A66 Northern Trans-Pennine Project
TR010062

3.4 Environmental Statement Appendix 14.8 Desk Study Karst Risk Assessment

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3.4 ENVIRONMENTAL STATEMENT APPENDIX 14.8 DESK STUDY KARST RISK ASSESSMENT

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14.8 Desk Study Karst Risk Assessment

14.8.1 Introduction

14.8.1.1 The A66 Northern Trans-Pennine Preliminary Sources Study report (PSSR) (HE565627-ARC-HGT-A66-RP-CE-2005, 7 October 2019)[1] states that dissolution in the gypsum and limestone bedrock present in scheme areas can develop dissolution features. These features, such as caves, voids, dolines, stream sinks and risings, are referred to as karst and are significant geotechnical subsidence hazards. Although dissolution features occur underground, they frequently develop surface expressions, and the presence of these surface features is generally well documented.

14.8.1.2 The PSSR identifies those schemes that are located on gypsum and limestone as being at risk of subsidence from preferential dissolution and states that the proposed ground investigation will investigate these dissolution features. However, the PSSR does not provide reference to sources in the public domain where information on karst features are available.

14.8.1.3 In designing a ground investigation tasked with identifying dissolution features, the first stage is to undertake a desk study review of publicly available information on surface karst features (dolines, stream sinks and risings) as well as underground features (caves and voids) so that the presence of karst processes (dissolution) can be assessed and quantified.

14.8.1.4 Available sources of karst features include the British Geological Survey National Karst Database (Farrant and Cooper, 2008)[2] as well as public documents and academic journals. In addition, simple well established remote sensing tools, such as processing of LIDAR (Light Detection and Ranging) elevation data, are widely recognised to identify where surface karst features are present.

14.8.1.5 This karst desk study report provides a review of the existing public databases, documents and publications of karst occurrence along the A66 Northern Trans-Pennine. This report also uses LIDAR ground elevation data to screen where surface karst features may be present. These data, in conjunction with the distribution of rock types, are used to assesses the potential for karst risk along sections of the A66 Northern Trans-Pennine proposed for upgrade to dual carriageway ('the Project'). The alignment upgrade is proposed for eight individual sections (or 'schemes') of the existing A66, with the works comprising of online upgrades as well as new sections of road. The sections of upgrade/new roads comprise of:

- M6 Junction 40 to Kemplay Bank
- Penrith to Temple Sowerby

[1] Highways England (2019) HE565627-ARC-HGT-A66-RP-CE-2005. A66 Northern Trans-Pennine Project. Preliminary Sources Study Report.
[2] Farrant A & Cooper A (2008) Karst geohazards in the UK: the use of digital data for hazard management. Quarterly Journal of Engineering Geology and Hydrogeology, 41 (3) 339-356

- Temple Sowerby to Appleby
- Appleby to Brough
- Bowes Bypass
- Cross Lanes to Rokeby
- Stephen Bank to Carkin Moor
- A1(M) Junction 53 Scotch Corner.

14.8.1.6 The aim of this report is to identify where there is a karst risk along the Project based on available information. Karst risk is defined as the likelihood of dissolution potential in bedrock that could cause natural subsidence or collapse of the ground surface. As per Ford (2007)[3] and Gunn (2004)[4], karst is described as:

'Terrain with distinctive hydrology and landforms arising from the combination of high rock solubility and well-developed solution channel (secondary) porosity underground.'

14.8.1.7 This desk study is used to inform the design of the Project and construction risks, especially where karst features are identified near scheme design elements. The information from this report is also used to inform Environmental Statement (ES) assessments.

14.8.1.8 It is acknowledged that uncertainty is inherent to the assessment of karst risk along the route as karst hazards are identified by surface topography which can be influenced by a variety of natural and anthropogenic (human) factors. As such, any potential karst features that are a significant risk to the scheme should be validated by site investigation. In addition, karstic features may be encountered that have not been identified in this desk study, requiring appropriate additional investigation and control measures (e.g., a voids treatment protocol).

14.8.2 Identification of Karst Features

14.8.2.1 Those rock types with high solubility that support karst process are mainly restricted to carbonate and evaporite rock types; specifically limestone, dolomite and evaporites (most notably halite, gypsum and anhydrite). Other rock types can host karst (such as marble and quartzite) however, karst in these 'other' rock types generally do not occur in the British Isles.

14.8.2.2 Although karst processes largely occur in limestones, dolomites and evaporites, the process can impact adjacent rock types also. In the British Isles there are many examples where the development of karst has led to the development of subsidence and collapse structures in the overlying cap rock. This is particularly the case for gypsum karst of the Ripon area in Yorkshire as well as the limestone karst of the Yorkshire Dales and the Brecon Beacons. On this basis, karst risk is assessed for those limestone, dolomite and evaporite strata along the proposed upgraded/new sections of the alignment as well as those strata that overlie them.

[3] Ford D & Williams P (2007) Karst Hydrogeology and Geomorphology. Wiley, 576 pp.
[4] Gunn J (2004) Encyclopedia of Caves and Karst Science. Fitzroy Dearborn

14.8.2.3 This section focuses on the identification of karst features, which includes both surface landforms and caves. This section is divided into the following subheadings:

- Available information and data sources
- Geological setting
- Known karst landforms and caves
- Assessment of karst landforms using LIDAR and aerial photographs
- Summary: Stratigraphic setting of karst features.

Available information and data sources

14.8.2.4 British Geological Survey (BGS) provide geological mapping for the project area, which has been used to identify those limestone, dolomite and evaporite strata that have the potential to host karst (License: OS 100030649). 1:50,000 scale BGS mapping has been used for the assessment (British Geological Survey, 1969)[5], (British Geological Survey, 1974)[6], (British Geological Survey, 1997a)[7], (British Geological Survey, 1997b)[8], (British Geological Survey, 2004)[9] (British Geological Survey, 2022)[10].

14.8.2.5 BGS maintain a database of cave and karst features in the National Karst Database (NKD), which has been accessed for use on this project.

14.8.2.6 Ordnance Survey provide topographic maps for the region, which often include identifying features such as caves, potholes, pits and springs.

14.8.2.7 The Environment Agency provides national LIDAR data at a resolution of 1m for England[11].

14.8.2.8 Caving and potholing societies and clubs have undertaken exploration of caves and surface karst features in the North Pennines area. Where relevant, reference is made to karst landforms and caves. Of particular note is the Caves and Karst of the Yorkshire Dales (Volume 2 The Caves), which includes a section on the Caves of the North Pennines (Chapter 32: Ryder P. and Harrison T.) that provides a detailed overview of cave explorations in the region (Waltham and Lowe, 2017)[12].

[5] British Geological Survey (1969) Geological Survey of Great Britain - Barnard Castle, Keyworth: BGS.
[6] British Geological Survey (1974) Geological Survey of Great Britain - Brough-under-Stainmore - Map 31, Keyworth: BGS
[7] British Geological Survey (1997a) Geological Survey of Great Britain - Richmond - Map 41, Keyworth: BGS.
[8] British Geological Survey (1997b) Geological Survey of Great Britain - Kirkby Stephen - Map 40, Keyworth: BGS.
[9] British Geological Survey (2004) Geological Survey of Great Britain - Appleby - Map 30, Keyworth: BGS.
[10] British Geological Survey (2022) Geoindex [Online] Available at: http://mapapps2.bgs.ac.uk/geoindex/home.html
[11] Department for Environment Food and Rural Affairs (2017) Defra Data Services - LIDAR datay
[12] Waltham T and Lowe D (2017) Caves and Karst of the Yorkshire Dales. Buxton: British Cave Research Association, 328pp.

14.8.2.9 Additional publicly available scientific literature and reports (e.g. BGS research reports) have been reviewed which are referenced where appropriate.

