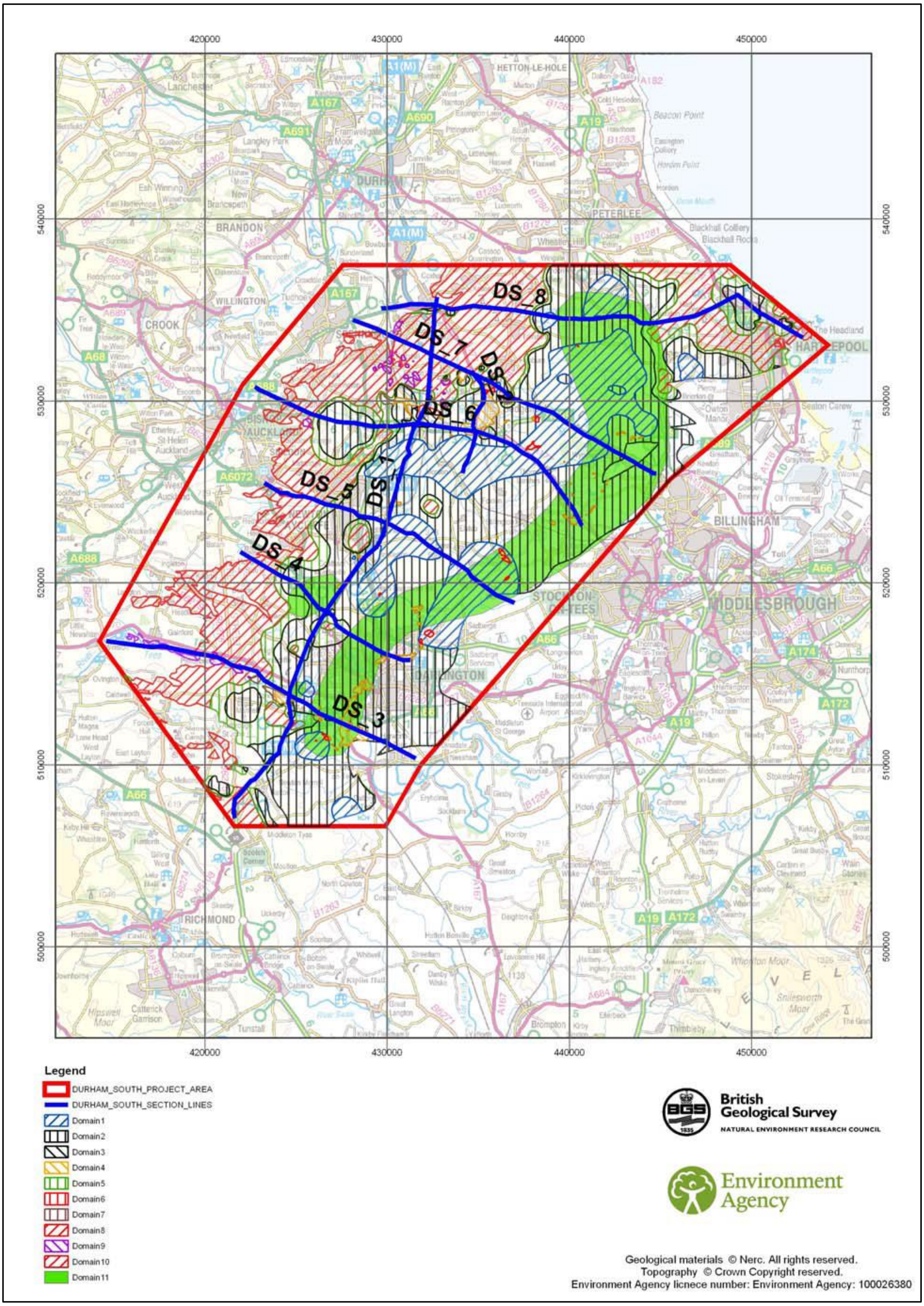

Figure 5. Superficial deposit domains (south) from Price et al. (2007a)

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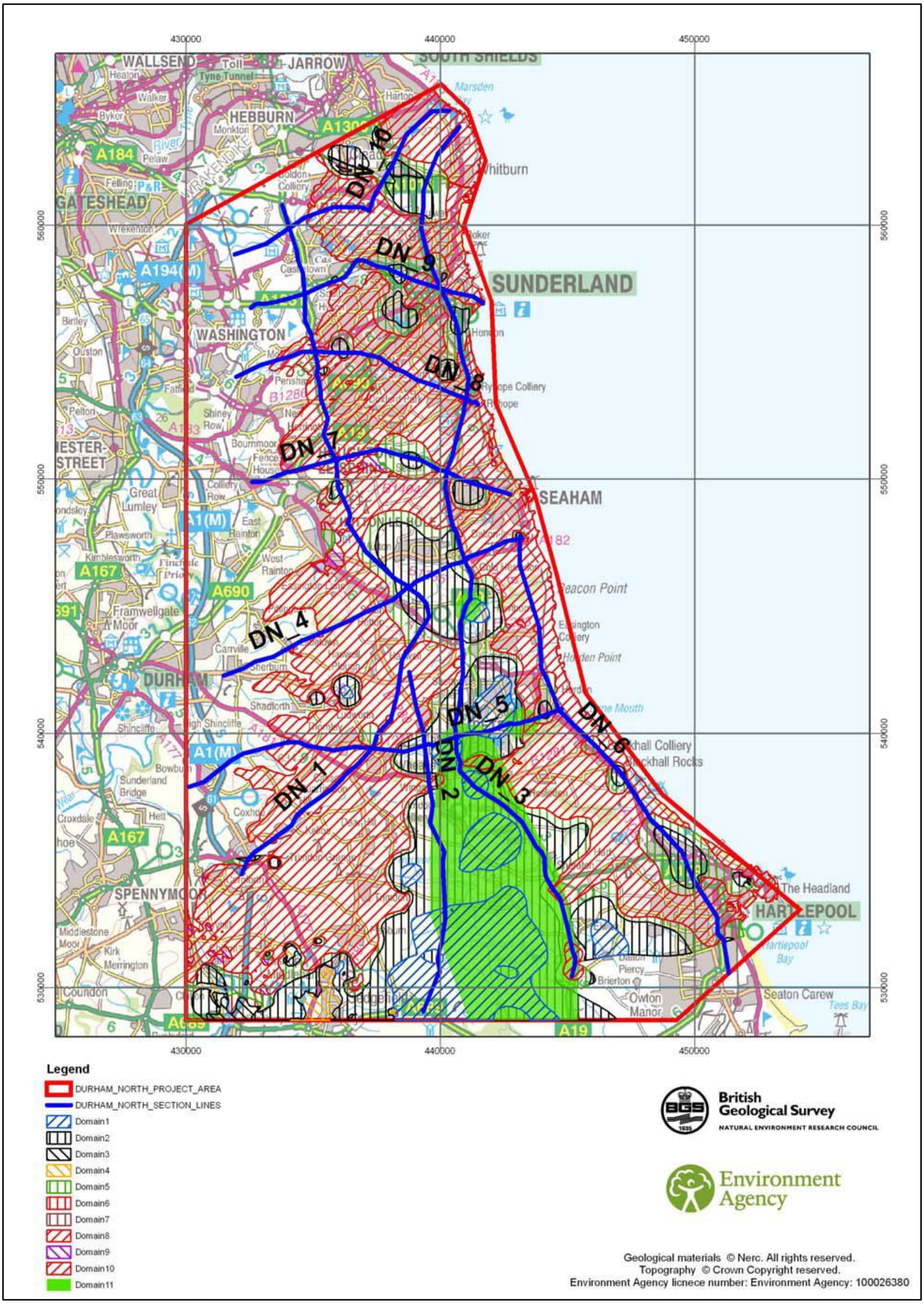

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Figure 6. Superficial deposit domains (north) from Price et al. (2007b)

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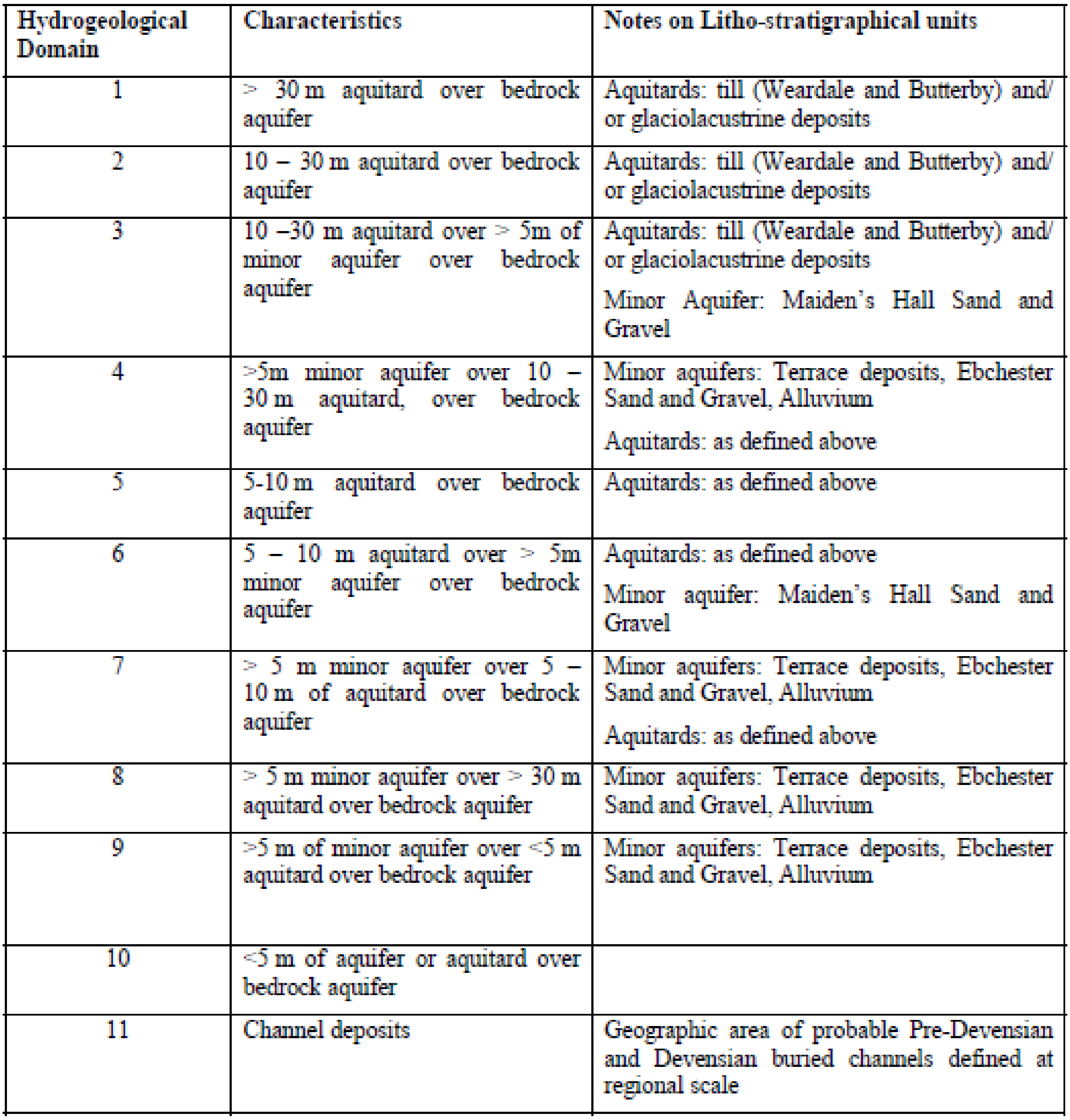
Table 2. Description of hydrogeological domains from Price et al. (2007a,b)



Hydrogeological Domain	Characteristics	Notes on Litho-stratigraphical units
1	> 30 m aquitard over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits
2	10 – 30 m aquitard over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits
3	10 –30 m aquitard over > 5m of minor aquifer over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits Minor Aquifer: Maiden's Hall Sand and Gravel
4	>5m minor aquifer over 10 – 30 m aquitard, over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium Aquitards: as defined above
5	5-10 m aquitard over bedrock aquifer	Aquitards: as defined above
6	5 – 10 m aquitard over > 5m minor aquifer over bedrock aquifer	Aquitards: as defined above Minor aquifer: Maiden's Hall Sand and Gravel
7	> 5 m minor aquifer over 5 – 10 m of aquitard over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium Aquitards: as defined above
8	> 5 m minor aquifer over > 30 m aquitard over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium
9	>5 m of minor aquifer over <5 m aquitard over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium
10	<5 m of aquifer or aquitard over bedrock aquifer	
11	Channel deposits	Geographic area of probable Pre-Devensian and Devensian buried channels defined at regional scale

1.2 WATER PROVIDERS AND REGULATORS

Northumbrian Water is the main water provider for the P1 area (Figure 4). Anglian Water is the provider for the east and Yorkshire Water for the very south of the area. P1 is in the North East Environment Agency area, with the southern extremity in the Yorkshire area (Figure 5).

