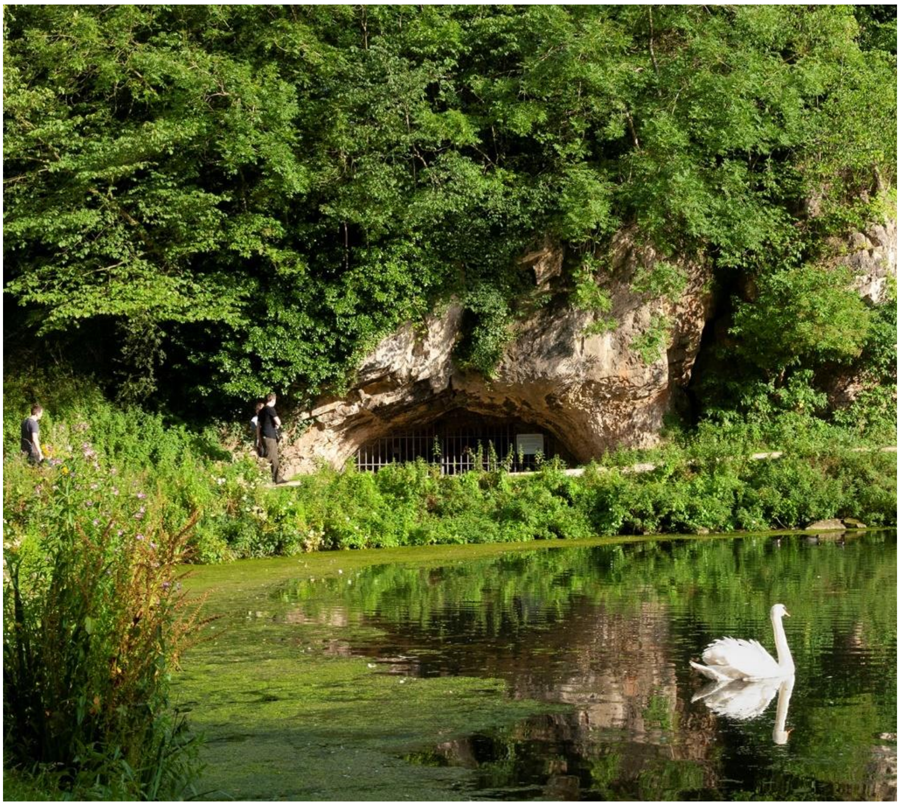
BGS Karst Report Series: P2. Karst in the southern outcrop of Permian limestones (and associated gypsum)

Environmental Change, Adaptation and Resilience Programme

Open Report OR/23/057



BRITISH GEOLOGICAL SURVEY

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BGS Karst Report Series: P2. Karst in the southern outcrop of Permian limestones (and associated gypsum)

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

Keywords

Karst, Groundwater, Permian limestones, Magnesian limestone, Dolomite, Evaporite karst.

Front cover

Limestone karst cave entrance in the Cresswell Gorge. Photo courtesy of Tony Waltham Geophotos.

Bibliographical reference

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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
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD
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
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Executive summary

This report documents the evidence for karst and rapid groundwater flow in the southern outcrop of the Permian limestones in Northern England, together with the associated gypsum karst. 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. These reports provide data and information on karst in each area.

The Permian dolomitic limestones comprise the Cadeby Formation and the Brotherton Formation. These formations are separated by the Edlington Formation and overlain by the Roxby Formation, both of which contain extensive evaporite karst (in gypsum and anhydrite) interspersed with low permeability mudstones penetrated by karstic collapse features. This report is primarily focused on the dolomitic limestone karst, but the variable geology results in high complexity with interactions between the limestone and evaporite karst. Karst in the Permian gypsum associated with the limestones has not been well-recognised in hydrogeological studies. Evaporite karst in the area is well developed and documented with caves, dolines, and dissolution pipes. Collapse features extend into the limestones, especially in the Brotherton Formation, and there is evidence of groundwater connectivity between the evaporite and limestone karst, for example with sulphate-rich groundwater in the limestones and overlying strata. The gypsum sequences in contact with the limestones result in locally very high transmissivities and mixing of waters from the two types of karstified rocks.

There is also clear evidence for karstification within the dolomitic limestones. Quite large, although short and dry, dolomitic limestone caves occur in the Cadeby Formation, with 21 karst caves recorded, ranging from 2.5 to 290 m in length. There is also evidence that smaller solutional conduits and fissures occur in the limestones which are likely to be an important component of groundwater flow. There are many other caves, some of which are formed by mass movement (slip rift caves) and some for which it is unclear whether they are mass movement caves or karst caves. In some instances, slip rift caves form a focus for recharge to the limestones, but many may be largely dry. There are significant karst stream sinks into the Cadeby Formation at Wadworth Wood near Doncaster and near Darrington, and a major karst river sink into the Cadeby Formation on the River Skell. Some limestone dolines and dissolution pipes have been recorded in the Cadeby and Brotherton formations. There are large numbers of springs in the Permian limestones, and although their flows and characteristics are generally not well documented, it appears that many are quite small, and a few may have substantial flows. Tracer tests have been carried out at one location, and these demonstrated connectivity between a groundwater abstraction and both a leaking sewer and a surface water course, over distances of 10s to 100s metres. At this locality high transmissivity, and high yields (> 80 l/s) also indicate solutional development of permeability. There are other abstractions in the P2 area with high yields and transmissivities of > 1000 m^2/day suggesting they may be supplied by karstic solutional networks. Detailed borehole investigations using slug tests and water level monitoring have revealed rapid flow velocities of 13 to 242 m/day in the Cadeby Formation at the Leeds University study site, and modelling work over a wider area suggested very rapid flows of up to 9000 m/day (Medici et al 2019a,b). These studies also showed that very low effective porosities (2.8×10^{-4}) are needed to represent the karstic development of permeability in the Permian limestones and the potential large scale of contaminant transport.

The data collated in this report demonstrate that a component of unsaturated zone flow in the Permian limestones is rapid, but the proportion of rapid flow, and the frequency of rapid flowpaths that extend through the entire unsaturated zone, is uncertain. Evidence of cave, conduit and solutional fissure development; and some high transmissivities and high borehole yields, especially where gypsum is present, suggest that there are saturated zone networks of solutional fissures and conduits which might enable pollutant transport over long distances and in unexpected directions, but further work is needed to determine how frequently these networks occur and how extensive they are. Such networks can form along stream sink to spring flowpaths or through mixing corrosion. Overall, this report highlights the importance of karst in the Permian limestones, the complexities of the interactions with the evaporite karst, and the need for further development of karst datasets and conceptualisation of the karst hydrogeology to assist with groundwater studies and management in this area.

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 Tony Waltham, Pete Ryder, Mike Higgins John Gunn, and Phil Walker for giving permission to reproduce their photographs in this report, and Mike Higgins for providing additional information on the Wadworth Wood stream sinks.

At BGS we thank Vanessa Banks for reviewing the report, and who also 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.

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Introduction to the BGS Karst Report Series

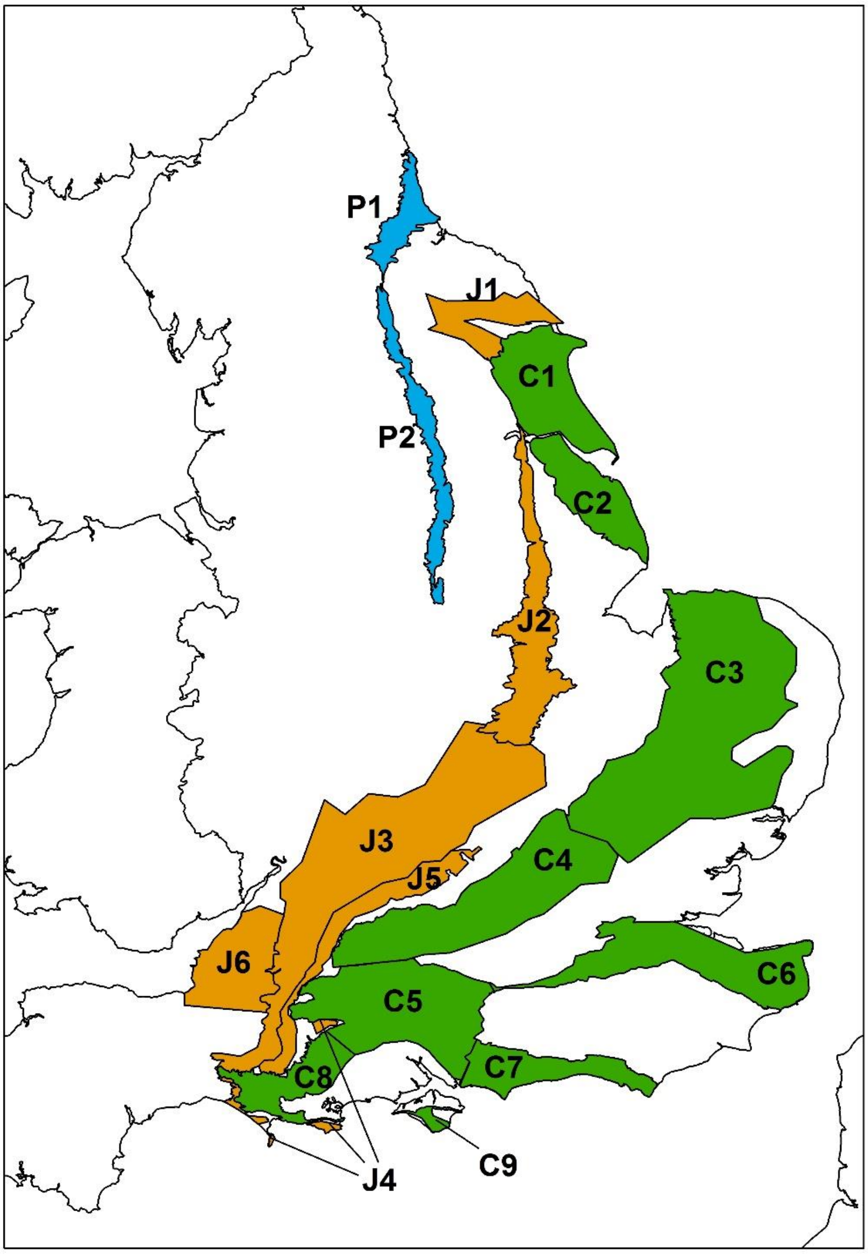
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – The Chalk and the Jurassic and Permian limestones (plus associated gypsum). The series is derived from the NERC funded Knowledge Exchange fellowship “Karst knowledge exchange to improve protection 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 reports are a resource for hydrogeologists, managers and regulators working on these aquifers to enable improved aquifer conceptualisation and understanding of karst data.

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 (and associated gypsum) 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 they function. 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 subject area and its 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 Chalk of the Wessex basin (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 common. 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, Jurassic limestones, Permian limestones, Permian gypsum and overlying strata. 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.

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 most springs are recorded as of unknown discharge. However, in most areas some springs with large known 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, Jurassic and Permian limestones and gypsum, 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 investigations 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 southern outcrop of Permian limestones (and gypsum)

1.1 AREA/GEOLOGY

The P2 karst area of the Zechstein Group covers the southern outcrop of the Permian limestones and extends from Scotch Corner in North Yorkshire, southwards to Nottingham (Figure 1; Figure 2). The drainage is generally towards the east. The Swale, Ure, Wharfe, Aire and Don rivers all drain eastward towards the River Ouse. The River Meden in the south of the area also drains eastward to the Idle.

The Permian Zechstein Group in the P2 area is shown in Figure 2; the nomenclature of the group was defined by Smith et al. (1986) with palaeogeographic and sequence stratigraphical interpretations by Smith (1989) and Tucker (1991) respectively. Further information on the geology of the Zechstein Group can also be found in Doornenbal and Stevenson (2010). 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 and there are numerous faults. The Zechstein Group is underlain by the Yellow Sands Formation of the Rotliegend Group which unconformably overly strata of Carboniferous age (the Pennine Coal Measures Group in the south and Millstone Grit Group in the north), and these older strata outcrop to the west of the Zechstein Group. To the 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 map figures throughout the report) for clarity, although the Zechstein Group is present beneath younger strata to the east. The stratigraphy of the Zechstein Group is outlined in Table 1. The dolomitic limestones of the Cadeby Formation underlie much of the P2 area, outcropping in the west. These are separated from the dolomitic limestones of the Brotherton Formation by the Edlington Formation, which north of Doncaster contains thick gypsum. The Brotherton Formation is overlain by the Roxby Formation that also contains gypsum. The Brotherton and Roxby formation are absent in the most southerly part of the area.

The Edlington and Roxby formations comprise calcareous mudstones and include extensive evaporite deposits (gypsum and anhydrite). The gypsum in the Roxby and Edlington formations is highly karstic, with major significance for hydrogeology and engineering - the gypsum karst poses a substantial subsidence hazard with frequent collapse dolines. Karst features in the gypsum, include karstic depressions, and significant phreatic caves are postulated (Cooper, 1986; Cooper, 1989; Cooper, 1996; Cooper, 1998; Cooper 2006 a,b; Cooper, 2018; and Cooper, 2020; Cooper et al., 2001; Cooper et al., 2011). Although the main focus of this report is the karst of the Permian limestones of the Cadeby and Brotherton formations, the limestones north of Doncaster are impacted by the evaporite karst. For example, the limestones of the Brotherton Formation are highly foundered and brecciated due to the dissolution of the underlying gypsum of the Edlington Formation (Cooper, 1998, 2020; Farrant and Cooper, 2008). Groundwater flow in the Cadeby Formation can pass up through the gypsiferous deposits which in places are so strongly karstified that they result in high connectivity between the Cadeby Formation, the Edlington Formation and the Brotherton Formation (Cooper et al., 2013), and sulphate-rich springs may discharge water from both the limestones and gypsum (Cooper et al., 2013). Allen et al. (1997) described the Edlington Formation as a “leaky” aquitard in some places, but the gypsum makes it a very connected aquifer in much of the area. South of Doncaster the unit becomes less gypsiferous and the Edlington Formation along with the similar Roxby Formation act as aquitards. There is further discussion of the evaporite karst throughout the report and particularly in Sections 2.2, 2.3.4 and 2.5.1.

The limestones of the Zechstein group, which form the main focus of this report, are dolomitic in nature (comprising calcium magnesium carbonate) and were previously known as the Magnesian limestones. The limestones are compact, 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 carbonate limestones of Carboniferous age (Farrant and Cooper, 2008). Local brecciation, which can contribute to permeability, occurs in the Brotherton Formation and is mainly related to foundering caused by the dissolution of the underlying gypsum in the Edlington Formation (Cooper 2020). The Cadeby Formation is not generally brecciated except in fault zones. The lower limestones of the Zechstein Group are usually hydraulically connected to the underlying Yellow Sands Formation. Although the intervening Marl Slate Formation can act as an aquitard in some areas (Bearcock and Smedley, 2009), in the P2 area this formation is very thin, generally less than 1 m and is missing south of the Ripon area. In the south the sequence formerly called the Lower Marl is muddy facies present in the lower part of the Cadeby Formation, it does not correlate to the Marl Slate Formation. Groundwater flow generally follows the topography and is towards the east (Allen et al., 1997; Medici et al., 2019b), though it can locally be strongly influenced by intersections with major river valleys such as those of the rivers Ure, Wharfe and Calder (Cooper et al., 2013).

In the north of the area there are widespread superficial glacial till deposits (Figure 3). Alluvium deposits fringe river systems with some glacial sand and gravel in the interfluves. Lacustrine deposits are present in the east. The superficial geology in Figure 3 is from the BGS 1:625,000 mapping. The BGS BSTM (Basic Superficial Thickness Model) suggests that, where present, the superficial deposits are generally very thin (< 10 m), with a few patches of deposits of 10 to 50 m thickness in the north and east (Figure 4). This model gives a very rough approximation of superficial deposit thickness and should be used with caution as the data are interpolated from borehole records.

Table 1. The Zechstein Group in the P2 area (Smith et al 1986; Powell, 1998; Allen et al., 1997)

Group	Formation	Lithology	Thickness
Zechstein Group	Roxby Formation	Calcareous mudstone and evaporites⁺	0-130 m
	Brotherton Formation	Dolomitic limestone	0-20 m
	Edlington Formation	Calcareous mudstone and evaporites⁺	0-65 m
	Cadeby Formation	Dolomitic limestone	0-100 m
	Marl Slate Formation*	Dolomitic/calcareous siltstone	<1 m*
Rotliegend Group	Yellow Sands Formation	Aeolian Dune sands	0 to 15 m
⁺Note evaporites includes gypsum at outcrop and near surface with anhydrite below c. 120 m in the east, *Note the Marl Slate Formation is thin and patchy at outcrop in the P2 area and not present in the south where what was formerly called the Lower Marl is a muddy facies of the Cadeby Formation.			

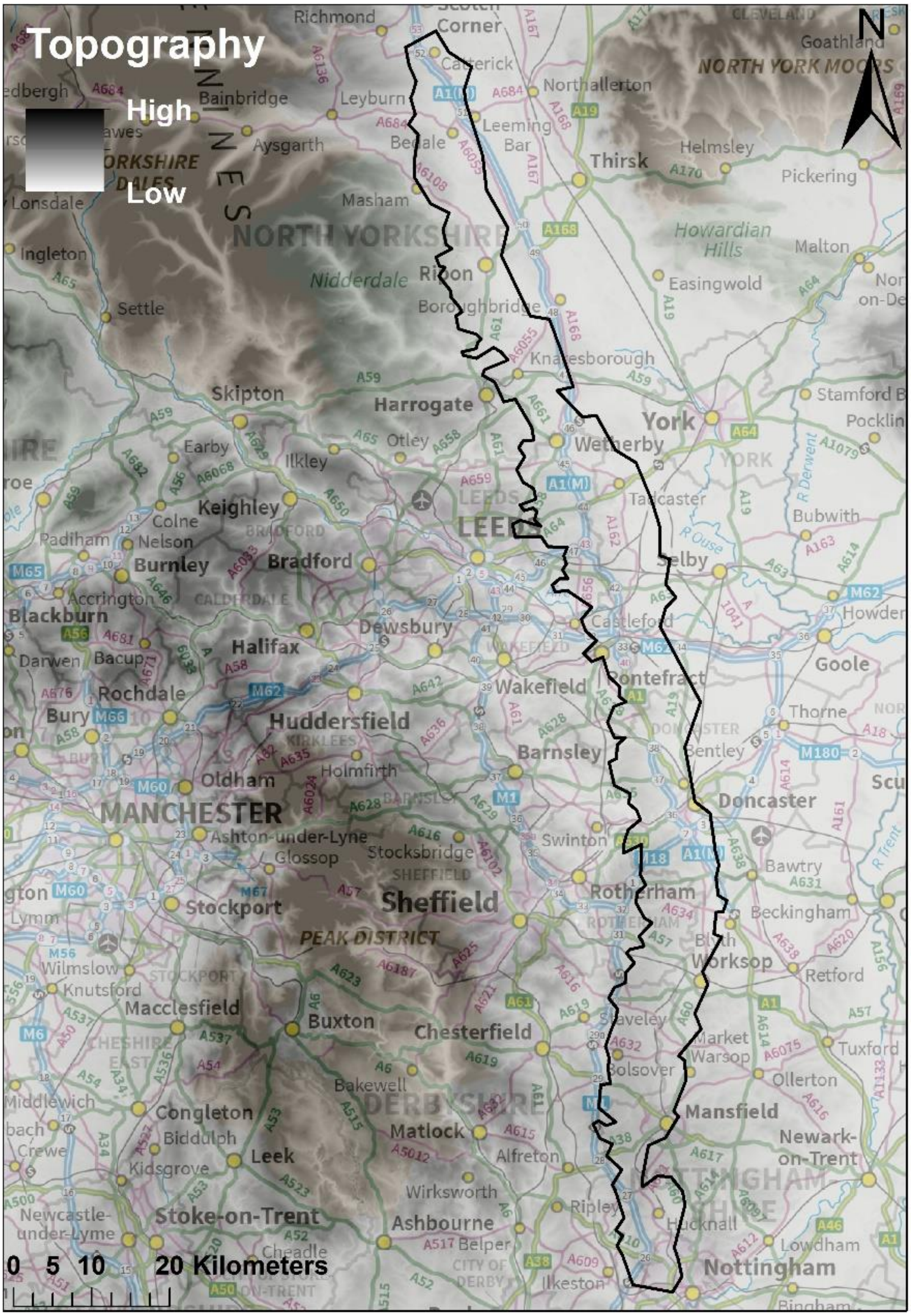


Figure 1. The P2 southern outcrop area of the Zechstein Group.

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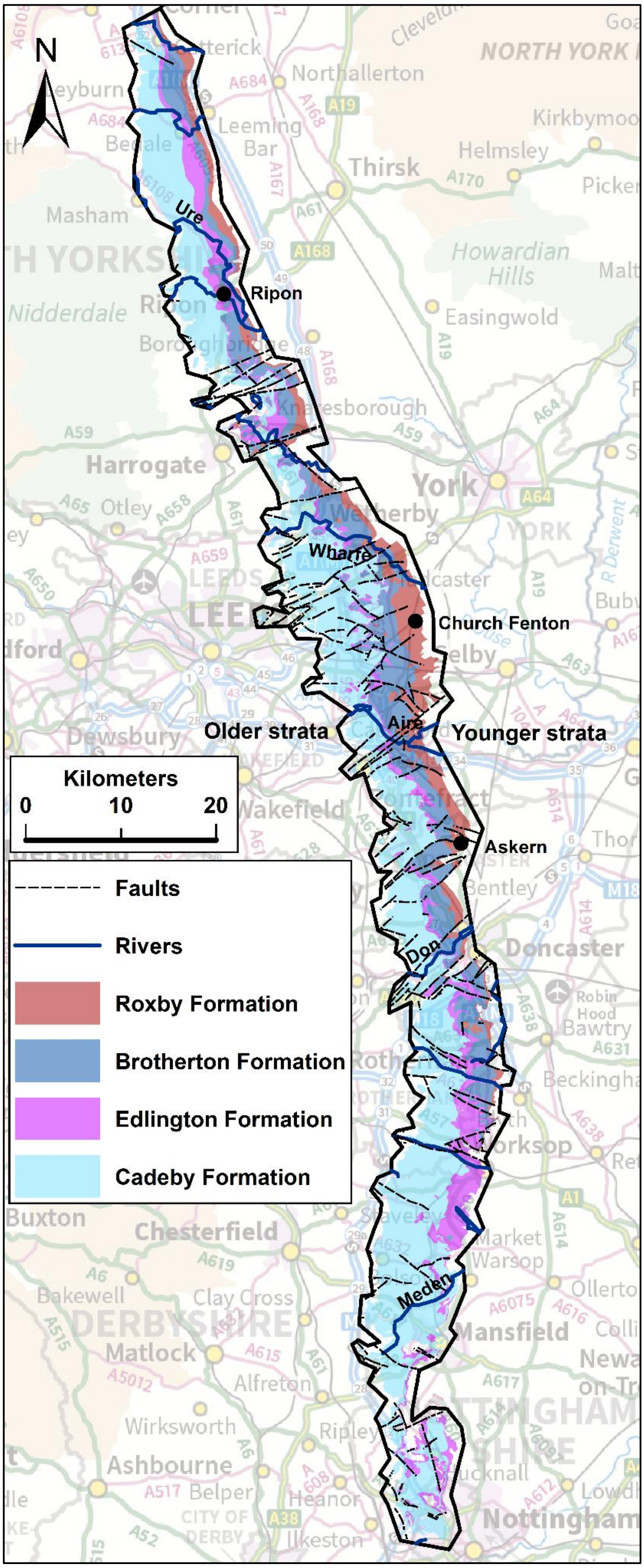

Figure 2. The Zechstein Group in the P2 area.

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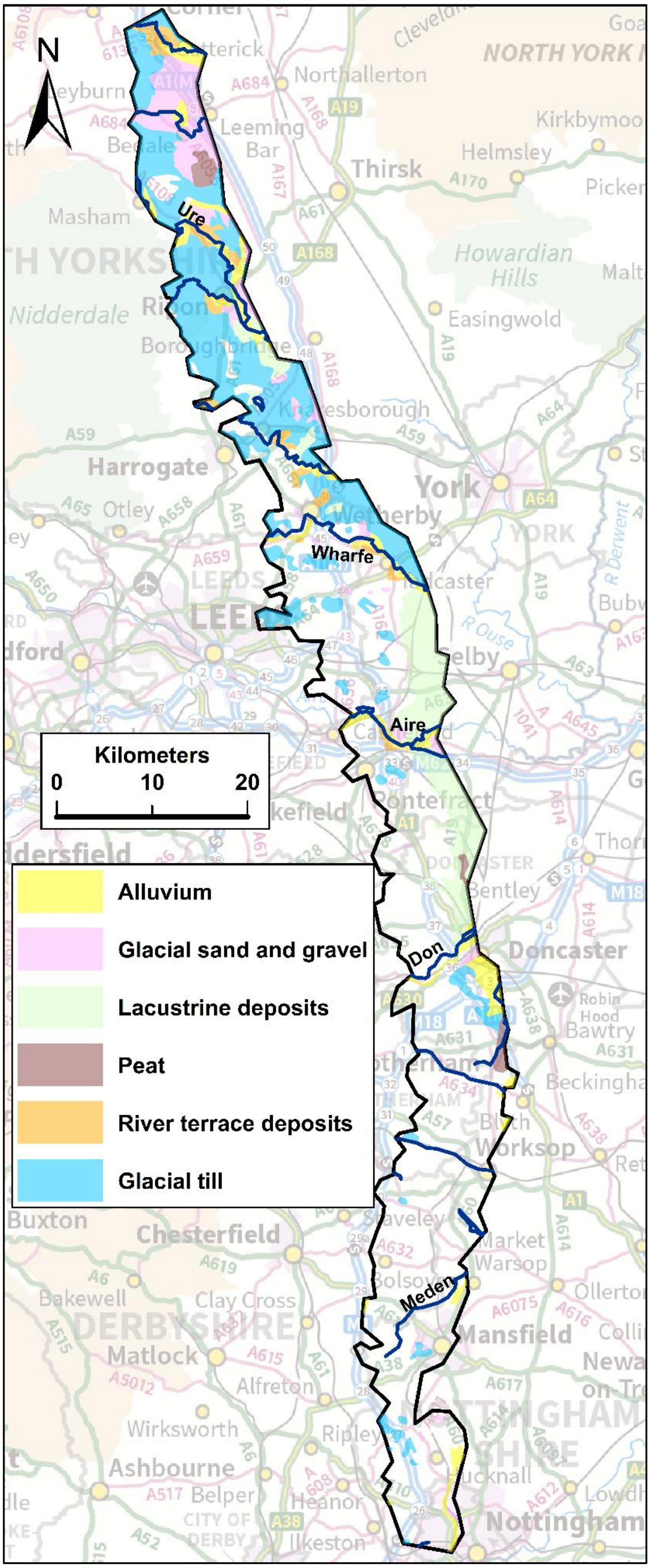

Figure 3. Superficial geology.

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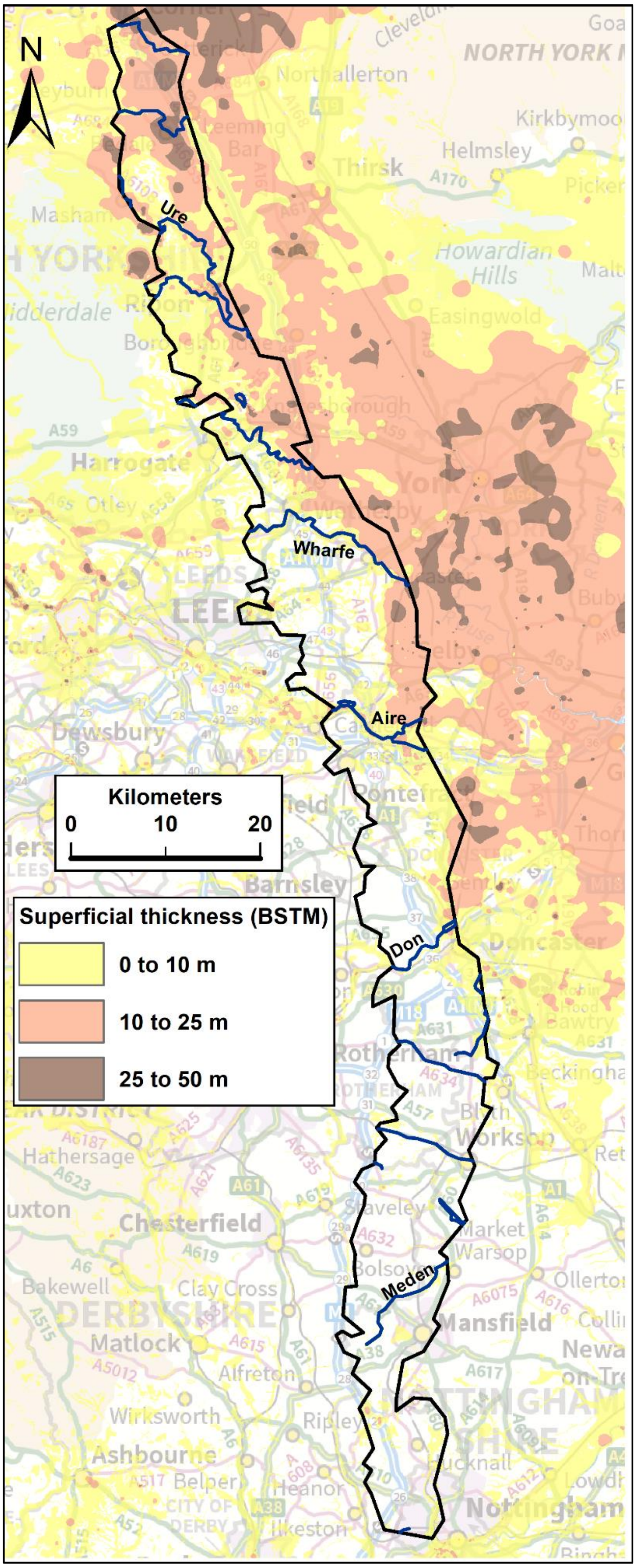

Figure 4. The BGS Basic Superficial Thickness Model (BSTM).

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1.2 WATER PROVIDERS AND REGULATORS

Yorkshire Water is the water provider for the north of P2 and Severn Trent Water is the provider for the south (Figure 5). The north of P2 is in the Yorkshire Environment Agency area and the south is in the East Midlands area (Figure 6).

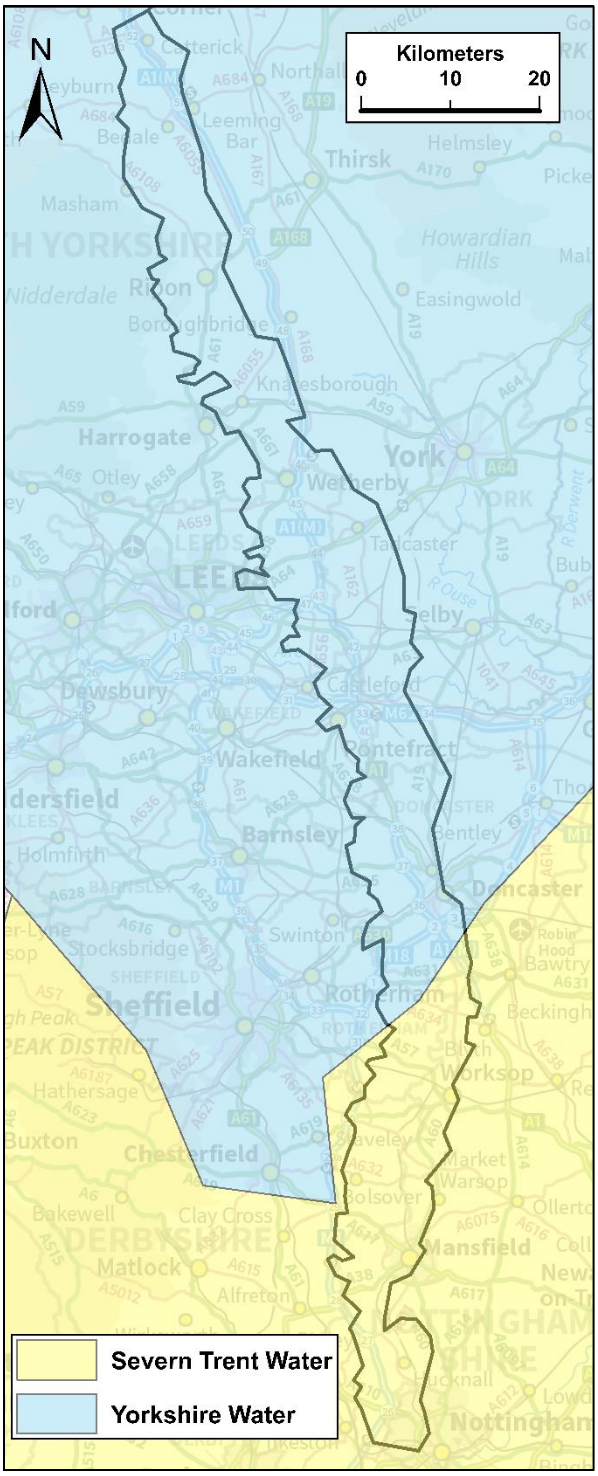

Figure 5. Water providers in the P2 area.

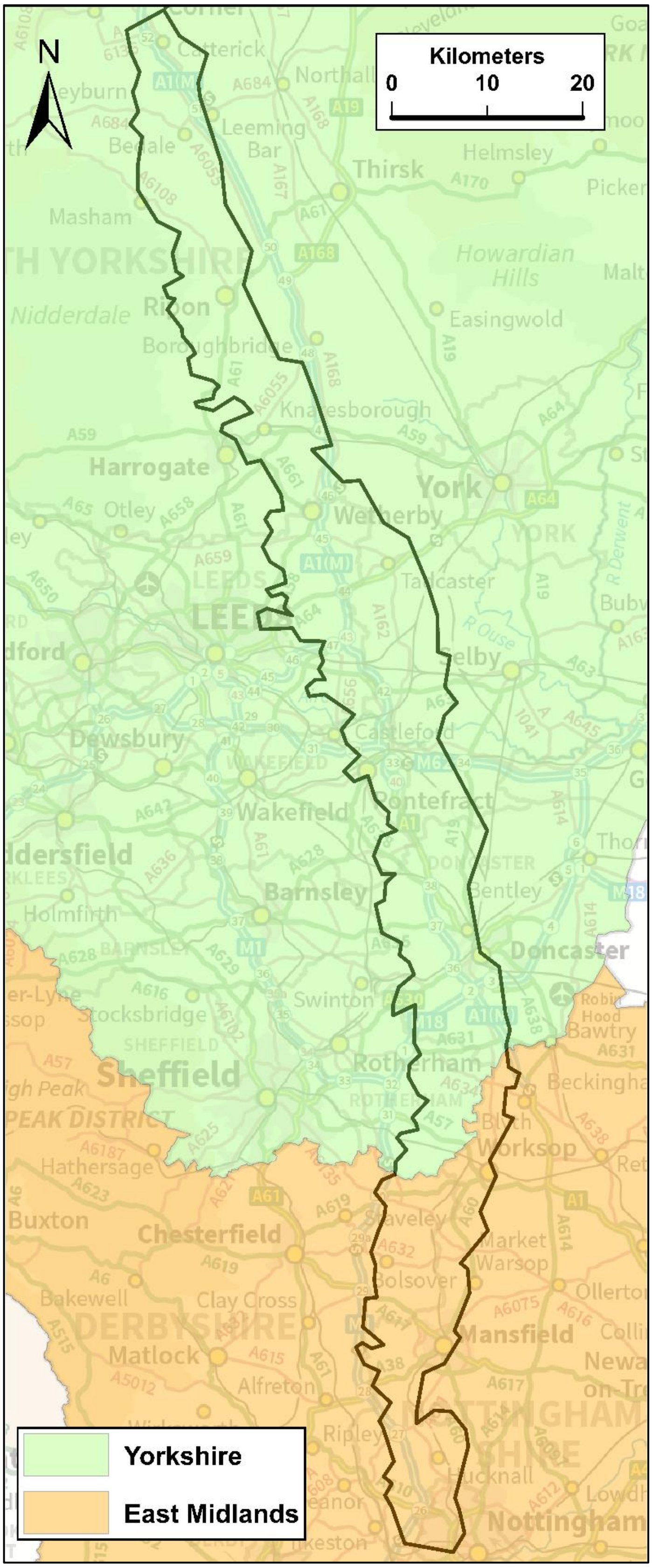

Figure 6. Environment Agency areas in the P2 area.