Geological setting

14.8.2.10 The geology that the A66 traverses is presented as an indicative West to East cross section in Plate 1: Indicative geological cross section of A66 route below. The geology that the A66 traverses may be summarised as comprising:

- Permo-Triassic sandstone sequences with shales and gypsum west of the Pennines between Penrith and Brough in the Vale of Eden.
- Carboniferous sandstones, limestone and shales in the uplands of the Pennines between Brough and Scotch Corner.

14.8.2.11 The Permo-Triassic and Carboniferous strata are faulted against each other near Brough by the Penrith Fault, which forms the steep escapement backdrop along the North Pennines from Brough to Penrith.

Bedrock geology

14.8.2.12 A stratigraphic column of the bedrock geology encountered by the A66 is shown in Plate 2: Stratigraphic column of geological units encountered by the A66 route and Plate 3: Stratigraphy of gypsum beds in the Vale of Eden, which provides a detailed stratigraphy of the geology in the Vale of Eden (the western half of the route).

14.8.2.13 The Permo-Triassic sandstone sequence in the Vale of Eden comprises largely of the Penrith Sandstone, which underlies most of the valley between Brough to Penrith. As the topography steepens northwards into the Pennines the overlying Eden Shales Formation and St Bees Sandstone outcrop. The Eden Shales Formation includes a number of gypsum horizons, some of which are mined locally, notably at Kirkby Thore, where the lowest gypsum horizon (Bed A) directly overlies the Penrith Sandstone Formation.

14.8.2.14 The Carboniferous Yoredale Group consists of interbedded limestone, shale and sandstone cyclical facies successions. The lower unit, the Alston Formation consists of Bioclastic limestones, sandstones, mudstones, siltstones and rare coals typically in regular cyclic sequence. The uppermost unit of the Alston Formation is the Great Limestone Member. The overlying Stainmore Formation consists of cyclical repetition of sandstones, siltstones, mudstones, with thin limestones and some coals.

Superficial deposits

14.8.2.15 Superficial deposits underlie large sections of the scheme, except for the escarpment ridge where bedrock is exposed.

14.8.2.16 The superficial deposits generally comprise of (from oldest to youngest):

- Glacial deposits
- Glacial till - diamicton

- Glaciofluvial - sands and gravels
- Alluvium - clay, silt, sand and gravel
- Peat.

14.8.2.17 Generally, peat is found on the uplands of the Pennines in the middle of the Project, whilst glacial and alluvial deposits are found along the side of the valleys at the eastern and western ends of the Project.

14.8.2.18 The thickness of the superficial deposits varies across the route from 1.5m to 41.5m. However, most historical borehole logs indicate thickness of less 4.5m.

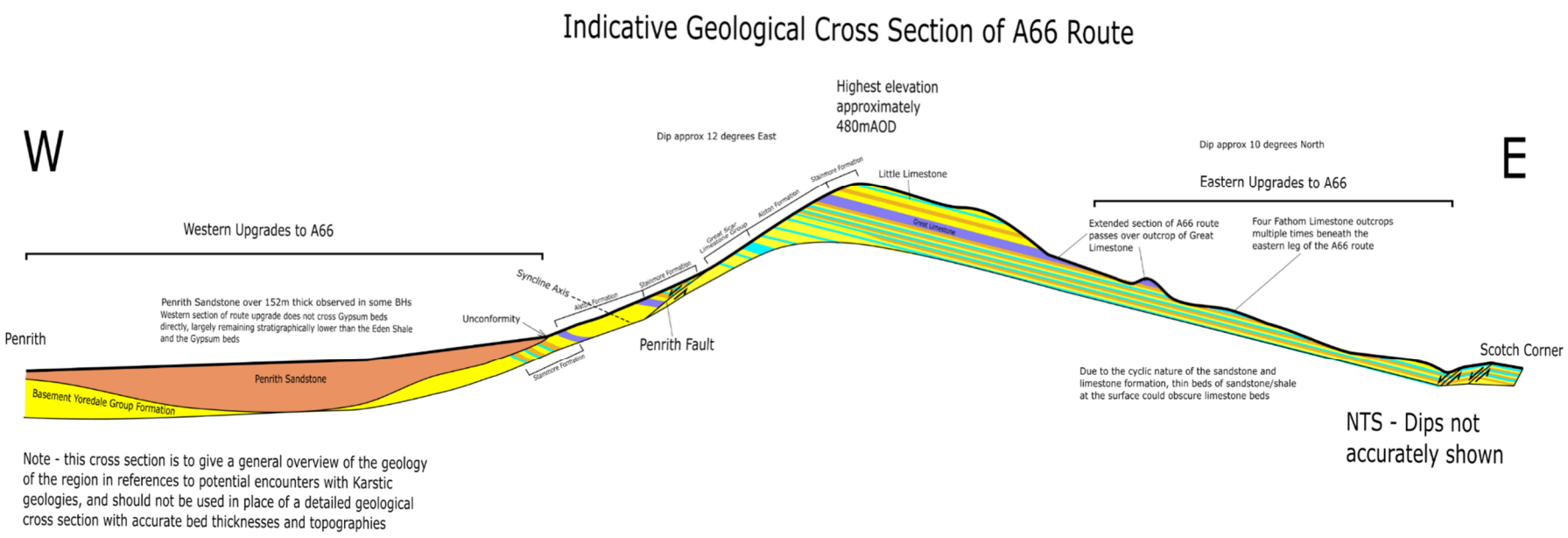

Plate 1: Indicative geological cross section of A66 route (compiled based on BGS 1969, 1974, 1997a, 1997b, 2004)

