Caves and karst of the Chalk in East Sussex, UK: implications for groundwater management

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Abstract

The Upper Cretaceous Chalk of East Sussex is well exposed on the coastal cliff sections between Brighton and Eastbourne. Previous work by Terry Reeve and members of the Chelsea Spelaeological Society identified several caves along the Sussex coast, highlighting the presence of karst. Other evidence of karst comes from active conduits intersected in boreholes and in adits dug for groundwater abstraction, dissolution pipes and cavities encountered in construction projects, and dolines observed on remote sensing data. To understand the extent of cave and conduit development in the Chalk, and how they are related to Chalk lithostratigraphy, a review of the evidence for karst in the area was undertaken, coupled with a detailed survey of the coastal section between Seaford and Eastbourne. Over 50 cave and karst features were identified along the coast, the vast majority being associated with key inception horizons in the Chalk, particularly marl seams and sheet flints. Some are developed on vertical fractures. The data are used to develop a conceptual understanding of Chalk karst and examine the implications for groundwater management.

Keywords. Chalk, Sussex, karst, groundwater, cave, conduit, dissolution.

Introduction

The Upper Cretaceous Chalk outcrop of East Sussex (Figure 1) includes the eastern part of the South Downs National Park. The Chalk forms magnificent coastal exposures between Brighton and Eastbourne, including the iconic Beachy Head (Mortimore 1986, Mortimore, 2011). As well as being of scenic value, the Chalk of the South Downs is also a major aquifer, with several important water supply abstractions in the Seaford and Eastbourne area. Previous work by Terry Reeve and other members of the Chelsea Spelaeological Society (CSS) identified many cave and karst features along the Sussex coast indicating that karst is present in the Chalk. Details of these were published in the Chelsea Spelaeological Society Records (Chelsea Spelaeological Society 1978; 1979; 1982; 1992; 1997; 2010; 2012) with some of the major sites discussed by Reeve (1977, 2021) and Bradshaw et al., (1991). This is likely to impact groundwater flow and increases the potential for groundwater contamination. Karst features, both surface dolines and voids at depth are also important from an engineering perspective. Karst can affect engineering projects, buildings and infrastructure, putting them at risk of differential settlement and collapse. Poor ground conditions associated with karst can impact foundation design, affect cutting stability, and reduce the quality of material for earthworks. The presence of dissolution pipes, rapid flow pathways and conduits can cause issues for tunnelling, with zones of significant water ingress and poor stability. This can severely affect the cost and design of construction projects. This paper reviews the evidence for karst in the East Sussex area, both from surface features identified from geological mapping, construction projects, LiDAR data, and other remote sensing imagery, and from a detailed survey of karst features exposed along the coastal section between Newhaven and Eastbourne.

The eastern part of the South Downs can be divided into several Chalk 'blocks' divided by the major valleys of the Cuckmere River and the River Ouse (Figure 1). The topography is characterised by a primary Chalk escarpment in the north, curving round to the coast at Eastbourne, rising to a maximum elevation of 248 m at Ditchling Beacon. The corresponding dip-slope descends to the south and west, dissected by a dendritic network of dry valleys. The Eastbourne block represents the easternmost extent of the South Downs. It covers the area from Eastbourne to the Cuckmere River, bounded by the coast to the south, and the low-lying Gault Clay lowlands to the north and east. The adjacent Seaford block is bounded by the River Ouse and the Cuckmere River, whilst to the west the Brighton block extends from the River Ouse at Newhaven westwards to the River Adur, and includes the major conurbations of Brighton, Hove and Shoreham-by-Sea.