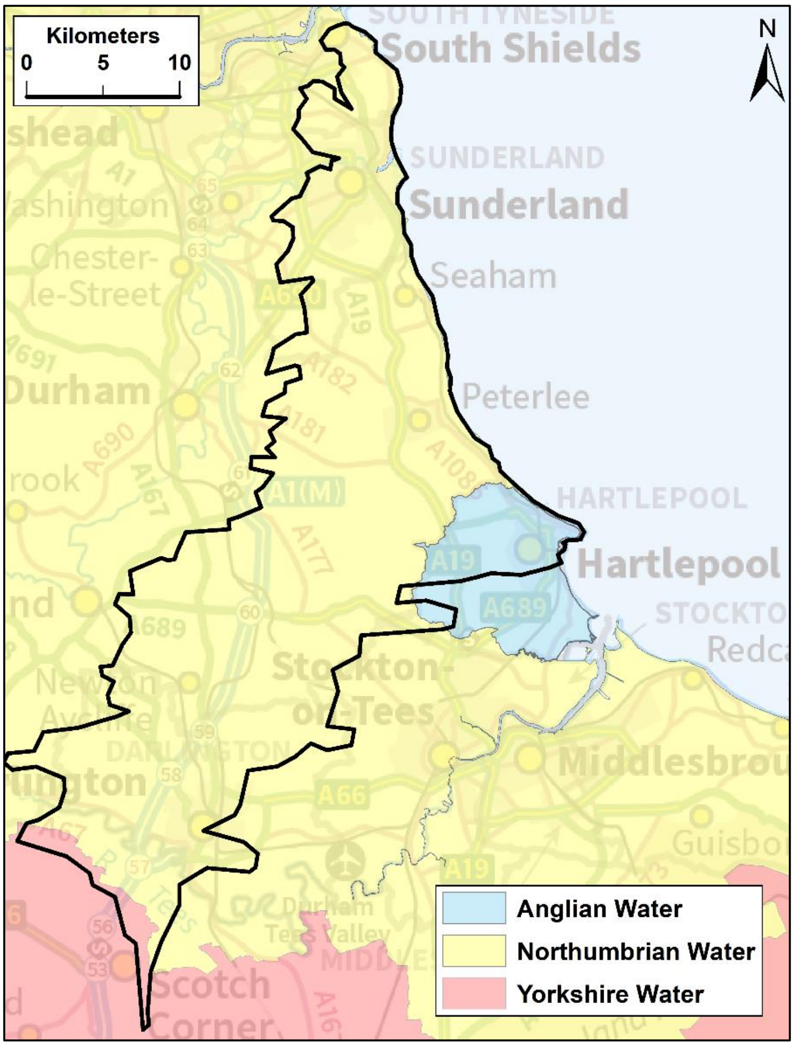


Figure 7.   Water providers in the P1 area

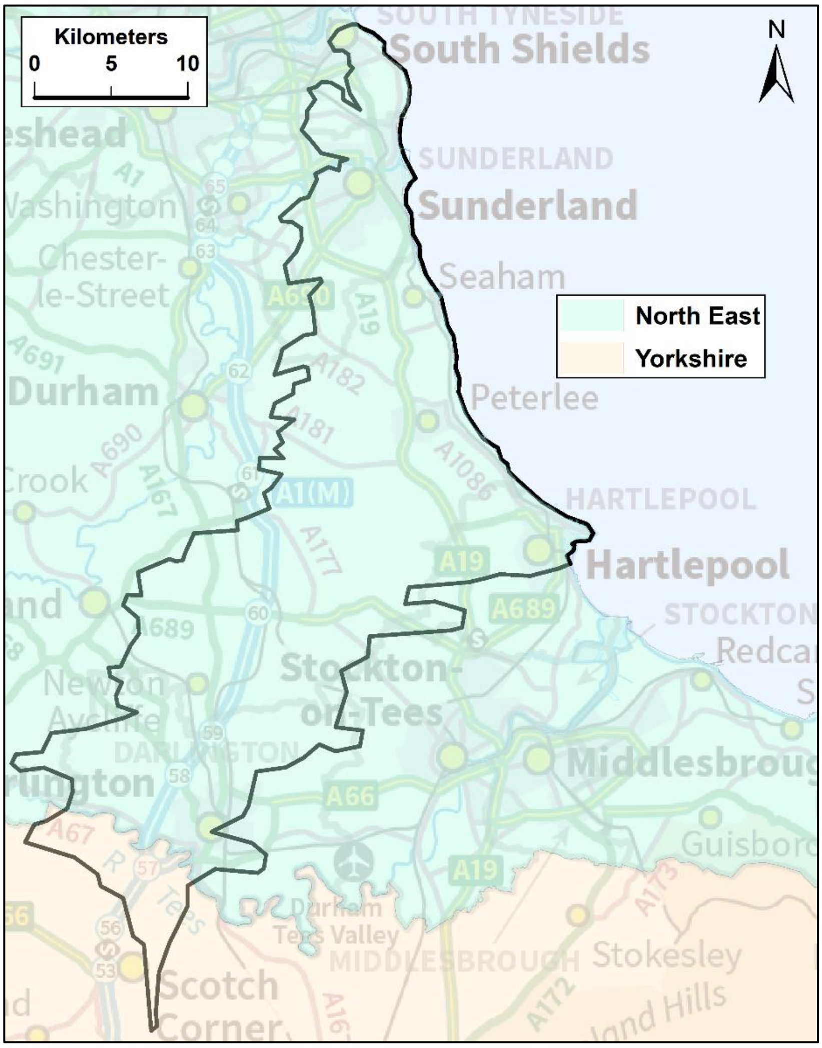


Figure 8. Environment Agency areas in the P1 area

2 Karst geomorphology

2.1 CAVES, CONDUITS AND FISSURES

2.1.1 Introduction

Records of caves, conduits and fissures are shown on Figure 9. These include records of 12 locations with one or more caves from a review of the caving literature undertaken for this report (Table 3), and an additional 15 records of sites reported in Kortas and Younger (2013) where different sized “caverns” were observed. Kortas and Younger (2013) report that water-worn features were observed in outcrops of Permian limestones in the County Durham area, including “small caverns” at six localities, and “larger ovoid caverns and holes” at Aycliffe Quarry and three other localities; and “very large caverns and sea washouts passing into caves in coastal areas, especially at five localities”. Figure 9 also includes records from the Natural Cavities database. This is a legacy dataset held by The British Geological Survey and Stantec. It comprises data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). There is some overlap between the three datasets presented in Figure 9, with some sites recorded in more than one dataset.

As well as karstic cavities, there are many “slip rifts” (described as “gull fissures” in the Natural Cavities database) in the Permian limestones (Murphy and Cordingley, 2010; Gibson et al., 1976). These are formed by mass movement processes and are similar to the “windy pits” in the Corallian limestones of the North Yorkshire Moors. Data on the locations of slip rifts in the P1 area were not systematically collated for this report, and therefore there are likely to be more than shown on Figure 9. It can be difficult to determine whether the origin of a cave is karstic dissolution or mass movement, and at some sites, cavities may have been enlarged by a combination of both (Gibson et al., 1976; Engering and Barron, 2007). Caves occurring in coastal outcrops may have formed by marine or karst processes, or a combination (Gibson et al., 1976; Gibbs, 1995c; Gibbs, 1996a).

There may be additional caves in the P1 area that have not been identified for this report. There are also likely to be karstic caves that have not been discovered where entrances have been obscured by the extensive superficial deposits (Murphy and Lowe, 2021) that cover much of the area (Figure 3). Solutional fissures and smaller karstic conduits appear common, but there are no systematic datasets for these features. The different types of cavities are discussed below, along with further details on the features shown on Figure 9.

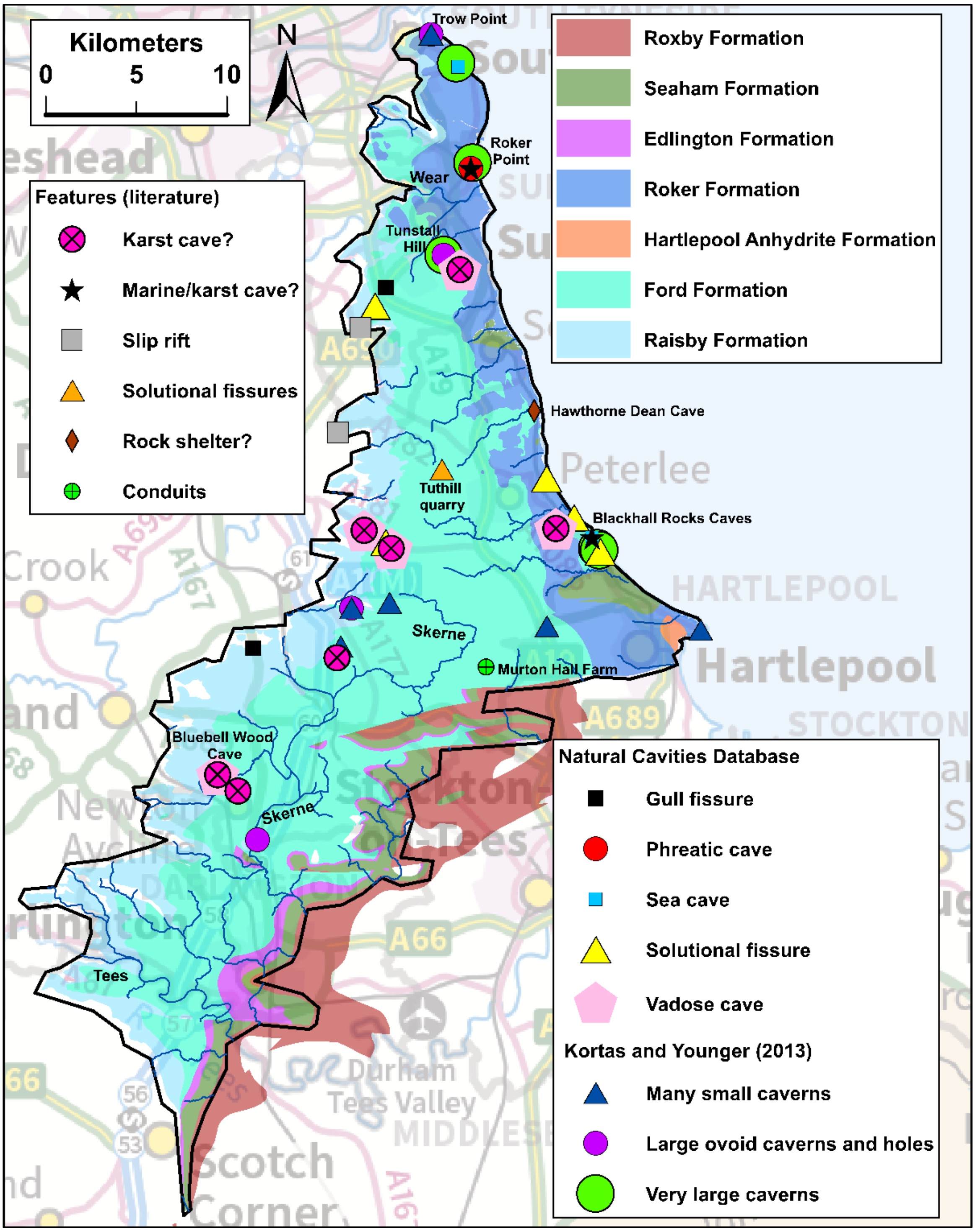


Figure 9. Cavities in the Zechstein Group in the P1 area

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2.1.2 Caves and conduits

Long, complex karst cave systems such as those developed in the Carboniferous aged limestones in the UK do not appear to be present in the Permian limestones. Gibson et al. (1976) suggest that the lack of extensive cave development may be because the Permian limestones are low lying and/or because these dolomitic limestones are less soluble than the purer calcium carbonate limestones. Nevertheless, there are some short but significant karst caves in the Permian limestones (e.g. MSG, 1974; Gibson et al., 1976; Brook et al.,1988; Gibbs 1994a,b; 1995a,b,c; 1996a,b), and it is highly likely that smaller sized conduits are common. Together with solutional fissures, these smaller conduits may form extensive networks within the aquifer.

Kortas and Younger (2013) provide evidence of solutional conduit development on different scales throughout the P1 area (Figure 9). The "caverns" identified by Kortas and Younger (2013) are described as "water worn" suggesting that they are likely to be solutional cavities. They also identify six locations where there are "many small caverns", with five of these distributed across the centre of the P1 area (Figure 9), and one in the very far north at Trow Point [NZ 384 667]. It seems likely that these are sites where there are many small-scale karstic conduits. At two of these sites, and two other sites "large ovoid caverns and holes" are reported by Kortas and Younger (2013) suggesting larger solutional conduits. At Tunstall Hill, which is an inland site [NZ 391 545], in addition to the "large ovoid caverns and holes", "very large caverns" were reported. The four other "very large caverns" appear coastal (Figure 9) and may be caves that are formed by some combination of marine and karst processes.

Karst caves in the Permian limestones in general are discussed by several authors: Allen et al. (1997) report that the limestones are cavernous in areas east of Durham and note the potential influence of phreatic cave development on aquifer characteristics. Waltham et al. (1997) note that there are some small, abandoned caves in some of the valleys that cross the Permian limestone outcrops. Farrant and Cooper (2008) also report that there are numerous small cave systems along the outcrop of the Permian limestones, although some of these are mass-movement caves. Some recorded caves are no longer accessible due to landfilling or quarrying (Murphy and Low, 2021). The conservation of, and threats to, caves in the Permian limestones are discussed by Gibbs (2016).

According to a recent review of karst in the Permian dolomitic limestones in north-eastern England (Murphy and Lowe, 2021), no hydrologically active karstic caves have been identified, but there are relict phreatic karst caves in addition to the slip rift caves formed by tectonic processes. Most known karst cave entrances in the Permian limestones are in quarries or natural outcrops in incised river valleys (Murphy and Lowe, 2021). Their karstic origin is indicated by their tubular cross sections and scallops and roof domes indicating a karstic phreatic (sub water table) origin (Murphy and Lowe, 2021). The caving literature on the Permian limestone is outlined by Murphy and Lowe (2021), and caves are listed and described in the caving guidebook by Brook et al. (1988).

Many of the known karstic caves in the Permian limestones are in the outcrops to the south which are covered in the P2 karst report (Maurice et al., 2024). In the P1 area the caving literature includes records of 14 caves which are likely to be wholly or partially karstic in origin (Figure 9; Table 3). Further details of these caves are provided below.

Table 3. Caves in Permian limestones in the P1 area

Name	Type	Length (m)	Altitude (m)	References
Ryhope Cave 1	Karst cave?	~ 9	~ 46	Gibbs (1995c); MSG (1973); Brook et al. (1988)
Ryhope Cave 2	Karst cave?	~ 61	~ 46	Gibbs (1995c); MSG (1973); Brook et al. (1988)
Ryhope Cave 3	Karst cave?	~ 12	~ 46	Gibbs (1995c); MSG (1973)
Bluebell Wood Cave	Karst cave?	~ 39	~ 110	Gibson et al. (1976); MSG (1971); Brook et al. (1988)
Hardwick Dean Cave 1	Karst cave?	~ 21	~ 61	Gibbs (1995c); Brook et al. (1988)
Hardwick Dean Cave 2	Karst cave?	~ 4	~ 61	Gibbs (1995c); Brook et al. (1988)
Dene House cave	Karst cave?	~ 12	~ 180	Brook et al. (1988)
Thornley Hall Cave	Karst cave?	~ 5	~140	Brook et al. (1988)
Newton Aycliffe Cave	Karst cave?	> 20	unknown	Ryder (2008)
Bishop Middleham Cave	Karst cave?	Unknown, short	~ 110	Raistrick (1932)
Blackhall Rocks Cave 1	Marine/karst?	~ 38	~ 3	Gibson et al. (1976); Gibbs (1995c;1996a); Brook et al. (1988)
Blackhall Rocks Cave 2	Marine/karst?	~140	~ 3	Gibson et al. (1976); Gibbs (1995c;1996a); Brook et al. (1988)
Roker Park Caves 1 and 2	Marine/karst?	16 and 4	~10	Gibbs (1995c); Brook et al. (1988)
Hawthorne Dean Cave	Rock Shelter?	~ 6	~ 15	Gibbs (1995c); Brook et al. (1988)
Houghton-le-spring	Slip Rift	several	~ 31	Gibbs (1995c); Murphy and Cordingley (2010); Brook et al. (1988)
Pittington Pot and Rift	Slip Rift	62 and 39	150,157	MSG (2021)

There are seven inland sites with one or more caves that are likely to be karstic in origin. These are shown as pink circles with a cross inside on Figure 9 (identified from the caving literature for this report, with five of them also recorded in the Natural Cavities database as vadose caves):

(1) Ryhope Caves: Ryhope caves 1, 2 and 3 were in the north of the P1 area [NZ 400 537], just south-east of Tunstall Hill (Figure 9). With a length of ~ 61 m, Ryhope Cave 2 is the longest recorded inland cave in the P1 area likely to be of karstic origin. These caves were described as "*quite roomy and dry*" and they were used as wartime air-raid shelters (MSG, 1973). Brook et al. (1988) report the caves were accessed from a railway cutting that was filled in, so they are no longer accessible. Further information is provided in Ryder (2008) who describes one cave at Ryhope with a rounded arched roof indicating that it is of karstic phreatic origin. Murphy and Low (2021) note that Ryhope caves are developed in dolomitic limestone close to the boundary between the Ford and Roker Formations.