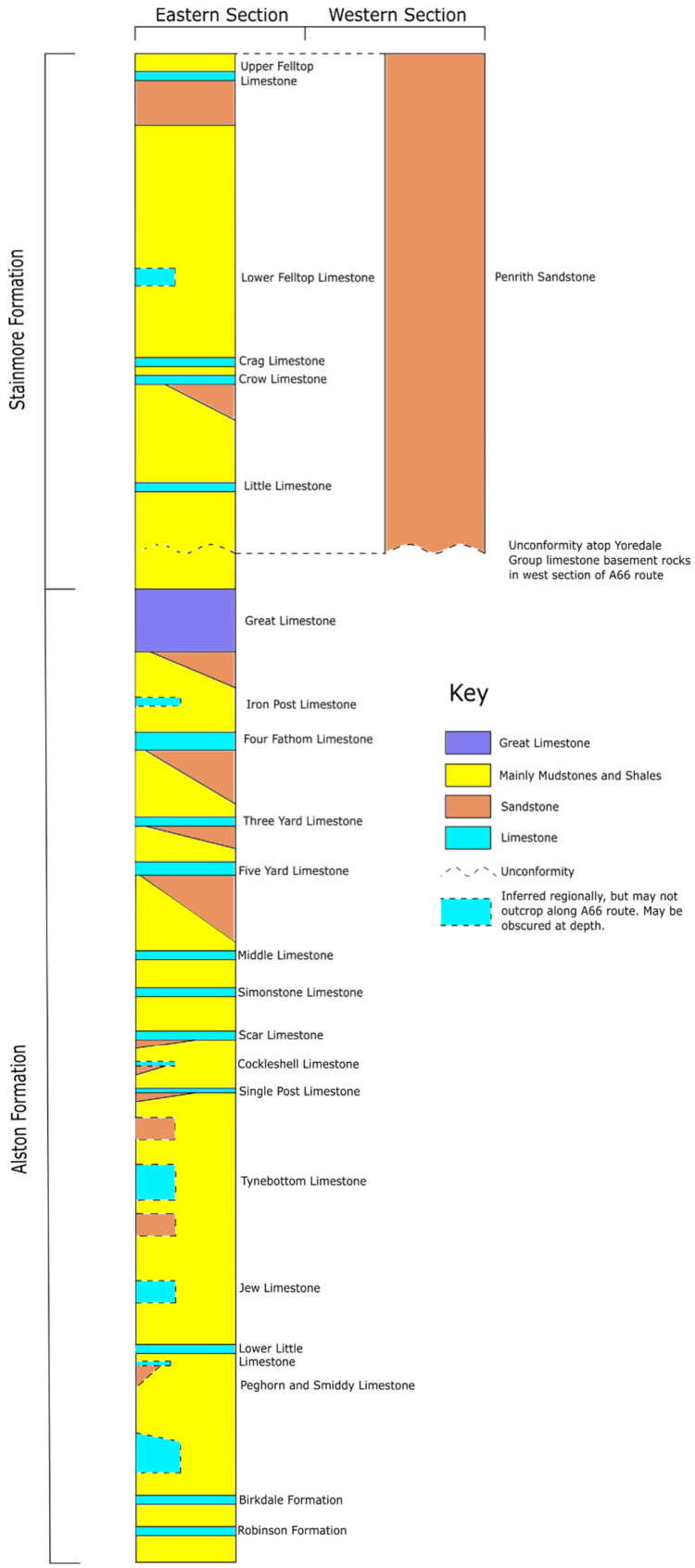

Plate 2: Stratigraphic column of geological units encountered by the A66 route (compiled based on BGS 1969, 1974, 1997a, 1997b, 2004)

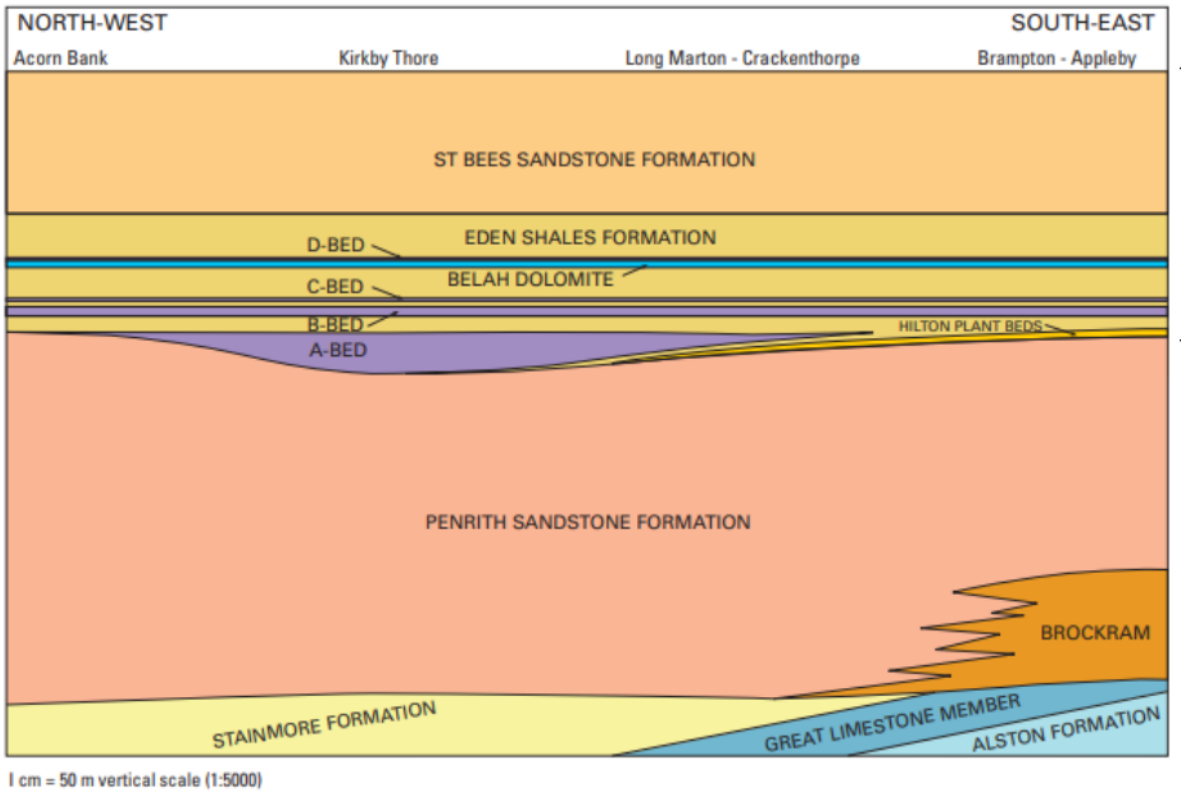

Plate 3: Stratigraphy of gypsum beds in the Vale of Eden (Hughes, 2003)[13]

Geological structure

14.8.2.19 From west to east, the A66 traverses a fault structure that comprises of the Permo-Triassic sedimentary basin in the west and Stainmore Trough in the east.

14.8.2.20 The Penrith Sandstone Formation is generally flat lying or with a slight northward dip. The contact between Penrith Sandstone Formation and the overlying Eden Shales Formation is unconformable.

14.8.2.21 The Carboniferous strata in the Stainmore Trough dip gently eastwards from Stainmore. At the highest point of the escarpment, the A66 runs first along the dip slope of the Stainmore Formation. At God's Bridge, the A66 crosses onto the dip slope of the underlying Great Limestone Member of the Alston Formation, which it traverses for several kilometres as far as Rokeby, near Greta Bridge. From Greta Bridge, the A66 continues to traverse down through the sequence of the Alston Formation crossing the Four Fathom Limestone Member and the Five Yard Limestone Member.

Hydrostratigraphy (Aquifers, aquitards and aquicludes)

14.8.2.22 The aquifers traversed by the A66 comprise of the Penrith Sandstone Formation in the west, and the limestone and sandstone members of the Alston and Stainmore Formations in the east. The Environment Agency

[13] Hughes RA (2003) Permian and Triassic Rocks of the Appleby district (part of Sheet 30, England and Wales). British Geological Survey Research Report, RR/02/01. 21pp.

have classified the Penrith Sandstone Formation as a Principal aquifer, whilst the sandstones and limestones of the Alston Formation and Stainmore Formation are classed as Secondary A aquifers.

14.8.2.23 Within the Permo-Triassic sequence the Eden Shales Formation will form an effective hydraulic barrier that separates the Penrith Sandstone Formation from the St Bees Sandstone Member. Within the Carboniferous Alston Formation and Stainmore Formation, the sandstone and limestone members will form separate aquifer units that are hydraulically separated by interbedded shales.

Known caves and karst

14.8.2.24 This section describes those caves and karst features that have been identified in the region of the A66 and the geological units that the caves have developed within.

14.8.2.25 In total there are two known cave systems that occur within 2km of the existing A66, shown on ES Figure 14.8.1: Karst Hazard Map (Features within 2km) (Application Document 3.3). These are Smeltmill Beck Cave and God's Bridge River Cave (Ryder and Harrison, 2017)[14]. Both Smeltmill Beck Cave and God's Bridge River Cave occur within the Carboniferous Great Limestone Member. Note that these two caves occur adjacent to the existing A66 and do not occur near those sections that are being upgraded as part of the proposed works. These two caves are also included in the BGS NKD. The BGS NKD also includes two cavity features located near Bowes (referred to as K2 and K4 that are shown on Figure 14.8.1: Karst Hazard Map (Features within 2km) Sheet 7 of 10 (Application Document 3.3) , both of which are in the Great Limestone Member.

Smeltmill Beck Cave

14.8.2.26 Smeltmill Beck Cave occurs between Stainmore and Brough in the scarp slope of the Great Limestone Member on the western flank of the Pennines. It is a branching cave system (1.9km long) that crosses below the existing A66:

- NGR: NY 8475 1465
- Length 1.9km
- Vertical Range <60m
- Mapped geology: Great Limestone Member (Alston Group).

God's Bridge River Cave (Gretadale)

14.8.2.27 God's Bridge River Cave is located near Bowes. It is a short cave system associated with the cave remnant that forms a natural arch at God's Bridge, though which the Greta River flows. At God's Bridge the river sinks and rises several times into solutionally enlarged bedding planes and fractures.