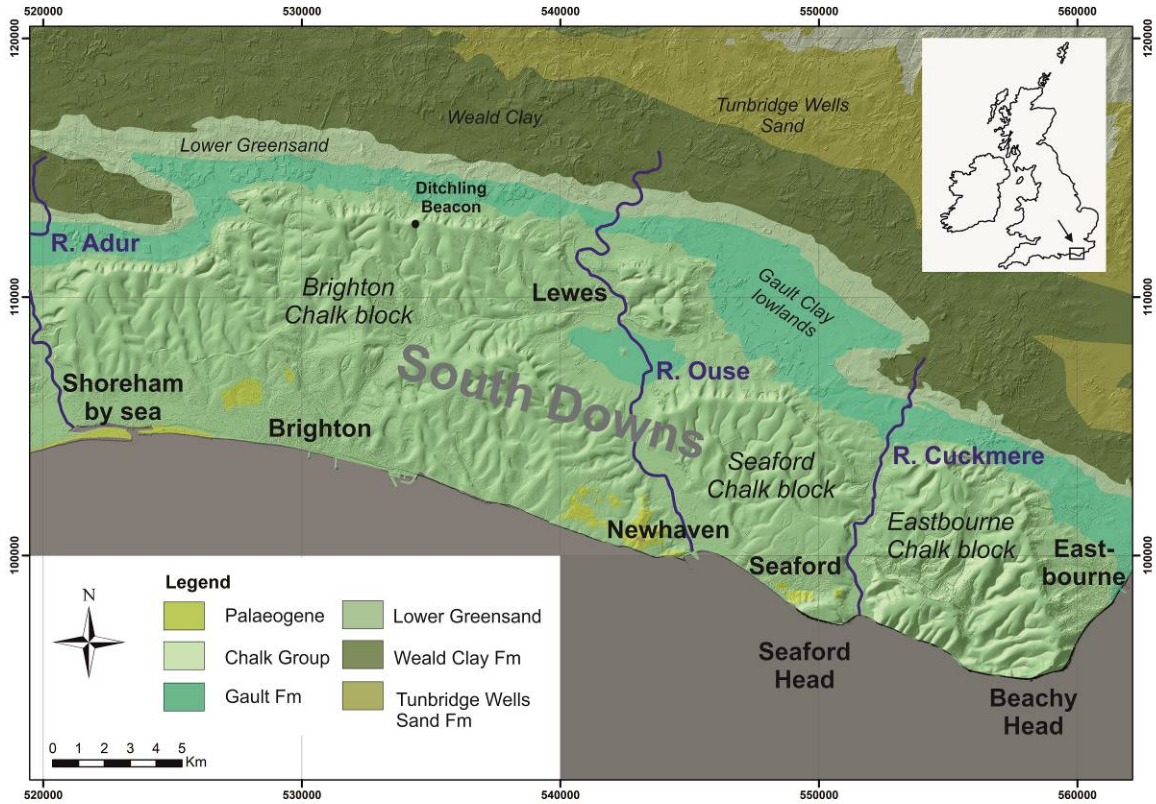

Figure 1. Geological map of East Sussex. Geology is based on BGS 250K scale Geology GB British Geological Survey © UKRI 2021. NEXTMap® Britain elevation data from Intermap Technologies.

Geological setting

The Upper Cretaceous Chalk Group crops out extensively in southern and eastern England, where it varies between about 200 and 560 m in total thickness. Mainly it comprises pure fine-grained microporous limestones, although with important variations in clay content, hardness, texture, fossil content and occurrence of flint. These lithological variations influence the engineering and hydrogeological properties of the Chalk (Mortimore, 1993; Warren and Mortimore, 2003; Mortimore, 2011) and its topographical expression (Aldiss et al., 2012). As well as these lithological variations, the Chalk Group also contains numerous regionally extensive stratigraphical discontinuities (Figure 2). These are important for groundwater flow as they may act as potential conduit inception horizons (Lowe, 2000; Lowe and Gunn, 1995, 1997; Gallagher et al., 2012; Gaillard et al., 2018; Ballesteros et al., 2020; Nehme et al., 2020; Farrant et al., 2021). These include hardgrounds, marl seams, and various types of flint bands (semi-tabular, nodular and sheet-flints). Some are local in extent, locally arranged in complex 3D geometries; others are more regional in scale or are basin-wide features (Woods, 2015; Mortimore, 2018). Unlike joints and faults, these stratigraphical discontinues may extend laterally for many kilometres, offering potential long-distance groundwater flow pathways.

The South Downs have developed on the southern limb of the Weald anticlinorium, extending from Eastbourne west to Winchester. However, until the early 1990s, geological maps of the South Downs showed just two divisions in the Chalk Group (Figure 1): the ‘Lower Chalk’ Formation and the undivided ‘Middle & Upper Chalk’ formations (Young et al., 1988). Mortimore (1986) demonstrated that the Chalk Group in the South Downs could be subdivided into many more lithostratigraphical units (Figure 2), each with different engineering and hydrogeological properties. More recent geological mapping demonstrated that these lithostratigraphical units were associated with distinct topographical features in the landscape and could be mapped accordingly (Aldiss et al., 2012). This led to the adoption of a revised Chalk stratigraphy for the southern Chalk province (Rawson et al 2001; Hopson, 2005). The Chalk Group is currently subdivided into nine formations that can be mapped consistently across southern England including the South Downs (Figure 2). These formations can be further subdivided into units (members and beds) based on distinct marker horizons, mainly marl seams, sponge beds and flint bands. Some of these marker beds can be traced right across the Anglo-Paris basin.