(2) Hardwick Dene Caves: These are located to the south and a short distance inland from the coast near Blackhall Rocks at [NZ 453 394]. Gibbs (1995c) describes these as "*two short caves in an interesting location"*. Brook et al. (1988) suggest that Hardwick Dene Cave 1 is a walking sized passage in the side of a gorge which may be partly artificial, whilst Cave 2 is "*a prominent circular entrance*" about 6 m above a gorge. The circular shape and gorge location suggest that these are quite likely to be karstic caves.

(3 and 4) Dene House Cave and Thornley Hall cave: In the west of the P1 area there are two sites close together where short caves are reported by Brook et al. (1988). These are Dene House cave [NZ 347393] and Thornley Hall Cave, [NZ 362383]. The passages are described as "*tubes*" which suggests that they are likely to be karstic in origin.

(5) Bluebell Wood Cave: Further south in the P1 area, just to the north-west of Newton Aycliffe, Bluebell Wood Cave [NZ 266 258], "*is probably of solutional origin*" according to MSG (1971), who also describe a stream inlet in the roof and suggest that the cave acted as a stream sink with flood debris present. The cave was later filled in (Ryder, 2008).

(6) Newton Aycliffe cave: Ryder (2008) describes the exploration of a cave in a small disused quarry in a housing estate in Newton Aycliffe in 1970. The cave was at least 20 m long and described as of karstic phreatic origin, and the cave "*seemed to have filled with water fairly recently*" (Ryder, 2008). The precise location of this cave is uncertain and the record on Figure 9 is at the location of Newton Aycliffe village.

(7) Bishop Middleham Cave: Approximately 10 km to the north-east of Bluebell Wood Cave, in June 1932 a cave was intersected during quarrying activities at Bishop Middleham (Raistrick, 1932). The cave was largely sediment filled and of considerable archaeological significance, containing bones, including human skulls (Raistrick, 1932; Leach, 2015). The descriptions of this cave suggest that it is of karstic origin, with "*abundant evidence of water action on the floor and sides of the cave*" and "*the joints in the limestone were rounded and opened, fragments of stalagmite were present*" (Raistrick, 1932). The cave was later quarried away (Leach, 2015).

In addition to these seven sites, Hawthorne Dean Cave [NZ 441 459] is described by Gibbs (1995c) and Brook et al. (1988) as a rock shelter, with a length of 6 m. It is not clear if there is karstic development at this site.

There are two main areas where caves are reported within coastal outcrops. The origin of caves present within coastal cliffs can be difficult to determine, many may be entirely marine in origin, and in some cases both marine and karst processes may have contributed to cave development:

(1) Blackhall Rocks Caves: In the caving literature, there was particular interest in Blackhall Rocks Caves 1 and 2 [NZ 473 389], which are close to the very large caverns identified by Kortas and Younger (2013), so could be the same sites. There is some evidence that these caves may be in part karstic in origin. Blackhall Rocks Cave 1 is described by Gibbs (1996a) as having two entrances, with an upper entrance 4.5 metres up the cliff that has the appearance of a large diameter phreatic passage that soon closes. Blackhall Rocks Cave 2 is described by Gibbs (1996a) as being developed on two levels, with a lower level sculpted by the sea but possibly exploiting a karstic phreatic passage, and an upper level that resembles the Herne Hills caves (which are karstic caves in the Permian limestones in the P2 area). Gibbs (1996a) also suggests that there are other caves at this locality including a "*maze of passages*" in a sea stack. It is possible that the coastal cliffs at Blackhall Rocks have intersected a relict karstic cave system. Figure 10 to Figure 12 are pictures from the BGS archives of some caves at Blackhall Rocks.

(2) Roker Point Caves 1 and 2: There is also some evidence of karstic development at Roker Point where caves are recorded in all three datasets (Figure 9). The Natural Cavities database documents a "phreatic cave" (the red circle on Figure 9 at Roker Point). This cave is reported in Brook et al. (1988), and also discussed by Gibbs (1995c) who reports that "*Roker Park cave 1 is a large phreatic tube*" which suggests that it has a karstic origin. Kortas and Younger (2013) also report "*very large caverns and sea washout passing into caves*" at Roker Point [NZ 407 596]. It appears that there are caves here with a combination of a marine and karstic origin. Pictures of some caves at Roker Point are shown in Figure 13 and Figure 14.

Figure 9 also shows the locations of some slip rifts. Several slip rifts have been identified in the caving literature at Houghton-le-Springs [NZ 345 505], and two in a quarry in the Permian limestones at Pittington Hill (about 6km NE of Durham city, close to the western boundary of the P1 area). The latter are discussed by MSG (2021). Two of the sites in the Natural Cavities database are described as "gull caves" which is another term for a mass movement cave. Slip rift caves in the Permian limestones can be well decorated with flowstone deposits including stalactites and stalagmites, indicating small water flows (see examples from the P2 area in Gibson et al., 1976).

In the south of the Permian outcrop area cave development is also inferred to occur in the gypsum karst creating phreatic cave systems (Farrant and Cooper, 2008; Lamont-Black et al., 2002). These are present in the P1 area mainly from Darlington to Croft where they are inferred from the presence of significant dolines, some of which occurred in historical times (e.g. Hell Kettles – Cooper et al., 2013). Active gypsum karstification is indicated by sulphate-rich springs and water in boreholes with a local groundwater flow from the north-west through the Raisby and Ford formations up through the Edlington Formation and gypsum in the south-east along the Tees valley (Lamont-Black et al., 2002; Lamont-Black et al., 2005; Cooper et al., 2013).

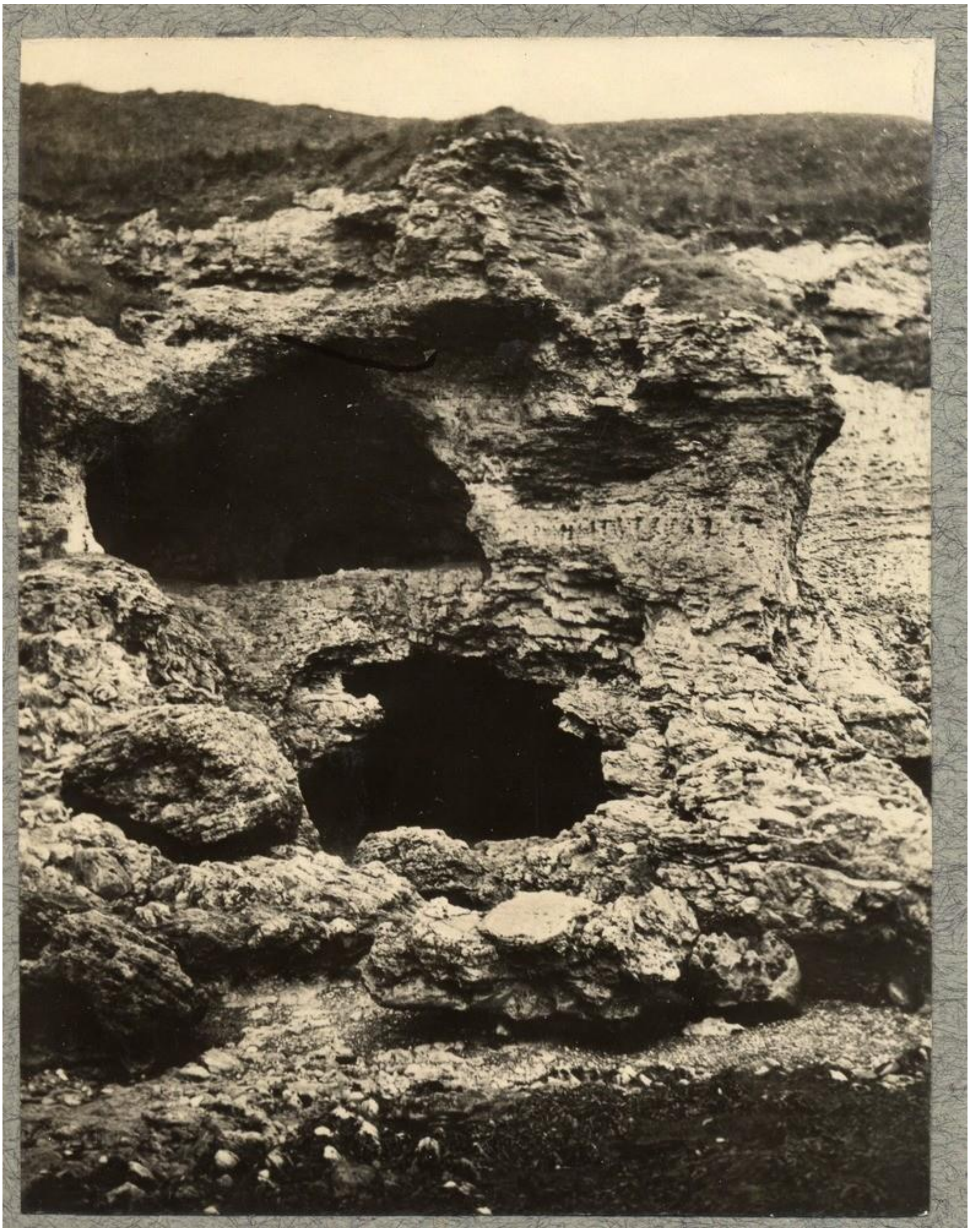

Figure 10. Caves at Blackhall Rocks. Photo by S.H. Reynolds, 1931

BGS photo archive image P253636

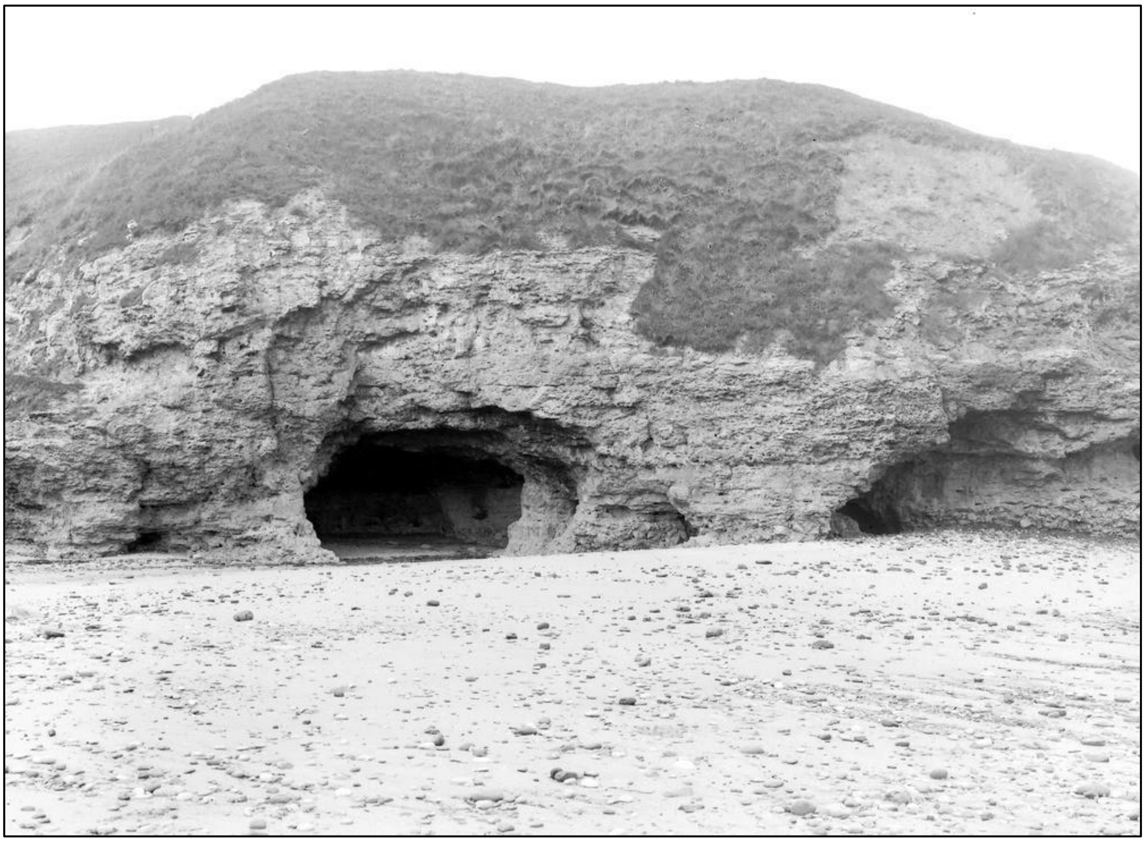

Figure 11. Caves at Blackhall Rocks. Photo by J. Rhodes, 1930

BGS photo archive image P205192.

