BGS Karst Report Series: C7. Karst in the Chalk of the South Downs

Environmental Change, Adaptation & Resilience Programme

Open Report OR/21/057

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Karstic conduits at Castle Hill, Newhaven

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Executive Summary

This report documents the evidence for karst and rapid groundwater flow in the Chalk of the South Downs area in Southern England. It is part of the BGS karst report series on those karst aquifers in England in which cave development is limited – principally the Upper Cretaceous Chalk and the Jurassic and Permian limestones. The series is the main output of the NERC funded Knowledge Exchange fellowship “Karst knowledge exchange to improve protection of groundwater resources”. The term “karst” applies to rocks that are soluble. In classic karst there are extensive caves and large scale surface karst landforms such as dolines, shafts, stream/river sinks, and springs. In the past, the Chalk and the Jurassic and Permian limestones of England were not considered karstic because they have limited cave development, and because karst features are usually small and have not been well documented. However, permeability in these aquifers is determined by their soluble nature and groundwater flow is predominantly through small-scale karstic solutional features. These reports provide data and information on karst in each area. Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; reports and peer reviewed papers; from geological mapping, and through knowledge exchange with the Environment Agency, universities, water companies and consultants.

This report shows that in the C7 karst knowledge exchange area, the South Downs area of the Chalk, there is extensive evidence for karst development with dry valleys, caves, stream sinks, dolines, dissolution pipes, and springs present. Short caves have been recorded in the area, and the longest known Chalk cave in England (~350 m) is in this area at Beachy Head. Observations of coastal cliffs have been particularly important in demonstrating that caves and conduits can occur even beneath interfluves and in the absence of obvious surface karst. Coastal sections also provide evidence for pervasive stratigraphical influence on subsurface karst with distinct stratigraphical horizons (particularly sheet and semi-tabular flints, marl seams and hardgrounds) being important for conduit development. In the Beachy Head area, the Seven Sisters Flint, the Belle Tout Marls, the Shoreham Marls, the Navigation Marl, and the Hope Gap sheet flint all host cave and conduit systems.

Locally, many stream sinks occur in association with the Chalk-Palaeogene margin, particularly in the west of the area. Stream sinks are less common or absent in the eastern parts of the area where the Palaeogene cover is absent, although major rivers cross the Chalk and their contribution to point recharge via losses to the aquifer was not established during this work. Soakaways and SUDs with high infiltration rates into the Chalk have also not been identified. Dolines also occur in the area, although many recorded surface depressions are likely to be pits of anthropogenic origin. Dissolution pipes are extremely common, especially where the Chalk is overlain by thin unconsolidated superficial deposits, and in some cases can be 10s of metres deep and/or wide. There are many springs in the area, which would have formed the natural outlets for the karstic solutional networks, although little is known about the discharge of most springs and how this has changed in response to groundwater abstraction. Five large springs are identified, the largest being the Bedhampton and Havant complex with a discharge of ~ 600-1900 $l.s^{-1}$.

Evidence from 22 tracer test connections demonstrate very rapid groundwater flow, with velocities ranging from 0.2 to 12.3 km/day over distances of up to 6.6 km; and tracer recoveries ranging from 0.1 to 100 %. Other evidence of karst comes from hydrogeological studies including investigations of transmissivity and pumping tests, water level data from observation boreholes, downhole imaging and borehole logs, groundwater quality, inflows during tunnel construction, saline intrusion, and groundwater flooding. There is considerable evidence for karst and rapid groundwater flow at groundwater abstractions throughout the South Downs area.

Karst is clearly important in enabling rapid recharge and providing some rapid flowpaths through the unsaturated zone, especially via stream sinks but also via solutional fissures with no surface expression. However, there appears to be a higher degree of protection from surface pollutants than in highly karstic aquifers, perhaps due to fewer and smaller stream sinks and the potential for more attenuation in the unsaturated zone. Saturated zone networks of solutional fissures and conduits appear to be very common, and there is evidence to suggest that they extend over distances of several kilometres suggesting that karst specific approaches to Source Protection Zone delineation are likely to be useful.

Consideration of the karstic processes that result in the enhanced permeability of the aquifer through the development of solutional fissures and conduits is key to understanding the hydrogeology of this area; and improved understanding of rapid flow in both the unsaturated and saturated zones is important for groundwater protection and management of water resources. This report presents an overview of the current conceptual understanding of karst in the Chalk in the South Downs and provides a basis for further investigations of karst in this area to enable improved management and protection of groundwater resources.

Introduction to the BGS Karst Report Series

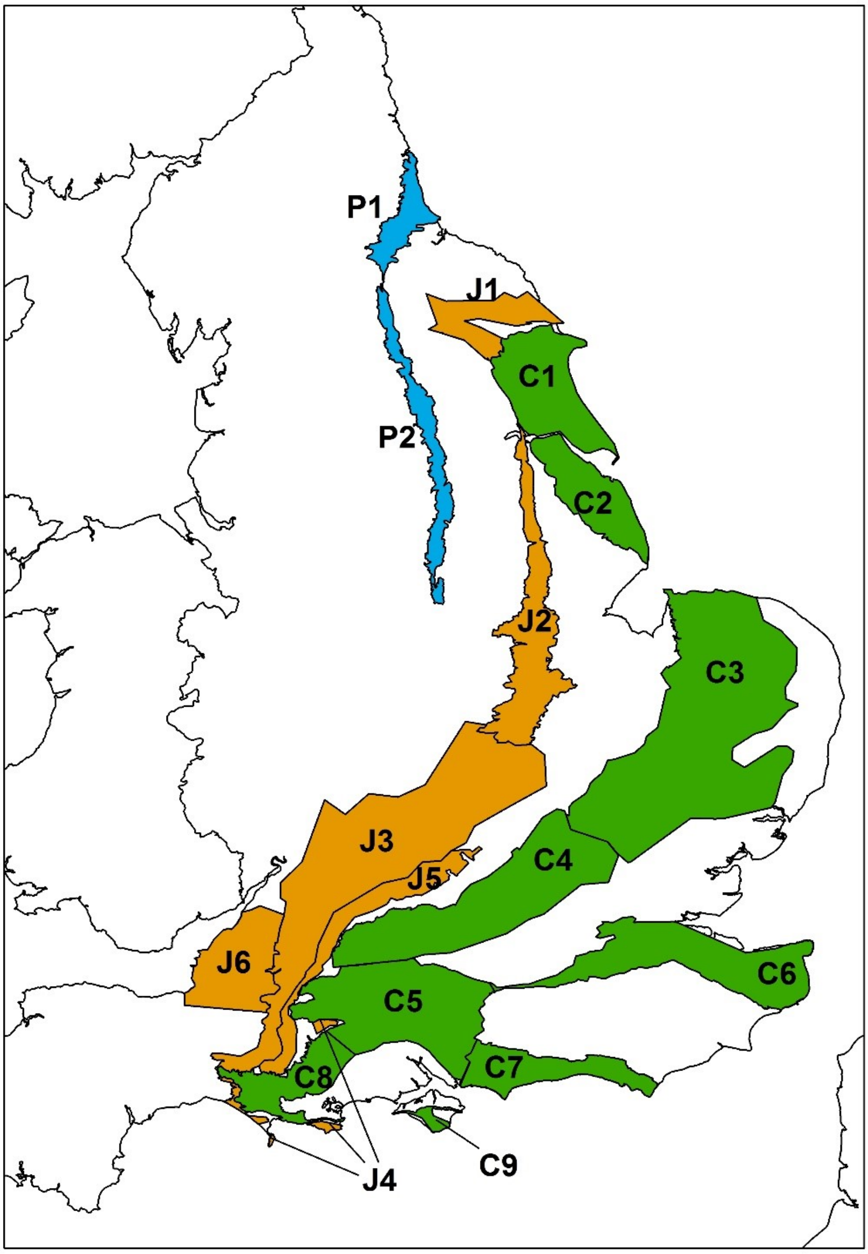
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – The Chalk and the Jurassic and Permian limestones. The series is the main output of the NERC funded Knowledge Exchange fellowship "Karst knowledge exchange to improve protection of groundwater resources" undertaken between 2015 and 2022.

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

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

Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; peer reviewed papers and reports; geological mapping; and through knowledge exchange between 2015 and 2021 with the Environment Agency, universities, water companies and consultants. The data are not complete and further research and knowledge exchange is needed to obtain a fuller picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports provide an initial overview of the evidence for karst and demonstrate that surface karst features are much more widespread in these aquifers than previously thought, and that rapid groundwater flow is common. Consideration of karst and rapid groundwater flow in these aquifers will improve understanding of how these aquifers function, and these reports provide a basis for further investigations of karst to enable improved management and protection of groundwater resources.

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



Map of the locations of the Karst reports

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

Introduction to Karst Data

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

Stream sinks

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

Data on stream sink locations in the Chalk and Jurassic and Permian limestones are variable and although there are many records, the dataset is incomplete, and further surveys are likely to identify additional stream sinks. Stream sink records are predominantly from the BGS karst database in which many were identified by desk study and geological mapping. Several stream sink field surveys have also been carried out, predominantly in areas of the Chalk in Southern England. Some additional records were obtained through knowledge exchange.

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

Further information on the discharge and nature of the stream sinks is generally sparse, but where available, information from reports and papers are summarised.

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

Caves and smaller conduits

Karstic caves (conduits large enough for humans to enter) occur in the Chalk and Jurassic and Permian limestones, providing clear evidence of the importance of karst in these aquifers. Caves were identified from literature review, predominantly from publications of the British Cave Research Association, and local and regional caving societies. Many chalk caves were identified by Terry Reeves of the Chelsea Spelaeological Society/Kent Underground Research Group, who provided pictures and information about the caves, many of which are documented in the Chelsea Spelaeological Society Records and publications of the Kent Underground Research Group.

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

Dolines

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

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

Dissolution pipes

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

Dissolution pipes occur at very high spatial densities in some areas, and are commonly encountered in civil engineering projects. Some data on dissolution pipes come from the Natural Cavities database. This is a legacy dataset held by the British Geological Survey and Peter Brett Associates. It is comprised of data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). In some areas dolines and dissolution pipes are not distinguished in the Natural Cavities database. Information from reports and papers with information on dissolution pipes in the area are summarised.

Springs

Large springs are indicative of connected networks of karstic voids that provide flow to sustain their discharges. Data on spring locations were collated from the BGS karst and springs databases, and Environment Agency spring datasets. Further information on springs was obtained through knowledge exchange and literature review. The springs dataset presented in this report series is not complete, and there are likely to be more springs than have been identified. In England there are very few data on spring discharges and most springs are recorded as of unknown discharge. However, in most areas some springs with known discharges of > 10 or > 100 $l.s^{-1}$, have been identified. There are also some springs with no discharge data, but which are likely to be large (> 10 $l.s^{-1}$) based on visual observations during field visits, or based on their use as monitoring outlets in tracer studies. There remains much work to be done to develop a useful dataset on the discharges and characteristics of springs in the Chalk and Jurassic and Permian limestones, but the data presented here provide an initial overview, and suggest that large springs are common in these aquifers.

Tracer tests

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

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

Other evidence of karst and rapid groundwater flow

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

There is substantial evidence of karst from groundwater abstractions from these aquifers. Whilst all successful abstractions are likely to be supplied by connected networks of solutional voids, the higher the transmissivity, the more widespread and well developed the karstic networks are likely to be (Foley and Worthington, 2021; Maurice et al., 2021). Transmissivity data from the national aquifer properties manual (Allen et al., 1997; MacDonald and Allen, 2001) are presented.

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

Acknowledgements

We thank Terry Reeve for providing information, photos and surveys of caves, as well as his article on Caves in the Seven Sisters area reproduced here in Appendix 2 with permission from the Kent Underground Research Group. For their advice and input we thank: James Bucknall and Simon Deakin from Portsmouth Water; Debbie Wilkinson, Graham Earl and Steve Howe from South East Water; Simon Cook, Richard Gamble and Chris Woolhouse from Southern Water; Dawn O'Neill, Ally Thomas, Tom Wickens, Polly Wallace and other staff from the Environment Agency; and Tim Atkinson from University College London. We thank Aimee Felus from the South Downs National Park authority for highlighting the karst information from the Patcham area. We also thank Timo Roth for his assistance compiling cave and tracer data. We thank Matt Ascott at BGS for reviewing the report. This work was carried out under the Natural Environmental Research Council (NERC) Knowledge Exchange Fellowship Scheme, grant ref NE/N005635/1.

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1 Introduction

1.1 AREA/GEOLOGY

The karst knowledge exchange area C7 comprises the Chalk of the South Downs, and includes the cities of Chichester and Brighton & Hove, and the major towns of Havant, Worthing and Lewes (Figure 1). The city of Portsmouth is on the western boundary of the area, with Eastbourne in the far east. The largest river, the River Arun, crosses the region from north to south until it enters the sea at Littlehampton. The eastern part of the area is drained by the Adur, Ouse and Cuckmere rivers (Figure 2). The hydrology in the west is dominated by Chichester harbour, a large natural harbour discharging flows from the River Lavant into the English Channel. However, surface drainage over much of the South Downs area is absent with many dry valleys (Jones and Robins, 1999).

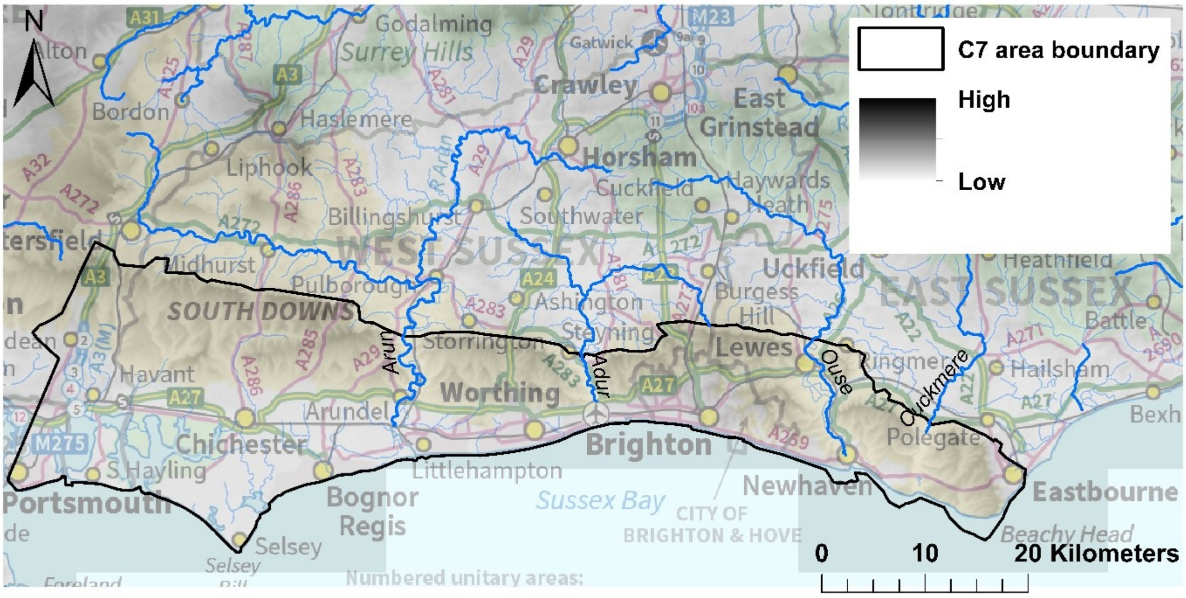

Figure 1. The C7 Chalk area.

In the C7 area the Cretaceous Chalk is overlain by Palaeogene strata in the southwest (Figure 2, Table 1). The area is defined by a prominent escarpment in the north, the sea in the south and east, and the groundwater divide near Portsmouth in the west. Groundwater generally flows in a southerly direction towards the coast (Jones and Robins, 1999).

The Chalk outcrop is part of the southern limb of the Wealden Anticline, dipping south into the Hampshire-Dieppe Basin (Jones and Robins, 1999). The subsidiary Chichester Syncline dominates the subsurface structure of the area, alongside the associated Singleton Anticline (Figure 2). The Chichester Syncline extends from Worthing to Chichester and highlights the asymmetry in Wealden structures, with a steeply dipping northern limb but a gently dipping south limb (2-3°) (Jones and Robins, 1999). The Chalk aquifer in the South Downs is commonly divided into five blocks (Eastbourne, Seaford, Brighton, Worthing, and Chichester), defined by the southerly flowing rivers that rise in the Weald to the north of the Chalk (Jones and Robins, 1999).

Superficial deposits, including sand and gravel, alluvium and Clay-with-Flints are present in area, concentrated within the Chichester syncline (Jones and Robins, 1999). Sands and gravels are primarily found in the river valleys, whilst small areas of Clay-with-Flints occur on the higher interfluve areas (Figure 3).

Table 1. The stratigraphy of the Chalk in the C7 area.

Age	**Group**	**Formation**	**Lithology**
Palaeogene	Bracklesham Group	Selsey Sand Formation	Fine grained silty sand and silty clay
		Marsh Farm Formation	Laminated clay and silt with sand interbeds
		Earnley Sand Formation	Silty sand and sand with a basal pebble bed
		Wittering Formation	Laminated clay with some sand interbeds
	Thames Group	London Clay Formation	Clay, some silt and sand and pebbles
	Lambeth Group	Reading Formation	Clay and sand
Upper Cretaceous	White Chalk Subgroup	Portsdown Chalk Formation	Soft white chalk with thin marl seams and some flint present
		Culver Chalk Formation	Soft white chalk with flint seams
		Newhaven Chalk Formation	Soft to medium hard smooth white chalk with numerous marl seams and flint bands.
		Seaford Chalk Formation	Firm white chalk with large nodular and tabular flints. Marls in the lower part.
		Lewes Nodular Chalk Formation	Hard to very hard nodular chalks with interbedded soft chalk and marls.
		New Pit Chalk Formation	Firm and blocky white chalk with sporadic flint and numerous marls.
		Holywell Nodular Chalk Formation	Hard nodular chalk with thin marls and often significant shell debris.
	Grey Chalk Subgroup	Zig Zag Chalk Formation	Pale grey blocky chalk with alternations of marl in the lower sections.
		West Melbury Marly Chalk Formation	Soft grey and off-white chalk with marl and limestone.

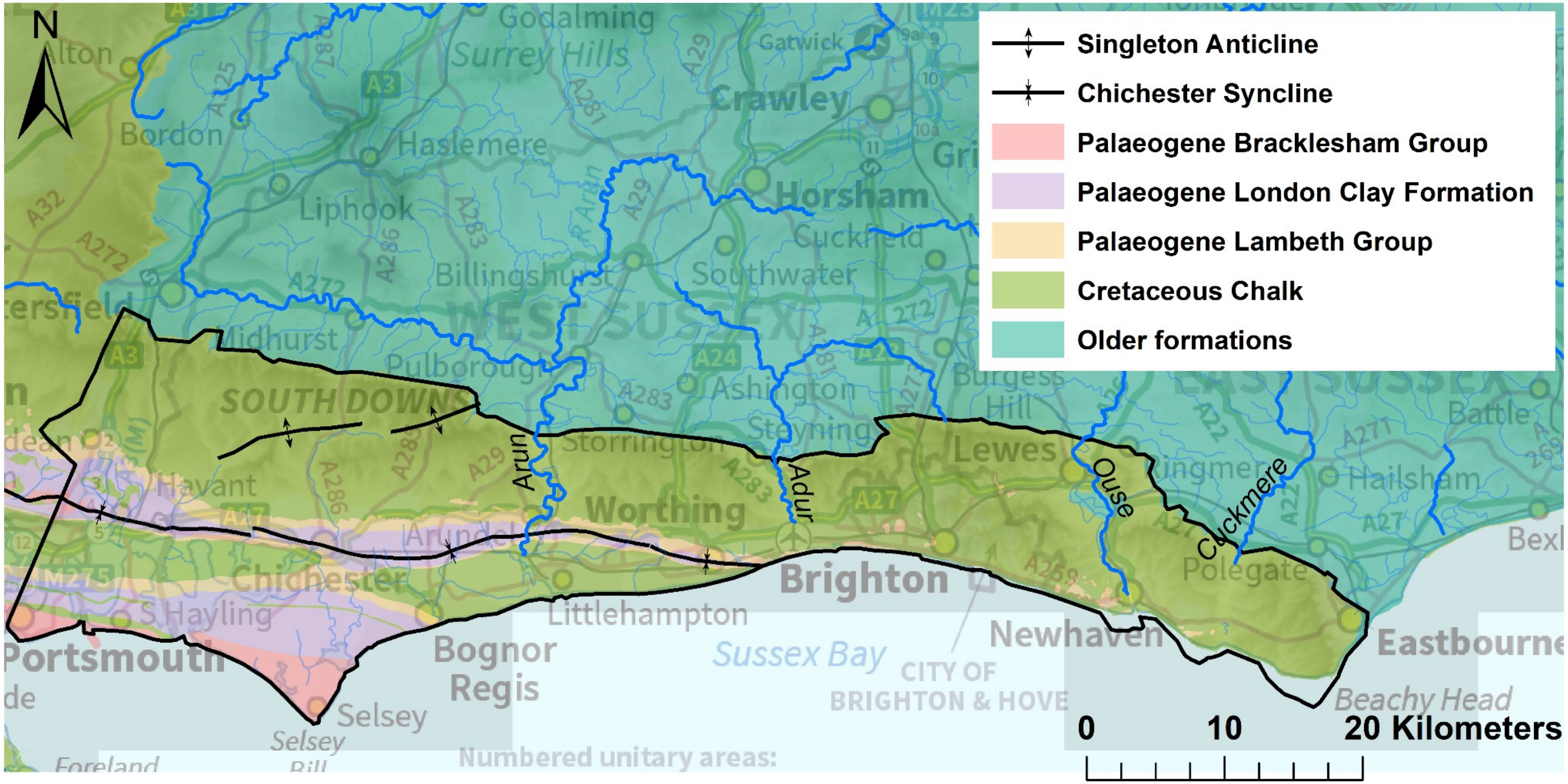

Figure 2. Bedrock geology and major rivers in the area.

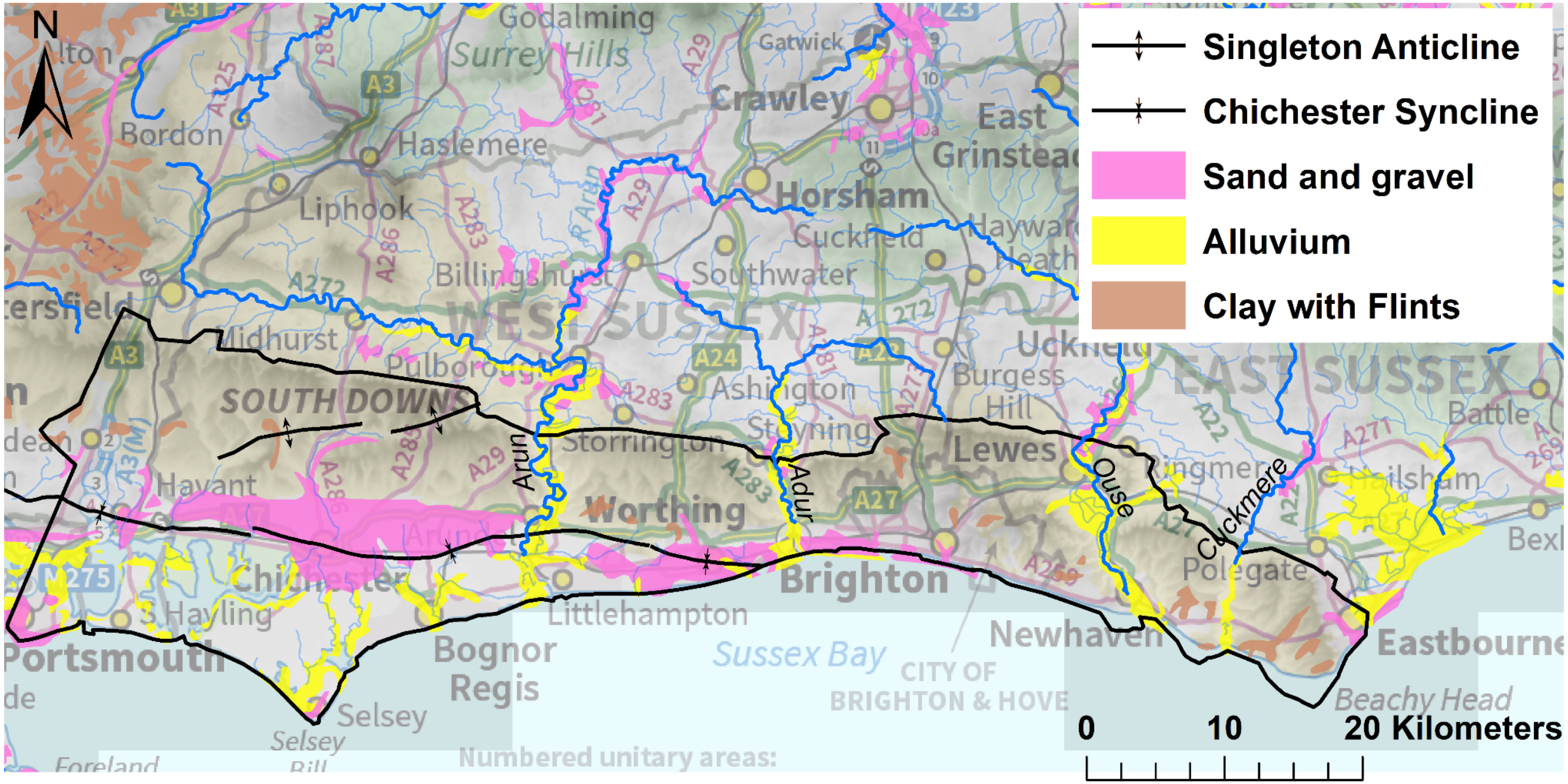

Figure 3. Superficial geology.

1.2 WATER PROVIDERS AND REGULATORS

Southern Water, Portsmouth Water and South East Water are all major public water suppliers in the C7 Chalk area (Figure 4). The area lies entirely within the Solent & South Downs Environment Agency management area (Figure 5).

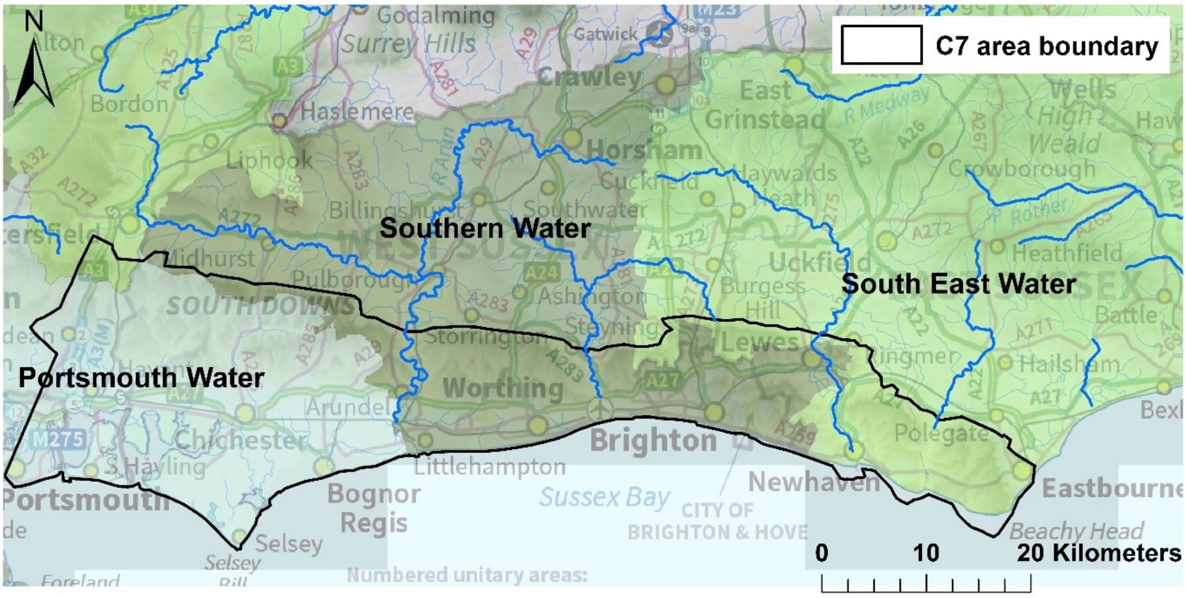

Figure 4. Water providers in the C7 Chalk area.

