

Appendices

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Appendix A. Engineering Geology Desk Study

(Unchanged from LSRA 2018)

Proposed extension to Linhay Hill Quarry

Engineering Geology Desk Study

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1. Introduction

1.1. Background

Following submission of the Environmental Statement for the proposed extension to Linhay Hill Quarry and receipt of comments from statutory consultees and other parties, Atkins has undertaken additional geological desk study work, which is reported herein.

1.2. Objectives

Regarding land stability, the objective of this desk study was to provide an enhanced understanding of the karst character and sink-hole formation processes in the limestone bedrock.

1.3. Scope of work

Carry out a review of publicly available and project-specific information to allow the hazards associated with land stability, in particular the karst features in the limestone bedrock, to be assessed further. The following scope of work has been undertaken by Atkins:

- a. The creation of geological cross sections to depict the relationship between the quarry and the Chercombe Bridge Limestone Formation within a broad geological context.
- b. A search for, and review of published material relevant to the local situation, including aerial photographs, old maps and publications.
- c. Meeting with Bentham Geoconsulting Limited to consider what further insight may be gained from the Electromagnetic Conductivity Mapping Survey [1].
- d. Further consideration of the hydrogeological setting and integration with the hydrogeological impact assessment, including assessment of options for monitoring the surface water and groundwater.
- e. Assessment of land stability hazards and associated risks in relation to the karst limestone setting of the quarry and the Land Stability Study Area.

1.4. Deliverables

The main deliverable is this report, comprising an engineering geology desk study to inform an updated hydrogeological conceptual model within the Hydrogeological Impact Assessment 2018 (ES Appendix 12B) and updated ES Chapter 12 Water Resources, Flood Risk and Drainage, and an updated Land Stability chapter (ES Chapter 17).

2. Engineering Geology Desk Study

2.1. Overview

This desk study presents the findings of a review of publicly available literature, maps, and data, assessment of existing information acquired from site-specific studies and investigations, and from Atkins' site visits.

2.2. Sources of Information

The sources of information used by Atkins to inform the engineering geological desk study are summarised in Table 2-1. A list of site-specific reports viewed as part of the desk study is given in Table 2-2. A separate list of academic and technical references used to support the desk study is provided in Section 3.

Relevant data and interpretations derived from the sources of information listed in the below tables has been compiled into a project-specific Geographic Information System (GIS) database, where appropriate.

Table 2-1 Sources of information used in the production of the engineering geology desk study.

Class of information	Type of information
Topography	Maps (Ordnance Survey and others) Aerial and satellite photographs (historical and recent) Site-specific surveys
Geology and Hydrogeology	Maps, memoirs, and reports BGS borehole records Aerial and satellite photographs Published papers and books Quarry records Thematic databases Previous ground investigations and site-specific studies Published rivers and groundwater information
Site Condition, Land Use, and History	Archaeological site and historic building records Landfill and waste disposal records Historical maps
Site Walkover / Reconnaissance	Targeted inspections of the site and locality based on the findings of other desk study information, such as aerial photographs.
Local Knowledge and Experience	Land owners / occupiers Local records offices / archives
Precedent	Construction and development records Records and observations from nearby analogous sites
Codes, Standards and Guidance	Professional and government bodies, institutes, and guidance

Table 2-2 Site-specific geological, geotechnical, and geophysical reports relating to Linhay Hill Quarry, that were made available during the preparation of this present report.

Report Title	Prepared by	Report Date
Report on the rock slope stability of existing and proposed workings at Linhay Hill Quarry, Ashburton, Devon.	Engineering Geology Ltd. [2]	March 1987
Linhay Quarry, Ashburton, Devon. Geotechnical Assessment of the stability of the excavated slopes and tips classified as Significant Hazard in accordance with the Quarries Regulations 99.	Frederick Sherrell Ltd [3]	August 2008
Linhay Quarry, Ashburton, Devon. Geotechnical Assessment of the stability of the excavated slopes and tips classified as Significant Hazard in accordance with the Quarries Regulations 99.	Frederick Sherrell Ltd [4]	September 2010
Linhay Quarry. Letter report with plan and sections, Figs 1 & 2.	Frederick Sherrell Ltd [5]	July 2011
Linhay Quarry, Ashburton, Devon. Geotechnical Assessment of the stability of the excavated slopes and tips classified as Significant Hazard in accordance with the Quarries Regulations 99.	Frederick Sherrell Ltd [6]	May 2013
Resistivity Imaging Surveys to Characterise the Geological Boundary Between the Chercombe Bridge Limestone Formation and the Overlying Superficial Deposits.	Bentham Geoconsulting Ltd [7]	September 2014
The Alston Extension to Linhay Quarry, Ashburton, Devon. Site Investigation and Design Report.	Sandybed Geological Services [8]	January 2016
Electromagnetic Conductivity Mapping Survey to Characterise the Thickness of Clay Deposits Overlying the Chercombe Bridge Limestone Formation. Report Number BGC779a.	Bentham Geoconsulting [1]	March 2016
Linhay Quarry, Ashburton, Devon. Land Stability Risk Assessment.	Frederick Sherrell Ltd [9]	May 2016

2.3. Site Condition

2.3.1. Existing Topography

The quarry is approximately 1km northeast of Ashburton. It is broadly rectangular in outline, with its longest axis aligned roughly northeast-southwest, parallel to the alignment of the A38 dual carriageway. It lies at the top of the catchment of the Balland Stream which flows south west to the River Ashburn which flows to the River Dart, but the proposed extension is within the watershed between the Balland Stream and the Kestor Brook, the latter flowing east to join the River Lemon three kilometres east of Bickington. The terrain rises distinctly from the valley of the River Ashburn to the watershed which is approximately 1 km across at its widest point midway between Ashburton and Bickington, and then falls to the valley of the River Lemon at Bickington, with ridges to the northwest and southeast (Figure 2-1).

The area of the proposed extension lies to the northwest of the existing quarry and is situated in an area of agricultural land that slopes gently towards the south and east. The proposed extension area is bounded to the southeast by the A38 dual carriageway, which is situated on an embankment. The current elevation of the proposed extension area ranges from approximately 115mAOD in the south to approximately 145mAOD in the north, near to Alston Farm. It is proposed that the south-western part of the extension area will be excavated (the 'quarry extension area'), whereas the north-eastern part and a strip alongside the A38 will be used for bunds of overburden material.

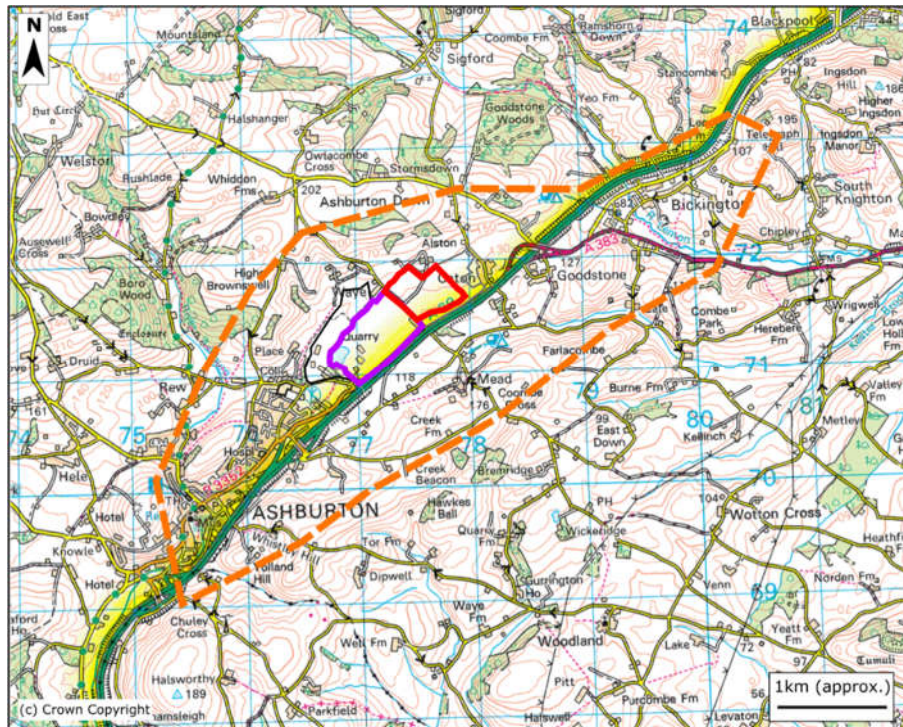


Figure 2-1 Excerpt from Ordnance Survey topographic map overlain with the existing Quarry extent (purple), the proposed quarry extension area (red), and the approximate extent of the Study Area (orange dashed). Crown Copyright and Database right 2016 Ordnance Survey 100018595.

2.3.2. Current Land Use

The proposed quarry extension is situated in an area of agricultural land that slopes gently towards the south. The land is divided into fields, some of which, at the time of the site visit (October 2017), were used as grazed pasture, some as ungrazed pasture, and others for turf production.

Most of the field boundaries consist of hedgebanks of 'Devon bank' construction. Drainage ditches are present along some of the field boundaries. The hamlet of Caton lies to the east of the proposed extension area and the A38 dual carriageway highway runs along the south-eastern edge of the proposed extension area.

The land to the east of Caton and to the south of the A38 is generally farmland, divided into fields, some of which, at the time of the site visit, were grazed pasture and others are used to produce crops. Some small woodland areas are also present to the north and south of the proposed quarry extension area.

2.3.3. Historical Land Use

For this desk study a brief review of historical maps for the area has been carried out to aid the conceptual understanding of the site. Particular focus has been placed on past land use, changes to water courses and water bodies, and evidence of construction or excavation in the surrounding area.

Key features identified to date are summarised below:

- The Parish Tithe map dated 1839 shows that the majority of plot descriptions in the area of the proposed quarry extension relate to the agricultural use of the land. Some may relate to topography, but there appears to be little in the field names of information relevant to the geology. Three lime kilns are marked within 500m of the current Quarry: one is located to the north, and two to the west, of the current quarry works.
- Later maps, by the Ordnance Survey, show changes to farm buildings, as well as field boundaries and water courses. Of particular relevance:

- The 1:2,500 scale Ordnance Survey county series map of 1886 shows that between 1840 and 1886 a new group of farm buildings had been constructed around an enclosed yard at Alston, to the northeast of the present-day quarry. By 1905 an aqueduct has been constructed, leading from a pond that was also marked on previous maps, located to the north of the existing farm buildings. A building, previously indicated to the south of the pond was also removed prior to 1905.
- From 1938 onwards, a water course is shown flowing from the pond at Alston, but the aqueduct appears to be disused, and a second smaller pond is shown to the north of the original pond. During visits made by Atkins to Caton, it has been observed that diversions have been made to surface water courses, which are not recorded on current Ordnance Survey maps.
- The A38 dual carriageway was constructed in the 1970s near to the alignment of the old Exeter Road. The A38 passes along the south-eastern edge of the present day Quarry.
- The expansion of small quarry workings, to eventually form the present day Quarry is documented through the historical maps. The earliest map to show quarry workings at the Quarry is the 1886 Ordnance Survey county series map.

2.3.4. Historical mining and quarrying

Several quarries have previously occupied the area of the present day Quarry, as identified from historical maps. There were also other nearby areas where the limestone has been quarried on a relatively small scale historically such as Pitley Quarry (which was landfilled) to the south between Dolbeare and Mead Cross, and around Goodstone to the south and west. The main or largest quarry at Goodstone has been redeveloped and is now used by West Country Storage Solutions, with the central area of the quarrying lying well below the elevation of the surrounding land.

Atkins' review of maps and other sources of historical mining activity has found five recorded mines near the Quarry, which are listed below and shown in Figure 2-2. Sources of information include the websites of the Coal Authority [10], BGS [11] Mindat [12], and the 'Old Ashburton' website [13].

In addition, adits have been identified in the hill slopes to the north-west of the Quarry, but their relationship to the historic mine workings listed below is not known. They may be drainage adits or they may be access adits that became drainage adits after the mines were abandoned.

Cleft Rock Iron Mine (also known as Ausewell Mine or Wheal Hazel)

Located in Ausewell Wood, north west of Ashburton. The mine's location may be indicated by the label 'Cleft Rock' on some maps.

Owlacombe & Stormsdown Mixed Mine (also known as Ashburton United or Beam West)

Reported to have been associated with the extraction of Tin, Arsenic, and Copper, the spoil heaps may have been reworked in 1937 and 1958. Aside from the dump of mine waste there may be little evidence of this mine on the ground. Two shafts are noted, from which streams of iron-stained water reportedly flow [12], but details of the locations of the shafts and streams are not provided.

Whiddon Mine

Tin, copper, and manganese are reported to have been mined at a location west of the Quarry, in Ashburton. The mine was worked on various occasions in the 18th & 19th centuries. Whiddon Smelting House Tin and Copper Mine, is shown on Donn's 1765 map of Devon. The mine was reopened in 1845 until 1851. Further exploration was reported to have taken place in 1859 under the name of 'Whiddon and Brownhill Mine', but this appears to have been unsuccessful [12].

Trial south of Sigford

Located in Goodstone woods, northeast of the Quarry. No further information about this mine has been found.

Ashburton UMBER Works

A 30ft (c. 9m) thick bed of umber, a brown clay containing iron and manganese oxides, was worked on the outskirts of Ashburton by two companies; the Devon and Cornwall Works and the Roborough

Works [12]. The umber appears to have been mined from within the CBLF, where it probably formed because of hydrothermal processes associated with the emplacement of igneous intrusions in the Devon region during Permian times.

The Devon & Cornwall Works reported the extraction of 6,946 tons from 1873-83, and the Roborough Works reported extraction of 850 tons in 1874. Operations are believed to have continued into the early years of the 20th century [12].

The umber works are labelled at NGR SX 762 704 on the 1906 edition 1:10,560 OS map. The umber is understood to have been used principally for paint manufacture and was processed in grinding mills nearby.