[14] Ryder and Harrison (2017) Caves of the Northern Pennines. Chapter 32 in Waltham T and Lowe D (eds.) (2017). Caves and Karst of the Yorkshire Dales (Volume 2). Buxton: British Cave Research Association.

- NGR: NY 958 126
- Length and vertical range not reported
- Mapped geology: Great Limestone Member (Alston Group)

14.8.2.28 There are other caves within 5km of the existing A66 and these include:

- Lost Pool Sink
- Eller Beck Head Cave
- Mousegill Cave
- Windmore End Cave
- Swindalehead Cave
- Lunehead Mine Caverns
- Far Beck Bridge Cave.

14.8.2.29 All the above caves are reported in Ryder and Harrison (2017) and are included in the BGS NKD.

14.8.2.30 Lost Pool Sink, Ellerbeck Head Cave, Mousegill Cave Windmore End Cave and Swindalehead Cave are in the Great Limestone Member. Lunehead Mine Caverns and Far Beck Bridge Cave, which based on BGS mapping, are in the Four Fathom Limestone Member.

14.8.2.31 There are no caves reported in the gypsum beds in the Permo-Triassic sequence in the Vale of Eden. However, multiple surface depressions are present, specifically in the area of Kirkby Thore, where gypsum beds are at or near surface.

14.8.2.32 Springs that are identified by Ordnance Survey mapping within the 1km study area are presented on Figure 14.8.2: Karst Desktop Study (Features within 1km) (ES Volume 2, Application Document Number 3.3). These springs identified by the OS in the north Pennines occur commonly in sandstone and limestone units. All springs appear to be of a small scale, with the only significantly large springs being associated with God's Bridge River Cave (Ryder and Harrison, 2017).

Assessment of karst landforms using LIDAR and aerial photographs

14.8.2.33 Karst features that are identified from BGS maps, Ordnance Survey maps and other publicly available information are presented in Section 2.3 Geological setting. These data sources generally include karst features such as caves, stream sinks, risings and springs. However, other karst features, specifically enclosed depressions (dolines), are generally not identified by these formats unless they are particularly large. Enclosed depressions are by far the most common karst landform and are a particularly useful indicator of groundwater pathways being present in limestone aquifers. Furthermore, the scale, shape and abundance of enclosed depressions can be used to provide information on the karst processes that may be present, as well as indication on seasonal flooding associated with them.

14.8.2.34 As part of the assessment of karst along the Project, LIDAR data was used to identify enclosed depressions, i.e. those topographic features where contours are circular and have lower elevations in the centre. In

general, LIDAR data has sub meter accuracy but for the purposes of this assessment only those features with a depth greater than 1m were considered.

14.8.2.35 The assessment was undertaken in GIS using an algorithm search tool to identify closed depressions only. In this way topographic highs (such as peaks of hills and buildings) were excluded. It is important to recognise that many man-made structures also appear as enclosed depressions and not just karst features. Those features such as quarries, mine pits, excavations, bunkers as well as drainage channels or attenuation ponds, golf course bunkers and craters on artillery ranges were also be identified. On this basis each LIDAR feature is screened using aerial photographs to identify if the feature has the potential to be an enclosed depression that is a doline and of karst origin. Most man-made structures are easily identified from aerial photographs and can quickly be discounted.

14.8.2.36 The results of the LIDAR assessment, with screening using aerial photographs, are provided in ES Figure 14.8.1: Karst Hazard Map (Features within 2km), (Application Document 3.3) for all those features identified as potentially being karst. These features are summarised below in terms of their stratigraphic location. Section 3 Karst and groundwater site survey provides hydrogeological characterisation of these features to consider the karst processes of each stratigraphic unit. In terms of identification numbers for the karst features, there are two datasets, one for gypsum karst and one for limestone karst. In each dataset it should be noted that only those features that have the potential to be karst are included. Gaps in the numbering system are caused by features being initially flagged by LIDAR but then discounted based on observations from aerial photographs.

14.8.2.37 A desktop survey of karst and groundwater features was undertaken for all nine scheme areas. The GIS analyses of LIDAR and aerial photographs was only undertaken in those schemes located on gypsum or limestone. These comprise of:

- Temple Sowerby to Appleby
- Bowes Bypass
- Cross Lanes to Rokeby
- Stephen Bank to Carkin Moor

14.8.2.38 Whilst the Kirkby Thore karst is related to the Permo-Triassic gypsum deposits, the karst in the Bowes Bypass, Cross Lanes to Rokeby and Stephen Bank to Carkin Moor sections are related to Carboniferous limestones.

Temple Sowerby to Appleby
(gypsum karst – Eden Shales Formation)

14.8.2.39 A total of 15 enclosed depressions have been identified near Kirkby Thore that occur either in gypsum or shale beds of the Eden Shales Formation.

14.8.2.40 ES Figure 14.8.4: LIDAR Enclosed Depressions Sheets 3 and 4 (Application Document 3.3) illustrate those features identified as depressions in the land surface at Kirkby Thore where the Penrith Sandstone Formation (pinkish red) is overlain by the Eden Shales Formation (yellow). Within the Eden Shales Formation are several gypsum beds (purple). LIDAR has identified multiple depressions across both geologies.

14.8.2.41 In the area underlain by the Penrith Sandstone Formation, the enclosed depressions are mainly shallow, being 1m or less. Most of these features are associated with the River Eden, and on inspection include multiple sand bars, cut off meanders as well as areas of drainage. Other areas identified by LIDAR as being depressions are associated with roads or rail infrastructure and are related to drainage and culverts.

14.8.2.42 Those depressions that are identified in the Eden Shales Formation differ from those in the Penrith sandstone Formation by generally being deeper and more angular. Often the depressions in the Eden Shales Formation occur above mapped gypsum units. Focusing on a number of these features demonstrates these characteristics.

14.8.2.43 ES Figure 14.8.1: Karst Hazard Map (Features within 2km) Sheets 3 and 4 (Application Document Number 3.3) identify several enclosed depressions that are unrelated to surface water features and often over lie the gypsum deposits. Owing to the shallow nature of the deposits these features are likely to be a result of dissolution and historical mining. Often the shape of the enclosed depressions is elongate and follow the location of the mapped gypsum. It is noted that the proposed bypass at Kirkby Thore (within the Temple Sowerby to Appleby scheme) follows the contact between the Penrith Sandstone Formation and Eden Shales Formation, the contact of which is where the thickest gypsum unit (bed A) occurs. Structures, including over bridges and junctions are located on or adjacent to the Gypsum Bed A outcrop. The contact presented in these figures uses BGS 1:50,000 mapping. It is noted that the BGS borehole database (public domain) confirms the location of the contact. However, borehole records held by BGS include confidential logs which are not in the public domain and have not been reviewed. It is recommended that the project requests these logs from BGS, if agreed by the relevant stakeholder.

Bowes Bypass
(limestone karst – Great Limestone Member)

14.8.2.44 The Bowes area includes ten potential karst landforms within 2km of the road alignment as well as God's Bridge natural arch and God's Bridge River Cave (refer to Section 2.3). All significant karst landforms in the Bowes area occur in the Great Limestone Member. The Four Fathom Limestone Member is present south of Bowes where it underlies the Great Limestone Member, but doesn't include any identified enclosed depressions or caves; only springs.

14.8.2.45 ES Figure 14.8.1 Karst Hazard Map (Features within 2km) Sheet 7 (Application Document 3.3) illustrates those karst landforms identified by the LIDAR analyses with review using aerial photography. The cave system at God's Bridge is located 2km west of Bowes at Mellwaters, which is the most western extent of the Great Limestone Member outcrop (see ES Figure 14.8.2 Karst Desktop Study Features within 1km Sheet 7 (Application Document 3.3)).