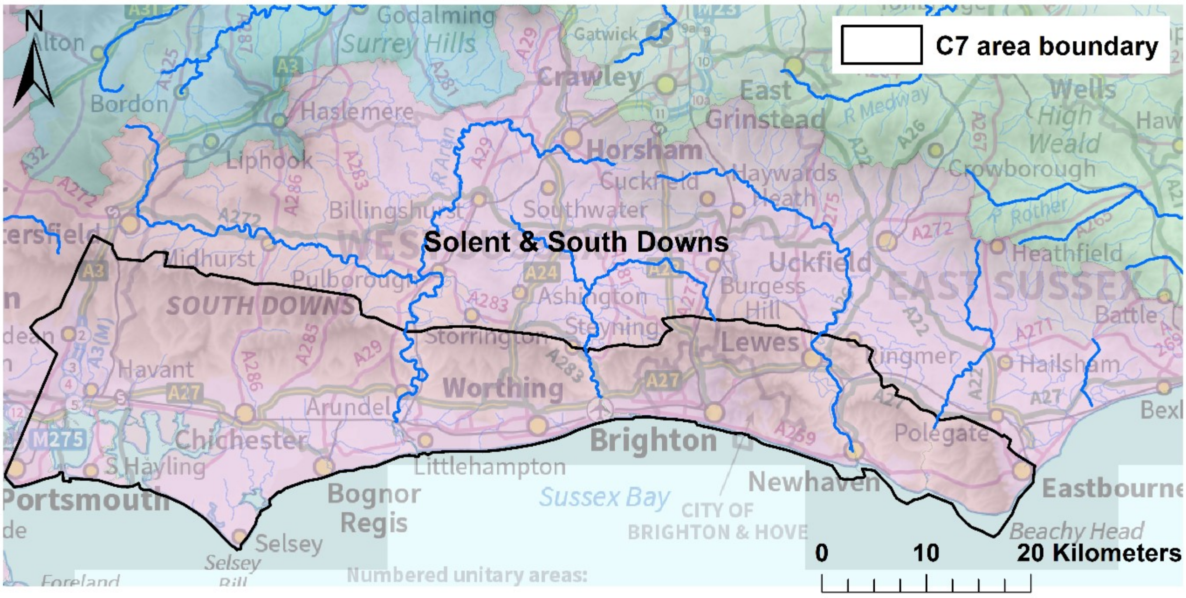

Figure 5. Environment Agency areas in the C7 Chalk area.

2 Karst geomorphology

2.1 CAVES AND CONDUITS

There is considerable evidence for cave and conduit development in the area, although the information is biased towards coastal cliff sections which have formed the focus of particular investigations. Caves in the area are discussed and reported in Reeve (1977,1979, 1981, 2021a and b); Lowe (1992) and Farrant et al. (2021a,b,c). The main sources of information on Chalk caves come from more than 50 years of observations along the coastal cliffs between Beachy Head and Newhaven by Terry Reeve; and a recent detailed survey of the coastal sections between Eastbourne and Splash Point conducted by BGS in 2020 (Farrant et al., 2021a,b,c).

Figure 6 shows the locations of 17 caves/areas of caves investigated by Terry Reeve. The precise locations of many of these caves is uncertain as detailed grid references are not available for most sites. Information on these caves comes from the references listed above, and also from discussions with Terry Reeve (personal communication, 2017; 2018; 2021; 2022), and is summarised in (Table 2). Further details of these caves, including descriptions, photographs and surveys from Terry Reeve are provided in Appendix 1. An article by Reeve (2021b) on numerous caves in the Seven Sisters area (site 16 on Figure 6), from the Kent Underground Research Group Newsletter from 2021, is included in Appendix 2.

The longest known chalk cave in England (Beachy Head cave, with a mapped length of 354 m), is present in the C7 area (site 9 on Figure 6 and in Table 2). Pictures, a survey and a description of the cave is provided in Appendix 1 (page 66). Beachy Head cave is also described in detail in Reeve (1981; 2021a) and reviewed by Lowe (1992) and Waltham et al. (1992). Farrant et al. (2021a) note that in 2020 the entrance was concealed by cliff fall.

Recorded caves are predominantly located along the south-eastern coastline near Eastbourne, an area of relatively high chalk cliffs. The coastal section between Birling Gap and Beachy Head was visited repeatedly by Terry Reeve to search for caves between 1975 and 2018 during which more than 20 caves were located (Reeve, 2021a). The coastal environment is highly dynamic with new caves being revealed and others being shortened or completely eroded away over the observation period. Reeve (2021a) notes that in some cases it is difficult to distinguish whether coastal caves are of marine or karstic origin, but these caves are clearly fully or partially karstic origin as they are either high up in the cliffs, too extensive, have been exposed by new cliff retreat, or exhibit clear karstic features (geomorphological or containing sediment infill). Some examples are shown in Figure 7.

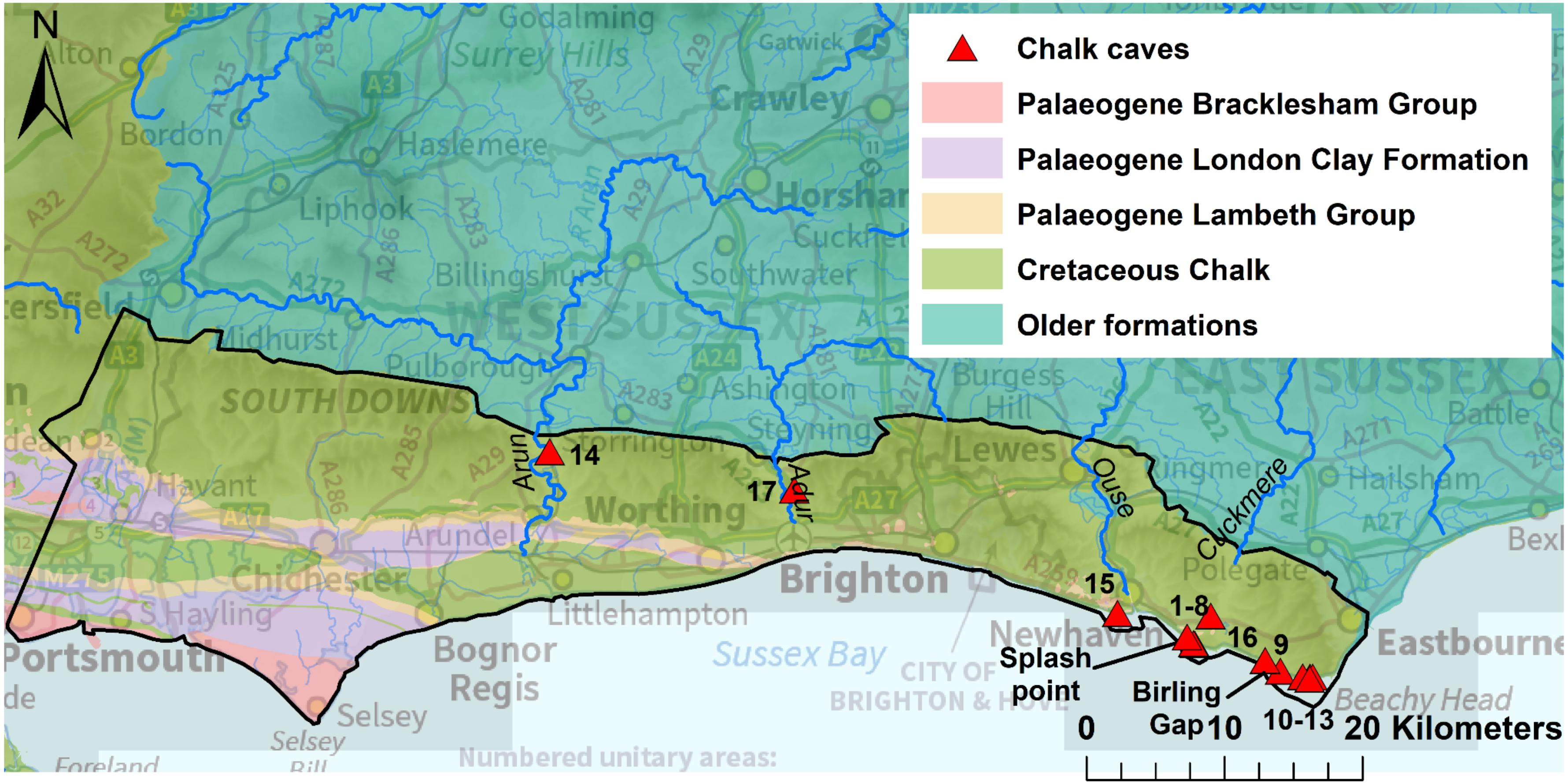

Figure 6. Recorded cave sites in the C7 Chalk area.

Table 2. Details of cave sites documented by Terry Reeve (Site numbers refer to locations on Figure 6)

Site number	Name	Length	Notes
1	Seaford Head Cave	10 m	Classic karst passage shape with scallops on the walls
2	Seaford Head small cave entrance	unknown	Karst cave 8 m above the beach
3	Cave No. 2 Seaford Head	< 20 m	Exposed by cliff retreat with karst features
4	Cave No 3a and 3b Seaford Head	< 15 m each	Scallops on the walls and dissolution features in the roof
5	Cave No. 6 Seaford Head	< 85 m	Karst passage shapes
6	Cave No. 7 Seaford Head	24 m	Scalloping on the walls
7	Cave No. 8 Seaford Head	unknown	On flint about 2 m above beach
8	Sea stack, Splash Point	cave remnant in sea stack	May be base of dissolution pipe
9	Beachy Head Cave	354 m	Fully karstic cave above beach level (longest chalk cave in England.
10	Cave No. 1 Beachy Head	unknown	About 3 m above beach; two small chambers connected by crawl
11	Cave No. 4 and 5 Beachy Head	unknown	Lower cave exposed by cliff retreat, with upper cave several metres above beach
12	Cave No. 6a Beachy Head	unknown	Exposed by cliff retreat, karst passage shapes
13	Patricks Rift	~ 28 m	About 2 m above the beach
14	Houghton Quarry Cave	< 15 m	Scallops and dissolution features
15	Newhaven caves	unknown	Several caves, mostly above beach level and inaccessible
16	Seven Sisters caves	Variable	Several caves exposed by cliff retreat over several decades
17	Shoreham Cement Works	unknown	Inaccessible entrance about 1 m diameter

Figure 7. Examples of coastal caves with evidence of karst. Photos courtesy of Terry Reeve.

Solutional scallops indicating past water flow in a cave at Seaford Head (top left), cave high up in the cliff at Seaford Head (top right), and a cave suddenly exposed by cliff retreat at Seven Sisters (bottom).

Figure 8. Cave intersected by quarrying near Amberley with dissolution on the walls and roof indicating water flow (photo courtesy of Terry Reeve).

Recent coastal surveys of karst conduits were conducted by the British Geological Survey in July 2020 between Birling Gap and Eastbourne, and between Hope Gap and Splash Point (Farrant et al., 2021a,b,c; see Figure 6 for locations of these places). These surveys covered much of the same areas that have been investigated by Terry Reeve, and GPS locations were obtained for all the conduits observed. In total, 54 conduits (or groups of conduits), including many large enough to enter (and therefore can be termed caves) were identified. Farrant et al. (2021a) provide a comprehensive documentation of these surveys including maps, pictures and descriptions of each conduit/group of conduits. Some pictures from the survey are included here in Appendix 3, and some maps from Farrant et al. (2021a) showing the locations of the conduits are included here in Appendix 4, with details of the conduits in a table in Appendix 5. The conduits observed are all unsaturated. They can be grouped into two broad types. The most common are small elliptical conduits/small caves developed on significant marl and flint inception horizons (in particular the Belle Tout Marls, the Shoreham Marls, the Navigation Marl and the Hope Gap sheet flint). The other type are solutionally enlarged vertical fissures that can extend the full height of the cliff, and can have localised conduits developed within them at various depths. More significant development often occurs where the fissure intersects major stratigraphical inception horizons. Sometimes these vertical fissures are sediment filled, but open solutionally enlarged vertical fissures can extend the entire height of the cliff (Figure 9), indicating the potential for rapid recharge through a deep unsaturated zone.

Of the 54 conduits (or groups of conduits) between Seaford and Eastbourne, the frequency varied from up to 7 per 100 m stretch of cliff, to just one conduit/group of conduits within an 800 m stretch of cliff. Most are developed in the upper Lewes Nodular Chalk and lower Seaford Chalk formations which host several favourable inception horizons. Fewer conduits were noted in the middle and upper Seaford Chalk. Farrant et al. (2021a,b,c) note that many conduits within the coastal cliffs contain sediment indicating connectivity with the surface (e,g. Light Point conduits 3 and 4 pictured in Appendix 3). Farrant et al. (2021b,c) also note that the spatial distribution of caves and conduits observed in the coastal cliff sections are independent of surface features. They occur below interfluve areas, in areas with no evidence of surface karst, and below dry valleys eroded at the surface at the top of the cliffs.

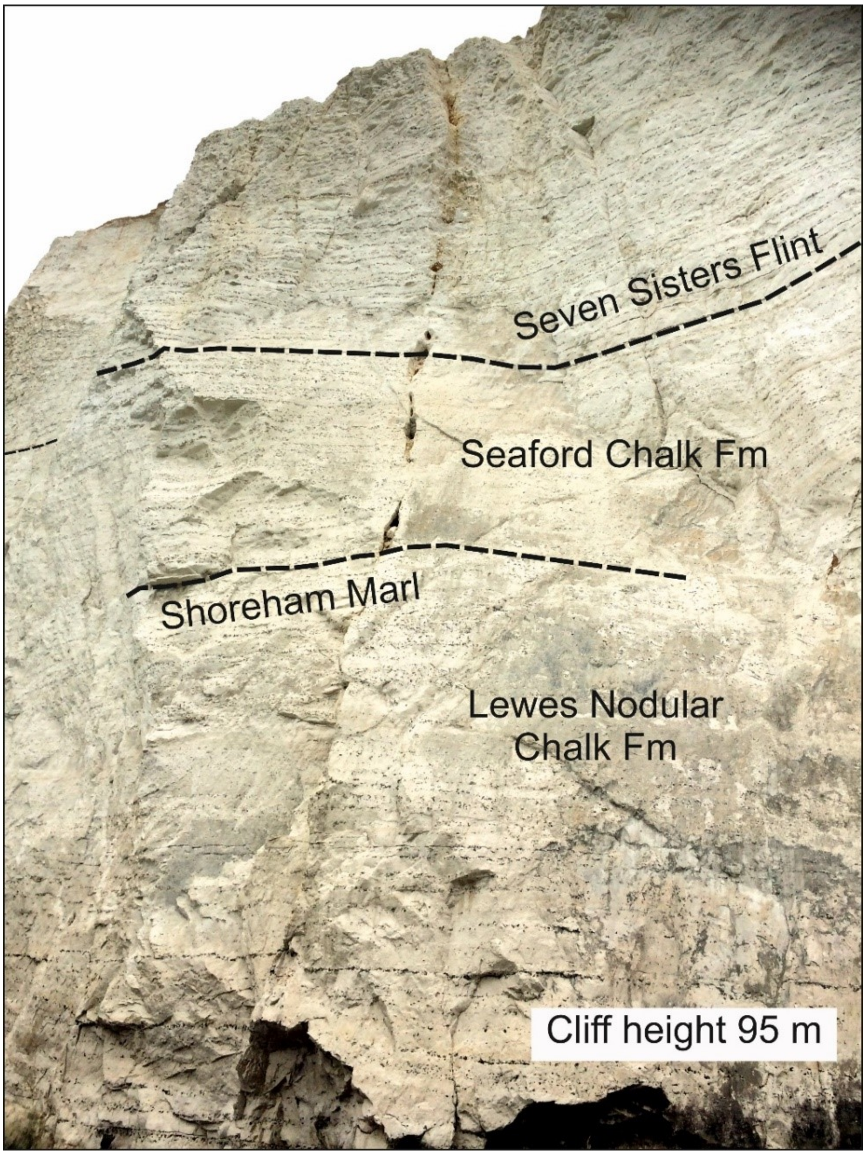

Figure 9. Beachy head conduit 8, solutionally enlarged vertical fracture extending length of cliff with conduits up to ~ 1-2 m high and ~0.5 m wide in upper parts. (Photo A Farrant)

“Dissolution tubules” are a particular type of karst feature described by Lamont-Black and Mortimore (2000). These are a dendritic network of small solutional voids of approximately 1-50 mm in diameter. They are typically developed along sheet flints, marl seams and hardgrounds, and are commonly found in association with larger karstic conduits and caves (Lamont-Black and Mortimore, 2000). Mortimore (2012) also reports tubular karst along sheet flints and bedding partings encountered during the construction of the A27 Brighton bypass.

There is also evidence for saturated zone conduits and fissures. Such features are commonly observed in image logs of abstraction boreholes (discussed in karst knowledge exchange meetings with water companies; also reported in Farrant et al., 2021b,c). Most successful abstraction boreholes where image logs have been undertaken have images revealing solutionally enlarged fissures, or more circular shaped karst conduits (e.g. Figure 10). Further work to develop a borehole image dataset to characterise the size and stratigraphical position of flowing karstic fissures and conduits observed in boreholes would be useful to improve understanding of where the karstic flowpaths occur within the aquifer. Hydrogeological evidence for solutional fissures/conduits in the saturated zone is reviewed in Section 4.

Figure 10. Conduit observed in an abstraction borehole (Photo courtesy of Portsmouth Water)

2.2 STREAM SINKS

There are 58 stream sinks recorded in the C7 Chalk area (Figure 11). Twenty-eight records come from the Natural Cavities database. This is a legacy dataset held by the British Geological Survey. It is comprised of data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). There are five stream sinks recorded in the BGS karst database, although this database is not complete/checked in this area. 26 other stream sink records are from a tracer test report by Atkinson and Smith (1974); reports by Barton et al. (undated); Price (1979); and Atkinson and Low (2000); with some of them reported in more than one of these references. These stream sinks are in the west of the C7 area, around the Havant/Horndean area. Price (1979) identified a total of 50 surface karst features in Hampshire, of which 25 were reported to transmit water and are therefore likely to be stream sinks. These are included on Figure 7 where they had not already been included from other references. Daily discharge measurements were taken at eight stream sinks with flows ranging from 0.05 to 7.4 $Ml.d^{-1}$ or 0.5 to 85 $l.s^{-1}$ (Price, 1979). Barton et al. (date unknown) suggest that there were about 50 "swallow-holes" in the Horndean area, but suggested that some of these do not receive water and are dolines.

Most stream sinks are located along the Chalk-Palaeogene boundary, and there may be other minor stream sinks associated with this boundary, which have not been recorded, and there may be some small stream sinks which were culverted, filled in or built over. Several major rivers cross the Chalk in the C7 area, and the karst knowledge exchange work has not established whether they contribute point recharge to the aquifer via losses to groundwater as they cross the outcrop. The contribution of soakaways and SUDs (Sustainable Urban Drainage systems) to point recharge has also not been considered for this report, but if any of these have high infiltration rates to the Chalk they must be feeding into some sort of karstic solutional network.

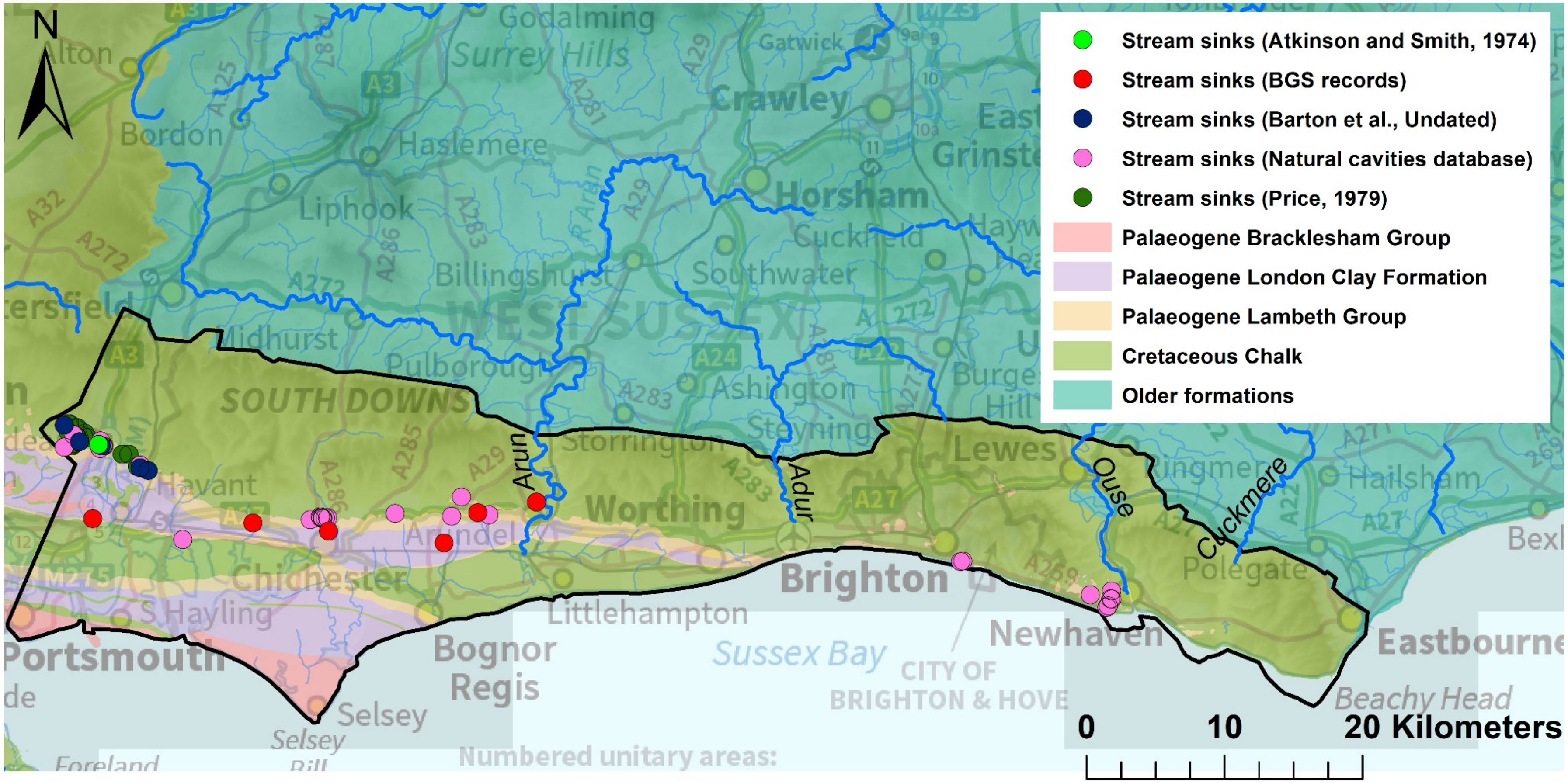

Figure 11. Stream sinks in the C7 Chalk area.

2.3 DOLINES AND DISSOLUTION PIPES

Surface depressions, dolines and dissolution pipes in the C7 area are shown on Figure 12. The distributions reflect the locations where studies have been conducted, and it is likely that surface depressions and dissolution pipes are prevalent in most areas.

As in all areas of the Chalk, it is often unclear whether surface depressions are natural karst dolines or whether they are excavations/pits, which can have very similar characteristics. On Figure 12, features are therefore generally recorded as surface depressions, rather than dolines. These include six surface depressions recorded in the BGS karst database, and a further 135 surface depressions which were mapped during a karst field survey in 2004 by BGS. Figure 12 also includes records of surface depressions identified by Portsmouth Water using satellite imagery (James Bucknall, personal communication, 2021), and records of 78 surface depressions identified by the Environment Agency (Dawn O Neill, personal communication 2019). There are also 43 "dolines" recorded in the BGS held legacy dataset from the Natural Cavities database (Applied Geology Ltd, 1993), although it is not clear whether some of these may be anthropogenic in origin. Figure 12 also includes some records from Price (1979) who identified karstic features in Hampshire. These are likely to be karstic in origin and the 25 features included on Figure 12 were reported by Price (1979) to have had no water draining into them, and are therefore assumed to be dolines rather than stream sinks. Figure 12 also includes 60 records of dissolution pipes from the Natural Cavities database.

There have been several other studies of solution features in the area. Edmonds (1983) suggests that there is a density of 5-10 solution features per 100 km^2 in this area, which is lower than densities reported in this study for other parts of the English Chalk. Edmonds (2008) reports the total number of natural cavities in the Peter Brett Associates Natural Cavities database for the Chalk. This database is an updated version of the Natural Cavities database held by BGS and records a total of 493 cavities in the chalk of the South Downs (Edmonds, 2008). McDowell et al. (2008) provide a map of the density of solution features in Southern England and note that there is an anomalously high density of 55 per km^2 in the area between Horndean and Rowlands Castle. They note that dolines in this area occur in dry valleys and can have linear trends, and that they are most common near the Chalk-Palaeogene boundary. McDowell et al. (2008) also describe two surface karst depressions that were identified from extensive drilling at the Hazelton interchange (Junction 2 on the A3(M)), a cluster of more than 70 drop out sinkholes at Fontwell in West Sussex following a burst water pipe, and solution features encountered at Chichester. Solution features have also been identified in the Patcham area near Brighton (Hadlow, 2014). A study from Markwells Wood, West Sussex identified 190 surface depressions from lidar and a walkover survey (Foley, 2017). During the site survey in 2017, 32 potential dolines were visited, of which 27 had no obvious signs of human excavation (Foley 2017). Jeffery et al. (2020) investigated solution features at Home Farm near Rowlands Castle using lidar and geophysical techniques (electromagnetic and ground penetrating radar) and concluded that the investigated features are likely to be karstic in origin. Farrant et al. (2021a,b,c) discuss surface karst features in East Sussex identified from geological mapping, construction, lidar and other remote sensing; and provide some maps documenting features as well as a review of the literature. They conclude that many surface depressions are likely to be anthropogenic pits rather than karst dolines. A survey of surface karst features in the area, using both desk based methods and field mapping, was conducted by Wood Consultants in 2021.

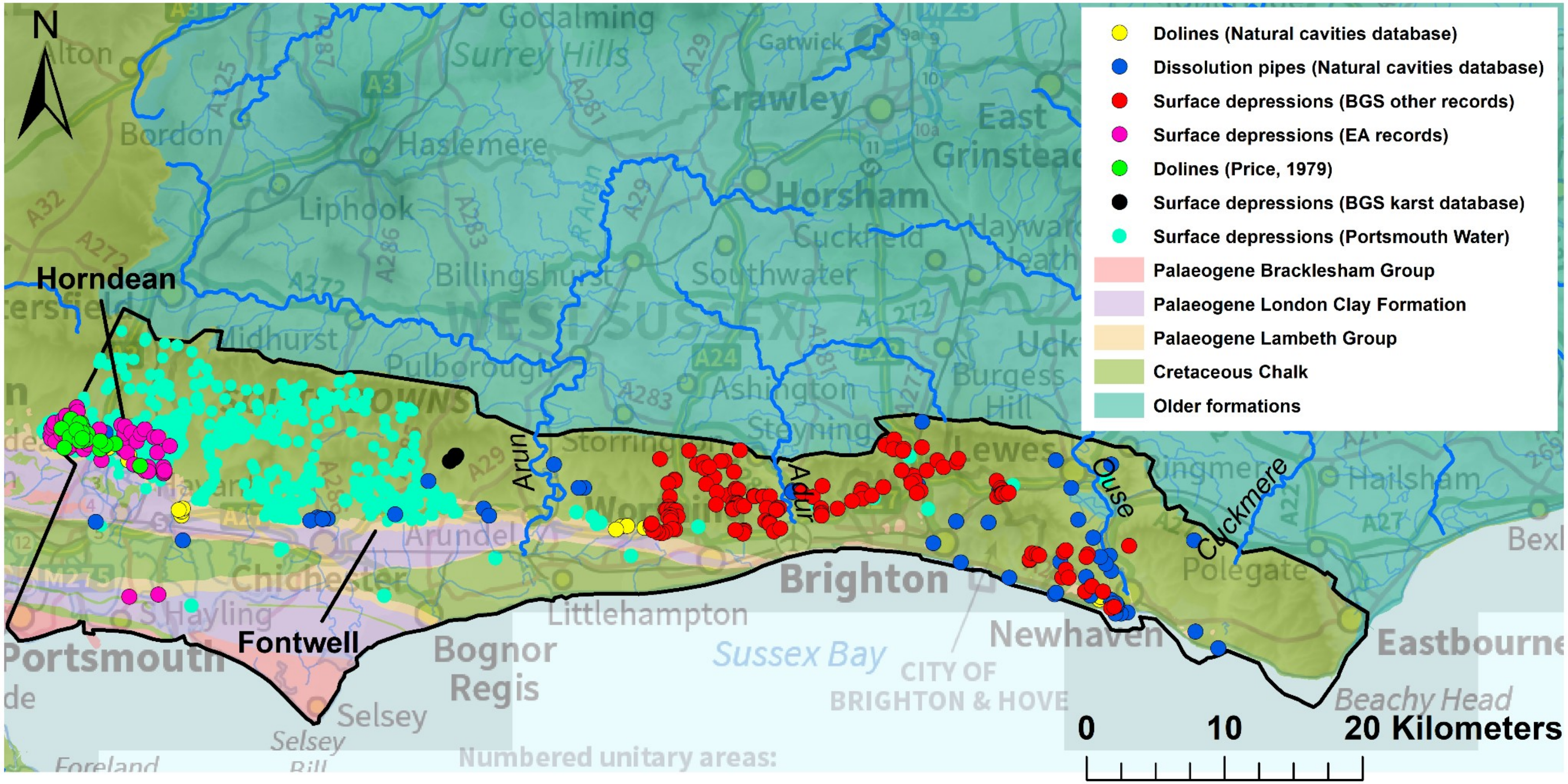

Figure 12. Surface depressions, dolines and dissolution pipes.