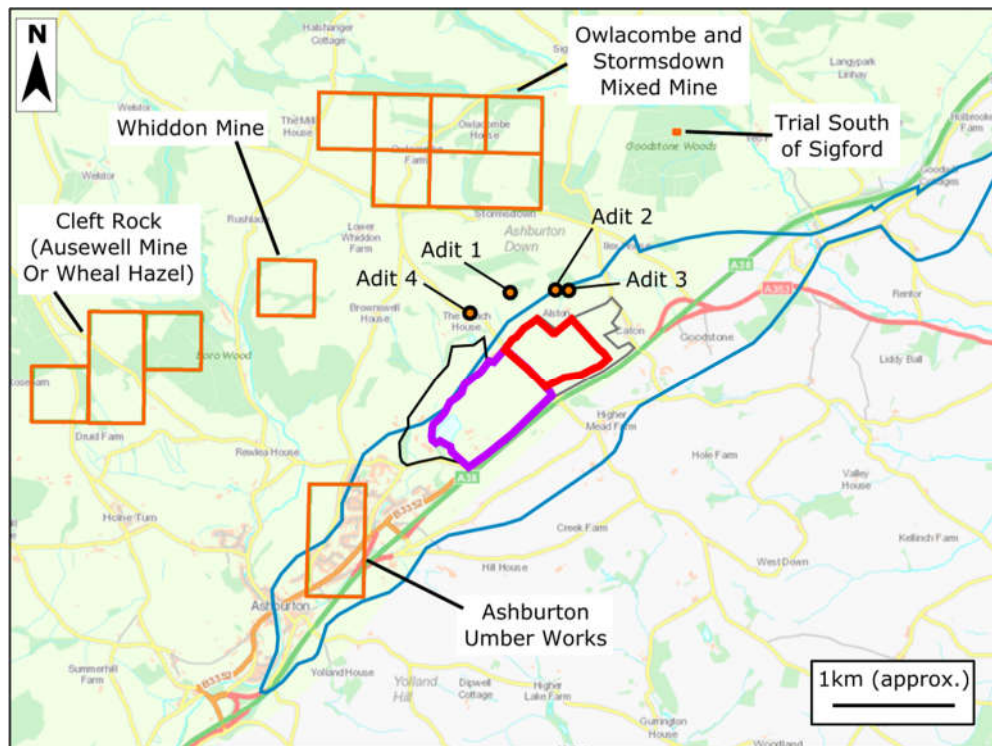


Figure 2-2 Known areas of historical mining activity in the vicinity of Linhay Hill Quarry [10] & [11]. Adits shown are not marked on the Coal Authority or BGS online maps but have been observed by Atkins during field walkovers. Existing Linhay Hill Quarry shown in purple, proposed quarry extension shown in red, extent of Chercombe Bridge Limestone outcrop shown in blue.

2.3.5. Ground Cavities

A cavity (i.e. cave) was encountered during the construction of the A38 Dual Carriageway to the south of Linhay Hill Quarry in the early 1970s. The cave opening was identified within the road cutting following a collapse at foundation level during construction (Malkin & Wood, [14]). Atkins understands the cave was infilled with concrete as part of the construction works.

More recently the BGS has produced a report [15] following its visit to the subsidence which adjacent to the A38 off slip road, east of Caton, in 2014. The BGS report, published in 2016, includes a map showing the locations of five 'cavity entry points' (south west to north east):

- Adjacent to the A38, south of the quarry, which relates to the cavity encountered during construction of the A38.
- In a bench in the southeast face of the quarry; a bridge has been built across this cavity entry point to maintain access along the quarry bench.

- Adjacent the A38 off slip road east of Caton.
- Lemonford Cave, which is a small disused quarry in a copse at Higher Lemonford, Bickington. Lemonford Stream originates from the east of the quarry. Oldham et al. [16], record “two short tunnels excavated by Walter Chesseman (sic) who found remains of woolly rhinoceros”. The total length is given as 20 feet (approximately 6m).
- Bickington Pot is recorded by Oldham et al. [16]) as being 400 feet long (approximately 120m), with a vertical range of 120 feet (approximately 37m). It is located in the south-east corner of the disused Bickington Barton Quarry, which is north east of the River Lemon. Oldham et al. [16] state that the first recorded exploration was in 1942. Although the quarry was used as a local authority tip and the cavity entry point area has been filled but has a protected entrance by way of an extended manhole, with an original aim of also providing an access point for bats.

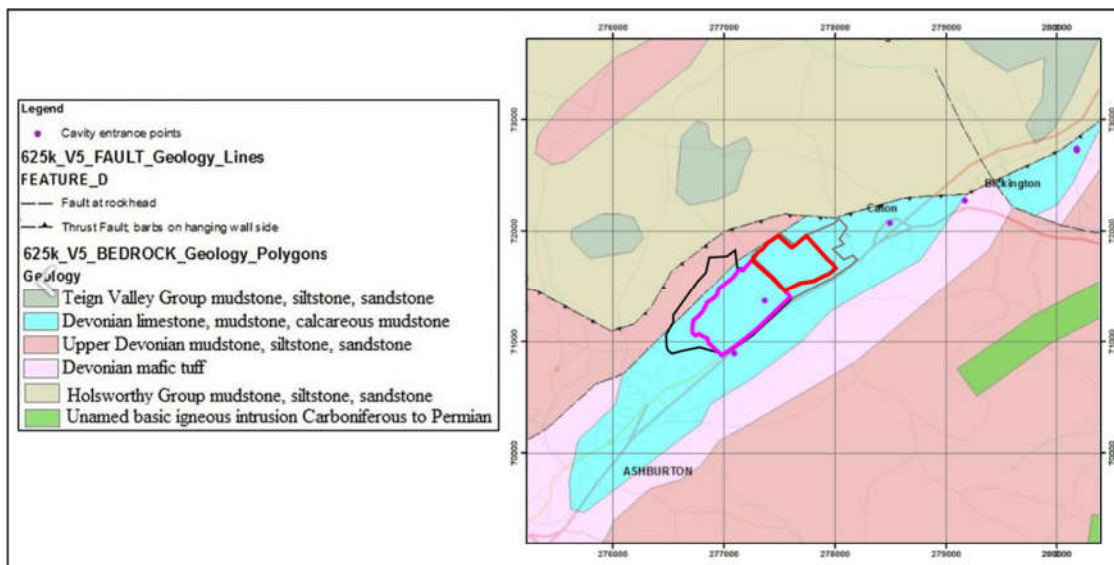


Figure 2-3 Map showing the locations of the BGS 'cavity entry points' in the vicinity of Linhay Hill Quarry Land Stability Study Area. The purple line indicates the quarry extent, the red line indicates the area of the proposed quarry extension (Adapted from BGS [15]).

2.3.6. Hydrology and Hydrogeology

Hydrology and hydrogeology, including the conceptual hydrogeological model, are addressed in detail in the Hydrogeological Impact Assessment 2018 and Chapter 12 of the Environmental Statement. An overview is provided below.

The main surface water features near to the Quarry are the Rivers Ashburn and Lemon, the Balland Stream and the Kester Brook.

The River Ashburn passes closest to the Quarry at Cuddyford Cross (approximately 1 km west of the quarry), where the river is at an elevation of around 95mOD. The River Ashburn flows roughly north to south, passing through the town of Ashburton.

The River Lemon is located to the northeast of the Quarry, where it flows roughly northwest to southeast. The river is closest to the quarry at approximately 2.3 km to the northeast of the quarry, near to where the river passes under the A38 at Bickington.

The Kester Brook is a tributary of the River Lemon and is located to the southeast of the Quarry and the A38. The major input of the Kester Brook is the Goodstone Spring, which is located approximately 1km east of the quarry. Goodstone Spring does not flow during periods of low rainfall.

Several seasonal springs are present along the hill slopes to the north of the Quarry. These springs generally drain southwards into the Balland Stream, which flows through the western part of the quarry grounds and then towards the south-west, roughly parallel to the A38, before joining the River Ashburn in Ashburton. Other springs are located further to the northeast and drain onto the land around the hamlet of Caton.

2.4. Geology

In this section the local geology of the Land Stability Study Area is described using information sourced during the desk study, and subsequent ground investigations. A conceptual geological model has also been developed and is represented by the cross sections in Figures A-1 and A-2 (Appendix A).

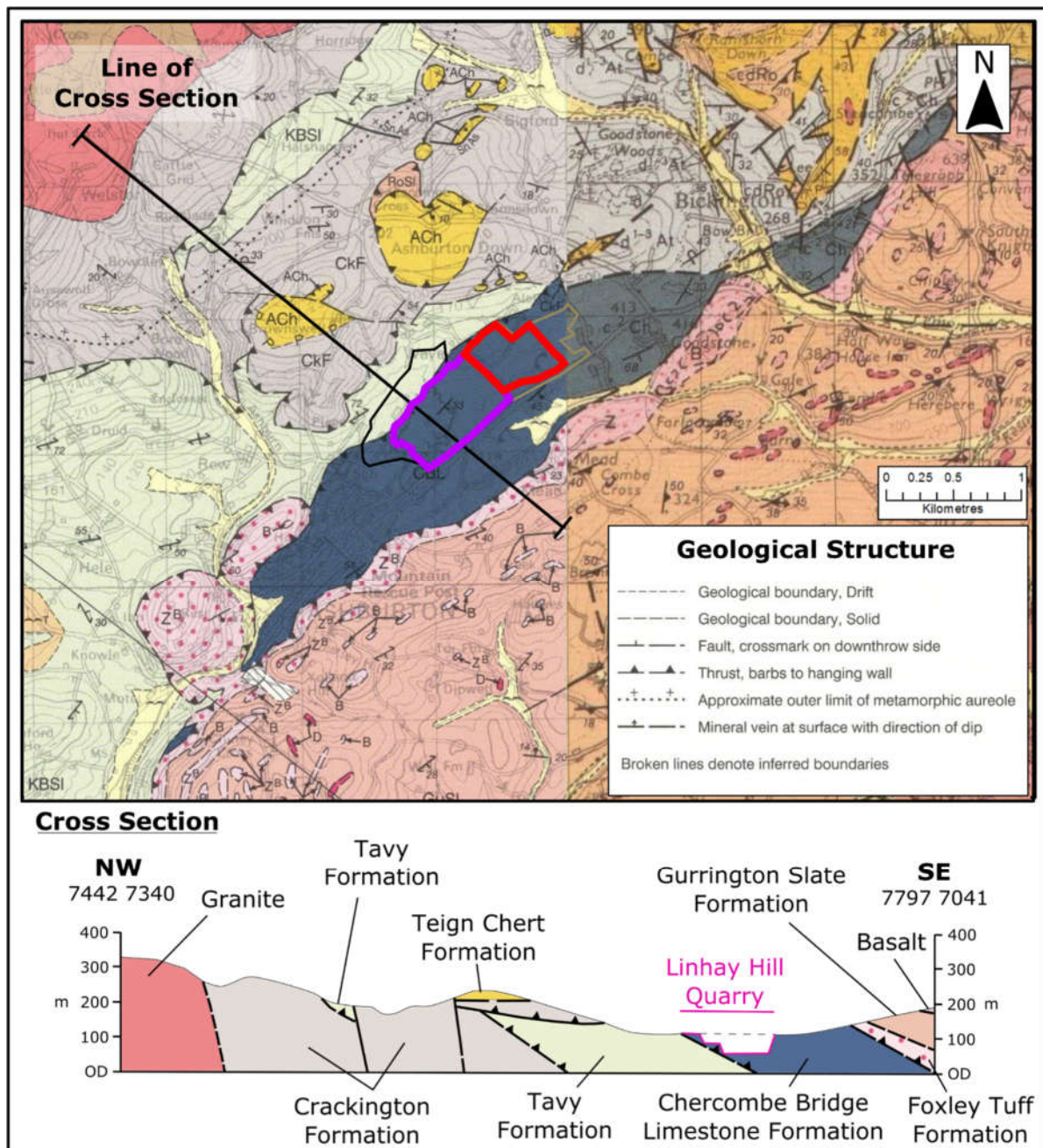


Figure 2-4 Geological map of the area around Linhay Hill Quarry and simplified geological cross section showing the existing quarry excavation (purple outline) and the proposed quarry extension (red outline). Map and cross section adapted from BGS Map sheet 338 [17] and sheet 339 [18]. The

cross section shown on BGS map sheet 338 has been re-drawn by Atkins to show the extent of Linhay Hill Quarry in the context of the bedrock geology.

2.4.1. Superficial Deposits

In general, superficial deposits are absent from the British Geological Survey (BGS) Geological Maps in the Land Stability Study Area (Figure 2-4). Where shown, they are limited to narrow ribbons of Alluvium (shown in pale yellow in Figure 2-3) associated with watercourses, namely (west to east), the River Ashburn and its tributaries, tributaries of the River Hems, the Kester Brook, and the River Lemon.

The Alluvium would have been deposited in a fluvial setting during the Holocene period. Typically it comprises soft to firm, normally consolidated, silty clay, but can contain layers of silt, sand, peat and basal gravel [19]. A stronger, desiccated surface zone may be present in some cases.

Alluvium is shown in BGS maps near to the north-western corner of the present day Quarry. A review of geological maps has revealed some changes in the mapped distribution of Alluvium. Between 1912 and 1977 the published 1 inch to 1 mile and 1:50,000 scale geological maps for Dartmoor Forest (Geological Survey of England and Wales, 1912; Geological Survey of Great Britain, 1977) show Alluvium extending towards the south-west through Ashburton where it joins with the Alluvium of the River Ashburn, which is consistent with the current BGS map. A smaller area of Alluvium was also indicated on the maps published between 1912 and 1977, located immediately east of the A38 junction at Alston Cross and associated with the Kester Brook. The extent of this deposit covers a smaller extent on the current BGS maps (BGS, 1995; 1997) than on the maps published between 1912 and 1977.

The geographical distribution of the Alluvium is shown in pale yellow in Figure 2-4, which is composed of extracts from the current BGS maps for Dartmoor Forest [17] and Newton Abbot [18].

Despite the absence of mapped superficial deposits, previous investigations within the study area (e.g. Subsurface Geotechnical, 2014; Subsurface Geotechnical, 2015; Frederick Sherrell Ltd, 2016; Geotechnics, 2017) indicate that the shallow subsurface is clay-rich, with weathered fragments of rock overlying bedrock.