14.8.2.46 LIDAR data clearly identifies quarries located east of Bowes and a drainage feature associated with a culvert on the existing A66 alignment. All features have been confirmed from aerial photographs.

14.8.2.47 Several features are identified adjacent to quarries that are north east of Bowes. These features are largely circular and generally shallow (2m deep or less) and up to 40m in diameter. One larger feature (3.8m deep and 443m wide) occurs on the north-eastern side of Bowes (ID 126) which occurs at the top contact of the Great limestone Member and may be related to surface water flooding.

14.8.2.48 There are no features identified in the Great Limestone Member along the online route of the Bowes Bypass.

Cross Lanes to Rokeby
(limestone karst – Great Limestone Member)

14.8.2.49 The proposed alignment at Cross Lanes to Rokeby is located mainly on the Great Limestone Member, with some upgrades to local roads on the Four Fathom Limestone Member. No karst landforms have been identified in this section of the proposed upgrade. There are multiple springs identified, however, these are all associated with areas mapped by BGS as sandstone.

14.8.2.50 Those features identified in this section (ES Figure 14.8.1 Karst Hazard Map (Features within 2km) Sheet 8 (Application Document 3.3)) of the proposed road alignment have been discounted as the aerial photographs confirms these as being land drainage related.

Stephen Bank to Carkin Moor
(limestone karst – Four Fathom Limestone Member and Five Yard Limestone Member)

14.8.2.51 The proposed alignment at Stephen Bank to Carkin Moor is located mainly on the Four Fathom Limestone Member the overlying interbedded limestones, sandstones and shales as well as the underlying Five Yard Limestone Member.

14.8.2.52 There are fifteen enclosed depressions located within 2km of this alignment upgrade section, as illustrated on ES Figure 14.8.1 Karst Hazard Map (Features within 2km) Sheet 9 (Application Document 3.3). These include two depressions adjacent to the alignment, one depression at the upper contact of the Four Fathom Limestone Member just north of Dunsa Manor (ID 40) and one depression in the Alston Formation (interbedded) at Mainsgill Bridge (ID 19).

14.8.2.53 There is a second feature in the Four Fathom Limestone Member at West grange farm (ID 20), which is a shallow but wide feature.

14.8.2.54 There are a further five small-scale enclosed depressions in the interbedded limestones, sandstones and shales outside of the main limestone members (ID 6, 7, 9, 51 and 53).

14.8.2.55 The Five Yard Limestone Member occurs below the most easterly part of the alignment at this section but there are no enclosed depressions identified in that part. There are two enclosed depressions in the Five Yard Limestone Member at Blackhill Farm and Moor end Plantation (both southeast of Mainsgill) and both occur at the contact with sandstone units.

14.8.2.56 There are five karst features to the north of the alignment that occur in the Great Limestone Member. Based on BGS mapping, the Stephen Bank to Carkin Moor section of the alignment does not cross the Great Limestone Member.

Summary: Stratigraphic setting of karst features

14.8.2.57 Based on the geology crossed by the A66 (Section 2.2 Available information and data sources), the record of known karst (Section 2.3 Geological setting) and the LIDAR assessment with aerial photograph review (Section 2.4 Known caves and karst) there are five rock types that have the potential to develop karst features:

- Eden Shales Formation (gypsum beds)
- Alston Formation (Great Limestone Member)
- Alston Formation (Four Fathom Limestone Member)
- Alston Formation (Five Yard Limestone Member)
- Alston Formation (Interbedded limestones, sandstones and shales).

14.8.2.58 The extent and type of karst features for each of these stratigraphic units is presented below.

Eden Shales Formation (gypsum beds)

14.8.2.59 The western section of the route mainly traverses the Penrith Sandstone Formation but at the Kirkby Thorpe bypass the new alignment crosses the mapped contact between the Penrith Sandstone Formation and the gypsum beds within the Eden Shales Formation. There are multiple enclosed depressions associated with the gypsum beds, which tend to be angular and elongate in form, and generally overlie the mapped gypsum units.

14.8.2.60 The shallow nature of the gypsum deposits indicates a significant karst risk where the road crosses these units. The karst risk comes from the susceptibility of gypsum to dissolution from rainfall and recharge. However, as the gypsum overlies the Penrith Sandstone Formation the southern extent of the gypsum is limited to that boundary contact.

Alston Formation (Great Limestone Member)

14.8.2.61 Due to the dip of the geology in the Alston Block, significant section of the A66 realignment follow the dip slope of the Great Limestone Member, particularly at the Bowes Bypass and Cross Lanes to Rokeby.

14.8.2.62 Most caves in the Teesdale, Gretadale and Brough area are developed in the Great Limestone Member. At approximately 30-35m thick the Great Limestone Member is the thickest limestone unit in the Alston Formation. Based on the data presented, the Great Limestone Member has potential to develop karst pathways in the North Pennine area. The types of karst identified include caves, stream sinks, risings and doline enclosed depressions. The features reviewed as part of the LIDAR/aerial photograph assessment indicate that the Great Limestone Member has the potential to have karst pathways, develop a vadose zone and can have a relatively deep unsaturated zone.

Alston Formation (Four Fathom Limestone Member)

14.8.2.63 As the A66 heads eastwards it steadily lowers and sequentially drops down through the stratigraphy of the Alston Formation. The most westerly section of the Stephen Bank to Carkin Moor section crosses the Four Fathom Limestone Member.

14.8.2.64 Karst features developed in the Four Fathom Limestone Member tend to be small scale and shallow that often include areas of seasonal flooding. These characteristics are indicative of a higher water table and small-scale restricted karst pathways.

Alston Formation (interbedded limestone, sandstones and shales)

14.8.2.65 The Stephen Bank to Carkin Moor section crosses the interbedded limestone, sandstones and shales of the Alston Formation that occur between the Four Fathom Limestone Member and the Five Yard Limestone Member. Although few features are reported elsewhere in the study area there are a small number in this section of the alignment, where they tend to be of a small scale and often are associated with seasonal flooding.

Alston Formation (Five Yard Limestone Member)

14.8.2.66 The most easterly section of the Stephen Bank to Carkin Moor section crosses the Five Yard Limestone Member. Karst features in the Five Yard Limestone Member are generally few and tend to be of a small scale and shallow.

14.8.3 Karst and groundwater site survey

Survey description

14.8.3.1 A combined karst and groundwater site survey was completed between the 19th and 22nd October 2020, to ground truth the features identified in Section 2 and inform the hydrogeological conceptual models for each scheme. The features considered for surveying within 1km are labelled

in ES Figure 14.8.2 Karst Desktop Features within 1km (Application Document 3.3) and comprise of:

- Springs and karst features on limestone
- Dissolution features related to gypsum
- Springs on sandstone
- Mining features.

14.8.3.2 A small number of features were excluded from the survey where there was no possible groundwater connectivity with the proposed road development. This included a cluster of springs on higher ground to the south of the River Greta in the Bowes Bypass area and spring S18 in the Cross Lanes to Rokeby area, where the scheme is located on the northern side of the river.

14.8.3.3 The classification terminology used for the site surveying comprises of:

- Spring: where a point outflow of groundwater occurs from rock or superficial deposits
- Groundwater to surface water interaction (GW to SW Interaction): an area of diffuse emerging seepage
- Sink: a point input to groundwater from a surface stream
- Surface water to groundwater interaction (SW to GW Interaction): an area of diffuse loss of surface water such as a losing stream
- Non groundwater/surface water interactions (Non GWSWI): for features the desk study identified but were subsequently confirmed as surface water features
- Enclosed depression - limestone: surface dissolution features in limestone such as doline or cave
- Enclosed depression - gypsum: surface dissolution features in gypsum rock
- Enclosed depression - non karst: artificial/anthropogenic features such mine workings and earthworks
- Non-enclosed depression: site survey confirms that the feature is not an enclosed depression

Results

M6 Junction 40 to Kemplay Bank

14.8.3.4 No karst or groundwater features were surveyed in the M6J40 to Kemplay Bank area.

Penrith to Temple Sowerby

14.8.3.5 In the Penrith to Temple Sowerby area, one potential groundwater-surface water feature (spring S29) was identified in Section 2: Available information and data sources for survey. This feature is presented on ES Figure 14.8.2: Karst Desktop Study (Features within 1km), (Application Document 3.3).