Dissolution pipes often have no surface expression but are commonly exposed by engineering works and quarrying. Farrant et al. (2021a) review the literature on dissolution pipes in the East Sussex area, and provide some maps showing where they have been encountered. Shallow subsurface dissolution pipes are encountered with very high densities during construction projects (e.g. Mortimore, 2012), and it is likely that they occur fairly regularly wherever Palaeogene or superficial cover, particularly Clay-with-Flints, is present (McDowell et al., 2008; Lamont-Black and Mortimore, 1999). Lamont-Black and Mortimore (1999) describe the spatial distribution, fill material, and morphology of dissolution pipes revealed by the A27 Brighton Bypass, reporting that dissolution pipes occur on hilltops and have densities of between 3 and 265 per hectare. Mortimore (2012) provides detailed and extensive descriptions, maps, and photographs of the many karst features encountered during the construction of the A27 Brighton bypass. He reports that in the Falmer area there were very large dissolution pipes 30 m wide and 30 m deep; and karst features were also especially prevalent in the Marquee Brow to Old Boat Corner section; at Red Hill Cross and at Round Hill. Mortimore (2012) also notes that many dissolution pipes were encountered during the construction of the Buckle bypass at Seaford.

Dissolution pipes are also observed in coastal cliffs (Reeve, 2021a; Farrant et al., 2021a). Reeve (2021a) reports that there are dissolution pipes exposed at Seaford and Beachy Head. He notes that at Seaford Head, the closely spaced pipes occur in dense clusters creating pinnacles of chalk resembling the egg box type karst that is seen in classical karst areas (Figure 13). Farrant et al. (2021c) note that there are dissolution pipes exposed in the coastal cliffs beneath the Clay-with-Flints capping Seaford Head which are up to 10 m deep. Additional pictures of dissolution pipes at Seaford Head are provided in Appendix 6.

Figure 13. Closely spaced dissolution pipes at Seaford Head (photo courtesy of Terry Reeve)

2.4 SPRINGS

Springs are relatively common in the C7 Chalk area. Figure 14 shows 128 chalk recorded by BGS, seven springs recorded by Hadlow (2014), and a further three Chalk springs that are used by the Environment Agency for water quality monitoring. There are likely to be other springs present in the Chalk, and these records do not include all the springs that are marked on Ordnance Survey maps. There have been few studies of chalk springs and their discharge and water quality characteristics are generally unknown. For this project there were just five springs identified for which discharge data are available to indicate that they are large. The locations of these are shown on Figure 15, with further details in Table 3. It is probable that there are other large springs with discharges of more than 10 $l.s^{-1}$ (equivalent to approximately 8.6 $Ml.d^{-1}$). It is also likely that there were more large springs in the past which formed the natural outlets of the karstic networks, but which have no or reduced flows since the development of water resources.

The largest springs in the area are the Bedhampton and Havant spring complex, which is one of the largest in the UK. Around 28 separate springs have a combined flow of around 1204 $l.s^{-1}$ or 104 $Ml.d^{-1}$ (Atkinson and Smith, 1974), and the combined flow ranges from approximately 600 to approximately 1900 $l.s^{-1}$, around 52-164 $Ml.d^{-1}$ (James Bucknall, personal communication 2017). The combined catchment area of the springs was defined by Day (1964), as an area of around 96 km^2 (Darling et al., 2007). The rapid nature of the flow, demonstrated through a series of tracer tests (Atkinson and Smith, 1974; Price, 1979) is typical of springs fed by karstic flowpaths. The springs are located in the upper part of the White Chalk subgroup, and are likely to be within the Newhaven or Culver Chalk formations. Karst in the catchment of these springs is assessed in Mathewson et al. (2019) and information on the Bedhampton and Havant springs can also be found on the BGS karst knowledge exchange webpages. Springs at Farlington marshes, approximately 2 km to the southwest of Bedhampton and Havant were also developed for supply (Jones and Robins, 1999).

Large springs are also reported at Arundel which may be fault guided, and at Fishbourne, with "copious chalk springs" described at Honeymens Hole near Shoreham Airport (Jones and Robins, 1999). The natural discharge of these springs (prior to abstraction) is not known, however there are indications that they are very large and therefore likely to be supplied by well-developed conduit and fissure systems. Headworth and Fox (1986) report that springs at Arundel "used for amenity and conservation" have an average discharge of 50 $Ml.d^{-1}$ (approx. 580 $l.s^{-1}$) and that this is in addition to the 18 $Ml.d^{-1}$ (approx. 210 $l.s^{-1}$) which is abstracted from nearby sources. They also report that springs at Fishbourne have discharges of 13-36 $Ml.d^{-1}$ (approx. 150-420 $l.s^{-1}$). Allen et al. (1997) note that the springs at Fishbourne appear to be fed by a network of "large fractures". BGS records suggest that springs at Shoreham had a discharge of 110 $l.s^{-1}$ (approximately 9.5$Ml.d^{-1}$) and those at Funtington 151 $l.s^{-1}$ or approximately 13 $Ml.d^{-1}$ (Table 3).

In addition to these springs with a large known discharge, literature review provides some additional information on springs in the C7 area. Many are associated with the scarp slope (Headworth and Fox, 1986; Jones and Robins, 1999). These scarp slope springs occur both at the base of the Chalk at the contact with the underlying Gault Clay (or Upper Greensand), and higher up in the Chalk sequence in association with the Plenus Marls. Bull (1936) describes a spring near to the Devils Dyke, and a spring in a deep coombe west of Sullington Hill. Springs at Poynings (~2 km west of Pyecombe) are described by Small (1962) although there is no indication of their discharge. Jones and Robins (1999) note that springs at the base of the northern scarp slope, especially at Poynings were considered for the water supply of Brighton but the scheme was not undertaken, probably because of the high costs of tunnelling involved. Given that they were considered for public water supply they were presumably large springs. Jones and Robins (1999) report that five small scarp slope springs (at Saddlescombe, Clayton, Whitelands, Coomb Down, and Offham) are used for supply with autumn drought outputs of ~3-12 $l.s^{-1}$. These presumably all have larger maximum discharges and therefore represent outputs from quite extensive solutional networks.

Hadlow (2014) provides a map of springs in the Patcham area near Brighton (Figure 3.2 of the thesis). Hadlow (2014) also notes that there are historical springs at Pyecombe and Braypool, and he also discusses the role of spring sapping in valley formation in the area.

Holywell spring (with minor solutional enlargement of fractures up to ~ 5 cm) is located on the coast a couple of kilometres northeast of Beachy Head and is developed on the Plenus Marls which are at the contact between the Zigzag Chalk Formation and the overlying Holywell Nodular Chalk Formation (Farrant et al., 2021b).

Reeve (personal communication, 2022) suggests that there are large springs at East Lavington at around NGR SU956168; and at Fulking at around NGR TQ247112.

Table 3. Large spring discharges in the C7 Chalk area

Name	**Easting**	**Northing**	**Geology at outcrop**	**Approximate Yield (l.s^{-1})**	**Reference**
Bedhampton and Havant Springs	470684	106365	Newhaven or Culver Chalk formations	600 to 1900	Atkinson and Smith (1974)
Arundel	501700	107700	Culver Chalk Formation	580 24	Headworth and Fox (1984) Edmunds (1928)
Fishbourne Springs	483380	104700	White Chalk subgroup	150-420 121	Headworth and Fox (1984)BGS SOBI record ID [SU80SW71/B/BJ]
Shoreham	521070	106878	Seaford Chalk Formation	110.5	BGS SOBI record ID [TQ20NW191/BJ]
Funtington	480960	107830	Newhaven Chalk Formation	151.5	BGS SOBI record ID [SU80NW255/BJ]

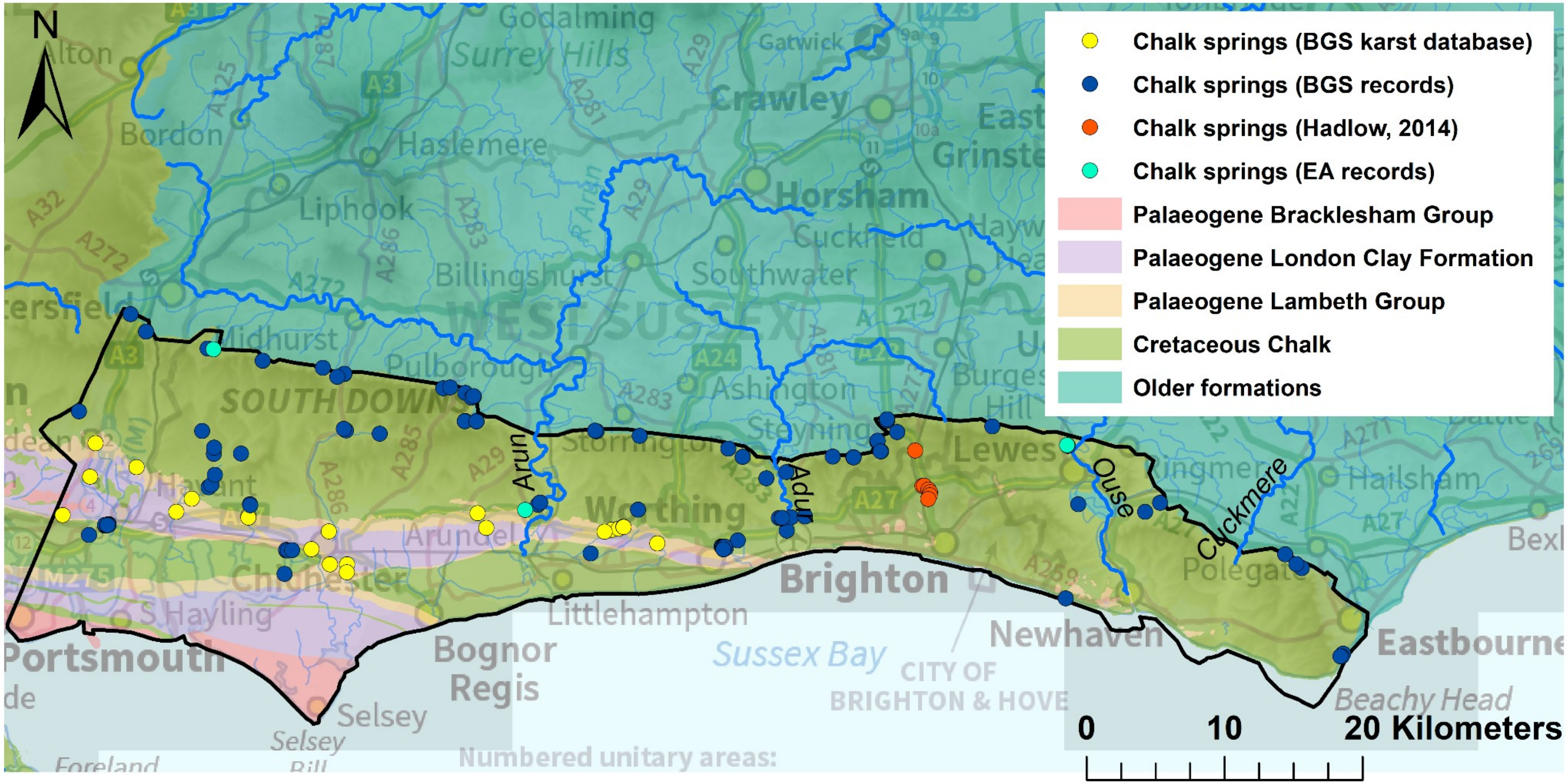

Figure 14. Chalk springs.

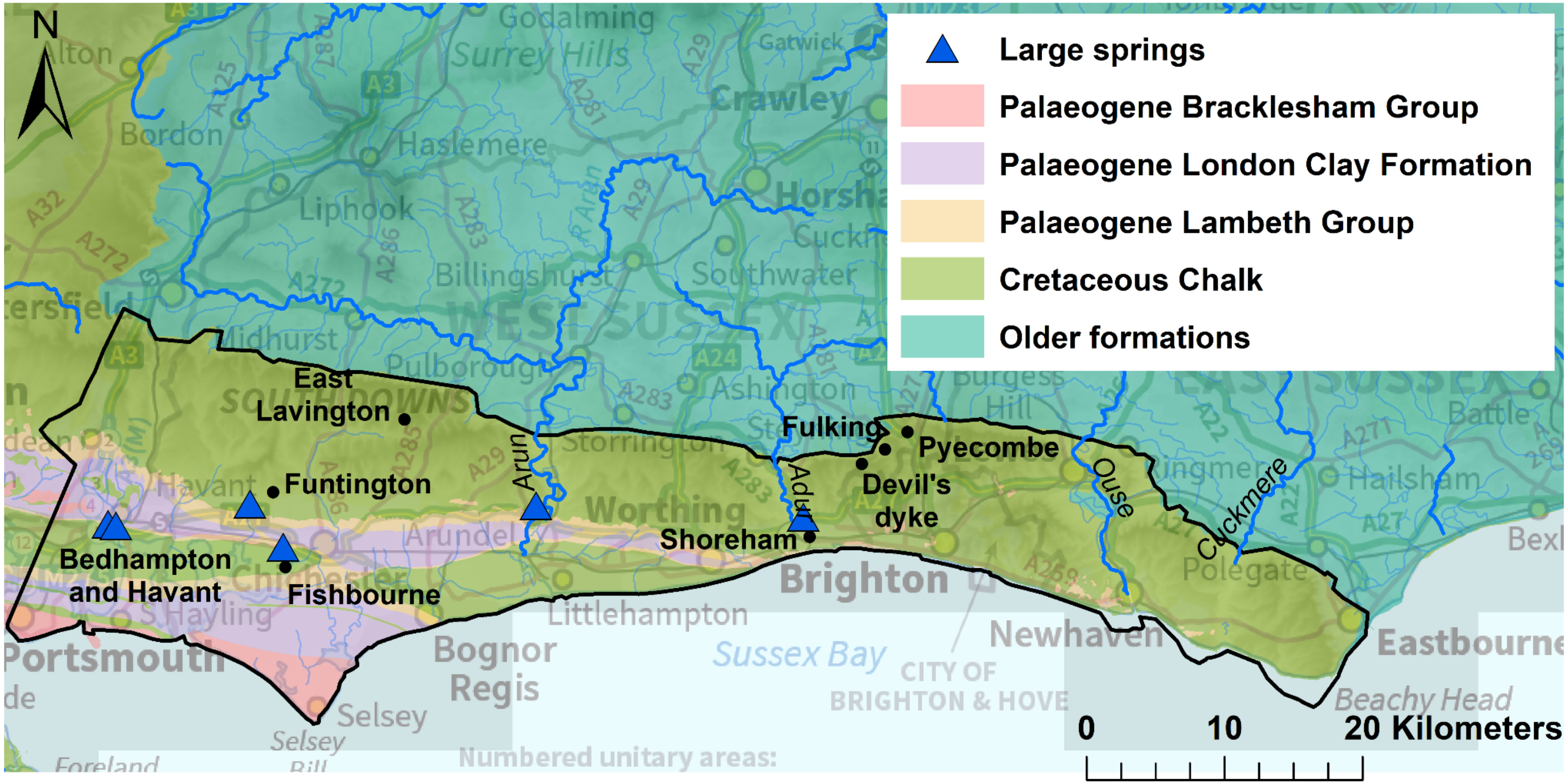

Figure 15. Large springs discharging Chalk groundwater (with some places mentioned in the text marked as black dots).

3 Tracer tests

Tracer tests have been carried out in the South Down area using injections into karst stream sinks and boreholes, and have established 22 groundwater connections (Figure 16, Table 4). Nevertheless, tracer tests have not been conducted in most spring and abstraction catchments.

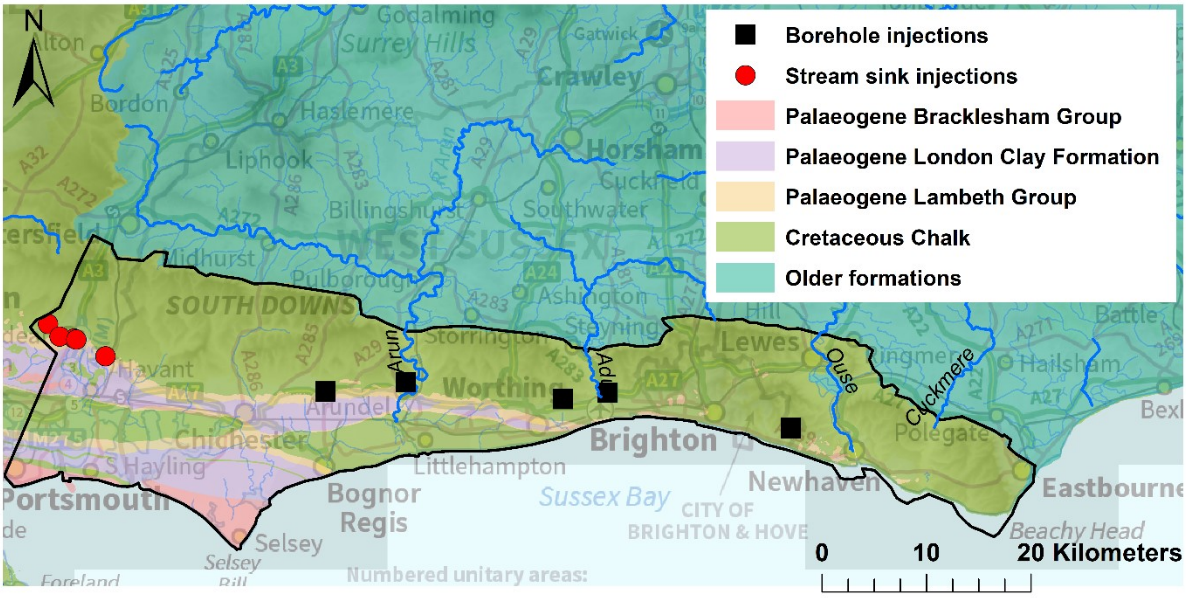

Figure 16. Tracer tests in the C7 Chalk area.

Table 4. Tracer tests recorded in the C7 Chalk area.

Test type	Injection Site	Recovery Site	Distance (m)	1st arrival Velocity ($m.d^{-1}$)	Recovery (%)	Reference
Stream sink to spring	Hazleton Wood Swallet	Bedhampton Springs	5750	2604	99.2% out of 69.7%*	Atkinson & Ingle Smith (1974)
Stream sink to spring	Hazleton Wood Swallet	Havant springs	5800	2078	0.8% out of 69.7%*	Atkinson & Ingle Smith (1974)
Stream sink to well	South-East Hampshire swallow holes, No. 13	Lovedean Well	900	600	0.1	Price (1979); Barton et al. (undated)
Stream sink to spring	South-East Hampshire swallow holes, No. 26	Havant springs	6600	3168	0.9 % out of 8.8 %*	Price (1979); Barton et al. (undated)
Stream sink to spring	South-East Hampshire swallow holes, No. 26	Bedhampton Springs	6300	2652	7.9 % out of 8.8 %*	Price (1979); Barton et al. (undated)
Stream sink to spring	South-East Hampshire swallow holes, No. 39	Havant springs	4600	12300	23.2 % out of 38.5 %*	Price (1979); Barton et al. (undated)
Stream sink to spring	South-East Hampshire swallow holes, No. 39	Bedhampton springs	4800	10500	15.2 % out of 38.5 %*	Price (1979); Barton et al. (undated)
Stream sink to spring	South-East Hampshire swallow holes, No. 41	Havant springs	5800	4000	9.9 % out of 49.6%*	Price (1979); Barton et al. (undated)
Stream sink to spring	South-East Hampshire swallow holes, No. 41	Bedhampton springs	5700	5067	39.7 % out of 49.6 %*	Price (1979); Barton et al. (undated)
Lake to borehole	Swanbourne Lake	Abstraction	220	2640	unknown	Atkinson and Low (2000).
Lake to borehole	Swanbourne Lake	Wildfowl Trust water supply	55	230	unknown	Atkinson and Low (2000).
Lake to borehole	Swanbourne Lake	Observation borehole No. 9	150	427	unknown	Atkinson and Low (2000).
Lake to adit	Swanbourne Lake	Adit	165	1189	unknown	Atkinson and Low (2000).
Lake to spring	Swanbourne Lake	Dairy Spring	220	940	unknown	Atkinson and Low (2000).
Lake to spring	Swanbourne Lake	Spring Arundel Castle moat	250	1622	unknown	Atkinson and Low (2000).
Borehole to borehole	Monitoring borehole	Abstraction borehole	850	1500	unknown	Maurice et al. (2016)
Borehole to borehole	Monitoring borehole	Abstraction borehole	2270	3900	unknown	Maurice et al. (2016)
Borehole to borehole	Monitoring borehole	Abstraction borehole	5.6	1161, >677	29, 42	Joseph and Brown (1976)
Borehole to borehole	Monitoring borehole	Abstraction borehole	2	720, 262	100, 98	Joseph and Brown (1976)
Borehole to borehole	Monitoring borehole	Abstraction borehole	1340	846	unknown	Howard (1982)

*these recovery rates are expressed as a percentage detected at each recovery site out of the total percentage recovery

3.1 STREAM SINK TRACER TESTS

Tracer tests from stream sinks in the catchments of the Bedhampton and Havant springs are reported by Atkinson and Smith (1974), and Barton et al. (unknown date); and are also discussed in the BGS karst knowledge exchange webpages on the karst hydrogeology of these springs:

https://www2.bgs.ac.uk/groundwater/about/karstAquifers/bedhamptonHavantSprings.html

Two tracer tests were undertaken from the Hazleton Wood stream sink and tracer was detected at both the Bedhampton and Havant springs, a distance of 5.7 - 5.8 km from the injection site (Atkinson and Ingle Smith, 1974). The groundwater velocities reported were 2.6 and 2.1 km/day (based on first arrival). High velocities experienced in these tracer tests highlights the well-connected nature of the karst system over many kilometres. The total tracer recovery was 69.7%. 99.2% of this was recovered at Bedhampton Springs, and the remaining 0.8% at the Havant Springs. Overall the tracer recoveries were high, suggesting that there is low attenuation along these karstic flowpaths and that the springs are very vulnerable to pollution.

A further five tracer tests were carried out from stream sinks proving connections to the Bedhampton and Havant springs over distances of 4.6 to 6.6 km (Price, 1979; Barton et al., undated). The tracer tests proved very rapid groundwater flow with velocities (based on first arrival of tracer) of 2.7 to 10.5 km/day to the Bedhampton springs and 3.1 - 12.3 km/day to the Havant springs. Total tracer recovery varied between 8.8 % and 49.6%. Tracer recovery was generally higher at Bedhampton springs than at Havant springs, although during the test from swallow hole No. 39 the tracer recovery was highest at Havant springs (Table 4). A sixth tracer test was carried out from a stream sink to a borehole at Lovedean, which demonstrated rapid groundwater flow of 0.6 km/day over a distance of 0.9 km, with a recovery of 0.1 % (Price, 1979; Barton et al., undated).

A tracer test was conducted in the Swanbourne Lake area to investigate whether there was a connection between the lake and a nearby borehole (Atkinson and Low, 2000). The tracer was introduced close to the bed of the lake and sampling was conducted at a total of nine locations between 55 and 250 m from the lake. Tracer was detected at seven of the monitoring sites. Rapid groundwater velocities of between 0.4 and 2.6 km/day (based on time to first arrival of tracer) suggest that well connected karstic flowpaths exist between the lake and the monitoring sites.

3.2 BOREHOLE TO BOREHOLE TRACER TESTS

Four borehole-borehole tracer studies have been carried out within the C7 Chalk area, with confidential locations.

Tracer tests were carried out between monitoring boreholes and abstraction boreholes (Maurice et al., 2016). Connections were demonstrated over distances of 2300 and 850 m, with groundwater velocities of 3.9 km/day and 1.5 km/day respectively. Tracer concentrations were extremely low, especially in the test over the distance of 3.9 km. Rapid karstic flow through the saturated zone over long distances in this area seems to be combined with very high dilution and/or attenuation of tracers through dispersion.

Tracer injections of Rhodamine WT and lithium chloride were carried out at two sites by Joseph and Brown (1976). These tests demonstrated a high degree of connectivity between the conduits and/or fissures present in the injection boreholes and those present at the abstractions over very short distances (~2-6 m). Tracer arrived very rapidly (within a few minutes) and recoveries were high.

Borehole to borehole tracer testing also proved a connection between a monitoring borehole and a pumping station over a distance of 1.3 km (Howard, 1982). The tracer test demonstrated rapid groundwater velocities of 850 m/day. This suggests the presence of a well-connected conduit and/or fissure network, which is also indicated by the extremely high transmissivity of 13000 $m^2 \cdot d^{-1}$ that has been estimated from pumping tests in the Chalk in the area.

Tracer testing was also carried out in the Burpham area (Southern Water Authority, 1975; Atkinson and Smart, 1981). Tracer injected into a borehole was detected at an abstraction borehole and at several springs within 12 hours, and after 48 hours it was detected in several observation boreholes. The tracer tests demonstrated connectivity between springs within the intertidal zone of a tidal reach of the River Arun and an abstraction which is 1 km away (Atkinson and Smart, 1981). These tests are not included in Table 4 as few details are available.

3.3 SINGLE BOREHOLE DILUTION TESTS

Single borehole dilution tests were performed on two boreholes to determine their suitability as injection points in a catchment scale tracer test (Maurice et al., 2016). In both boreholes there was rapid dilution and there were clearly identifiable outflowing horizons in which almost all of the tracer within that section of borehole left the borehole within one hour, and almost all the tracer had left the entire borehole within 24 hours. The tests highlighted the depths of major flow horizons within the boreholes. Given the rapid dilution, it is probable that these features are solutional fissures or conduits.

4 Other evidence of karst and rapid groundwater flow

There have been many hydrogeological studies conducted in the C7 area that provide further evidence of the role of karst and the presence of rapid groundwater flow, and this section provides a short literature review of these studies. In particular, the karstic nature of groundwater flow in the South Downs region is discussed in Allen et al. (1997); Jones and Robins (1999); and Robins and Dance (2003); and more recently by Farrant et al. (2021a,b,c).

4.1 PUMPING TESTS, ABSTRACTION YIELDS AND WATER LEVEL MONITORING

The aquifer properties of the South Downs area are described by Allen et al. (1997), and reflect pumping tests in abstraction boreholes which tend to be biased towards the more permeable parts of the Chalk. Some very high transmissivities of > 5000 $m^2 \cdot d^{-1}$ have been observed (Figure 17). Values range from 14 to 9500 $m^2 \cdot d^{-1}$ with a median of ~ 500 $m^2 \cdot d^{-1}$, and a general pattern of higher transmissivity with decreased depth to water table, and lithological and structural controls on transmissivity (Allen et al., 1997). The high transmissivities observed in the area are indicative of well-connected networks of solutional fissures and conduits supplying the abstractions. Whilst the locations of these karstic networks is unknown they are likely to extend quite far from the abstractions. For example pumping tests at Madehurst had a rapid impact (within 8 hours) on groundwater outflows 4 km away at Arundel and Swanbourne Lake (Jones and Robins, 1999).

High yields also indicate extensive karstic networks, and tables of autumn drought output for abstractions in the Brighton, Worthing, Chichester, Seaford and Eastbourne chalk blocks presented by Jones and Robins (1999) indicate some very large abstractions (5-20 $Ml.d^{-1}$ or ~ 60-230 $l.s^{-1}$). Headworth and Fox (1986) also report high yields exceeding 200 $l.s^{-1}$ from the upper parts of the Chalk in the South Downs.

Borehole water level monitoring in the South Downs demonstrates that there can be high variability in the water levels recorded in boreholes within close proximity (Allen et al., 1997), suggesting flow is through discrete karstic networks. Over larger geographical scales, low groundwater gradients in the area suggest well connected solutional networks (Jones and Robins, 1999).