2.4.2. Made Ground

BGS mapping shows one instance of Made Ground in the area surrounding the Quarry. It is located at Chuley Bridge, where the A38 crosses Chuley Road, approximately 2km southwest of the quarry (Figure 2-4). Historical maps of this location show that the Made Ground was created when remediating old quarry workings prior to the upgrade of the A38 at Ashburton during the early 1970s.

Made Ground will be present in places along the route of the A38 where it is constructed on highway embankment fill. Made Ground under main trunk roads is not presented on BGS mapping.

The quarry's existing spoil tip to the north of the quarry's northwest face is an area of Made Ground up to 20 m thick, formed from the placement of overburden and other unusable natural materials from the quarry since 1975, although the current profile was approved in the early 1990s. The former spoil tip to the northeast of the quarry has been restored for agricultural use, while spoil placement to the southwest of the quarry is currently nearing completion.

2.4.3. Bedrock Geology

2.4.3.1. Stratigraphy

The geological formations that crop out in the area around the Quarry are shown in Figure 2-4, and are described below in order of youngest to oldest. The formations are summarised in Table 2-3.

Crackington Formation

The BGS maps show the Tavy Formation pinching out towards the east of the quarry excavation, such that the CBLF lies adjacent to the Crackington Formation north of Caton and Goodstone. The Crackington Formation is younger than the CBLF and Tavy Formation, having been deposited approximately 323 to 315 million years ago during the Bashkirian Age (Lower Pennsylvanian Epoch of the Carboniferous).

The BGS lexicon [19] describes the Crackington Formation as *“rhythmically bedded, dark blue-grey mudstones and subordinate predominantly grey sandstones and siltstones”*. It also states that *“the sandstones are parallel-sided “Bouma-type” turbidites with abundant well-developed sole structures”*.

The online Geology of Britain Viewer [20] represents the outcrop of the Crackington Formation in Figure 2-4 as two separate formations as follows:

- a. the St Mellion Formation (located to the north and northeast of the existing quarry and the proposed extension); and
- b. the Crackington Formation (located further towards the northwest, and which is in turn bounded to the northwest by the Dartmoor Granite intrusion).

The boundary between the St Mellion and Crackington Formations is indicated by the southwest-northeast trending dotted black line on Figure 2-4. The proximity of the Crackington Formation to the Dartmoor Granite intrusion and the alignment of the boundary between the St Mellion and Crackington Formations (where it is shown) suggest that the Crackington Formation has been affected (metamorphosed) by the intrusion of the Dartmoor Granite and therefore mapped as a separate formation from the unaffected St Mellion Formation. Indeed, the Geology of Britain Viewer [20] provides the following description of the Crackington Formation at this location:

“Metamudstone And Metasandstone. Metamorphic Bedrock formed approximately 318 to 328 million years ago in the Carboniferous Period. Originally sedimentary rocks formed in swamps, estuaries and deltas. Later altered by low-grade metamorphism.”

By contrast, the older St Mellion Formation is described by the Geology of Britain Viewer as *“Sandstone, Siltstone And Mudstone...Sedimentary Bedrock formed approximately 324 to 359 million years ago”*, with no reference to metamorphism.

Teign Chert and Codden Hill Chert Formations

These two formations lie adjacent to each other at the boundary of BGS Map Sheets 338 [21] and 339 [18], highlighting inconsistency between the two maps as to how this outcrop should be classified. Given the similarity in their lithological descriptions, these formations have been grouped together for this desk study.

The BGS lexicon [19] describes these formations as comprising siliceous mudstones, shaly mudstones and cherts, formed approximately 331 to 347 million years ago during the Viséan Age (Middle Mississippian Epoch of the Carboniferous). The Codden Hill Chert is described as having limestones, turbidites and mudstones in the upper part of the sequence.

Rora Mudstone Formation

This formation is mainly present to the northeast of the Study Area (Figure 2-1 and Figure 2-4). A small outcrop is also present about 1.25km northwest of the proposed quarry extension. The Rora Formation is described on the BGS lexicon [19] as *“purple, green and greyish green mudstones”* with *“scattered siliceous and calcareous nodules”*, deposited around 372 to 347 million years ago during the Famennian (at the end of the Late Devonian) or the Tournaisian Age (the Early Mississippian Epoch at the start of the Carboniferous).

Gurrington Slate

The Gurrington Slate, which is Frasnian to Tournaisian in age and has no defined parent group, crops out on the hills to the southeast of the valley in which the Quarry is located. It has been described as *“typically bright green or purple when fresh (weathering black or ochreous brown)”*, but can be *“mottled and, in some cases, are poorly foliated”* [22]. The Gurrington Slate is sometimes found in association with *“deformed, vesicular, olive-brown lavas and tuffs”*. The thickness of the formation is unknown (Dean, A. 1992, Palynological evidence concerning the age of the Hyner Shale and Gurrington Slate Formations in the Newton Abbot area of south Devon. Proceedings of the Ussher Society, 8, 29-32).

Tavy Formation

The Tavy Formation (previously known as the Kate Brook Slate Formation within the Study Area) crops out to the north of the CBLF and is associated with a slight topographic rise. The Tavy Formation is younger than

the CBLF, having been deposited from the Frasnian to Famennian (Upper Devonian). The green slates of this formation are an important building stone resource in the region.

The BGS lexicon [19] describes the Tavy Formation as “*Pale green and grey-green slaty silty mudstone with minor thin fine-grained sandstone beds and lenses. Medium- to fine-grained sandstone interbedded with mudstone and laminated siltstone constitute the Trehills Member.*” The upper part of the unit is reported to comprise “*greenish grey slates*”, while the lower part contains “*purple and green mottled slates*” [22]. Trial pit investigations conducted by Frederick Sherrell Ltd (2016) found the Tavy Formation to be overlain by clayey material at the surface, with weathered fragments of slate.

Chercombe Bridge Limestone Formation

The Quarry works a southwest-northeast trending outcrop of the CBLF, which is thought to be Eifelian to Famennian in age (Middle to Late Devonian). The limestone was deposited approximately 393 to 383 million years ago on a shallow undersea ridge or ‘rise’ in a tropical marine environment. It is generally described in the literature as dark-grey, well-bedded limestone with interbedded shale. On BGS Map Sheet 338 [17] it is described as “*medium to dark grey limestone beds*”, and on BGS Map Sheet 339 [18] it is described simply as “*Grey limestone*”.

Historically the Devonian limestones in this area, including the CBLF, supported a local ‘marble’ (polished limestone) industry. These rocks have also been used locally as building stone.

The limestone has been subject to karst weathering (dissolution) processes forming a variety of solution features (e.g. BGS Caton Karst website [15]), with the karstic rockhead topography buried under clayey infill, as described in several previous investigations within the study area [23, 24, 25, 26]. The evolution of the CBLF is discussed further in Section 2.4.5.

Foxley Tuff Formation (part of the Kingsteignton Volcanic Group)

Located immediately west and south of the CBLF, this formation is part of the Kingsteignton Volcanic Group, which mainly comprises of extrusive igneous rocks but also includes beds of slate and limestone. The group is described by the BGS Lexicon as “*Spilitic lavas, interbedded dark green, spilitic tuffs and slates with lenses of limestone; some limestone is crinoidal*”. Spilitic lavas are indicative of underwater lava flows and tuffs originate from explosive volcanism. No description is provided on the BGS lexicon [19] for the Foxley Tuff Formation itself.

According to the BGS Lexicon the CBLF may rest conformably on the Kingsteignton Volcanic Group in some places, but this does not appear to be the case in the area around the Quarry.

Table 2-3 Summary of bedrock formations in the area around the Quarry in stratigraphic order (youngest at the top, oldest at the bottom).

Bedrock formation	Period	Epoch	Age	Thickness (approx.)	Depositional environment
Crackington Formation (Including St Mellion Formation)	Carboniferous	Lower (Pennsylvanian)	Bashkirian	>1000m	Basin (distal turbidites)
Teign Chert and Codden Hill Chert Formations	Carboniferous	Middle Mississippian	Visean	>70m	Basin / deep marine
Rora Mudstone Formation	Devonian to Carboniferous	Late Devonian to Early Mississippian	Famennian to Tournasian	Unknown	Basin
Gurrington Slate	Devonian to Carboniferous	Late Devonian to Early Mississippian	Frasnian to Tournasian	Unknown	Basin / deep marine with volcanism
Tavy Formation	Devonian	Late	Frasnian to Famennian	Unknown	Outer marine shelf / deep marine

Bedrock formation	Period	Epoch	Age	Thickness (approx.)	Depositional environment
Chercombe Bridge Limestone Formation	Devonian	Middle to Late	Eifelian to Famennian	>250m	Submarine rise / warm shallow seas
Foxley Tuff Formation (part of the Kingsteignton Volcanic Group)	Devonian	Middle	Eifelian	<30m locally. Up to 195m elsewhere	Volcanism (extrusive basic igneous rocks)

2.4.3.2. Structural Geology

The outcrop of the CBLF within which the Quarry is developed covers an area of more than 300 hectares, extending from Ashburton to Bickington (Figure 2-4). The quarry is located where the outcrop is at its widest (some 1000 metres northwest to southeast), but the quarry footprint is narrower lying between the A38 dual carriageway to the southeast and the geological boundary with the Tavy Formation to the North.

On BGS Map Sheets 338 [17] and 339 [18] the bedding within the CBLF strikes between approximately 030 and 065 degrees (relative to Ordnance Survey Grid North) and dips towards the southeast with no indication of overturning (Figure 2-4). Sheet 338 [17] shows dip of the CBLF to vary between 33 and 54 degrees in the area between Ashburton and Caton. Further east, near to Goodstone, sheet 339 [18] shows dips of 33 and 68 degrees. Northeast of Bickington, a strike of approximately 006 degrees is shown on Sheet 339 [18].

Several thrust faults are indicated near the Quarry on BGS Map Sheet 338 [17], showing older rocks to have been thrust over younger rocks. A major thrust fault is located immediately north of the quarry, aligned southwest to northeast, which is probably a continuation of the Bickington Thrust. The limestone has been thrust onto the younger slates of the Tavy Formation, which crop out to the north, meaning that the Quarry is located within the hanging wall of the thrust fault. An exposure of the thrust at the Quarry has been described as “*complex and irregular*”. Where it comes into contact with the limestone, the Tavy Formation is described as “*deformed*” and containing “*rafts of other rock types*” [27].

A second thrust fault is shown on Geological Map Sheet 338 [17] at the western and southern extent of the limestone outcrop where it marks the contact between the limestone and the Foxley Tuff Formation Figure 2-4). These extrusive igneous rocks have been thrust over the Chercombe Bridge Limestone and outcrop as a narrow (less than 500m wide) strip along the entire southern edge of the Limestone outcrop, extending to Bickington (approximately 2.3km northeast of the existing quarry).

The southwest-northeast trending thrust faults that bound the CNLF outcrop are believed to dip towards the southeast at angles broadly consistent with the bedding in the limestone (approximately 33 to 43 degrees in the vicinity of the Quarry).

A northwest-southeast fault is also present at Bickington, where it coincides with the course of the River Lemon and has caused a lateral offset of the Foxley Tuff Formation outcrop. Immediately west of Bickington the Crackington Formation is shown to be present as an inverted succession dipping 43 degrees towards the southeast. This structural deformation is likely to be associated with the numerous faults indicated in the area around Bickington [18].

The tectonic history of the area, including faulting and folding, has resulted in fracturing (jointing) of the limestone, as can be observed in the quarry where the joints act as preferential zones of dissolution associated with karst (described in Section 2.4.5).

2.4.4. BGS Borehole Records

Borehole records (also called ‘scans’) that are available from the BGS Onshore Geoindex [28] in the Ashburton to Bickington area of the Chercombe Bridge Limestone outcrop have been reviewed and are described below. The locations of the boreholes are shown in Figure 2-5. The geological sequence for each borehole has been summarised in

Table 2-4.

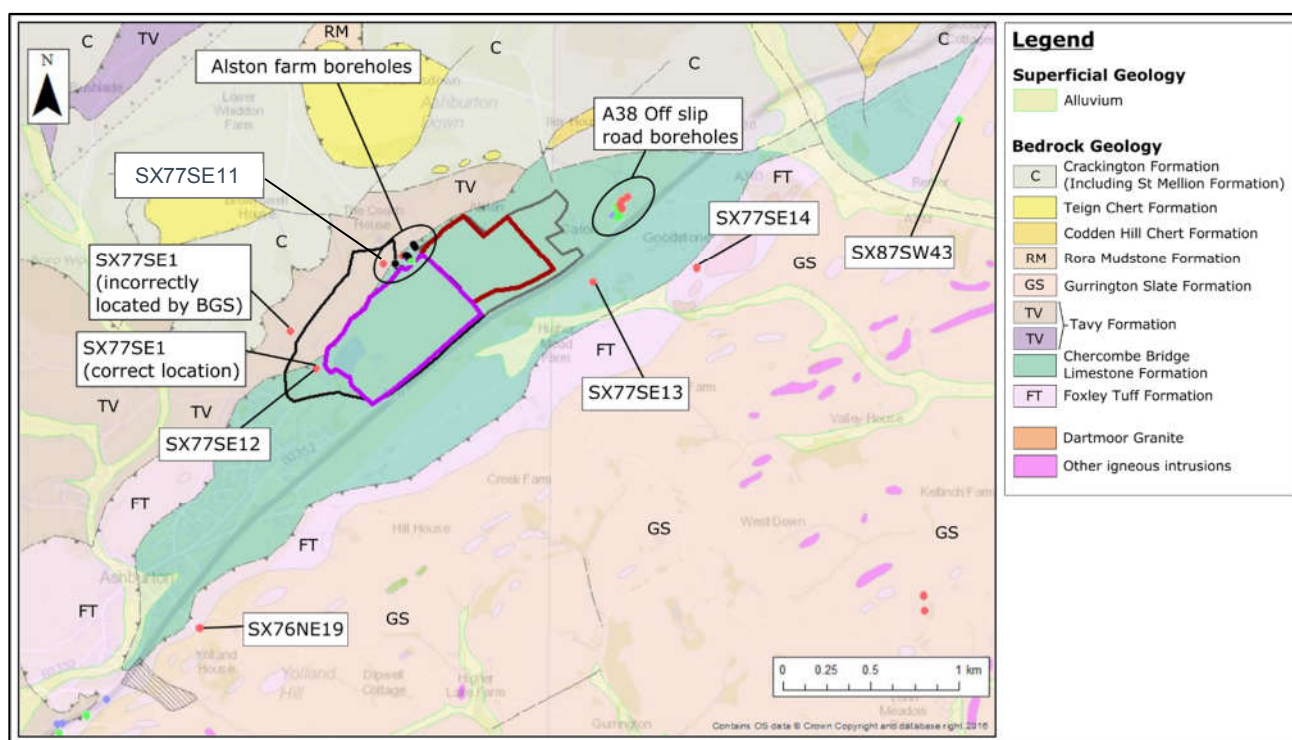


Figure 2-5 Map showing the locations of BGS borehole scans in relation to the existing Quarry excavation (purple outline) and the proposed quarry extension (red outline). Background mapping is taken from the BGS 1:50,000 scale geology (BGS Onshore Geoindex) and OS OpenMap Local. The Alston Farm boreholes are SX77SE11, SX77SE8, SX77SE9 and SX77SE10.