14.8.3.6 The results of the Penrith to Temple Sowerby survey are presented on ES Figure 14.8.3: Karst Survey Results Sheet 2 (Application Document 3.3) and summarised in Table 1: Penrith to Temple Sowerby survey

results summary. A site visit has confirmed S29 to be a drainage ditch and as such not a karst feature.

Table 1: Penrith to Temple Sowerby survey results summary

Classification	Feature	ID	Bedrock geology	Survey notes
Non GWSWI	Ditch (Non-karst)	S29	Penrith Sandstone Formation	Drainage line along the edge of a field that drains into the river Eamont.

Temple Sowerby to Appleby

14.8.3.7 In the Temple Sowerby to Appleby area, a total of 9 enclosed depressions and 5 springs were identified in Section 2: Available information and data sources for survey. These features are presented on ES Figure 14.8.2: Karst Desktop Study (Features within 1km), (Application Document 3.3). The study area is underlain by the Penrith Sandstone Formation, gypsum stone and Eden Shales Formation (mudstone).

14.8.3.8 The results of the survey are presented on Figure 14.8.3: Karst Survey Results Sheets 3 and 4 (Application Document Number 3.3) and summarised in Table 2: Temple Sowerby to Appleby survey results summary. A total of 7 enclosed depressions were confirmed to be associated with gypsum karst and ranged from local areas of undulating ground to larger, valley like features, often comprising standing water and boggy ground. Some dissolution features (ID: 124, 125, 136 and 137) were modified with road earthworks appearing to divide what would be naturally continuous features and at ID: 125, earthworks were used to modify the ponded water into a farm dam. Survey of ID: 82 discounted this location as an enclosed depression, but rather the head of a shallow valley that includes a watercourse to the west.

14.8.3.9 One spring mapped by OS was confirmed to be a spring (ID: S24) and a second comprised an area of boggy, hummocky ground, suggestive of diffuse groundwater seepage (ID: S26). No spring or seepage features were identified at the third location (ID: S25), which is considered to be a surface water feature.

Table 2: Temple Sowerby to Appleby survey results summary

Classification	Feature	ID	Bedrock geology	Survey notes
Spring	Spring (Non-karst)	S24	Penrith Sandstone Formation	Spring flowing from bedrock exposure
GW to SW Interaction	Seepage (Non-karst)	S26	Penrith Sandstone Formation	Spring is mapped by Ordnance Survey, area comprised boggy and hummocky ground with small puddles of standing water
Non GWSWI	None identified (Non-karst)	S25	Penrith Sandstone Formation	Spring is mapped by Ordnance Survey; however, no springs were identified on site

Classification	Feature	ID	Bedrock geology	Survey notes
Enclosed depression – gypsum karst	Gypsum dissolution (Karst)	124 125 126 136 137 138 139	Eden Shales Formation and gypsum stone	Enclosed depressions formed by dissolution of underlying gypsum beds, often including ponded surface water.
Non GWSWI	Valley (Non-karst)	82	Penrith Sandstone Formation	Pits identified in desk-study; however, these were not found on site. Depression was part of a larger valley feature.

Appleby to Brough

14.8.3.10 In the Appleby to Brough area, a total of two enclosed depressions and one groundwater spring were identified in Section 2: Available information and data sources for survey. These features are presented on ES Figure 14.8.2: Karst Desktop Study (Features within 1km), (Application Document 3.3). The study area is underlain by the Penrith Sandstone Formation and Eden Shales Formation (mudstone).

14.8.3.11 The results of the survey are presented on Figure 14.8.3: Karst Survey Results Sheets 5 and 6 (Application Document 3.3) and summarised in Table 3: Appleby to Brough survey results summary. One enclosed depression was confirmed (ID: 47) and is non-karst being created by earthworks spoil heaps from the adjacent railway line cutting. The site survey confirmed that feature ID: 50 is a drainage ditch but that the feature likely permits groundwater surface water interaction.

14.8.3.12 Feature ID: S23 is mapped by the OS as a spring and was confirmed during the site survey as being boggy ground associated with diffuse groundwater discharge.

Table 3: Appleby to Brough survey results summary

Classification	Feature	ID	Bedrock geology	Survey notes
GW to SW Interaction	Ditch (Non-karst)	50	Penrith Sandstone Formation	Low lying area with drainage line, which discharges into the River Eden downstream.
GW to SW Interaction	Seepage (Potential Karst)	S23	Great Scar Limestone Group	Spring is mapped by Ordnance Survey however boggy ground suggests diffuse seepage.
Enclosed depression – non karst	Artificial (Non-karst)	47	Penrith Sandstone Formation	The enclosure is created by earthworks spoil heaps and adjacent cutting for the railway line.

Bowes Bypass

14.8.3.13 In the Bowes Bypass area, a total of seven enclosed depressions, 19 groundwater springs and two caves were identified in Section 2: Available information and data sources for survey and are presented on Figure 14.8.2 Karst Desktop Study (Features within 1km) (Application Document 3.3). The study area is underlain by the Alston Formation and the Stainmore Formation including:

- Stainmore Formation sandstone
- Stainmore Formation undifferentiated mudstone, siltstone and sandstone
- Bottom Little Limestone
- Alston Formation sandstone
- Alston Formation undifferentiated limestone, sandstone, siltstone and mudstone
- The Great Limestone Member
- The Four Fathom Limestone Member.

14.8.3.14 The results of the survey are presented on Figure 14.8.3: Karst Survey Results Sheet 7 (Application Document 3.3) and summarised in Table 4: Bowes Bypass survey results summary. Of the enclosed depressions identified in Section 2, 4 of these were confirmed on site and were likely associated with shallow historical mine workings (ID: 95, 96, 97, 105). ID: 104 comprises of two longitudinal historical earthworks mounds that were discounted from being an enclosed depression. ID: 126 was identified on the northern side of the Hulands Quarry and comprises of two settlement ponds that are associated with the quarry water management, which discharge to Thorsgill Beck.

14.8.3.15 One spring mapped by the OS was confirmed on site to be a spring, S19, which feeds the headwaters of a stream that discharges into the River Greta. The spring identified at ID S20 was confirmed to be part of a culvert and as such is not karst.

14.8.3.16 The caves (ID K2 and K4) are features confirmed by the BGS NKD.

Table 4: Bowes Bypass survey results summary

Classification	Feature	ID	Bedrock geology	Survey notes
Spring	Heavily modified spring (Non-karst)	S19	Alston Formation and Four Fathom Limestone Member	Spring, modified by gravel access road. Associated with stream that flows into River Greta.
Non GWSWI	Watercourse (Non-karst)	S20	Stainmore Formation	Spring is mapped by Ordnance Survey however the watercourse comes from a culvert under the existing A66.
SW to GW interaction	Artificial (Non-karst)	126	Stainmore Formation and	Settlement ponds associated with quarry, which discharge Thorsgill Beck. Due to the depth

Classification	Feature	ID	Bedrock geology	Survey notes
			Great Limestone Member	of the quarry a zone of drawdown extends out from the quarry void.
Enclosed depression – non karst	Historical mine pits (Non-karst)	95 96 97 104	Great Limestone Member	Enclosed depressions created by historic shallow mine workings.
Non-enclosed depression	Artificial (Non-karst)	105	Great Limestone Member	Confirmed as longitudinal piles of spoil.