2 Karst geomorphology

2.1 INTRODUCTION

The Permian karst in the P2 area includes two distinct types. (1) Fissures and caves mainly in the Cadeby Formation dolomitic limestones in the lower part of the sequence, and (2) Caves, conduits, breccia pipes and sinkholes related to the dissolution of thick gypsum sequences affecting the Edlington Formation (Hartlepool Gypsum) and the Roxby Formation (Billingham and Sherburn gypsums) with the resultant subsidence and breccia-pipes affecting the Brotherton Formation limestone. This section provides an introduction to gypsum karst in the P2 area and then provides details of the different types of karst features (caves and conduits, stream sinks, and springs) in the area, with the main focus on the limestone karst, but some further details of gypsum karst where relevant.

2.2 GYPSUM KARST

North of the Doncaster area the Permian sequence contains thick gypsum units. Two gypsum units are in direct physical and hydrogeological contact with the underlying dolomitic limestones and located in a down-dip situation with phreatic artesian water from the underlying limestones driving the gypsum karstification; this is referred to as hypogene karst. The high dissolution rate of the gypsum (James et al., 1981; Klimchouk, 1996) means that this system is evolving on a human timescale with frequent cave collapses and material washed in to generate large dolines indicating the continuing collapse of significant karstic cavities (Cooper, 1986; 1998; 2020).

An indication of the style of the likely karst and cave development in the gypsum is revealed by studying the pattern of the size and frequency of the doline collapses (Cooper, 1986) and comparing them with similar geological and hydrogeological situations in the Ukrainian karst (Klimchouk, 1992; Klimchouk and Andrejchouk, 2005). It is postulated that much of the eastern part of the P2 Permian outcrop is underlain by significant joint-controlled maze caves in the gypsum, these have been dissolved by upward-welling waters from the Cadeby and Brotherton formations and are indicated both by their sinkhole patterns and the presence of sulphate-rich springs (Cooper, 1986,1998, 2020; Cooper et al., 2013). Significant cavities with cave-fill and collapse deposits have been recorded from boreholes drilled along this belt, but no caves have been entered and if they could be they would be water-filled.

The most active area is around the city of Ripon (see Figure 2 for location). Here gypsum dissolution related karstic collapses occur in the Edlington and Roxby gypsiferous formations and in the limestones of the Brotherton Formation, and continue right up into the lower strata of the Triassic Sherwood Sandstone Group (Cooper 1986, 1988, 1989, 1998, 2020). The subsidence-prone area with sulphate-rich springs, and by inference the presence of significant caves in the gypsum sequences, extends north from Ripon through Ripon Parks (Schwendel and Cooper, 2021) northwards to Bedale and Snape Mires (Cooper, 1986; Powell et al., 1992). In a southerly direction it includes the areas around the villages of Littlethorpe and Bishop Monkton (Cooper 1986; Cooper and Burgess, 1993). Karstification in Ripon and the areas north and south are strongly influenced by the incised buried valley of the River Ure that intersects the bedrock and forms the outlet for the artesian waters from the Permian sequence (Cooper, 1998). Further details of gypsum karst in the Ripon area are provided in Section 2.5.1.2.

Doline features occur further south with a cluster to the west of Church Fenton (Thompson et al 1996; Cooper, 2000; see Figure 2 for location). These largely peat filled dolines occur in the east of the Permian outcrop. Recent unpublished work by Cooper identified artesian sulphate rich groundwater in springs in this area. The Brotherton Formation dip slope to the west of the area would appear to be the source area for the water and the presence of significant gypsum in the Sherburn gypsum within the Roxby Formation appears to be the rock being dissolved, with the combination being the cause of the dolines. The Church Fenton area is discussed further in Section 2.5.1.4.

About 5km south-west of Church Fenton dolines are also present around Sherburn in Elmet. Here they affect the Brotherton Formation and must have formed by dissolution of the gypsum in the Edlington Formation. Just west of the village of Sherburn in Elmet a former quarry exposed sinkhole pipes in the Brotherton Formation filled with foundered mudstone from the now eroded Roxby Formation; similar features were noted long ago in the Brotherton area near Knottingley by Phillips (1828) who referred to them as “Red Horses” (Edwards et al., 1940; Murphy 2000). Further details of the karst in this area are provided in Section 2.5.1.3.

In the south, the River Aire valley has a control similar to that of the Ure valley in Ripon, acting as an outlet for water flow from the Cadeby and Brotherton formations through the gypsum. Probable or collapsed cave systems are indicated by the dolines around Brotherton, Burton Salmon and Byram (Ellison, 1989, Thompson et al., 1996, Murphy, 2000).

The most southerly significant gypsum-related dolines and springs are situated in the village of Askern (Figure 2) where sulphate-rich water emanates from water-filled dolines in the bottom of an anthropogenically modified lake (Cooper et al., 2013).

2.3 CAVES AND CONDUITS

2.3.1 Overview of cave and cavity records

Karstic cave development in the Permian limestones does not occur on the scale observed in the highly karstic Carboniferous aged limestones found in Derbyshire, Yorkshire and Wales. Nevertheless, there are records of some significant, though short, karst caves within the dolomitic limestones of the Cadeby Formation in the P2 area (Gibson et al., 1976; Gibbs 1994a, b; 1995a, b, c; 1996a, b; Murphy and Lowe, 2021). These caves were formed by water in the geological past and are now dry. The Brook et al. (1988) caving guidebook documents 43 sites with caves, including 47 individual caves in the Permian limestones in the P2 area, some of which are slip rift caves formed by mass movement processes.

The longest known karst cave in the Permian limestones is Robin Hood's Cave at Creswell which is 290 m long. Other karst caves are present within the Creswell Gorge. Details of these, and other significant caves are provided in Section 2.3.2. Although no hydrologically active caves have been found, it is likely that smaller solutional conduits and fissures (Section 2.3.5) transmit groundwater in the limestones of the P2 area, and it is possible that some short sections of hydrologically active conduits large enough to be termed caves are present. In addition to karst caves, there are many "slip rift" caves, also known as "gull caves" which are formed by mass movement processes. Some examples of slip rift caves are provided in Section 2.3.3. In some cases, it is unclear whether a cave is a slip rift or formed by karst processes, and sometimes there is some indication of both mass movement and karstic development within a cave. There are also cavities and caves associated with the gypsum within the Edlington Formation (Cooper, 2018). Records of gypsum caves and cavities were not collated for this report but are briefly discussed in Section 2.3.4.

Caves are recorded in the Natural Cavities Database which 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). In the P2 area, this database provides records of 1 "phreatic cave", 36 "vadose caves", 12 "gull fissures", and 12 "solutional fissures" (Figure 7). Most of these records are on the Cadeby Formation and are likely to represent cavities in limestone. However, the two vadose caves recorded in the north of the area are related to gypsum subsidence and karst in the Edlington Formation (Cooper, 1986). The "phreatic cave" recorded in the Natural Cavities Database near to the River Ure (Figure 7) is also related to gypsum subsidence (James et al., 1981), and due to dissolution of the gypsum, the cave no longer exists. The remaining "vadose caves" and "solutional fissures" recorded in the Natural Cavities Database are predominantly cave sites from the caving guidebook by Brook et al. (1988). Although the term "vadose" implies that they are of karstic origin, it is possible that some of these cave sites may be slip rifts, and it is often difficult to determine from descriptions in Brook et al. (1988) whether the caves are mass movement or karstic in origin. It is not clear whether the classification of "solutional fissures" in the Natural Cavities Database represent caves that were thought to have a solutional origin, or whether these are sites where solutional fissures have been observed within mass movement or other caves. Figure 7 also shows the locations of "gull fissures" formed by mass movement recorded in the Natural Cavities Database.

Figure 8 shows the locations of 74 cave sites in the limestones in the P2 area identified from a literature review for this report, and includes many of the sites recorded in the Natural Cavities Database. The literature was used to classify these caves as far as possible in terms of whether they are likely to be karstic. Two sites, at Knaresborough - St Roberts Cave and the Chapel of Our Lady of the Crag are artificially dug caves (BGS Geoscenic online photographs P222615 and P222612). 22 caves were classified as karst caves (pink circles with a diagonal cross on Figure 8), and two as sediment filled karst caves (light brown circles). 6 caves are likely to be predominantly slip rifts but with some evidence of karstic development of voids (green hexagons on Figure 8). Six sites are described as rock shelters, but with some evidence of karst development (brown diamonds). At 16 sites it is unclear if the cave is formed by karst or mass movement (large pink triangles on Figure 8). Eight caves were classified as slip rift caves of mass movement origin (large grey squares), and a further 13 caves are probably slip rifts rather than karst caves (small dark blue squares). There may be additional records of slip rift caves not reported here as the focus is on karst and a dataset on slip rift caves was not collated. Some of the caves in the Permian limestones are protected due to their archaeological importance, and many are designated RIGS (Regionally Important Geological Sites). However, many caves have no protection and the threats to, and impacts on caves are discussed by Gibbs (2016). It is probable that most of the known karst caves have been identified, as they are well documented by cavers, but it is possible that there are some additional short karst caves recorded in the extensive caving club literature, and quite likely that some caves have not yet been discovered.

Figure 8 also shows the location of a possible conduit at Nor Wood overhang, discussed by Gibbs (1995b), which is shown as a yellow circle with a cross. There is no comprehensive dataset of smaller conduits/solutional fissures, and a dataset on these was not compiled for this report, but it is likely that there are many more sites where these occur, as discussed in Section 2.3.5.

The distributions of caves and cavities shown in Figure 7 and Figure 8 shows that there is evidence for karst development within the Cadeby Formation throughout much of the P2 area, although there are some areas where there are no records of caves and cavities within the limestones, for example in the most northerly parts of the P2 area, in the area to the east of Leeds, and in the south of the P2 area. It is uncertain whether this reflects an absence of cavities, or an absence of studies and records. Superficial cover may obscure caves, especially in the north and east of the P2 area where these deposits are extensive (Figure 3). Higher resolution maps of the most important areas with caves, conduits and fissures identified from the literature review are provided in Figure 9, Figure 10, and Figure 11. In these figures, created in ARCGIS, records from the Natural Cavities Database were plotted below those from literature review, and therefore only those that are additional to the literature review sites are apparent on these figures.

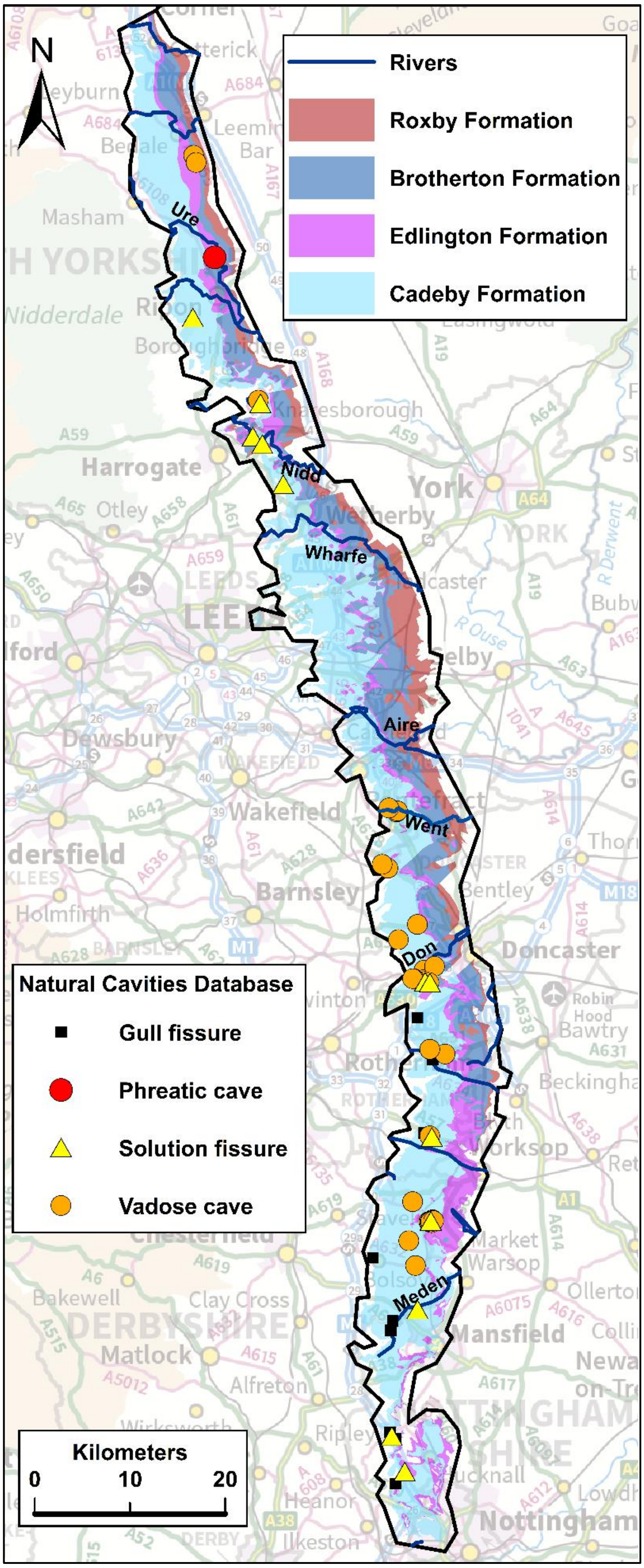

Figure 7. Caves and fissures in the Zechstein Group from the Natural Cavities Database.

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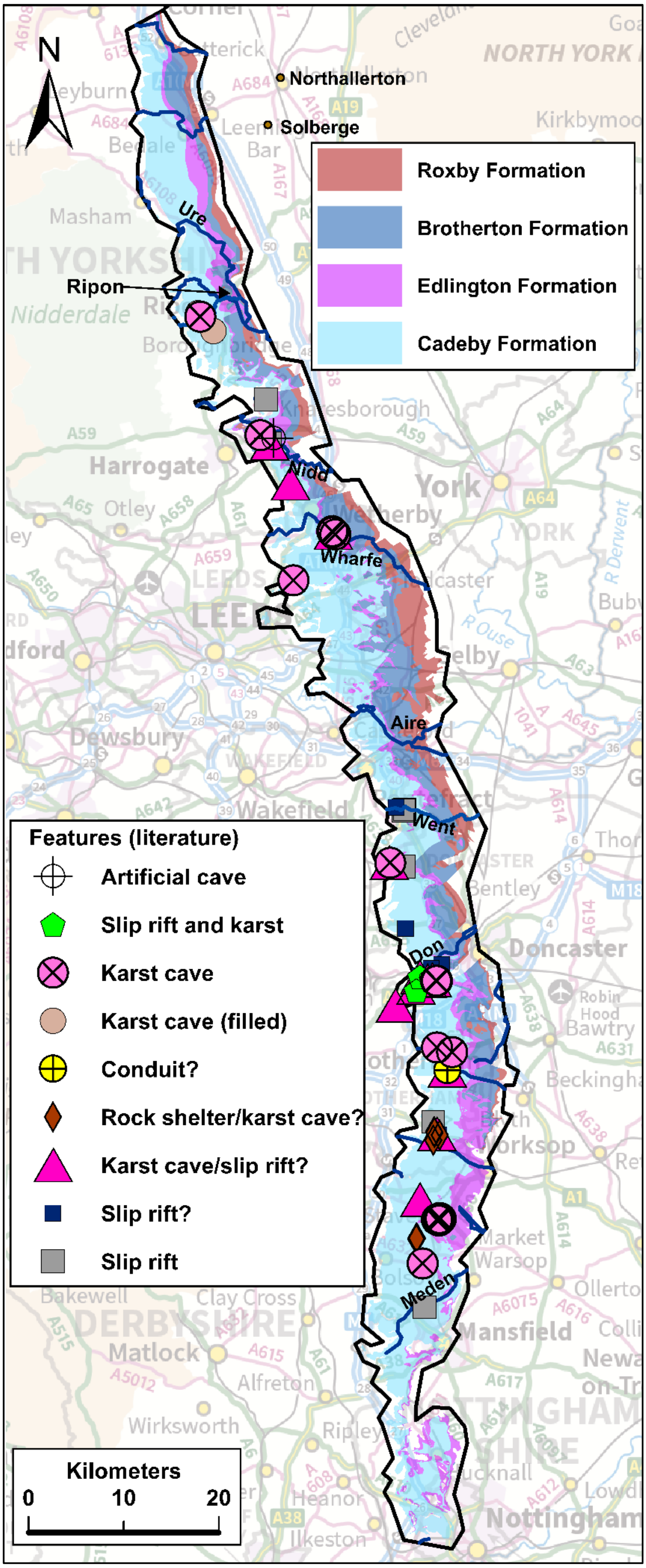

Figure 8. Caves and cavities in the Zechstein Group identified from literature review.

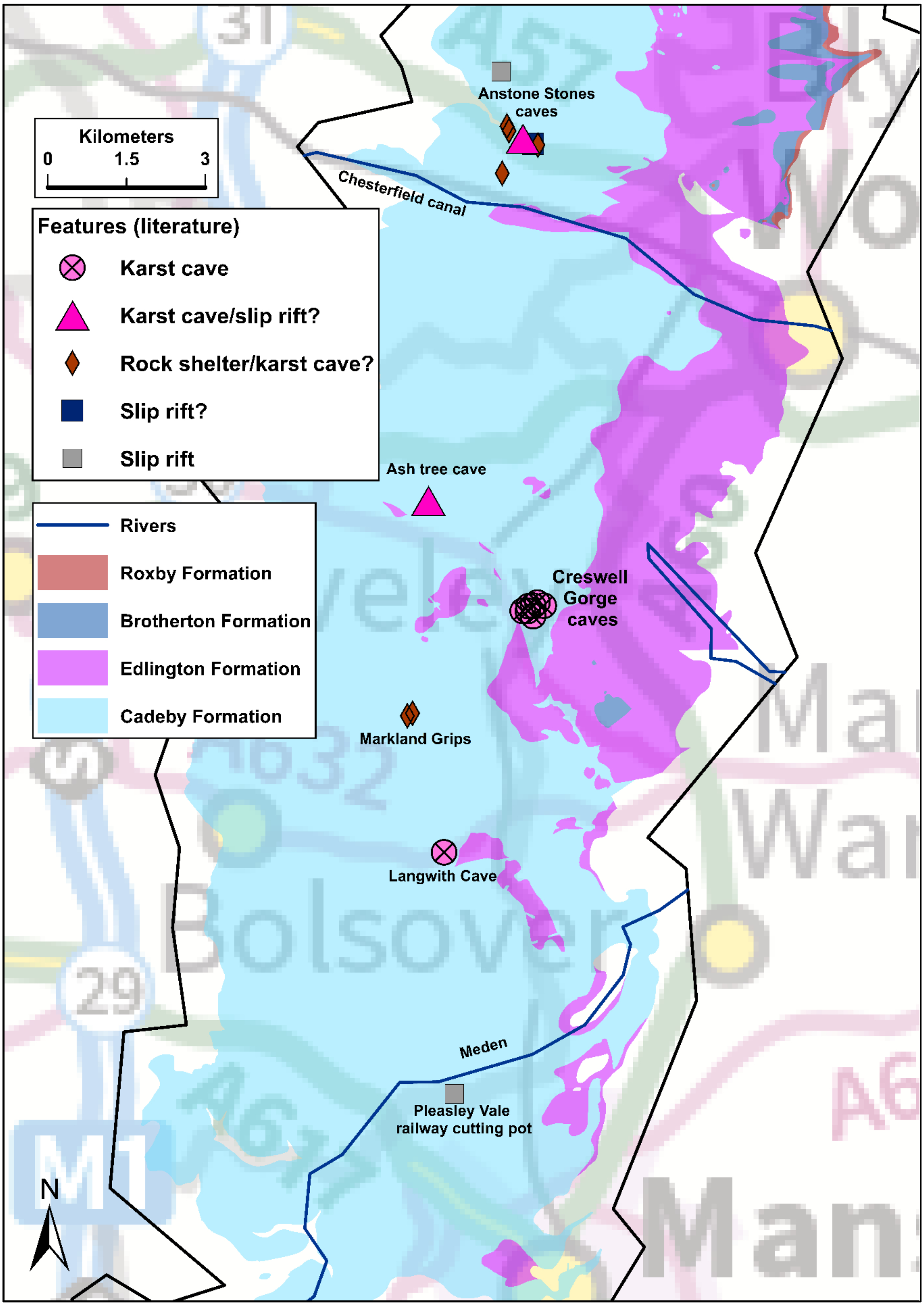

Figure 9. Caves and cavities in the southern part of the P2 area including Creswell Gorge.

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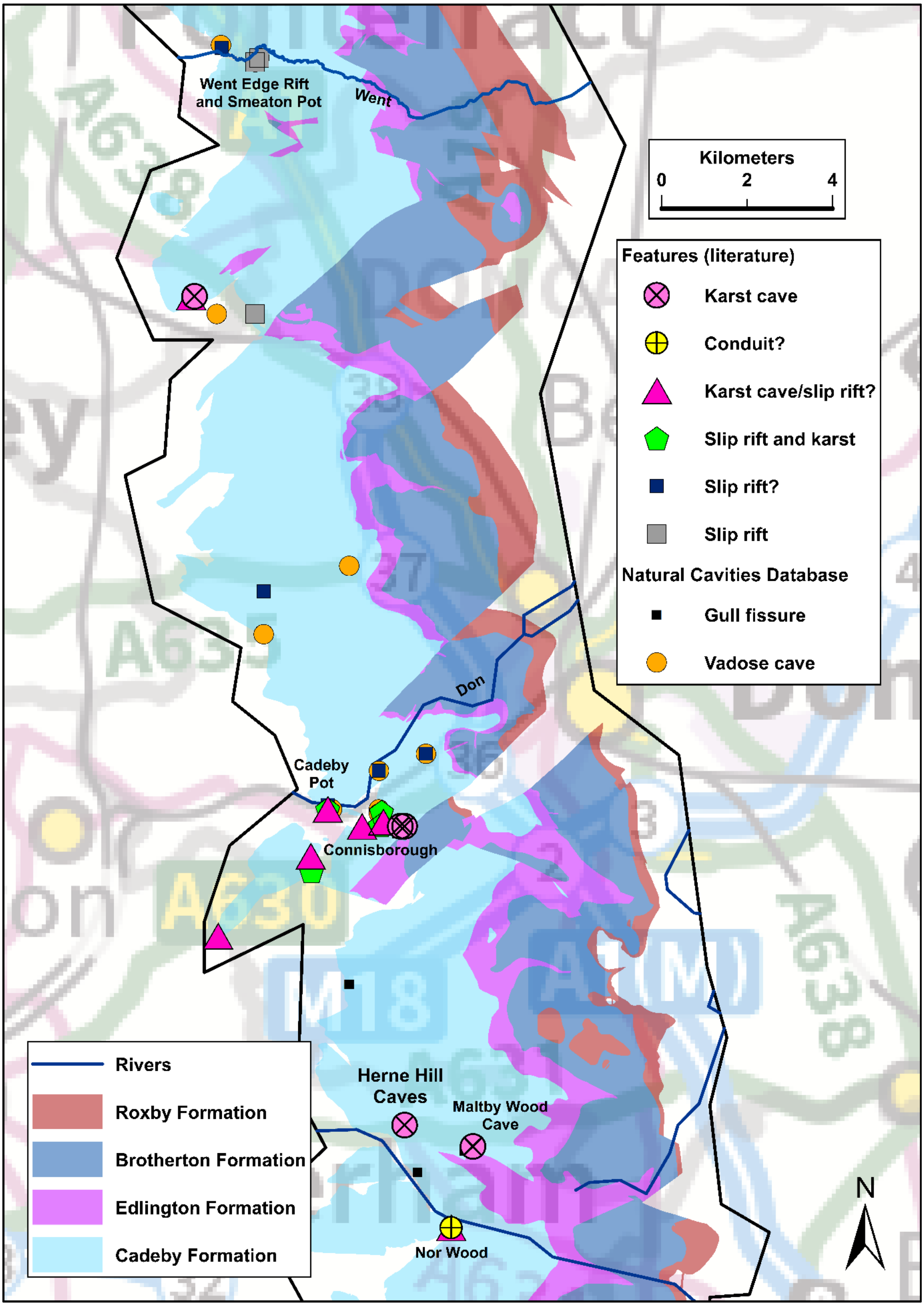

Figure 10. Caves and cavities in the central P2 area including Herne hill caves, Maltby.

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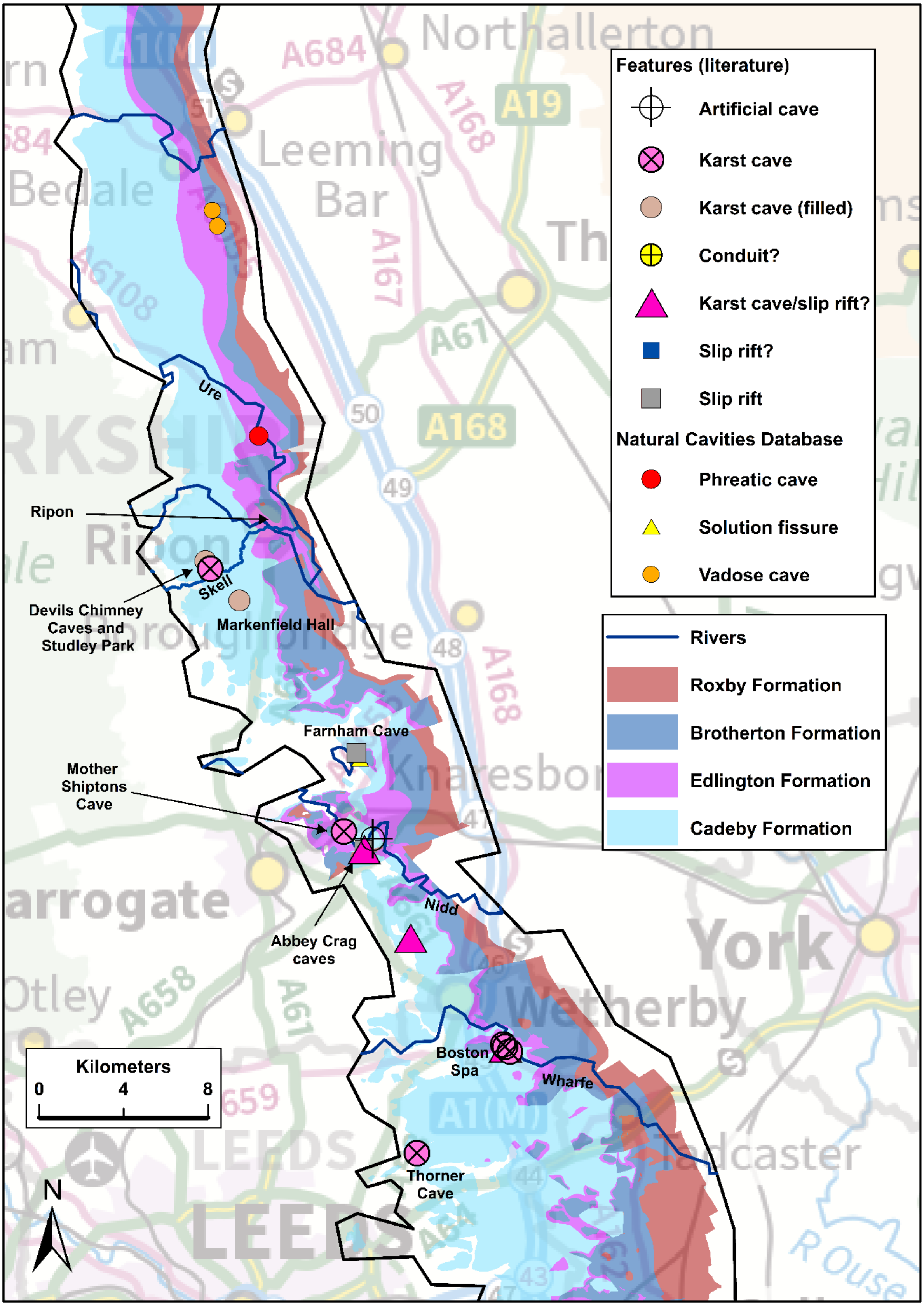

Figure 11. Caves and cavities in the northern part of the P2 area including Knaresborough.

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2.3.2 Karst cave details

This section provides some details of the karstic caves in the Permian dolomitic limestones in the P2 area (Table 2). These caves are fragments of karstic phreatic rift and maze caves that are no longer hydrologically active (Waltham et al., 1997, Farrant and Cooper, 2008; Murphy and Lowe, 2021). Their karstic origin is indicated by their tubular cross sections, and roof domes indicating a karstic phreatic (sub water table) origin, and scallops on cave walls indicating water flow (Murphy and Lowe, 2021). Most known cave entrances in the Permian limestones are in quarries or incised river valleys, and some other cave entrances may have been obscured by superficial deposits (Murphy and Lowe, 2021). Some caves have been lost to landfill, for example caves that were in South Elmsall quarry [SE 48381 11612] between Doncaster and Wakefield (Murphy and Lowe, 2021). Most of the known caves are only a few 10s of metres long (Table 2), with the exception of Robin Hood's Cave (290 m) and Herne Hill Cave No. 1 (168 m). The relevance of dry caves to modern day hydrogeology is that they demonstrate that karstic dissolutional processes in the Permian limestones can create substantial sized voids, and therefore modern-day groundwater flow is likely to be impacted by some conduit development, perhaps including cave-sized voids (Allen et al., 1997). Although none of the documented caves are hydrologically active, Gibbs (1996a) suggests that there is evidence of the development of active vadose karst caves in the Maltby area, although no further details are provided.

Caves in the P2 area which are either karstic or likely to have some karst development are described in more detail below, broadly from south to north.

Table 2. Karstic caves in the dolomitic limestones of the P2 area

Name	Location	Easting	Northing	Length (m)	References
Robin Hood's Cave	Creswell	453410	374190	290	MSG (1974); Gibson et al. (1976); Brook et al. (1988); Gibbs, (1995a); DCA Cave Registry; Barker and Beck (2010)
Church Hole	Creswell	453400	374100	75	Heath (1882); Gibson et al. (1976); Brook et al. (1988); Gibbs (1995a)
West Pinhole (Dog Hole cave)	Creswell	453300	374100	60	MSG (1974); Gibson et al. (1976); Brook et al. (1988); Gibbs (1995a); Barker and Beck (2010); DCA Cave Registry
Boat House Cave	Creswell	453700	374200	55	DCA Registry; MSG (1974); Brook et al. (1988); Barker and Beck (2010)
The Pin Hole	Creswell	453300	274100	52	Heath (1882); Armstrong (1936); MSG (1974); Gibson et al. (1976); Brook et al. (1988); Barker and Beck (2010); DCA Cave Registry
Loop Hole	Creswell	453500	374200	15	Gibson et al. (1976); MSG (1974); Brook et al. (1988); DCA Cave Registry; Barker and Beck (2010)
Mother Grundy's Parlour	Creswell	453580	374260	15	MSG (1974); Gibson et al. (1976); Brook et al. (1988); DCA Cave Registry; Barker and Beck (2010);
Quarry Cave	Creswell	453500	374000	15	MSG (1974); Gibson et al. (1976); Brook et al. (1988); Gibbs, (1995a); DCA Cave Registry; Barker and Beck (2010)
Herne Hill Cave 1	Maltby	453300	392200	168	MSG (1974;1979), Gibbs (1995b); Gibson et al. (1976); Brook et al. (1988); DCA Cave Registry; Barker and Beck (2010); Murphy and Lowe (2021)
Herne Hill Cave 2	Maltby	453300	392200	64	Brook et al. (1988); Gibbs (1995b); DCA Cave Registry; Barker and Beck (2010);
Herne Hill Cave 3	Maltby	453300	392200	25	Gibbs (1995a, b); DCA Cave Registry; Barker and Beck (2010);
Langwith Cave	Langwith	451800	369500	30	Mullins (1913); Gibson et al. (1976); Brook et al. (1988); Gibbs (1995a); MSG (1974); DCA Cave Registry; Barker and Beck (2010)
Maltby Wood Cave	Maltby	454900	391700	40	DCA Cave Registry; MSG (1987); Brook et al. (1988); Barker and Beck (2010).
Mother Shiptons Cave (show)*	Knaresborough	434738	456548	8	Gibson et al. (1976); Brook et al. (1988); Cooper 2006b)
Sandy Hole	Connisborough	453300	399200	9	Gibson et al. (1976); Brook et al. (1988); Gibbs, (1995b);
Connection Cave	Connisborough	453200	399200	7	Gibson et al. (1976); Brook et al. (1988); Gibbs, (1995b); Engering and Barron (2007)

Devils Chimney Cave 1	Skell, Ripon	428400	469000	12	Gibson et al. (1976); Brook et al. (1988); Murphy (1999)
Devils Chimney Cave 2	Skell, Ripon	428400	469000	5.5	Gibson et al. (1976); Brook et al. (1988); Murphy (1999)
South Elmsall Quarry	West Yorkshire	448381	411612	?	Murphy and Lowe (2021)
Cave at Deepdale, Boston Spa	West Yorkshire	442290	446450	2.5	Murphy (2023)
Robin Hood’s Cave, Boston Spa	West Yorkshire	442373	446342	?	Murphy (2023)
Churchfield Cave, Boston Spa	West Yorkshire	442610	446120	~3-4	Murphy (2023); Tymon et al. (2017)
Thorner Cave	West Yorkshire	438200	441300	6	Brook et al. (1988); Observations by P Murphy

*associated with tufa but not formed by karstic dissolution

2.3.2.1 Creswell Gorge Caves

The Creswell Gorge is located in the southern part of the P2 area (Figure 9) and has the most significant known karstic cave development in the Permian limestones. The downcutting of the gorge has intersected old caves of quite large dimensions (Figure 12, Figure 13). Eight caves are documented (Figure 14), including Robin Hood’s cave, which with a length of 290 m, is the longest karstic cave in the Permian limestones (MSG, 1974). This cave has classic karst shaped passages with clear evidence of dissolution (Figure 15). It is operated as a tourist show cave. The Creswell Gorge caves are described in Barker and Beck (2010) and discussed in detail by MSG (1974), Gibbs (1995a); and Murphy and Lowe (2021). The caves in the Cresswell gorge are clearly karstic in origin with phreatic shaped cave passages (Figure 12, Figure 15, Figure 16, Figure 17), and other evidence of dissolution (Figure 18). Furthermore, some contain some fairly substantial sized chambers (MSG, 1974). Surveys of the caves can be found in MSG (1974), and the caves are also discussed by Gillmore et al. (2002) who investigated their radon concentrations. Photos of caves in the BGS archives include a “natural fissure” in the dolomitic limestone intersected by a quarry just behind Cresswell Crags (Figure 19 and Figure 20). This is a cave sized void and suggests further cave development in the area.