2.4.4.1. Alston Farm

Borehole SX77SE11

This borehole is located in the Tavy Formation approximately 40m northwest of the thrust fault, which runs along the northern edge of the existing quarry, as shown on the BGS 1:50,000 scale mapping. The borehole log reports CBLF to a depth of 8.84 metres below ground level (mbgl). Tavy Formation Slate occurs at between 8.84 and 21.36 mbgl. Based on the log, the reported location of the borehole on the 1:50,000 scale BGS mapping may be slightly inaccurate.

Boreholes SX77SE8, SX77SE9 and SX77SE10

These three boreholes are located close to Alston Farm, near the northernmost corner of the existing quarry. "Middle Devonian Limestone" is noted on the well records. Detailed information on strata depths encountered is not given.

2.4.4.2. A38 off-slip road at Caton

Some of the exploratory holes commissioned as part of the ground investigations of a sinkhole that was recorded adjacent to the A38 off-slip road at Caton are shown on the BGS Onshore Geoindex. Further details of the investigations, including factual reports containing additional borehole logs and geophysical survey results, have been made available by Highways England. A summary of the available information relating to this sinkhole investigation is presented in Section 2.6.3.

2.4.4.3. Other relevant boreholes

Borehole SX77SE12 (deepened under reference SX77SE1)

Located in the western part of the Quarry, the reported stratigraphy for this borehole is broadly consistent with the BGS mapping in that the Tavy Formation was encountered (within the footwall of the Bickington

Thrust Fault). The Tavy Formation was found to be present as interbedded grey shale, slate and sandstone down to 91.40 mbgl, at the termination depth of borehole SX77SE12.

Borehole SX77SE1, given on the BGS Onshore Geoindex as being located on the southeast-facing slopes to the northwest of the quarry, is a continuation (deepening) of the existing borehole SX77SE12. Because SX77SE1 is assigned only a six-figure grid reference (as opposed to a more precise eight-figure grid reference for SX77SE12), its location on the BGS Onshore Geoindex is incorrect. Atkins has assigned a revised location to SX77SE1 as a result.

The deepened borehole records Tavy Formation (sandstone and shale) from depths of 91.40 m to 161.85 m bgl overlying limestone, which was encountered to a borehole termination depth of 161.95 m bgl. As the borehole is located to the northwest of the thrust fault, which dips towards the southeast, the limestone encountered is expected to be the CBLF where it has not been thrust over the younger Tavy Formation (i.e. it is in the footwall of the fault).

Borehole SX76NE19

This borehole is shown to be located at or very close to the boundary between the Foxley Tuff Formation and the Gurrington Slate Formation, approximately 180m southeast of the A38 Ashburton Bypass. The borehole log shows 0.61m of topsoil overlying light brown and buff coloured shales of the Gurrington Slate Formation. These shales were encountered down to 8.53 mbgl, below which interbedded sandstone and shale was encountered, with 3.05m of quartzite recorded at 11.28 mbgl. These sandstones and shales are thought to be the Foxley Tuff Formation. Pink coloured limestone of the CBLF was encountered from 27.74m bgl to the base of the hole at 31.09 mbgl.

This stratigraphic sequence is consistent with 'Cross Section 3' shown on BGS Sheet 338 [17].

Borehole SX87SW43

This borehole was drilled to a depth of 30m at a location approximately 700m east of Bickington and some 3km northeast of the existing quarry. From BGS mapping, the borehole appears to be located approximately 130m southeast of the CBLF outcrop near to the easternmost limit of the studied area.

The stratigraphy was recorded as 'drift' and 'slates'. No further geological descriptions or associated depths were recorded for this borehole. Based on the BGS mapping, it is reasonable to assume that the 'slates' are those of the Gurrington Slate Formation. It is expected that the Foxley Tuff and CBLF would be present below the base of this 30m deep borehole.

Borehole SX77SE14

This borehole was drilled approximately 100m southeast of Goodstone, in an area to the southeast of the CBLF outcrop, where the Foxley Tuff Formation has been mapped by the BGS. The 60m deep borehole encountered tuffs with clay, shale also noted. It is interesting that the CBLF was not encountered in this borehole, given the proximity of the borehole to the boundary between the Foxley Tuff Formation and the CBLF. As the boundary lies to the north of the borehole and is understood to dip towards the southeast, it would have been reasonable to expect the limestone to be present at depth in this borehole. However, it is also possible that the boundary is present below the base of the hole, i.e. greater than 60m depth.

Borehole SX77SE13

This borehole is located approximately 160m south of the A38 at Caton Cross, within the CBLF outcrop as mapped by the BGS. The borehole log shows 'Soil and Stones' to 1.21 mbgl, underlain by 'Hard Brown Sandstone' to 3.66 mbgl, which is in turn underlain by 'Brown Clay' to 10.67 mbgl. Limestone was encountered below 14.94 mbgl to the base of the hole at 30.78 mbgl. The limestone is described as 'hard' and varies in colour between pink and brown.

The origin of the sandstone is not clear, but sandstones have also been encountered at SX76NE19, located south of Ashburton, where they were interpreted to be part of the Foxley Tuff Formation.

It seems likely that the 7.01m thickness of 'Brown Clay' represents soil infill which is either covering the buried karst rockhead, or present as an infilled solution feature.

Table 2-4 Summary of geology encountered in BGS boreholes near to the Linhay Hill Quarry site

BGS borehole ID	Location	Interpreted geological strata	Depth from (m)	Depth to (m)
SX77SE11	Alston Farm	Chercombe Bridge Limestone	0	8.84
		Tavy Formation	8.84	21.36
SX77SE8 SX77SE9 SX77SE10	Alston Farm	Chercombe Bridge Limestone	Unknown**	Unknown**
SX77SE12 (SX77SE1)	Western part of Linhay Hill Quarry works	Tavy Formation	0	161.85
		Chercombe Bridge Limestone	161.85	161.95
Numerous	A38 Off Slip Road near Caton	Superficial sediments (Pleistocene in age)	0	Base of superficial sediments >49.5m deep in boreholes GH03 and GH05.
		Chercombe Bridge Limestone	Minimum of 2.50	Top of limestone >49.5m deep in boreholes GH03 and GH05.
SX76NE19	South of Ashburton Approx. 180m southeast of the A38 Ashburton Bypass	Topsoil	0	0.61
		Gurrington Slate Formation	0.61	8.53
		Foxley Tuff Formation	8.53	27.74
		Chercombe Bridge Limestone	27.74	31.09
SX87SW43	Approx. 700m east of Bickington	Superficial Sediments	0	Unknown
		Gurrington Slate Formation	Unknown	30.00
SX77SE14	Approx. 100m southeast of Goodstone	Foxley Tuff Formation	0	60.00
SX77SE13	Approx. 160m south of the A38 at Caton Cross	Topsoil	0	1.23
		Sandstone (unidentified)	1.23	3.66
		Superficial sediments (Pleistocene in age)	3.66	10.67
		Chercombe Bridge Limestone	14.94	30.78

*Depth at termination of borehole. ** Limited by borehole records and lack of detail given.

2.4.5. Karst formation and classification

2.4.5.1. Overview

Karst features are known to be present in the CBLF. They can be seen at the Quarry and in the surrounding area. An introduction to the formation and classification of karst has therefore been included as part of this desk study. Table 2-5 provides some definitions of karst terminology.

2.4.5.2. Formation of karst

Karst terrains develop from the solution weathering of soluble rocks, notably limestone. Dry valleys, closed depressions, pinnacle rock surfaces, and other smaller scale solution features may form at the ground surface. Underground, within the rock mass, caves and conduits or fissures may form within the rock mass as a result of mildly acidic water flow through joints or other fracture pathways such as bedding planes.

Limestone is a sedimentary rock formed from calcium carbonate. Fookes and Hawkins [29] describe the distinctive landforms that develop in ancient limestones where the rocks have low porosity but are strong, with well-developed joints. In such limestones, the formation of conduits and depressions in limestone rockhead will be influenced by the orientation of pre-existing structural and stratigraphic features of the limestone bedrock; including discontinuities (joints, and bedding planes) and faults, all of which are present in the CBLF in and around the Quarry.

Differential solution weathering of discontinuities can form “*pits and grooves*”, which are frequently related to individual lithological horizons meaning that they form in “*fairly distinct rows*” [29]. Rockhead is a term that describes the top of the bedrock, beneath superficial deposits.

In areas of limestone bedrock, surface water may escape downwards into a ‘swallow hole’ that leads to conduits underground, though during wetter conditions, there may be sufficient flow for the watercourse to extend beyond these swallow holes. Active streams are also likely to have seasonal flow, with water infiltrating or discharging into ‘sinks’ at higher elevations during low water periods (Figure 2-6).

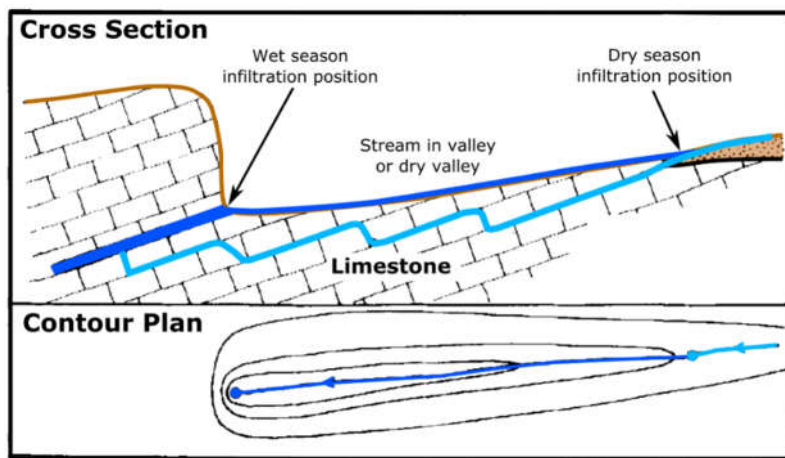


Figure 2-6 Development of seasonal stream sinks or 'swallow holes' (After Fookes & Hawkins [29])

Over time, conduits can become enlarged by dissolution resulting from the flow of mildly acidic water. Sinkholes can form at the ground surface above the intersections of joints and vertical conduits (shafts). Ground subsidence over such solution features may be triggered by heavy rainfall, water flows from soakaways, garden watering, leaking drains, and others [30]. Whilst obvious limestone karst features may not be observed on or immediately adjacent to a site, their presence in the vicinity may be very important to the overall understanding of the subsurface geology of the locality [29].

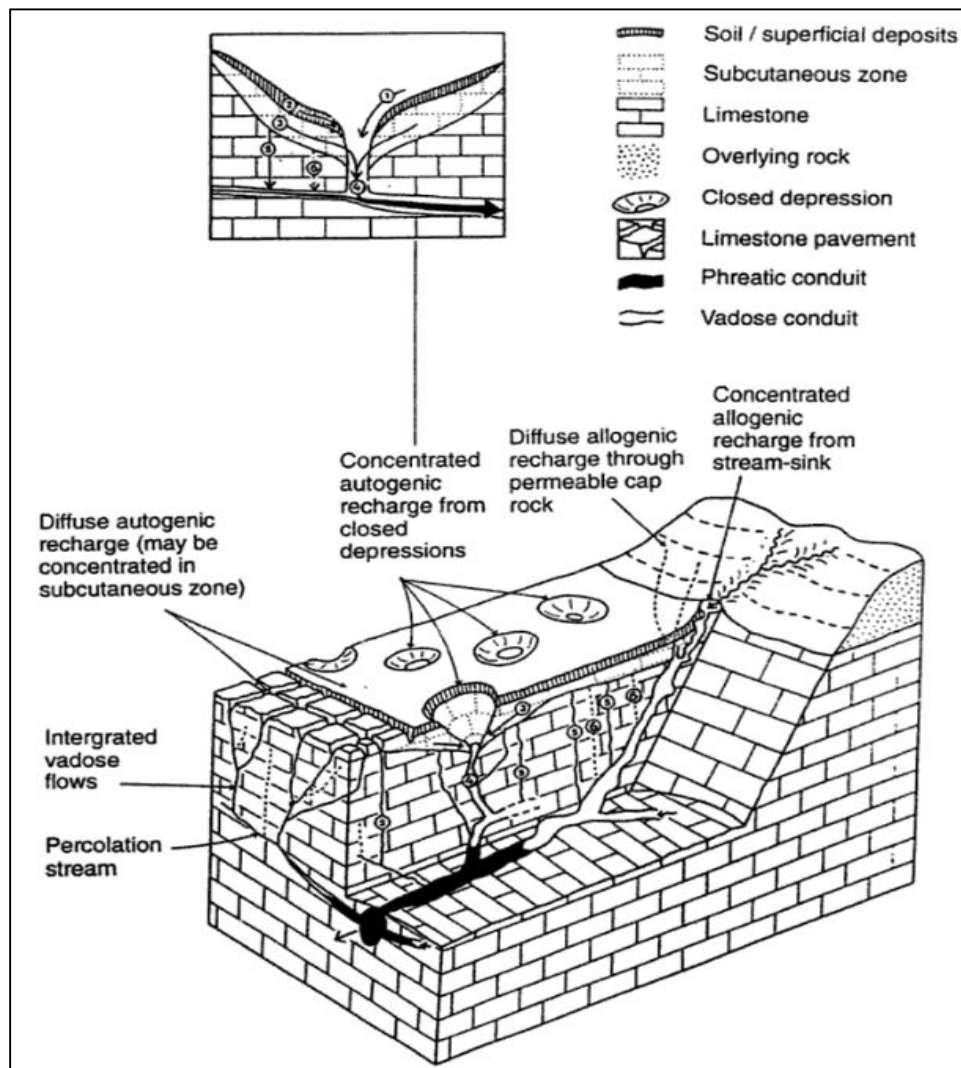


Figure 2-7 Conceptual model for conduit flow dominated karst aquifers, showing overland flow, throughflow, subcutaneous flow, shaft flow, vadose flow, and vadose seepage. The zone indicated as the 'Subcutaneous zone' is now widely referred to as the epikarst [31]

In some situations, the limestone bedrock may be overlain by unconsolidated deposits (generally taken to mean soils) which in this report are called collectively 'superficial deposits'. Such deposits include the insoluble remnants of the limestone or previously overlying strata [32]. Of relevance in such situations is the dissolution weathered bedrock just below rockhead. This upper part of the bedrock is commonly termed epikarst – it has more dissolution features than the rock at greater depth and is where most of groundwater is stored and transferred, and where sinkholes are formed (see 'subcutaneous zone' in Figure 2-7) [31].