Cross Lanes to Rokeby

14.8.3.17 In the Cross Lanes to Rokeby area, a total of one enclosed depression and two groundwater springs were identified in Section 2: Available information and data sources for survey and are presented on Figure 14.8.2: Karst Desktop Study (Features within 1km), (Application Document 3.3). The study area is underlain by the Alston Formation and the Stainmore Formation including:

- Stainmore Formation sandstone
- Stainmore Formation undifferentiated mudstone, siltstone and sandstone
- Alston Formation sandstone
- Alston Formation undifferentiated limestone, sandstone, siltstone and mudstone
- The Great Limestone Member
- The Four Fathom Limestone Member.

14.8.3.18 The results of the survey are presented on Figure 14.8.3: Karst Survey Results Sheet 8 (Application Document 3.3) and summarised in Table 5: Cross Lanes to Rokeby survey results summary. Feature ID: 62 was confirmed as being a fluvial feature and is not karst.

14.8.3.19 S21 comprises of hummocky wet ground adjacent to a small tributary to Tutta Beck and is considered likely to be a seepage zone.

Table 5: Cross Lanes to Rokeby survey results summary

Classification	Feature	ID	Bedrock geology	Survey notes
GW to SW interaction	Seepage (Potential karst)	S21	Great Limestone member	Site survey confirmed as boggy ground with diffuse seepage. Discharges into a tributary of Tutta Beck
Non-enclosed depression	Watercourse (Non-karst)	62	Alston Formation (sandstone) and Alston Formation (limestone, sandstone, siltstone and mudstone)	Fluvial feature associated with the River Greta

Stephen Bank to Carkin Moor

14.8.3.20 In the Stephen Bank to Carkin Moor area, a total of four enclosed depressions and one spring were identified in Section 2: Available information and data sources for survey. These features are presented on Figure 14.8.2: Karst Desktop Study (Features within 1km) (Application Document Number 3.3). The study area is underlain by the Alston Formation including:

- Sandstone
- Undifferentiated limestone, sandstone, siltstone and mudstone
- The Three Yard Limestone Member
- The Five Yard Limestone Member

14.8.3.21 The results of the survey are presented on Figure 14.8.3: Karst Survey Results Sheet 9 (Application Document 3.3) and summarised in Table 6: Cross Lanes to Carkin Moor survey results summary. The enclosed depressions identified in Section 2 have been confirmed by the surveying as non-karst. These include ID: 19 which are earthworks associated with the existing A66, ID: five is a historic mine adit and ID: 51 which is a lake with control gates.

14.8.3.22 The spring mapped by the OS (S1) is a pipe discharge to an ornamental pond. The discharge electrical conductivity and pH suggest groundwater and as such the pipe is considered to be a modified spring.

Table 6: Cross Lanes to Carkin Moor survey results summary

Classification	Feature	ID	Bedrock geology	Survey notes
GW to SW interaction	Lake (Non-karst)	51	Alston Formation (sandstone) and Alston Formation (limestone, sandstone, siltstone and mudstone)	Identified in Section 2 as an enclosed depression. Site survey confirms the lake has an outflow with weir gates to control the water level.
GW to SW interaction	Modified spring/seepage (Non-karst)	S1	Three Yard Limestone Member	Modified spring/seepage - water discharging from pipe into pond. Water quality parameters suggest this of groundwater origin
Enclosed depression – non karst	Artificial (Non-karst)	19, 40	Five Yard Limestone Member, Alston Formation (limestone, sandstone, siltstone and mudstone)	Enclosed depressions created by existing A66 fill earthworks enclosing the natural landscape slope
Enclosed depression – non karst	Artificial – mine adit (Non-karst)	5	Five Yard Limestone Member	Enclosed depression created by historical mine adit structures

14.8.4 Characterisation of karst aquifers

14.8.4.1 Section 2: Available information and data sources has provided an assessment of the karst features present and identified the stratigraphy in which they occur. This section uses that information to develops a characterisation of each geological unit so that the karst processes likely to be present can be conceptualised and considered in terms of karst risk. The below section considers the karst hydrogeology for each geological unit with karst.

14.8.4.2 Karst risk is based on the BGS GeoSure risk assessment for soluble rocks:

- Negligible – Soluble rocks are either not thought to be present within the ground, or not prone to dissolution. Dissolution features are unlikely to be present
- Very Low - Soluble rocks are present within the ground. Few dissolution features are likely to be present. Potential for difficult ground conditions or localised subsidence are at a level where they need not be considered
- Low – Soluble rocks are present within the ground. Some dissolution features may be present. Potential for difficult ground conditions are at a level where they may be considered, localised subsidence need not be considered except in exceptional circumstances
- Moderate – Soluble rocks are present within the ground. Many dissolution features may be present. Potential for difficult ground conditions are at a level where they should be considered. Potential for subsidence is at a level where it may need to be considered
- High – Soluble rocks are present within the ground. Numerous dissolution features may be present. Potential for difficult ground conditions should be investigated. Potential for localised subsidence is at a level where it should be considered.

Eden Shales Formation (gypsum beds)

14.8.4.3 The gypsum beds of the Eden Shales Formation lie at a shallow depth in the landscape at Kirkby Thore. The shallow depth makes the gypsum prone to dissolution at surface from rainfall and at a shallow depth by recharge. Where near surface it is likely that the gypsum has partially been removed by natural dissolution, which most likely has led to subsidence occurring.

14.8.4.4 It is also likely that the shallow extents of the gypsum have been worked by the long history of mining in the area. However, there remains risk that gypsum remnants are present adjacent to the proposed bypass route of Kirkby Thore and as such consideration of karst risk should be taken when working in the area north of Kirby Thore.

14.8.4.5 The local geological structure at Kirkby Thore includes several faults that have displaced and offset gypsum next to sandstone and shale. On this basis the contact between gypsum and underlying sandstone and overlying shale can locally be complex. Generally, the Penrith Sandstone Formation is not prone to karst risk, but this is not the case

where faulting displaces gypsum adjacent to sandstone, especially if the fault structure were to provide a pathway for recharge.

14.8.4.6 On this basis, the potential for karst may be divided into those areas where the gypsum is at or near surface and those areas where faulting has displaced the gypsum so that it lies at depth. Of particular note in this regard is the faulted contact at the eastern side of Kirkby Thore where there is potential for the gypsum to be buried at moderate depth in the area between Town Head and Bowrang Plantation (refer to ES Figure 14.8.1: Karst Hazard Map (Features within 2km) (Application Document 3.3)). Although there is a clear karst risk from the gypsum outcrops at surface at the southern end of the fault, the depth of the gypsum is uncertain at the location of the Town Head junction.

14.8.4.7 On a precautionary basis it is recommended that the contact between the Penrith Sandstone Formation and the gypsum is considered a high karst risk when designing scheme elements and developing the temporary and permanent works methodologies. A voids treatment protocol is to be developed to address any karst features encountered during additional site investigation works in the scheme area or during the construction works.

Alston Formation (Great Limestone Member)

14.8.4.8 The Great Limestone Member occurs in two sections of the Project, at the Bowes Bypass and at Cross Lanes to Rokeby. Both schemes have been assessed for karst and no karst landforms have been identified by this desk study below the footprint of either scheme.

14.8.4.9 The Great Limestone Member is c.30-35m thick in the study area. Karst landforms do occur in the unit locally and there is potential for karst features to be present. Based on review of those karst features present there is potential for flow paths to develop along preferential bedding planes and fractures sets in the unit. This is clear from God's Bridge River Cave, where the intersection of a bedding plane with the local fracture sets appears to have controlled the development of the cave (BCRA, 2017).

14.8.4.10 The type of karst features present in the Great Limestone Member suggest that where pathways are present in the unit, either along fracture or bedding planes, that they can develop into mature karst features and develop sinking streams, conduit, caves and risings.