The Creswell gorge caves are famous for their archaeological discoveries with evidence of Neanderthal/human cave occupation dating back to 50 000 to 60 000 years ago, and the remains of pre-glacial fauna including bears, woolly rhinoceros, mammoths, hyaenas and lions (Heath, 1882; Mello, 1877; Dawkins, 1877; Armstrong, 1936; Jenkinson, 1984; Charles et al., 1994; Gilmore et al., 2002). Palaeolithic cave art has also been found in the caves (Pike et al., 2005). Archaeological excavations have removed much of the clastic fill from the caves (Murphy and Lowe, 2021).

Speleothem dates from the Cresswell caves suggested that the fossil phreatic caves were drained relatively recently, and that the dated speleothems were probably no older than mid-Pleistocene (Rowe et al., 1989, discussed in Murphy and Lowe, 2021). The caves do not appear to extend over long distances suggesting that they are fairly localised features, which might have formed by mixing corrosion close to groundwater discharge points. Their size, with passages and chambers with dimensions of several metres, demonstrate that karstic caves of this scale can develop in the Permian limestones, at least locally.

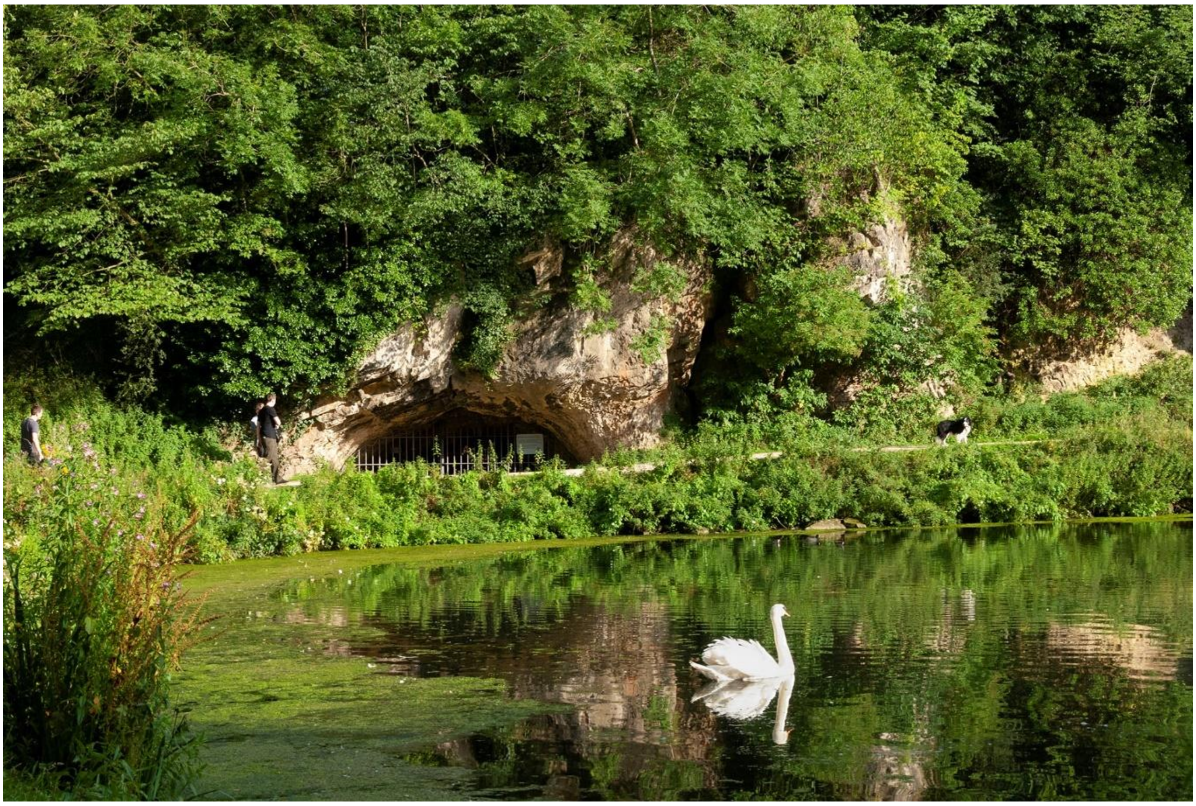

Figure 12. Phreatic shaped karst cave (Boat House Cave) intersected in the Creswell gorge. Photo courtesy of Tony Waltham Geophotos.

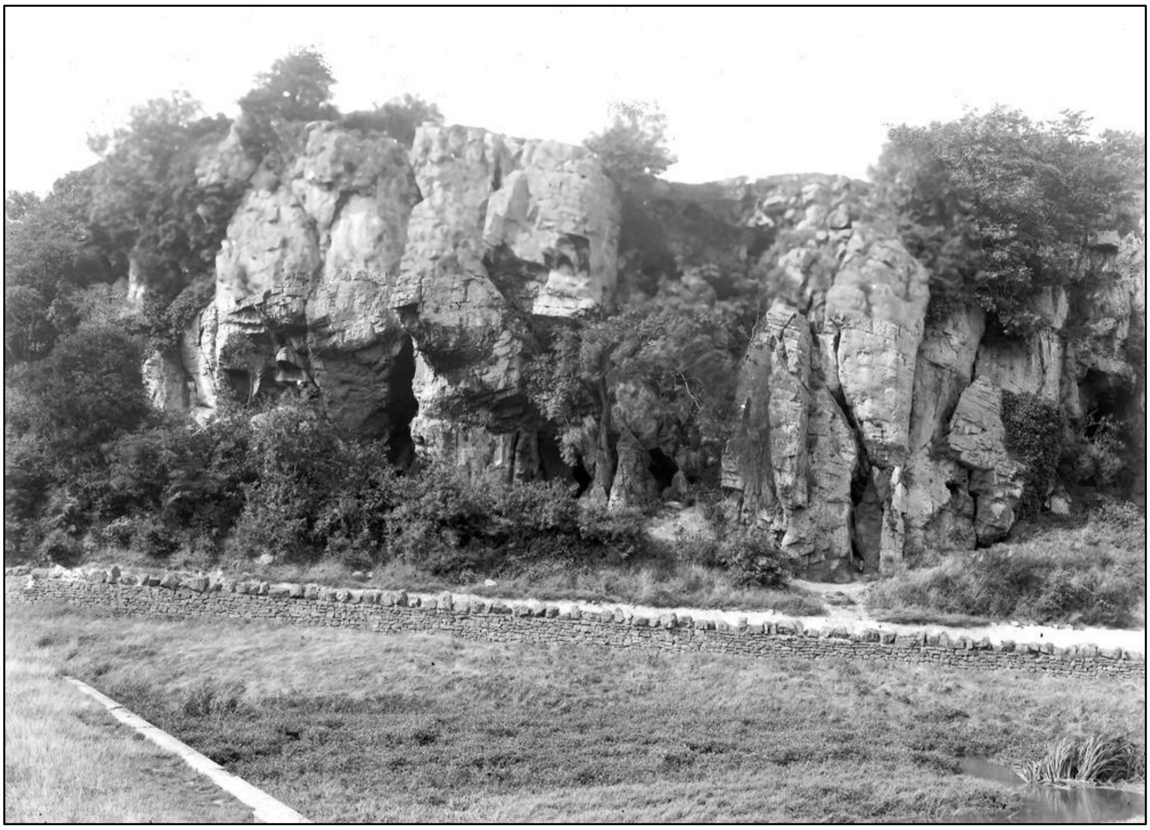

Figure 13. Looking east in the Creswell Gorge. Photo by J. Rhodes, August 1930.

BGS photo archive P205008. [SK 525 754]

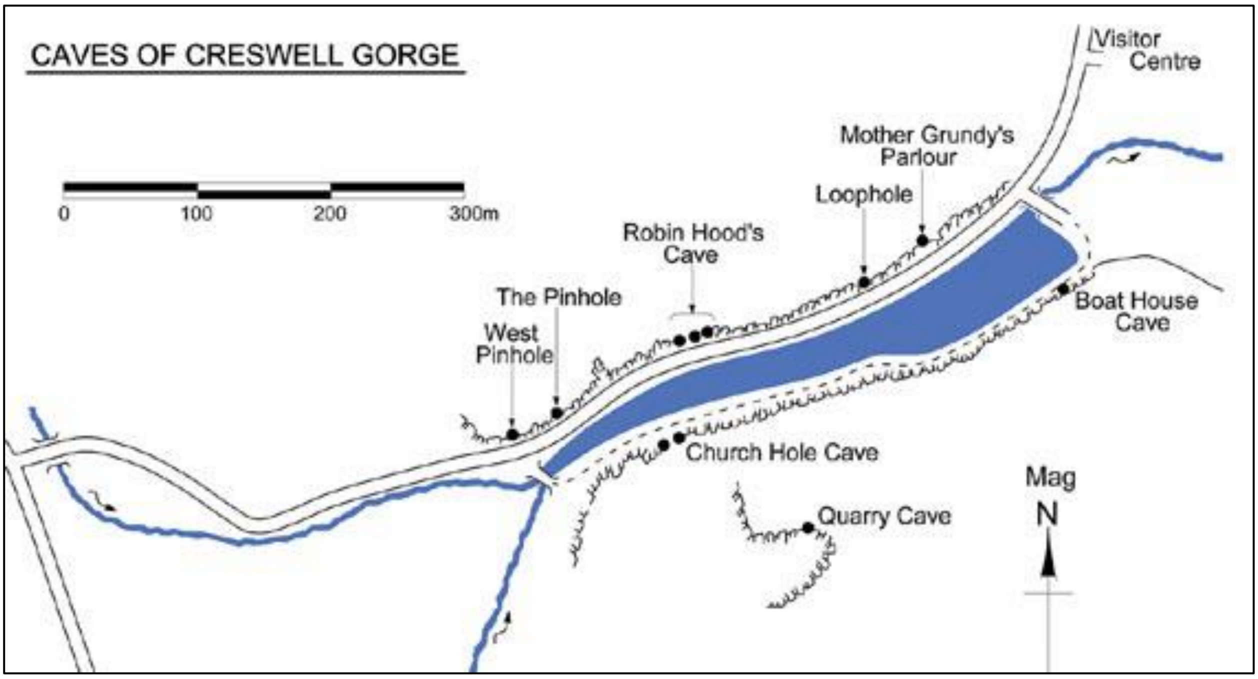

Figure 14. Caves in the Creswell Gorge (© Derbyshire Caving Association)

Figure 15. Robin Hoods Cave, Cresswell. Photo courtesy of John Gunn.

Figure 16. Church Hole cave, Cresswell gorge. Photo courtesy of Tony Waltham Geophotos.

Figure 17. Cave in north-western wall of Creswell Gorge near Pinhole Cave. Photo by J. Rhodes. May 1911.

BGS photo archive P201169 [SK 535 745]

Figure 18. Solutional feature at Creswell in 1913.

BGS photo archive P805037.

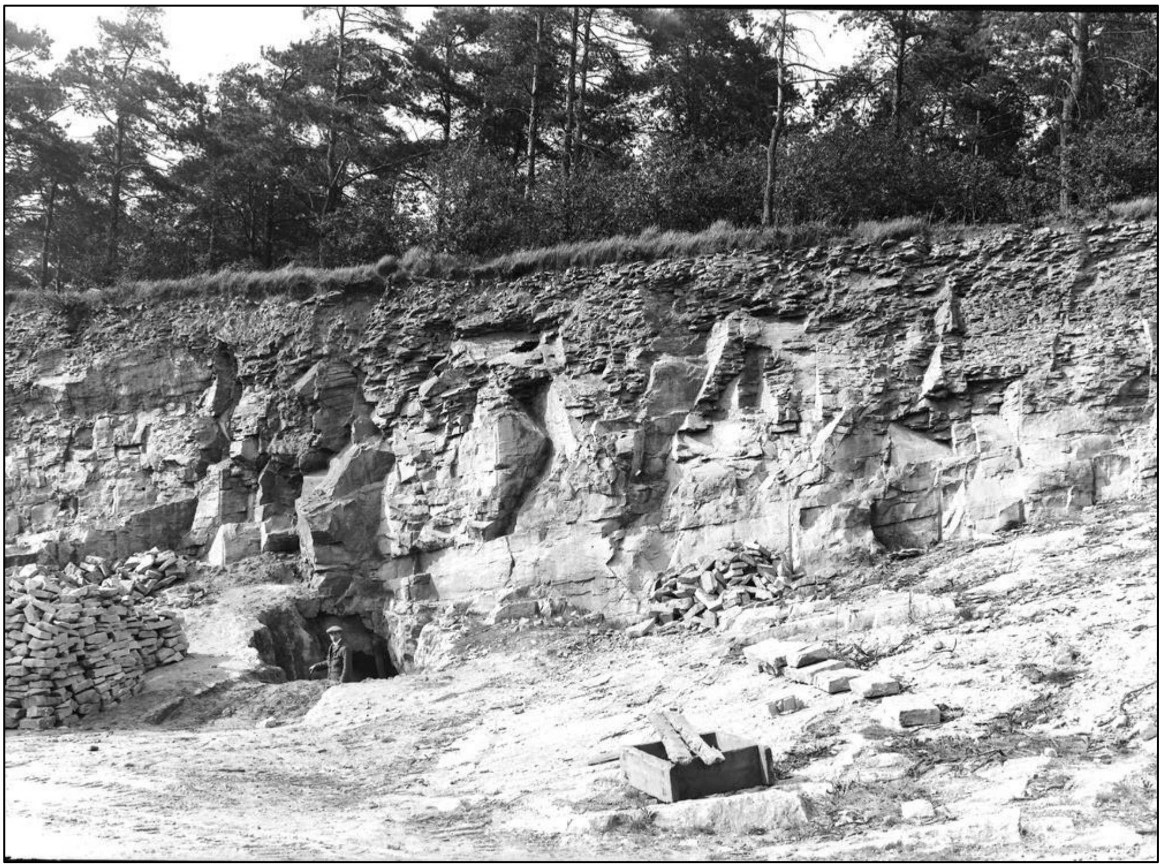

Figure 19. “Natural fissure” exposed in Cresswell Quarry. Photo by J. Rhodes, May 1911.

BGS photo archive P201170 [SK 535 745]

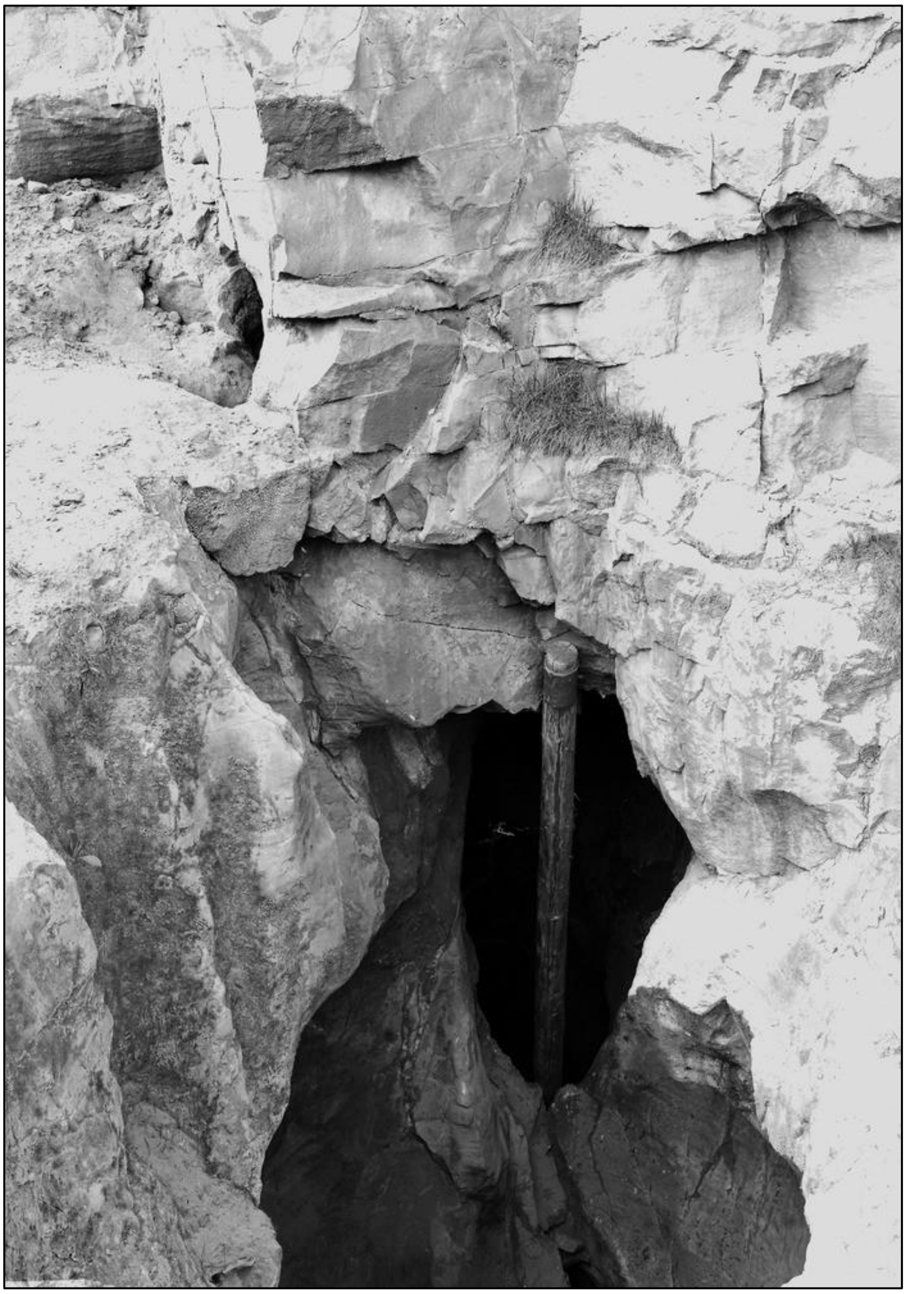

Figure 20. Close up view of “Natural Fissure” in dolomitic limestone at Creswell Quarry. Photo by J. Rhodes, May 1911.

BGS photo archive P201171. [SK 535 745]

2.3.2.2 LANGWITH CAVE AND ASH TREE CAVE

Langwith Cave is on the north bank of the River Poulter several kilometres south-south-west of the Creswell Gorge (Barker and Beck, 2010; Figure 9). The cave is 90 m long and comprises a chamber with several sandy crawls leading from it, and has been the subject of archaeological investigations (Mullins, 1913; MSG, 1974; Barker and Beck, 2010). Descriptions suggest that it is of karstic origin. A picture of the cave (Figure 21) shows a karstic shaped cave entrance which appears to have some indications of dissolution, but also that the cave is close to the surface suggesting a possible role of mass movement.

Ash Tree cave is north-west of the Creswell Gorge (Figure 9) and is an important archaeological site (Armstrong, 1950, 1956). It is only 7 m long and comprises a slope down to a chamber (Barker and Beck, 2010). It is unclear from the descriptions whether it is karstic in origin.

Figure 21. Langwith Cave (From Derbyshire Caving Association website). Photo courtesy of Phil Walker.

2.3.2.3 HERNE HILL CAVES

Herne Hill caves are located in the central part of the P2 area (Figure 10) near Maltby. Three significant karst caves occur, including Herne Hill Cave No. 1 which is 168 m long and contains several chambers with dimensions of several metres (Barker and Beck, 2010). The cave is discussed by Pete Ryder in MSG (1974; 1979) who also provides a survey which is reproduced in Murphy and Lowe (2021). The cave is clearly karstic in origin comprising fossil phreatic passages with scallops on the walls and ceilings indicating water flow (Murphy and Lowe, 2021; Figure 22). Herne Hill caves 2 and 3 are similar karstic caves located close to Herne Hill Cave No 1, and are described in Gibbs (1995a, b).

Figure 22. Herne Hill cave. Photo courtesy of Pete Ryder.

2.3.2.4 MALTBY WOOD CAVE

Maltby Wood Cave is a few kilometres east-south-east of Herne Hill caves (Figure 10). It is described by MSG (1987) who note that it is another unusual example of a phreatic karstic cave in the Permian limestones. It is 40 m long and contains a chamber of 8 m by 4 m, and another of 5 m diameter (Barker and Beck, 2010). A survey of the cave by Pete Ryder can be found in MSG (1987) and on the cavemaps.org website. The dolomitic limestones of the Cadeby Formation in the Maltby area also appear to have some solutionally widened fissures (Figure 23).

Figure 23. Cadeby Formation outcrop near Maltby. Photo by J. Rhodes July 1950.

BGS photo archive P208767. [SK528 917]

2.3.2.5 CONNISBOROUGH CAVES

There are many caves documented in the Connisborough area (Figure 10, Figure 24), including some significant slip rift caves. The difficulties in determining the origin of caves from literature review are illustrated by the two sites near the River Don which are recorded as vadose caves in the Natural Cavities Database which would imply a karstic origin. However, the valley of the River Don is reported to be an area known for slip rift caves (Gibson et al., 1976), and descriptions of these caves (Levitt Hagg Hole and Railway Pot) by Gibson et al. (1976) suggest that they are likely to be slip rifts of mass movement origin, although this is not certain.

At two sites in the Connisborough area (Sandy Hole and Connection cave) the descriptions include "*bedding development*" and/or "*phreatic development*" indicating a karstic origin (Gibson et al., 1976; Engering and Barron, 2007). There are two other caves at the same reported location as Connection cave (Badger Cave and High Cave which is also known as Connisborough Cave No. 2). These caves are also reported to have karstic features (Gibson et al., 1976), but are thought to be formed by a combination of mass movement and karst processes (Engering and Barron, 2007). Four other significant caves in the area that are predominantly slip rifts (Windy Cave, High Rift Cave, Holywell Quarry Cave and Cadeby Pot) also contain some evidence of karstic development and are therefore included on Figure 10 and Figure 24 as a combination of slip rift and karst. In an extensive description of Cadeby Pot, Gibson et al. (1976) suggest that although it is predominantly a slip rift, "*there is evidence to suggest that water action played some role in its development, particularly in the lower section*". Engering and Barron (2007) report that High Rift Cave (also known as Connisborough Cave No. 1) has some interesting bedding development suggesting a role of karst. Holywell Quarry cave is close to a spring suggesting the possibility of karst development, and Gibbs (1995b) reports that in this cave there is a large chamber with possible evidence of solutional development, which Engering and Barron (2007) suggest needs further investigation. Engering and Barron (2007) also report that Windy Cave is a slip rift with some karst development.

Overall, it appears that slip rifts are the main mechanism of cave development in the Connisborough area, but there is also evidence of some karstic solutional development of cave passages.

Table 3. Slip rift caves in the Connisborough area with some evidence of karstic development.

Name	Location	East	North	Length (m)	References
Badger cave	Connisborough	453200	399200	12	Gibson et al. (1976); Gibbs, (1995b);
Cadeby Pot	Connisborough	451500	399600	45	Gibson et al. (1976); Gibbs, (1995b); Murphy and Cordingley (2010)
High Cave	Connisborough	453200	399200	31	Gibson et al. (1976); Gibbs, (1995b);
High Rift Cave	Connisborough	452737	399231	27	MSG (1974); Gibson et al. (1976); Gibbs, (1995b);
Holywell Quarry Cave	Connisborough	451120	398150	5	Gibbs, (1995b); Engering and Barron (2007)
Windy Cave	Connisborough	452761	399540	10	Gibson et al. (1976); Engering and Barron (2007)

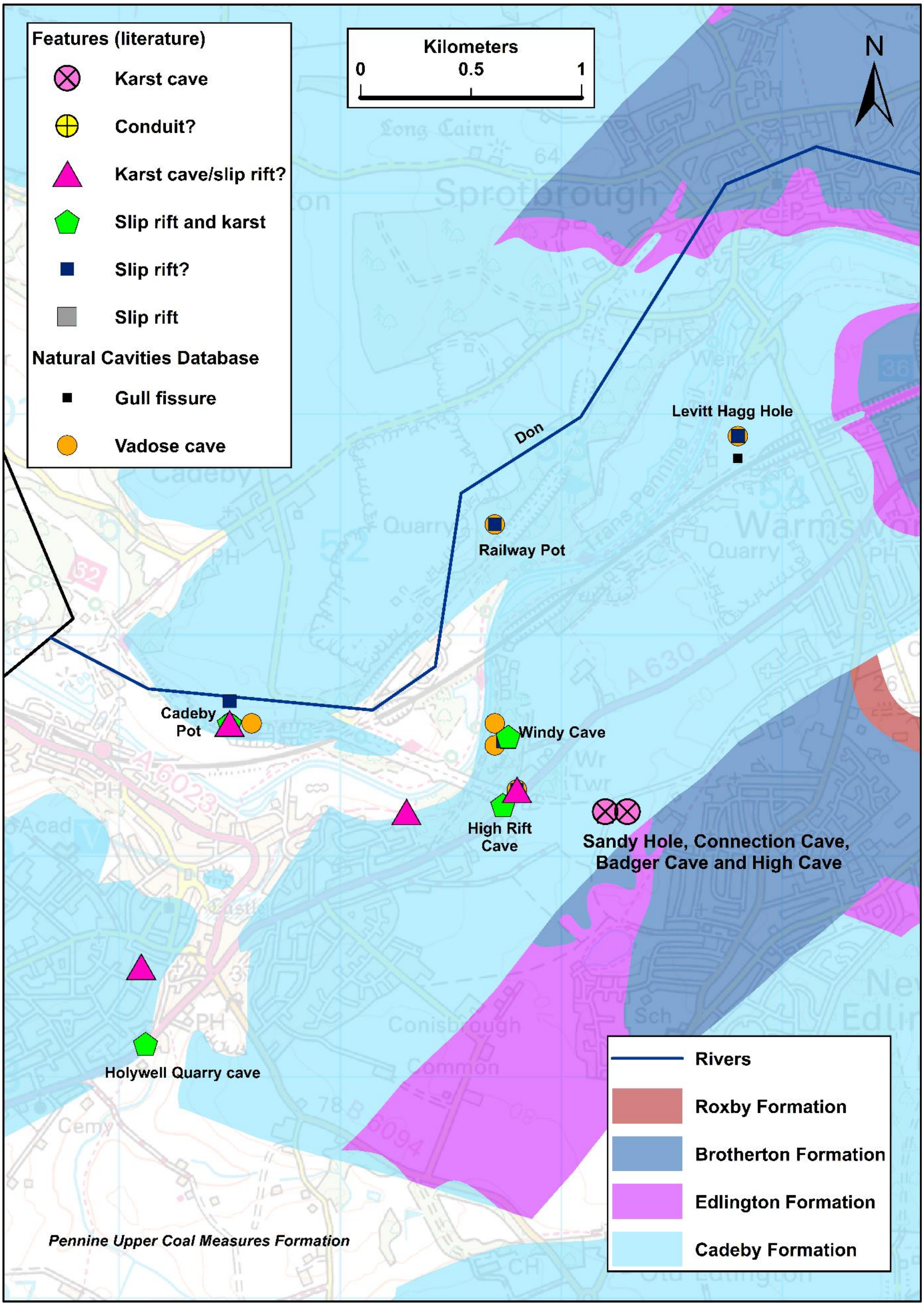

Figure 24. Caves in the Zechstein group in the Connisborough area.

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Note that areas with no colour are the Pennine Upper Coal Measures Formation which underlies the Zechstein Group

2.3.2.6 BOSTON SPA

Murphy (2023) describes karstic cave development at Jackdaw Crag near Boston Spa in the valley of the River Wharf in West Yorkshire (see Figure 11 for location which is about 6 km north-west of Tadcaster). Murphy (2023) notes that "Robin Hoods Cave" is shown on Ordnance Survey maps from 1980 and earlier at [SE 42373 46342]. The site was visited recently, and Murphy (2023) suggested that the cave might have been buried by fallen trees and debris. However, a 2.5 m long tube (0.6 x 0.8 m) was found at the cliff base at [SE 4229 4645], together with a slightly smaller tube-shaped cave entrance higher up the cliff which has scallops on the roof providing further evidence that it is of karstic origin (Murphy, 2023). Gibson et al. (1976) list "Jackdaw Crag Cave" at [SE 424 463] with a length of 10 feet which may be the same site, although no further details are provided by Gibson et al. (1976). Murphy (2023) discusses another site closer to Boston Spa village which is in the Cadeby Formation and known as Churchfield Cave [SE 4261 4612] according to Tymon et al. (2017). The cave is reported to be in an area known as Riverside Woods (Murphy, 2023). The cave appears to have a phreatic origin and comprises a chamber that is about 2 metres across and contains small tubes of approximately 30 cm diameter that continue into the walls (Murphy, 2023). Murphy (2023) notes that the Boston Spa Archaeological and Heritage Group (2009; 2013) suggest that the cave may have archaeological interest. Murphy (2023) also reports that there are other smaller tube-like features in the area.

Around 6.5 km to the south-west of Boston Spa, near the western edge of the Cadeby Formation outcrop, Thorner Cave is also karstic in origin (see Figure 11 for location and Table 2 for details). This cave is short and appears to be a phreatic shaped pocket.

2.3.2.7 KNARESBOROUGH CAVES

There are two famous caves near the River Nidd in the Knaresborough area to the north of Leeds (Figure 11). Mother Shipton's cave is a short (7 m) tourist cave which consists of a single chamber ~ 4 m high associated with a tufa deposit that has slipped and been excavated leaving a roughly triangular cross-section shape (Gibson et al., 1976; Cooper, 2006b, see Figure 25). Technically this cave is more of a mass movement feature, but of some interest because of the extensive tufa deposits. The Petrifying well, also known as the Dropping well [SE 348 565] is close to the cave (Figure 66 and Figure 67) and is a sulphate-rich spring discharging over the dolomitic limestones of the Cadeby Formation from the Edlington Formation and gypsum to the west (Burrell 1896,1897; Cooper and Burgess, 1993; Cooper, 2006b; Cooper et al., 2013). This spring is famous for the rapidity with which the tufa is deposited from the carbonate and sulphate rich groundwater discharged from the spring (Cooper, 2006b).

St Robert's Cave, Knaresborough [SE 36108 56211] is also within the Cadeby Formation dolomitic limestones, but it is not karstic in origin, having been carved out of the rocks by humans (Cooper and Burgess, 1993; Cooper, 2008). It is unclear whether there were any karstic cavities present before the cave was created. Another man-made "cave" is the Chapel in the Rock [SE 35140, 56440] (formerly St Robert's Chapel) which is a rock-hewn opening with a door and window (BGS GeoScenic photo P222612 and Cooper, 2008).

Two other short (4 to 5 m) caves are recorded nearby: Abbey Crag caves No. 1 and No. 2 (Gibson et al., 1976; Gibbs, 1995c). These are recorded as karst cave/slip rift on Figure 11 as their origin is not certain. Abbey Crag cave No. 1 is reported to "*end in a 6 feet wide bedding*" (Gibson et al., 1976) which suggests some solutional development, and Abbey Crag cave No. 2 is described as a "*7 feet high fissure*" (Gibson et al., 1976) which might imply that it is a slip rift. Cave No 1 is probably the cave shown in the upper right of BGS picture P29251 (Figure 26) taken during the resurvey of the area in 1976 when Cooper also noted the caves in his notebooks. The cavity in this picture does not look like a slip rift and appears to be solutional in origin.

Figure 25. Mother Shipton’s Cave.

From https://commons.wikimedia.org/wiki/File:MotherShipton%27sCave.jpg

Figure 26. Abbey Crags, Knaresborough showing the basal part of the Cadeby Formation resting unconformably on Carboniferous sandstone. A small cave with ochre clay deposits is present in the upper right of the picture - BGS photo archive P222617.

2.3.2.8 CAVES ASSOCIATED WITH THE RIVER SKELL

Murphy (1999) reports two dry cave fragments in the base of the cliff above the main River Skell sink point (Section 2.4) which are described by Brook et al. (1988). The locations are shown on Figure 11. These are Devils Chimney Cave No 1 which comprised a small 12.5 m long passage leading to a chamber where the continuation was blocked by a collapse, and Devils Chimney Cave No 2 which was a small 5.5 m long passage that became too low to follow (Murphy, 1999). There was no active flow in these caves, and they may be karst caves created when the River Skell was at a higher level (Murphy, 1999). These caves have now become buried beneath flood debris and are no longer accessible. In this area, Fox-Strangeways et al. (1886) and Fox-Strangeways (1908) reported sediment-filled caves in quarries at Studley Park and Markenfield Hall (Figure 11). For example, Fox-Strangeways et al. (1886) reported that "*in Studley Park the limestone is hollowed out by numerous small caves and fissures, which in many cases have been filled with gravel and clay washed in from above*". The precise locations of these quarries and caves are unknown, and the locations on Figure 8 and Figure 11 are approximate.

2.3.2.9 BLOWING WELLS

Fox-Strangeways (1908) suggested that small caves occur fairly frequently in the Permian limestone and postulated that caverns and fissures in the limestones may be the cause of the "*blowing wells*" in the sandstone boreholes at Solberge, Langton and Ornhams near Northallerton which were investigated by Fairley (1881) and discussed by Strahan (1883) in the journal Nature. In these boreholes strong currents of air flow in and out in response to changes in barometric pressure (Fox-Strangeways, 1908). Fairley (1881) investigated the borehole at Solberge and concluded that the water chemistry was similar to that of chalk or limestone. He also measured the air flows to and from the borehole and concluded that the total capacity of the "fissures" causing the air flows must be "*nearly 10 000 000 cubic feet*" (Strahan, 1883). However, modern geological work has shown that these blowing wells are situated near the top of the Sherwood Sandstone Group where there are 200-250 m of sandstone overlying the Permian strata and therefore they are not related to Permian karst. They are near to the base of the overlying Mercia Mudstone Group where gypsum is present (Powell et al., 1992), and it is possible that the blowing wells relate to cavities in this gypsum, or to fissures in the Sherwood Sandstone Group. This area is to the east of the most northerly part of the P2 area and the villages of Northallerton and Solberge, are shown on Figure 8.

2.3.2.10 ROCK SHELTERS WITH POSSIBLE KARST DEVELOPMENT

At Anstone and Clowne towards the south of the P2 area (Figure 9; Table 4) there are reports of "rock shelters" which appear to have some limited karstic cave development associated with them. At Anstone Stones, five caves are reported. Anstone Stones cave No. 5 is described as a slip rift, but cave Nos. 1 to 4 as rock shelters with some karstic development. "*Many open joints and pipe like fissures*" are described in relation to the Anstone Stones caves in general (Gibbs, 1995a). Specifically, Anstone Stones cave 2 is described as "*a small rock shelter with 5 m of low accessible bedding plane*" (Gibbs, 1995a). In the Clowne area, Gibbs (1995a) reports similar sites at Markland Grips, including a cave known as Whaley Cave. The Whaley cave site is described by Barker and Beck (2010) as two archaeological sites excavated by Armstrong (Radley, 1967). The Derbyshire Historic Environment Record describes caves and rock shelters in the Markland Grips and Hollinhill Grips valleys (https://her.derbyshire.gov.uk/Monument/MDR6415). They report a survey of caves, rock shelters and fissures in which 12 caves were identified in the Hollinhill Grips or in the north-west end of the Main branch of Markland Grips, as well as 41 possible rock shelters that ranged from 3 to 30 m long, and numerous "fissures", although only two "fissures" were thought to have archaeological potential.