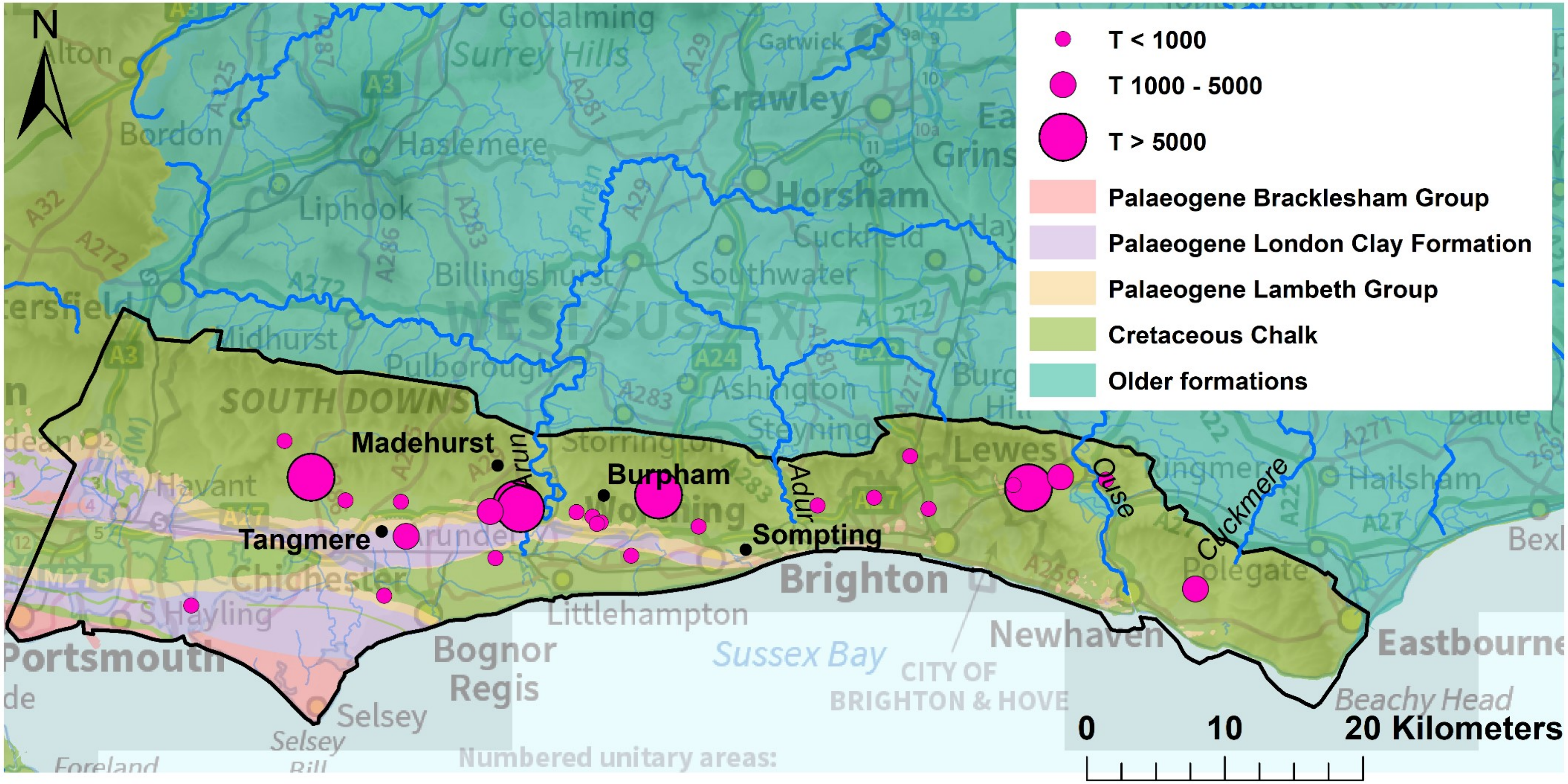

Figure 17. Transmissivities (m^2/day) in the C7 South Downs Chalk

4.2 KARSTIC FISSURE FLOWS

There is considerable evidence that high transmissivities and high yields occur due to a small number of solutional fissures intersected by boreholes and adits. In many reports and papers it is not clear whether “fissures” are planar solutional fissures as defined in this report (see glossary), or more circular shaped solutional conduits, because many studies do not distinguish between them. It is likely that karstic flowpaths comprise complex networks of both, with conduits embedded within the fissures. In this section the term fissure is used as in the original studies. Whatever their morphology at the point they are intercepted in boreholes or adits, these individual solutional features can have very high yields. While studying an adit system, Mustchin (1974) reports a number of individual large yielding fissures at 8 different locations. The fissures are generally reported at intervals of about 30-50m, and have flows of up to 4000 $m^3.d^{-1}$ or 46 $l.s^{-1}$ (Allen et al., 1997; Macdonald et al., 1998). Foley (2017) also highlighted the importance of karstic fissure flow, discussing three boreholes in the Horndean area with either large yields with low associated drawdown, or logs recording the presence of large fissures.

Borehole flow logging studies provide evidence of the importance of individual fissures, and the karstic inception horizons with which they are associated. For example, flow logging at the Tangmere borehole indicated 60% of flow associated with the Lancing Flint and 40% of flow associated with flint bands close to the Castle Hill marl (Jones and Robins, 1999). In another example, flow logging at the Victoria gardens borehole in central Brighton indicated ~55% of the flow from a feature associated with the Seven Sisters Flint, ~20% from the Belle Tout Marls, ~ 20 % from a feature on the Shoreham Marl, and ~ 5 % from above the Lightpoint Marl and the Hope Gap hardground (Jones and Robins, 1999).

Further evidence of large subterranean fissure flows comes from construction projects. Mortimore (2012) reports on large water ingresses through karstic features during construction of the Brighton and Hove Stormwater tunnel. In the Madeira B shaft at ring 18 there were inflows that required pumping estimated at 9600 l/min (160 $l.s^{-1}$), whilst at ring 20 the flows were estimated to have reached 11300 l/min (almost 190 $l.s^{-1}$). Large inflows estimated to total about 7560 l/min also occurred into the Norfolk shaft which was considerably higher than the estimates of ~900 l/min that were expected based on permeability testing (Mortimore, 2012). These inflows included a “sudden burst of water at the base of the shaft…..related to some cavity in the Chalk filled with Quaternary sediment” (Mortimore, 2012). Mortimore (2012) also reports that the Hove Street shaft had high water inflows.

Although solutional fissures have generally been shown to decrease in frequency with depth, and the zone of water table fluctuation is thought to be most important for groundwater flow in the South Downs chalk, there is evidence of deep solutional development, with groundwater flow identified at depths of up to 140 m below the surface (Allen et al., 1997). At one site in the South Downs, a borehole was pumping sand from within “solutional bedding-plane fractures” at a depth of 70 m (Southern Science, 1992; MacDonald et al., 1998; Charalambous et al., 2013). This suggests that there are connected networks of solutional fissures and conduits with sufficiently rapid flow to transport the sand to 70 m below the surface.

4.3 DRY VALLEYS AND GROUNDWATER FLOODING

In karst areas dry valleys can occur due to the capture of surface water into solutional voids in the subsurface, and due to springs fed by conduit systems becoming unsaturated as new conduit systems are developed at greater depths in response to base level lowering. The surface geomorphology of the South Downs Chalk is also indicative of karst with dry valleys reflecting the solutional development of subsurface permeability. Dry valleys are very prevalent, and high yielding boreholes in the principle dry valleys have high permeability and low storativity (Jones and Robins, 1999). Many successful abstractions are located in dry valleys (Farrant et al., 2021b; Farrant et al., 2021c). The Devil’s Dyke is a deep dry valley incised into the north-facing scarp slope of the South Downs which is 1000 m long, 400 m wide and up to 80 m deep. It is generally thought to be of glacial or periglacial origin (Waltham et al., 1997), but one theory is that it was formed by spring capture processes (Small, 1962; Waltham et al., 1997), and it is possible that spring migration due to the development of subsurface solutional development contributed to the formation of the feature.

The karstic nature of the Chalk is also indicated by groundwater flooding in the area. In 1994 flooding occurred in Chichester due to the activation of a large volume spring at a higher elevation than the normal spring system (MacDonald et al., 1998; Robins et al., 2003). Groundwater flooding from reactivation of springs has also occurred in the Patcham area near Brighton (Hadlow, 2014). In these cases the capacity of the karstic conduit/fissure system supplying the normal groundwater outlets was exceeded, resulting in the activation of a normally unsaturated fissure/conduit network, discharging at a higher elevation.

4.4 WATER QUALITY INDICATORS OF RAPID GROUNDWATER FLOW

Some contaminants are indicative of a rapid flow component at a spring or borehole, with connectivity with the surface (e.g. coliforms, turbidity, pesticides that degrade rapidly in the subsurface). These are observed fairly commonly in the C7 South Downs chalk area (e.g. Stuart et al., 1999, 2002, 2016; Farrant et al., 2021b,c). Jones and Robins (1999) also give examples including: bacteriological contamination of groundwater at Patcham near Brighton within 24 hours of rainfall; bacteria and turbidity at Burpham; and phenol pollution of an abstraction related to soakaway drainage from a nearby road (location not reported). In the C7 area, the levels of these pollutants that are indicative of a rapid groundwater flow component are very variable.

Work undertaken by the British Geological Survey (Stuart et al., 1999; 2002; 2016) to assess the risk of Cryptosporidium at 22 Portsmouth Water sites concluded that 6 were at high risk, 5 were at low risk but with possible evidence of rapid groundwater flow, and 11 were at low risk (Stuart et al. 2016). Stuart et al. (2016) note that 7 of the sites are in particularly karstic areas. At 18 of the 22 sites coliforms have been detected indicating a component of rapid groundwater flow. However counts were usually fairly low (less than 50 cfu/100 mls), and at 4 sites only 1 or 2 samples contained coliforms in very low numbers. Relatively small numbers of microbiological samples were taken (32 to 304, average 103). Turbidity is also an issue at some sites. Residence time data from CFC and SF_6 sampling generally indicated fairly large components of longer residence time groundwater, although in samples taken between 2012 and 2016, at 18 of the 22 sites the groundwater samples were contaminated by CFCs. Overall the work suggests that there is a component of rapid groundwater flow at most abstractions, with connectivity to microbiological contamination sources at the surface, although there appears to be considerable dilution with longer residence time groundwaters at many sites.

4.5 SALINE INTRUSION

Saline intrusion is a common problem in the South Downs area and occurs as the result of connected networks of solutional fissures and conduits. Jones and Robins (1999) provide a chapter on saline intrusion which includes details of the extensive studies that were carried out in the 1970s using borehole logging. Data from these investigations are presented, with specific information on saline intrusion at many sites for the Chichester, Worthing, Brighton, Seaford and Eastbourne Chalk blocks. These studies provide evidence for the presence of karstic solutional networks because the work identified: saline intrusion via specific inflowing fissures, salinity impacts several kilometres inland, boreholes with fluctuating salinity in response to daily tidal cycles, boreholes at similar distances inland with very different salinity responses, abstraction rate variations resulting in altered salinity, and large variations in salinity in boreholes only a short distance apart. Examples include connectivity with saline groundwater over at least 2 km distance at Burpham, and saline impacts over distances of 3-4 km at Sompting, with potential connectivity with large springs at Honeymans Hole near

Shoreham airport (Jones and Robins, 1999). More recently, a study of saline intrusion in a monitoring borehole at Saltdean, East Sussex, 1.7 km inland from the coast was carried out using Self-Potential measurements (MacAllister, 2016; MacAllister et al., 2018).

4.6 CONCLUSIONS AND CONCEPTUAL UNDERSTANDING OF KARST IN THE SOUTH DOWNS

There is considerable evidence for karst in the C7 Chalk area from a range of different types of investigations and studies, and recent studies have conceptualised the role of karst in the Chalk: Farrant et al. (2021a) present a conceptual model of karst in East Sussex with many maps and photographs, and discuss some implications for groundwater management, whilst aspects of the general understanding of karst hydrogeology of the Chalk in England provided by Maurice et all. (2021) are also relevant to the C7 chalk area.

Overall there is clear evidence that abstraction boreholes in the C7 area can be impacted by karst and rapid groundwater flow, and this was highlighted in knowledge exchange meetings with water companies (2017-2021) and in recent reports by Farrant et al. (2021b,c). Evidence includes conduits observed in borehole images (some up to 30-60 cm diameter); successful abstractions located close to springs and/or in dry valleys; and/or the presence of water quality indicators of rapid flow (which might include the presence of coliforms, detection of rapidly degrading pesticides, turbidity, salinity from road applications, or indicators of connectivity with the sea or surface water rivers). Many water quality issues occur in the South Downs as a result of the presence of solutional karstic networks.

The evidence suggests that karst may be more common in the saturated zone than in the unsaturated zone. These different parts of the aquifer are discussed below, with some remaining uncertainties highlighted.

4.6.1 Unsaturated zone karst

Contaminants indicating a rapid flow component and connectivity with the surface are present at many abstraction sites in the C7 Chalk area, suggesting that karstic bypass recharge is widespread. However, there is also evidence that the proportion of rapid unsaturated zone flow may be quite small. At many sites coliform counts/turbidity levels are low, suggesting that there is a higher degree of attenuation and/or dilution with longer residence time groundwater than is observed in more classically karstic aquifers. Further work considering indicators of rapid groundwater flow alongside land use and pollutant sources, with comparisons to highly karstic aquifers would be useful to confirm this. There is also evidence for longer residence time groundwaters from studies of bulk groundwater ages at public water supply abstractions in the Chalk of this area using chlorofluorocarbons and sulphur hexafluoride (Darling et al., 2007). These results did also show that some rapid recharge was occurring, with complex mixing processes, and considerable variation was observed between sites (Darling et al., 2007).

The presence of rapid "bypass flow" in the Chalk has been known for some time. A study of tritium in groundwater in this area by Downing et al. (1978) is discussed by Jones and Robins (1999), and the study estimated that about 15 % of the overall recharge was rapid. However, the proportion of rapid bypass recharge via unsaturated zone karst is likely to be spatially very variable. This is reflected in the levels of contaminants indicating rapid flow that are observed at abstractions, which are very variable, and include a few sites with very high levels of coliforms and/or turbidity.

A conceptual understanding of karst can provide some clues about the spatial distribution of rapid unsaturated zone flow. Within the C7 Chalk area there are places, mostly associated with the Chalk-Palaeogene margin, where stream sinks are well developed creating point recharge. It is almost certain that there is a higher proportion of rapid bypass recharge in these areas compared to other areas. This is because at many stream sinks heavy or prolonged rainfall leads to a large volume of water directly recharging the Chalk, and because karst stream sinks are likely to be feeding into well developed conduit networks (Maurice et al., 2021). There will also be rapid unsaturated zone flow and a higher proportion of bypass recharge where there are rivers, soakaways or SUDs (Sustainable Urban Drainage systems) enabling point recharge to the Chalk. However, the extent to which this occurs is unclear, and datasets on point recharge (other than via stream sinks associated with the Chalk-Palaeogene margin) are not well developed. There is evidence for vertical solutional features with no surface expression, with examples in coastal exposures extending vertically up to 95 m (Section 2.1). These appear to be more common in the Seaford Chalk Formation than in other formations (Farrant et al., 2021a), but there remains considerable uncertainty on how frequently vertical solution features occur, and the controls on their distributions. The presence of these features has implications for groundwater quality if pollutant sources, such as septic tanks and manure piles, happen to be located on or near to them enabling rapid transport of pollutants in the unsaturated zone.

One large area of uncertainty concerns soakaways and SUDs providing drainage for unwanted runoff from roads, urban areas and fields. Where soakaways or SUDs have high infiltration rates into the Chalk it is likely that they are feeding into karstic solutional fissures that enable rapid flow through the unsaturated zone (unless there is a thick/extensive gravel aquifer above the Chalk which distributes the flow). It seems unlikely that the unmodified chalk fracture network would have the capacity to take large flows. However, the threshold infiltration rate for unmodified fractures versus solutional fissures is not known, and where there is a thick unsaturated zone it may be less likely that such fissures extend all the way to the saturated zone. Data on the infiltration capacities of soakaways and SUDs are not available, but identifying those with high infiltration rates into the Chalk would be useful, as well as further work to investigate connectivity between such features and the saturated zone, perhaps using tracer testing. This would enable a better understanding of how frequently vertical solution fissures occur, and how their distribution relates to other geological factors; as well as providing better knowledge of point recharge and vulnerability to pollution in the Chalk.

Uncertainties remain about how frequently there are well connected solutional pathways through the unsaturated zone providing connectivity between the surface and the saturated zone and how these pathways (and hence the proportion of rapid bypass recharge) vary spatially. In a 2022 project for the Environment Agency, the BGS has created GIS based karst domains that reflect the likelihood of the presence of solutional pathways in the unsaturated zone connecting the surface to the saturated zone, based on currently available data and conceptual understanding.

4.6.2 Saturated zone karst

Although no studies have systematically assessed the distribution of karst in the saturated zone of the South Downs, the evidence outlined here suggests that saturated zone karst is extremely widespread with many springs/abstractions that are fed by karstic solutional networks. Whilst there are some uncertainties about the geographical extent of such networks, evidence from tracer tests, pumping tests and saline intrusion demonstrate that these networks commonly extend out over distances of several kilometres from the abstraction or spring. Whilst some karst networks in the area are related to stream sink to spring karst connections, many are not. This is conceptually possible as even in the absence of surface karst stream sinks karstic solutional networks of conduits and fissures can develop in the saturated zone due to mixing dissolution processes (Farrant et al., 2021a, Farrant et al., 2021d). It is also possible that saturated zone conduits may have formed as part of stream sink to spring karst networks in the geological past, but that the stream sinks that originally supplied them have been eroded away as the Palaeogene recover retreated (Maurice et al., 2021). The saturated zone karstic networks enable pollutant transport over long distances, and present challenges for groundwater modelling, protection, and management because the precise locations of the karstic flowpaths are unknown.

Further work would be useful to improve understanding of saturated zone karst and could include: development of better datasets on springs and their discharge; investigations of karst inception horizons using borehole imaging, flow logging and spring locations combined with geological data; developing improved conceptual models of the flowpaths supplying abstractions and springs; and tracer testing. Given the evidence for karst, it is likely that many Source Protection Zones (SPZs) that were derived using groundwater models will underestimate the distance from which groundwater in the saturated zone can reach a source within 50 days (the criteria for definition of SPZ1), as suggested for the Chalk more generally in Maurice and Ascott (2021). It is likely that a karst specific approach to source protection, would be useful in this area.

5 Summary

- There is substantial evidence of karst in the Chalk of the C7 area including karstic caves and conduits, stream sinks, large springs, dolines, and dissolution pipes.
- The report provides descriptions, photos and surveys of more than 17 sites with short natural caves with evidence of karstification that have been identified by speleologist Terry Reeve.
- The longest Chalk karst cave in England occurs in the area and is 354 m in length.
- Smaller conduits (~0.1 to ~0.4 m) appear to be common.
- A recent coastal cliff survey identified 54 conduits/caves (or groups of conduits) which varied in frequency from up to 7 per 100 m stretch of cliff, to one conduit/group of conduits within an 800 m stretch of cliff (Farrant et al., 2021a,b,c).
- Most of these conduits are associated with specific inception horizons (marl seams and sheet flints) or major vertical fractures.
- These coastal surveys revealed that caves and conduits can occur in the Chalk below interfluve areas and below areas with no evidence of surface karst.
- These surveys also revealed fissures and conduits containing terrigenous sediment indicating connectivity with the surface over vertical distances of up to ~ 100m, as well as open vertical fissures extending up to 95 m below the surface providing potential pathways for rapid unsaturated zone bypass flow.
- Conduits and fissures are also commonly observed in the saturated zone in boreholes.
- 58 stream sinks are recorded in the C7 area, with most in the western parts of the area, and associated with the Chalk-Paleogene boundary around Horndean and Havant.
- There may be additional stream sinks that have not been identified along the Chalk-Palaeogene boundary, and this knowledge exchange work has not established whether the major rivers that cross the area also contribute any point recharge to the Chalk. The contribution of soakaways and SUDs has also not been assessed.
- Surface depressions are common in the C7 area, and although some may be karst dolines, many are likely to be pits of anthropogenic origin.
- Subsurface dissolution pipes are very common in the C7 area where there are thin superficial or Palaeogene sediments overlying the Chalk, and these can be 10s metres deep and/or wide.
- There are more than 100 recorded chalk springs in the area, and there may be many more.
- There is little information on spring discharges. However, there are five springs which are known to have very substantial flows of > 100 $l.s^{-1}$. The largest are the Bedhampton and Havant springs which have a discharge of around 600 to 1900 $l.s^{-1}$ and are known to have karstic characteristics. It is likely that there are many springs that have (or had) large flows (> 10 $l.s^{-1}$).

- Tracer tests have been carried out from nine injection points, revealing rapid groundwater flow velocities ranging from 0.2 to 12.3 km/day over distances of up to 6.6 km. Tracer recoveries ranged from 0.1 % to 100 %.
- Many hydrogeological investigations provide further evidence of the role of karst and rapid groundwater flow in the area.
- Karst enables rapid recharge and unsaturated zone flow via stream sinks, and also via solutional features with no surface expression. However, there appears to be a higher degree of protection from surface pollutants than in classic karst aquifers perhaps due to fewer or smaller stream sinks and the potential for more attenuation in the unsaturated zone.
- Saturated zone networks of solutional fissures and conduits appear to be very common, and can extend over distances of many kilometres, enabling long distance pollutant transport. Karst specific approaches to SPZ delineation are therefore likely to be appropriate.
- This report provides a basis for further investigations of karst in this area to enable improved management and protection of groundwater resources.
- Further work would be useful to improve karst datasets (especially on large springs, point recharge via riverbeds and soakaways, conduits observed in boreholes, and tracer tests); and to develop improved conceptual models at the catchment scale by integrating geological and hydrogeological data and tracer testing.

Glossary

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

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

Doline: A surface depression formed by karst processes.

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

Dissolution tubules: Networks of small cylindrical solutional voids ~ 0.5 cm in diameter found in chalk.

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

Fissure: An enlarged fracture with aperture of ~ 0.5 to > 2 cm, and a planar cross-sectional shape. In these reports the term is used for fractures that are enlarged by dissolution. Those developed on bedding partings may extend laterally both along strike and down dip.

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

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

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

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

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

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

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

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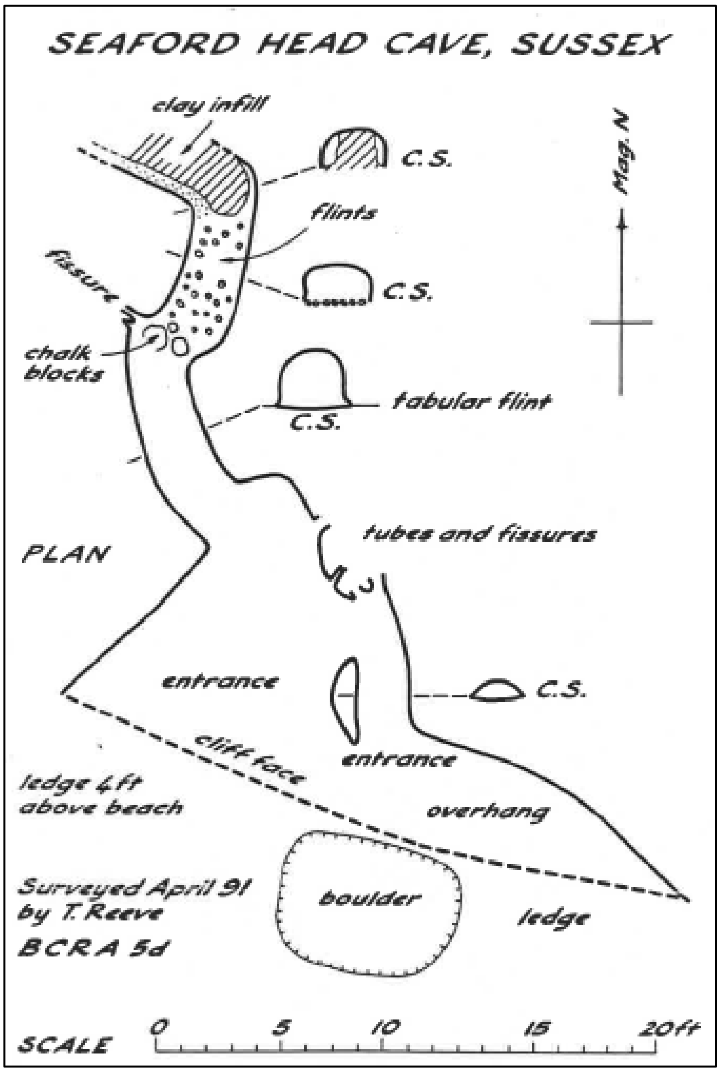
Appendix 1. Descriptions, photos and surveys of chalk caves from Terry Reeve

The following cave descriptions, photos and surveys are from Terry Reeve (personal communication 2017, 2018; 2021; 2022). The descriptions are based on notes provided by Terry Reeve and phone discussions. Some information on these caves can also be found in Reeve (1977,1979, 1981, 2021a and b). The numbers (1-17) refer to the site numbers shown in Table 2 and Figure 6 in Section 2.1. A number of other caves in the Seaford Head area have been photographed by Terry Reeve, and some of these pictures are included at the end of this appendix.

1. Seaford Head Cave, Seaford Head, Sussex

Seaford Head cave has a large entrance about 1 m above the beach. The tube shaped passage is developed on a sheet flint and has the appearance of a karstic phreatic (sub water table) formed passage. There are also some scallops indicating water flow, and solutional rounded pockets in the roof suggesting karstic dissolution. The cave is blocked with Palaeogene sediments about 10 m from the entrance. Pictures and a survey are provided below. This cave is developed in the Lewes Nodular Chalk Formation at the level of the Hope Gap sheet flint.



Survey of the Seaford Head Cave, courtesy of Terry Reeve

Entrance to Seaford Head Cave, (photo courtesy of Terry Reeve)

Seaford Head Cave - tube shaped passage on a sheet flint layer, with scalloped walls (photo courtesy of Terry Reeve)

Small conduits in the side of the passage above the tabular flint in Seaford Head Cave (photo courtesy of Terry Reeve)

Blocked end of Seaford Head Cave, with clay infill beyond the beach pebbles (photo courtesy of Terry Reeve)

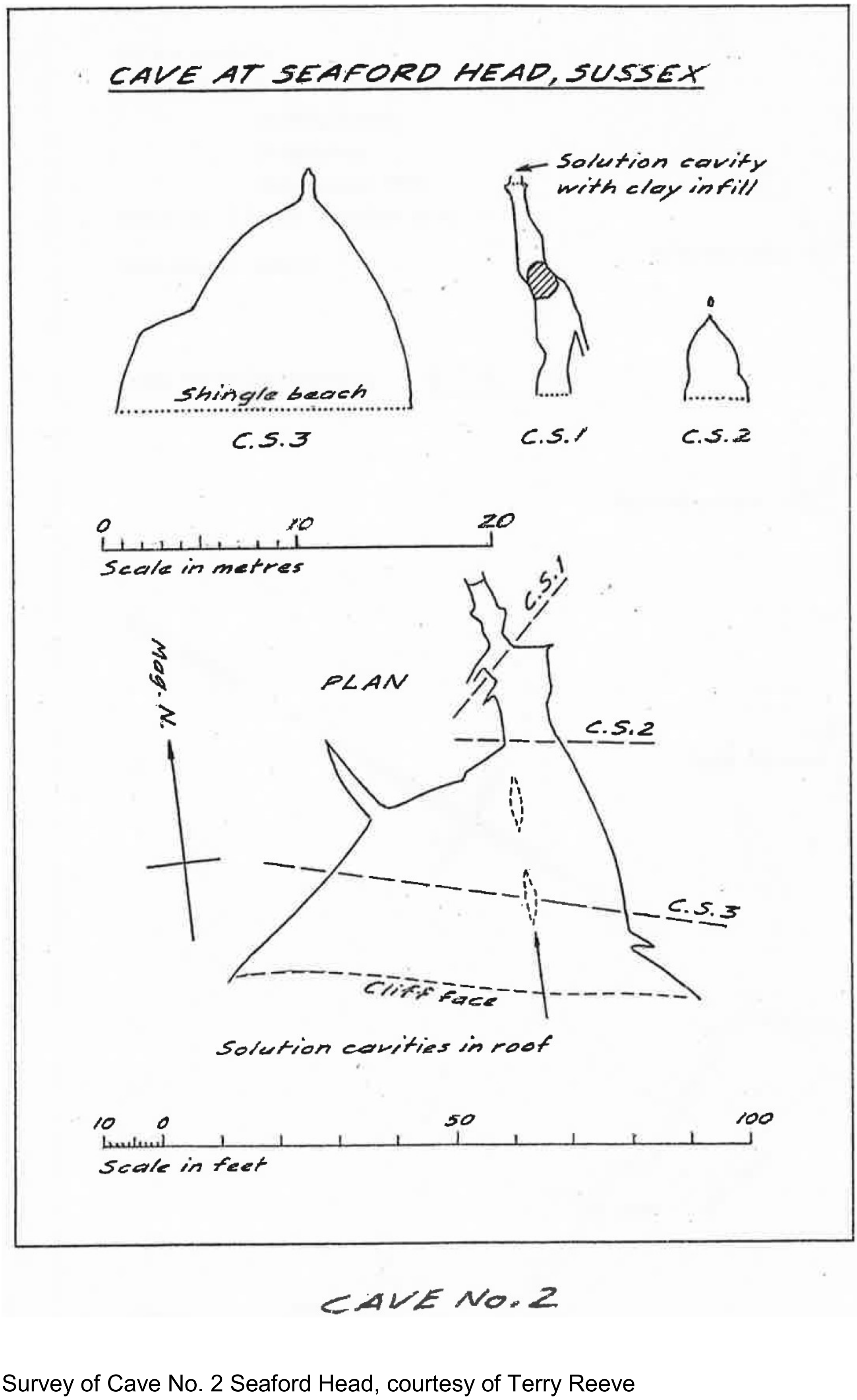
2) Seaford Head small cave entrance, Seaford Head, Sussex

A 0.8 m wide cave entrance was observed about 8 m above the beach in the Seaford Head cliffs. It is likely to be developed within the upper part of the Lewes Nodular Chalk Formation that dominates this section of the coastline, and may have been lost to cliff retreat.