14.8.4.11 On the basis that the Great Limestone Member has the potential to form well developed karst, there is also the potential that it includes palaeokarst; karst features that have formed and subsequently been buried by superficial deposits.

14.8.4.12 Often associated with karst features and particularly palaeokarst is significantly weathered bedrock and reduced rock strength.

14.8.4.13 In the case that karst features in the Great Limestone Member are encountered during construction then there is the potential for these to impact on foundation design and particularly on load bearing structures.

On this basis the Great Limestone Member is considered to have a moderate karst risk and it is recommended that the ground is investigated where load bearing structures and attenuation basins are located.

14.8.4.14 A voids treatment protocol is to be developed to address any karst features encountered during additional site investigation works in the scheme area or during the construction works.

Alston Formation (Four Fathom Limestone Member)

14.8.4.15 The Four Fathom Limestone Member is reported in the BGS lexicon as having a thickness of between 5 to 12m, and it is crossed by the proposed alignment of the Stephen Bank to Carkin Moor scheme. No karst features were identified during surveying on the Four Fathom Limestone Member, however, small-scale karst features may be encountered related to local fracturing or weathered zones that facilitate groundwater flow.

14.8.4.16 The Four Fathom Limestone Member is of low karst risk. However, where features are encountered near the scheme then they should be investigated.

Alston Formation (Interbedded limestones, sandstones and shales)

14.8.4.17 The interbedded limestones, sandstones and shales of the Alston Formation are crossed by the Stephen Bank to Carkin Moor scheme.

14.8.4.18 No karst features were identified during surveying in the Stephen Bank to Carkin Moor area. A number of potential karst features have been identified from LIDAR mapping that are shallow but can be of wide diameter. These features are typically associated with thin limestone units in interbedded sequences and are often related to locally perched water tables above shales and sandstones. They can locally cause a high-water table or seasonal groundwater flooding.

14.8.4.19 The interbedded Alston Formation is of low karst risk. Where karst features are identified near design features (particularly structural features and attenuation basins) then these should be investigated.

Alston Formation (Five Yard Limestone Member)

14.8.4.20 The Five Yard Limestone Member is crossed by the Stephen Bank to Carkin Moor scheme.

14.8.4.21 No karst features were identified during surveying in the Stephen Bank to Carkin Moor area. Several potential karst features have been identified from LIDAR mapping but all are shallow, with a wide diameter. They can locally cause a high-water table or seasonal groundwater flooding.

14.8.4.22 The Five Yard Limestone Member is of low karst risk. Where karst features are identified near design features particularly structural features and attenuation basins, then these should be investigated.

14.8.5 Conclusions and Recommendations

14.8.5.1 Based on the characterisation of the karst features, the geology of the A66 includes five stratigraphic units that host karst features. Based on the abundance and scale of karst features each unit has been assessed in term of karst risk with the following conclusion:

Table 7: Summary of karst risk for each stratigraphic unit with karst features (all other Formations have negligible karst risk)

Stratigraphic unit	Karst risk
Eden Shales Formation (Gypsum beds)	High karst risk
Alston Formation (Great Limestone Member)	Moderate karst risk
Alston Formation (Four Fathom Limestone Member)	Low karst risk
Alston Formation (Interbedded limestones, sandstones and shales)	Low karst risk
Alston Formation (Five Yard Limestone Member)	Low karst risk

14.8.5.2 Based on this assessment the following recommendations are made for each of the above stratigraphic units.

Eden Shales Formation (gypsum beds)

14.8.5.3 The high karst risk for the Kirkby Thore bypass is the result of the high solubility of gypsum that lies immediately adjacent to the bypass to the east and north. The complex fault block structure at Kirkby Thore juxtaposes the gypsum against underlying sandstone and overlying shales so that the gypsum occurs both in shallow and deeper (est. <100m) settings.

14.8.5.4 It is recommended that where feasible, no cuttings are excavated into the gypsum beds of the Eden Shales Formation. Where gypsum is encountered, additional site investigation is recommended to ascertain the extent of the gypsum, with mitigation implemented to reduce the risk of dissolution (such as voids treatment). Cuttings that encroach into areas mapped to be underlain by the Eden Shales (based on 1:50000 mapping) are limited primarily to auxiliary roads, and are likely to be located within the overlying superficial deposits (Glacial Till). The karst risk to the road is lowered by avoiding cuttings within the Eden Shales Formation.

14.8.5.5 There is potential for subsidence in the case that gypsum underlies the pavement, structures or drainage system. A settlement monitoring plan is recommended in areas at risk of subsidence, to periodically monitor any changes pre, during and post construction. Areas at risk of settlement would include areas where karst features are encountered during further site investigation or during construction, or areas where cuttings encounter the Eden Shales Formation. A voids treatment protocol is to be developed to address any karst/dissolution features encountered along the route during additional site investigation works or during the construction works.

14.8.5.6 As part of on-going operation and maintenance of the road, it is recommended that drainage is designed so that it can be periodically inspected for karst feature development.

14.8.5.7 Where confidential borehole logs are located in the vicinity of the scheme, it is recommended that the project requests these logs from the BGS, if agreed by the relevant stakeholder.

Alston Formation (Great Limestone Member)

14.8.5.8 A moderate karst risk has been identified for the Great Limestone Member of the Alston Formation. The karst feature assessment has identified that the Great Limestone Member is capable of developing karst systems, including active caves and conduits, as well as palaeokarst.

14.8.5.9 The karst survey did not identify any features on the alignment, nor did it indicate that karst flow paths (including caves or conduit) crossed the line of the alignment. However, based on the potential for karst in the Great Limestone Member, where ground investigation is being undertaken at structures (including attenuation basins) then the ground investigation data is to be reviewed to determine if indicators for karst are present.

14.8.5.10 A settlement monitoring plan is recommended in areas at risk of subsidence, to periodically monitor any changes pre, during and post construction. Areas at risk of settlement would include areas where karst features are encountered during further site investigation or during construction, or areas where the road lies directly on the Great Limestone Member.

14.8.5.11 A voids treatment protocol is to be developed to address any karst/dissolution features encountered during additional site investigation works in the scheme area or during the construction works.

14.8.5.12 As part of on-going operation and maintenance of the road, it is recommended that drainage is designed so that it can be periodically inspected for karst feature development.

Alston Formation (Four Fathom Limestone Member)

14.8.5.13 A low karst risk has been concluded for the Four Fathom Limestone Member. This assessment was made based on the thin nature of the member but also due to the low occurrence of karst features in the area of the alignment.

14.8.5.14 Where karst features are identified near design features (particularly structural features and attenuation basins) then these should be investigated. Where karst features or voids are encountered, mitigation as detailed in the 'Alston Formation (Great Limestone Member)' section above should be implemented (such as a voids treatment protocol and settlement monitoring).

Alston Formation (Interbedded limestones, sandstones and shales)

14.8.5.15 A low karst risk has been concluded for the interbedded limestone, sandstone and shales of the Alston Formation. This assessment was made based on the thin nature of the member but also due to the low occurrence of karst features in the area of the alignment.

14.8.5.16 Where karst features are identified near design features (particularly structural features and attenuation basins) then these should be investigated. Where karst features or voids are encountered, mitigation as detailed in the 'Alston Formation (Great Limestone Member)' section above should be implemented (such as a voids treatment protocol and settlement monitoring).

Alston Formation (Five Yard Limestone Member)

14.8.5.17 A low karst risk has been concluded for the Five Yard Limestone Member. This assessment was made based on the thin nature of the member but also due to the low occurrence of karst features in the area of the alignment.

14.8.5.18 Where karst features are identified near design features (particularly structural features and attenuation basins) then these should be investigated. Where karst features or voids are encountered, mitigation as detailed in the 'Alston Formation (Great Limestone Member)' section above should be implemented (such as a voids treatment protocol and settlement monitoring).

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