Table 4 Some "Rock Shelters" with some evidence of karst development

Name	Location	East	North	Length (m)	References
Anstone Stones cave 1	Anstone	453590	382980	?	Gibbs (1995a); Yorkshire Subterranean Society (undated)
Anstone Stones cave 2	Anstone	453040	383250	~5?	Gibbs (1995a);
Anstone Stones cave 3	Anstone	453000	383340	~5?	Gibbs (1995a);
Anstone Stones cave 4	Anstone	452910	382440	~7?	Gibbs (1995a);
Whaley Cave	Clowne	451100	372100	?	Gibbs (1995a); DCA Cave Registry (accessed 2023); Radley (1967)
Markland Grips	Clowne	451200	372150	?	Gibbs (1995a); Derbyshire Historic Environment record (accessed 2023)

2.3.3 Slip rift caves

Slip rift caves commonly occur due to the effects of valley cambering, although some mass movement caves are not associated with obvious topographical features and may be related to folding (Murphy and Lowe, 2021). Mass movement caves have been noted in the valleys of the Don at Connisborough, the Went at Wentbridge, and the Nidd at Knaresborough (Gibson et al., 1976; Murphy and Cordingley, 2010). In addition to those in the Connisborough area described in Section 2.3.2.5, some examples of major slip rift caves include: Farnham Cave near Knaresborough (Figure 11), Went Edge Rift and Smeaton Pot in the Went valley (Figure 10), and Pleaseley Valley Railway Cutting Pot near the River Meden (Figure 9). Details of these caves are provided in Table 5. The hydrological function of slip rift caves is not well documented, but they could provide a pathway for recharge where they intersect runoff. Actively flowing water inlets have been reported at a small number of slip rift caves. For example, Lowe (1978) reports an inlet in Farnham cave which has "*substantial*" flow at times. Many of the caves described in Table 5 (and other slip rift caves) are reported to have quite extensive speleothem formations within them indicating the presence of saturated dripwaters. At Farnham Cave and Smeaton Pot tectonic fissures contain some solutional features (Lowe, 1978; Brook et al., 1988).

Farnham cave is an example of a slip rift cave that is parallel to the dip direction and perpendicular to the scarp edge suggesting that it has not formed by classic valley cambering mass movement processes (Lowe, 1978). Lowe (1978) discusses various potential mechanisms that might have led to the formation of the cave and reports that there is is little evidence for vadose or phreatic karstic development and that the cave may be related to synclinal folding. Photographs, surveys and descriptions of flowstone and sediment deposits in Farnham Cave are also provided in Lowe (1978).

Table 5. Examples of some major slip rift caves in the dolomitic limestones of the P2 area

Cave	Location	Length (m)	Depth (m)	References
Farnham Cave	Knaresborough	130	30	Lowe (1978); Gibbs (1995c); Murphy and Cordingley (2010)
Went Edge Rift	Went	29 (213*)	12	Gibson et al. (1976); Gibbs (1995c); Murphy and Cordingley (2010); DCA Cave Registry
Smeaton Pot	Went	300	34	Gibbs (1995c); Murphy and Cordingley (2010); DCA Cave Registry
Pleaseley Valley Railway Cutting Pot	Meden	90	23	Gibson et al. (1976); Gibbs (1995a); MSG (1974;1979); DCA Cave Registry; Barker and Beck (2010)

* Recent information suggests Went Edge Rift is 29 m long cave, but 3 caves were broken into in the quarry in the 1960s with the longest being 213 m (Gibson et al., 1976)

2.3.4 Gypsum caves

Gypsum strata are highly susceptible to dissolution and there are many cavities present in and associated with the gypsum strata within the Zechstein Group (James et al., 1981; Cooper, 1986; 1989,1998, 2002, 2018, 2020). Gypsum karst can occur throughout this geological setting but is of particularly note in the Ripon area (see Figure 8 and Figure 11 for location of Ripon and Section 2.5.1 for further details). Cave development in the gypsum karst is reported to create phreatic cave systems (Farrant and Cooper, 2008). Cooper (2018) suggests that subsidence in the Ripon area is due to the partial collapse of a cave system in the gypsum and suggests that the cave system at Ripon is phreatic and discharges artesian groundwater (Cooper et al., 2013 and Section 2.6.3). Cooper (1986), Brook et al. (1988), and Cooper et al. (2013) describe the Hall Garth Ponds site which is north-west of Nunwick. Here in 1939, a collapse 30 m across was formed in the Brotherton Formation due to the dissolution of the underlying gypsum (Figure 68 and Figure 69). The water in the collapse is 7 m deep and divers reported water flowing out of fissures in the rock below the water surface. This pond contains sulphate-rich groundwater that does not freeze readily and steams in the winter (Cooper et al., 2013). The pattern of dolines/sinkholes that affects the Permian and immediately overlying strata (see section 2.5.1) is interpreted by Cooper (1986 and later papers) to relate to an extensive hypogene/artesian maze cave system comparable to those described in Ukraine (Klimchouk 1992,1996, 2013; Klimchouk and Andrejchouk 2005). The pattern and size of the dolines indicate that significant caves are present beneath the area underlain by the Edlington, Brotherton and Roxby formations, and in places the western part of the overlying Sherwood Sandstone Group. In the P2 area caves are inferred to be very well developed south-east of Bedale beneath Snape Mires, along the Ure Valley through Ripon, and in the Brotherton area; in all these areas the Hartlepool gypsum sequence in the Edlington Formation is the main karstic rock, but the Billingham gypsum in the Roxby Formation also contributes and is karstified, especially from Ripon northwards. In the vicinity of Church Fenton, the Sherburn gypsum in the Roxby Formation is responsible for significant doline formation and is also likely to have karstic cavities formed by artesian water from the Brotherton Formation.

2.3.5 Smaller karst conduits and fissures in the Permian limestones

Data on smaller karstic conduits and solutional fissures are not routinely collected and there is no dataset of such features to enable an assessment of their distribution in the Permian limestones in the P2 area. However, there is evidence that they occur, and it is likely that as in other similar karst aquifers in which there is only limited cave development, groundwater flow is greatly influenced by networks of these smaller scale solutional voids. Indeed, as early as 1914, Lamplugh et al. (1914) suggested that "*joints*" in the limestones "*are frequently enlarged near the surface into fissures and irregular solution cavities*"; and Edwards et al. (1940) note that there are "*gaping joints due to solution by groundwater in the Lower Magnesian Limestone, sometimes to considerable depths, and the usually extremely free circulation of underground water would suggest the presence of a network of such joints*". Crabtree and Trudgill (1984) note that the limestones are highly fissured; and solutional development of fractures, joints and bedding planes in the Permian limestones are also noted by Barclay et al. (1990). More recently, Farrant and Cooper (2008) suggest that numerous solutional joints, conduit systems on bedding planes, palaeokarst, and sediment filled fissures are observed in road cuttings and quarries in the Permian dolomitic limestones.

Karstic enlargement of fractures in the Permian limestones can be associated with faulting which concentrates flow (Allen et al., 1997; Medici et al., 2019a). Aldrick (1978) reported that the Permian limestones are "*extremely fissured and jointed*" in a quarry located on the Bramham fault. Medici et al. (2019a) report that scanline surveys from quarries in the Permian limestones of Yorkshire by Walker (2006) indicated that the development of fissures with apertures of several cm was related to extensional faults.

Scanline surveys of 6 quarries in the area between Leeds and York, which included visual observations of karst features, are reported by Medici et al. (2019b). Figure 8 shows the general location of the Leeds-York area to the south of the River Wharfe, and figures in Medici et al. (2019b) provide the detail of the quarry locations. The surveys were undertaken in five quarries in the Cadeby Formation (Jackdaw, Highmoor, Newthorpe, Wellhouse Farm, and Byram Nurseries quarries) and two in the Brotherton Formation (Byram Nurseries and Dales quarries).

Some voids associated with faulting exhibited evidence of dissolutional enlargement, with apertures of 0.1 to 0.6 m. These voids had a range of shapes from circular to tabular to polygonal (Medici et al., 2019b). Medici et al. (2019b) suggest that some flow in the Permian limestones is in these karstic "*pipe cavities*" which generally follow normal faults, and they used a pipe network of 0.2 m diameter in their groundwater model to represent these karstic features. However, at the Leeds University Farm study site investigated by Medici et al. (2019a), no karstic sized voids were observed in the borehole image logs for the three 30-40 m deep boreholes in the Cadeby Formation.

A small cavity possibly associated with faulting was seen in borehole SE42SE694 [448570,422520] located near the A1/M62 interchange with a cavity from 15.54 to 16.45 m depth. Cavities were also recorded in the Cadeby Formation at a depth between 64.01 and 67.97 m in borehole SE52SW38 [450049, 421616]. In this area, which is near the Darrington stream sinks (Section 2.4.4), two out of 78 boreholes reviewed contained cavities.

Solutional fissures and cavities are reported by Cooper and Burgess (1993) in quarries near Abbey Crags, near Knaresborough (see Section 2.3.2.7 for information on caves here and Figure 11 for the location). Cooper and Burgess (1993) report that dolomitic limestones in the upper part of a quarry located south-east from Abbey Crags at [SE 35700 55741] contain "*many water-worn cavities, joints and small caves*". They also report "*numerous water-worn fissures*" in the dolomite in another quarry at [SE 35730 55721]. Murphy (2023) also reports tube-shaped features too small to enter in the Boston Spa area near the small caves discussed in Section 2.3.2.6.

Gibbs (1995b) notes that the overhang at Norwood (Figure 10) is water-worn and has "*a definite tube-like appearance at its north end*" which suggests that there is some small-scale conduit development. Most of the "solutional fissures" recorded in the Natural Cavities Database (Figure 7) are reported to be from Brook et al. (1988). This is a caving guidebook and therefore the grid references will be for sites where cave sized cavities (karst or slip rift) are present. It is not clear whether "solutional fissure" is a misclassification or whether they reflect sites where small-scale solutional fissures have been observed in the larger cave sized cavities.

2.4 STREAM SINKS

2.4.1 Introduction

There are some records of stream sinks in the P2 area (Figure 27). There are no stream sinks recorded in the Natural Cavities Database but there are 20 records in the BGS Karst Database (green circles with a cross on Figure 27). These are mostly located in the north of the area where some are on the Roxby, Brotherton and Edlington formations to the east and may therefore be associated with gypsum karst, and others are on the Cadeby Formation further west. These records were identified from Ordnance Survey maps and would need to be investigated further to verify that they are karst features because small shallow sinks into superficial deposits and/or field drains can appear similar to karst stream sinks on Ordnance Survey maps. The BGS Karst Database has not been verified or completed in the P2 area and there has been no systematic desk or field survey of karst stream sinks, and therefore there may be more karst stream sinks present. Data on losses as rivers cross the Permian limestone geologies were not collated for this report, so it is uncertain whether these provide an important contribution to recharge into solutional fissures and conduits in the unsaturated zone. A small number of karst stream sinks, including one river site, were identified from literature review undertaken for this report (red circles on Figure 27). The more classical karst stream sinks are sites 1 to 3 on Figure 27 and are discussed in more detail below, broadly from north to south. It is possible that some of the slip rift caves also enable some point recharge. For example, Gibbs (1995b) notes that Ranch Rift Cave [SK 52800 99300] takes water, and Lowe (1978) describes a substantial inlet within Farnham Cave [SE 3533 6029]. These are sites 4 and 5 on Figure 27. Data on recharge via slip rift caves has not been collated for this report.

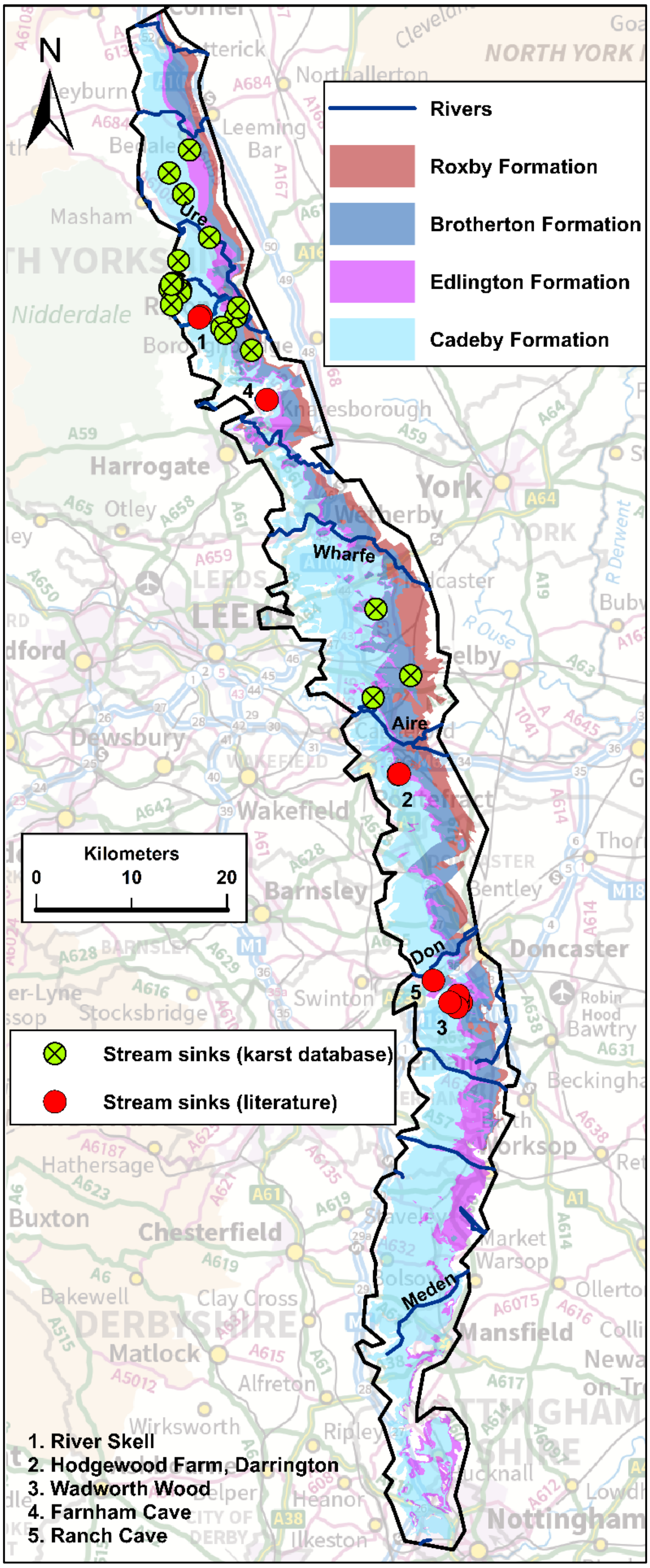

Figure 27. Stream sinks in the P2 area.

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2.4.2 The River Skell

There is a major sink into the Cadeby Formation through the bed of the River Skell south-west of Ripon (Fox-Strangeways, 1908; Lowe, 1978; Murphy, 1999). This is site 1 on Figure 27, and more details are shown on Figure 28. Murphy (1999) reports that the main summer sink is at [SE 284 691]. This is a substantial karst feature (Figure 29, Figure 30), and Murphy (1999) notes that Lowe (1974,1978) suggested that there might be some down dip cave development at this site, and that two short dry caves called Devils Chimney 1 and 2 are described by Brook et al. (1988). These are discussed in Section 2.3.2.8. The river re-emerges through superficial deposits at Hell Wath which is about 2 km from the main upstream sink, and about 40 m lower (Murphy, 1999). It should be noted that Murphy (1999) reports an NGR of [SE 289 699] for the spring, but this point is quite far from the river valley and not at Hell Wath which is located on the River Skell at [SE 29929 69928] and is presumably the actual location of the spring resurgence. Murphy (1999) also reports that there is another downstream sink point under higher water level conditions at approximately [SE 282 689] which is reported by Kendall and Wroot (1924) to only take about half the flow and to be about “*half a mile*” from the point where the river re-emerges. NGR [SE 282 689] is a point quite close to the River Skell, but upstream from the main summer sink point reported by Murphy (1999), and therefore appears to be an incorrect grid reference, as the water will sink further downstream under higher flow conditions. Assuming that the re-emergence point at Hell Wath is the same under high and low water level conditions [SE 29929 69928], then a point on the river about half a mile upstream from here would be [SE 282 689], and this is marked as the approximate high water sink point on Figure 28. Overall, the River Skell represents an important example of karstic development in the Permian limestones with a major river sink and spring resurgence, and a considerable distance of underground flow.

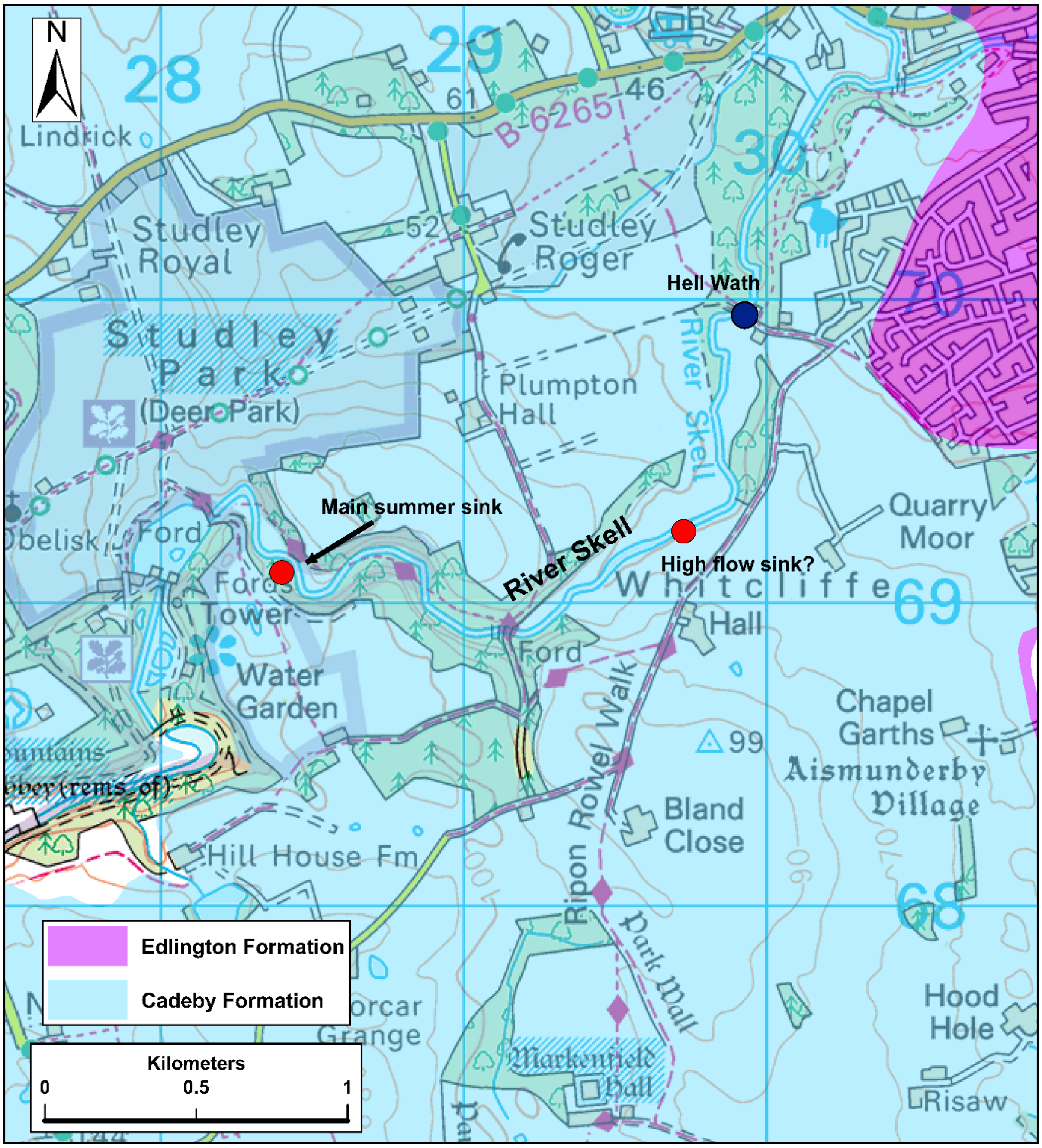

Figure 28. Karst on the Cadeby Formation along the River Skell which is reported to be dry from the Main Sink to Hell Wath under “normal” summer conditions.

Figure 29. Large karst sink into the Cadeby Formation on the River Skell near Ripon. Photo by Phil Murphy.

Figure 30. The River Skell “swallowhole”. Photo by G. Bingley, January 1899.

BGS photo archive P236561

2.4.3 The River Ure

Fox-Strangeways et al. (1886) suggested that there is a situation similar to that on the River Skell on the River Ure (which is to the north of the River Skell, see Figure 27). They noted that between North Stainley and Ripon "*much of the river water flowed underground for a considerable distance*". It appears that much of the course of the River Ure between North Stainley and Ripon is on the Edlington Formation (Figure 31) which might suggest that any river losses to karst could be associated with gypsum karst or with limestone karst in the underlying Cadeby Formation. There is a stream sink recorded in the BGS Karst Database near the junction of the Edlington and Cadeby formations [SE 29288 77330] which might possibly indicate some losses to the Cadeby Formation. Consideration of the old Ordnance Survey maps and LiDAR (National Library of Scotland, 2023), suggest that the stream sink in the BGS Karst Database is located on a small watercourse about 40 m from the channel of the River Ure although there is no obvious karst stream sink apparent at this point on LiDAR. This suggests that if there are sink points on the River Ure, as indicated by Fox-Strangeways et al. (1886) the stream sink recorded in the BGS Karst Database is not likely to be one of them. Recent work by Schwendel and Cooper (2021) has shown that there is strong dissolution at rockhead through or over the Edlington Formation gypsum in the Ure valley north of Ripon. There are also sinkholes related to artesian water coming up through the gypsum from the underlying Cadeby Formation. This dissolution resulted in the propagation of numerous sinkholes in the flood plain of the River Ure and has helped to control the river meander break-through.

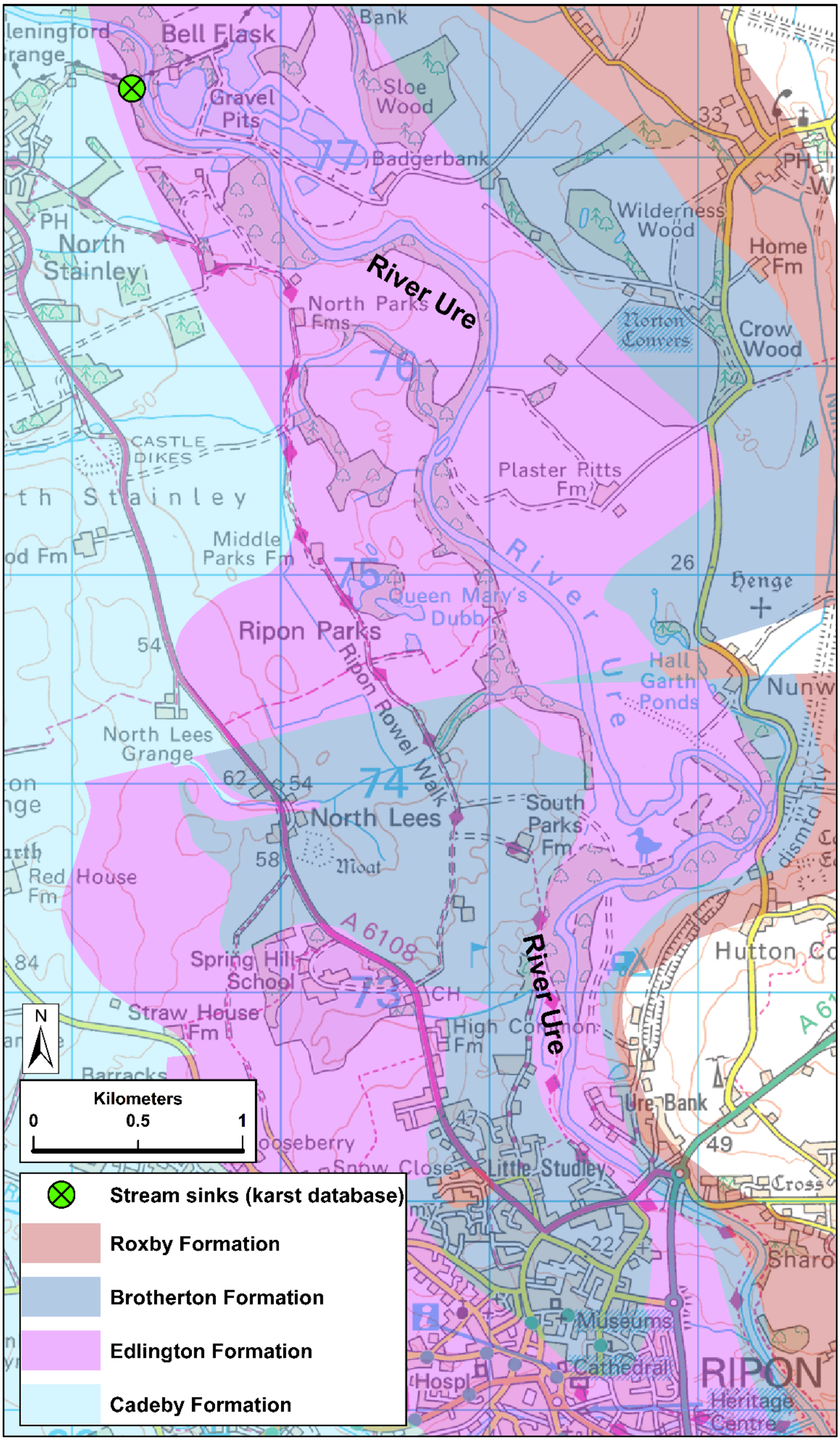

Figure 31. The River Ure between North Stainley and Ripon.

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2.4.4 Darrington

Two stream sinks in the Permian Zechstein Group near Hodgewood Farm, Darrington are discussed by Murphy (2000). These are site 2 on Figure 27, and the area is shown in detail in Figure 32. The westerly stream sink is the doline at [SE 4910 2094] reported by Ellison (1989), and discussed in Section 2.5.2. Murphy (2000) suggests that this karst stream sink is a result of limestone rather than gypsum dissolution as the water sinks into the Cadeby Formation. Murphy (2000) describes a nearby second stream sink on the Darrington golf course on the Edlington Formation where water originally sank into a doline which has been filled in. The most likely site for this is labelled as "*Supposed swallow hole*" on the 1936 geological standard for the area at location [SE 49216 20987]. This grid reference is used in the map figures in this report. Other dolines are reported in the area of the golf course (Murphy, 2000). Figure 32 shows that the golf course is located at the boundary between the Edlington Formation and the underlying Cadeby Formation, which suggests that the stream sink is likely to be draining into solutional fissures/conduits in the limestones of the Cadeby Formation, rather than being associated with gypsum karst in the Edlington Formation. Murphy (2000) notes that this was also suggested by Ellison (1989). There are records of two springs to the north of, and uphill of the stream sinks, and it is possible that the stream sinks are fed by runoff from these springs flowing over the lower permeability mudstones of the Edlington Formation before sinking into the limestones of the Cadeby Formation. The groundwater outlets for these stream sinks are unknown and no information on the groundwater flow directions in this area was identified for this report. Springs recorded in the wider area are shown on Figure 33. Cadmaer spring on the Cadeby Formation, which is known to be a substantial spring (Section 2.6.2) is approximately 8 km north-west of the Darrington stream sinks. There are a number of other springs recorded in the area that are discussed further in Section 2.6. (records shown on Figure 64 are simplified and combined here on Figure 33 to show all spring records from different sources as blue triangles, with only the sulphate-rich springs from Cooper et al. (2013) shown separately). Further work is required to determine the likely outlets for the stream sinks near Hodgewood Farm, Darrington.

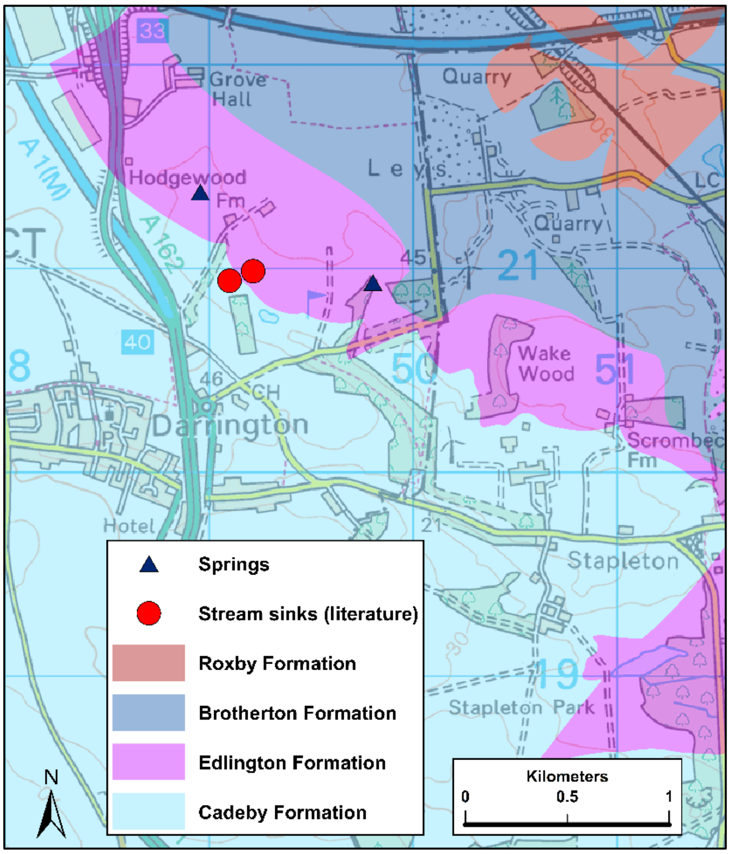

Figure 32. Stream sinks at Hodgewood Farm near Darrington.

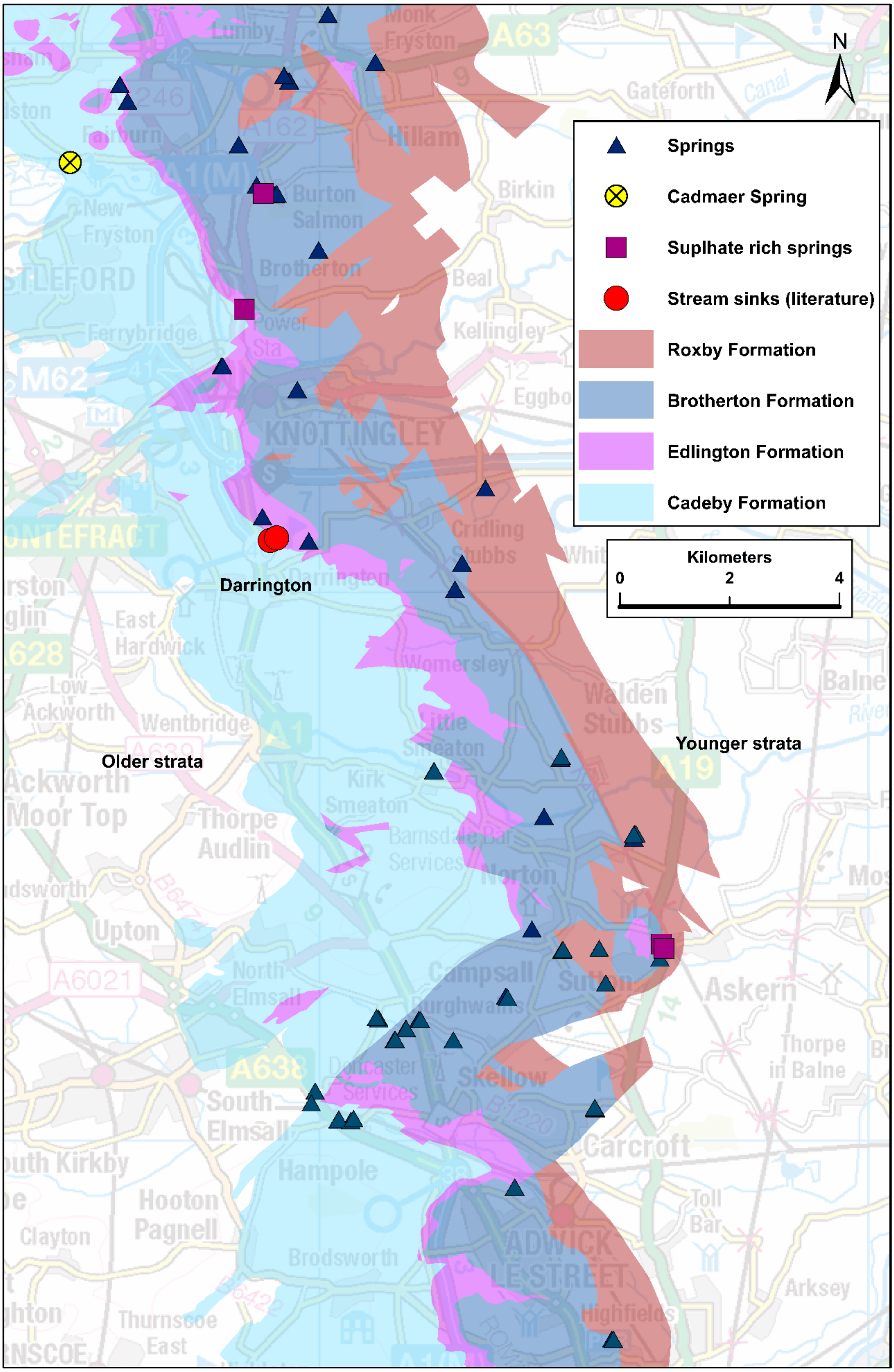

Figure 33. The wider area around Darrington stream sinks.

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2.4.5 Wadworth Wood, near Doncaster

There are karst stream sinks at Wadworth Wood near Doncaster (site 3 on Figure 27). Descriptions and photos of seven stream sinks at Wadworth Wood are reported by Higgins (2018), and the locations of six of them for which Higgins (2018) provided grid references are shown on Figure 34, where the numbers refer to the stream sink numbers of Higgins (2018). Figure 34 shows that the stream sinks are located on the Edlington Formation, and it is unclear whether gypsum karst within the Edlington Formation may have played a role in their formation. However, most of them are very close to the boundary with the Cadeby Formation and therefore it seems likely that they formed due to runoff over the lower permeability mudstones of the Edlington Formation sinking into the Cadeby Formation limestones, and that they are an example of Permian limestone karst. Flows have not been measured at these stream sinks, but the descriptions and photographs in Higgins (2018) suggest that they are substantial features and form an important component of recharge in this area. The sinks were visited by Higgins on 1st March 2017 and there had been "*fairly heavy rainfall*" two days before (Higgins, 2018). At Wadworth Wood Sink 1 [SK 55739 96974], Higgins (2018) reports that "*water can be heard falling underground*" and notes that the channel feeding the sink is quite deep (Figure 35). At Wadworth Wood Sink 2 [SK 55412 96882] water was sinking "*into a small hole*" (Figure 36), and other holes and a collapse doline (Figure 37) are described by Higgins (2018) around this locality. Water sinks into a circular depression at Wadworth Wood sink 3 [SK 55245 97015] as shown in Figure 38. At Wadworth Wood sink 4 (Figure 39, no grid reference), there was water in a steep sided channel that sank and could be heard flowing underground (Higgins, 2018).