Cave entrance about 8 m above the beach at Seaford Head (photo courtesy of Terry Reeve)

3) Cave No. 2 – Seaford Head, Sussex

This cave appeared suddenly about 12 years ago. The entrance was originally 23 metres wide, but there has since been some breakdown of the walls and roof. Although this cave is likely to have been substantially enlarged by marine erosion and cliff collapse, there is evidence for karst. Large areas of the roof of the cave exhibit signs of karstic development and dissolution features including a cavity filled with sediment. The cave is likely to be developed in the Seaford Chalk Formation.



Survey of Cave No. 2 Seaford Head, courtesy of Terry Reeve

Cave No. 2, Seaford Head (photo courtesy of Terry Reeve)

Dissolution features on the roof of the entrance chamber to Cave No. 2 with conduits above (photo courtesy of Terry Reeve)

Back of the entrance with an arch leading to a second chamber and high level aven (photo courtesy of Terry Reeve)

Close up of archway and small conduit above, (photos courtesy of Terry Reeve)

Second chamber looking inwards with possible solutional scallops on the walls (photo courtesy of Terry Reeve)

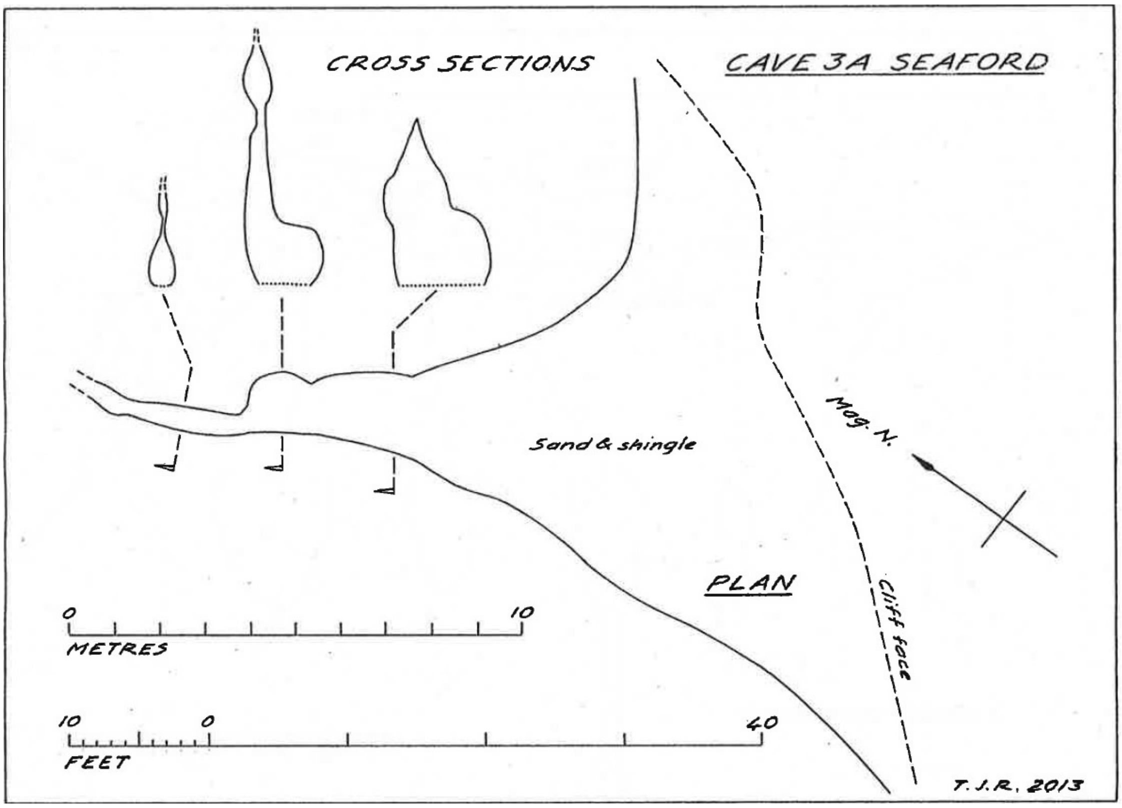
Seaward view from second chamber with possible solutional scallops (photo courtesy of Terry Reeve)

Looking up at rounded solutional features and a sediment filled cavity in the cave roof (photo courtesy of Terry Reeve).

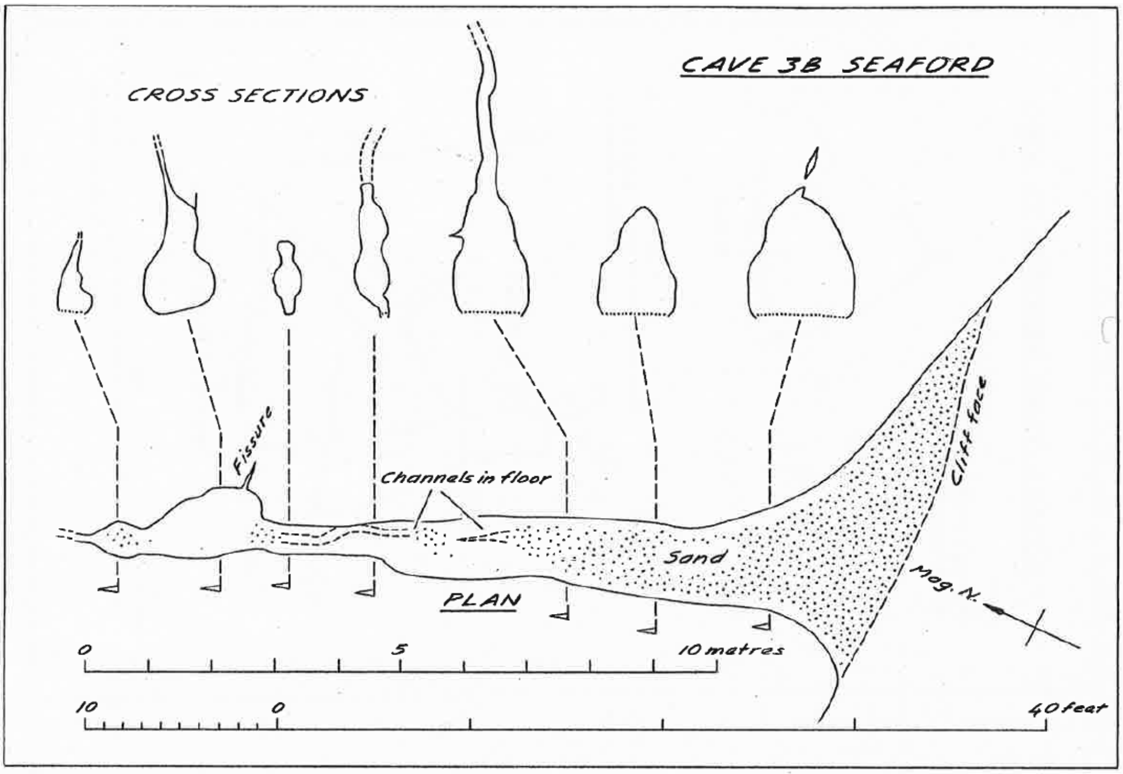
Entrance area almost completely eroded away in 2017 (photo courtesy of Terry Reeve)

4) Caves 3A & 3B, Seaford Head

Surveys for these two short caves are shown below, with pictures of cave 3B showing the scalloped walls indicating past stream flow and dissolution features in the roof. The caves are likely to be developed in the Lewes Nodular Chalk Formation.



Survey of Cave No. 3A Seaford Head, courtesy of Terry Reeve



Survey of Cave No. 3B Seaford Head, courtesy of Terry Reeve

Passage at rear of Seaford Head cave 3A with solutional scallops (photo courtesy of Terry Reeve)

Looking into Cave No. 3B - a float is wedged into a constriction which leads to the final chamber (photo courtesy of Terry Reeve)

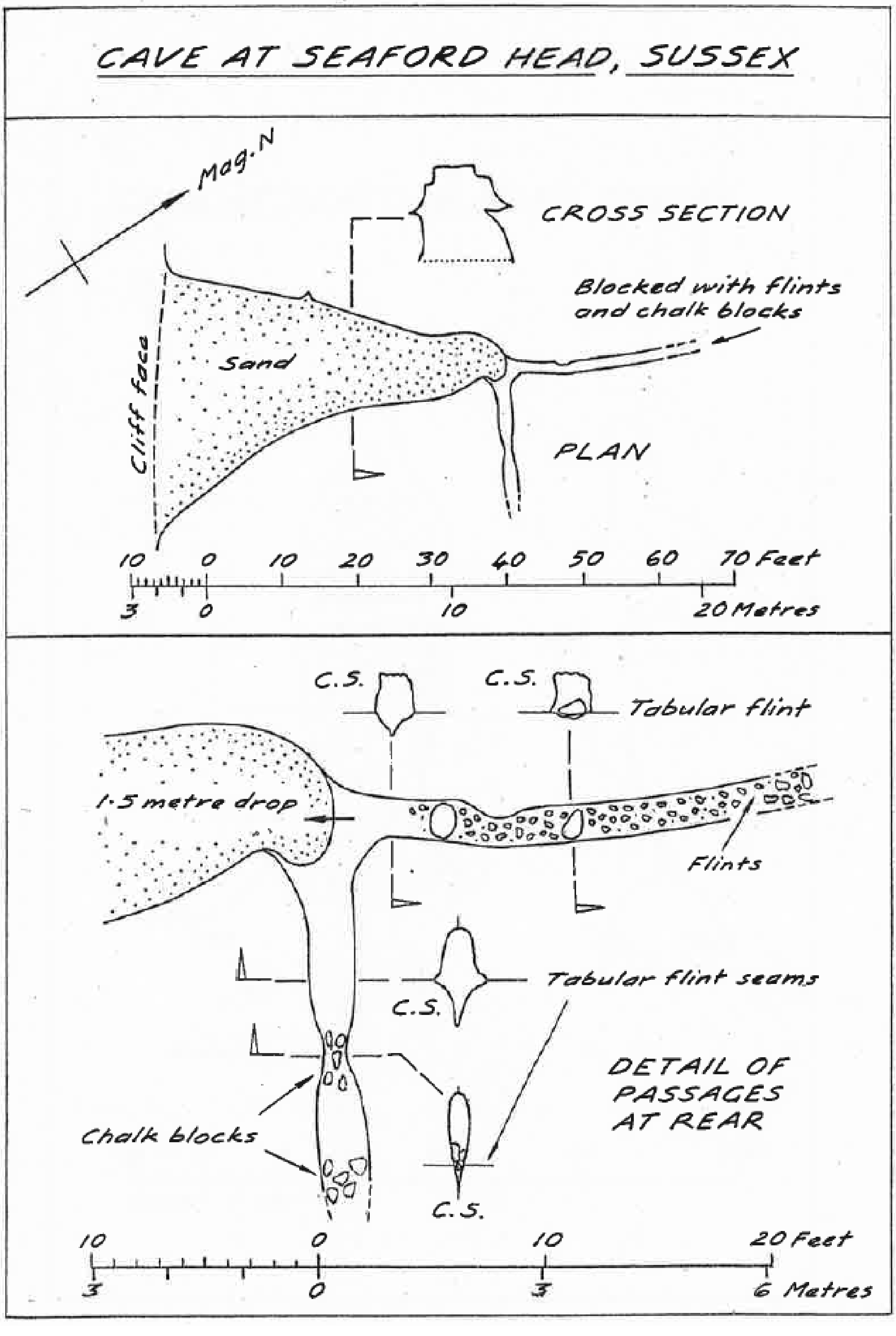
Solutional scallops on the passage walls of Seaford Head cave 3b (photo courtesy of Terry Reeve)

Cave remnant near Seaford Head Cave 3B (photo courtesy of Terry Reeve)

5) Cave No. 6, Seaford Head, Sussex

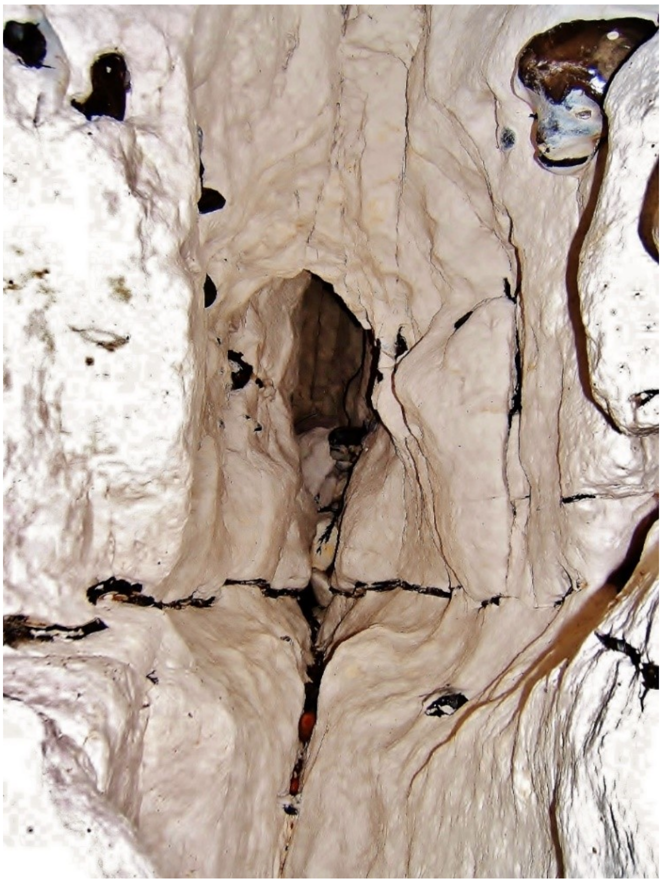
The original survey of the cave is provided below showing a side passage. The entrance to this cave was affected by rapid cliff retreat and when measured in December 2017 was found to be 6 m shortened. The pictures below show dissolution features on the walls and roof. A probable continuation of the side passage has since been located around a corner of the cliff, as well as some passages that have been dissected lengthways following the joints along which they were formed. These features were previously hidden behind a rock fall. This brings the total length to 85 metres and there could be a link to more passages behind another rock fall on the other side of a narrow promontory which is riddled with small conduits at the level of the sheet flint.

The cave is associated with a sheet flint just above the Hope Gap hardground and is likely to be developed in the Lewes Nodular Chalk Formation.



Survey of Cave No. 6, Seaford Head, courtesy of Terry Reeve.

The back of the chamber in Cave No. 6 (photo courtesy of Terry Reeve)



Conduit formed above a sheet flint layer (Hope Gap sheet flint) in Cave No. 6 (photo courtesy of Terry Reeve)

Fissure with sediment fill outside entrance to Cave No. 6a (photo courtesy of Terry Reeve)

6) Cave No. 7, Seaford Head, Sussex

Originally 24 m in length, the cave has been shortened by 8 m after a cliff fall. The roof, walls and boulders on the floor all show signs of dissolution and past water flow. The cave is likely to be developed in the Lewes Nodular Chalk Formation.

View inside Cave No. 7 at Seaford Head, showing clear signs of dissolution (photo courtesy of Terry Reeve)

Looking out of cave No. 7 at Seaford Head (photo courtesy of Terry Reeve)

7) Cave No. 8, Seaford Head, Sussex

This cave is developed on a thin flint seam about 2 m above the beach and cliff erosion revealed this cave is connected to part of cave No. 6. There are also several small tubes, between 10 cm and 60 cm wide on this flint layer. To the right of these conduits, a predominantly sediment filled fissure was also observed extending halfway up the cliff. The cave is likely to be developed in the Seaford Chalk Formation.

Solutional erosion of roof and walls, cave 8 at Seaford Head (photo courtesy of Terry Reeve)

8) Sea stack, Splash Point

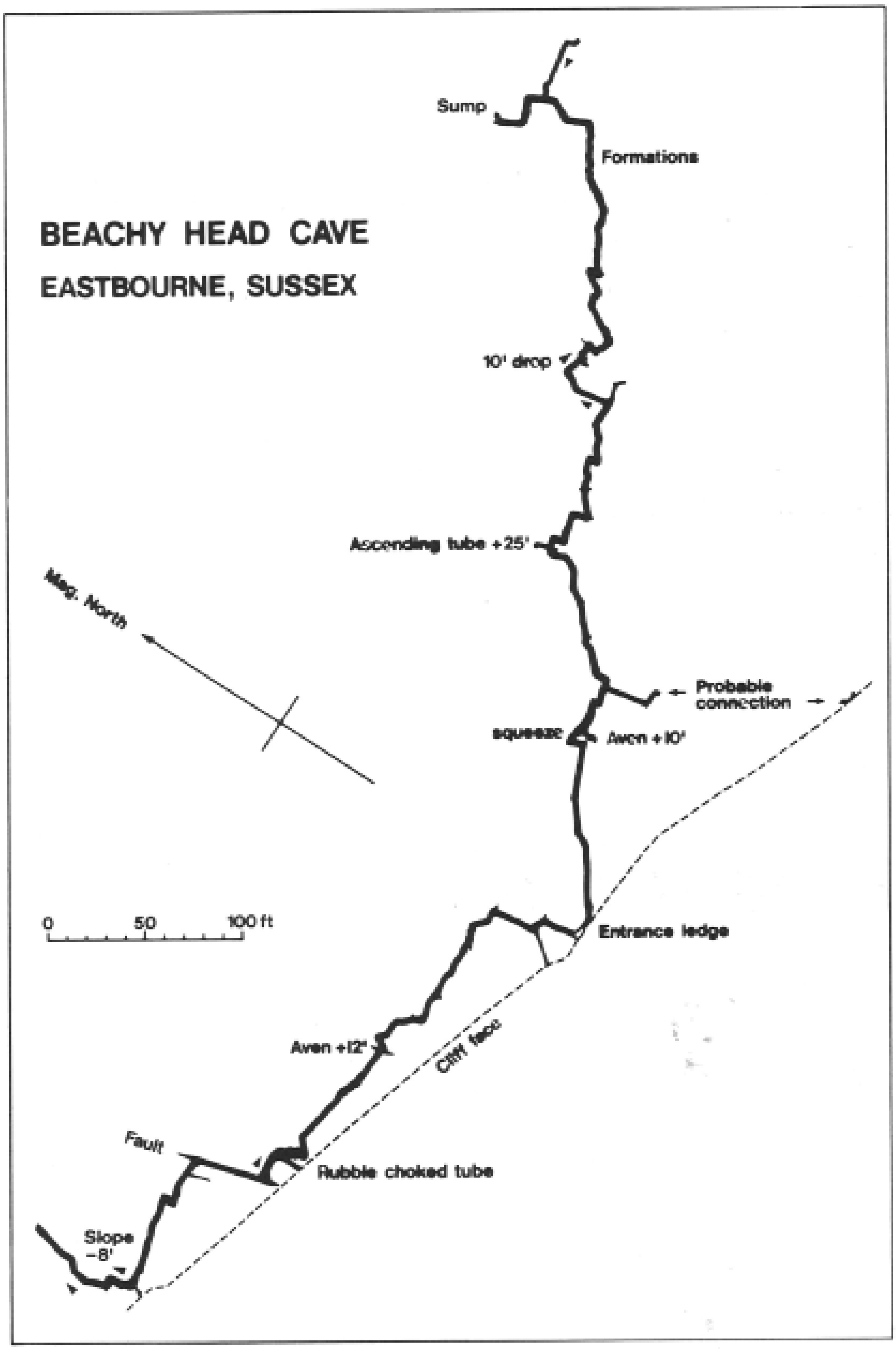
A hole can be observed in the side of a large sea stack at Splash Point, Sussex. The feature potentially forms the base of a deep solution pipe. The hole is thought to pre-date the formation of the stack as the spur that was breached to form the stack formed part of the wall of a cave with a complex network of tubes and cavities. The cave is developed in the lower part of the Newhaven Chalk Formation.

Sea stack at Splash point (photo courtesy of Terry Reeve)

9) Beachy Head Cave, Beachy Head, Sussex

Beachy Head cave is described in detail in Reeve (1981; 2021) and reviewed by Lowe (1992) and Waltham et al. (1992). It is also discussed by Farrant et al. (2021a) who note that in 2020 the entrance was concealed by cliff fall. The following description is from these references and from Terry Reeve (personal communication, 2022):

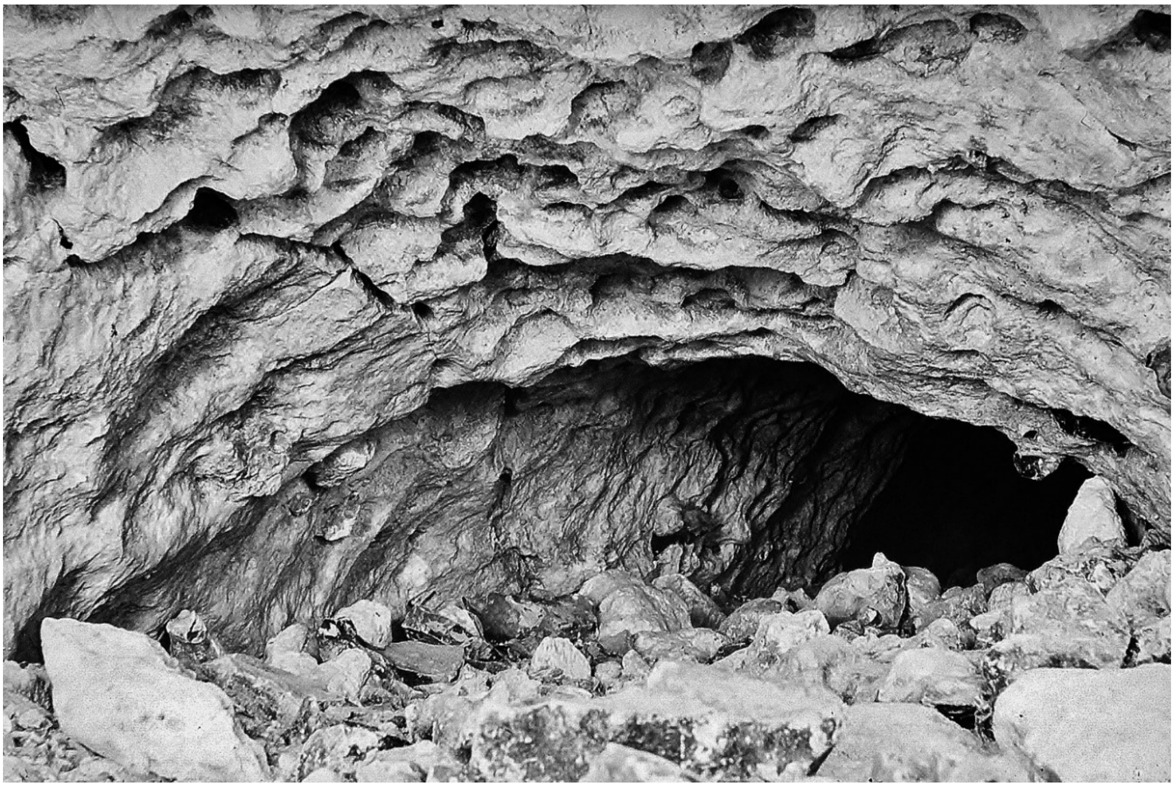
The cave had a total surveyed length of 354 m and extended in two directions from the entrance (although may be shorter now due to cliff retreat). The right passage went 178 m into the cliff in a north east direction, ending in a static sump (Reeve 1981). This passage is mostly flat out crawling and roughly oval in cross section. The main passage appears phreatic in origin and is floored with either earthy sediment or flint nodules. The main passage mostly requires crawling but there are some areas of stooping and walking dimensions. Some of the smaller side passages are more canyon shaped, and there are also some vertical tubes. Within the cave there is a transition between the early part, which is dry and dusty to the section beyond the drop, which is damp (Reeve, 1981; 2021). The left hand passage is mostly a flat out crawl, and is very similar to the right hand passage. After about 76 m the passage size increases to enable crawling on hands and knees. A bit further on daylight enters the cave through tubes and fissures. After 141 m there is an accumulation of sediments which reduces the height to a few inches, which is the end of the accessible cave (Reeve 1981; 2021). The cave is close to horizontal, and is developed on a sheet flint (Waltham et al., 1992). This is within the Lewes Nodular Chalk Formation.



Survey of Beachy Head Cave, courtesy of Terry Reeve

The climb to the entrance of Beachy Head Cave (photo courtesy of Terry Reeve)

Entrance to Beachy Head Cave (photo courtesy of Terry Reeve)



Passage near the entrance of Beachy Head Cave (photo courtesy of Terry Reeve)

Tube in the roof of Beachy Head Cave (photo courtesy of Terry Reeve)

Crystal formations inside Beachy Head Cave (photo courtesy of Terry Reeve)

Botryoidal stalactite inside Beachy Head Cave (photo courtesy of Terry Reeve)

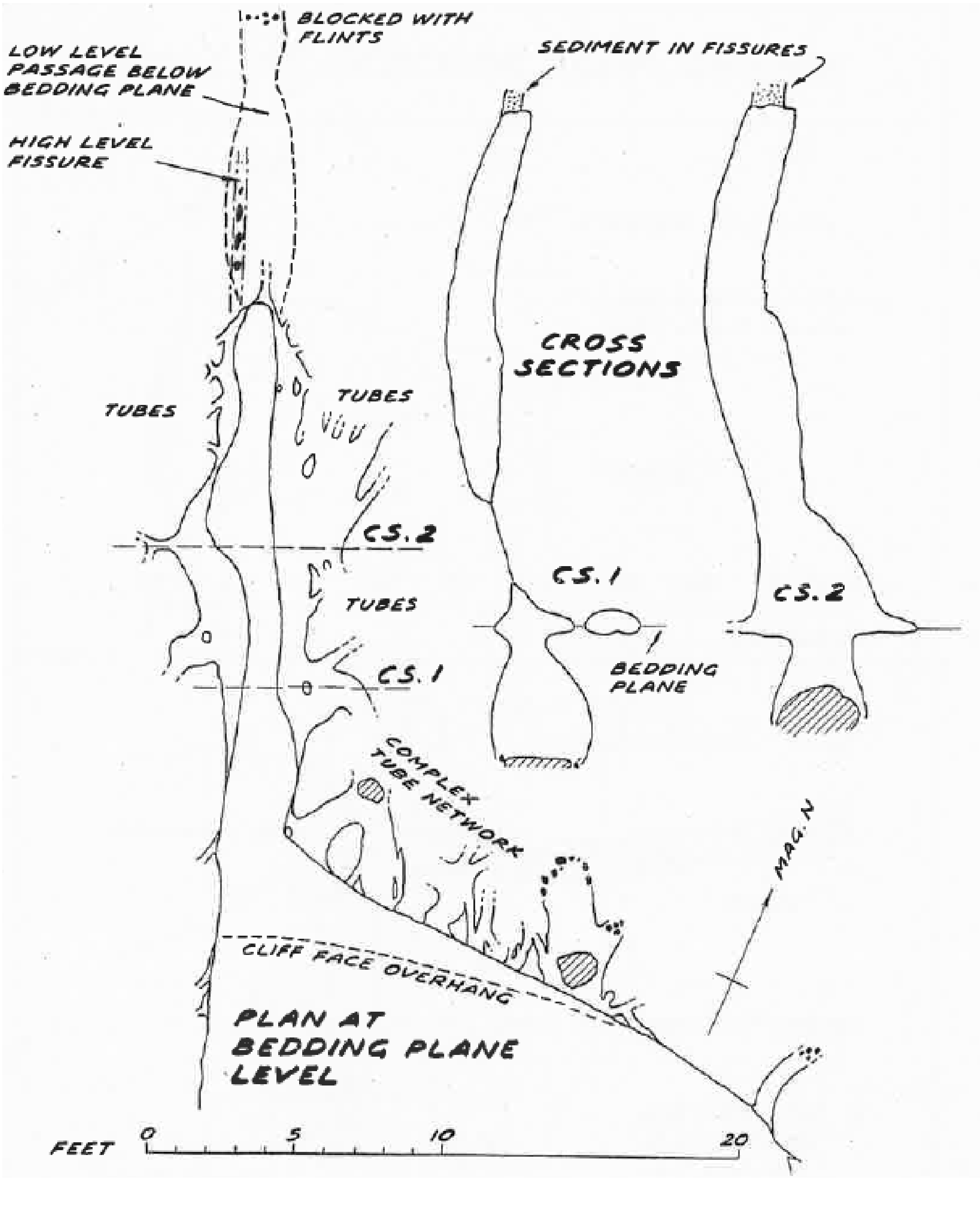
10) Cave No. 1, Beachy Head, Sussex

This cave is about 3 m above the beach and consists of two small chambers connected by a crawl. There is no survey of this cave. It is likely to be developed within the Lewes Nodular Chalk Formation.