Figure 12. Caves at Blackhall Rocks. Photo by J.Rhodes, 1930

BGS photo archive image P205195

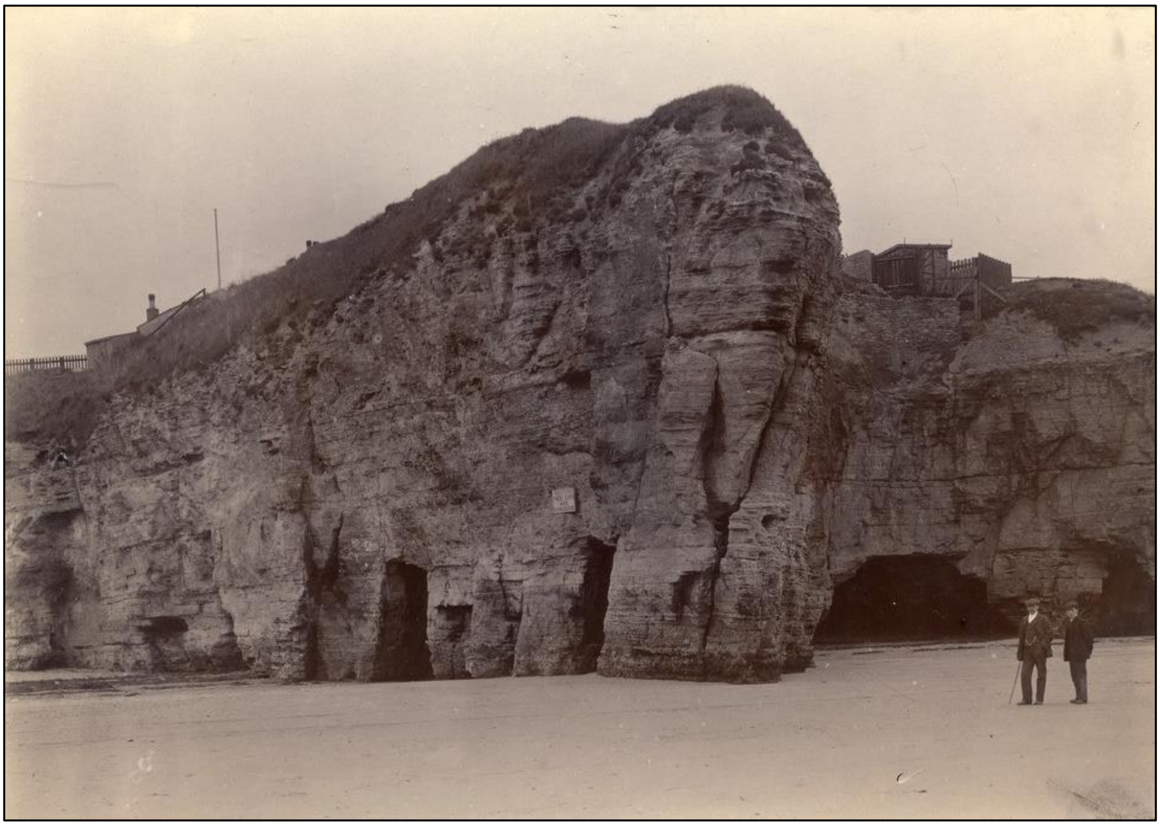

Figure 13. Caves and fissures at Roker. Photo by G. Bingley, 1910

BGS photo archive image P247287.

Figure 14. Caves at Roker. Photo by J Rhodes, 1930

BGS photo archive image P205208

2.1.3 Solutional fissures

Several studies indicate that solutional fissures occur in the Permian limestones. For example, Farrant and Cooper (2008) report that numerous solutional joints, conduit systems on bedding planes, palaeokarst, and sediment filled fissures are observed in road cuttings and quarries in the Permian limestones. Waltham et al. (1997) note that the Permian limestones have high fissure permeability specifically in the County Durham area. Karstic fissures are observed in coastal exposures of the Permian limestones (Lawrence, 2009). These are discussed by Smith et al. (1967). They report "*numerous vertical or steeply inclined breccia filled clefts*", suggesting that they almost all extend vertically for the height of the cliffs ("*up to 80 feet*"), and that they are generally "*3 to 25 feet wide and linear, but some are approximately circular in plan*". These features are best interpreted as breccia pipes as later described by Smith (1972 and 1994). Smith et al. (1967) also report "*marked solutional widening of some joints and the formation of large solution cavities*" in a fault zone at and near Tuthill Quarry [NZ 38999 42655]. They suggest that others may occur beneath large sink holes in adjacent fields. Tuthill Quarry is included on Figure 9, which also shows the locations of six sites in the Natural Cavities database which are listed as solutional fissures.

The paper by Kortas and Younger (2013) discussed above, reports an extensive survey of fractures in the Permian limestones in County Durham that was undertaken in 2006. Measurements of orientation, aperture, frequency and trace length were made at 84 faces within 33 natural exposures and 8 working quarries. Many fractures with apertures of several cm were observed, suggesting possible solutional enlargement (Table 4). Kortas and Younger (2013) also reported that many of the wider apertures were associated with N-S trending faults.

Table 4. Permian limestone fracture characteristics observed by Kortas and Younger (2013)

Fracture type	**Fracture type description**	**Aperture range (cm)**	**Average aperture (cm)**	**Frequency (number per meter)**
A	High dip (90 to120°) Strike NNE-ENE	0.25 to 20.5	3.26	0.03 to 3.09 (average: 0.58)
B	Lower Dip (70 to 90°)	0.25 to 12.5	3.11	0.05 to 3.00 (average: 0.62)
C	Bedding parallel	0.2 to 10	1.94	0.07 to 32 (average: 4.06)
D	Small fractures	0.15 to 3.4	0.73	0.27 to 22.5 (average 6.04)

2.1.4 Borehole images

Limestone cavities/conduits have been observed in boreholes in the area (D. Steele, EA, personal communication, 2023). One example is a monitoring borehole drilled at Murton Hall Farm near Wingate [NZ 41439 31761], where a void was observed at about 60 m below ground level (Figure 15). The location of Murton Hall Farm, to the west of Hartlepool, is shown on Figure 9. Borehole image data have not been systematically collated, and further study of these could be used to provide insights into how frequently these types of conduits occur, and what controls their distributions.

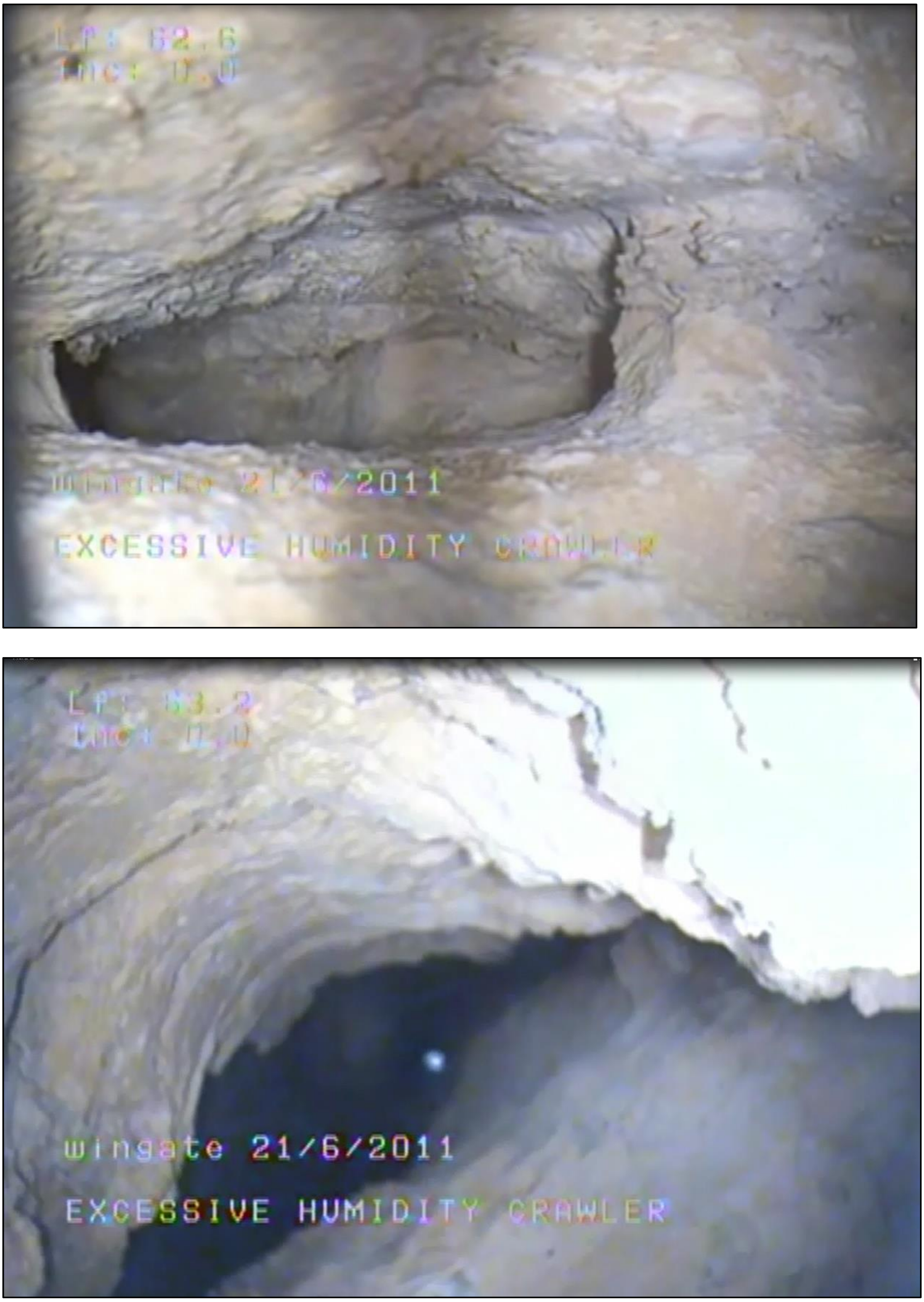

Figure 15. Borehole images of a conduit intercepted by a borehole at Murton Hall Farm

Pictures Courtesy of Anglian Water Services

2.2 STREAM SINKS

Some stream sinks occur in the Permian limestones (Farrant and Cooper, 2008). Stream sinks recorded in the P1 area are shown on Figure 16. Thirteen are from the BGS Karst Database (black circles on Figure 16) and were identified from a brief review of Ordnance Survey maps. These have not been researched further and have not been verified in the field. They are all located in the south of the area, on the lower parts of the Ford Formation and underlying units in the Zechstein Group. There are superficial deposits covering the Zechstein Group throughout most of the P1 area (Figure 3, Figure 4), and the type and thickness of superficial cover is likely to influence where stream sinks have developed. Bearcock and Smedley (2009) note that the amount of rainwater infiltration to the Permian limestones is highly variable, and focused on bare limestone dip slopes, with little recharge where the limestones are covered by low permeability glacial deposits. Some of the BGS Karst Database stream sink records are located in places with thick superficial cover (according to the BGS BSTM superficial thickness model, Figure 4), suggesting that these may be insignificant shallow features associated with the superficial cover or artificial drains, rather than karst stream sinks recharging the karst of the Zechstein Group. The BGS Karst Database has not been completed in this area and there may be other stream sinks present.

A review of the literature for this study identified six stream sinks (red circles on Figure 16). These are located in areas where superficial cover is thin or absent, and are discussed in more detail below:

Grid references for three "*swallow-holes*" are provided by Smith et al. (1967). These are near Sedgefield [NZ 36330 29760], Pess-Pool Hall [NZ 38150 43190] and Standalone [NZ 25920 29120]. Few details are provided other than that the one at Pess-Pool Hall is described as "*large*". These are all located on the Ford Formation, with some very thin superficial cover, and there is a swallow hole marked on the old Ordnance Survey maps at the site near Sedgefield.

The other three stream sinks shown as red circles on Figure 16 are all associated with the River Skerne and its tributaries. The River Skerne is a large river that flows through much of the P1 area. It is separated from the Permian limestones by varying types and thicknesses of glacial deposits but has long been known to have connectivity with the Permian limestones, with riverbed losses. Environment Agency (2021) report that the Skerne rises near Trimdon village and is impounded at Hurworth Burn Reservoir which is just upstream of natural swallow holes (Figure 17). A "*swallow hole*" is also marked on the old Ordnance Survey maps on the River Skerne at this point [NZ 40547 33109], and features are visible on LiDAR data: https://maps.nls.uk/geo/explore/side-by-side/#zoom=16.0&lat=54.69100&lon=-1.37119&layers=6&right=LIDAR_DTM_2m.

In the western parts of the Skerne catchment, the superficial cover is thin and locally highly permeable resulting in recharge to the Permian limestones through the riverbeds (Cairney and Hamill, 1977). Burgess (1970) reported that gauging on the Woodham Burn tributary of the Skerne suggested that it had losses of at least one million gallons per day (equivalent to approximately 50 l/s), just north of Newton Aycliffe. A karst sinkhole has been observed on the Woodham Burn in Woodham Village north of Newton Aycliffe at approximately [NZ 28311 26026], with no flow for about 50-100 m downstream, and during dry periods all the water enters this sink and can be heard cascading below ground (D. Steele, EA, personal communication, 2023). Figure 18 shows pictures of the river sinking here. Direct leakage was also reported "*via a pothole in the limestone from at least one of the west bank tributaries of the Skerne*" by Cairney and Hamill (1977), who also show a leakage point on the Woodham Burn on a map figure. Flow gauging data suggested that there was also leakage downstream of Preston-le-Skerne which was thought most likely to be at a point 4 km downstream from Preston-le-Skerne where limestone outcrops in the riverbed (Cairney and Hamill, 1977). The approximate NGR for this point is [NZ 28586 21787]. Daily fluctuations in water level in a borehole in the Permian limestones related to flooding in the River Skerne, provide further evidence of the connectivity between the river and the aquifer (Cairney and Hamill, 1977). The river losses and relationships with mine water discharges to the river are complex, but Cairney and Hamill (1977) found that the percentage of mine water discharges lost to the Permian limestones was variable over short, daily timescales; and concluded that the losses from the River Skerne were increasing in response to groundwater abstraction from the Permian limestones to the east of the river, with losses of ~37% of the river flow at the end of the study period.

River losses from the River Skerne are also extensively discussed by Palumbo-Roe et al. (2019) who present a cross sectional figure from Environment Agency (2012) which shows the losing sections of the river along with variations in the superficial cover thickness, and groundwater levels in the Permian limestones. Palumbo-Roe et al. (2019) also present a map from JBA (2017) which shows the gaining and losing sections of the River Skerne and its tributaries (Figure 19). This river connectivity classification was developed by JBA on behalf of the Environment Agency. It identifies losing sections along the upstream reaches of the Skerne and some of its tributaries, as well as downstream near Coatham Mundeville.

In addition to the stream sinks discussed above, Bluebell Wood cave was reported to take water (Section 2.1.2), and is therefore included on Figure 16. No systematic desk or field based survey of stream sinks was undertaken for this report, and there are likely to be other stream sinks. For example, potential stream sinks can be seen on old Ordnance Survey maps (National Library of Scotland, 2023) near Kelloe [NZ 35544 36031] and in three places near Walworth [NZ 23940 20350], [NZ 23370 20751] and [NZ 24681 20272]; and these sites are also included in Figure 16 (as orange circles containing a cross).