Wadworth Wood sink 5 in Higgins (2018) is on the north side of the M18 and is fed by a large pipe draining the motorway (Figure 40). This site is described by Smith (1971) as a "*swallet*" at NGR [SK 553 974]. Smith (1971) reports that this swallet has been artificially enlarged to be about 25-30 m across and about 9 m deep at its deepest point, with karst features apparent on the motorway side that resemble the fossil karst features exposed in the motorway cutting (Section 2.5.2). Smith (1971) notes that the feature takes water from the motorway drains "*from a considerable distance*" and that the water does not appear to back up suggesting that this stream sink could take large volumes of flow. Higgins (2018) reports that there was some pooling of water during the visit to the site in 2017 and suggests that there may be sediment blockages in the subsurface conduit system that were not present previously. Smith (1971) suggests that there are karst features aligned parallel to the motorway and reports another artificially enlarged swallet "*where a minor road enters the south-west corner of Edlington Wood*", and notes that there are several other small depressions in this area. No grid reference is provided but these may be near [SK 54542 96989], and this is included on Figure 34 with the label "Smith, 1971". Smith (1971) also notes that there are large limestone blocks in the northern part of the woods which resemble the karst clints seen in the Yorkshire Carboniferous aged limestones and provide additional evidence of limestone dissolution.

Wadworth Wood sink 6 [SK 55396 97737] is a site where a channel ends in a hollow which Higgins (2018) reported was dry at the time of the 2017 visit (Figure 41). Wadworth Wood sink 7 is the "Whirly Pit" marked on Ordnance survey maps [SK 55279 96482] and was flowing during the 2017 visit (Figure 42). There appears to be a large quarry about 100 m from the Whirly Pit, which may have impacted natural groundwater flows in the area. This is apparent on maps on the Grid Reference Finder website (https://gridreferencefinder.com/) and also on LiDAR from the National Library of Scotland (2023), see Figure 43.

There has been no tracer testing from the stream sinks in the Wadworth/Edlington Wood area and the outlets for these stream sinks are unknown. Smith (1971) postulated that the water from the large motorway sink [SK 553 974] might discharge at the Edlington Colliery [SK 54398 99046] where there are inflows. This is approximately 1.5 to 2.5 km north-north-west of the stream sinks (Figure 44). No information on the groundwater flow directions in this area was identified for this report. There are records for a number of springs in the wider area (Figure 44) which are described in Section 2.6. Most of these springs are of unknown or small discharge and most of those discussed in Section 2.6 are amalgamated together as blue triangles on Figure 44. However, there are a small number of springs which had measured flows of > 0.1 l/s in the 1977 survey reported by Cradock-Hartop and Steel (1979) which are included separately on Figure 44. Of particular note are a spring 2 to 3 km to the north-north-east of the stream sinks (St Catherine's

Well, the large blue square on Figure 44) which had a flow of > 5 l/s, and a spring approximately 3 to 4 km to the south which had a flow of 1 to 5 l/s (Cradock-Hartop and Steel, 1979). St Catherine’s Well [SK 56482 99369] was visited by Mike Higgins on 21/10/2016 when it “*was flowing quite strongly*” and had a temperature of 10.5°C (air temperature 8.7°C), a pH of 7.26 and an electrical conductivity of 1243 µS/cm; (Mike Higgins, personal communication, 2024). There is a line of depressions on LiDAR running north of the M18 from the Wadworth Woods stream sinks towards St Catherines Well which might indicate that this is the outlet for the stream sinks (Mike Higgins, personal communication, 2024). Mike Higgins also recorded an electrical conductivity of 964 µS/cm at Gospel Well [SK 56597 97379] on 07/10/2021.

Further work is needed to identify whether there are or were larger springs present in the area that might be potential groundwater outlets for the Wadworth Wood stream sinks, as well as to determine whether there are any pumped outlets that could be connected to them.

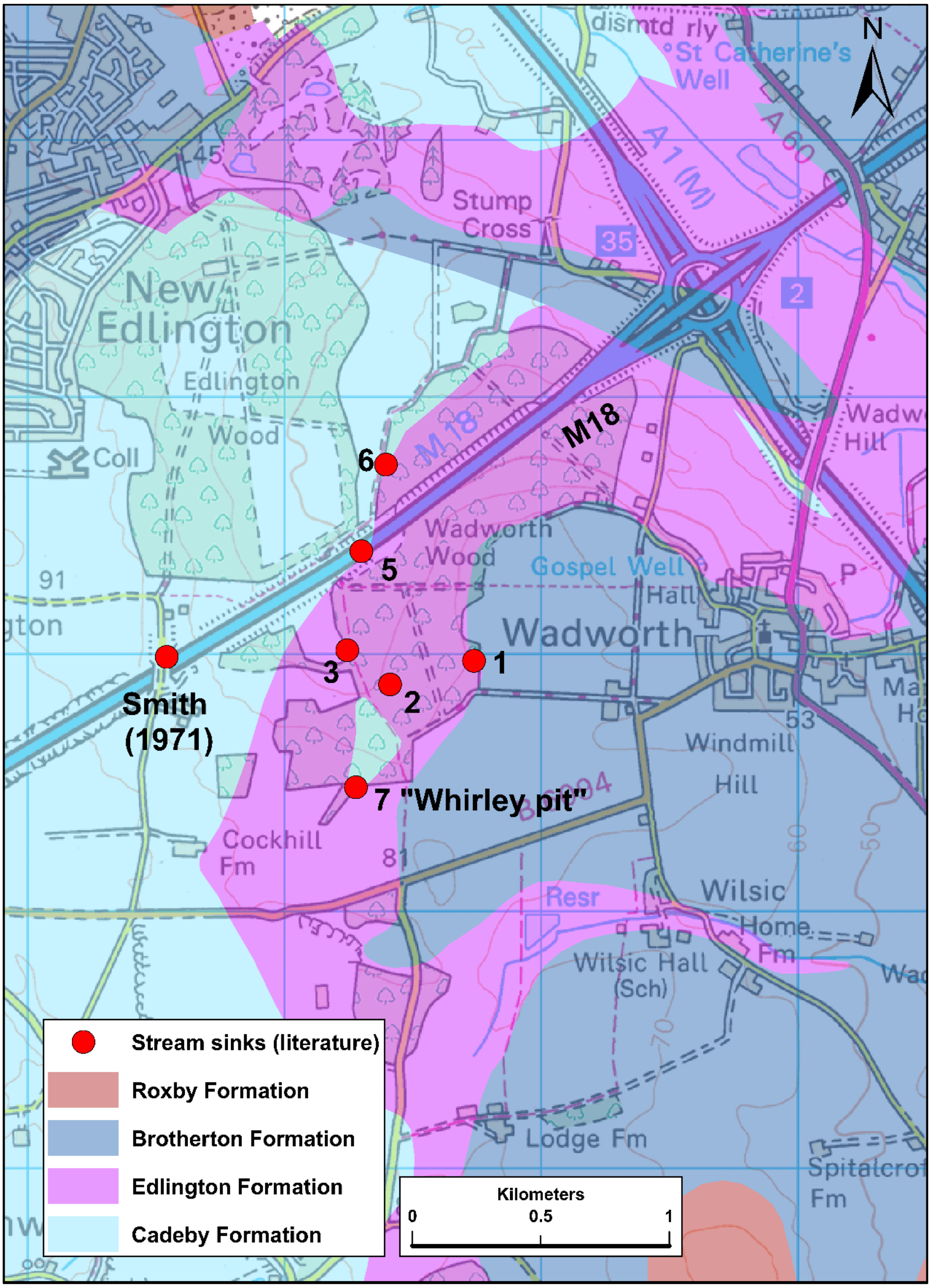

Figure 34. Stream sinks at Wadworth Wood. Numbers refer to sites from Higgins (2018).

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Figure 35. Wadworth Wood Sink 1 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 36. Wadworth Wood Sink 2 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 37. Depression near Wadworth Wood Sink 2 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 38. Wadworth Wood Sink 3 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 39. Wadworth Wood Sink 4 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 40. Motorway drainage pipe feeding Wadworth Wood Sink 5 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 41. Wadworth Wood sink 6 (from Higgins, 2018). Photo courtesy of Mike Higgins.

Figure 42. Wadworth Wood sink 7 – “The Whirly Pit” (from Higgins, 2018). Photo courtesy of Mike Higgins.

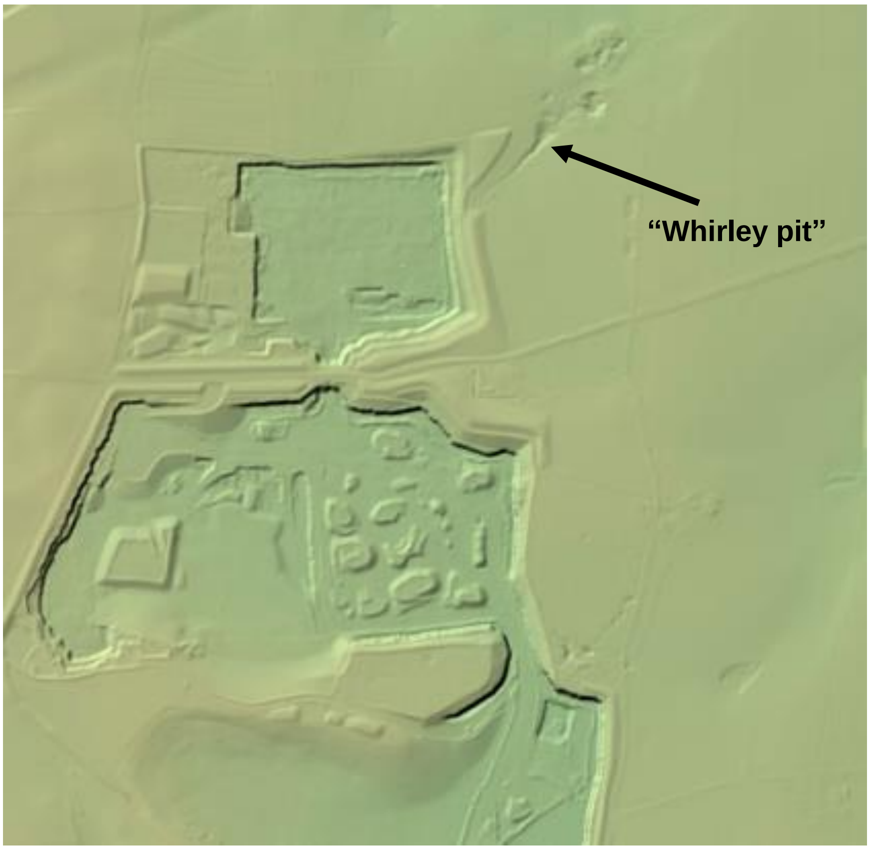

Figure 43. LiDAR data from National Library of Scotland (2023) showing quarry adjacent to “Whirley Pit” stream sink.

https://maps.nls.uk/geo/explore/side-by-side/#zoom=14.0&lat=51.75036&lon=-0.28192&layers=10&right=LIDAR_DTM_2m

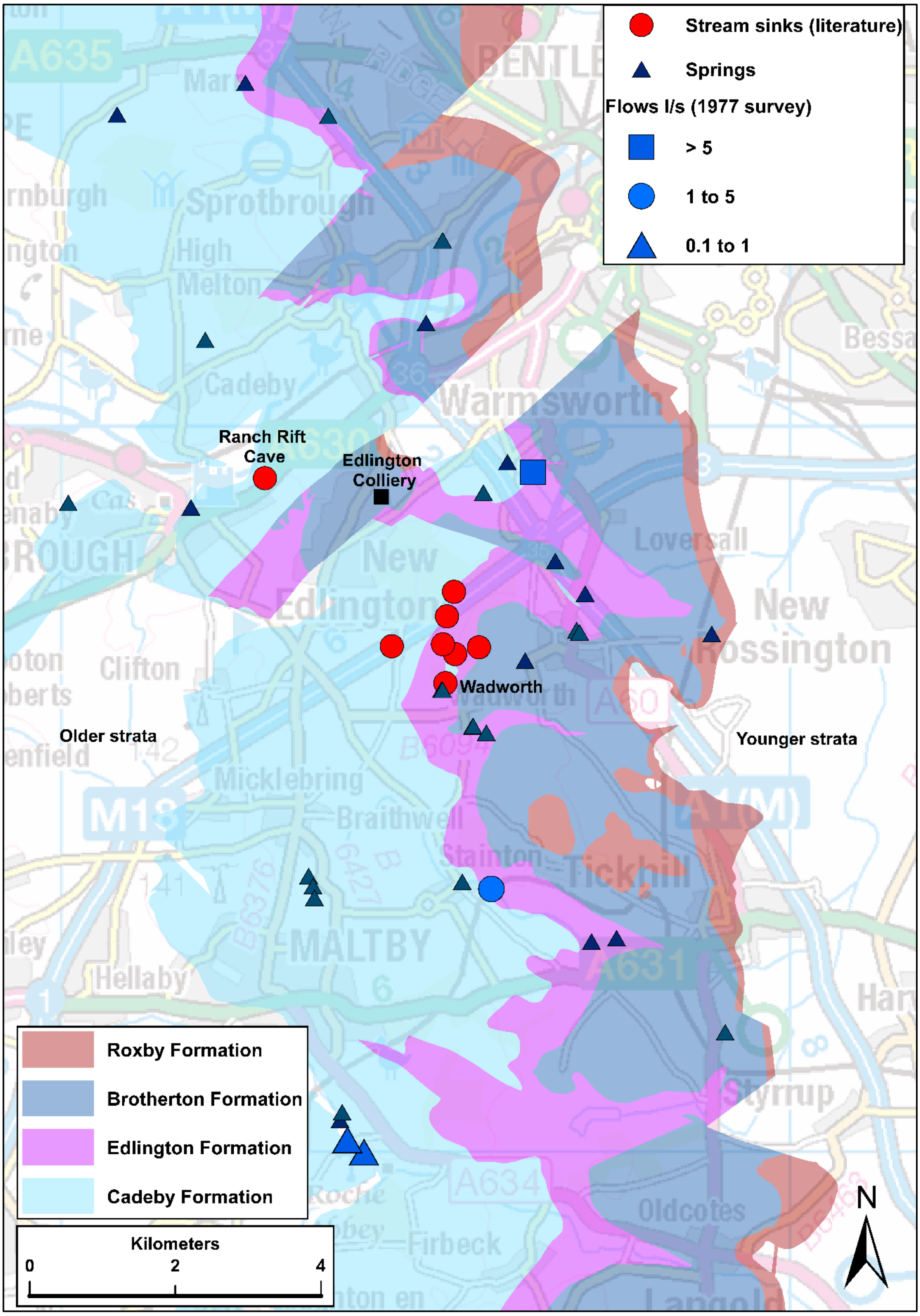

Figure 44. The wider area around Wadworth Wood stream sinks.

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2.5 DOLINES AND DISSOLUTION PIPES

There is little information on dolines or dissolution pipes in the limestones of the P2 area. The BGS Karst Database has not been completed in this area. There are 13 “sinkholes”, 315 “sinkhole/solution pipe” and one “solution pipe” recorded in the Natural Cavities Database (Figure 45). This is a legacy dataset held by the BGS 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). The majority of these features are on or near the Edlington Formation or the Roxby Formation (Figure 45) and are therefore likely to be within or associated with gypsum karst, and most were collated from BGS standards and the work of Cooper (1986). The gypsum karst of the Zechstein Group is well documented (Cameron, 1879; Smith, 1972; Cooper, 1986, 1989, 1998, 2020; Waltham et al., 1997; Farrant and Cooper, 2008; Cooper et al., 2013). Surface karst in the gypsum and the interaction with the adjacent limestone formations is discussed in Section 2.5.1. A small number of karst features which are likely to be predominantly limestone karst were identified from a review of the literature (Figure 45), and dolines and dissolution pipes in the limestones are discussed in Section 2.5.2.

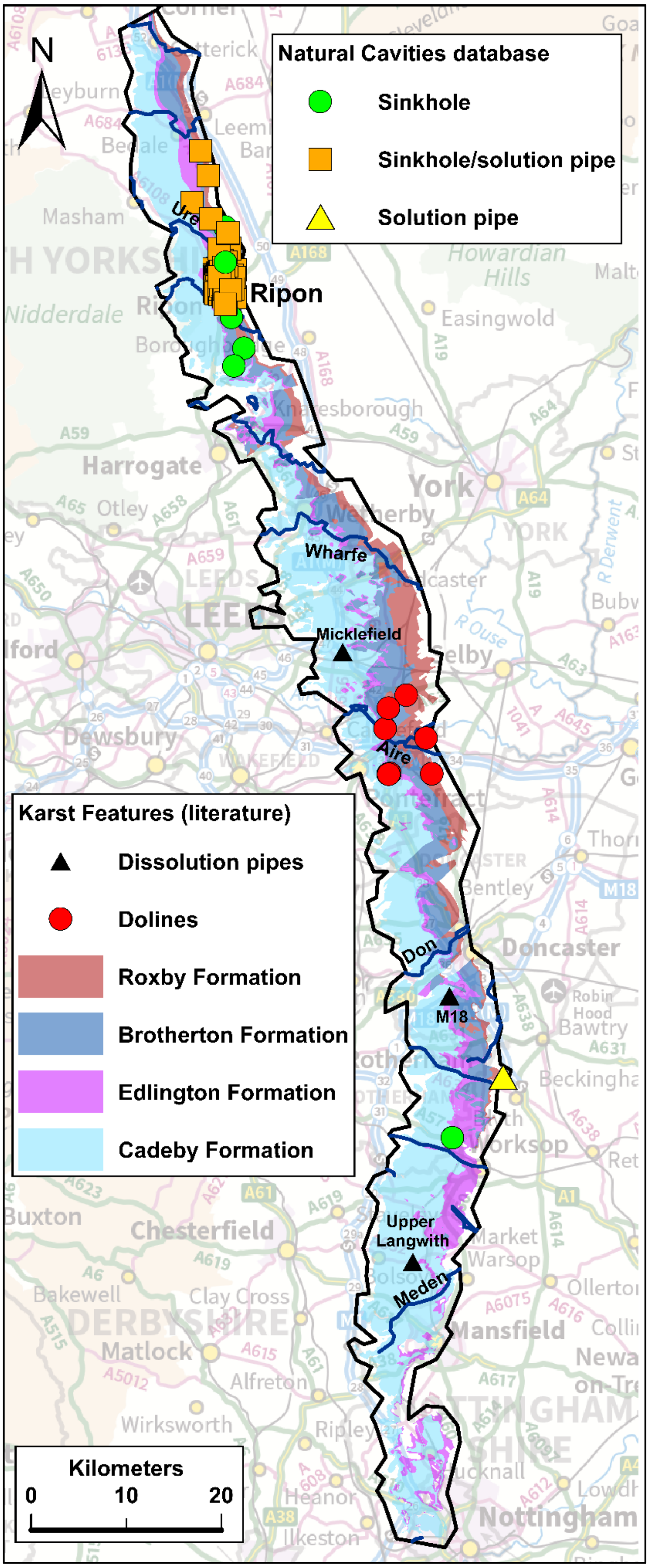

Figure 45. Surface depressions and dissolution pipes.

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2.5.1 Evaporite karst dolines and dissolution pipes

2.5.1.1 INTRODUCTION

The evaporite karst features recorded in the Natural Cavities Database (Figure 45) were digitised from the work of Cooper (1986) and are associated with gypsum dissolution. Gypsum and anhydrite occur within the Edlington and Roxby formations which outcrop along the eastern side of the P2 area (Figure 45). The gypsum units are equivalent to the anhydrite units at depth and occur at or near outcrop (at depths generally less than about 120 m). The Hartlepool Gypsum is in the Edlington Formation, and the Billingham and Sherburn gypsums are in the Roxby Formation. The Hartlepool and Billingham gypsum units are best developed and thickest in the north of the P2 area, whilst the Sherburn Gypsum is only thick in the south. Karst features are developed within these formations, but also within the Brotherton Formation limestones which can collapse into gypsum cavities in the underlying Edlington Formation (Cooper, 1986, 1998). A map in Cooper et al. (2013) shows that there is little gypsum present to the south of Doncaster, and therefore evaporite karst in the P2 area is likely to be concentrated to the north of Doncaster.

Collapse dolines in the Permian gypsum karst are extremely common, and the high rates of dissolution in the gypsum mean that the karst evolves on human timescales (Farrant and Cooper, 2008). 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, as well as the impact and role of the adjacent Brotherton Formation dolomitic limestones are outlined in Farrant and Cooper (2008), who suggest 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. Particularly high subsidence risk from the Permian gypsum karst occurs in the Ripon, Brotherton and Tadcaster/Church Fenton areas (Farrant and Cooper, 2008). Cooper et al. (2013) show that there is a close relationship between the locations of sulphate-rich springs and dolines.

In addition to dolines, there are also dissolution pipes associated with the gypsum karst, which have little surface expression. Large pipes filled with breccia are observed in the beds overlying gypsum (Smith, 1972; Cooper, 1986, 1988; Waltham et al., 1997; Allen et al., 1997). These karstic dissolution pipes contain stratigraphically younger material and can be developed in the limestones of the Brotherton Formation. The dissolution pipes are locally hydrogeologically significant because they can connect the overlying superficial deposits to the Permian limestone aquifer (Allen et al., 1997).

Locations of surface karst features in the evaporite karst were not collated for this report, and there are likely to be many more dolines and dissolution pipes associated with the evaporite deposits than shown on Figure 45. An indication of how many can occur locally is given in Figure 46, but this is the worst-affected area.

Further details of gypsum karst features in the Ripon, Sherburn in Elmet/Brotherton and Church Fenton areas are provided below.

2.5.1.2 DOLINES AND DISSOLUTION PIPES IN THE RIPON AREA

Gypsum karst is particularly prevalent in the Ripon area (Figure 45, Figure 46). There is early documentation of this karst with “natural pits” near Ripon described by Tute (1868, 1870) and later by Cameron (1879) who describes a significant conical surface depression formed by subsurface collapse that occurred in 1877. Similar smaller depressions are described within close proximity to these pits, which have been noted to “*swallow water and sediment fill material*”. The subsidence rate for one of these holes was observed as “*four or five inches in a year*” (Cameron, 1879).

In more recent times substantial work has been conducted to investigate and document the gypsum karst in the Ripon area (Cooper, 1986;1989,1998; 2002; 2018, 2020). The ”sinkholes” recorded in the Natural Cavities Database are karstic dolines that are reported by Cooper (1986; 1989) and the most recent iteration is shown in Figure 46. Figure 47 is an aerial photograph image that shows some of the depressions described by Cooper (1989) at Hutton Conyers, which is in the north-east corner of Figure 46. This area is underlain by sandstone of the Triassic Sherwood Sandstone Group, and the dolines have penetrated the Edlington, Brotherton and Roxby formations and the lower part of the Sherwood Sandstone Group, a thickness of strata in excess of 60 m. Figure 48 is an example of a feature that has penetrated the Sherwood Sandstone Group. Some of the dolines around Hutton Conyers and Ripon are up to ~ 20 m deep. Their mode of formation is discussed in Cooper (1986, 1989, 1998, and 2020). These depressions vary in shape (conical or steep-sided) depending on the presence or lack of unconsolidated superficial deposits (Cooper, 1986). Both the orientation and the distribution of dolines near Ripon have been shown to correlate with joint orientation in the Zechstein Group rocks (Cooper, 1986). It has also been suggested that these features are associated with wet areas and their subsidence associated with wet seasons (Cameron, 1879; Cooper, 1989). Detailed descriptions and photographs of several of these features are given in Cooper (1986, 1989). Cooper (1998) provides an extensive overview of the subsidence features in the Ripon area and illustrates the changes in how the karst manifests itself across the area and is affected by the incised valley of the River Ure (Figure 49). In the west, the Hartlepool Gypsum of the Edlington Formation is present beneath superficial cover with boreholes and geophysics suggesting that the gypsum has a pinnacle surface and cavities (Figure 50). Towards the middle of the subsidence belt, the Brotherton Formation occurs at rockhead and dissolution in the Hartlepool Gypsum in the Edlington Formation affects the full sequence above the Cadeby Formation (Figure 51). In the east of the subsidence area both the Hartlepool gypsum and the higher Billingham gypsum (in the Roxby Formation) dissolve to produce very large dolines/sinkholes (Figure 52). Examples of dolines in the Ripon area are shown in Figure 53, Figure 54, and Figure 55.

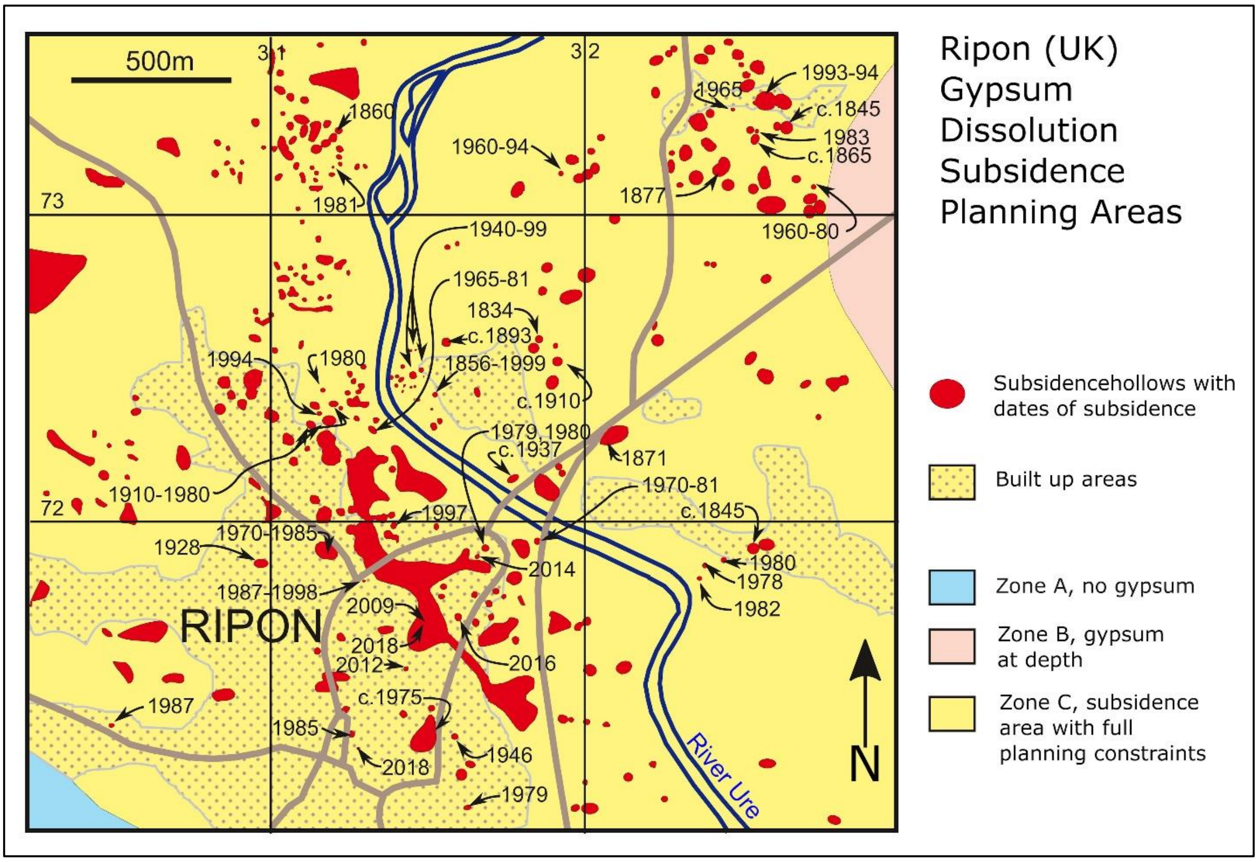

Figure 46. The distribution of dolines (subsidence hollows) in red at Ripon with known dates of collapse (from Cooper 2020). The planning zones are shown – yellow area includes Edlington, Brotherton and Roxby formations, and part of the Sherwood Sandstone Group in the east.

Figure 47. Aerial Photograph of surface depressions around [SE 32421 73149] as shown in Cooper (1989) affecting an area of glacial till over Sherwood Sandstone Group near Hutton Conyers (https://goo.gl/maps/fY4ZDjM4kny)

Figure 48. Doline (sinkhole) that penetrated upwards through the Triassic Sherwood Sandstone Group strata near Ripon Railway Station. The collapse occurred in 1834 and was about 14 m across and 15 m deep (Cooper 1986, 1989). Photo A. H. Cooper.

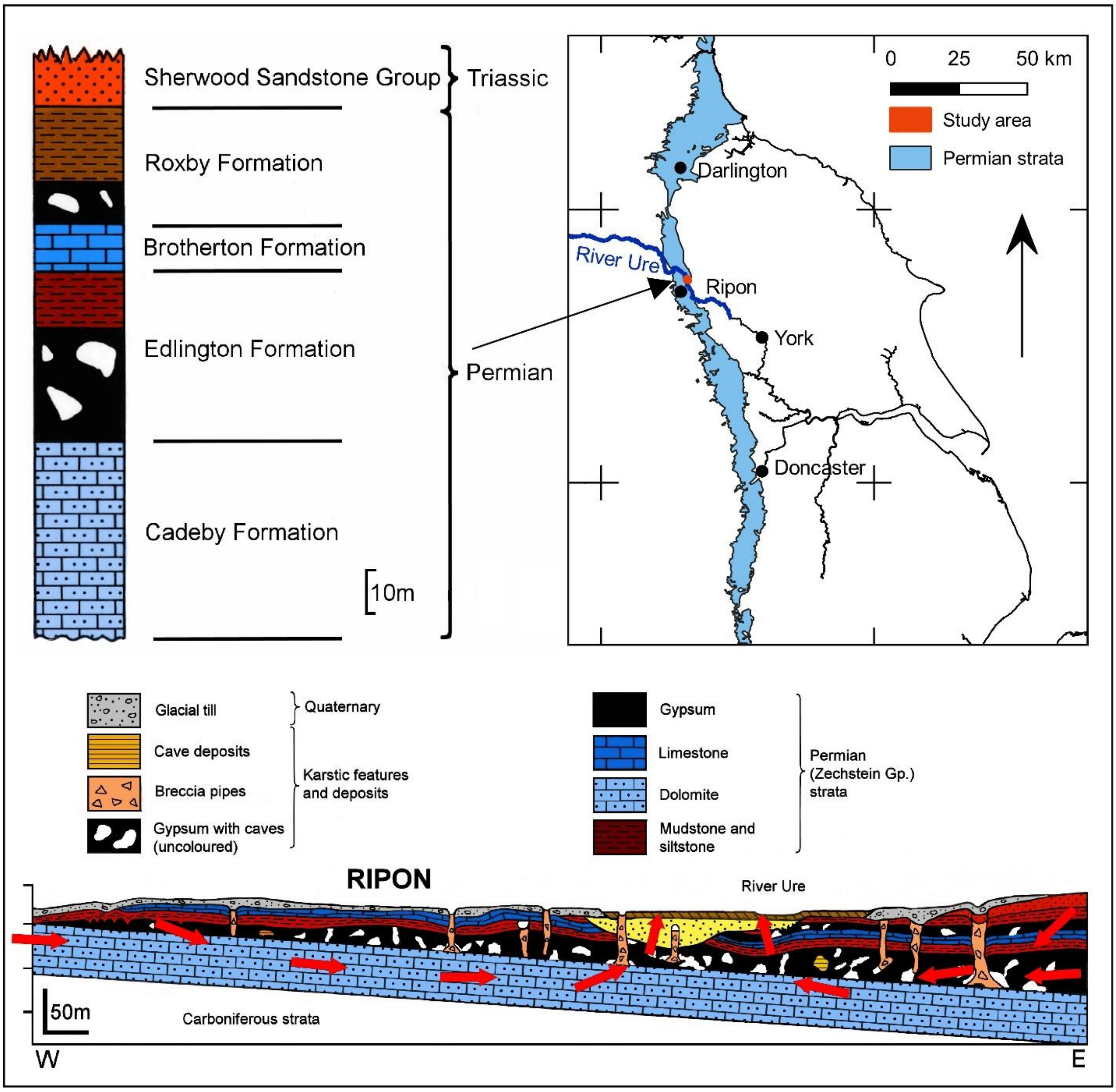

Figure 49. The general sequence and disposition of the Permian strata at Ripon, broadly applicable to most of the outcrop - After Cooper (1998).

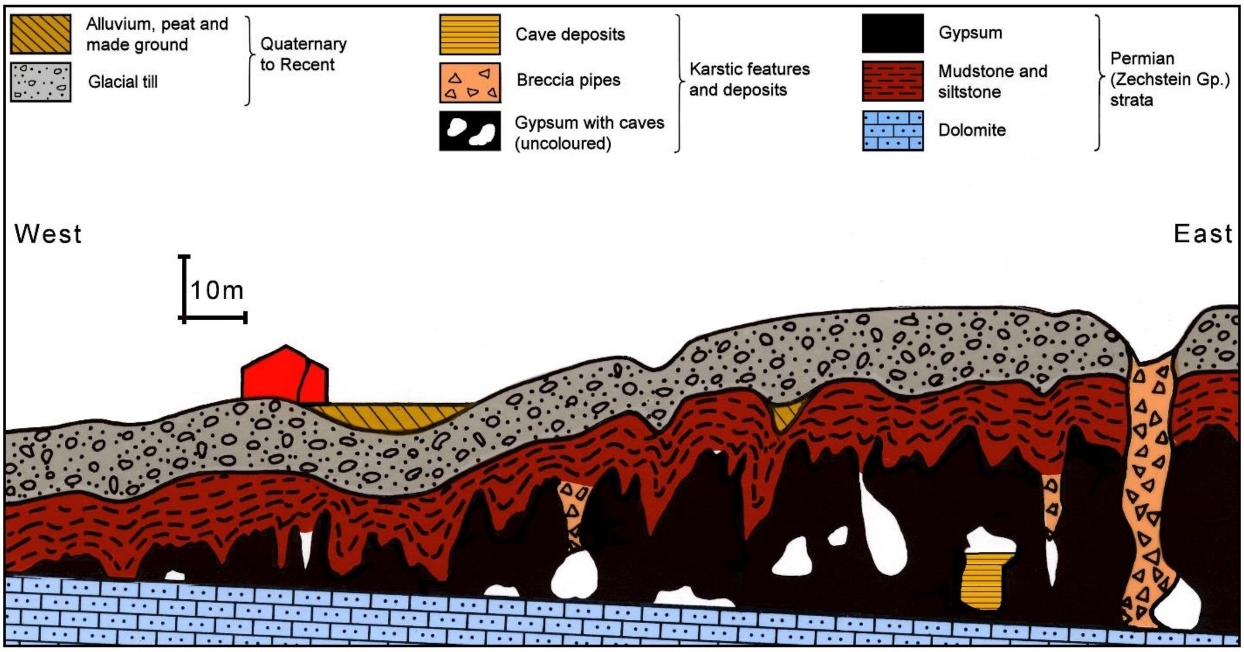

Figure 50. The inferred nature of the gypsum karst towards the west of the sequence - after Cooper (1998).