2.4.5.3. Classification of karst for engineering purposes

Numerous classification systems for karst can be found in the scientific literature. Sparks [33] described how karst develops gradually over four stages (youth, maturity, late stage maturity, and old age). The concept of the stages of development of karst terrains has been used in classifications for engineering purposes, which are "based on the specific features that have the major influence on ground conditions, namely the caves, the sinkholes, and the rockhead morphology" [34].

Class	Major features	Descriptive profile with no soil cover	Site investigation	Foundations
I Limestone surface	Minor solution along joints		Literature and geomorphological appreciation. Trenching	Normal for good rock
II Minor karst	Some joints enlarged by solution		Literature and geomorphological appreciation of local area. Trenching. Probe/rotary drilling to determine presence of any cavities. Use of geophysics	Normal and/or strengthened ground beams, after open joints infilled with lean mix concrete
III Karst	Major solution along many joints above ground water level		Literature and geomorphological appreciation of local area. Trenches to determine nature of disturbed ground. Probe/rotary drilling to determine presence of any cavities. Use of geophysics	Strengthened ground beams after infilling of open joints with lean mix and/or rafts
IV Doline karst	Development of dolines above ground water level		Literature and geomorphological appreciation of local area. Probe/rotary drilling to determine presence of any cavities. Use of geophysics. Trenches to determine nature of disturbed ground.	Strengthened ground beam/rafts or structural bridging. May be necessary to excavate loose material to ensure no major cavities that may induce ground collapse
V Major doline karst	Major development of dolines. Cave system left when ground water level dropped		Literature and geomorphological appreciation of local area. Trenches to determine nature of disturbed ground. Probe/rotary drilling to determine presence of any cavities. Use of geophysics	Structural bridging of collapsed/potential collapse zones and/or heavily reinforced rafts

Figure 2-8 Engineering classification for crystalline limestone terrain in temperate latitude with suggestions for site investigation and foundation considerations [29]. (Green box added by Atkins; see text below.)

Note - the karst shown in the Figure 2-7 classification is not buried by superficial deposits, whereas the karst at the Quarry and nearby is buried by superficial deposits.

For engineering applications, karst may be classified in accordance with a scheme proposed by Fookes & Hawkins [29] in which the five classes are a measure of the severity or complexity of morphological features present (Figure 2-8). The two classes of karst expected to be predominantly present in the vicinity of the proposed extension to the Quarry are indicated with the green box. The Fookes & Hawkins [29] classification includes suggestions for site investigation techniques and foundation considerations for each of the five classes of karst.

Waltham & Fookes [34] developed further the idea of a five-fold classification system by linking the size and number of caves, size and number of sinkholes, frequency of new sinkhole events, topographic relief, and rockhead relief, as shown in Figure 2-9. The importance of this engineering classification system in developing a conceptual understanding of karst morphology was reiterated recently by Waltham [35]. The present report has employed the Waltham & Fookes [34] classification scheme (Figure 2-9.) The predominant karst terrain expected to be present in the vicinity of the proposed extension to the Quarry is mature karst kIII, although elements of kII and kIV are also expected.

To ensure consistency when referring to features of karst in relation to the Quarry and the surrounding area, a list of standard terms and definitions associated with karst has been adopted for this report, shown in Table 2-5.

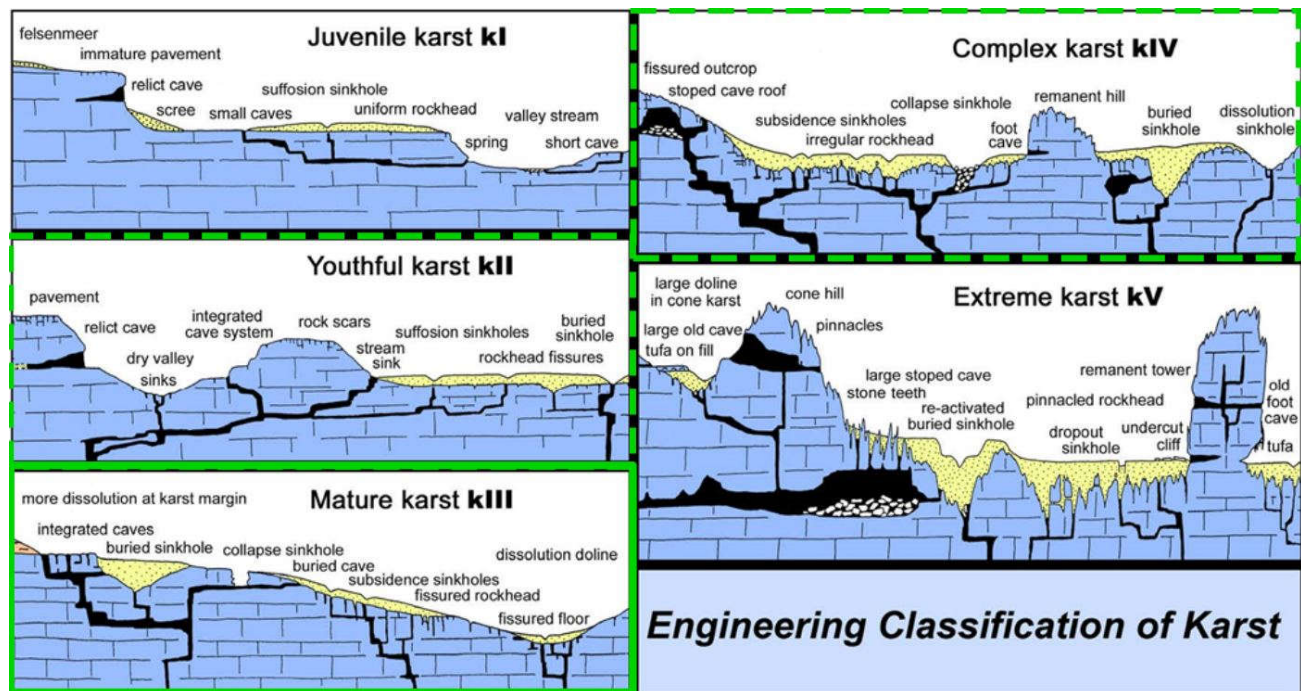


Figure 2-9 Engineering classification of karst morphology showing the increased sizes and number of caves, sizes and number of sinkholes, frequency of new sinkhole events, topographic relief and rockhead relief in increasingly mature karst terrains [34] & [35].

Table 2-5 Terms associated with karst and definitions as used in this report.

Adopted Term	Other terms in common use	Definition
Cave	Cavern	A natural underground room or series of rooms and passages large enough to be entered by a man; generally formed by solution of limestone (United States Department of the Interior – Geological Survey, 1972).
Cavity	Crevice	A natural underground void, smaller than a cave and not large enough to be entered, which may have been formed or enlarged by solution of limestone. Over time, cavities may enlarge due to dissolution and become caves.
Conduit		A cavity within the rock mass, through which water may flow or be stored as part of a karst aquifer.
Discontinuity		A boundary, layer, or fracture (including joints), within a rock mass.
Dissolution	Solution	The development of underground cavities due to water passing through soluble rocks.
Epikarst		The upper part of the bedrock in a karst environment, having more dissolution features than the rock at greater depth and is where the majority of groundwater is stored and transferred, and where sinkholes are formed ([31]; see Figure 2-7).
Fissure		An open discontinuity in the rock mass, which may include joints and other fractures.
Joint	Fracture	A break within a rock mass that has no observable displacement.
Karst		Weathering forms produced by dissolution on bare rock surfaces, beneath soil at rockhead, and within the rock (adapted from Waltham [36]).

Adopted Term	Other terms in common use	Definition
Pinnacled Rockhead	Pinnacles	Highly fissured limestone surface beneath a soil cover. Tall, narrow, unstable or loose pinnacles may be supported only by soil, and fissures may extend far below into caves [36].
Rockhead		The top of the bedrock, beneath superficial deposits.
Shaft		A near vertical type of conduit. Generally considered to be present below discrete swallow holes or sinkholes.
Sinkhole	Doline	A closed surface depression with drainage sinking underground (Waltham, 2009). The term 'sinkhole' is used regardless of whether streams sink within them.
Sinking stream	Sink Stream sink	Gradual or diffuse infiltration of stream flow into the ground.
Swallow hole	Sink Stream sink Sinking stream Swallet	Discrete point at which stream flow enters the ground.

2.4.5.4. Classification of the Land Stability Study Area

With reference to the engineering classification of karst adopted by Waltham [35] and Figure 2-9 herein), an appropriate description of the karst in the vicinity of the Quarry would be: a buried Mature karst (kIII), with the possibility of open conduits associated with continuing karst activity, and irregular rockhead of the kind that might be expected from Complex karst (kIV) (Figure 2-9 and Figure 2-10). This description is broadly consistent with Fookes & Hawkins [29] who classified the karst of the Caton Cross area (1km northeast of the existing quarry) as “*typical of Class III to IV*”. It is important to note that karst of a particular class may exhibit localised features of both higher and lower classes.

Although no superficial deposits are indicated on the BGS maps, it is known from the local geomorphology and from intrusive ground investigations that the karst in the Land Stability Study Area is a buried karst, with a variable cover, predominantly of clay.



Figure 2-10 Photograph showing the northeastern area of excavation at Linhay Hill Quarry with the irregular karstic rockhead after the overburden has been stripped off. The overburden comprised superficial clays and the infill of karst features. A mechanical excavator is shown in the foreground, providing a sense of scale [2].

2.4.5.5. Engineering Considerations

Karst ground conditions can be considerably complex, especially where karst formation is well-developed. The distribution of sinkholes and caves can be largely unpredictable. Techniques such as aerial photograph interpretation, geophysical surveys, boreholes, geomorphological walkovers and the mapping of the ground surface and underground can provide useful results, although results from remote sensing, including geophysical techniques, are indicative and require verification by other means. Examples of karst features and formation processes, together with implications for engineering and suggested engineering responses are shown in Figure 2-11.

In a mature (kIII) karst, dropout sinkholes may be expected to occur within a few years of water table lowering, but where such karst is buried beneath superficial deposits a greater amount of time is expected to pass as material is removed from infilled conduits by erosion and collapse. Sinkhole collapse can also form because of soil cover being washed down into fissures or cavities, which may occur during heavy rainfall, where surface drainage is uncontrolled.

Karst feature or process	Implications for civil engineering	Engineering response
New dropout sinkholes in the soil cover	Rapid ground failure, mostly induced by drainage change	Compaction grouting within soil; minimize by control of drainage
Ground subsidence by soil loss into fissures	Slow settlement, commonly induced by drainage change, may precede dropout failure	Compaction grouting within soil; minimize by control of drainage
Pinnacled rockhead	Huge variations in depth to rock, and in the stability and shape of pinnacles, for solid founding of structures	Anticipate large variations; clear soil and fill with crushed rock, or prove every footing
Buried sinkhole filled with soil	Large rockhead depression filled with weak and/or soft soil, which may compact under load and/or be lost by suffosion in drainage	Budget for deeper foundations; control the drainage
Unexpected cavity in bedrock	Size, shape and depth of a cave are almost totally unpredictable in strong limestone	May need to relocate structure, or fill cave with lean concrete, or pile through to solid floor
Bedrock collapse under structural load	Potential roof collapse over large or small cavities with totally random distribution	Prove sound rock beneath every pile tip and structural element; see Table 4
Subsidence over a breccia pipe	Effectively a deep buried sinkhole, with fill that may be dense or weak	May need to relocate to avoid
Solution depression	Large surface basin with soil floor and internal drainage	Best avoided, as soil floor is prone to subsidence sinkholes

Figure 2-11 Selected features and processes of karst terrain that are considered to be widespread and significant to civil engineering, and which may be present in the vicinity of Linhay Hill Quarry (copied from Waltham (2016), who presented additional karst features and processes not shown here)

2.4.6. Geological Evolution

The CBLF was deposited on shallow submarine ridges in a tropical marine environment during the Middle Devonian period. At around the same time, the Foxley Tuff Formation was formed further to the south. Later, during the Upper Devonian, the CBLF was overlain by the Tavy Formation, and the Gurrington Slate Formation was deposited over the Foxley Tuff Formation. A geological map of the quarry and its surrounds is shown in Figure 2-4; schematic cross sections are shown in 0

Folding and thrusting occurred during the Variscan Orogeny due to the collision of continental land masses, which began towards the end of the Devonian and continued through the succeeding Carboniferous period and into the early Permian.