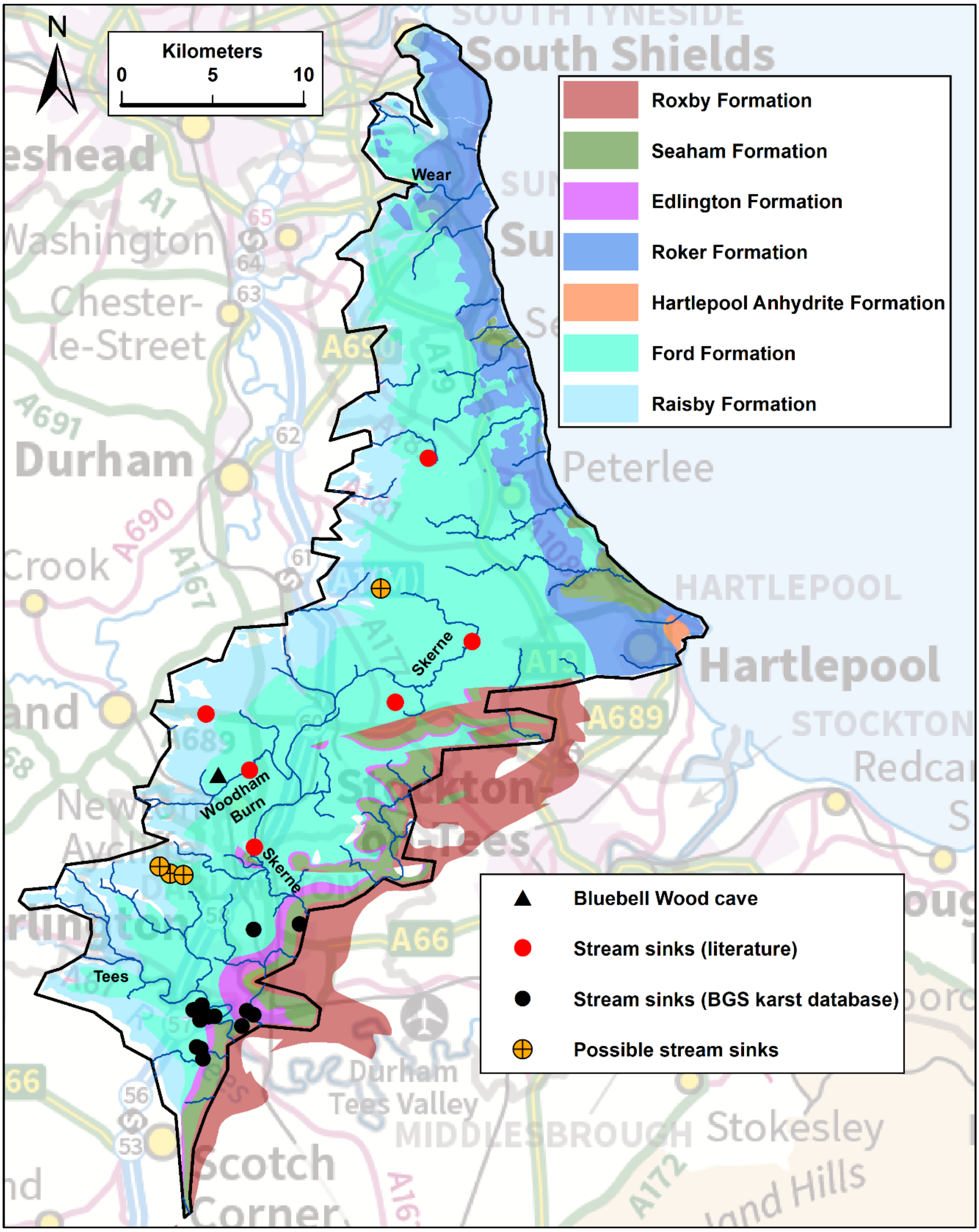

Figure 16. Stream sinks in the P1 area

Figure 17. Sinkhole along the River Skerne downstream of Hurworth Reservoir

Photo courtesy of the Environment Agency (D. Steele, personal communication 2023).

Figure 18. Sinkhole on the Woodham Burn

Photos courtesy of the Environment Agency (D. Steele, personal communication 2023).

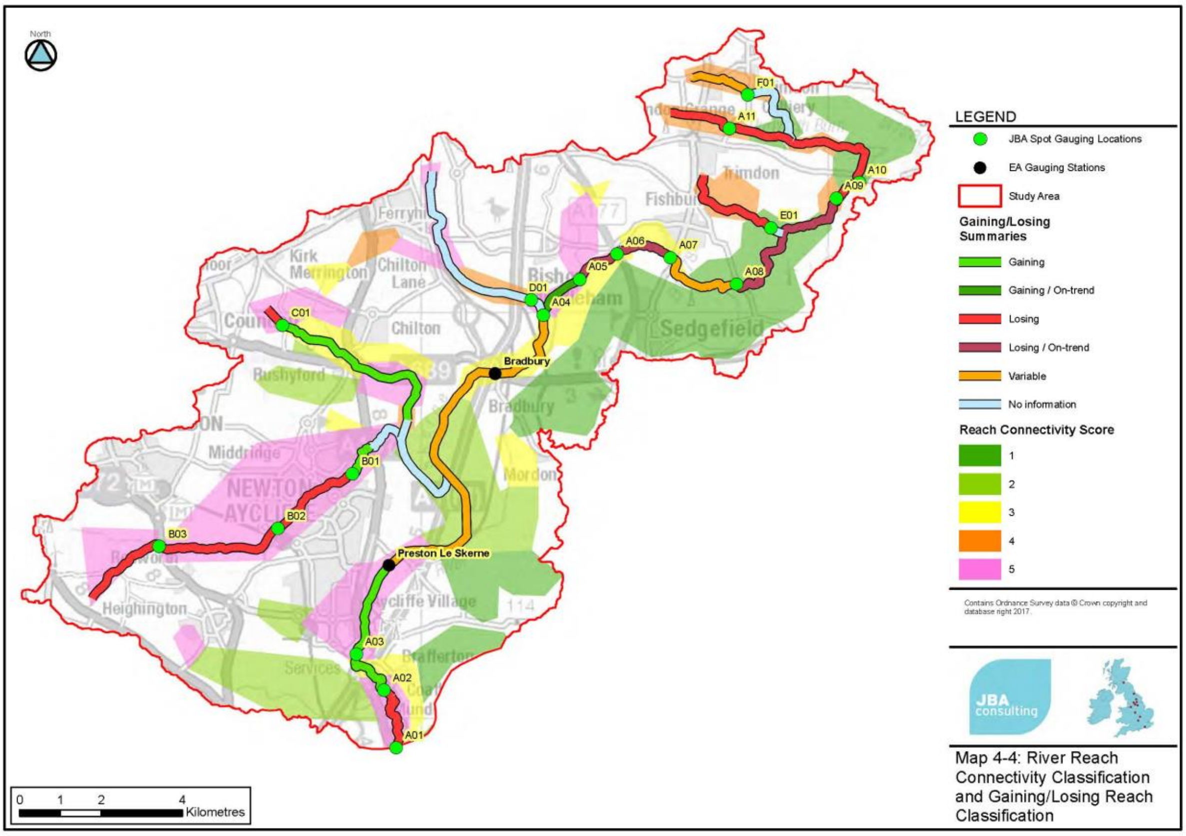

Figure 19. Losing river sections in the Skerne catchment (from JBA, 2017)

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2.3 DOLINES AND DISSOLUTION PIPES

There is little information on dolines or dissolution pipes in the Permian limestones. There are no limestone dolines recorded in the BGS Karst Database in the P1 area, although this area has not been systematically assessed for this database. There are two records of “sinkhole/solution pipe” in the Natural Cavities database (Applied Geology Ltd., 1993). Both records are also listed as “*subsidence*”. There is no further information on these features, or references related to them listed in the database. Their locations are included as red triangles on Figure 20, which shows that the northernmost feature is located on the Roker Formation, and the feature to the south is located on the Ford Formation.

In contrast, collapse dolines in the Permian gypsum karst are extremely common (Waltham et al., 1997; Farrant and Cooper, 2008), and the high rates of dissolution in the gypsum enable the karst to evolve on human timescales (Farrant and Cooper, 2008). Subsidence is common around the gypsum outcrops, especially around and to the south and east of Darlington (Lamont Black et al., 2002; Lamont-Black et al., 2005; Farrant and Cooper, 2008). These are mainly associated with the Edlington Formation gypsum deposits – the Hartlepool gypsum (Figure 20), but the Billingham gypsum in the Roxby Formation is also implicated. Sinkholes were mapped to the east and south of Darlington (British Geological Survey, 1987) and these are included in the BGS Karst Database. Building damage and subsidence at Parkside in the south-east of Darlington prompted investigation and the EU-funded ROSES project https://research.ncl.ac.uk/roses/index.html to investigate gypsum dissolution and subsidence in the area and throughout Europe (https://research.ncl.ac.uk/roses/studysites.html#DARLINGTON). The bedrock geology maps of Darlington were updated as part of this project utilising additional boreholes drilled to investigate gypsum dissolution (Cooper and Gordon, 2000; Lamont-Black et al 2002; Lamont-Black et al 2005) A small karst sinkhole about 1.5 m wide and 1.1 m deep formed at Skerne Park, Darlington on Monday 21st February 2011 [NZ 28294, 13271], it was recorded and filled in (BGS GeoReport GR_202777/1). Karst in the gypsum causes very difficult ground conditions (Cooper and Saunders, 1999; Farrant and Cooper, 2008). The spatial patterns and controls on the gypsum subsidence karst are outlined in Farrant and Cooper (2008). Lamont-Black et al. (2005) and Cooper (2008) indicated that the amount of water flow through the sequence is an important control on karst, with higher concentrations of dissolution features associated with river valleys and buried river valleys. These are the controlling factors for the development of the four (now three as one was filled) dolines at Hell Kettles between Darlington and Croft (Figure 21, Figure 22). Locations of surface karst features in the gypsum karst were not collated for this report which is focused on the limestones. Collapse dolines related to the gypsum occur mainly where the Hartlepool gypsum is present in the Edlington Formation in the south-east of the P1 area.

Breccia pipes are very common in the north of the P1 area where they are present in the Seaham and Roker formations due to collapse into cavities caused by the dissolution of the former evaporites inferred mainly to have been gypsum/anhydrite in the sequence underlying these formations and overlying the Ford Formation. These features are all palaeokarst breccia pipes and their upper surfaces are either infilled with superficial deposits or planed off at the base of the superficial deposits by glaciation. These features were originally called “breccia gashes” and were initially described by Sedgwick (1829) and Lebour (1884). They were described more fully by Smith et al. (1967) though their full mode of origin was not implied until Smith (1972) described such features more widely. Further descriptions of them were given by Smith (1994 and 1995) and by Daniels et al. (2022). Pictures of a breccia pipe in Marsden Bay are shown in Figure 23 and Figure 24.

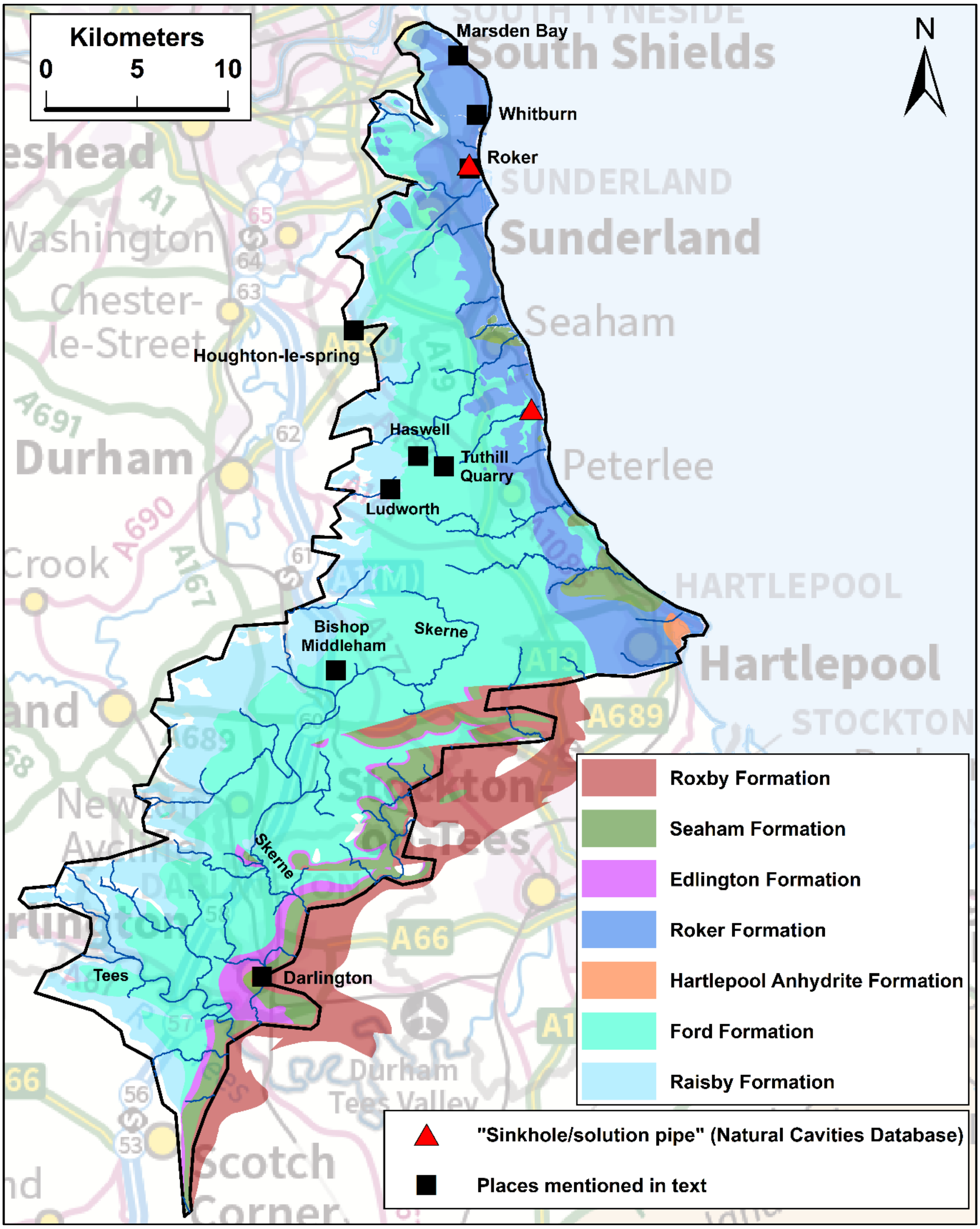

Figure 20. Dolines and dissolution pipes

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Figure 21. Croft Kettle, the most southerly of the Hell Kettles

(Photo A. H. Cooper)

Figure 22. Hell Kettles south of Darlington.

(Double Kettle is to the north and Croft Kettle with the bluish green water to the south. A further karst sinkhole near the road was infilled; BGS Geovisionary oblique view).

Figure 23. Breccia pipe at Marsden Bay

(Photo A. H. Cooper)

Figure 24. Foundered breccia of Seaham Formation at Marsden Bay

(Photo A. H. Cooper)

Farrant and Cooper (2008) suggest that there are very few dolines associated with the Permian limestones, although they note that this could be due to infilling of karst features by agricultural practices. They also suggest that the rock is not generally problematic for engineering, suggesting limited karstic collapse features. A literature review for this report suggests that some limestone dolines and dissolution pipes may occur in the P1 area, although data on their locations is scarce.