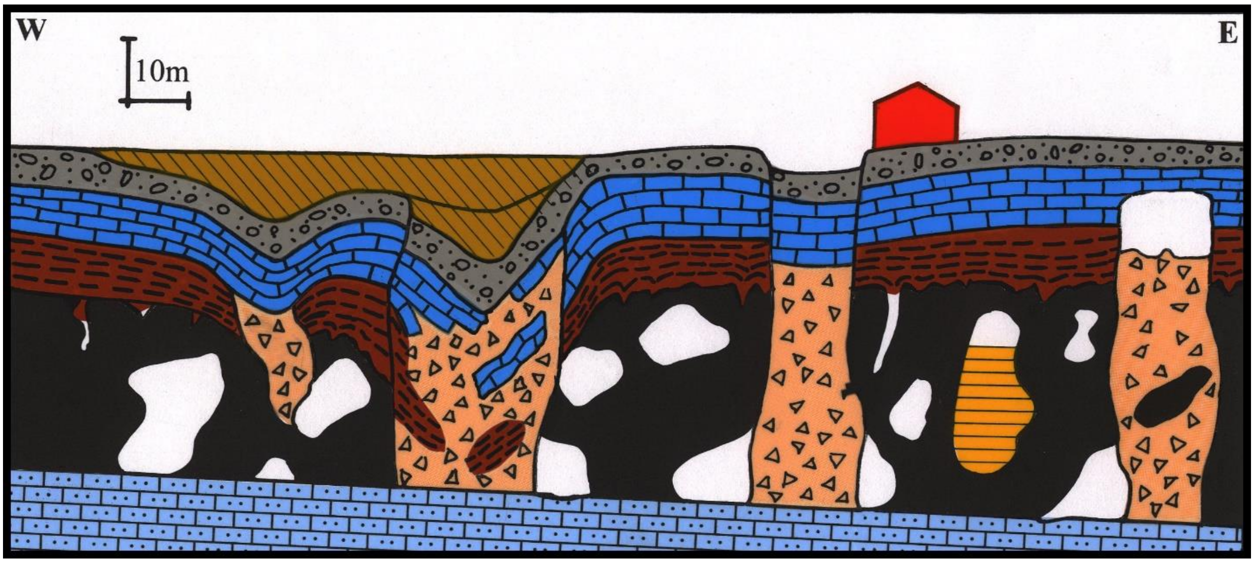

Figure 51. The inferred nature of the gypsum karst in the middle of the subsidence belt where the Brotherton Formation is at rockhead - after Cooper (1998) see Figure 50 for legend.

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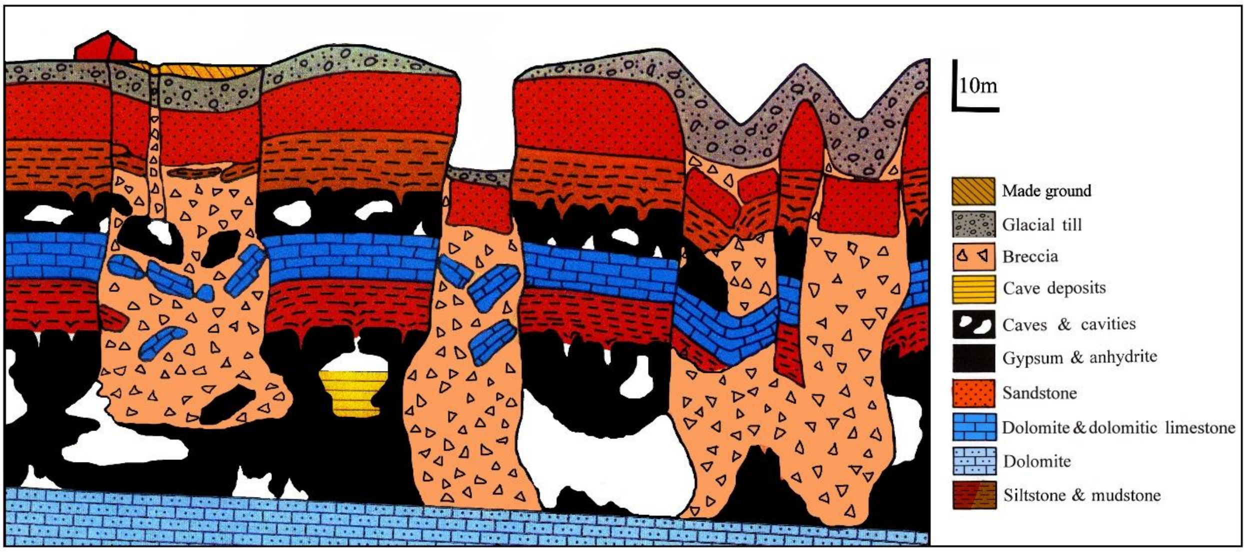

Figure 52. The inferred nature of the gypsum karst in the east of the subsidence belt where the Sherwood Sandstone Group is at rockhead - after Cooper (1998).

Figure 53. A well-developed doline underlain by glacial till and the Brotherton Formation at Ripon Golf Course - a natural bunker. Photo A. H. Cooper.

Figure 54. A sinkhole that occurred near Sharow on February 1st 1982 affecting alluvial deposits (SE 3238 7182). Photo A. H. Cooper.

Figure 55. Sinkhole that formed in 1997 on Ure Bank, Ripon, destroying four garages and damaging the adjacent house. (Photo P. Tod © UKRI/BGS).

2.5.1.3 DISSOLUTION PIPES IN THE SHERBURN IN ELMET AND BROTHERTON AREAS

The former Copley Lane Quarry that exploited limestone in the Brotherton Formation to the north of Sherburn in Elmet [SE 4839 3480] exposed several examples of breccia pipes penetrating the limestone. These displayed brecciated red mudstones that had collapsed down the pipes due to dissolution of the gypsum in the Edlington Formation below. The collapses are obviously vertical pipes (Figure 56), but have an illusionary appearance of not reaching the surface (Figure 57 and Figure 58). This is due to the fact that the quarry face is not vertical, and it cuts obliquely through the cylindrical breccia pipe. In the past the fact that the mudstone breccia does not appear to reach the surface led to the "red horses" theory that the breccia was pushed up from below - Red horses was the quarryman's name for these areas. Phillips (1828) described and illustrated (Figure 59) them:

"The limestone quarries of Knottingley and Brotherton exhibit another phaenomenon, of great interest to the geologist, and well known to the workmen from the loss and disappointment which it occasions: —I mean those masses of red and white clay called "horses", which range through the quarries, some twenty, and some a hundred yards in length, and from a few feet to many yards in breadth. On first viewing these "red horses," we are apt to imagine that they fill wide fissures in the rock, produced by ordinary dislocations, which uplift the strata on one side above those on the other: but this is not the case. They are indeed uniformly situated at the convergence of opposite declinations: but these are sometimes unaccompanied by any fracture in the upper beds; and the open space below, instead of being an ordinary fissure with parallel sides, widens greatly downwards like a wedge. In consequence of this peculiarity, the red horses do not always reach the surface of the limestone; and the workmen, after removing the upper beds of that rock, find with extreme vexation that they cover a subterranean mass of red clay. By tracing the course of one of these wedge-shaped dykes, we perceive that for some distance the limestone walls of the fissure are separate, and the red clay reaches to the diluvial covering; but further on, the limestone walls approximate, and finally unite above and exclude the clay from the surface. (See Plate II.) The red and white clay in the deepest parts of a "horse" contains not a single pebble such as lie in the diluvium, but abounds in fragments seemingly very little worn, of the lower shelly bed of the limestone. At the surface, indeed, where the red clay and diluvium come in contact, the pebbles of the latter deposit are more or less mixed with the former; but still the appearances are such that no person can doubt the conclusion, that the diluvium was laid on the surface long after the red clay had been introduced into the chasm of the limestone.

Observing that the spaces which are filled by these red horses are not necessarily connected with the surface, but are often subterranean, and descend quite to the base of the limestone, while the long straight joints which were open to the surface are filled by other materials, I am induced to believe that the red clay was forced into its present situation from beneath. In appearance it is very similar to the stratum which lies beneath the limestone: from all that can be observed, it is probably connected with it; and it is remarkable that the angular fragments which it contains belong chiefly to the lower shelly bed of the rock. In what manner such an upward flow of the red clay could be occasioned, is not easy to conjecture; nor will my silence on this subject be condemned by those who have learned from experience what difficulties at tend the theory of ordinary dykes and mineral veins".

The injection from below theory was also carried on by Edwards et al. (1940) in their Leeds memoir. A consideration of the geometry, however, shows this interpretation to be wrong. Of note is that the Roxby Formation that has collapsed down the breccia pipes no longer exists at the surface, where a thin impersistent layer of glacial till is present. This suggests that in this particular area the karst development predates the last (and possibly earlier) ice-ages. Further east, however, there is active dissolution and subsidence. The fact that the Roxby and Edlington formations are lithologically very similar helps to explain why Phillips (1828) thought the material had been pushed up from below, he was perhaps not familiar with the poorly exposed Roxby Formation.

Figure 56. Breccia pipe of red mudstone in the limestone of the Brotherton Formation. Copley Lane Quarry, Sherburn in Elmet. Photo courtesy of Dr D. B. Smith.

Figure 57. Breccia pipe of red mudstone in the limestone of the Brotherton Formation. Copley Lane Quarry, Sherburn in Elmet. Photo A. H. Cooper.

Figure 58. Breccia pipes of red mudstone in the limestone of the Brotherton Formation. Copley Lane Quarry, Sherburn in Elmet. Photo A. H. Cooper.

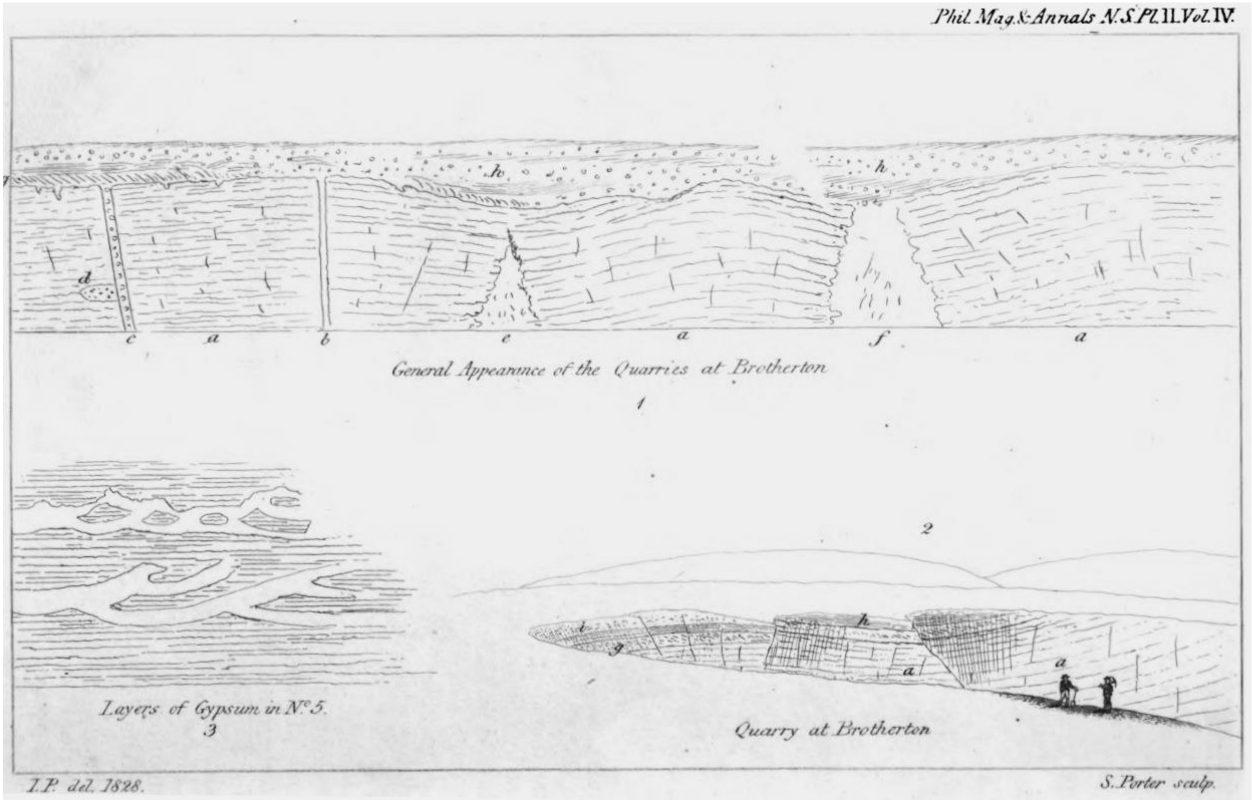

Figure 59. Sketches of the quarries at Brotherton and Knottingley made by Phillips (1828).

2.5.1.4 DOLINES IN THE CHURCH FENTON AREA

The area to the north-west of Church Fenton (see Figure 2 for location of Church Fenton) has numerous subsidence features or dolines, many of which are partly peat or alluvium-filled and associated with sulphate-rich springs and sulphate-rich water in boreholes. Recent unpublished work by A H Cooper shows that the subsidence areas derived from EA Lidar are more extensive than recorded in the BGS Karst Database and that there are numerous artesian springs associated with them. Figure 60 shows low areas in dolines (red) and the surrounding nearly flat glacial lake deposits in green. The area is underlain by the Sherburn Gypsum that is present in the Roxby Formation. This gypsum was formerly mined at Sherburn in Elmet mine, but water was struck at high pressure which was coming from the Brotherton Formation, and the mine was flooded and closed. Thompson et al. (1996) noted:

> *"The mine was forced to close when an underlying unit of heavily fractured waterbearing marl was intersected. Despite the lack of any structural discontinuity at this point the inflow of water was considerable, amounting to some 15 000 to 20 000 gallons per minute (1.1 to 1.5 m^3 per second). The surging water was accompanied by a strong smell of hydrogen sulphide and the water itself was found to have a sulphate content of 1400 ppm, indicative of substantial gypsum dissolution."*

Further south, flooded dolines are present in the lake at Askern, these are illustrated with the description of the springs in Section 2.6.3.

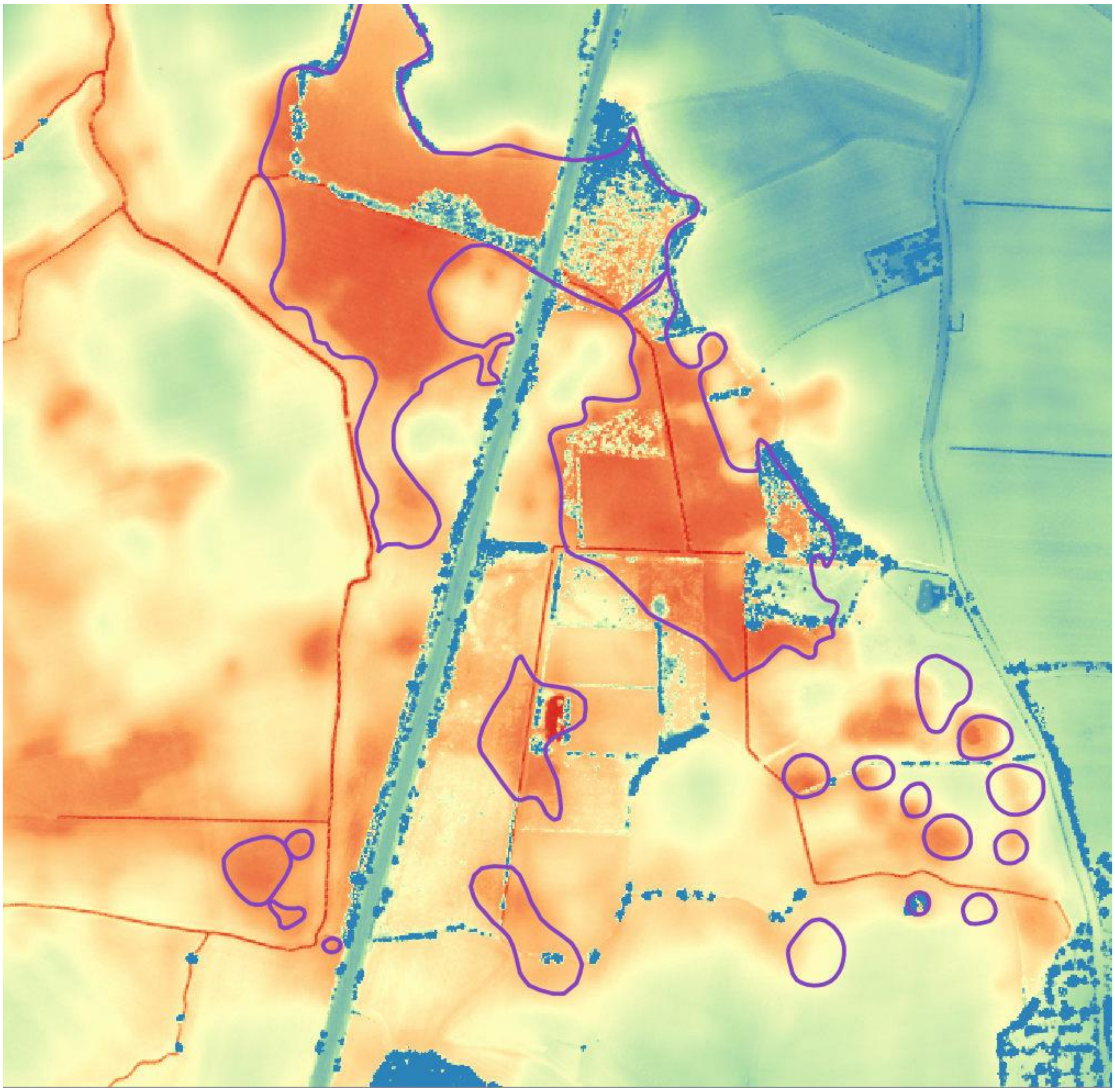

Figure 60. EA LiDAR for the area north-west of Church Fenton. The LiDAR is the 2 m DSM colour-ramped from red (4 m AOD) to green (9 m AOD). The outlines in purple are the dolines in the present BGS Karst Database; these need revising in line with the LiDAR.

2.5.2 Limestone dolines and dissolution pipes

Most known dolines and dissolution pipes in the Permian limestones are in the beds overlying gypsum. Whilst these have developed predominantly because of gypsum dissolution, the solubility of the limestone may also influence the development of these karst features. Whether this is the case or not, the development of karst in the limestones due to the gypsum may have hydrogeological implications for the limestones. For example, the permeability of the limestones may be enhanced by mass movement collapse and subsidence, as well as dissolutional processes; and water flow and quality within the limestones may be impacted by connectivity with overlying and underlying strata induced by the formation of karst dolines or dissolution pipes.

Farrant and Cooper (2008) suggest that there are very few dolines solely associated with the Permian limestones, but that some features may have been obscured by infilling of karst features by agricultural practices. They also suggest that the rock is not generally problematic for engineering, suggesting limited karstic collapse features. Whilst there are few records of limestone dolines or dissolution pipes away from the gypsum in the Natural Cavities Database (Figure 45), there is some evidence that such karst features do occur. Waltham et al. (1997) report that there are some lines of dolines along the edges of the Permian limestone outcrops. There are a number of streams that sink into the limestones in the P2 area (Section 2.4), some of which sink into dolines. There may therefore also be some dolines present where streams sank in the past when the geomorphological and/or geological setting was different.

Dolines recorded in the literature from the area east of Leeds, including some that may not be associated with gypsum karst, are discussed by Murphy (2000; 2003). Dolines sites discussed by Murphy (2000) are shown on Figure 61, and maps showing more detail of the doline locations can be found in Murphy (2000; 2003). Murphy (2000) notes that dolines on the Sherwood Sandstone Formation at Kellingley are an example of intrastratal karst, and include a large doline at [SE 5290 2465]. It is likely that the karst dolines here are related to dissolution in the underlying gypsum. Dolines discussed by Murphy (2000) at Hillam and Gale Common may also be associated with gypsum in the Roxby or Edlington formations (Figure 61). Murphy (2003) suggests that many of the dolines in the area East of Leeds are associated with gypsum, but notes that small dolines on the Cadeby Formation indicate karstification of the limestones. Murphy (2003) also discusses the palaeokarst features in the Brotherton Formation that result from subsidence into the Edlington Formation evaporites.

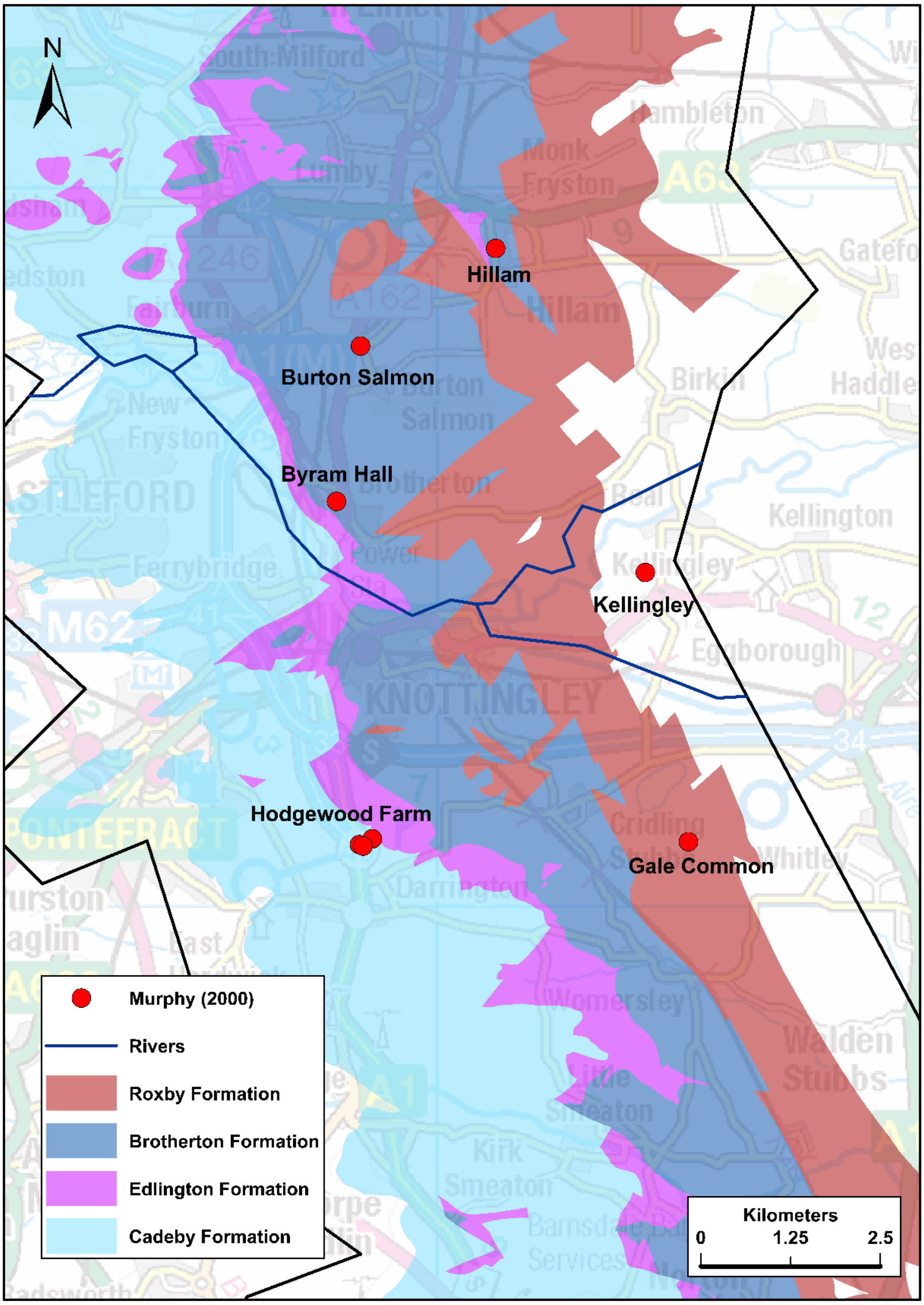

Figure 61. Locations of places with dolines discussed by Murphy (2000).

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Of particular note from the Murphy (2000) review are reports of dolines on the Brotherton Formation near Burton Salmon (Barclay et al., 1990) and near Byram Hall (Edwards et al., 1940). These places are shown on Figure 61. Barclay et al. (1990) report that "swallow holes" are developed within a dry river channel near Burton Salmon, and that this river channel extends from the Punch Bowl [SE 485 280] to Byram Lake [SE 499 262]. Edwards et al. (1940) describe "*a line of subsidence hollows, on the north-west side of the hall*" at Byram Park, and suggest that these may indicate the course of an underground stream. Edwards et al. (1940) also suggest "*evidence of a similar underground stream running NNW from the permanent spring at Burton Salmon*", and describe an additional "*subsidence crater*" north-west of Burton Salmon station. Murphy (2000) provides a map of the Burton Salmon area showing the locations of dolines reported in different studies and notes that some have been filled in. The presence of gypsum in the Edlington Formation beneath this area suggests that the dolines around Burton Salmon and Byram Hall on the Brotherton Formation are most likely a consequence of gypsum dissolution though an element of limestone dissolution cannot be ruled out. The sites shown on Figure 61 (Burton Salmon and Byram Hall) are for the villages at these locations and not the precise positions of the dolines, but Byram Hall is located close to the boundary with the underlying Edlington Formation.

Murphy (2000) also discusses dolines near Hodgewood Farm (Figure 45) in the Darrington area and provides a map showing the locations of karst features. These are the dolines in a dry valley to the south of Hodgewood Farm (Ellison, 1989; Barclay et al., 1990), that include two active stream sinks (Section 2.4). Ellison (1989) reports that there is a "*sinkhole*" in the Cadeby Formation that is partially filled with superficial deposits in the dry valley south of Hodgewood Farm at [SE 4910 2094]. Ellison (1989) notes that this feature presumably formed as a result of dolomite dissolution as the Cadeby Formation is exposed in the side of the doline. He also reports that there are two other shallow depressions on the south flank of the valley [SE 4892 2086 and SE 4897 2084] and suggests that these may be related to subsidence of solution pipes. It is probable that these are limestone karst features as they are located on the Cadeby Formation (Figure 61). Murphy (2000) reports that there are other isolated dolines throughout the Cadeby Formation outcrop, although he notes that some on the western edge of the outcrop may be collapse crown holes associated with mine workings. In their study of contaminant transport in the Permian limestones, Medici et al. (2019b) also note that dolines have been mapped in association with faults in the Cadeby and Brotherton formations ~ 40 km to the south of their model area, which is to the east of Leeds.

There is some localised evidence for dissolution pipes in the Cadeby Formation. Kendall and Wroot (1924, page 280) reported dissolution pipes at a quarry at Micklefield (Figure 45). These were photographed by Godfrey Bingley on the 24th November 1900 (Figure 62). More recently, Murphy (2000) republished the photograph and notes that the morphology of these pipes shows similarities to the karst dissolution pipes that are observed in the Chalk. Smith (1971) reports that there are several "*fossil swallets*" exposed in a shallow cutting in the M18 motorway near Doncaster where the Permian limestones are "*evenly bedded and well jointed*". The M18 motorway cutting is located at the boundary between the Edlington Formation and the Cadeby Formation (Figure 45), suggesting that these features may be associated with limestone dissolution in the Cadeby Formation. The description provided by Smith (1971) suggests that these are dissolution pipes: the features are conical shaped and between about 1 and 6 m across infilled with alluvial material and clay. There are substantial active stream sinks in this area (Section 2.4). There is also a photograph in the BGS archives of dissolution pipes in a railway cutting near Upper Langwith (Figure 63).

In summary, there are only a few records of dolines and dissolution pipes in the Permian limestones that are not associated with gypsum karst, and it appears that such features are not common. However, the BGS Karst Database has not been completed in this area, and there has been no systematic field or desk-based study of dolines and dissolution pipes, and it is possible that more are present. It would be most likely that these would occur where there is a thin cover of superficial deposits overlying the limestones, as observed in other karst aquifers in the UK.

Figure 62. Dissolution pipes at the top of Micklefield Quarry. Photo by G. Bingley

BGS photo archive P238840.

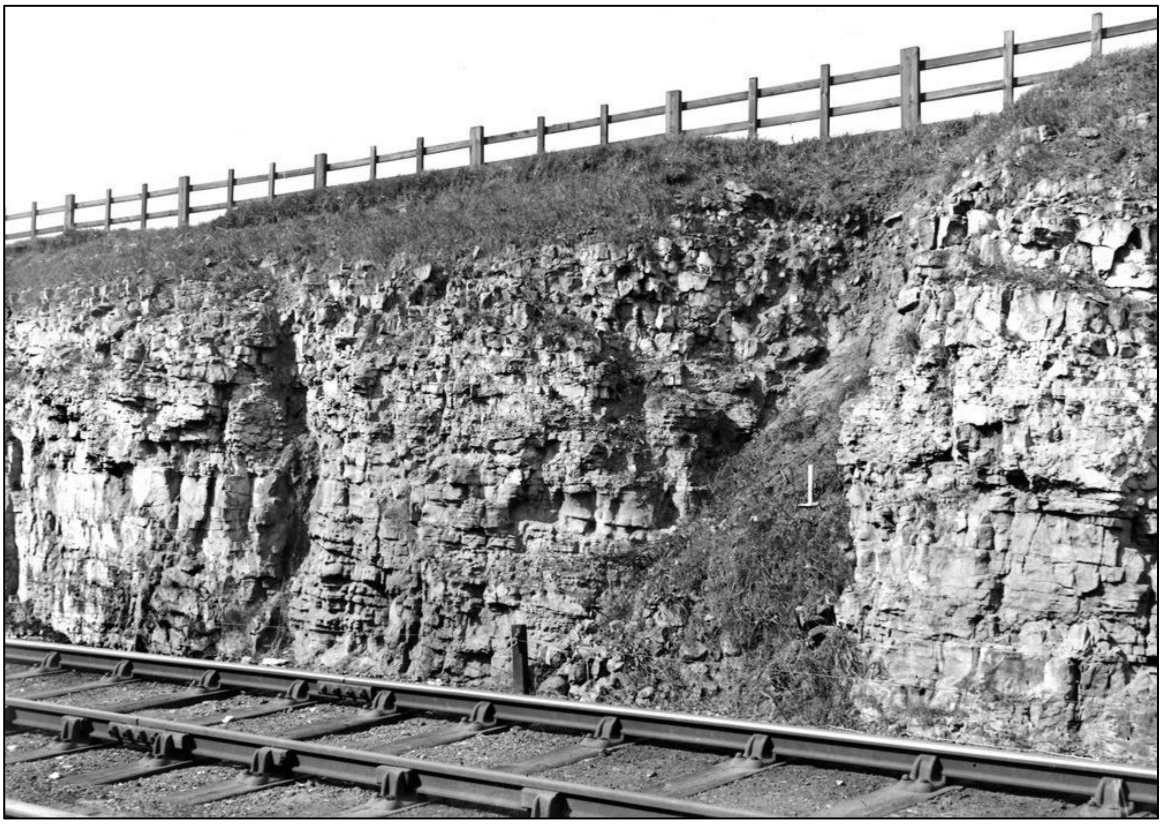

Figure 63. Dissolution pipes in a railway cutting near Upper Langwith. Photo by J. Rhodes.

BGS photo archive P201145 [SK 515 695]

2.6 SPRINGS

2.6.1 Introduction

Farrant and Cooper (2008) suggest that there are numerous springs in the Permian limestones, and there are many recorded in the P2 area. Figure 64 shows spring locations which have been clipped to the Zechstein group geologies. 436 of these are from BGS spring records (shown as blue triangles). Fifty-three additional springs were identified for this report using historic six-inch (1:10 560) Ordnance Survey maps for Yorkshire, Derbyshire and Nottinghamshire (the green triangles on Figure 64). 138 springs sites that were surveyed in 1977 (Cradock-Hartop and Steel,1979) and are discussed in Section 2.6.2, are shown as red circles on Figure 64. Also discussed in Section 2.6.2, Figure 64 shows eight sites (yellow triangles) that are the approximate location of some springs mentioned in the BGS memoir on the water supply of Nottinghamshire from underground sources (Lamplugh et al., 1914), four springs (black squares) studied by Crabtree and Trudghill (1993), and Cadmaer spring (yellow circle with a cross inside) on the River Aire (Edwards, 1940). There are also major springs at Hell Wath on the River Skell [SE 29929 69928] which discharge water from limestones of the Cadeby Formation through superficial deposits (Murphy, 1999, see Section 2.4), and these are shown on Figure 64 as a red asterisk. A spring is reported by Gibbs (1995b) in the west of the area (black circle on Figure 64). Finally, seven springs related to the gypsum that are discussed by Cooper and Burgess (1993) or Cooper (2006b) are also included on Figure 64 (orange squares), and 26 sulphate rich springs from Cooper et al. (2013) which are purple squares.

For many of the spring sites shown on Figure 64, there is no information on their flow rates and characteristics. Many of those in the east may be discharging water from the gypsum; and Murphy and Lowe (2021) suggest that the larger springs in the Zechstein Group may be associated with the gypsum karst. There are superficial deposits present, particularly in the north of the P2 area (Figure 3 and Figure 4), and it is also possible that some springs are discharging water from these superficial deposits, although these appear to be generally thin and dominated by low permeability glacial till.

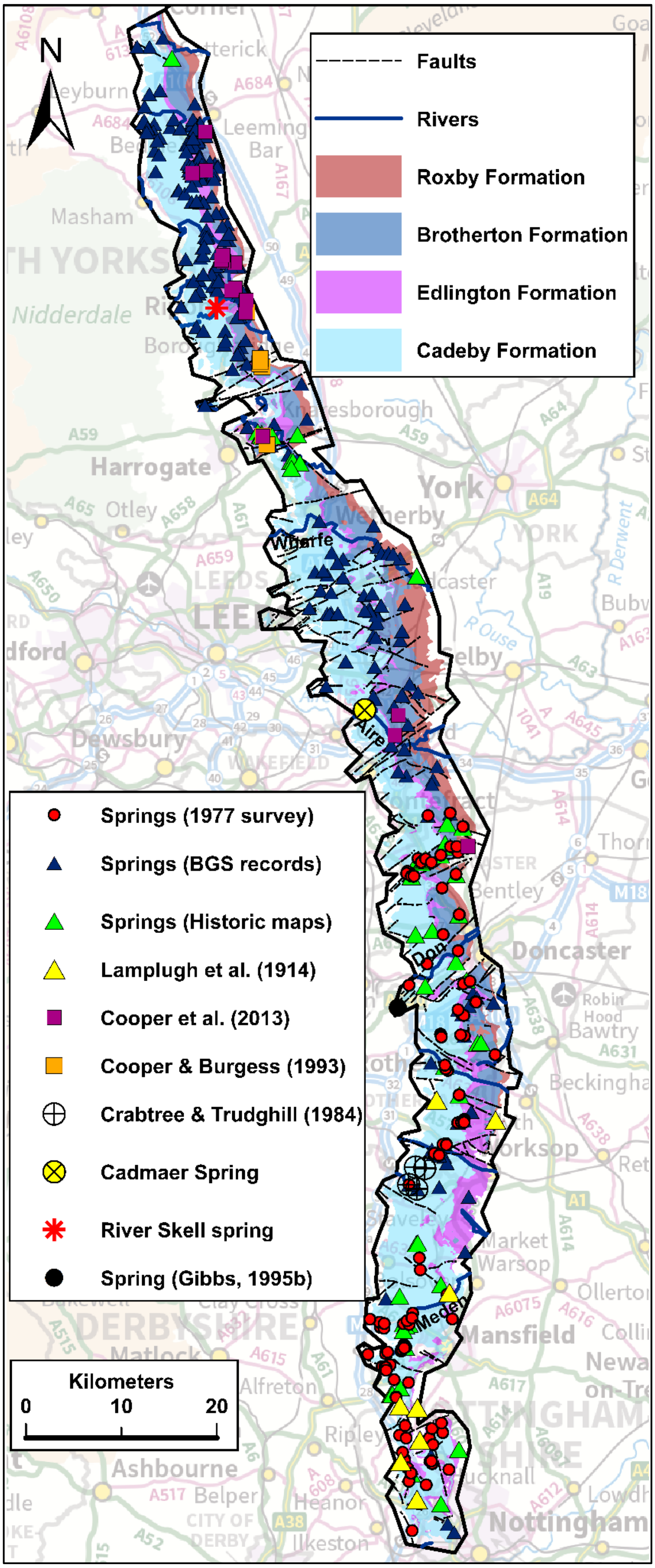

Figure 64. Springs associated with the Zechstein Group in the P2 area.