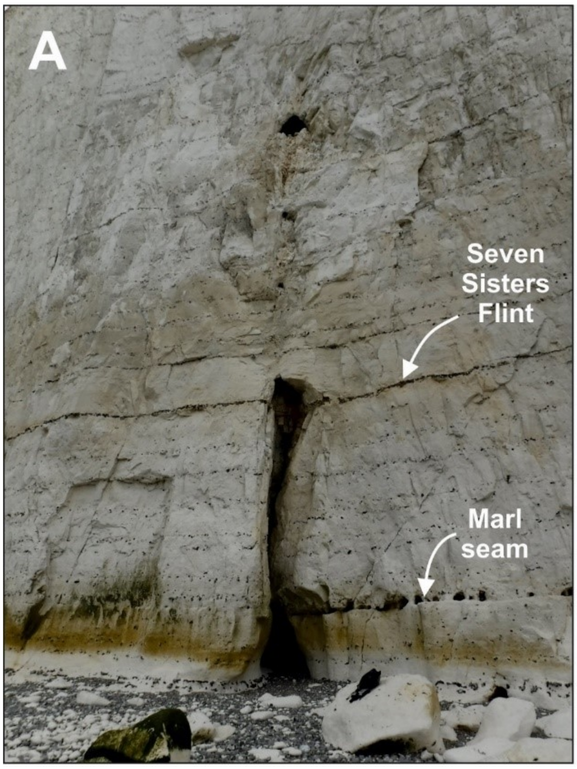
One of the chambers of Cave No. 1 at Beachy Head (photo courtesy of Terry Reeve)

11) Cave No. 4 and 5, Beachy Head, Sussex

At Beachy Head there were also two cave entrances developed along the same vertical fracture. The upper cave was inaccessible but about 1.8 m wide and 2 m high. The lower cave was exposed by cliff retreat and was accessible. This feature is the same as Belle Tout conduit 5 from the 2020 coastal survey by Farrant et al. (2021a), providing an interesting comparison of how the cave changes through time due to cliff retreat (see photos below). The caves are likely to be developed in the Lewes Nodular Chalk Formation.



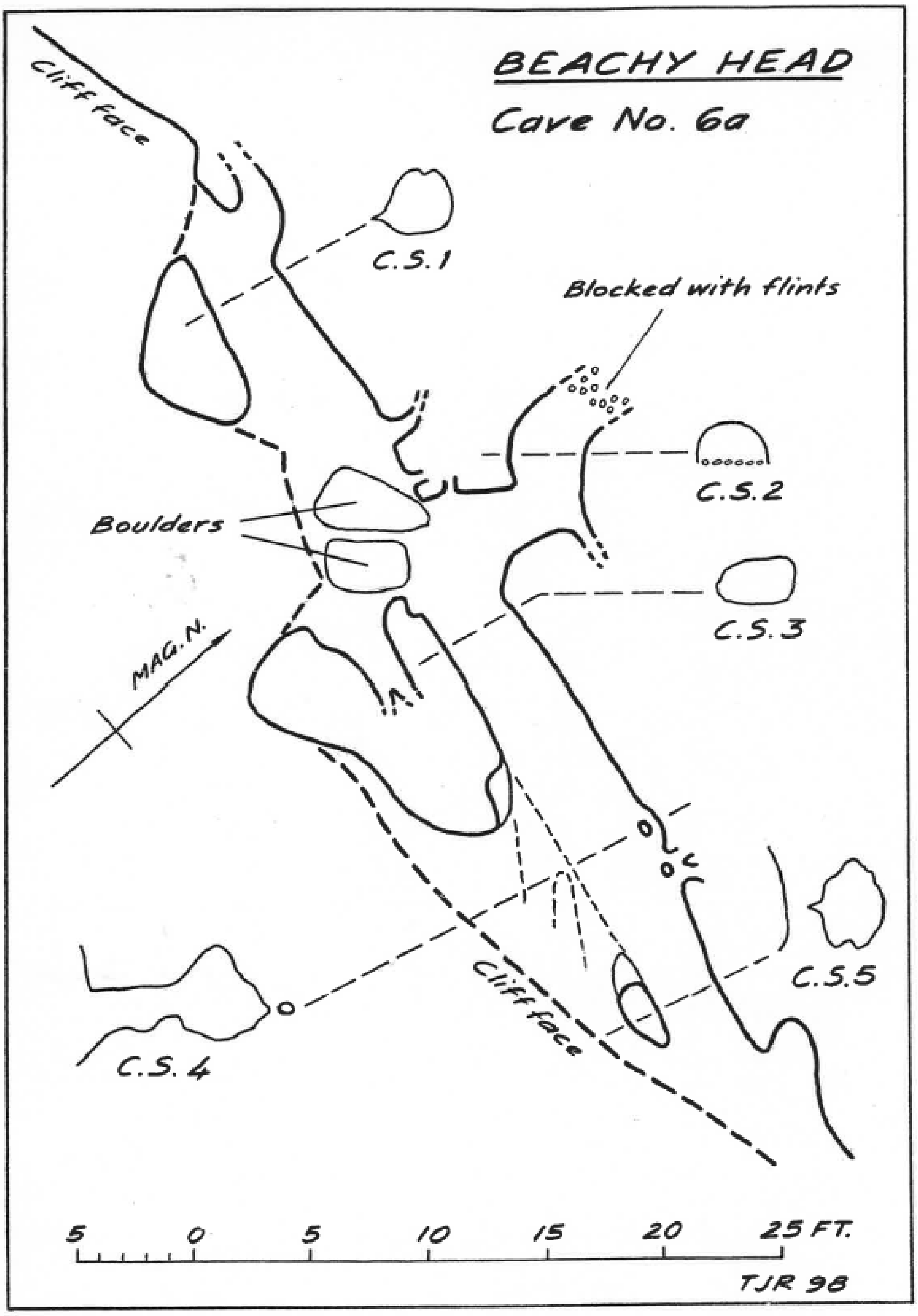
Survey of Cave 4, Beachy Head, courtesy of Terry Reeve

Entrance of Reeve Cave No. 4 and 5 at Beachy Head (left, photo courtesy of Terry Reeve), with 2021 comparison (photo by A Farrant).

12) Cave No. 6a, Beachy Head, Sussex

Another cave with karstic passage shapes and dissolution features was exposed by cliff retreat at Beachy Head. The entrance was located at sea level and completely eroded away soon afterwards. The cave is likely to have been within the Lewes Nodular Chalk Formation.

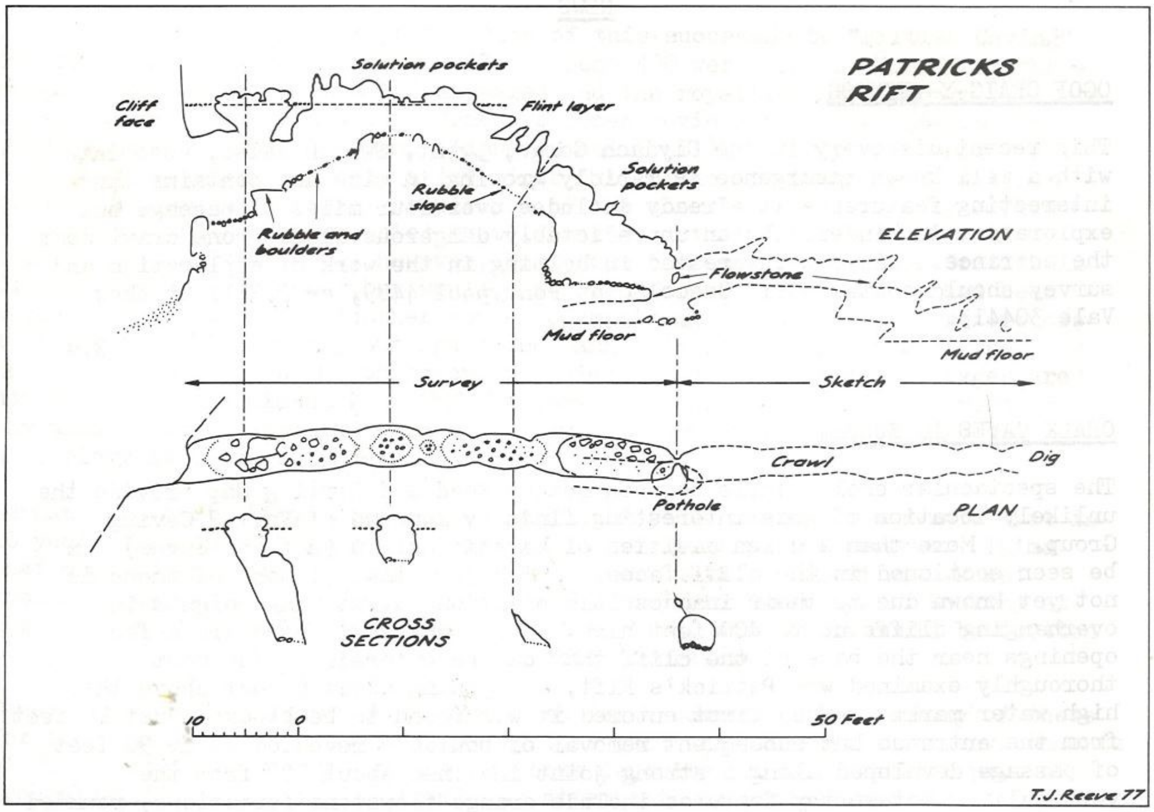


Survey of Cave No. 6a at Beachy Head in Sussex, courtesy of Terry Reeve

Seaward view to the entrance of Cave No. 6a (photo courtesy of Terry Reeve)

13) Patrick's Rift, Beachy Head near Birling Gap, East Sussex

The entrance to this cave was just 1.8 m above the high water mark. The removal of boulders revealed about 28 m of passage along a strong joint which was inclined 10 degrees from the vertical. Noteworthy features included orange flowstone formations, rounded solutional pockets in the roof, rubble filled potholes in the floor and a few small mud formations. The cave is described in Reeve (1979) and Reeve (2021a). The Seven Sisters flint could be seen in the roof of the upper chamber. This flint occurs at the top of the Belle Tout beds in the lower part of the Seaford Chalk Formation. It is possible that Belle Tout conduit 2 from the 2020 coastal survey by Farrant et al. (2021a) may be the remnant of Patricks Rift, truncated by cliff erosion (see pictures in Appendix 3).



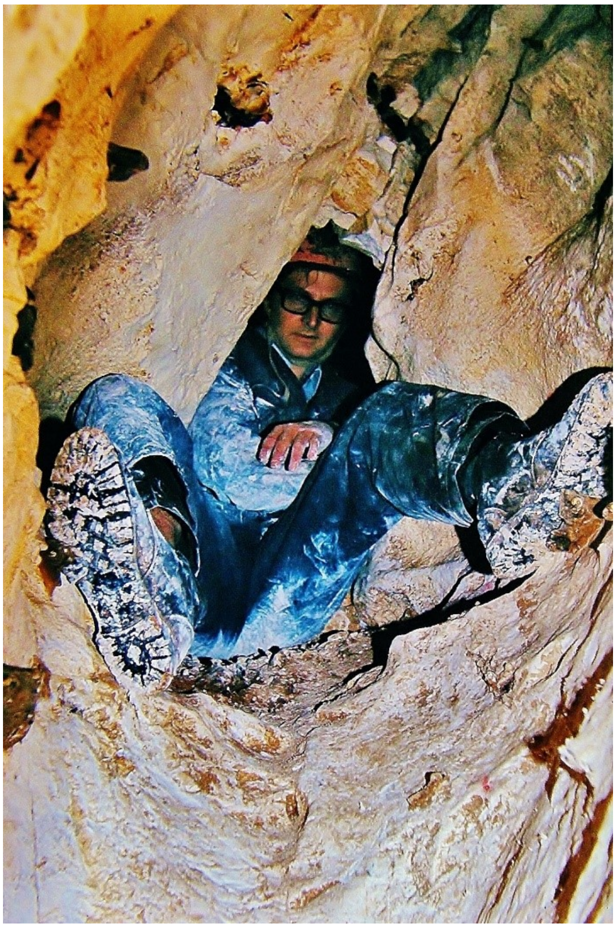
Survey of Patrick’s Rift Cave, courtesy of Terry Reeve

Entrance of Patricks Rift (photo courtesy of Terry Reeve)

Looking out from Patricks Rift (photo courtesy of Terry Reeve)

Seven Sisters flint seam in Patricks Rift (photo courtesy of Terry Reeve)

Dissolutional feature in the roof of Patricks Rift (photo courtesy of Terry Reeve)



Typical connections between small chambers in Patricks Rift (photo courtesy of Terry Reeve)

14) Houghton Quarry Cave, Amberley, West Sussex

A walking sized cave was entered in Houghton quarry near Amberley in the River Arun valley. The quarry was overgrown. The cave was 3 m high, 2 m wide, and 10-15 m long, ending in a shattered zone. Geomorphological evidence of water flow on the cave walls and roof suggest that this cave is likely to be of karstic origin, and not a manmade mine. The cave is discussed in Reeve (2021a). The surrounding geology suggests that the cave is likely to be within the Holywell Nodular Chalk Formation.

Photo of Houghton Quarry Cave (photo courtesy of Terry Reeve).

15) Newhaven caves, Sussex

On the coast adjacent to the fort at Newhaven there are phreatic tubes up to 1 m wide infilled with sediment and some smaller cavities up to 30 cm wide. There are also several other karstic openings higher up in the cliff. There are three entrances in the cliff face about 8 metres above the beach. Two are probably connected. There is also a 2 m wide but inaccessible cave entrance below the junction of the Palaeogene strata and the Chalk. The cliff section here is at the top of the Newhaven Chalk Formation and the base of the Culver Chalk Formation.

Two cave entrances at Newhaven (photo courtesy of Terry Reeve)

Third cave entrance at Newhaven (photo courtesy of Terry Reeve)

Fourth cave entrance at Newhaven, about 2 m wide and inaccessible (photo courtesy of Terry Reeve)

Anastomoses filled with Paleogene sediment at Newhaven (photo courtesy of Terry Reeve)

16) Caves in the Seven Sisters, Sussex

Several caves have been exposed by cliff retreat at the Seven Sisters (Reeve, personal communication 2021). An article on these caves (Reeve, 2021b) from the July 2021 Kent Underground Research Group newsletter is provided here as Appendix 2, with some additional pictures of a cave exposed by a cliff fall in 2008 below. The caves at the Seven Sisters are likely to be karstic caves that have been heavily modified by coastal erosion and cliff retreat.

Cave entrance exposed by recent erosion of the cliff at Seven Sisters (photo courtesy of Terry Reeve, taken 2018)

Closer view of caves exposed by cliff retreat at Seven Sisters (photo courtesy of Terry Reeve)

17) Shoreham cement works quarry, West Sussex

A cave entrance of about 1 m diameter was seen in Shoreham cement works quarry but could not be accessed. Two smaller tubes were visible below the cave, and all three openings were encrusted with flowstone. There were also some openings at lower levels. The site is discussed in Reeve (2021a).

Additional caves at Seaford Head

Small inaccessible cave about 6 m above the beach (photo courtesy of Terry Reeve)

Cave 4a at Seaford Head (photo courtesy of Terry Reeve)

Cave 5 at Seaford Head (photo courtesy of Terry Reeve)

Cave entrance beneath dry valley, (photo courtesy of Terry Reeve)

Small karstic conduit about 60 to 80 cm wide and 30 to 40 cm high (photo courtesy of Terry Reeve)

Small karst conduits high up in cliff, (photo courtesy of Terry Reeve):

Small dissolution cavities on a vertical fissure, (photo courtesy of Terry Reeve)

Closer view of solutional cavities (photo courtesy of Terry Reeve):

Gulls in a small cave high up in the cliff (photo courtesy of Terry Reeve)

Conduit on a sheet flint 1.5 m above beach (photo courtesy of Terry Reeve)

Small cave about 30 m above the beach (photo courtesy of Terry Reeve):

Rubble filled cavity about 50 cm wide (photo courtesy of Terry Reeve):

Picture of one of three caves connected by a narrow passage at the rear, about 2 m above the base of the cliff, now eroded away (photo courtesy of Terry Reeve)

Appendix 2. Caves at Seven Sisters, Sussex (Reeve, 2021b).

The following article, written by Terry Reeve, was published in the July 2021 Kent Underground Research Group newsletter (Reeve, 2021b). All the photographs were taken by Terry Reeve, and all the surveys were drawn by him.

SEVEN SISTERS, SUSSEX
TERRY REEVE, JULY 2021

INTRODUCTION - CAVES AND COASTAL EROSION

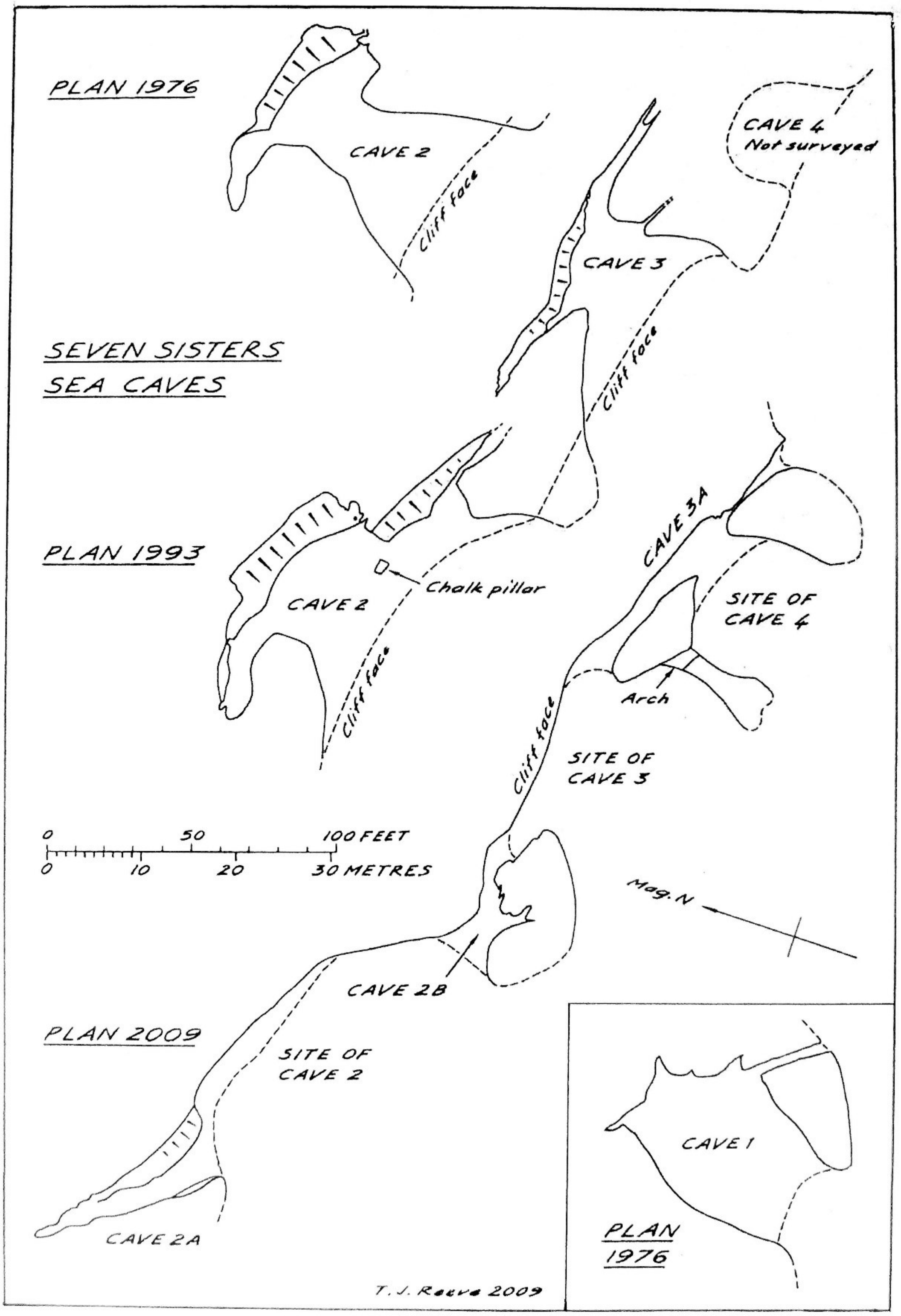
The system of dry valleys, seen in transverse cross section in the spectacular sea cliffs, known as the Seven Sisters, are probably the best known karst features of the English Chalk. The origin of these valleys is still a topic of debate but they clearly date from a time when climatic conditions were very different from today. A widely accepted theory is that they were formed by glacial meltwater during periglacial conditions when the ground was rendered impermeable by permafrost.

These cliffs are also the location of some very interesting and surprisingly large - albeit extremely transient - natural caves, which have appeared periodically on this ever changing coastline. Coastal caves are generally described as littoral caves or sea caves, implying that they were formed by marine erosion exploiting various weaknesses such as joints, faults and bedding planes. However, for many of the caves located in Chalk sea cliffs, this theory of origin is highly questionable. The alternative explanation - for which there is considerable evidence in this and other Chalk cliff exposures - is that they are actually pre-existing relict karst features intersected by rapid cliff line recession and then modified to varying degrees by the processes of marine erosion.

When these cliffs were first examined by the author more than 53 years ago only one surprisingly large cave was found in what were otherwise featureless cliffs (Cave No.2 on the accompanying plan), but only 8 years later the number had increased to three and since then no less than twenty have been recorded, along with several new sea stacks and natural arches. Evolutionary changes involving the development of caves, stacks and arches - which in harder rocks would have taken thousands of years - have been observed and recorded from their initial appearance through to eventual destruction by coastal erosion in the space of a few decades or in some cases only a few years.

Although some evidence of erosion and changes attributable to wave action has been observed in some of these caves, the sudden appearance of substantial caverns in what were previously featureless cliffs provides compelling evidence of karstic origins. Most of the cave development in this area is clearly influenced either by major joints or fault lines with slight throws, which are aligned parallel to the cliffs. These fracture planes are also a major cause of cliff face instability and extremely rapid erosion of this stretch of coastline. There is also some evidence of bedding related speleogenesis initiated by inception horizons (Lowe,1992) in the form of tabular sheet flints and the prominent, semi- tabular, Seven Sisters Flint Seam, both of which occur at or near sea level in this area. All the caves described here are formed in the Seaford Chalk Formation. The Newhaven Chalk Formation is also exposed near the top of some of the cliffs.

These descriptions, surveys and photographs provide a unique record of changes that could easily have gone unnoticed and unrecorded, as well as providing a useful benchmark against which to measure coastal erosion. They also show that natural chalk caves are not limited to little crawls.



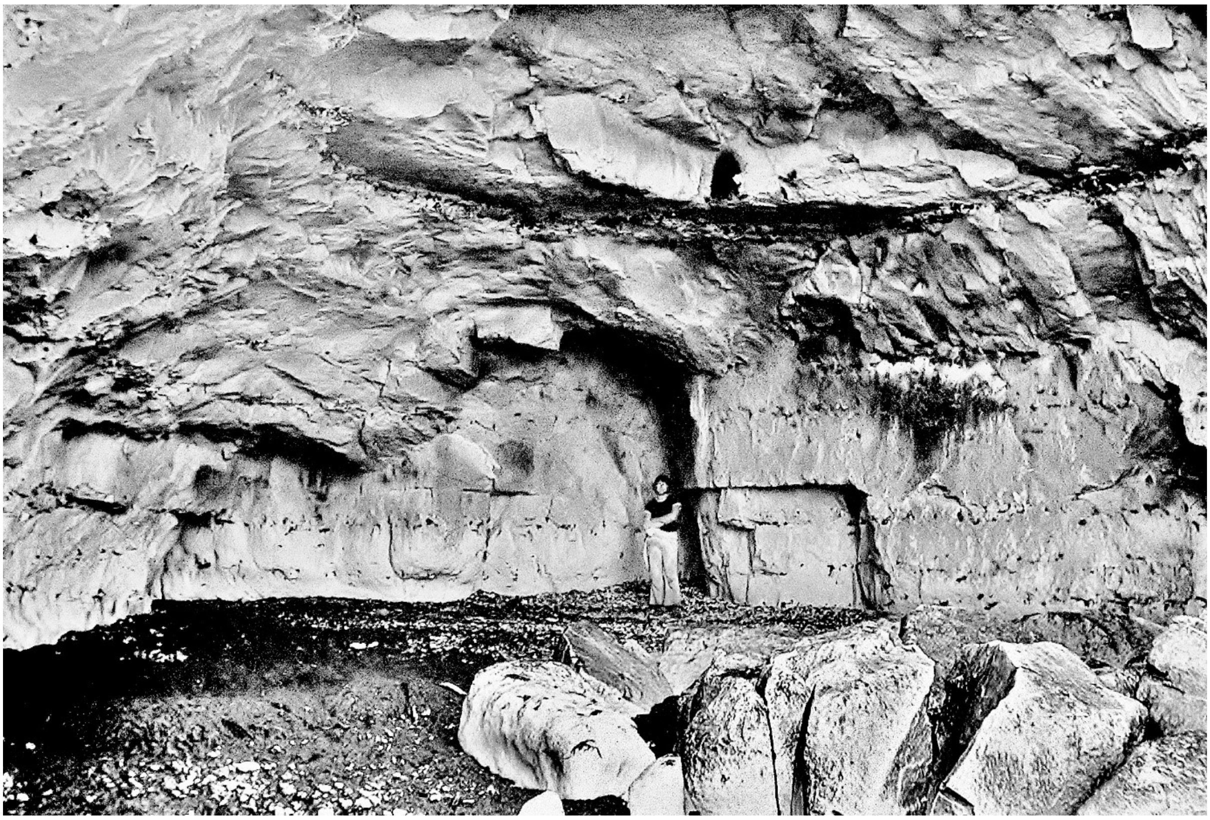
Survey of caves in 1976, 1993 and 2009

CAVE DESCRIPTIONS

The largest cave (No.1) was located beneath the dry valley known as Limekiln Bottom (NGR 530971), about 1.5 kilometres east of the mouth of the River Cuckmere. It was first noted in 1976 and seemed to have appeared suddenly in an area that was previously devoid of any trace of cave development. Given its size it would have been impossible to miss it during several earlier visits unless it was hidden behind a large rock fall, but this seems unlikely as there is no recollection of any significant cliff collapse at that time. The only plausible explanation is that it originated as a pre-existing isolated karst feature, which was subsequently intersected by the rapidly retreating cliff. Further evidence in support of this explanation can be seen in one of the photographs showing what at first glance appear to be large boulders that have fallen from the roof above the entrance. These are actually part of the seabed and are probably remnants of the base of a cliff face that had previously concealed the cavern from view before the sea broke into it.

The cave measured 10 metres wide and over 9 metres high at the entrance and widened out into a cavern 21 metres long and up to 15 metres wide, which is considerably larger than anything seen in artificial excavations such as chalk mines and deneholes. There were also two narrow side passages, formed along a joint crossing the rear of the cavern, one of which led out to a second entrance around a corner of the cliff. At the time it was the largest natural chamber ever recorded in the Chalk of Kent, Sussex, Dorset or Devon. A cave of similar dimensions has since been discovered at Kingsdown in Kent and some even larger examples have been described in the much harder well-indurated Chalk on the Isle of Wight and at Flamborough Head in Yorkshire. (Reeve, 1978).

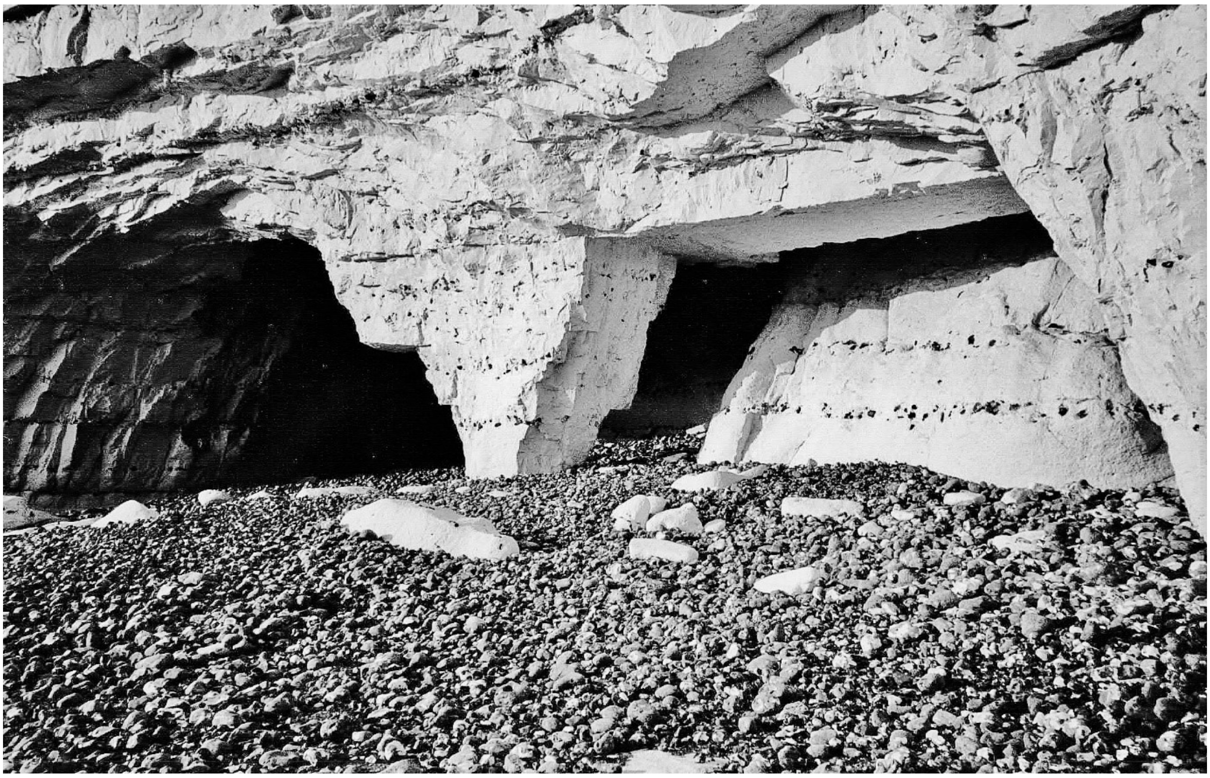
Cave No.1 entrance in 1976


Cave No.1 interior in 1976

Very little remains of Cave No.1 today though its site is still discernible. It has been almost completely eroded away by cliff falls and the main surviving remnant is a 3 metre high sea stack, the sides of which are formed from the original corner of the cliff, part of the right hand wall of the cavern and one wall of the side passage.