Green et al. (1998) discuss "*a hazard map of the Magnesian Limestone in County Durham*". They compiled a dataset of dolines using BGS 1:10000 geological maps of the area, and 750 aerial photographs from 1968. They identified approximately 400 dolines, and report that where possible solution features that were identified on aerial photographs were verified in the field. Green et al. (1998) suggest that where there is a thin till cover on the dip slopes of the limestones, "*cuestas are commonly punctured by lines of sinkholes a few metres in diameter which form where till has collapsed into solution features*". Quite large parts of the P1 area are covered by thin till deposits (Figure 3 and Figure 4). Although karst dolines are associated with till cover, sometimes the naturally hummocky nature of the till can resemble dolines, and especially where the till cover is thick, some surface depressions may be related to the till deposits rather than karst. Green et al. (1998) also report that the distribution of "*sinkholes*" is related to structural geology, in particular to faulting, but also to folding. Green et al. (1998) do not provide either data or maps of the 400 dolines, and it is not clear where the dolines are located, but the general geological maps in the paper suggest that it covered the whole P1 area. The hazard maps that were created and discussed in the paper are also not provided. More recent work by BGS produced the Geosure database that provides an assessment of the risk of subsidence in all soluble rocks in the UK, including the Permian limestones and gypsum (Farrant and Cooper, 2008).

In a study of the Whitburn to Roker area (Figure 20), Davis and Horswill (2002) note that in addition to subsidence due to dissolution of the Hartlepool Anhydrite Formation, there is also some solution within the dolomitic limestones. They discuss breccia filled pipes and fissures in the Permian limestones. This area is on the Roker Formation and near to one of the features recorded in the Natural Cavities database (Figure 20). To the south-west, In the Houghton-le-spring area (Figure 20), frequent "fissures" have opened up in the limestones, sometimes over short timescales of a few days (Young and Culshaw, 2001; Young and Lawrence, 2001; Young, 2003). These comprise linear collapse features and holes and depressions, and are associated with faults. The cause of these collapses is not known for certain, although it was thought that landslipping, cambering and limestone dissolution did not account for the ground movements, and that perhaps they might be due to fault reactivation or perhaps rising groundwater levels in the abandoned coal workings in the underlying Pennine Coal Measures Group (Young and Culshaw, 2001; Young, 2003). It does not appear that karst is an important process in the development of these features, but further information, including descriptions, pictures and grid references for many features can be found in Young and Culshaw (2001), and Young and Lawrence (2001). Further south, Smith et al. (1967) report large *"sink holes*" in fields near Tuthill Quarry, where solutional development of fissures is observed (Section 2.1.3). There is a surface depression near Tuthill Quarry apparent on LiDAR (National Library of Scotland, 2023) at [NZ 39055 42761]. This site is on the Ford Formation (Figure 20).

Waltham et al. (1997) suggest that there are some lines of "*sinkholes*" along the edges of the Permian limestone outcrops, but their locations are not reported. The Environment Agency have also noted sinkhole features along fault boundaries or at the edge of the Permian strata, for example at Haswell, Ludworth and Houghton Cut near Houghton-le-spring (Figure 20). It is not clear whether these are karst features, or crown holes associated with mining (D. Steele, EA, personal communication, 2023). They could also be related to mass movement gull features. The Environment Agency also know of a number of small sinkholes in the Bishop Middleham area (Figure 20) where holes have opened up overnight and subsidence has been observed (D. Steele, EA, personal communication, 2023). They note that this area is underlain by Coal Measures, and impacted by lowered water tables during mining, followed by large increases in groundwater level to close to the surface after mine dewatering stopped. The coal measures are quite deep below the limestones in this area (87 m according to one borehole at Bishop Middleham, NZ 33SW/160), and the role of karstic dissolution/mining dewatering in the formation of these features is unclear but could warrant further investigation.

In summary, there are no comprehensive datasets on dolines and dissolution pipes in the Permian limestones of the P1 area, but some general observations can be made. Collapse features in the Permian limestones commonly occur where the limestone is underlain by the highly soluble gypsum deposits especially in the Hartlepool gypsum where it occurs within the Edlington Formation. Palaeokarst breccia pipes are widespread in the Roker and Seaham formations. There is some evidence that small karst dolines that are not associated with the gypsum do occur in the Permian limestones. These may be distributed in areas where there is a thin cover of glacial till overlying the limestones, or where there is faulting or folding. Collapse features can also be present where gulls/slip rifts occur. Current evidence suggests that in the Raisby and Ford formations dissolution pipes may be less common than in other karst areas of the UK (such as the Chalk). If they are present, they are likely to occur where there is a thin superficial cover over the limestones. Further work is needed to develop datasets on dolines and dissolution pipes in this area, and improve understanding of their prevalence and distributions.

2.4 SPRINGS

There are more than 200 springs recorded in the P1 area (Figure 25). The records are from the BGS springs database with one exception which was identified from historic Ordnance Survey maps. Current and historic Ordnance Survey maps were not systematically checked to identify springs for this report, and therefore it is possible that there are additional springs.

Springs are distributed throughout the P1 area covering all units of the Zechstein Group (Figure 25). It is possible that some springs are discharging groundwater from superficial deposits where they comprise thicker permeable deposits. There is little information on springs and no spring discharge data were identified for this report. It is difficult to assess how much karstic spring development there is in the Permian limestones. Farrant and Cooper (2008) suggest that there are numerous springs in the Permian limestones. Murphy and Lowe (2021) report that accessible caves have not been found at spring sites in the Permian limestones. This suggests that the springs may be discharging groundwater from networks of smaller conduits and solutional fissures, although it is possible that cave-sized voids are present within these networks if there is dispersal of the discharge through superficial deposits or sediments at the spring site.

Younger (1995) suggests that there are some limited groundwater discharges from the Permian limestones to the Wear and Tyne Rivers. However, most of the outflow from the limestones is thought to be via submarine springs (Younger, 1995; Bearcock and Smedley, 2009). If there are larger springs discharging beneath the sea, then these may be outlets for karstic networks. The only river that is reported to receive substantial inputs from the Permian limestones is the River Skerne (Younger, 1995; Bearcock and Smedley, 2009; Palumbo-Roe et al., 2019). The Skerne catchment was recently investigated by Palumbo-Roe et al. (2019). This work showed that some hyporheic zone water chemistry is similar to the Permian limestones, indicating that the limestones are contributing flow to the surface streams. Palumbo-Roe et al. (2019) report some springs in the Skerne catchment, including springs at [NZ 32033 30464] and [NZ 33771 31305] on the Mansforth tributary. These springs may be fed by deeper groundwater upwelling via a fault zone, or by shallow superficial deposits (Palumbo-Roe et al., 2019). Spring discharges are not reported by Palumbo-Roe et al. (2019), but springs are generally described as "*small*". "*Bubbly spring*", on the Woodham Burn tributary of the Skerne discharges water through the stream bed and the western stream banks (Palumbo-Roe et al., 2020). The discharge of this spring is not reported, but its chemistry suggests that it is derived from the Permian limestones or the underlying Permian Coal Measures Group which would be via flowpaths in the Permian limestones. It does appear that there may be some development of solutional karstic networks in the Skerne catchment, which is also indicated by losing sections in these rivers (Section 2.2).

Springs occur associated with the gypsum sequence and overlying strata in the south of the P1 area, these are documented by Cooper et al. (2013). The most notable spring emanates from the most southern karst doline of Hell Kettles (Figure 26). This feature is fed by sulphate-rich artesian groundwater at a temperature that means the pond does not easily freeze and it steams in winter. The pond is an SSSI and also supports a unique flora characterised by the alga *Chara hispida* (Giantzoudis, 2003). Giantzoudis (2003) quoted an unpublished report by Hedley (1997) for English Nature that documented the flora and water at Croft Kettle (the most southerly of the Hell Kettles), along with how it was influenced by groundwater abstraction from the Raisby and Ford formations west of Darlington at Broken Scar boreholes and pumping station.

Giantzoudis (2003) noted:

"*Different (experimental) rates of pumping from Broken Scar accompanied by monitoring of the farm supply outfall* [from Croft Kettle] *for the whole of 1985, provided strong evidence that an abstraction in excess of 9000 m^3 per day (2 million gallons per day) reduces throughflow in Croft Kettle, though the relationship is not straightforward, there being a delayed effect.*"

"The NWA installed a borehole at the nearby farm in 1990, solving the farm's water supply problem. This change also largely solved any problem of water shortage for Croft Kettle, since the only outflow from the pond was then the balancing pipe connecting the two ponds. However, in late September 1990 doubling of abstraction at Broken Scar led to obvious falls in the levels of both ponds and cessation of borehole supply for the farm."

This information along with the local groundwater gradient shown by Lamont-Black et al. (2005) show the southerly groundwater flow and the interconnection of the Ford Formation, the Edlington Formation (with Hartlepool gypsum) and the overlying Brotherton/Seaham formations. The local nature of the sinkholes and surrounding geology was investigated using geophysics by Sargent and Goulty (2009). The fact that the water levels at Hell Kettles were strongly affected by water abstraction from the Ford Formation at Broken Scar (Low Coniscliffe) about 4.5km to the north-west show the interconnection between the Ford Formation, the Edlington Formation and the Brotherton Formation. Compared with the situation at Ripon to the south (Cooper, 2020) it is likely that much of the water flow is actually within the gypsum sequence and that the various formations are linked together hydrogeologically by the subsidence features and breccia pipes.

A little further south sulphate-rich springs from the same sequence were recorded at Croft and formed the basis of a Spar installation (Cooper et al., 2013). To the east of this, another sulphate-rich spring occurred at Dinsdale (Cooper et al., 2013; Jackson, 2023) related to the upper part of the sequence including the Roxby Formation and Billingham gypsum along with local faulting. The presence of sulphate-rich groundwater and springs shows the interconnection of limestone and gypsum sequences in the Permian strata.

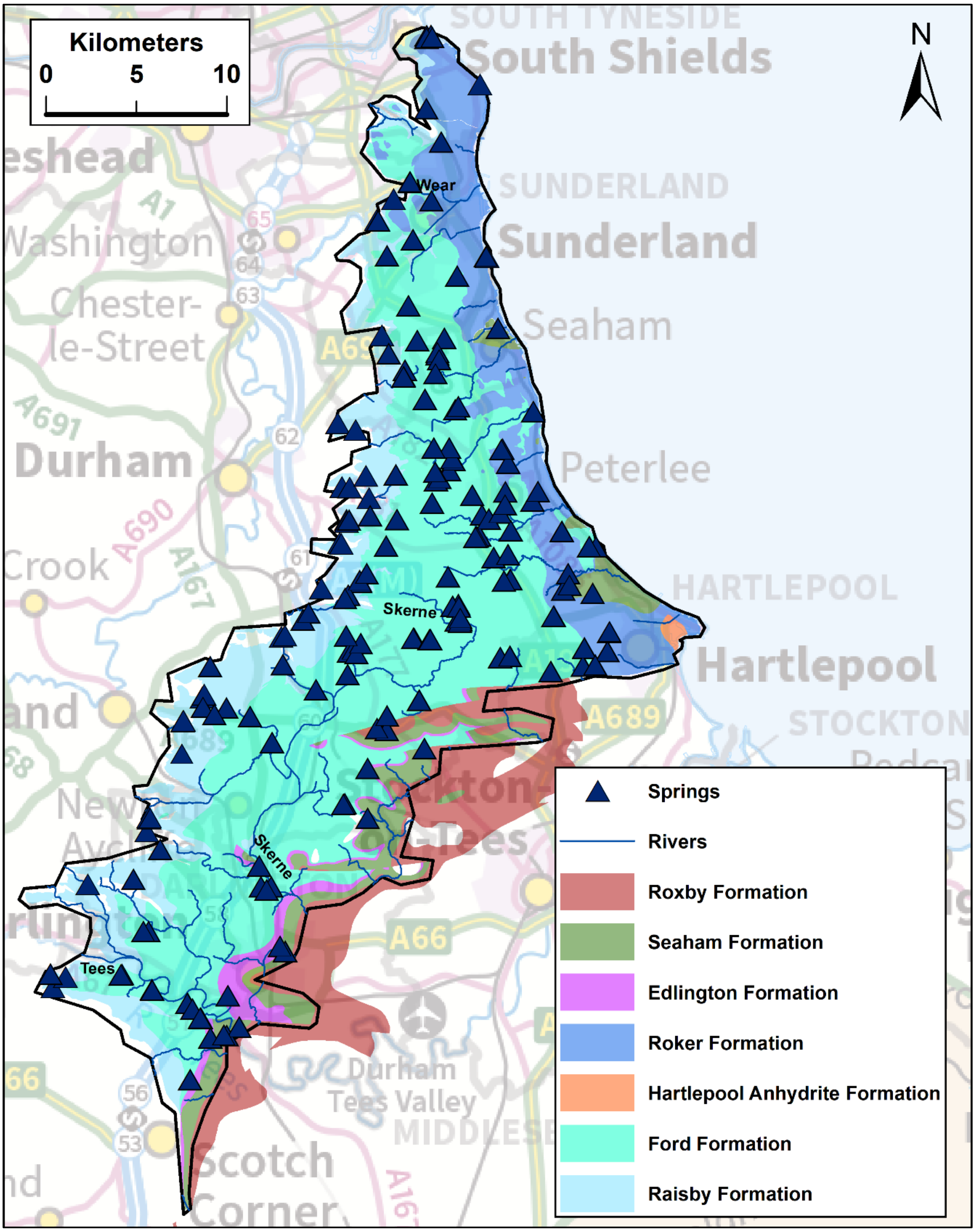

Figure 25. Springs in the P1 area.

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Figure 26. Groundwater fed south pond at Hell Kettles

Photo courtesy of the Environment Agency (D. Steele, personal communication 2023).

3 Tracer tests

No records of successful tracer tests undertaken in the P1 area were identified during this study. Recent tracer testing at an abstraction site did not result in tracer detection at the borehole (D. Steele, EA, personal communication, 2023); this test has not been reviewed for this report.

4 Other hydrogeological evidence of karst

4.1 SATURATED ZONE KARST

There has been little work to investigate or determine the extent of saturated zone karst development in the P1 area. The size of the many recorded springs (Section 2.4) is unknown, and therefore it is unclear how many springs have (or had) substantial flows indicative of well-developed karstic networks. However, there is some evidence that karstic solutional networks of fissures and conduits occur in the saturated zone, with some high transmissivities and high yields, and some fissure inflows encountered during construction; and this is discussed below. Dry valleys are incised into the dip slopes of the Permian limestones (Murphy and Lowe, 2021), which is also indicative of subsurface solutional development of permeability.

There are 44 sites in the Permian limestones in the County Durham area where transmissivities have been estimated from pumping tests and data are available in the BGS aquifer properties database (Allen et al., 1997). The data from this database are shown as red circles on Figure 27. Most of the boreholes with pumping test data are distributed on the upper parts of the Ford Formation (Figure 27). Transmissivity values range from 11 to 2800 m^2/day, with an average of 448 m^2/day and a median of 205 m^2/day. Transmissivities are generally lower than in the Chalk where boreholes commonly have transmissivities of > 1000 m^2/day due to well-developed karstic networks of conduits and fissures (Allen et al., 1997; Maurice et al., 2021). In the P1 area, only 5 sites have transmissivities > 1000 m^2/day. These are mainly distributed in the central and southern parts of the P1 area, in the catchments of Skerne and Tees (Figure 27). Most other sites (38) have transmissivities > 100 m^2/day suggesting that there may be some less extensive solutional development of permeability.