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2.6.2 Limestone springs

There is some information on Permian limestone springs in the old BGS water supply memoirs for Nottinghamshire (Lamplugh et al., 1914) and Derbyshire (Stephens, 1929). The locations of the springs mentioned in these memoirs have not all been digitised for this report as they are mostly described as small, and many may already have been identified in the BGS spring records. However, the locations of eight springs reported by Lamplugh et al. (1914) that are likely to be substantial are included in Figure 64 and described here: Of particular note are "powerful" springs in Nottinghamshire at the base of the Permian limestones, for example "near Beauvale Priory [SK 4923 4905], Annersley Park [SK 5122 5129] and those forming the source of the Erewash near Kirkby-in-Ashfield" [SK 4916 5492] (Lamplugh et al., 1914). Construction of the Annersley Tunnel [SK 5096 5470] intersected "*a great spring that originally ran at several millions of gallons per day*" (Lamplugh et al., 1914), which suggests flows of more than 100 l/s. Lamplugh et al. (1914) report that springs at Sookholme Bath were used to supply Nettleworth Manor, and Sookholme Bath is shown as a substantial looking spring on Ordnance Survey maps [SK 5432 6676]. Lamplugh et al. (1914) also report that there are springs at the boundary with the lower permeability marls at the base of the Cadeby Formation, for example in railway cuttings east of Kimberley [SK 5092 4509] and in the upper part of the Meden valley (Figure 64). There are small springs reported at Carlton-in-Lindrick [SK 5915 8483] and Oldcoates [SK 5297 8694] associated with the boundary between the Brotherton Formation and the Edlington Formation (Lamplugh et al., 1914). The grid references provided here (and shown as yellow triangles on Figure 64) are for the places mentioned by Lamplugh et al. (1914) and are therefore not necessarily the actual locations of the springs. Lamplugh et al. (1914) and Stephens (1929) both note that springs in the Permian limestones are impacted by contamination due to the development of fissures and cavities. However, most spring supplies described are small, with yields equivalent to less than 1 l/s where numbers are reported (Lamplugh et al., 1914; Stephens, 1929).

Some springs in the Permian limestones used for water supply are discussed by Edwards at al. (1940) in the geological memoir for Wakefield. These include Cadmaer Spring (Figure 64) which discharges water from the Lower Magnesian Limestone (now Cadeby Formation) "*on the north side of the River Aire half a mile east of Newton*" which is at approximately [SE 4545 2783]. A "*daily quota of 200 000 gallons*" was pumped, which is equivalent to 10 l/s of constant pumping. Edwards (1940) also mentions a permanent spring at Burton Salmon that is associated with dolines (Section 2.5.2) and which may be fed by "*an underground stream*", but the location of this spring is uncertain and there are no obvious springs on the Ordnance Survey maps at Burton Salmon.

A spring at [SK 48939363] is reported by Gibbs (1995b) near to Hooton Cliff caves. These are classified as karst cave/slip rift in this report as it is unclear which they are from the description. The spring is described by Gibbs (1995b) as having "*no prospect of entry*" from a speleological perspective. It is located on a fault at a boundary between the Cadeby Formation and the underlying Pennine Coal Measures Group and therefore may be discharging water from the Cadeby Formation.

There is information about 138 spring sites in the Zechstein Group of the East Midlands that were surveyed by the BGS in 1977 (Cradock-Hartop and Steel,1979; these are the red circles on Figure 64). These are distributed throughout the southern part of the P2 area, and many of these springs do not appear to be in the other datasets shown on Figure 64. During this survey all spring sites shown on the 1:25,000 Ordnance Survey maps that were located on the "*Lower or Upper Magnesian Limestone*" outcrop were visited, together with 14 springs on the "*Lower and Middle Permian Marls*" (in the south of the area rather than being the Marl Slate Formation the Lower Marl is most likely a muddy facies of the Cadeby Formation and the Middle Marl is the Edlington Formation). Fourteen other springs on the Coal Measures were also visited and these are not included on Figure 64. The survey provides grid references, elevations, flows and notes about the springs. Flows of springs discharging from a pipe or discrete point were measured using a container, but in most cases this was not possible, and the flows were estimated from the velocity of the stream and the approximate cross-sectional area (Cradock-Hartopp and Steel, 1979).

The results of this 1977 spring survey by Cradock-Hartop and Steel (1979) provide useful insights into the nature of groundwater discharge from the Permian limestones. Most of the springs visited had small flows. 11 were described as "*seepages*". 9 springs had very small flows of < 0.01 l/s, 17 had flows of 0.01 to 0.1 l/s and 21 had flows of 0.1 to 1 l/s. There were 15 larger springs with flows of 1 to 5 l/s which might be indicative of discharge via solutional features. Only four springs had flows of > 5 l/s which might suggest a more connected solutional network. Three of these had flows of 5-10 l/s, and one spring, St Catherine's Well near Doncaster (Figure 65), had a flow of 72 l/s suggesting an extensive solutional network. This spring is reported to have previously flowed "*into a well of about 12 feet diameter*" suggesting that it may have been potable water used for supply although this is not specifically mentioned.

The survey by Cradock-Hartop and Steel (1979) involved a single visit to the springs in 1977 on 10th to 14th October or 14th to 18th November, and there is no information about whether there had been much rainfall in the period leading up to the field visits. This is the time of year when groundwater levels can be at or near their lowest following the summer. It is also possible that flows were still being impacted by the 1976 drought. Some of the springs that were dry were noted as "*only flowing in winter*", and the survey usually did not record information about flow variability or whether there were indications of more substantial flows at other times (such as the size of stream channels fed by the springs). There is some suggestion that some of the springs have dried up, the most notable example being a spring at Owlands Wood Dike, Woodsetts [SK 5586 8481], reported to have dried up "*11 years ago*". The notes stated that "*during war used for water supply of Sheffield*". This implies that it was a substantial spring, and that it was of potable quality so perhaps not derived from gypsum groundwater, although this spring is located at the boundary between the Edlington Formation and the Cadeby Formation.

Whilst the springs surveyed by Cradock-Hartop and Steel (1979) are distributed throughout the southern part of the P2 area, there are records of other springs in this area in the other datasets shown on Figure 64. It appears that none of the datasets are comprehensive, and there may be other springs that are not shown on Figure 64. The data suggest that springs occur in all parts of the Zechstein Group, but the largest ones appear to be near the top of the Cadeby Formation, or on the Edlington Formation. Cradock-Hartop and Steel (1979) report that some of the springs they surveyed were used as small supplies for houses, farms and villages, suggesting that they were potable groundwater from the Permian limestones. But overall, the measured and estimated discharges reported by Cradock-Hartop and Steel (1979) suggest that most of the limestone springs are small. Murphy and Lowe (2021) also note that springs in the Permian limestones have not been found to be associated with cave development, and suggest that many arise from larger areas of seepage. Some springs are reported to be located near to faults (Cradock-Hartop and Steel, 1979; Medici et al., 2019b), which is also apparent to some extent on Figure 64 and Figure 65.

Crabtree and Trudghill (1984) undertook a hydrochemical budget for the Bondhay Dyke catchment a few kilometres west of Worksop. This study included water chemistry sampling of four springs: Cinders, the largest [SK 5092 7763]; Castlehill [SK 5007 7809], Loscar [SK 5078 7993] and Dry Valley [SK 5175 7979]. The grid references of these springs are not reported but there is a map showing the locations of the springs and this was used to estimate the approximate grid references using Ordnance Survey maps, and these locations are the black squares on Figure 64. The spring discharges are not reported but there is a graph showing a year of discharge (June 1979 to May 1980, timestep not reported) for the Bondhay Dyke catchment. This includes the combined discharge of all the springs and any surface runoff, and shows flow varying seasonally from just a few l/s in the autumn to a peak of > 150 l/s in February; and some quite variable flows over the winter period. Crabtree and Trudgill (1984) reported that spring discharges and solute concentrations vary throughout the year suggesting fissure flow. They also note that the springs have a rapid flow response to rainfall but without dilution of the solutes, suggesting a piston-flow response to recharge. Overall, they conclude that, in terms of the dominance of fissure flow, these Permian limestone springs are intermediary between those in the Carboniferous Limestone and those in the Chalk. The observations of Crabtree and Trudgill (1984) are consistent with an aquifer in which there are connected networks of solutional fissures and conduits in the saturated zone that discharge via springs, but which have little connectivity with the surface and might suggest that there is little rapid recharge via fissures in the unsaturated zone in this catchment.

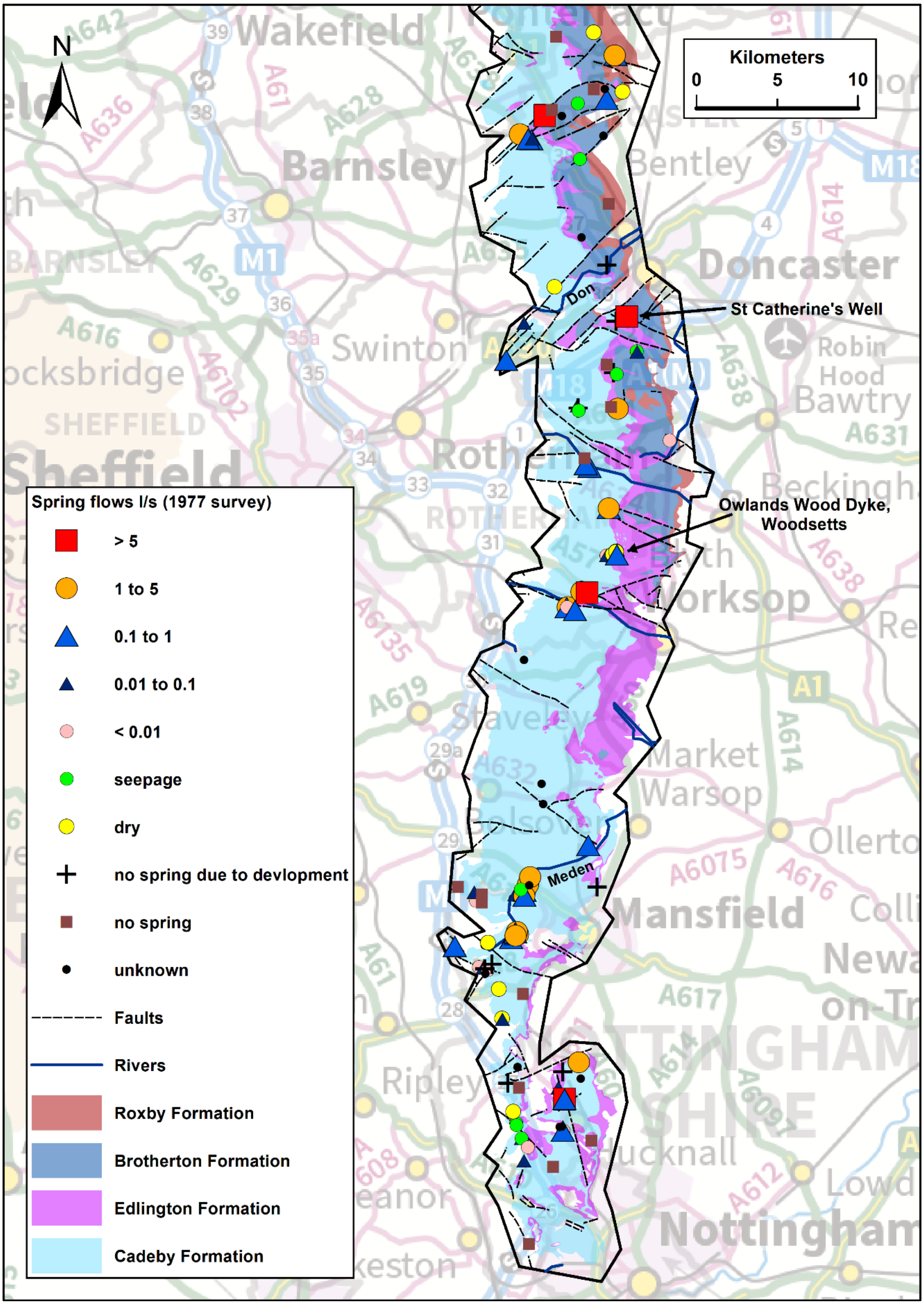

Figure 65. Spring flows (l/s) from 1977 survey (Cradock-Hartopp and Steel, 1979).

2.6.3 Springs related to gypsum

There are also many springs related to the gypsum karst. Many, but not all the springs associated with gypsum are included on Figure 64 from Cooper and Burgess (1993), Cooper (2006b), and Cooper et al. (2013). In the description of the Geology of Harrogate, Cooper and Burgess (1993) discuss six springs including four springs on the Holbeck: Mongah's Well and three other "*fairly prolific*" springs that are most likely supplied by water from the Cadeby Formation, but which emerge from the Edlington and Brotherton formations through thick superficial cover. They also reported springs at Ripon racecourse, and discuss the famous Dropping Well spring near Knaresborough (Figure 66, Figure 67). The latter is near to Mother Shipton's Cave (see Section 2.3.2.7), and is also discussed by Cooper (2006b) and Cooper et al., (2013) The Dropping Well is a spring emerging over the Cadeby Formation, but which contains sulphates from the gypsum in the Edlington Formation just to the west; the water deposits tufa that has formed the Dropping Well screen and which is used to petrify absorbent objects for tourist sales (Burrell, 1897; Cooper 2006b; Greenwood, 2008; Cooper et al., 2013; see Figure 67). The Dropping Well screen is manually scraped to prevent excess build-up and weight as the whole structure has a void behind and could topple if too front-heavy. There are subsidence hollows within the catchment of the spring to the south and west, which are probably formed due to gypsum dissolution (Cooper, 2006b). Analysis of the water issuing from the Dropping Well spring is described in Burrell (1897) and Cooper et al. (2013). Cooper (2006b) also describes a large spring, in the valley of the River Nidd, Knaresborough [SE 356 556]. This spring issues from the Roxby Formation (Table 1), close to the boundary with the Brotherton Formation and the Grimbald Crag Fault (Cooper, 2006^{b}). Cooper et al. (2013) discuss the role of springs with high sulphate in the formation of dolines on the Permian gypsum deposits. They describe 27 springs or dolines/sinkholes, the details of which are shown in Table 6 and Table 7; the locations of these are included as purple squares on Figure 64.

The sulphate-rich springs include mainly normal and artesian springs, but there are also artesian springs emanating in water-filled dolines/sinkholes. These include the newest of the Hall Garth Ponds at Nunwick north of Ripon, which is 30 m across by 9 m deep and collapsed in 1939 (Cooper, 1986 and Figure 68). Here sulphate-rich water (Cooper et al., 2013) issues from fissures in the Brotherton Formation limestone exposed underwater in the sinkhole, and the Brotherton Formation is also exposed in the back of the sinkhole (Figure 69).

In the south of the P2 area, Askern Lake also comprises sinkholes with sulphate-rich water emanating in and near them (Cooper et al., 2013; Table 6, Table 7, and Figure 70).

Sulphate-rich springs have also been recently recognised in the area of dolines/sinkholes west of Church Fenton where they relate to the Brotherton Formation and Sherburn gypsum. Sulphate rich water is extracted from boreholes south of Tadcaster where the high gypsum content means that the water is already "Burtonised" for brewing beer (Cooper and Lawley, 2007).

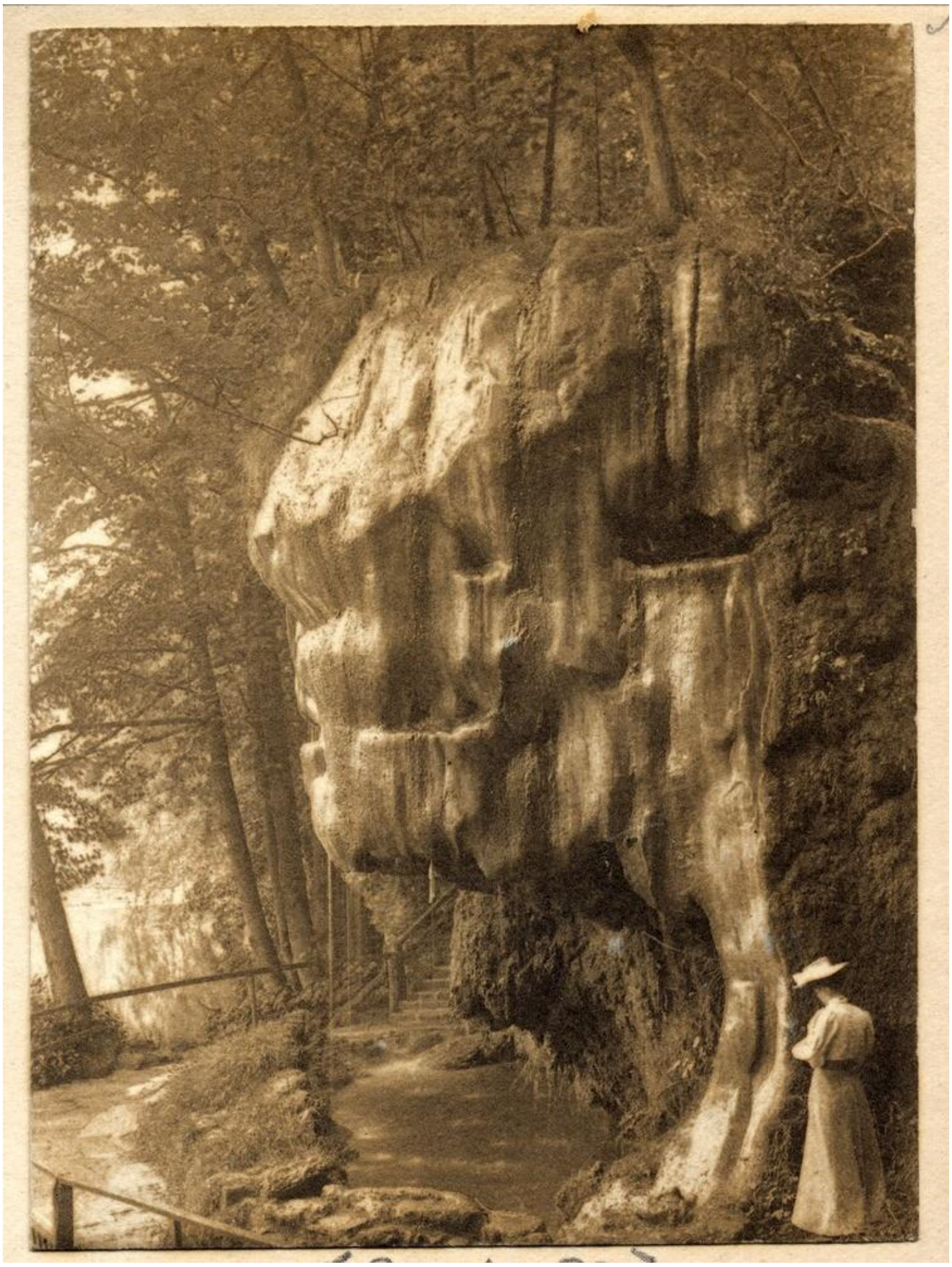

Figure 66. Dropping Well spring. Photo by S.H. Reynolds, January 1906.

BGS photo archive P246692

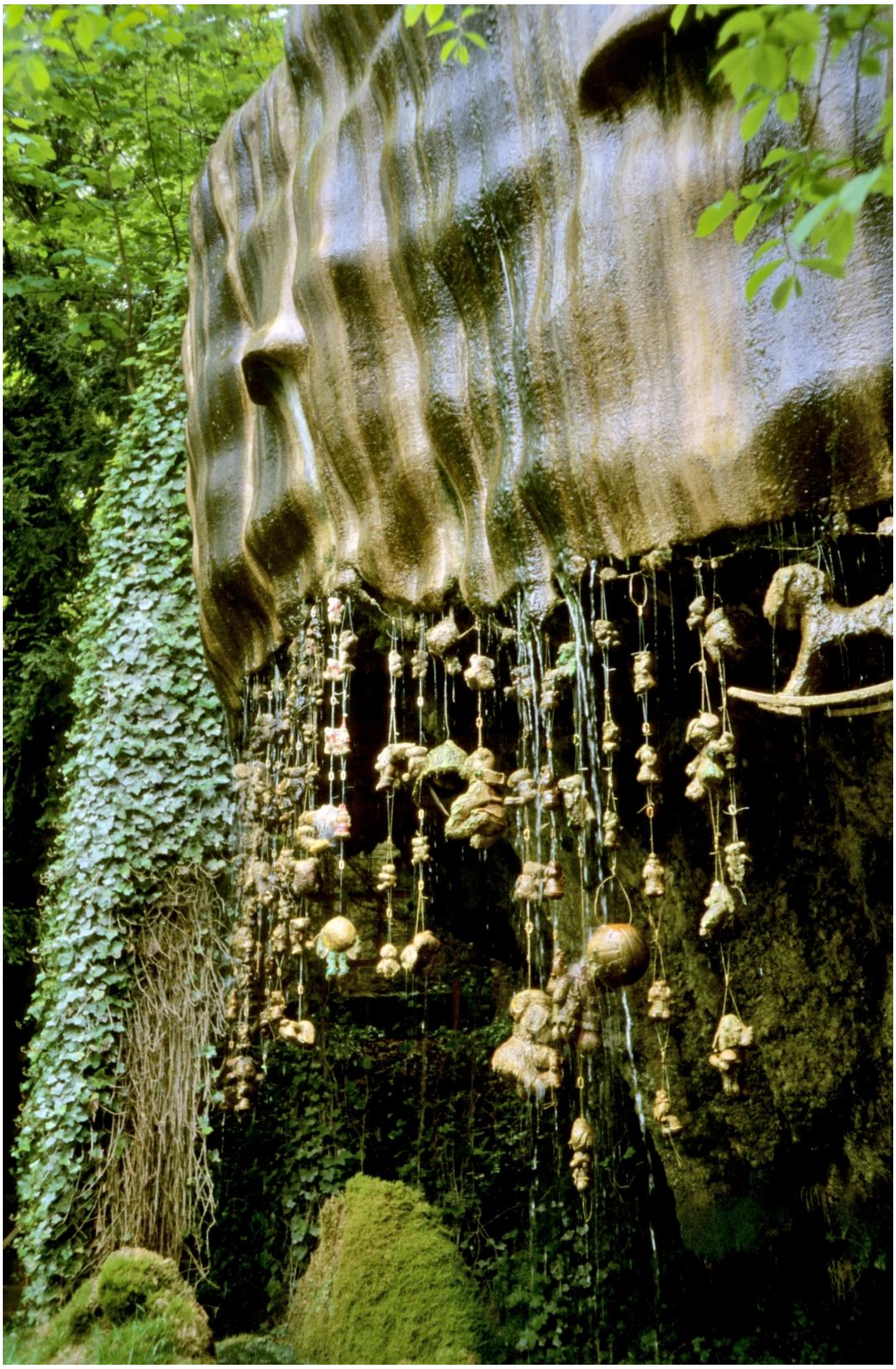

Figure 67. The Dropping Well (petrifying spring) at Knaresborough showing petrified objects being made for sale at the attraction. Photo A. H. Cooper, 2007.

Spring Name	NGR E	NGR N	pH	Temp	Con-duc-tivity	Concentrations mg/l				Analyst or reference
				ºC	mS/cm	Ca^{2+}	SO_4^{2}-	HCO_3-	TDS	
Snape Mires; Pudding Pie Hill	427815	484458	7.6	13.5	0.161	58.7	32.4	N/A	416.4	Brown (2010)
Snape Mires; The Gallops 1	428767	484395	7.34	12.0	0.320	548.9	952.5	N/A	1943.8	Brown (2010)
Snape Mires; The Gallops 2	428794	484359	7.34	20.6	0.720	189.7	306.9	N/A	1305.2	Brown (2010)
Snape Mires east; Gruntland Springs 1	428723	488409	7.26	10.0	0.320	211.4	228.3	71.2	698.2	Brown (2010)
Snape Mires east; Gruntland Springs 2	428723	488409	7.26	10.0	0.315	247.9	338.1	83.4	948.4	Brown (2010)
Snape Village; Mill House Spring 2	427408	484065	7.46	9.9	0.202	92.2	45.4	24.4	408.5	Brown (2010)
Ripon, Hall Garth Ponds; 1939 sinkhole (N3) at 6.6 m	431842	474707	8.03	10.2	1.700	490.7	1172.4	227.4	2001.0	Miller (2006)
Ripon, Hall Garth Ponds; east pond (E3) at 0.8 m	431895	474681	7.82	17.3	1.210	281.3	549.6	230.3	1146.6	Miller (2006)
Ripon Parks, Queen Mary's Dubb at 4 m	430662	474828	7.41	14.9	0.072	34.7	9.5	50.8	128.4	Brown (2010)
Ripon Parks, Black Heath Pond at 1.4 m	430435	474959	7.34	14.9	0.147	66.4	42.8	63.0	214.4	Brown (2010)
Ripon Parks spring 4	430594	475472	8.27	11.6	0.220	122.9	55.7	91.5	368.4	Brown (2010)

Table 6. Names, locations and main sulphate and carbonate compositions of the mainly sulphate-rich springs and sinkholes in the study area.

Spring Name	NGR E	NGR N	pH	Temp	Con-duc-tivity	Concentrations mg/l				Analyst or reference
				°C	mS/cm	Ca^{2+}	SO_4^{2}-	HCO_3-	TDS	
Ripon, Spa Field (Nr Spa Well at 431573 471607) at 1.6 m	431505	471746					2015.0			Site investigation report
Ripon, Bridge foundations	431889	472039					1360.0			Thomson et al. (1996)
Ripon, Racecourse gravel pit (approx. locality)	432950	469500					289.0			Thomson et al. (1996)
Ripon, Sharow spring	433041	470763	7.54	9.5	1.340	247.0	409.0	320.0		Simon Warwick pers. comm.
Knaresborough, Dropping Well spring	434766	456498	6.9	10.7	N/A	681.0	1360.0	298.0	N/A	Greenwood (2008)
Knaresborough, Dropping Well tufa screen top	434773	456518	7.6	11.7	N/A	709.0	1420.0	264.0	N/A	Greenwood (2008)
Brotherton; Burton Salmon - Lake outflow	448979	427269				178.7	65.8			P Murphy (2000)
Brotherton: Byram - drainage ditch	448626	425162				256.1	358.3			P Murphy (2000)
Askern; main lake inlet	456238	413583	7.1	13.8	N/A	610.0	1400.0	166.0	N/A	Greenwood (2008)
Askern; main lake deep sinkhole (A1N) at 5 m	456286	413505		17.5	N/A	561.0	1310.0	122.0	N/A	Greenwood (2008)
Askern: Manor Bath (well)	456322	413525				433.0	947.0		2361.0	Bothamley (1894) (page 351)
Askern; Lake borehole (location unconfirmed)						697.0	1172.0	306.0	N/A	Env. Agency (Greenwood. 2008)
Askern; Colliery borehole	455690	413640				585.0	1422.0	279.0	N/A	Env. Agency (Greenwood. 2008)
Askern; Manor Well at 0.9 m	456322	413525		9 to 17		594.0	1085.0			Brewerton (1818) (Greenwood, 2008)
Askern; Manor Well	456322	413525				573.0	1493.0			Lankester 1842 (Greenwood, 2008)
Askern; Charity Well	456197	413392				584.0	1251.0			Lankester (1842); (Greenwood, 2008)

Table 7. Continuation of Table 6, Names, locations and main sulphate and carbonate compositions of the mainly sulphate-rich springs and sinkholes in the study area.

Figure 68. The newest of the Hall Garth Ponds at Nunwick; this doline (sinkhole) collapsed in 1939 and is fed by sulphate rich water that commonly steams in the winter; Brotherton Formation exposed back right.

Figure 69. Brotherton Formation limestone in the back wall of the 1939 Hall Garth Ponds doline (sinkhole).

Figure 70. Askern lake showing the dolines (sinkholes) within it as deeper water in the middle, south-east and south-west. Air Photography copyright UKP/Getmapping reproduced under license No UKP2006/01.

3 Tracer tests

Only one record of tracer testing in the Permian limestones (Short, 1988) was identified for this report. Tracer tests were conducted at Bramham, east of Leeds, in response to a contamination incident at a public water supply borehole (Section 4.3, see Figure 73 for location of Bramham). A variety of different tracers and injection points were used (Figure 71). The results are summarised in Table 8 which includes an approximate estimate of the distance over the surface between the tracer injection points and the monitoring borehole (borehole 4). These distances were measured from Figure 71 and used to estimate approximate tracer velocities. The injection points were sewers and surface water courses, and it is not clear where tracer entered groundwater following injection, therefore these velocities do not represent groundwater velocities but a combination of both the groundwater and surface water/sewer velocity between the injection points and the abstraction borehole. The flow was rapid, with tracer reaching the abstraction borehole from the sewer within 8 hours over a surface distance of ~ 100 m (Short, 1988). As well as indicating connectivity between the sewer system and the abstraction borehole, the tracer tests also indicate connectivity between the Carr Beck surface stream and the abstraction borehole. Short (1988) present a breakthrough curve for *Serratia Marcescens* injected into the sewer, and a conceptualisation of the source of contamination at the site (Figure 72).

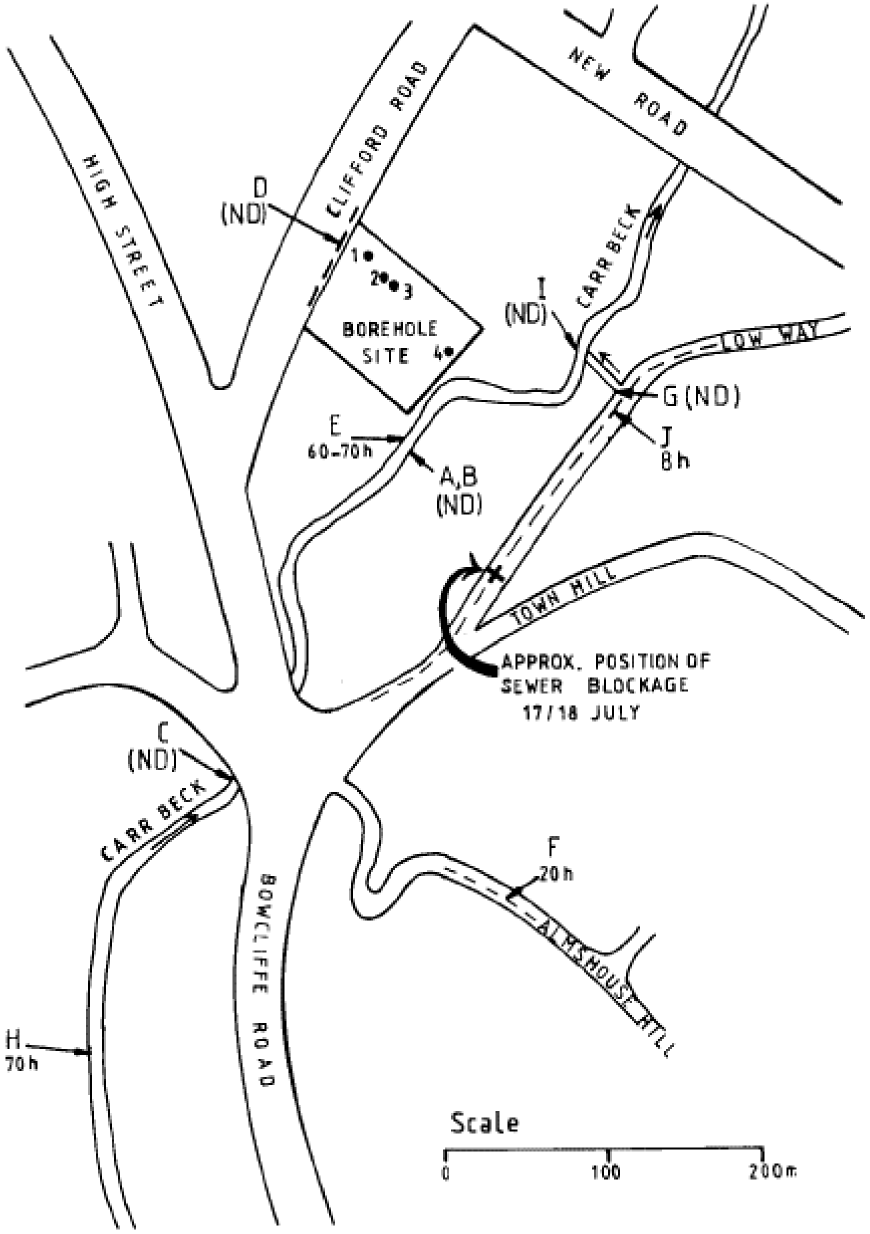

Fig. 2. Bramham village plan, showing tracer injection points

Key to tracer tests:

A, B, C	Lithium chloride to stream
D	Lithium chloride to vicinity of sewer leak
E	Radiotracer Br-82 to stream
F	Bacteriophage *S. Marcesens* to stoppered sewer
G	Bacteriophage *S. Marcesens* to stoppered storm sewage outfall pipe
H	Bacteriophage *B. Globigii* to stream
I	Bacteriophage *B. Globigii* to stream at storm sewage outfall
J	Bacteriophage *S. Marcesens* to stoppered sewer

Times of travel of tracer to Borehole 4 are indicated in hours (ND) = not detected

Figure 71. Tracer testing at Bramham from Short (1988).

Table 8. Tracer tests conducted at Bramham with approximate distances and tracer velocities.