Cave No.2 was situated at the base of the cliff between Rough Bottom Valley and Brass Point (NGR 533970), approximately 150 metres east of No 1. It was first recorded as long ago as 1968 but only a rough sketch was made at that time. Another far more accurate survey was made in 1976 (at the same time as that of the newly discovered Cave No.1) and hardly anything seemed to have changed since the time of the earlier sketch plan. The entrance measured nearly 20 metres wide at the cliff face and tapered over a distance of 12 metres to an opening 7.6 metres wide and 3.5 metres high. This gave access to spacious passages extending parallel to the cliff for 24.4 metres, including a chamber 15 metres long by 9 metres wide. The rear wall of these passages followed a steeply inclined joint with sediment filled cavities at roof level and a small open dissolution tube network in the eastern end wall of the main chamber.

Chamber and side passage at rear of Cave No.2 in 1976



Cave No.2 entrances in 1993

When the cave was revisited and surveyed again in 1993, it was found that the cliff face above the entrance had receded by about 7.6 metres, whereas marine erosion in the rear chambers had resulted in comparatively minor increases in dimensions. One of the many surprises of this visit was the appearance of a completely new passage, 18.3 metres in length, branching off from the south- east corner of the main rear chamber. A large section of a wall of chalk about a metre thick, that had originally separated this new passage from the rapidly retreating cliff face, had collapsed inwards creating a second large entrance, 9.8 metres wide, situated next to the original entrance passage, from which it was separated by a pillar of chalk measuring only 1.8 by 1.3 metres at its base. This was supporting the centre of a flat roof more than 20 metres wide.

The main surprise of 1993, however, was the discovery of two completely new caves located in the cliff face east of Cave No.2. These had either been formed or intersected by coastal erosion during the previous 17 years - in a stretch of cliff previously devoid of any evidence of cave development . The largest of these (Cave No.3) consisted of a vast overhung recess 24 metres wide, at the rear of which a semi-circular opening 8 metres wide led into a large chamber with side passages extending parallel to the cliff for 36.6 metres and coming within 3 metres of the new side passage of Cave No.2, from which it was separated by a rubble choke.

Cave No.4 was another spacious cave with an entrance 12 metres wide. This was not surveyed on this occasion due to the limited time available during low tides. The intention had been to survey this cave at a later date but another visit, a few years later, revealed that a major cliff fall had occurred and everything was buried behind an enormous talus slope of rubble and boulders. It seemed likely that the slender pillar of chalk supporting the roof between the entrances of Cave No.2 had finally given way due to the constant pounding of the waves. This probably triggered the collapse which consequently spread to the large overhang at the mouth of Cave No.3 and the undercut cliff above Cave No.4, as well as some of the other large chambers.

When the site was eventually re-examined in January 2009, all the debris from the cliff fall had been washed away by the sea revealing an interesting group of caves piercing chalk promontories. These were mainly the remnants of the earlier caves, now separated by bays and inlets which had formed from the sites of previous large collapsed chambers. It is also possible that for a brief period prior to the cliff fall, all of the earlier caves could have become temporarily connected forming a continuous system with 5 entrances and more than 120 metres of passage.

Cave No.2b was the result of the linking and slight enlargement by marine erosion of the side passages originally belonging to caves No.2 and No.3. Another cave (No.2a), which at first sight seemed to be an enlargement of the original Cave No.2 side passage, was actually a completely new and separate entity beginning beyond the point where the previous cave had ended. This cave was probably exposed by the cliff fall and then temporarily hidden from view under rubble and boulders. Cave No.2 in its original form, had now been completely eroded away - the cliff face having receded by about 27 metres in the space of 43 years.

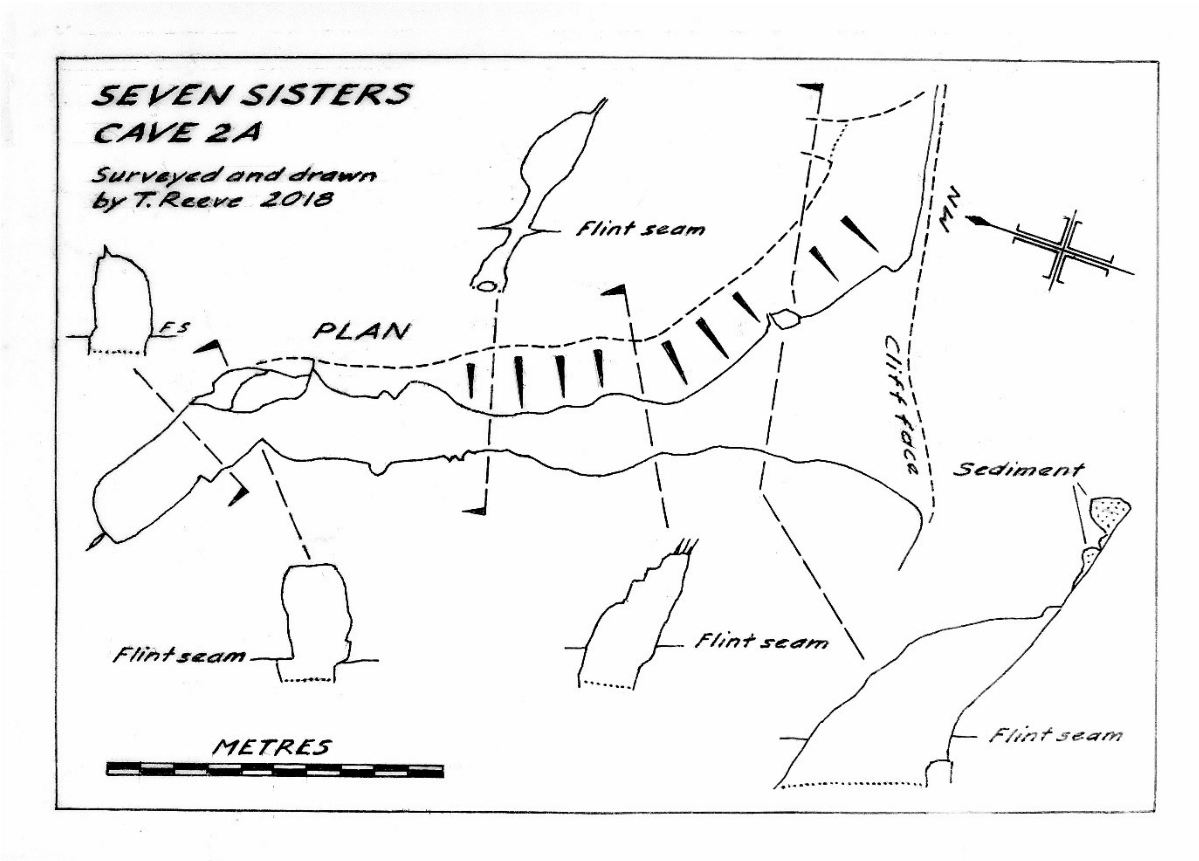
The largest of the newly formed caves was No.3a. This had three entrances and extended parallel to the cliff for 30.5 metres and was formed partly from the eastern side passage of Cave No.3, which had become connected to another chamber and passage that was either created or exposed by further marine erosion at the back of Cave No.4.

These surveys still do not provide a definitive explanation of exactly how these caves were formed but it is interesting to note that marine erosion is far more aggressive at the cliff face than in the cave interiors. This obviously raises the question – how can a cave be formed by marine erosion if the cliff face erodes at a faster rate than the back of the caves? The most likely explanation is that pre-existing isolated caves and large open fissures widened by dissolution, originally formed by inland karst drainage, are being exposed by cliff retreat and consequently enlarged, connected, modified and eventually eroded away by the sea. Cavities and fissures filled with sediments - that must have originated from the overlying Paleogene sediments including Clay-with-Flints and dry valley deposits - can be seen in some of these caves proving that at the very least there was some karstic influence involved in their initial development.

When the area was examined again in 2018 it was found that the entrance chamber and left hand side passage of Cave No.3a had collapsed resulting in the creation of a narrow sea stack about 5 metres high, while the right hand side passage survived as a short arch-like cave piercing a narrow chalk promontory. Cave No.2b had now acquired a third entrance where further erosion of the sloping cliff face had encroached on the roof of the small side passage.


Stack and arch formed from remains of Cave No.3 after a cliff fall

Some of the most interesting changes of 2018 involved Cave No.2a, which had now become the longest in the area at 25 metres even though its entrance passage had already been shortened by 5 metres as a result of cliff retreat. There were now two additional spacious chambers, between 2 and 3 metres wide and 3 to 5 metres high, located beyond the narrow rubble choked constriction that was previously the limit of the cave. Although most of the rubble had now been washed away by the sea, the walls of this constriction showed little evidence of any further enlargement resulting from marine erosion. The roof of this cave contained many small fissures and cavities filled with reddish brown sediment. There was also a sediment- choked cavity, about a metre in diameter, exposed in the cliff face above the entrance. These sediments are probably derived from some shallow dry valley deposits sectioned in the cliff face directly above the cave entrance. The evidence of karstic origin is particularly compelling as it seems inconceivable that a cave of this length and size could have been created purely by marine erosion in the limited time available after the large cliff fall.



Survey of Cave No.2a in 2018

Chamber post-constriction in Cave No.2a in 2018

Seaward view of the constriction in Cave 2A in 2018

Two new caves with enormous entrances (No.2b and No.2c) had also appeared in the cliff below Rough Brow, between Cave no.2a and the site of Cave No.1 (TV530971). These are perhaps best described as large overhung recesses than true caves, in that the widths of the entrances exceed that of their length, but the overall dimensions were very impressive and may be close to the limit of what will hold up in the chalk. That said, they have withstood rough seas and storm conditions for several years without any obvious changes. The largest of these was hastily surveyed and found to be 34 metres wide at the cliff face and went back at least 17 metres and perhaps a little farther, as a steep flint cobble beach was obscuring the true extent of the rear walls at the time. These recesses were probably formed by the sea breaking into pre-existing isolated cave passages or large open fissures running parallel to the cliffs, followed by further marine erosion and progressive collapse.

Cave No.2b in 1993

Several similar features were also noted in May 2018. These were situated beneath Flagstaff Brow, between the dry valleys of Flagstaff Bottom and Gap Bottom (NGR 538967), but not surveyed due to concerns about their stability. They comprised four large openings very close together, each about 20 to 25 metres wide, undercutting the cliff by some 10 to 16 metres. The safety fears were realised a few weeks later when everything collapsed in what was the largest cliff fall to have occurred in recent times and a spectacular video of the event was captured by someone in a passing kayak using a mobile phone. This also illustrates the intermittent nature of coastal erosion in this area because - although about 10 metres of land was lost to the sea in the space of less than a minute - the debris from the fall will probably protect this part of the cliff from any further erosion for many years to come.

OTHER CAVES IN THE AREA

This is not a comprehensive list but includes several caves which provide convincing evidence of karstic rather than marine origins.

CAVES 7, 8 AND 9

A cave entrance (No. 7) had been visible for many years just below the surface of the summit of the second hump of the Seven Sisters known as Baily's Hill (NGR 545966) west of Birling Gap, its shape and size changing each time there was a cliff fall, the width and height varying between 1 and 2 metres. There was also a narrow ledge about 10 metres in length leading up to the entrance, which was obviously the floor of another stretch of passage where the roof and one wall had fallen away. The passage extended into the cliff at an acute angle and although it was never entered, it is estimated that at least 25 metres of passage has been lost to the sea. A sediment filled cavity about a metre wide is all that remains of it today.

In 2018 two more caves, No.8 and No.9 (NGR 54589647), situated in the same fault line - the largest of which measured about 2 metres wide and 3 metres high - were photographed just after they were exposed by a cliff fall. Both of these were almost completely filled with Paleogene or more recent sediments, thus providing indisputable proof of karstic origin despite the sea level location. This obviously strengthens the argument that other sea level caves in the area are of similar origin and perhaps only slightly modified as a result of being exposed to wave action.

CAVE No.1b. (approximate location NGR 5297)
The entrance to this cave is usually buried under a steep flint cobble beach but during a visit in 2019 the beach level had dropped slightly exposing a low crawl about 1 metre wide which gave access to a spacious chamber approximately 3.5 metres wide, 7 metres long and 4 metres high with a chalk rubble floor. This chamber ran parallel to the cliff, from which it was separated by less than 2 metres, ending in a wall of shattered chalk. The cave appears to have formed in a zone of fault breccia consisting of small fragments of chalk in a matrix of dried out chalky mud. Caves of this type form when the breccia is reduced in volume by the solvent action of water flowing through it, eventually resulting in passages which take the shape of the shattered zones within otherwise massive chalk. A prominent flint seam exposed in the cave walls had slumped downwards where it crosses the shattered zone and just below the deepest point of this dip there was a large pocket of brown clay, indicating the presence of a system of cavities capable of transporting overlying sediments to this depth. It is important not to confuse fault breccia with chalk rubble that has run back into caves previously buried behind rock falls.

CAVE No.5
This interesting cave was exposed following a small cliff fall in the late 1970's and subsequently eroded away by further cliff retreat before an accurate survey could be made. It was located in the lowest part of the cliff below Flat Hill Bottom Valley (NGR 542966) and consisted of a chamber about 15 metres long, 7 metres wide and 4 metres high, with a semi-circular cross section and a chalk rubble floor. The chamber ran parallel to the cliff face from which it was separated by less than a metre. The main entrance, about 3 metres wide, was located in the side of a large recess which was probably formed by the collapse of another similar adjoining chamber. A second entrance, about a metre wide, led directly into the end of the cave from the cliff face. The cave development was clearly influenced by an inception horizon at its floor level, in the form of a tabular sheet flint seam 10 to 20 mm in thickness, about a metre above the bottom of the cliff. Several smaller caves and numerous small conduits and anastomoses (also known as tubules), have also been observed at this horizon from time to time.

CAVE No.6
This cave is located below the dry valley known as Flagstaff Bottom (NGR 54029669) about 1¼ kilometres west of Birling Gap and did not exist in any form before 2015. The large entrance, which was 12 metres wide at the cliff face, may have been created suddenly - probably during a storm - when a wall of chalk separating a pre-existing chamber from the cliff face gave way. The passages and chambers to the left of this entrance contained several large domes characteristic of phreatic cave development. Another phreatic feature, situated in the roof of the eastern end of the entrance chamber, consisted of a small oval opening 65 cm long and 30 cm wide. This was almost completely blocked by a large rock wedged between its sides which had obviously fallen from above but by peering through a small gap next to this obstruction with the aid of a torch, it could be seen to widen out into an aven some 1 to 2 metres wide and at least 5 metres high. Further visits during the following year revealed that the entrance chamber had collapsed and that all the debris resulting from this cliff fall had been rapidly washed away by the sea. The collapse had also revealed some additional high level chambers which were probably connected to the aven in the roof above the original

entrance. Part of the floor of these upper chambers had collapsed into the passage underneath leading to the formation of a rock bridge. There are also some shallow dry valley deposits sectioned in the cliff top, the deepest part of which is directly above the cave.

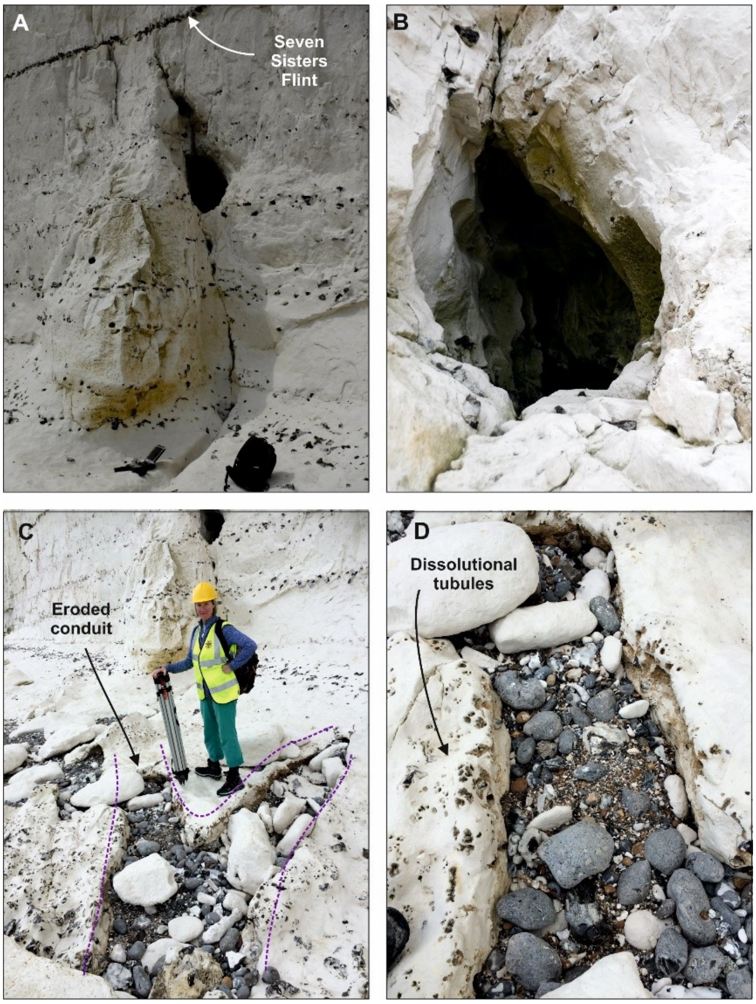
NOTES ON SURVEYS

Most of these surveys involved taking numerous offset measurements from a centre line or in the case of Cave No.1 by offsets from a traverse line around its perimeter. Some of the other large chambers were surveyed using numerous radial measurements and bearings taken from a centre point. Heights were either measured where this was possible or estimated from photographs. Any further research would obviously benefit from the use of GPS and laser scanning methods.

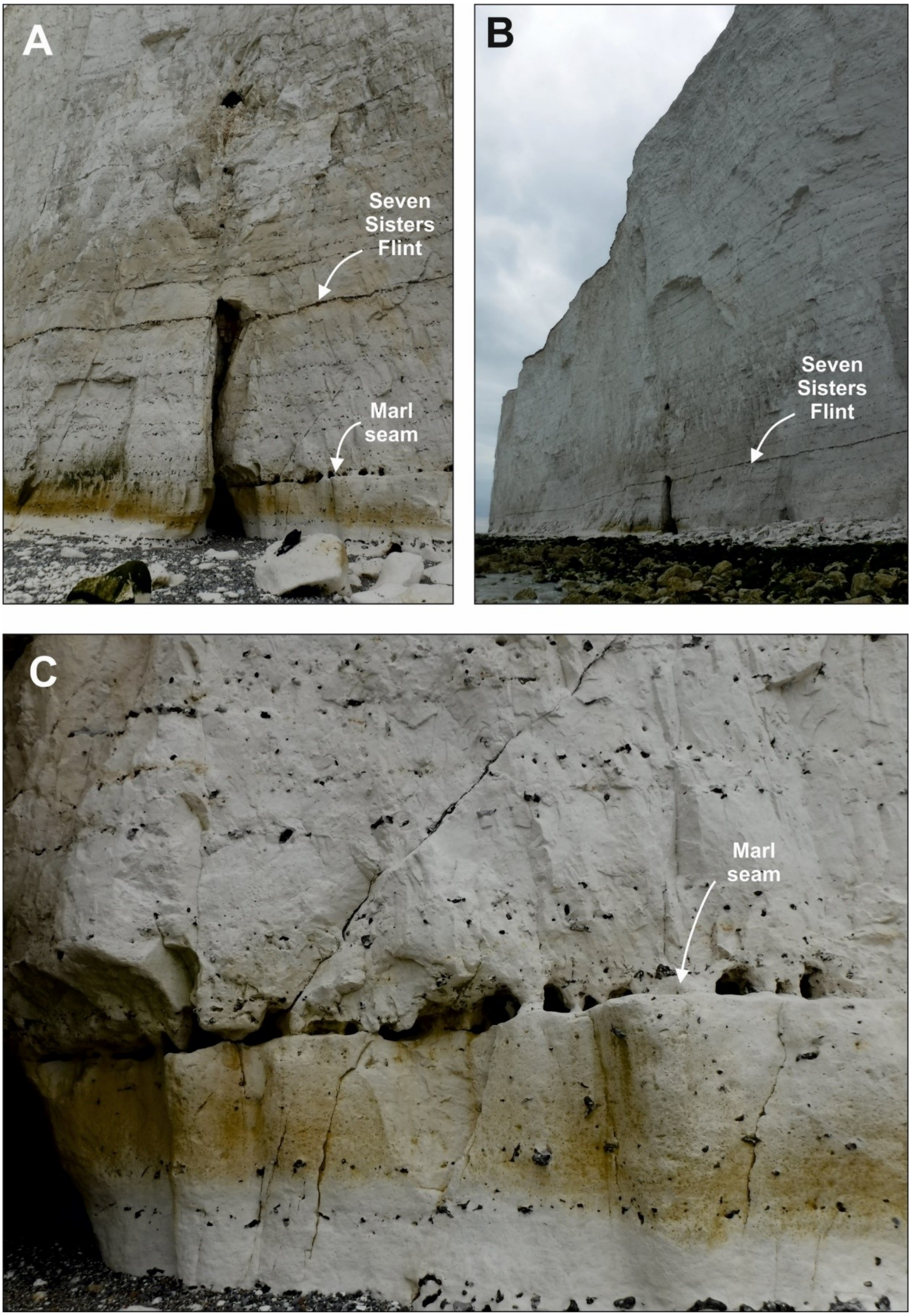
Appendix 3. Some examples of conduits documented by Farrant et al. (2021a,b,c)

Belle tout conduit 1, approx. 0.3 m diameter:

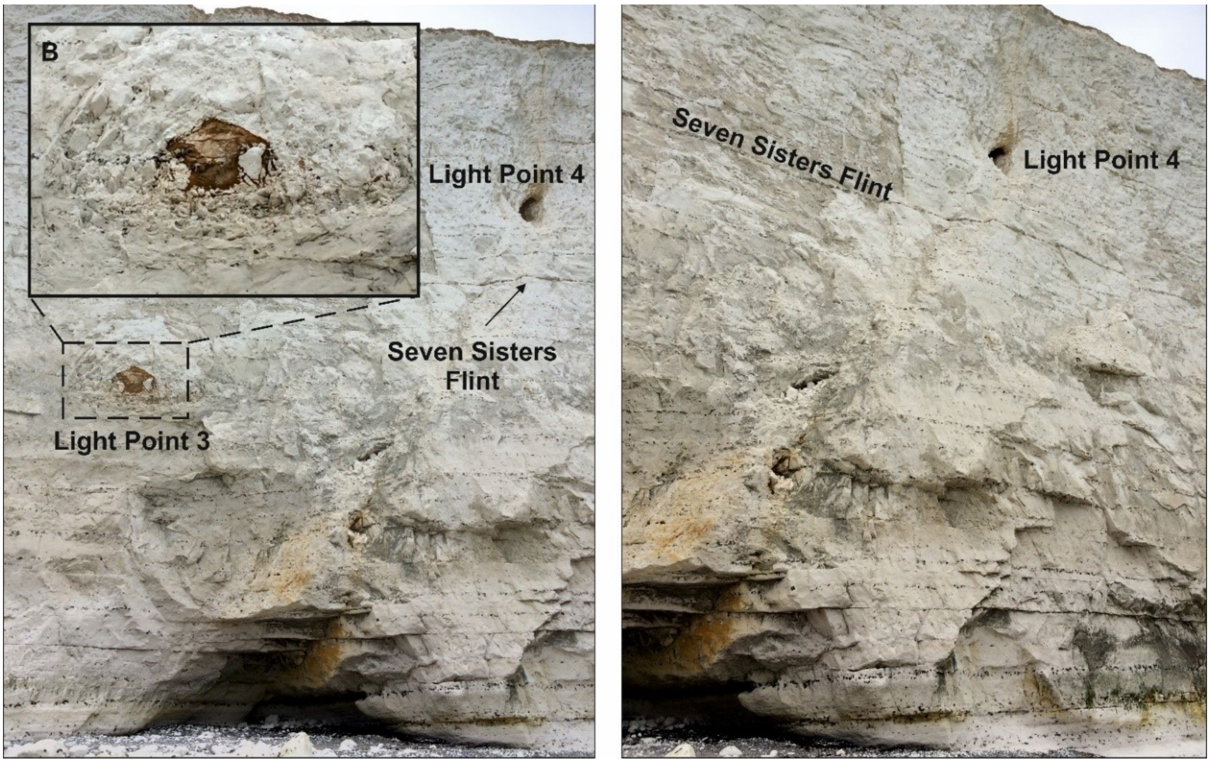
Belle tour conduit 2, approx. 0.4x 0.5 m:



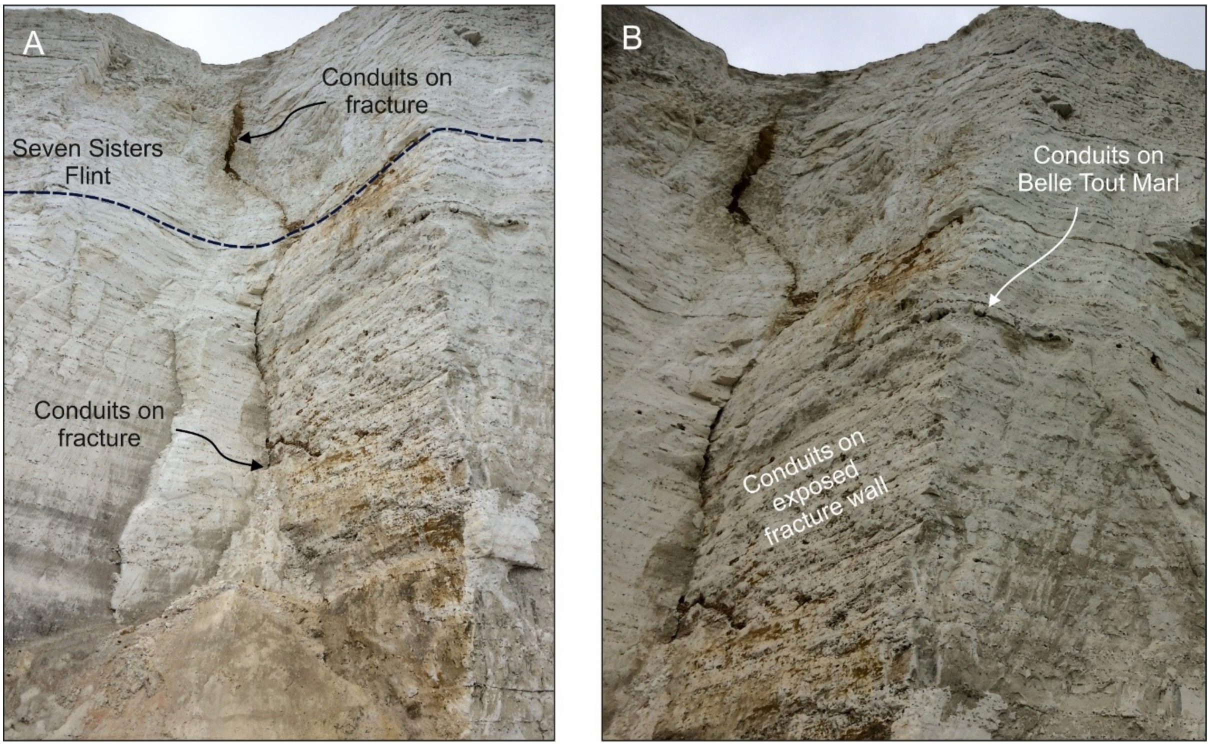
Belle tout conduit 5, cave at base is ~ 4.5 m high, 6 m long, 0.5-1 m wide; upper circular conduit in cliff ~ 0.4 m diameter:



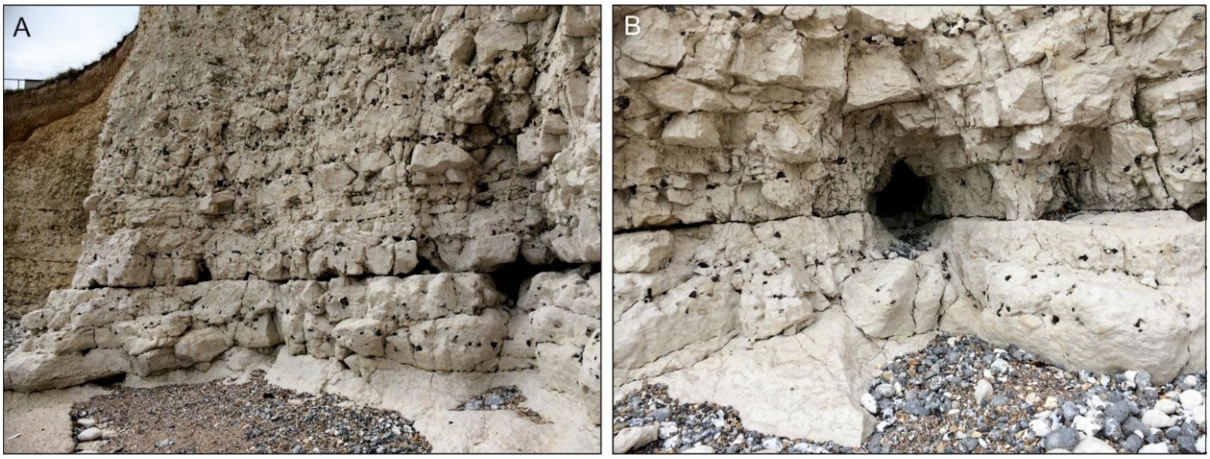
Light point conduits 3 (~ 1m diameter sediment filled, and 4 (~3-4 m high and 2-3 m wide:



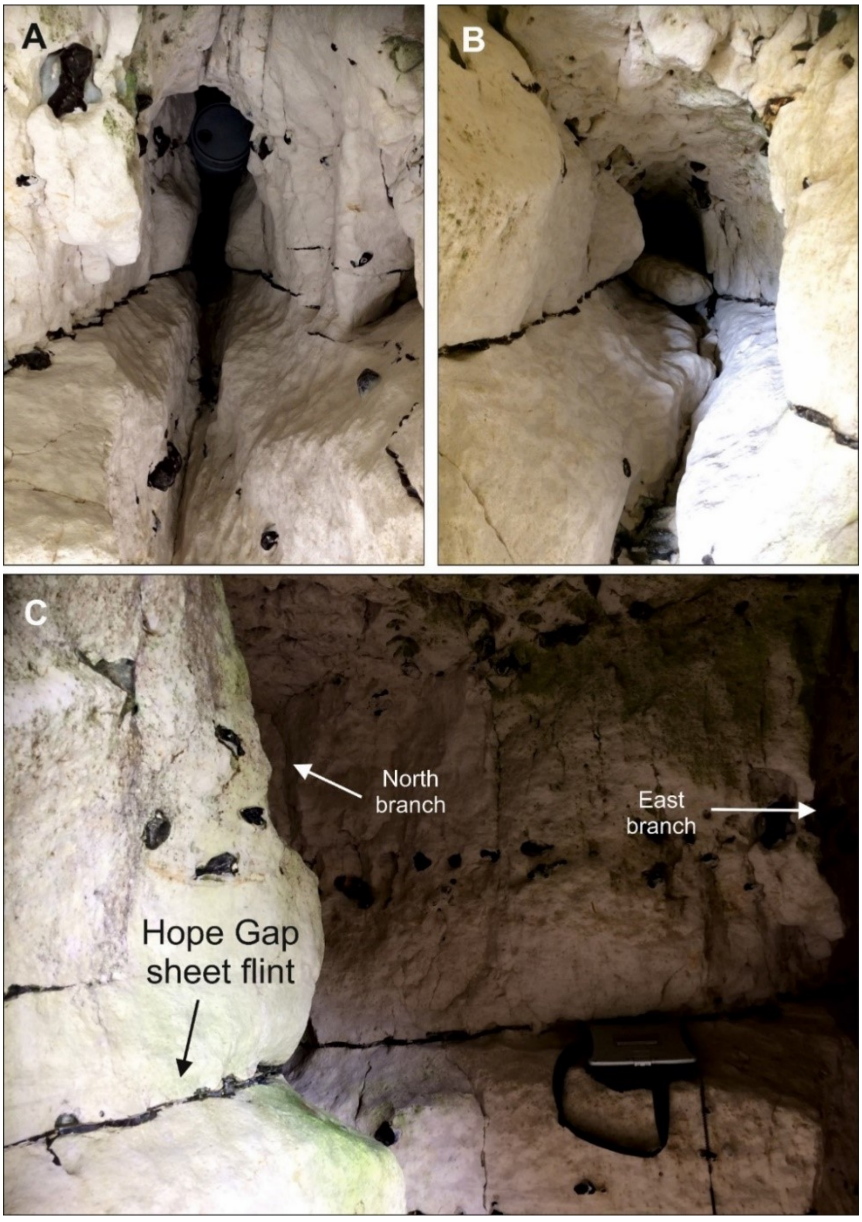
Beachy head conduit 3: many conduits ~ 0.2-0.4 m wide on vertical fracture:



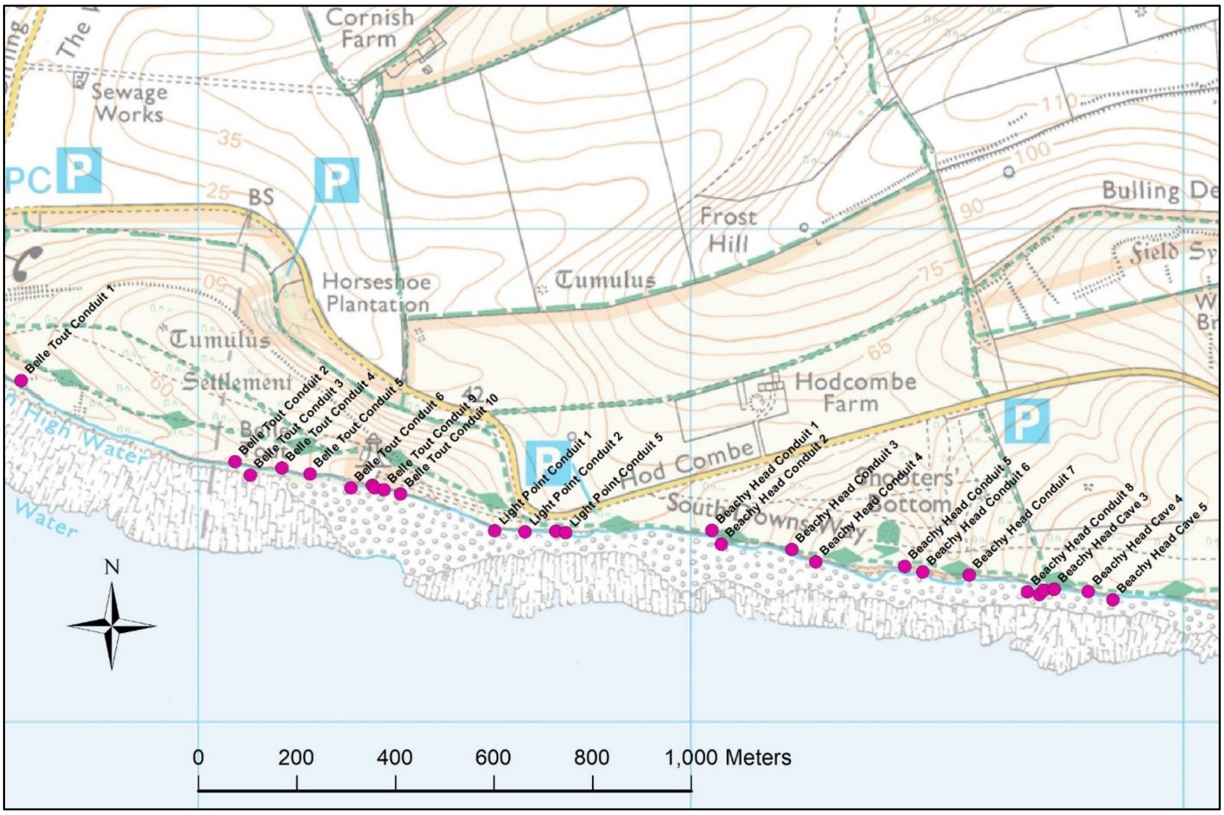
Hope gap conduit 1, zone of many elliptical conduits ~ 0.3 to 0.4 m wide and 0.1 to 0.2 m high:



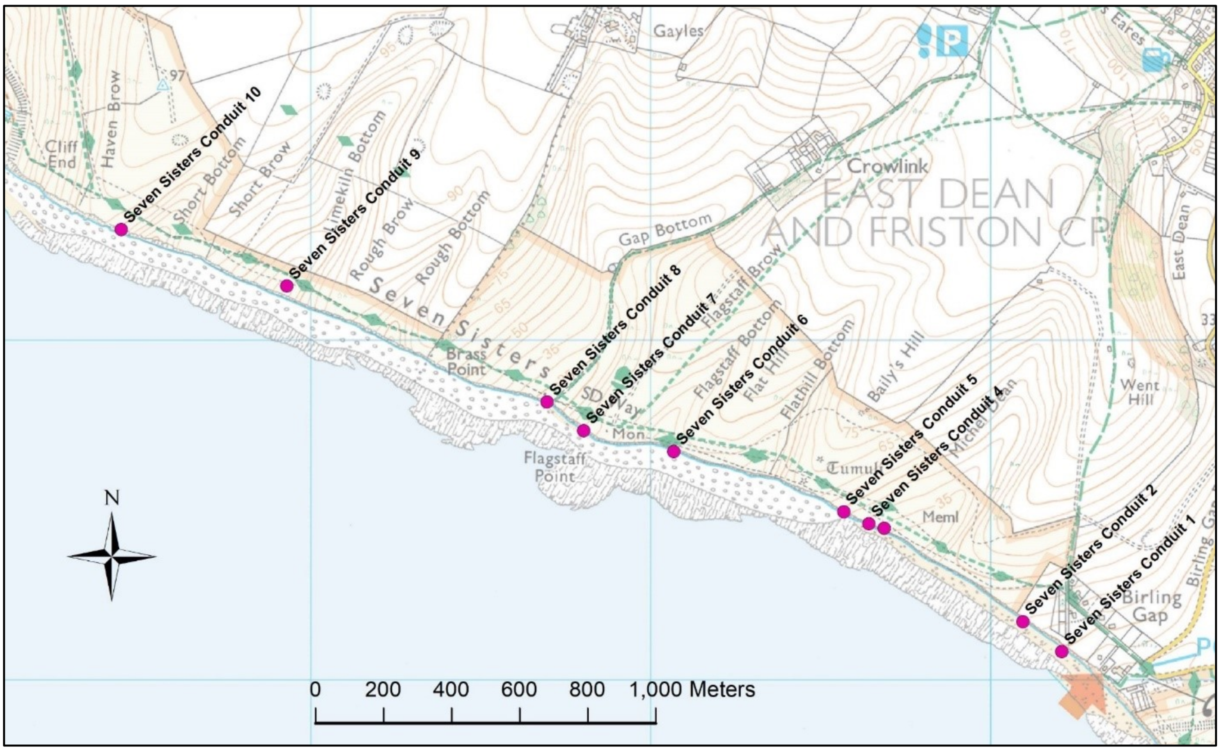
Hope gap conduit 14, cave > 18 m long, probably Seaford Head cave No. 8 from Reeve (Section 2.1 and appendix 1):



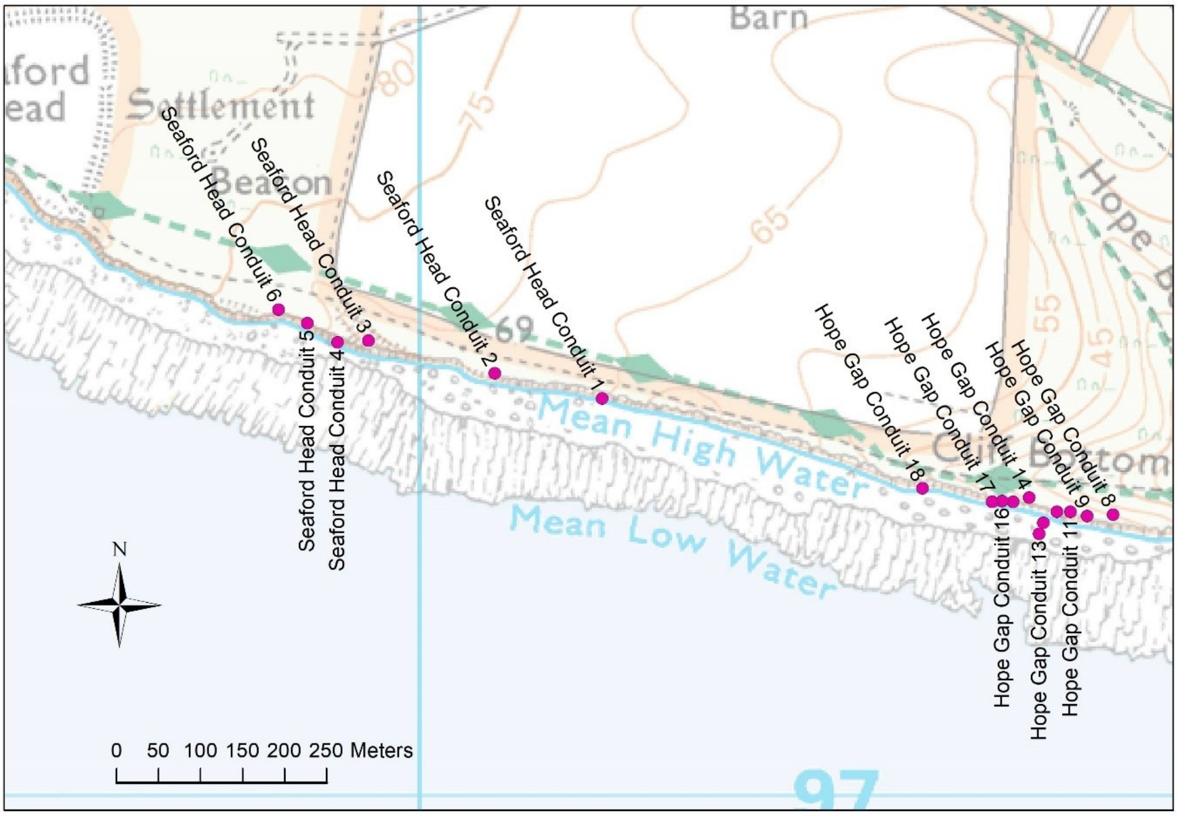
Appendix 4. Locations of caves and conduits observed in 2021 coastal survey (from Farrant et al., 2021a)



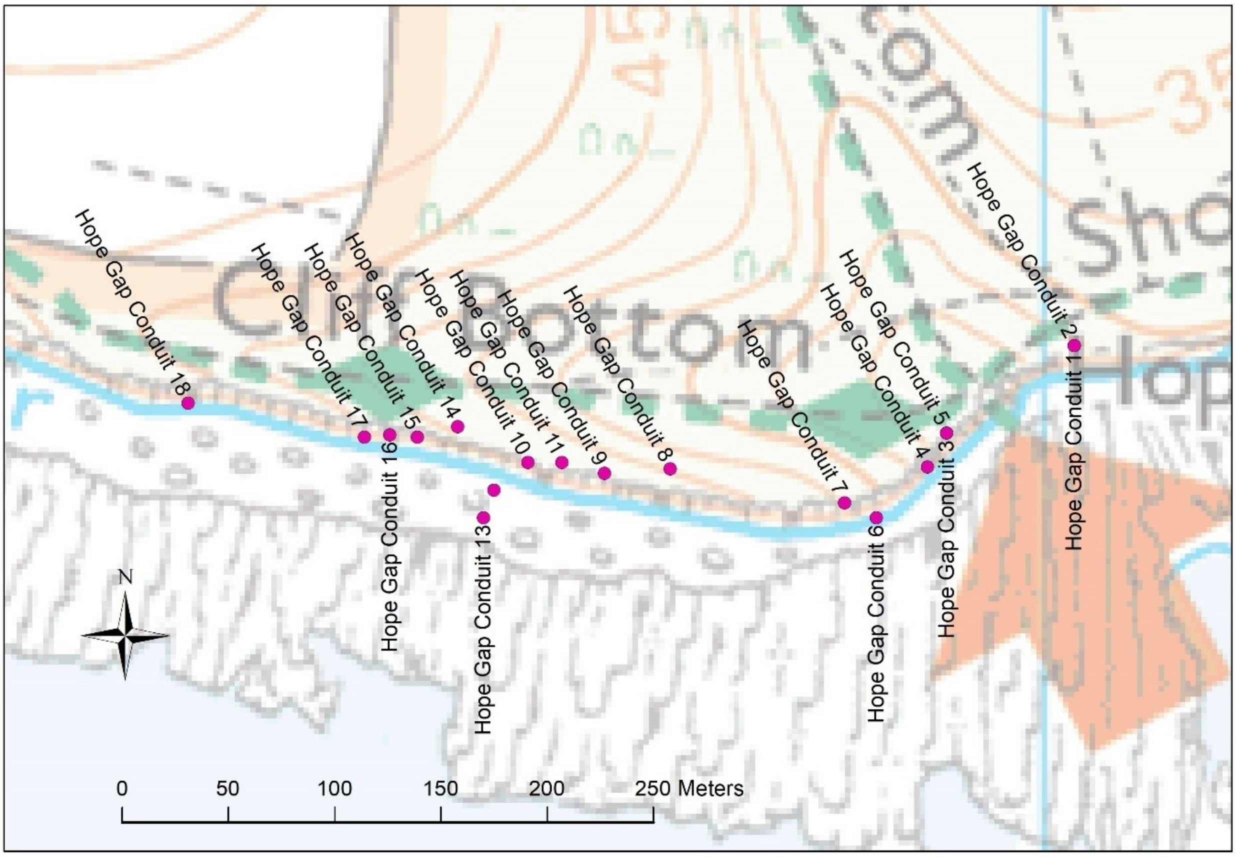
Conduits and caves between Birling Gap (left) and Beachy Head (right). Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.



Conduits and caves between Birling Gap (right) and Cuckmere Haven (left). Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.



Conduits and caves around Seaford Head. Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.



Conduits and caves around Hope Gap. Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.

Appendix 5. Caves and smaller conduits identified during the 2021 BGS coastal survey (Farrant et al., 2021a,b,c)

Name	NGR	Chalk Formation	Stratigraphy (Bed)	Inception horizon	Cave/conduit	Reeve cave name
Belle Tout Conduit 1	555641 95694	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 2	556075 95529	Seaford Chalk	Belle Tout beds	Belle Tout marls	cave	Patricks Rift?
Belle Tout Conduit 3	556106 95502	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 4	556170 95516	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 5	556227 95504	Seaford Chalk	Belle Tout beds	Belle Tout marls	cave	Beachy Head cave 4 and 5
Belle Tout Conduit 6	556310 95476	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 7	556354 95481	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 8	556358 95476	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 9	556377 95472	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 10	556411 95464	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Light Point Conduit 1	556602 95389	Seaford Chalk	Belle Tout beds	Shoreham Marl 2	cave	
Light Point Conduit 2	556664 95387	Seaford Chalk	Belle Tout beds	Shoreham Marl 2	conduit	
Light Point Conduit 3	556726 95388	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Light Point Conduit 4	556746 95385	Seaford Chalk	Cuckmere beds	Fault	conduit	
Light Point Conduit 5	556746 95385	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Beachy Head Conduit 1	557043 95390	Lewes Nodular Chalk	Shoreham beds	Sheet Flint	cave	
Beachy Head Conduit 2	557062 95362	Lewes Nodular Chalk	Shoreham beds	Sheet Flint	conduit	
Beachy Head Conduit 3	557205 95351	Lewes Nodular Chalk	Seaford Chalk	Fault	conduit	
Beachy Head Conduit 4	557254 95326	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Beachy Head Conduit 5	557434 95317	Lewes Nodular Chalk	Cliffe beds	Navigation Marl	conduit	
Beachy Head Conduit 6	557471 95305	Lewes Nodular Chalk	Cliffe beds	Navigation Marl	conduit	
Beachy Head Conduit 7	557565 95299	Lewes Nodular Chalk	Cliffe beds	Navigation Marl	conduit	
Beachy Head Conduit 8	557683 95265	Lewes Nodular Chalk and Seaford Chalk		Fault	conduit	
Beachy Head Conduit 9	557708 95260	Lewes Nodular Chalk and Seaford Chalk		Fault	conduit	

Name	NGR	Chalk Formation	Stratigraphy (Bed)	Inception horizon	Cave/conduit	Reeve cave name
Beachy Head Cave 1	557717 95269	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	conduit	
Beachy Head Cave 2	557737 95270	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	cave	
Beachy Head Cave 3	557737 95270	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	conduit	
Beachy Head Cave 4	557807 95266	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	cave	Beachy Head Cave
Beachy Head Cave 5	557857 95249	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	conduit	
Seven Sisters Conduit 1	555210 96086	Seaford Chalk	Cuckmere beds	Sheet Flint	conduit	
Seven Sisters Conduit 2	555095 96174	Seaford Chalk	Cuckmere beds	Sheet Flint	conduit	
Seven Sisters Conduit 3	554687 96449	Seaford Chalk	Cuckmere beds	Fault	conduit	Seven Sisters cave 2B
Seven Sisters Conduit 4	554642 96462	Seaford Chalk	Cuckmere beds	Fault	conduit	Seven Sisters cave 2A
Seven Sisters Conduit 5	554568 96497	Seaford Chalk	Cuckmere beds	Fault	conduit	
Seven Sisters Conduit 6	554068 96674	Seaford Chalk	Cuckmere beds	joint	conduit	
Seven Sisters Conduit 7	553803 96736	Seaford Chalk	Haven Brow beds	unknown	conduit	
Seven Sisters Conduit 8	553695 96820	Seaford Chalk	Cuckmere beds	joint	conduit	
Seven Sisters Conduit 9	552929 97161	Seaford Chalk	Cuckmere beds	joint	conduit	
Seven Sisters Conduit 10	552442 97327	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Hope Gap Conduit 1	551014 97394	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 2	551014 97394	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 3	550954 97353	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 4	550945 97337	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 5	550954 97353	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	
Hope Gap Conduit 6	550921 97313	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 7	550906 97320	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 8	550824 97336	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	

Name	NGR	Chalk Formation	Stratigraphy (Bed)	Inception horizon	Cave/conduit	Reeve cave name
Hope Gap Conduit 9	550793 97334	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 10	550757 97339	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 11	550773 97339	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 12	550741 97326	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Hope Gap Conduit 13	550736 97313	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 14	550724 97356	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	Seaford Head Cave No. 6
Hope Gap Conduit 15	550705 97351	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 16	550692 97352	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	
Hope Gap Conduit 17	550680 97351	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	Seaford Head Cave no. 3
Hope Gap Conduit 18	550597 97367	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Seaford Head Conduit 1	550216 97474	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Seaford Head Conduit 2	550088 97504	Lewes Nodular Chalk	Seaford Chalk	joint	conduit	
Seaford Head Conduit 3	549938 97543	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Seaford Head Conduit 4	549901 97541	Lewes Nodular Chalk and Seaford Chalk		joint	conduit	
Seaford Head Conduit 5	549865 97564	Lewes Nodular Chalk and Seaford Chalk		joint	conduit	
Seaford Head Conduit 6	549831 97580	Lewes Nodular Chalk and Seaford Chalk		joint	conduit	

Name	NGR	Chalk Formation	Stratigraphy (Bed)	Inception horizon	Cave/conduit	Reeve cave name
Belle Tout Conduit 1	555641 95694	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 2	556075 95529	Seaford Chalk	Belle Tout beds	Belle Tout marls	cave	Patricks Rift?
Belle Tout Conduit 3	556106 95502	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 4	556170 95516	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 5	556227 95504	Seaford Chalk	Belle Tout beds	Belle Tout marls	cave	Beachy Head cave 4 and 5
Belle Tout Conduit 6	556310 95476	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 7	556354 95481	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 8	556358 95476	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 9	556377 95472	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Belle Tout Conduit 10	556411 95464	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Light Point Conduit 1	556602 95389	Seaford Chalk	Belle Tout beds	Shoreham Marl 2	cave	
Light Point Conduit 2	556664 95387	Seaford Chalk	Belle Tout beds	Shoreham Marl 2	conduit	
Light Point Conduit 3	556726 95388	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Light Point Conduit 4	556746 95385	Seaford Chalk	Cuckmere beds	Fault	conduit	
Light Point Conduit 5	556746 95385	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Beachy Head Conduit 1	557043 95390	Lewes Nodular Chalk	Shoreham beds	Sheet Flint	cave	
Beachy Head Conduit 2	557062 95362	Lewes Nodular Chalk	Shoreham beds	Sheet Flint	conduit	
Beachy Head Conduit 3	557205 95351	Lewes Nodular Chalk	Seaford Chalk	Fault	conduit	
Beachy Head Conduit 4	557254 95326	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Beachy Head Conduit 5	557434 95317	Lewes Nodular Chalk	Cliffe beds	Navigation Marl	conduit	
Beachy Head Conduit 6	557471 95305	Lewes Nodular Chalk	Cliffe beds	Navigation Marl	conduit	
Beachy Head Conduit 7	557565 95299	Lewes Nodular Chalk	Cliffe beds	Navigation Marl	conduit	
Beachy Head Conduit 8	557683 95265	Lewes Nodular Chalk and Seaford Chalk		Fault	conduit	
Beachy Head Conduit 9	557708 95260	Lewes Nodular Chalk and Seaford Chalk		Fault	conduit	
Beachy Head Cave 1	557717 95269	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	conduit	
Beachy Head Cave 2	557737 95270	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	cave	
Beachy Head Cave 3	557737 95270	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	conduit	

Name	NGR	Chalk Formation	Stratigraphy (Bed)	Inception horizon	Cave/conduit	Reeve cave name
Beachy Head Cave 4	557807 95266	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	cave	Beachy Head Cave
Beachy Head Cave 5	557857 95249	Lewes Nodular Chalk	Cliffe beds	Sheet Flint	conduit	
Seven Sisters Conduit 1	555210 96086	Seaford Chalk	Cuckmere beds	Sheet Flint	conduit	
Seven Sisters Conduit 2	555095 96174	Seaford Chalk	Cuckmere beds	Sheet Flint	conduit	
Seven Sisters Conduit 3	554687 96449	Seaford Chalk	Cuckmere beds	Fault	conduit	Seven Sisters cave 2B
Seven Sisters Conduit 4	554642 96462	Seaford Chalk	Cuckmere beds	Fault	conduit	Seven Sisters cave 2A
Seven Sisters Conduit 5	554568 96497	Seaford Chalk	Cuckmere beds	Fault	conduit	
Seven Sisters Conduit 6	554068 96674	Seaford Chalk	Cuckmere beds	joint	conduit	
Seven Sisters Conduit 7	553803 96736	Seaford Chalk	Haven Brow beds	unknown	conduit	
Seven Sisters Conduit 8	553695 96820	Seaford Chalk	Cuckmere beds	joint	conduit	
Seven Sisters Conduit 9	552929 97161	Seaford Chalk	Cuckmere beds	joint	conduit	
Seven Sisters Conduit 10	552442 97327	Seaford Chalk	Belle Tout beds	Belle Tout marls	conduit	
Hope Gap Conduit 1	551014 97394	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 2	551014 97394	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 3	550954 97353	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 4	550945 97337	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 5	550954 97353	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	
Hope Gap Conduit 6	550921 97313	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 7	550906 97320	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 8	550824 97336	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 9	550793 97334	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 10	550757 97339	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	

Name	NGR	Chalk Formation	Stratigraphy (Bed)	Inception horizon	Cave/conduit	Reeve cave name
Hope Gap Conduit 11	550773 97339	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 12	550741 97326	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Hope Gap Conduit 13	550736 97313	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 14	550724 97356	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	Seaford Head Cave No. 6
Hope Gap Conduit 15	550705 97351	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Hope Gap Conduit 16	550692 97352	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	
Hope Gap Conduit 17	550680 97351	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	cave	Seaford Head Cave no. 3
Hope Gap Conduit 18	550597 97367	Lewes Nodular Chalk	Beachy Head Zoophycos	Hope Gap sheet flint	conduit	
Seaford Head Conduit 1	550216 97474	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Seaford Head Conduit 2	550088 97504	Lewes Nodular Chalk	Seaford Chalk	joint	conduit	
Seaford Head Conduit 3	549938 97543	Lewes Nodular Chalk	Beachy Head Zoophycos	joint	conduit	
Seaford Head Conduit 4	549901 97541	Lewes Nodular Chalk and Seaford Chalk		joint	conduit	
Seaford Head Conduit 5	549865 97564	Lewes Nodular Chalk and Seaford Chalk		joint	conduit	
Seaford Head Conduit 6	549831 97580	Lewes Nodular Chalk and Seaford Chalk		joint	conduit	

Appendix 6. Pictures of dissolution pipes at Seaford Head (from Terry Reeve)

Large dissolution pipe in the cliff (photo courtesy of Terry Reeve)

Dissolution pipes with sediment filled solutional fissures below (photo courtesy of Terry Reeve)

Looking down at a dissolution pipe from the cliff top (photo courtesy of Terry Reeve)

Looking up at a dissolution pipe from the beach, (photo courtesy of Terry Reeve)

Dissolution pipe with a cavity at the bottom, perhaps where a sediment fill has been eroded away, June 2020 (photo courtesy of Terry Reeve)