Towards the end of the Carboniferous (the geological period after the Devonian) the Crackington Formation was deposited and later deformed by further faulting in the area.

The most significant effects of the Variscan Orogeny took place in the late Carboniferous to early Permian (about 300 to 290 million years ago). The Dartmoor Granite was also intruded at the end of the Carboniferous and during the early Permian, causing metamorphism of the surrounding country rock.

After many millions of years of subsequent deposition and erosion, the CBLF was exposed and subjected to dissolution. Sinkholes developed on the land surface, with underlying shafts and a conduit system developed at depth, possibly including caves. It is likely that the water transported through the conduit system was discharged at springs.

The landscape developed into one of mature karst. During the present Quaternary period, the climate alternated between periglacial (cold) and interglacial (warm). As Quaternary glaciation in the British Isles did not extend as far south as South Devon, the karst was not subjected to erosion by ice sheets or glaciers, as was the case for the limestone karst terrain of Ireland, Wales and northern England. Instead, it was covered by clayey superficial deposits, probably originating from periglacial and post-glacial weathering of the hill slopes to the north-west of the site. It is not clear how many phases of superficial deposition have occurred. The deposits are likely to have infilled many of the now buried conduits and sinkholes. Where this is the case, the conduits would be less important for groundwater flow.

The superficial deposits presently cover all the limestone outcrop, except where the limestone has been exposed by excavations at the Quarry and elsewhere, or by construction projects such as the A38 duelling.

The spatial and temporal relationship between phases of deposition of superficial deposits and development of karst are not known. Based on general experience of karst terrain elsewhere, there may have been periods of relative inactivity (perhaps even dormant) and periods when karst development was particularly active. Variations in the amount and location of surface and sub-surface water movement will have been an important factor in determining the activity of the karst.

2.5. Remote Sensing and Geophysics

2.5.1. Satellite and aerial photograph imagery

Satellite and aerial (photograph) imagery of the Land Stability Study Area has been viewed to identify features of the ground surface that may be indicative of the underlying geology and geological processes. Details of the satellite imagery used and the historical aerial photographs that have been obtained by Atkins from Historic England are listed in Table 2-6 below. Other aerial photographs were identified and viewed during Atkins' visit to Historic England's offices, but were found to be unsuitable, e.g. because of poor quality or limited spatial extent.

2.5.1.1. Satellite imagery

Satellite imagery from several years was sourced using Google Earth. As well as providing evidence of changes over time, interpretation of imagery from several dates can reveal additional features because of the differing lighting conditions and vegetation cover.

Interpretations were made from the satellite imagery across the outcrop of the CBLF. Localities of interest interpreted from the imagery, together with information from other sources (including ground investigations, geophysical surveys, and anecdotal evidence), were used to produce a map of targets for visual inspection during the field walkover (described in a separate technical note provided as an appendix to Chapter 17 of the Environmental Statement). The targets were assigned a priority based on consistency with other sources of information and the likelihood of the target representing a sinkhole or sinkholes.

2.5.1.2. Aerial imagery (photographs)

The satellite imagery has been supplemented by the interpretation of historical aerial photographs sourced from Historic England's archives. These photographs have the advantages that (a) they are generally higher resolution than the satellite imagery, and (b) pairs of images can be viewed in 3D with the aid of a mirror stereoscope. Having inspected relevant photographs at Historic England's Swindon office, Atkins has obtained high resolution electronic scans of 31 black and white aerial photographs that were considered as likely to be of particular benefit to the project. Atkins has studied these images, and further field walkovers will include features of potential interest identified from the aerial photographs.

Table 2-6 Satellite and aerial imagery used for interpretation of ground surface features.

Type	Date	Source	Colour / black and white	Reference	Number of images ordered
Satellite	6 Apr 2013	Google Earth (Digital Globe)	Colour	-	Accessed via the internet
Satellite	2 Oct 2011	Google Earth (Digital Globe)	Colour	-	Accessed via the internet
Satellite	1 Jan 2010	Google Earth (Getmapping plc)	Colour	-	Accessed via the internet
Satellite	1 Jun 2006	Google Earth (Infoterra Ltd & Bluesky)	Colour	-	Accessed via the internet
Satellite	1 Jan 1999	Google Earth (Infoterra Ltd & Bluesky)	Colour	-	Accessed via the internet

Type	Date	Source	Colour / black and white	Reference	Number of images ordered
Aerial	29 Jun 1969	Historic England	Panchromatic (black and white)	OS/69297	6
Aerial	29 Jun 1969	Historic England	Panchromatic (black and white)	OS/69296	7
Aerial	12 Jul 1946	Historic England	Panchromatic (black and white)	RAF/3G/TUD/UK/223	5
Aerial	10 Dec 1946	Historic England	Panchromatic (black and white)	RAF/CPE/UK/1890	4
Aerial	2 May 1949	Historic England	Panchromatic (black and white)	RAF/58/220	9

2.5.2. Drone Surveys

Two drone surveys were commissioned by E&JW Glendinning in 2016: one covering the existing Quarry, and one covering the proposed extension area to the northeast. Each of the surveys comprised a LiDAR (Light Detection and Ranging) topographic survey and aerial photography.

The survey of the proposed extension area was subsequently used by the survey contractor [37] to identify discrete localised areas of elevation change. The contractor identified five such areas in the fields between the existing quarry and the hamlet of Caton. At least four of the identified areas appear to relate to the locations of trial pits excavated to provide information on the shallow ground conditions in the area of the proposed bunds for the quarry extension.

2.5.3. Geophysical surveys

Geophysical surveys have been carried out within and around the proposed quarry extension:

- Two surveys were commissioned by E&JW Glendinning in relation to the proposed extension area: one covering the proposed extension area itself [7] and one covering the land to the northeast of Caton [1]. Neither of these surveys was designed to investigate sinkholes or other land stability hazards but were to obtain reconnaissance information on the thickness of clay over the CBLF, and to identify anomalous areas that may potentially relate to karst features.
- Other surveys were commissioned by EM Highways Services Ltd. of land to the east of Caton in response to a sinkhole that developed adjacent to the A38 off slip road [38] [39] [40] [41] (Table 2-8) (Section 2.4.4.2 and Section 2.6.3). Highways England have confirmed that a depression was present at the time of construction of the slip road and that the ground movement reported in 2014 was preceded by high rainfall in December 2013 and January 2014.

In general, the two geophysical surveys that were carried out for the proposed extension [7] [1] provide an indicative assessment of the shallow geology, but there are numerous unexplained features within the data. Atkins' review of Bentham Geoconsulting Ltd.'s geophysical (Electro-magnetic, EM) survey has found the following:

1. The results of the EM appear to provide an indicative assessment of the variation of the thickness of the clay superficial deposits overlying weathered limestone bedrock in some parts of the survey. However,

the results from large parts of the survey areas appear to be strongly influenced by other features or factors that are unrelated to the thickness of the superficial deposits or nature of the bedrock.

2. EM techniques have limited use in the identification of karst features because only the karst features that are infilled with clay may be identified using EM techniques. Situations where the overlying materials bridge a sinkhole or where a cavity is close to the top of the rockhead will not be identified using EM techniques.

In September 2017 BGS staff carried out a series of passive seismic survey trials in the vicinity of Linhay Hill Quarry as part of its research programme to assess the viability of using the passive seismic survey technique to determine the position of rockhead and karst features [42]. The surveys were carried out on land at Alston Farm, and also at Caton Farm near the A38 off slip and in general terms the results were thought to provide an indication of the depth to rockhead or the thickness of the superficial deposits, but the draft conclusions also detailed some uncertainties and hence the draft survey findings have not been utilised further herein.

Other geophysical survey methods considered to have the most potential for acquiring further data if required to help improve understanding of the subsurface in the locality of the extension area are:

- Microgravity geophysical survey can be used to identify karst features, particularly cavities. Microgravity may not be cost effective due to the time required for data acquisition over a wide area.
- Resistivity imagery, provides data in profile form so stratigraphic relationships can be interpreted and it may be a more successful electrical method than the EM method for identifying karst features, although this method also has limitations. Voids generally appear as areas of extremely high electrical resistance but features infilled with clay will have a relatively low resistance that may have little contrast with the surrounding weathered limestone.

2.6. Past Ground Investigations

2.6.1. 1986-1987 Ground Investigation and Quarry Stability Assessment

In 1987 Engineering Geology Ltd produced a report on the rock slope stability of the existing and the then proposed workings at the Quarry [2]. The investigation was carried out between June 1986 and March 1987. It included a desk study, mapping of the quarry faces present at that time, and drilling of three rotary cored boreholes along the south-eastern boundary of the quarry workings.

Information was also obtained from numerous machine-excavated trial pits and associated laboratory test results, which were relevant to the assessment of the stability of the south-eastern and north-eastern slopes of the quarry. The trial pits were excavated to provide information about the nature of the superficial deposits overlying the karstic limestone.

Engineering Geology Ltd.'s [2] mapping of the quarry faces identified the presence of joint sets in addition to the following structural features of the rock mass:

- a. Curved slickensided and polished structures (interpreted by Engineering Geology Ltd as probably minor faults with a lateral component of displacement)
- b. Continuous open or clay filled structures (interpreted to have been formed by solution)

Observation presented by Engineering Geology Ltd. of the rockhead where the overburden had been stripped away showed a pinnacled karstic rockhead with up to 8 m of superficial deposits above the rock pinnacles. Two units of superficial deposits (also termed 'overburden' in the report) were identified from the trial pit excavations and were described as follows:

1. Upper Unit: "*Firm yellow brown to red brown silty clay*" with "*irregular lenses and patches of more gravelly and sandy material*"
2. Lower Unit: "*Dark brown gravelly silty clay with lenses of reddish gravel and black manganese-rich clay*"

The Lower Unit is described in the Engineering Geology Ltd. report [2] *as infilling the hollows and voids of the karst. It has a planar upper boundary with the base of the Upper Unit*, suggesting that the Upper Unit was deposited after the majority of the karstic weathering at rockhead had taken place and the depressions in the limestone rockhead had become infilled.

Evidence of open and infilled solution features and joints that showed evidence of solution processes were recorded in the boreholes drilled. Borehole 3 reportedly penetrated “11.15m of overburden with clay filled joints occurring to about 23m” (presumably below ground level). In general, an increasing thickness of superficial (overburden) materials was found towards the northeast of the current Quarry. A summary of the borehole data is provided in the following table.

Table 2-7 Geological descriptions from Engineering Geology Ltd. 1987 borehole logs

Hole ID	Location	Depth (m bgl)	Summary of geological features	Groundwater levels
BH1	Within south west corner towards Balland Lane	95.2 (121.0 to 25.8mOD)	- Limestone from 1.5 m depth. “Dark grey highly deformed sheared argillaceous limestone 65.1-65.4m” zone of deformation continues to about 70m.	90.8-103.8mOD from 10/11 to 21/11 1986.
BH2	Midway between quarry’s south west corner and Alston Cross	95.2 (118.0 to -3.95mOD)	- Limestone from 0.15 m depth. - Core loss 4.6-4.8m and 8.2-8.36m. 24.5-24.7 “recovered as angular limestone gravel in soft brown clay matrix 0.2m noted by Driller”. 44.35 “Several 1 to 2cm black carbonaceous partings”, below about 50m carbonaceous partings becoming common. 101-103.6 “Frequent black 1-2mm carbonaceous partings on bedding surfaces”.	99.0-106.8mOD from 6/11 to 21/11 1986.
BH3	Towards Alston Cross	35.4 (119.0 to 83.6m)	Limestone from 11.15 m depth.	107.5 and 108.5mOD on 12/11 & 13/11 1986.

2.6.2. 2015 Ground Investigation

The ground investigation carried out in January 2015 [8] by Sandybed Geological Services (hereafter referred to as Sandybed) focused on an area to the northeast of the current Quarry. The investigation was commissioned by E & JW Glendinning Ltd. to provide information about the overburden thickness above bedrock (i.e. superficial deposits) for the design the proposed quarry extension. The 2015 ground investigation [8] was not designed to investigate the underlying karst from an engineering or environmental perspective.

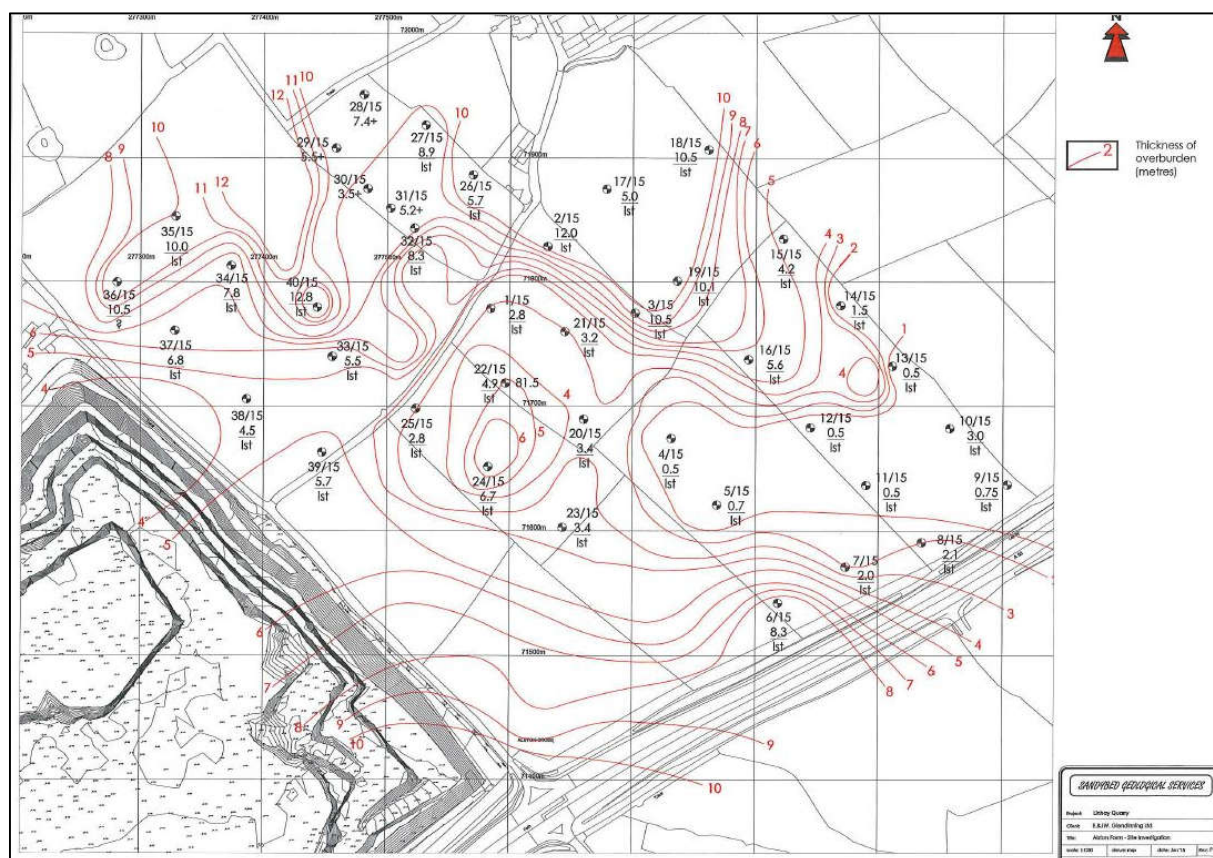


Figure 2-12 Map produced by Sandybed [8] showing borehole locations and their interpreted depth to base of overburden. The grid lines on the map are 100m apart.