Injection site	Tracer	Travel time (hours)	Straight line distance on surface (m)	*Tracer velocity based on straight line distance (m/hour)	*Tracer velocity based on straight line distance (m/day)
A, Carr Beck, downstream	Lithium Chloride	Not detected	73		
B, Carr Beck, downstream	Lithium Chloride	Not detected	73		
E, Carr Beck, downstream	Radiotracer BR-82	60 to 70	64	1	24
C, Carr Beck, middle	Lithium Chloride	Not detected	314		
D, “vicinity of sewer leak”	Lithium Chloride	Not detected	100		
F, “Stoppered sewer”	Bacteriophage *S. Marcescens*	20	355	18	432
G, “stoppered storm sewage outfall pipe”	Bacteriophage *S. Marcescens*	Not detected	109		
H, Carr Beck, upstream	Bacteriophage *B. Globigii*	70	518	7.4	178
I, “stream at storm sewage outfall”	Bacteriophage *B. Globigii*	Not detected	82		
J “stoppered sewer”	Bacteriophage *S. Marcescens*	8	114	14	342

* Note that these are not groundwater velocities, but combined velocities of surface/sewer and groundwater flow

THE BRAMHAM INCIDENT

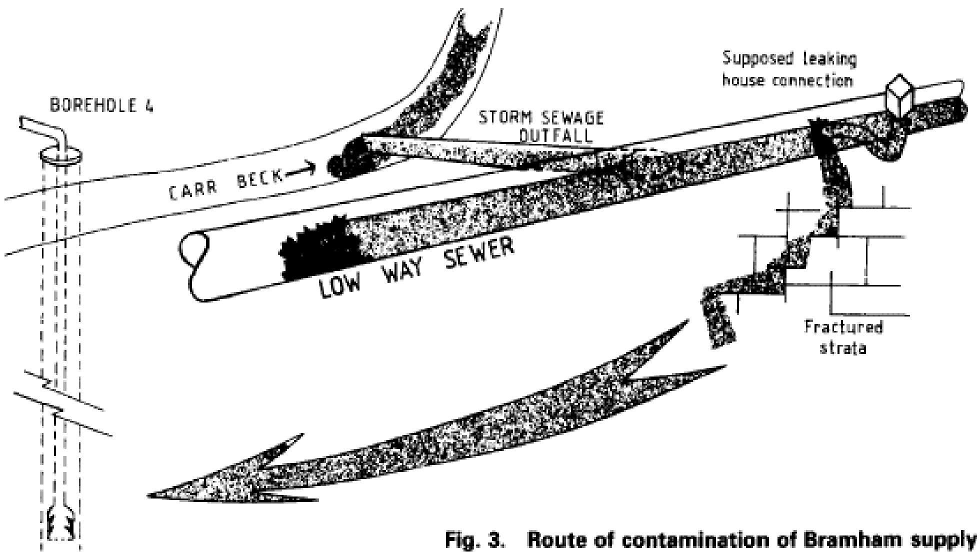

Fig. 3. Route of contamination of Bramham supply

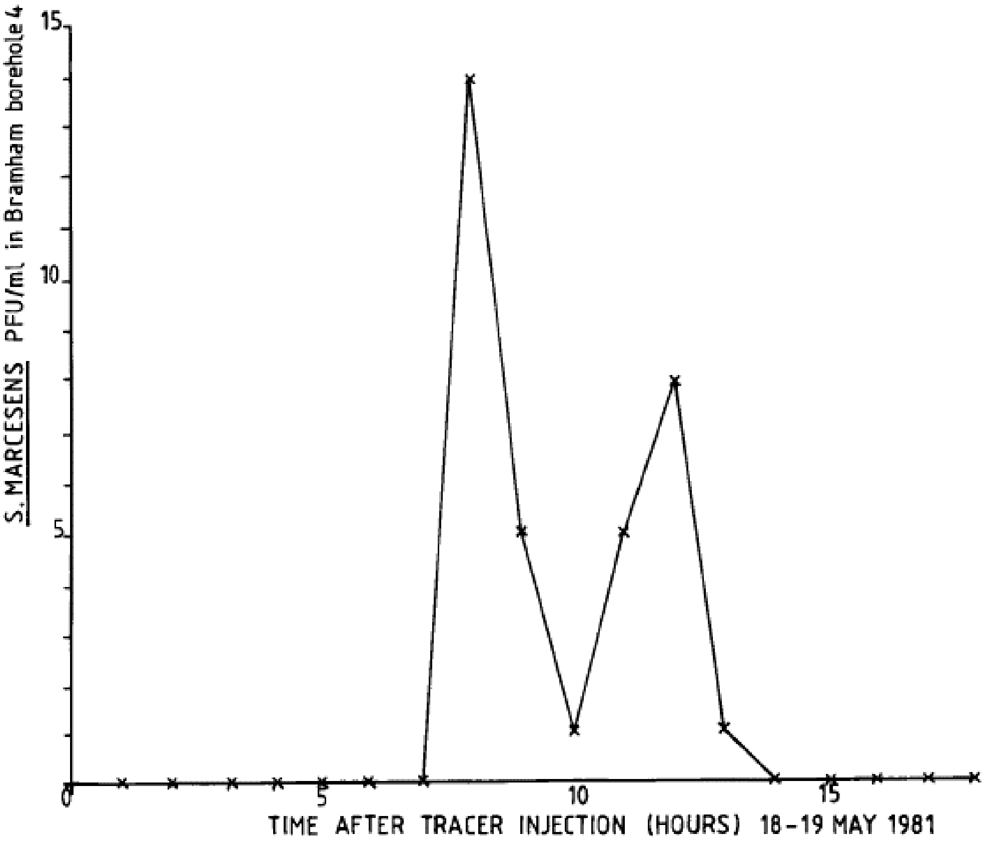

Fig. 4. Response to tracer in Low Way sewer

Figure 72. Figures from Short (1988) showing tracer breakthrough curve and conceptualisation of the Bramham contaminant incident.

4 Permian limestone karst hydrogeology

4.1 INTRODUCTION

This report shows that karst features (caves, conduits, stream sinks, dolines, dissolution pipes and springs) are fairly widespread in the limestones in the P2 area. It is therefore highly likely that the hydrogeology of the limestones is strongly influenced by karst processes, and that flow through solutional features is an important component of groundwater flow. In the baseline hydrogeochemical survey reported by Bearcock and Smedley (2009) most samples were supersaturated with respect to calcite and dolomite, suggesting there may be limited potential for limestone dissolution in the saturated zone. However, samples were undersaturated with the highly soluble gypsum and anhydrite evaporites, indicating significant potential for dissolution of these geologies. Medici et al. (2019b) also reported that groundwater from the Cadeby Formation was saturated with respect to calcite, aragonite and dolomite, but that despite this fracture apertures in the dolomitic limestones were solutionally enhanced. Medici et al. (2019b) suggested that karstic development might be driven by in situ bacterial consumption of Dissolved Organic Carbon (DOC), as well as external input of CO_2 gas from the soil zone. It is also possible that conduit development occurs as a result of mixing corrosion that is common in karst aquifers where saturated solutions of different PCO_2 mix resulting in a locally unsaturated groundwater enabling subsurface dissolution (Bögli, 1964; Dreybodt, 1981). The subsurface solutional development of permeability is also indicated by dry valleys which are commonly incised into the dip slopes of the Permian limestones (Murphy, 2003; Murphy and Lowe, 2021). Bourne behaviour (streams that are seasonally dry) and springhead migration, sometimes over considerable distances, is a common feature of karst aquifers (Ford and Williams, 2007). In wet periods or seasons, the capacity of the conduit system is exceeded leading to activation of upstream ephemeral springs. An example in the Permian limestones is in the Bondhay Dyke catchment (Figure 73) where springs migrate up/down valley in relation to changing groundwater levels (Crabtree and Trudgill, 1984). These springs are discussed in Section 2.6.2.

There has been little work on the karst hydrogeology of the Permian limestones, but this section provides a brief overview of how transmissivity and water quality provide some insights into karstic groundwater flow, and a preliminary conceptualisation of karstic groundwater flow in the Permian limestones. The interaction between the limestone and gypsum karst is considered in Section 5.

4.2 TRANSMISSIVITY AND BOREHOLE YIELDS

Transmissivity can provide an indication of karstification because more extensive networks of solutional fissures and conduits have higher transmissivity than unmodified fracture networks. However, there are other factors unrelated to limestone karst which could contribute to transmissivity: (1) The most influential cause is the increased transmissivity due to connectivity between the limestones and overlying karstified gypsum sequences, along with the interconnection caused by breccia pipes linking the Cadeby Formation to the Edlington, Brotherton and Roxby formations. (2) permeable superficial deposits may increase transmissivity, but this is unlikely in much of the P2 area as superficial deposits are largely absent in the south, and are dominated by low permeability glacial till in the north (Figure 3). (3) In some places the Cadeby Formation is hydraulically connected to the underlying Yellow Sands Formation of the Rotliegend Group (Bearcock and Smedley, 2009) and therefore it is possible that these deposits contribute to the transmissivity of some boreholes abstracting from the Cadeby Formation. (4) Allen et al. (1997) suggest that the brecciated nature of the limestones contributes to their permeability. The local hydrogeology therefore needs to be considered on a site by site basis. However, there is clear evidence for solutional development of fissures and conduits in the limestones of the Zechstein Group (Section 2.1), and it is therefore likely that the degree of solutional development and extent of the karst networks in the Permian limestones influences the transmissivity variations that are observed.

Figure 73 shows transmissivity estimates from pumping tests classified in the BGS aquifer properties dataset (Allen et al., 1997) as from the "*Magnesian Limestone*" aquifer. These include three estimates from mineshafts outside, and to the east of, the main P2 the area, between York and Selby (Figure 73). These are on the younger Sherwood Sandstone Group (part of the younger strata labelled on Figure 73), but with tests undertaken in the underlying Permian limestones. These three sites have lower transmissivity than many sites within the main P2 area suggesting a lack of karstification. At shallower depths the Permian limestones have much higher transmissivities. Here, there are estimates for 30 abstraction sites, which range from 5 to 4200 m^2/day with a mean of 745 m^2/day and a median of 260 m^2/day. Seven sites have transmissivities of > 1000 m^2/day suggesting that the abstractions may be fed by well developed solutional networks, and these are concentrated in the middle part of the P2 area (Figure 73).

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 73 are these “best locality” values. The maximum and minimum transmissivity values for each site are also available. Three additional sites in the P2 area had a maximum value of more than 1000 m^2/day, and the highest maximum transmissivity reported is 5600 m^2/day. Whilst the “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.

Despite the fact that most of the evidence for limestone karst documented in this report is associated with the Cadeby Formation rather than the Brotherton Formation, transmissivity of the Brotherton Formation is reported to be higher than that of the Cadeby Formation, and this was thought to be because the Brotherton Formation is less dolomitised and contains more calcite making it more prone to dissolutional development of permeability (Allen et al., 1997; Medici et al., 2019a).

Faults are an important control on permeability, and at many sites high transmissivities are associated with faulting. For example, high yields of up to 80 l/s at Bramham [SE 425430], Tadcaster [SE 485431] and Grimston [SE487416] are reported to be associated with fault lines that result in increasing fissuring (Aldrick, 1978; Allen et al., 1997). These sites are shown on Figure 73. The best locality estimate of transmissivity at Tadcaster is 790 m^2/day, and the maximum is 2000 m^2/day. This may be influenced by gypsum karstification as much of the water abstracted in Tadcaster contains dissolved gypsum (Cooper et al., 2011). At Bramham it is thought that dissolution has enhanced the permeability in the zone of water table fluctuation, with lower yields when water levels are lower (Allen et al., 1997). Allen et al. (1997) note that faulting results in higher yields at Norton and Sprotborough (Figure 73). They also suggest that faults can act as barriers to compartmentalise the aquifer. Where faults act as a barrier there may be karstic solutional enhancement of permeability due to the concentration of groundwater flow at the barrier.

Many of the transmissivity estimates are for sites located in the upper part of the Zechstein Group in the east of the P2 area, and therefore the boreholes are very likely to penetrate gypsum within the Roxby and Edlington Formations. It is likely that the gypsum in the Edlington and Roxby formations in these areas could contribute more to the local transmissivity than the Cadeby and Brotherton formations. However, it is probable that the Cadeby Formation is the main water source and artesian upward flow from this has caused the karstification in the overlying gypsum.

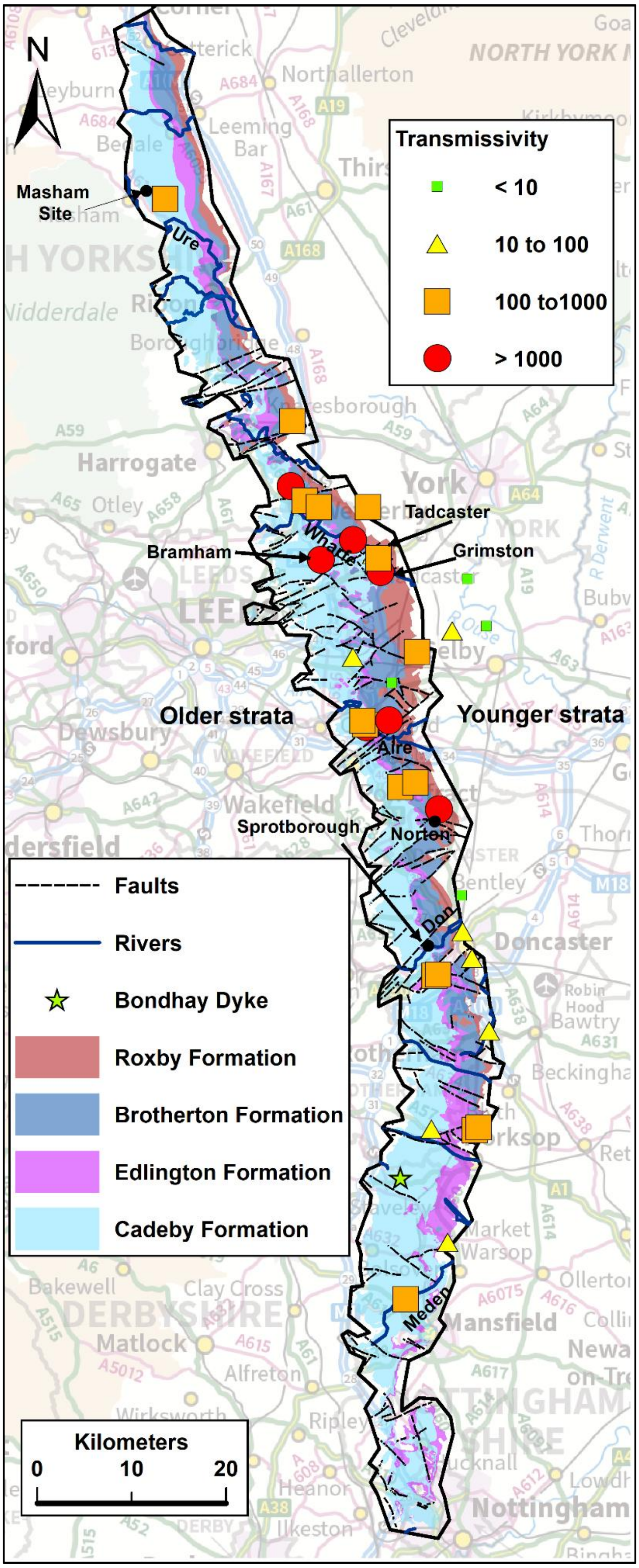

Figure 73. Transmissivity in the Permian limestones (m^2/day).

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4.3 WATER QUALITY INDICATORS OF RAPID FLOW

Data on water quality indicators of rapid flow at borehole abstractions have not been collated for this report. However, there are some indications from the literature of water quality indicating rapid groundwater flow and Murphy and Lowe (2021) note that the Permian limestones are vulnerable to rapid pollutant transport. For example, when the Permian limestones at Bramham were used for public supply, there was a contamination incident due to sewer leakage which led to an estimated 3000 cases of gastro-enteritis in the supply area (Short, 1988). In the run up to the contamination incident, there are bacteriological data for 35 occasions between December 1979 and July 1980 (Short, 1988). In this period coliform counts ranged from 0 to >18 and Short (1988) suggested that contamination was likely to be restricted to one of four boreholes at the site. This was the last borehole to be constructed (borehole 4) and there had been little evidence of bacteriological contamination at the other three boreholes prior to this (Short, 1988). This illustrates the high heterogeneity in the Permian limestones, with variable solutional development of permeability resulting in nearby boreholes intercepting different solutional networks.

The reported baseline groundwater chemistry in the area indicates that Permian limestone groundwater residence times can be short, for example sites with depleted δ13C, suggesting limited isotopic equilibration (Bearcock and Smedley, 2009). Bearcock and Smedley (2009) also report an unusual site near Masham in Yorkshire [SE 24 82] which has particularly low specific electrical conductance (203 µS/cm) suggesting very recent recharge and limited contact with aquifer minerals. However, specific electrical conductance was high at other sites in the Permian limestones. Further assessment of water quality indicators of rapid flow (e.g. coliforms, turbidity, short residence time pesticides) would provide more insights into the frequency and distribution of rapid flow.

4.4 FLOW VELOCITIES AND CONTAMINANT TRANSPORT

Contaminant transport properties of the Permian limestones have been investigated by Medici et al. (2019a, b) who consider flow velocities and effective porosities in light of the conduit development in the aquifer. Medici et al. (2019a) use slug tests and groundwater level monitoring to estimate groundwater velocities of 13 to 242 m/day in fractures enhanced by dissolution in boreholes at the University of Leeds Farm study site. This site is near Tadcaster (Figure 73) and the boreholes are located on the Cadeby Formation. Borehole inflows were bedding plane controlled, and karstification was observed for about 15 m below the water table, with a rapid decrease in slug test permeability with depth below the water table (Medici et al., 2019a). Medici et al. (2019b) modified an existing MODFLOW model of a large area between Leeds and York, and included karst development (pipeflow) associated with faults in the model. In fault zones, the modelled groundwater flow velocities for the conduit flowpaths ranged from 500 to 9000 m/day suggesting very rapid flow, whilst modelled flow velocities in un-faulted areas were still rapid at ~ 100 to ~ 500 m/day (Medici et al., 2019b). Very low effective porosities (2.8×10^{-4}) were calculated using borehole data for the Permian limestones in the Leeds-York area by Medici et al. (2019a,b); who note that the more widely applied higher effective porosities used in groundwater modelling result in a large underestimation of the rates of contaminant transport in the aquifer, and suggest that the lower values are more appropriate. Medici et al. (2019b) also report that although larger karstic solutional fissures and conduits occur in the Permian limestones, especially in relation to faults, the majority of fractures have narrow apertures of < 1 mm. This would suggest that whilst the karstic networks may have the greatest impact on transmissivity and flow, and may enable long distance and/or rapid contaminant transport, there is likely to be considerable potential for attenuation through dispersion and diffusion into the smaller fracture network, and dilution of contaminants.

4.5 KARST DISTRIBUTIONS

Figure 74 brings together the different features and factors indicating karst in the Permian limestones using subsets of the data presented in previous sections to focus on the features that are most likely to be indicative of karstic development in the limestones. The data presented here comprise: caves that are known to be of karstic origin; dissolution related stream sinks; dolines, that may be associated with limestone karst; dissolution pipes; springs that are likely to be substantial; borehole sites where maximum estimates of transmissivity exceed 1000 m^2/day; the tracer test location at Bramham; and the Annersley Tunnel inflow site. The datasets are not comprehensive, but nevertheless show that there is evidence for karstic development within the Permian limestones throughout much of the P2 area.

Areas with particularly notable indications of karst include: (1) the River Skell in the north where there is a major karst river sink and the river is dry for several kilometres (2) The Bramham-Tadcaster-Boston Spa area to the east of Leeds around the River Wharf where there is evidence of cave and conduit development, surface-groundwater interaction, rapid groundwater flow indicated by water quality data and tracer tests, and high borehole transmissivities and yields. (3) the area to the south-west of Doncaster with the Wadworth Wood stream sinks. (4) The area near the River Aire where there are surface karst features and some high transmissivities. (5) the Maltby and Cresswell Gorge areas where there is significant karstic cave development.

In the north of the area no karst features are recorded (other than the potential losses from the River Ure discussed in Section 2.4.3). Whilst this could reflect biases in where studies have been undertaken, it is also the area where there is the most extensive and deepest superficial cover, predominantly comprising low permeability glacial till (Figure 3 and Figure 4). It is therefore quite likely that surface karst features and larger springs could be absent, and there may be less potential for subsurface development of conduit networks, although any surviving karst that predates glaciation will be concealed beneath the cover. There is also less evidence for karst in the southernmost part of the P2 area. However, there are some springs in this area that are likely to be substantial which would suggest the development of subsurface solutional networks, and the Annersley Tunnel site where large inflows of more than 100 l/s were recorded (Lamplugh et al., 1914) is also located in this area, suggesting that extensive solutional networks occur.

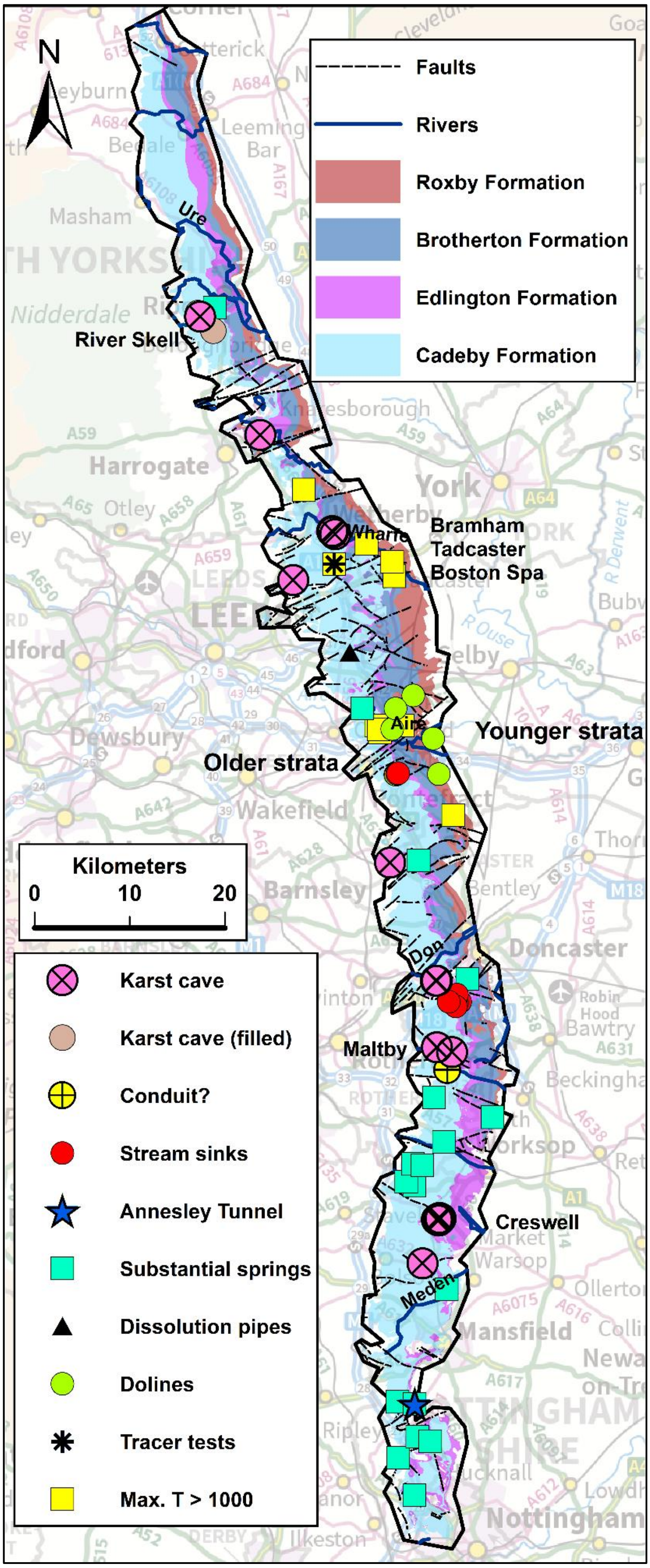

Figure 74. Compilation of karst features and indicators in the limestones of the P2 area.

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4.6 KARSTIC GROUNDWATER FLOW IN THE PERMIAN LIMESTONES

Subsurface karstic networks can develop along stream sink to spring flowpaths (Ford and Williams, 2007) or by mixing corrosion (Bögli, 1964). There has been insufficient work on the karst of the Permian limestones to establish the relative contributions of these processes. Although there are karst stream sinks present, the stream sinks dataset is incomplete, and there have been no tracer tests undertaken to establish their groundwater outlets or the characteristics of the flowpaths. There is no dataset on spring characteristics and discharges to enable identification of those that might form the more important groundwater outlets, and it is likely that spring discharges have been impacted and reduced by anthropogenic development and groundwater abstraction making it harder to identify natural outlets for karst networks. The lack of known cave development associated with stream sinks and springs in the Permian limestones suggests that any currently active stream sink to spring karst networks represent a much smaller scale of conduit development than those observed in highly karstic aquifers such as the Carboniferous aged limestones in the nearby Yorkshire Dales and Derbyshire Peak District. Stream sink to spring karstic networks may have developed in the past under different geological, geomorphological and hydrogeological settings, but again there is no clear evidence that this resulted in extensive large scale cave development. Whilst the dry karst cave systems of the Cresswell Gorge and Maltby, with large passages and chambers, prove that larger scale conduit development has occurred in the Permian limestones, these caves are short, suggesting that they may have been fairly localised systems. Mixing corrosion is well established as an important mechanism of karstic development in the sub-surface (Bögli, 1964, Dreybodt, 1981), and solutional fissure and conduit development in the Permian limestones could be a result of mixing corrosion. The hydrochemical studies indicating that groundwaters are usually saturated with respect to calcite and dolomite (Section 4.3) might support this hypothesis.

The data collated in this report demonstrate that a component of unsaturated zone flow in the Permian limestones is rapid. Rapid unsaturated zone flow will occur where there are karst stream sinks or point recharge via riverbeds, and may also occur where there are dolines, or via solutional fissures where there is no surface expression or obvious karst feature. Where the limestones are covered by low permeability till deposits (Figure 30) rapid unsaturated zone flow is unlikely, although these deposits are generally thin (Figure 4). Where thicker till deposits occur it is possible that they enable some surface runoff that subsequently sinks into the limestones where the cover becomes very thin or absent, although no stream sinks in this setting were identified from literature review. Based on data and information collated for this report, it is not possible to draw any conclusions about the proportion of flow in the unsaturated zone that is rapid, or how frequently rapid flowpaths extend through the entire unsaturated zone. Although stream sink records are sparse, there are karst stream sinks in different parts of the P2 area (Figure 27), and there may be other areas with stream sinks enabling rapid unsaturated zone flow. Rivers may also provide rapid recharge into solution fissures and conduits where they cross the Cadeby and Brotherton Formation limestones in the absence of low permeability superficial cover.

It is difficult to assess how common and how extensive saturated zone karst networks are. Evidence of cave, conduit and solutional fissure development; and some high transmissivities and high borehole yields suggest that there are saturated zone networks of solutional fissures and conduits which could enable pollutant transport over long distances and in unexpected directions, but further work is needed to determine how frequently these networks occur and how extensive they are. Overall, it appears that the Permian limestones are more similar to the English Chalk than the UK Carboniferous limestones in terms of the size and scale of karst features. The karst hydrogeology of the Permian limestones is complicated by interactions with the extensive karstification of the adjacent evaporite strata and this is discussed in Section 5.

5 Preliminary conceptualisation of Permian limestone and gypsum karst hydrogeological interactions

5.1 INTRODUCTION

The hydrogeology of the Permian limestone karst divides into two regimes, the largely vadose system that drains the outcrop of the Cadeby Formation mainly in a westerly direction and the phreatic artesian system that drains eastwards combining with the karstic groundwater of the gypsum. The Cadeby Formation dip slope is the main aquifer catchment, but the Brotherton Formation also has a small catchment. The easterly drainage and water from them which is under artesian pressure is responsible for the karstification of the gypsum sequences in the Edlington and Roxby Formation and the development of hypogene karst (Klimchouk, 2013) in these rocks. This section outlines the unusual artesian hydrogeology that results from interactions between the limestone and gypsum karst (Section 5.2), and provides a brief overview of the process of dedolomitization which occurs during interactions between the dolomite of the Cadeby Formation and the underlying gypsum (Section 5.3).

5.2 ARTESIAN HYDROGEOLOGY OF THE LIMESTONE AND GYPSUM SEQUENCES

The hydrogeology of the Permian limestones is complicated by interactions with the gypsum sequences in the Edlington and Roxby formations lying between and above the main limestones of the Brotherton and Cadeby formations (Table 1). In the south of the study area, where gypsum is thin or not present, the low permeability mudstones of the Edlington and Roxby formations might enable surface runoff that sinks into the limestones of the Cadeby and Brotherton formations. This has also been suggested by Buckland et al. (2017) as the cause of possible sinkholes further north at Wadworth Wood. The Roxby Formation is classified as an aquitard (Allen et al., 1997), and in places low permeability mudstones within the Roxby Formation can confine the underlying aquifers (Allen et al., 1997); this is of relevance in the south. However north of Doncaster, there is extensive karstic dissolution of the gypsum within the Edlington and Roxby formations (Section 2.3.4 and 2.5.1). In some places there are breccia-filled subsidence pipes and foundering within the Brotherton Formation as a consequence of dissolution of the underlying gypsum in the Edlington Formation (Cooper, 1989). There are also breccias related to the dissolution of the gypsum in the Roxby Formation. Sulphate rich springs, largely fed with water from the Cadeby Formation occur above the Edlington, Brotherton and Roxby Formations (Cooper et al., 2013) indicating strong connectivity between the limestones, gypsum and breccia pipes. In places these also link up with the overlying Sherwood Sandstone Group aquifer (Cooper, 1989). The system is largely driven by artesian water that is recharged on the wide limestone dip slopes and fed downdip. It can emerge as artesian springs in the low ground to the east, but is particularly influenced by the intersection of the bedrock sequence by partly buried valleys incised during the ice-ages.

The Edlington Formation is described as a leaky aquitard by Allen et al. (1999) who note that there is generally a small head difference between the Brotherton and Cadeby Formation aquifers, suggesting limited connectivity. However, dissolution of the extensive evaporite deposits within the Edlington Formation results in frequent karstic collapse features and foundering within the overlying Brotherton Formation (Cooper, 1986,1989,1998, 2020; Ellison, 1989). Cooper (1986, 1998) shows that some breccia solution pipes beneath larger subsidence areas on the Edlington Formation emanate from as deep as the top of the underlying Cadeby Formation. Artesian groundwater flow in the Cadeby Formation can move up through the geological sequence and into the Edlington Formation where the magnesium and calcium rich waters dissolve the gypsum in an enhanced way (Cooper et al., 2013). Cooper (1998), Cooper et al., (2013); and Cooper et al. (2013) note that recharge onto the dip slopes of the Cadeby and Brotherton formations flows down dip (east) and into the adjacent evaporite strata before being discharged in river valleys via buried valleys. Cooper (1988) suggests that groundwater abstraction from the Permian limestones and gypsum is greatly enhancing the rate of gypsum dissolution in the Ripon area, with greater dissolution adjacent to boreholes with rapid flow. The artesian flow of water down through the Cadeby and Brotherton formations is responsible for strong-flowing carbonate-rich springs at the east of the Cadeby Formation (such as Mill House and Pudding Pie Hill springs - Table 6 and Table 7). Further east where the water has passed through significant gypsum karst the springs above the Edlington, Brotherton and Roxby formations are high to very high in dissolved sulphates (most of the springs in Table 6 and Table 7).

5.3 DEDOLOMITIZATION

A further feature of the Cadeby Formation is the local presence of dedolomite that manifests itself as low-strength calcitic boxwork or calcitic sand in the upper part of the formation; this occurs where the dolomitic limestone is in contact, or has formerly been in contact, with gypsum or sulphate-rich water. Such materials were noted in mineral assessment boreholes north of Ripon (Powell et al., 1992) and calcitic sand was being washed out of springs on the west of Snape Mires (Cooper et.al., 2013; Mill House Spring - Table 6). Similar material was seen by Cooper in commercial boreholes drilled in 2018 near Knottingley and no recovery from this interval was noted in BGS registered borehole SE52SW41.

The passage of gypsum-rich water down into the dolomitic limestones causes the dedolomitization chemical reaction to occur and has been referred to as karstification without carbonic acid (Bischoff et al. 1994; Raines and Dewers 1997; Williams and McNamara 1992). This reaction dedolomitizes the dolomite turning it to calcite leaving a porous rock, commonly with very little strength. The occurrence of dedolomitization can produce cavities and enhanced porosity. Similar boxwork and breccia-looking dedolomite deposits (often tectonised) are also referred to as Cargneule or Cornieule in France, Corniola in Italy and Rauhwacke (plus the related Zellendolomit) in Germany.

6 Summary

- Permian dolomitic limestone karst occurs within both the Brotherton and Cadeby formations in the P2 area.
- There are at least 21 limestone karst caves which range from 2.5 to 290 m in length, and often include passages with dimensions of several metres. None of these karst caves are currently hydrologically active. These Permian limestone karst caves are in the Cadeby Formation.
- There are many other “slip rift” caves which are formed by mass movement, and many caves where it is unclear whether they are slip rifts or caves that are partially or fully karstic in origin.
- The longest known karst cave in the Permian limestones is Robin Hood’s Cave in the Creswell Gorge which is 290 m long. Other significant karst caves are present within the gorge.
- There is evidence that smaller scale conduit and fissure development is common in the Brotherton and Cadeby formations.
- Stream sink records in the area are incomplete, but some streams sinking into the Cadeby Formation have been documented including a significant karst river sink on the River Skell, and an area of significant karst stream sinks near Doncaster.
- Data on river losses indicating recharge to karstic fissures and conduits were not collated for this report.
- There are many springs on the Permian limestones. For many, there is little information about their discharge and characteristics. Most appear to be small features with some that are likely to be substantial.
- The larger springs may be fed by combined limestone and gypsum karst systems.
- A “spring” in Annersley Tunnel was reported to have flows of more than 100 l/s suggesting that the tunnel intersected a karstic network.
- Tracer tests at one site over short distances (10s to 100s m) demonstrate rapid flow and connectivity between a groundwater abstraction borehole and both a leaking sewer system and a nearby surface water course.
- There is little information on limestone karst dolines and dissolution pipes, although some are known to occur.
- Dolines and dissolution pipes in the limestones that are associated with the adjacent gypsum karst of the Roxby and Edlington formations are common.
- Karst is extensive in the gypsum and includes caves, dolines, and dissolution pipes, and groundwater interaction occurs between the evaporite and limestone karst.
- Considering solutional karstic development within the dolomitic limestones of the Zechstein Group, there appears to be more evidence for solutional enlargement of fractures to form stream sinks, fissures, conduits and caves in the Cadeby Formation than in the Brotherton Formation, although both are karstic.
- There is particularly strong evidence for karst associated with the River Skell and in the Wadworth Wood area near Doncaster.
- There is also strong evidence for karst in the area around Bramham/Tadcaster/Boston Spa with conduit development, surface-groundwater interaction, rapid groundwater flow indicated by water quality data and tracer tests, and high transmissivities and yields.
- Further work is needed to develop better datasets and understanding of karst in the Zechstein Group dolomitic limestones and how it interacts with the evaporite karst to assist with groundwater studies and management.

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.

Hypogene Karst: Karstic solutional cavities formed by upwelling groundwater from below which is independent of recharge from the surface (Ford and Williams, 2007; Klimchouk, 2013)

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.

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 swalllow 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.

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