At many sites there are multiple estimates of transmissivity, either because pumping tests were carried out on different boreholes, or because multiple tests were carried out on the same borehole. For each borehole, the best estimate of transmissivity was determined based on factors such as the length of the test, and then a site "*best locality*" value (incorporating all tests within 100 m) was determined by selecting the most reliable test result (Allen et al., 1997). The transmissivity values presented on Figure 27 are these "*best locality*" values. The maximum and minimum transmissivity values for each site are also available. Many sites in the P1 area had higher maximum values, with a total of 10 having a maximum value of more than 1,000 m^2/day, and the highest being 7,300 m^2/day. Whilst the "*best locality*" values may generally be the most useful, in considering karst, the maximum values may also be of interest where within site variation is due to karstic heterogeneity.

Since the compilation of the aquifer properties database there have been a few additional pumping tests in the Permian limestones (D. Steele, EA, personal communication, 2023). These generally support the patterns observed in Figure 27 although there is a new transmissivity value in the area to the north-west of Darlington where the bedrock is confined by thick superficial deposits, and a low transmissivity of 87 m^2/day was calculated (D. Steele, EA, personal communication, 2023). This point is shown as an orange triangle on Figure 27, and is substantially lower than the other transmissivity estimates from the area west of Darlington.

Allen et al. (1997) report that the glacial drift was not thought to be contributing vertical leakage to the limestone aquifer, suggesting that high transmissivities are due to the permeability of the limestones. They also note that higher transmissivities occur in the more brecciated limestones. Allen et al. (1997) report that the middle limestones (the Ford Formation) with the higher porosity are generally thought to have the highest permeability, but that the underlying Raisby Formation and the higher Roker and Seaham Formations can locally have substantial transmissivities where fracture frequencies are high. Allen et al. (1997) also suggest that transmissivity in the Permian limestones in general tends to be highest along major fault zones. Price et al. (2007) also report that transmissivities of the Permian limestones are higher around fault zones and also where the limestones have collapsed due to dissolution of the underlying gypsum. These patterns are not immediately obvious from Figure 27, and all the sites with transmissivity > 1000 m^2/day are located on the Ford Formation and therefore do not intercept the gypsum that occurs in the upper formations. Overall, there are some sites with high transmissivity which may indicate well developed solutional networks, but the evidence for these from transmissivity data is not strong, with many sites with relatively low transmissivity.

There are some high yielding boreholes reported for the Permian limestones (Smith et al., 1967; Cairney, 1972; and Allen et al., 1997), which might suggest that there are some well-developed networks of conduits and solutional fissures. Smith et al. (1967) report large yields from the Permian limestones at Amerston Hall, Pudding Poke, Naisberry, Dalton Percy, Howbeck and West Hartlepool (yellow squares on Figure 27). Yields were commonly more than 50,000 gallons per hour (equivalent to > 60 l/s), with only small declines in the water table (Smith et al., 1967). The hydrogeology of the Permian limestones was investigated by Cairney (1972) who estimated "*anticipated yields*" based on the results of pumping tests in large diameter boreholes. He reported that for 12 boreholes in the catchment of the Billingham Beck and lower Skerne tributaries of the River Tees, anticipated individual yields ranged from 0.26 to 4.4 million gallons per day (equivalent to ~13 to 231 l/s), with eight sites having anticipated yields of more than 1 million gallons per day (> 50 l/s). No grid references are provided for these sites, although the locations are in a figure in Cairney (1972), which shows that the boreholes are in the area around, and to the north of Darlington (Figure 27). Allen et al. (1997) report that large diameter boreholes in south-east Durham have high yields of up to 8720 m^3/day (equivalent to ~100 l/s of continuous pumping). The locations of these boreholes are not reported.

There is evidence of large inflows from the Permian limestones during construction (Davis and Horswill, 2002). Detailed investigations carried out for the construction of the Whitburn-Roker Sewer tunnel are reported by Davis and Horswill (2002) who emphasise the highly variable nature of the ground conditions and variable permeability of the Permian limestones, with the potential risks of engineering complications from groundwater inflows during tunnel construction. Pumping tests with quite a high average pumping rate of 21 l/s were conducted, indicating high permeability. Trial shafts of ~ 7 to 8 m depth encountered inflows of ~ 4 to 6 l/s from "*subvertical open joints*" and from weathered dolomite. The maximum groundwater inflow during the construction of the tunnel was 8 l/s, and it was thought that the mitigations (which included the construction of a grout curtain and groundwater dewatering) had substantially reduced the inflows (Davis and Horswill, 2002). Flows through "*open joints*" were reported, and some of the permeability was thought to be from the weathered brecciated limestones. The Whitburn-Roker area is in the far north of the P1 area (Figure 27).

4.2 UNSATURATED ZONE KARST

In addition to the records of stream sinks (Section 2.2), there is a study which provides some further evidence of rapid unsaturated zone flow in the Permian limestones in the P1 area. An artificial recharge experiment was carried out at a Permian limestone quarry at Thrislington [NZ 316 331] to the east of Ferry Hill in County Durham (Wardrop et al., 2012, see Figure 27 for location of Thrislington). Infiltration into a purposely constructed feature was rapid, with maximum infiltration rates of 2120 m^3/day, and the target infiltration rate of ~1100 to 1500 m^3/day (~ 12 to 17 l/s) was easily achievable. These infiltration rates are high and suggest well developed fissures in the limestones. The experiment demonstrated rapid flow through an unsaturated zone of ~ 30 to 35 m, with a water table response in nearby monitoring boreholes within about one day.

Overall, the frequency and distribution of rapid unsaturated zone flow in the Permian limestones is not well characterised - stream sink records are incomplete, there may be losses through riverbeds which are often not well documented, and there may be solutional features with no surface expression enabling rapid recharge. The distribution of rapid unsaturated zone flow in the Permian limestones will be highly dependent on the thickness and nature of the overlying superficial deposits. Superficial deposit domain mapping (Price et al., 2007a,b) suggest that in large areas in the west and north of the P1 area there are only thin superficial deposits overlying the Zechstein Group (Figure 5 and Figure 6). In these areas there is potential for rapid recharge to the limestones where solutional fissures have developed. Figure 5 and Figure 6 also indicate some areas with superficial deposit aquitards of more than 30 m (especially in central parts of the P1 area). These are likely to restrict direct recharge to the Permian limestones, and result in surface runoff which might sink where streams or rivers cross onto areas with thin or more permeable superficial deposits. Assessments and conceptualisation of point recharge and rapid unsaturated zone flow in the Permian limestones could use these superficial domains maps to target desk and field-based assessments of surface karst and rapid recharge.

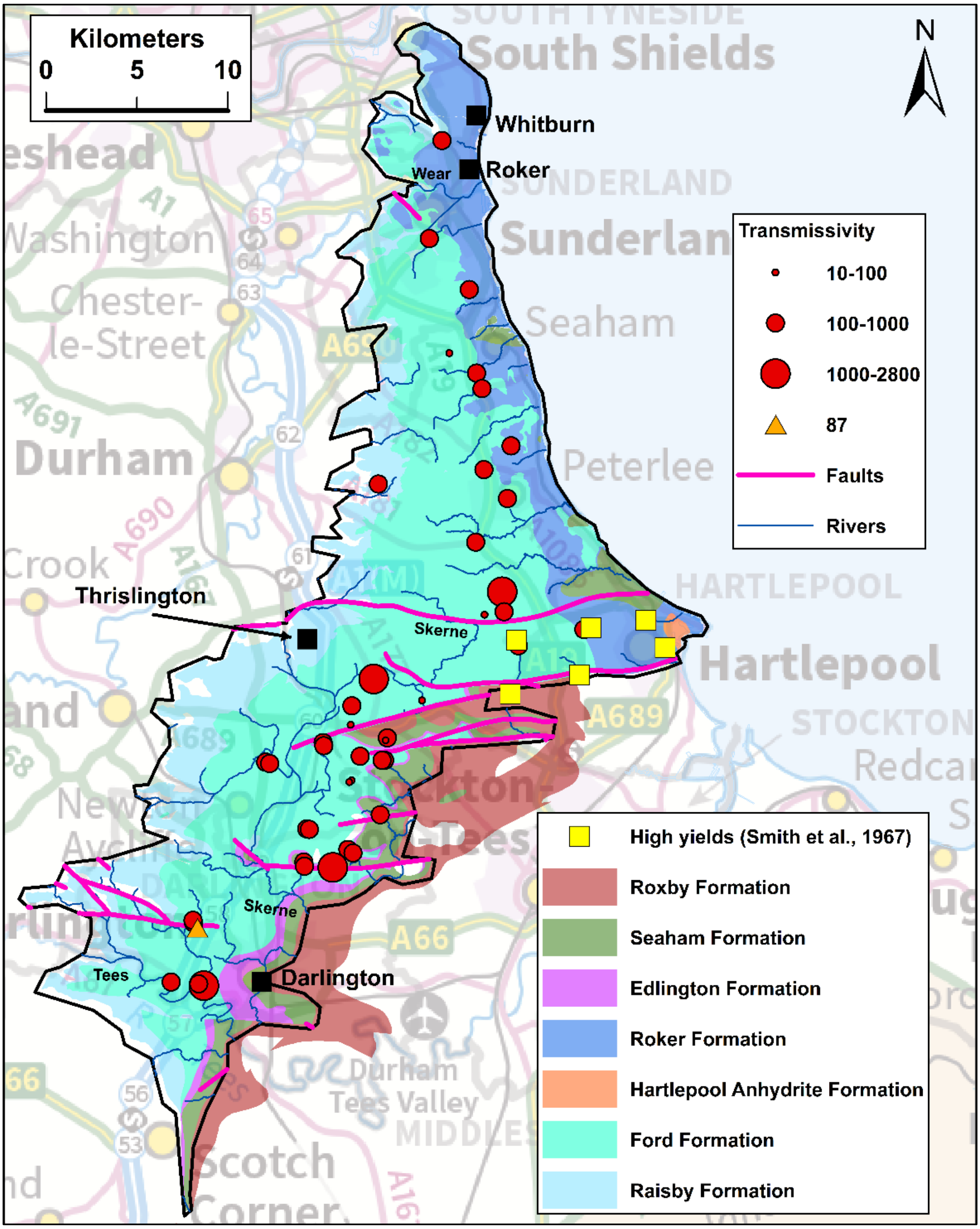

Figure 27. Transmissivities (m^2/day) in the Permian limestones from the BGS aquifer properties database (and new pumping test value of 87 m^2/day in the confined aquifer near Darlington).

5 Summary

- Karst is well developed in the gypsum in the southern part of the P1 area, and this impacts the limestones through collapse into underlying gypsum karst and enhancing hydrological connectivity between geological units.
- There is evidence of karstic cave and conduit development throughout the dolomitic limestones of the P1 area. Caves are short and not currently hydrologically active but demonstrate that cave sized solutional voids can develop within the Permian limestones.
- There is evidence that smaller conduits and solutional fissures occur in the limestones, but their frequencies and distributions are not well characterised.
- There are some records of stream sinks showing that karstic point recharge occurs via karst features. Stream sink data are limited, and the frequency and distributions of stream sinks are uncertain.
- There is evidence for karst along the River Skerne and its tributaries, where there are both losses to, and discharges from, the aquifer.
- There are a few reports of karstic dolines and dissolution pipes in the limestones which are not associated with the gypsum karst. However, there is little information on these features, and datasets have not been developed.
- Palaeokarst and breccia pipe development is widespread in the Roker and Seaham formations in the north of the P1 area.
- There are records of more than 200 springs in the P1 area, but no information on their discharge was identified for this report and the extent of the karstic networks feeding these springs is unclear.
- No successful tracer tests have been identified in this area.
- There is some evidence that karstic networks of solutional fissures and conduits occur in the saturated zone, with some high transmissivities and yields, and fissure inflows during construction.
- Overall, there is clear evidence that the Permian limestones are karstic, but the extent and distribution of karstic networks is uncertain.
- Further work is needed to develop datasets on stream sinks, dolines and springs, and to consider further how karst is impacting the hydrogeology of these aquifers.

Glossary

Cave: A subsurface solutional conduit large enough for humans to enter.

Conduit: A subsurface solutional void which is usually circular or cylindrical in cross section. In these reports the term is used predominantly for conduits which are too small for humans to enter.

Doline: A surface depression formed by karst processes.

Dissolution pipe: A sediment filled solutional void at rockhead in the subsurface, often with no surface expression.

Estavelle: A karst feature in a stream or river which acts as a spring under high water levels and a sink under low water levels.

Fissure: An enlarged fracture with aperture of ~ 0.5 to > 2 cm, and a planar cross-sectional shape. In these reports the term is used for fractures that are enlarged by dissolution. Those developed on bedding partings may extend laterally both along strike and down dip. The term fissure is also widely used for larger aperture fractures that are not formed by dissolution. In this report the distinction is made between solutional fissures and fissures formed by mass movement processes.

Inception horizon: Lithological horizon which favours dissolution and the development of fissures, conduits and caves.

Karst: Term applied to rocks which are soluble and in which rapid groundwater flow occurs over long distances. The development of subsurface solutional voids creates characteristic features including caves, dolines, stream sinks, and springs.

Palaeokarst: ancient karst features that are not active and which may be filled in by later deposits.

Phreatic: Sub-water table. Cave passages that are described as phreatic are those thought to have been formed beneath the water table and are generally circular or oval in shape.

Scallop: Small-scale dissolution features on cave walls caused by the flow of water which indicate the direction and relative speed of groundwater flow.

Sinkhole: Term widely used for surface depressions. These may be karstic in origin and synonymous with dolines but can also arise from surface collapse into anthropogenic voids such as mines and pits. This term is not generally used for surface depressions in these reports due to the confusion arising from sinkholes of both karstic and anthropogenic origin but is used for some features where it is unclear whether the feature is anthropogenic or karstic. The term has also been used for the actual hole into which water sinks into karstic voids in the subsurface through the base of a stream or river and may be used in this context in these reports.

Stream sink: A stream which disappears into solutional voids in a karst rock. The stream may fully sink into a closed depression or blind valley or may partially sink through holes in the stream bed. The term is used in these reports in preference to sinkhole which can be confused with dolines or depressions caused by collapse into anthropogenic voids.

Sump: Cave passage in which the water reaches the roof (i.e. the passage is entirely water filled).

Surface depression: The term used in these reports for all surface depressions where it is unclear whether they are karstic or anthropogenic in origin.

Swallow hole: Another term for stream sink, although it has been used in the past for dry dolines that do not contribute surface runoff to the aquifer. Therefore, the term stream sink is generally used in these reports, as the presence of an active stream recharging the aquifer is directly inferred. However, many older reports of stream sinks use the term swallow hole to describe stream sinks.