Forty boreholes were drilled using rotary open-hole techniques. They showed that the depth to rockhead was variable over the investigated area, with a minimum encountered depth below ground level of 0.5m and a maximum of 12.8m. This variation is consistent with other ground investigations nearby and with historical records of quarry excavation at the Quarry. Such variations in rockhead would be expected in a buried mature karst setting. Two trial pits were also excavated where the limestone had been found to be shallow, so that measurements of the bedding plane orientations could be made.

Sandybed interpreted the presence of sinkholes at locations where the depth to rockhead was found to be particularly great; that is where the thickness of superficial deposits (overburden) was greatest. A contour map produced by Sandybed shows their interpreted 'thickness of overburden' (Figure 2-12). Atkins considers that the map represents an overly simplified version of the actual rockhead topography, because the 50m to 100m spacing of the Sandybed boreholes is too great to enable the identification of individual pinnacles and smaller depressions in rockhead. Rock pinnacles approximately 1 to 2m wide were found nearby during construction of the Caton Cross overbridge [29] and Atkins has noted ribs of rock (or pinnacles) approximately 1m to 7m wide in the current south-east face of the quarry).

2.6.3. A38 Off-slip Road at Caton: Sinkhole Investigation

In early March 2014, a 3m wide by 3m deep new sinkhole formed within an existing sinkhole depression adjacent to the off-slip road of the northbound carriageway of the A38 near the hamlet of Caton. Highways England has confirmed that the larger depression was present when the Caton Cross Overbridge A38 off slip road Junction was constructed during 1969 and the early 1970s. Surface and sub-surface investigations were carried out on behalf of EM Highways Services Ltd. by Geotechnics Ltd. [43] and others, including several phases of borehole and geophysical investigation (see Table 2-8, Figure 2-13, **Error! Reference source not found.**Figure 2-14).

The new sinkhole was partially remediated by infilling. It was visible in June 2016 as a "remnant depression of at least 3 m depth and 5 m diameter" (BGS Caton karst webpage, 2017) [15]. Records from boreholes

drilled adjacent to the off-slip road in response to the sinkhole development in 2014 show that karstic solution features exist to depths more than 49.5 m. Borehole records from the nearby Caton Cross overbridge investigation presented by Fookes & Hawkins [29] showed infilled solution features to at least 11m below ground level (see Section 2.6.4).

Table 2-8 Available ground investigation information for the investigation of a sinkhole on the A38 off-slip road near to Caton between 2014 and 2015.

Date of investigation	Type of investigation	Carried out by	Investigation phase (as stated in investigation report)	Spatial coverage
April 2014	Geophysics: Resistivity	Subsurface Geotechnical Ltd [38]	1	Two survey lines in the verge of the off-slip road and two survey lines in the adjacent field to the northwest of the slip road.
June 2014	Drilling: GH01, GH04, P1, P2, P3, P4, P5, P8, P9, and P10.	Geotechnics Ltd [43]	2	Two 'Rotary/Percussive' boreholes on the eastern edge of the off-slip road (GH01 and GH04) and eight 'Rotary Open Hole' boreholes in the field to the northwest of the off-slip road (P-series holes).
September to October 2014	Geophysics: Electromagnetic	Subsurface Geotechnical Ltd [39]	Unknown	Two fields between the off-slip road and the main A38 carriageway and three fields to the north, northwest, and southwest of the off-slip road.
April 2015	Geophysics: Electromagnetic	Subsurface Geotechnical Ltd [40]	III	Two fields to the southeast of the main A38 carriageway.
April 2015	Drilling: GH02, GH03, and GH05	Geotechnics Ltd [44]	4	One 'Rotary/Percussive' borehole and two 'Rotary Open Hole' boreholes on the north-western edge of the off-slip road.
August 2015	Geophysics: Resistivity	Subsurface Geotechnical Ltd [41]	IV	One survey line in the verge of each Carriageway of the A38, southeast of the off-slip road.
November 2015	Drilling: BH6_1, BH6_2, BH6_2A, BH6_3, BH6_4, and BH6_5	Geotechnics Ltd	6	Two rotary cored boreholes on the northern edge, and two on the southern edge, of the main A38 carriageway. One rotary cored borehole on the southwestern edge of the north abutment of the Caton overbridge.

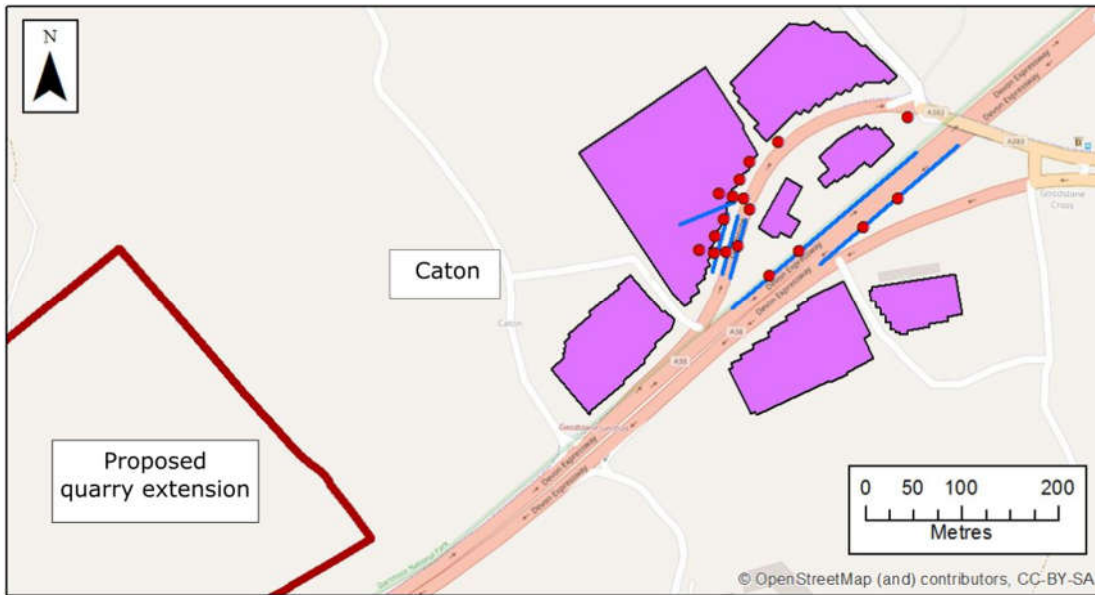


Figure 2-13 Map showing the location of site investigations carried out on behalf of EM Highways Services Ltd. in the vicinity of the A38 off slip road between 2014 and 2015. Red circles indicate borehole locations, blue lines indicate resistivity survey lines, and the purple areas have been investigated by electromagnetic surveys.

In an article on their web-site, the BGS has noted about the boreholes that “*Although insufficient to determine the full depth of the associated karst, they confirm that it exceeds 49.50m in one of the boreholes and 45m in two of the other boreholes*” [15].

Atkins’ notes the shape of the sinkhole, as depicted in Figure 2-14A from the report commissioned by E.M Highway Services Ltd [44] is highly speculative. In particular:

1. none of the boreholes depicted in the cross section penetrated the base of the sinkhole, which may be deeper than the c.40m depth shown in the cross section and
2. some of the “*cobble/boulder fill*” may be a karstic rib or other body of in situ rock which was difficult to recover as intact drill core.

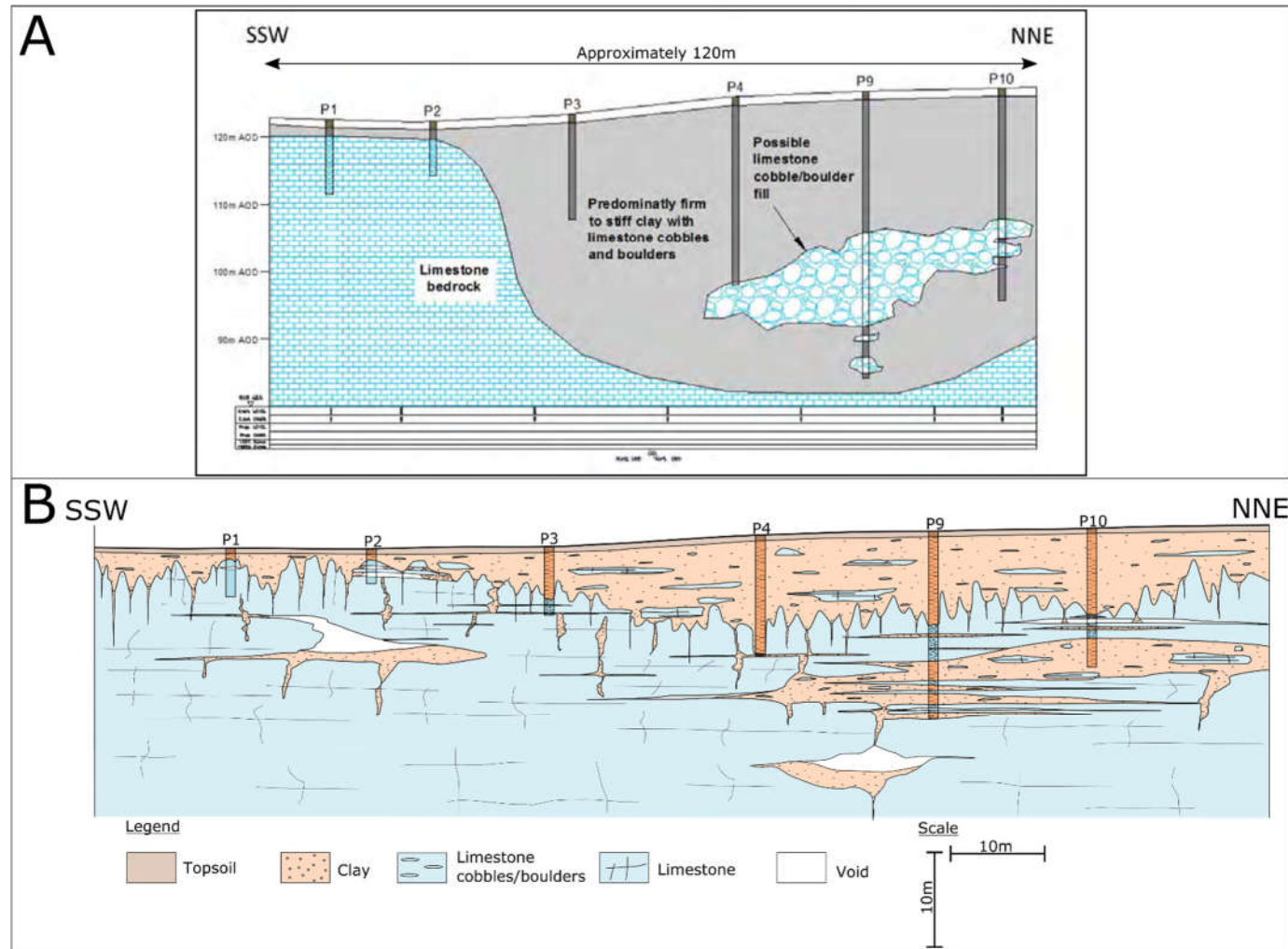


Figure 2-14 Cross sections of the solution feature adjacent to the A38 off slip road near to Caton:
A: From EM Highway Services Ltd.'s Specification for the Phase 4 Ground Investigation in: Geotechnics, 2015. Atkins has added the approximate horizontal scale.
B: Atkins' schematic reinterpretation of the EM Highway Services Ltd. boreholes.

2.6.4. Caton Cross Overbridge Investigation

Fookes & Hawkins [29] described a site investigation carried out in 1969 at the Caton Cross Overbridge, approximately 600m northeast of the proposed quarry extension and 200m northeast of the sinkhole described in Section 2.6.3 above. The bridge was to be constructed over the new A38, which served to bypass traffic around Caton. The A38 and the overbridge were constructed during 1969 and the early 1970s.

The boreholes revealed that superficial deposits were present to variable depths, up to 6m (Figure 2-15), with clay filled solution features found within the limestone to approximately 11m below ground level. Correlations could not be drawn between boreholes as some encountered almost continuous limestone whilst others encountered limestone and clay, particularly at shallow depths. Various types of limestone were encountered, including brecciated limestone, limestone with calcite veins, and limestone with calcite-lined voids.

Fookes and Hawkins [29] report that during construction, the upper superficial deposits were removed with ease, with occasional large boulders being pushed aside. Rockhead was later found to be present as a series of limestone pillars (3 to 4m high and 1 to 2m in diameter), protruding up into the clays. The boreholes appeared to have penetrated through varying amounts of bedrock (pillars) and the superficial sediment infill (clays). The karst in this area was classified by Fookes and Hawkins [29] as Class III or Class IV (as shown in Figure 2-8).

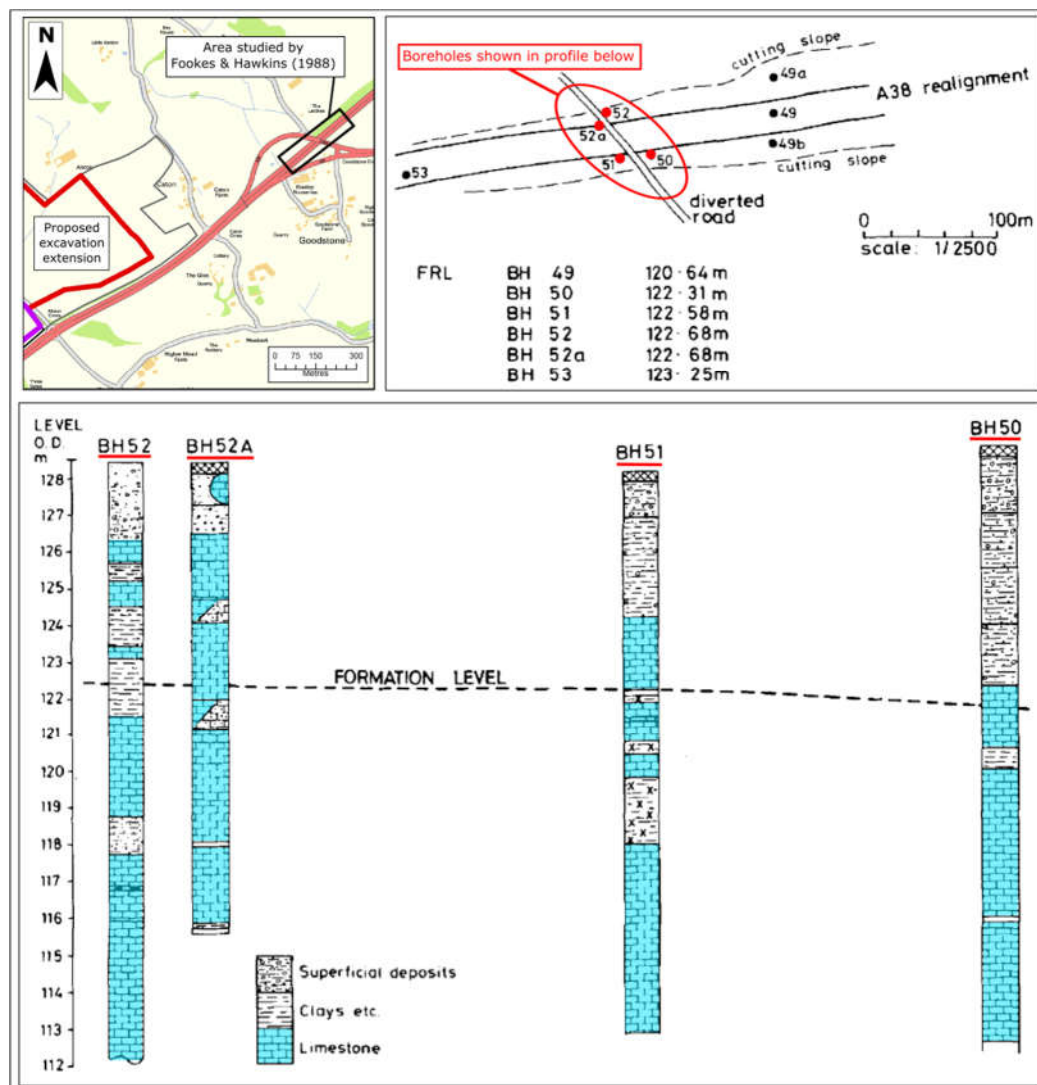


Figure 2-15 Map and borehole profiles from the A38 Caton Overbridge site investigation undertaken in 1969 (Extracted from Fookes & Hawkins [29]). Atkins' additions are: inset map (top left), red annotations on original location plan (top right), red annotations and blue shading on borehole sketch (bottom).

2.6.5. Installation of Shallow Monitoring Boreholes 2016

Eleven shallow monitoring boreholes, mainly to the top of the Chercombe Bridge Limestone Formation around the proposed quarry extension were installed in August 2016 as summarised in the following table to enable monitoring for groundwater within the superficial deposits. Details of that investigation are provided in Appendix B.

Table 2-9 Monitoring boreholes installed by Frederick Sherrell Ltd. in August 2016

Hole ID	Ground level (to 1dp) mAOD	Drilled depth (mbgl)	Depth to rockhead (mbgl)	Screen depth (mbgl)	Standpipe diameter (mm)
AF1	142.2	18	10.5	10-16	19
AF2	139.8	8.5	6	5.5-8.5	19
AF3	143.6	17.5	Not encountered	11-17	19
AC1	138.1	11	8	5-11	19
AC2	136.0	16	Not encountered	6-12	50
AC3	136.2	11.5	8.5	5-11.5	19
NE4	125.4	19	Not encountered	11-17	19
NE5	129.9	6	6	3-6	19
NE6	133.5	14	11	6-12	50
NE7	132.7	17.5	16	11.5-17.5	19
NE8	133.7	13	10	7-13	19

The boreholes intersected clay-rich material, with weathered fragments of rock overlying bedrock. Monitored groundwater levels are shown in the following figure, with the boreholes monitored manually generally monthly and with three of the boreholes having data loggers since the end of December 2017. Gaps in the data indicate groundwater levels fell below the base of the standpipes.

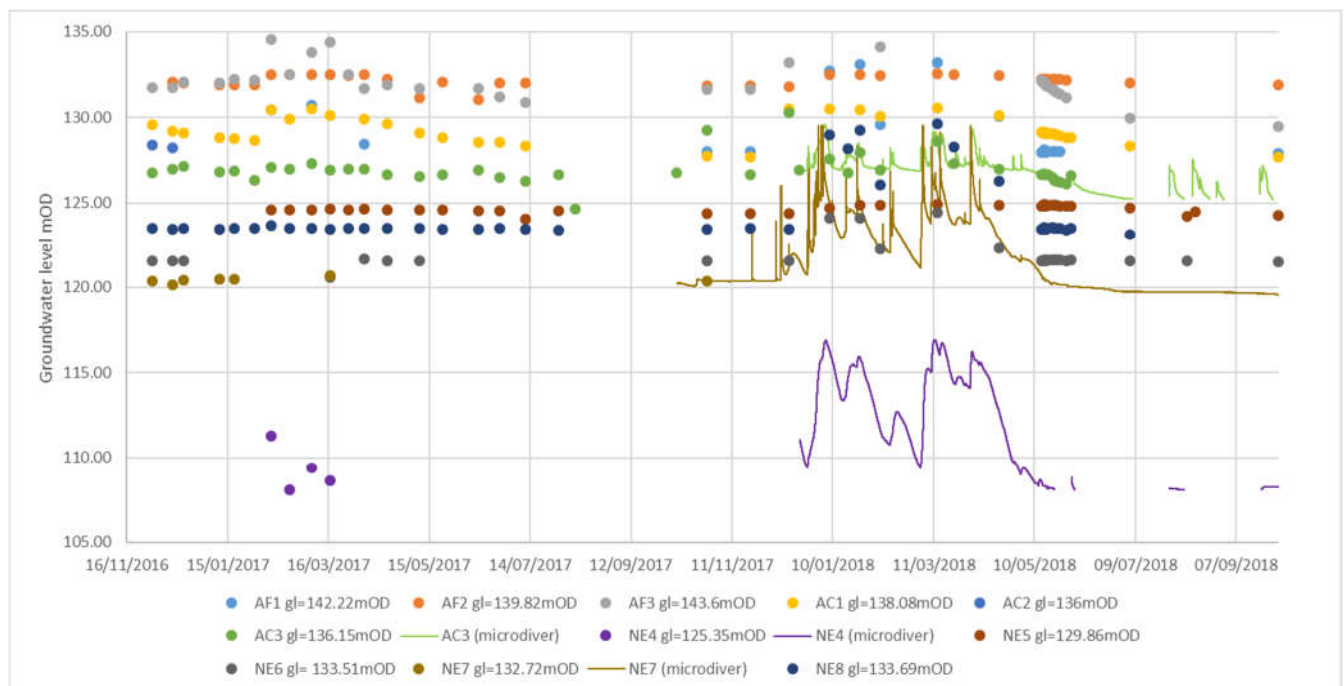


Figure 2-16 Groundwater level hydrographs at shallow boreholes installed 2016

The groundwater level data from borehole monitoring indicates quite variable groundwater levels with rapid response to rainfall and declines thereafter and that levels at some locations fluctuate within the overburden.

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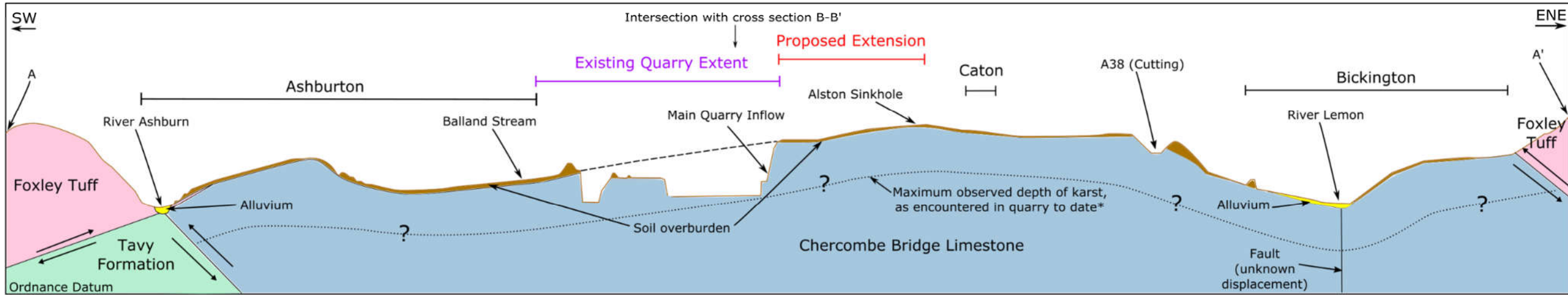
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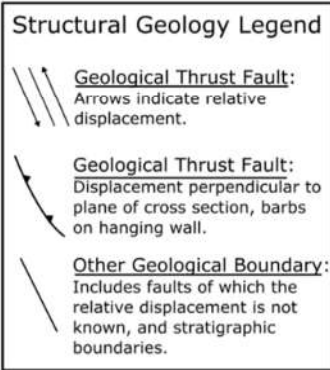
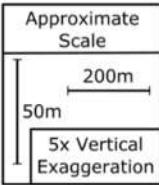
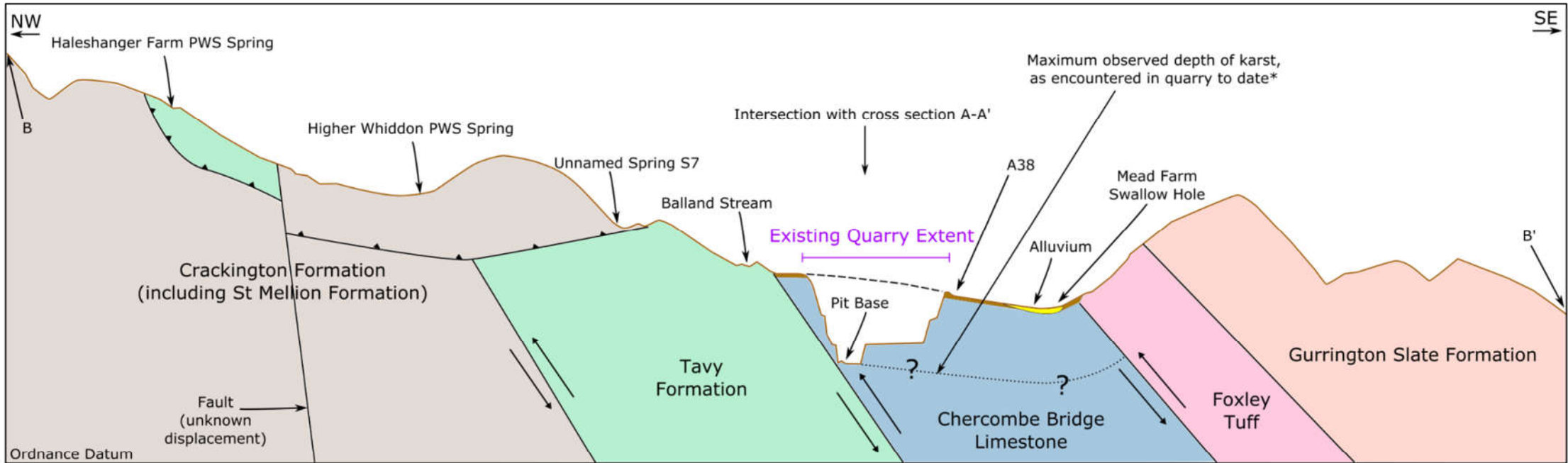
Appendix A. Large Figures

Figure A-1 Schematic cross sections showing the conceptual geological and hydrogeological model of Linhay Hill Quarry and its surroundings

Cross Section A-A'



Cross Section B-B'



*The maximum observed depth of karst shown is based on the approximate depth to the base of the quarry during Atkins' site visit in May 2018. The actual depth of karst features should be expected to vary across the Chercombe Bridge Limestone, and the maximum depth is expected to be greater than that observed in the quarry to date.

	Schematic cross sections showing the conceptual geological and hydrogeological model of Linhay Hill Quarry and its surroundings. A location plan is shown in Figure A-2	Drawn By: SDP / PM	Figure A-1
		Date: 28/Sep/2018	

Figure A-2 Location of conceptual geological cross sections