Vadose: Vadose cave passages are those that have formed above the water table and are often taller than they are wide.

References

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

Allen, D. J., Brewerton, L. T., Coleby, L. M., Gibbs, B. R., Lewis, M. A., MacDonald, A. M., Wagstaff, S. J. & Williams, A. T., 1997. The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report WD/97/34. Environment Agency R&D Publication 8. 312 pp.

Applied Geology Limited, 1993. Review of instability due to natural underground cavities in Great Britain. Applied Geology Ltd, Royal Leamington Spa.

Bearcock, J and Smedley, P.L., 2009. Baseline groundwater chemistry: the Magnesian Limestone of County Durham and north Yorkshire. British Geological Survey Open Report, OR/09/030. 63 pp.

British Geological Survey, 2008. Durham. England and Wales Sheet 27. Bedrock. 1:50 000. (Keyworth, Nottingham: British Geological Survey).
https://webapps.bgs.ac.uk/data/maps/maps.cfc?method=viewRecord&mapId=10265

British Geological Survey. 1987. Stockton, England and Wales Sheet 33. Solid and Drift Geology. 1:50,000. (Keyworth, Nottingham: British Geological Survey)

Brook, D, Davies, G M, Long, M H and Ryder, P F, 1988. Northern Caves: Volume 1; Wharfedale and the North-East.

Burgess, A.S., 1970. Engineering geology and geohydrology of the Magnesian Limestone of Northern England (PhD thesis, Durham University). 397 pp.

Cairney, T., 1972. Hydrological investigation of the Magnesian Limestone of south-east Durham, England. Journal of Hydrology, 16, 323-340.

Cairney, T. and Hamill, L., 1977. Interconnection of surface and underground water resources in south-east Durham. Journal of Hydrology, 33, 73-86.

Cooper, A.H., 2020. Geohazards caused by gypsum and anhydrite in the UK: including dissolution, subsidence, sinkholes and heave. Geological Society, London, Engineering Geology Special Publications, 29(1), 403-423.

Cooper, A.H., 1998. Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation. Geological Society, London, Engineering Geology Special Publications, 15(1), 265-275.

Cooper, A.H. 1996 Gypsum karst of Great Britain. International Journal of Speleology, 25 (3-4). 195-202.

Cooper, A.H., 1986. Subsidence and foundering of strata caused by the dissolution of Permian gypsum in the Ripon and Bedale areas, North Yorkshire. Geological Society, London, Special Publications, 22(1), 127-139

Cooper, A.H., Odling, N.E., Murphy, P.J., Miller, C., Greenwood, C.J. and Brown, D.S., 2013. The role of sulfate-rich springs and groundwater in the formation of sinkholes over gypsum in eastern England. In: Land, Lewis; Doctor, Daniel H; Stephenson, J.Brad, (eds.) Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the Thirteenth Multidisciplinary Conference May 6 through 10, 2013, Carlsbad, New Mexico. Carlsbad, New Mexico, National Cave and Karst Research Institute (NCKRI), 141-150, (NCKRI Symposium 2).

Cooper, A.H., Farrant, A.R. and Price, S.J., 2011. The use of karst geomorphology for planning, hazard avoidance and development in Great Britain. Geomorphology, 134(1-2),118-131.

COOPER, A.H., WHITBREAD, K, AND IRVING, A.M., 2007. Environment Agency: Durham Permian Sections. British Geological Survey Internal Report, CR/07/117. 52pp.

COOPER, A.H. AND GORDON, J. 2000. Revised Geological Maps of Darlington Based on New Borehole Information: Explanation and Description. Technical Report CR/01/001.

COOPER A. H & SAUNDERS, J. M. 1999. Road and bridge construction across gypsum karst in England. In: Beck, B., Pettit, A. J. & Herring, G. (eds). Hydrogeology and engineering geology of sinkholes and karst 1999. Proceedings of the 7th multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst. Harrisburg/Hershey, Pennsylvania. Balkema, Rotterdam, 407–411.

DANIELS S. E., TUCKER M. E., MAWSON M. J., HOLDSWORTH R. E., LONG J. J., GLUYAS J. G., AND JONES R. R. 2022. Nature and origin of collapse breccias in the Zechstein of NE England: local observations with cross-border petroleum exploration and production significance, across the North Sea. Geological Society, London, Special Publications, 494, 269–299.

DAVIS, G.M. AND HORSWILL, P., 2002. Groundwater control and stability in an excavation in Magnesian Limestone near Sunderland, NE England. Engineering geology, 66(1-2), 1-18.

ENGERING, S., AND BARRON, H.F., 2007. Doncaster Geodiversity Assessment. British Geological Survey Commissioned Report. CR/07/025N. 139 pp.

ENVIRONMENT AGENCY, 2021. Skerne Operational catchment.
https://environment.data.gov.uk/catchment-planning/OperationalCatchment/3406

ENVIRONMENT AGENCY, 2012. Hydrology Flow Investigation Stage 2. Northumbria River Basin District Investigation: NE2010- 10005. Report CR/00/94.

FARRANT, A.R. AND COOPER, A.H., 2008. Karst geohazards in the UK: the use of digital data for hazard management. Quarterly Journal of Engineering Geology and Hydrogeology, 41(3), 339-356.

GIANTZOUDIS, D. 2003. Phosphorus Dynamics and Submerged Aquatic Macrophytes in Hell Kettles. PhD thesis, Durham. http://etheses.dur.ac.uk/4079/1/4079_1598.pdf

GIBBS, T., 2016. Magnesian limestones caves east of the Pennines.
http://speleo.org.uk/conservation/magnes.htm

GIBBS, T., 1996a. Magnesian limestone. Derbyshire Caving Association Newsletter 93, 5-6.

GIBBS, T., 1996b. Magnesian limestone. Derbyshire Caving Association Newsletter 92, page 3.

GIBBS, T., 1995a. Magnesian limestone. Derbyshire Caving Association Newsletter 88, 7-11.

GIBBS, T., 1995b. Magnesian limestone. Derbyshire Caving Association Newsletter 87, 7-10.

GIBBS, T., 1995c. Magnesian limestone caves east of the Pennines. Derbyshire Caving Association Newsletter 86, 12-13.

GIBBS, T., 1994a. Magnesian Limestone caves east of the Pennines. Article 1 of 4. Derbyshire Caving Association Newsletter 85, 9-12.

GIBBS, T., 1994b. Magnesian Limestone caves east of the Pennines. Derbyshire Caving Association Newsletter 82, 4-5.

GIBSON, R., BLISS, M., AND SHACKLETON, R., 1976. Caves of the Magnesian limestone. Yorkshire Subterranean Society Journal 1, 9-22.

GREEN, M.R., FORTH, R.A. AND BEAUMONT, D., 1998. A hazard map of the Magnesian Limestone in County Durham. Geological Society, London, Engineering Geology Special Publications, 15(1), 239-246.

JACKSON, I. 2023. Durham Rocks: 50 Extraordinary Places That Tell the Story of the Durham Landscape.

JBA 2017. Skerne Magnesian Limestone. Skerne catchment assessment, 46pp.

KORTAS, L. AND YOUNGER, P.L., 2013. Fracture patterns in the Permian Magnesian limestone aquifer, Co. Durham, UK. Proceedings of the Yorkshire Geological Society, 59(3), 161-171.

LAMONT-BLACK, J., BAKER, A., YOUNGER, P.L. AND COOPER, A.H. 2005. Utilising seasonal variations in hydrogeochemistry and excitation-emission fluorescence to develop a conceptual groundwater flow model with implications for subsidence hazards: an example from Co. Durham, UK. Environmental Geology, 48, 320–335, https://doi.org/10.1007/s00254-005-1278-2.

LAMONT-BLACK, J., YOUNGER, P. L., FORTH, R. A., COOPER, A. & BONNIFACE, J. 2002. A decision logic framework for investigating subsidence problems potentially attributable to gypsum karstification. Engineering Geology, 65, 205-215.

LAWRENCE, D.J.D., 2009. Limestone Landscapes - a geodiversity audit and action plan for the Durham Magnesian Limestone Plateau. British Geological Survey Open Report, OR/09/007. 114pp.

LEACH, S., 2015. Going Underground: An anthropological and taphonomic study of human skeletal remains from caves and rock shelters in Yorkshire. Yorkshire Archaeological and Historical Society, Leeds. Page 299.

LEBOUR, G.A. 1884. On the “breccia-gashes” of the Durham coast and some recent earth shakes at Sunderland. Transactions of the Northern England Institute of Mining and Mechanical Engineers, 33, 165–177.

MACDONALD, A.M., AND ALLEN, D.J., 2001. Aquifer properties of the Chalk of England. Quarterly Journal of Engineering Geology 34, 371-384.

MAURICE, L.D., FARRANT, A.R., AND MATHEWSON, E., 2024. BGS Karst Report Series: P2. Karst in the southern outcrop of Permian limestones (and associated gypsum). British Geological Survey Open Report, OR/23/057.

MAURICE, L., FARRANT, A.R., MATHEWSON, E., ATKINSON T., 2021. Karst hydrogeology of the Chalk and implications for groundwater protection. In Farrell, R. P., Massei, N., Foley, A. E., Howlett, P. R. and West, L. J. (eds) The Chalk Aquifers of Northern Europe. Geological Society, London, Special Publications, 517.

MSG, 2021. Moldywarps Speleological Group Journal 14, 40-41.

MSG, 1974. Moldywarps Speleological Group Journal 7,16-20, 35.

MSG, 1973. Moldywarps Speleological Group Journal 6, 13.

MSG, 1971. Moldywarps Speleological Group Journal 4, 26-27.

MURPHY, P.J., AND CORDINGLEY, J.N., 2010. Mass movement caves in Northern England. Proceedings of the University of Bristol Speleological Society 25 (1), 105-112.

MURPHY, P.J., AND LOWE, D.J., 2021. Karstification of the Upper Permian limestones and dolostones in north-eastern England: 1 review. Cave and Karst Science 48 (3), 115-120.

NATIONAL LIBRARY OF SCOTLAND SIDE BY SIDE VIEWER. Accessed 2023. https://maps.nls.uk/geo/explore/side-by-side/

NEYMEYER, A., WILLIAMS, R.T. AND YOUNGER, P.L., 2007. Migration of polluted mine water in a public supply aquifer. Quarterly Journal of Engineering Geology and Hydrogeology, 40(1), 75-84.

PALUMBO-ROE, B., BANKS, V.J., AND BRAUNS, B., 2019. Characterising the hyporheic zones in the Skerne Catchment. British Geological Survey Commissioned Report, CR/19/004. 173 pp.

PRICE, S.J., MERRITT, J.E., WHITBREAD, K., LAWLEY, R.S., BANKS, V., BURKE, H., IRVING, A.M., AND COOPER, A.H., 2007a. Superficial Geology and Hydrogeological Domains between Durham and Darlington Phase 1 (Durham South). British Geological Survey Commercial Report, CR/07/002. 47pp.

PRICE, S.J., MERRITT, J.E., WHITBREAD, K., LAWLEY, R.S., BANKS, V., BURKE, H., IRVING, A.M., AND COOPER, A.H., 2007b. Superficial Geology and Hydrogeological Domains between Durham and Darlington Phase 2 (Durham North). British Geological Survey Commercial Report, CR/07/022. 50pp.

RAISTRICK, A., 1932. Excavation of a cave at Bishop Middleham, Durham. Archaeologia Aeliana 4th series, 10, 111-122.

RYDER, P F, 2008. Memoirs of a Moldywarp – episodes of underground exploration. Broomlee Publications, Chapter 16 (81–84) – underground in Newton Aycliffe: the Magnesian Limestone.

SARGENT, C. AND GOULTY, N.R. 2009. Seismic reflection survey for investigation of gypsum dissolution and subsidence at Hell Kettles, Darlington, UK. Quarterly Journal of Engineering Geology and Hydrogeology, 42, 31-38, https://doi.org/10.1144/1470-9236/07-071.

SEDGWICK, A. 1829. On the geological relations and internal structure of the Magnesian Limestone, and the lower portions of the New Red Sandstone Series in their range through Nottinghamshire, Derbyshire, Yorkshire, and Durham to the southern extremity of Northumberland. Transactions of the Geological Society of London, 3 (Second Series), 37-124.

SMITH, D.B. 1995. Marine Permian of England. Geological Conservation Review Series (8).

SMITH, D.B. 1994. Geology of the country around Sunderland. Memoir of the Geological Survey of Great Britain, Sheet 21 (England and Wales).

SMITH, D.B., HARWOOD, G.M., PATTISON, N.J. AND PETTIGREW, T. 1986. A revised nomenclature for Upper Permian strata in eastern England. In: Harwood, G. M. and Smith, D. B. (eds) The English Zechstein and Related Topics. 9-17.

SMITH, D.B. 1989. The late Permian palaeogeography of north-east England. Proceedings of the Yorkshire Geological Society, 47, 285-312.

SMITH, D.B. 1972. Foundered strata, collapse breccias and subsidence features of the English Zechstein. In: Richter-Bernburg, G. (ed.) Geology of saline deposits. 255–269.

SMITH, D. B., FRANCIS, E. A., CALVER, M. A., GAUNT, G. D., PATTISON, J., EDWARDS, A. H. & HARRISON, R. K., 1967. Geology of the country between Durham and West Hartlepool. Explanation of Sheet 27, New Series. Memoirs of the Geological Survey of Great Britain, England and Wales. HMSO, London. 396pp.

WALTHAM, A.C., SIMMS, M.J., FARRANT, A.R., AND GOLDIE, H.S., 1997. Karst and Caves of Great Britain. Geological Conservation Review Series. Chapman & Hall, London. 358pp.

WARDROP, D.R., SALMON, S. AND BLACKBURN, J.K. 2012. Water recharge into the Magnesian limestone aquifer. Pp. 124-132 in Hunger, E. and Walton, G. (Eds.) Proceedings of the 16th Extractive Industry Geology Conference, EIG Conferences Ltd, 194pp.

YOUNG, B., 2003. Fissuring in the Magnesian Limestone of County Durham. Open University Geological Society Journal 24 (2), 19-24.

YOUNG, B AND CULSHAW, M.G., 2001. Fissuring and related ground movements in the Magnesian Limestone and Coal Measures of the Houghton-le-Spring area, City of Sunderland. British Geological Survey Technical Report, WA/01/04.

YOUNG, B AND LAWRENCE, D.J.D., 2001. Recent fissuring in the Magnesian Limestone at Houghton le- Spring, City of Sunderland. British Geological Survey Research Report, RR/02/03. 22pp.

YOUNGER, P L. 1995. Chapter 11: Hydrogeology 353-359. In: Robson's Geology of North East England (Second edition). Johnson, G.A.L. (editor). 56. (Newcastle upon Tyne: Transactions of the Natural History Society of Northumbria).