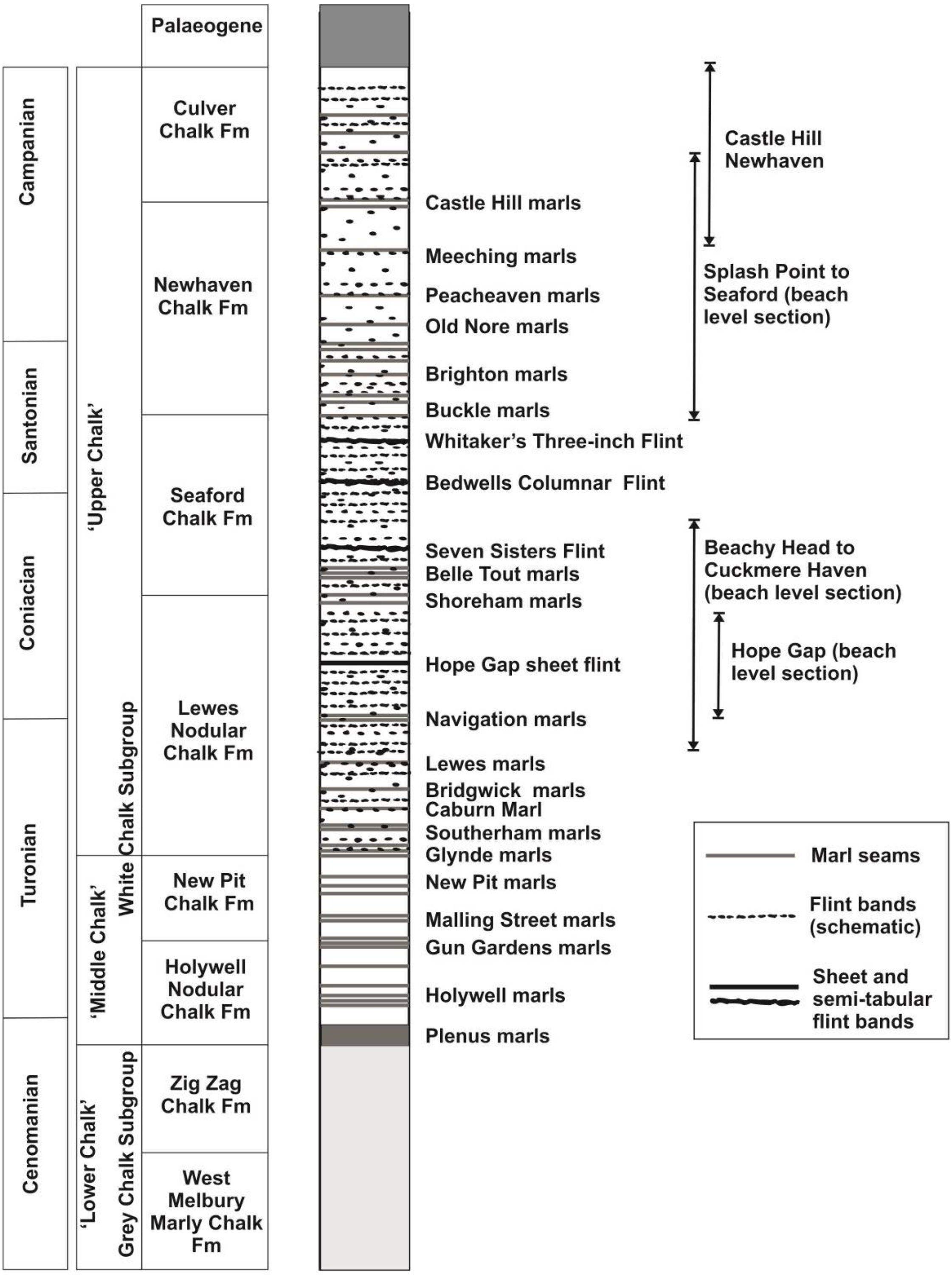

Figure 2 Stratigraphy of the Chalk of the East Sussex showing key marl bands and flints. Not to scale.

The adoption of this revised stratigraphy has important consequences for the understanding of Chalk karst and the impacts on groundwater behaviour. Firstly, cave and karst features identified on the coast, in quarries, road cuttings and boreholes can be related to distinct stratigraphical horizons allowing inferences to be made about possible lithological guidance of conduits and caves (Gallagher et al., 2012, Ballesteros et al., 2020). Secondly, the revised mapping has led to an improved understanding of the geological structure, and its possible effects upon groundwater flow. Moreover, the existence of a high resolution stratigraphy for the Chalk enables detailed analysis and interpretation (and correlation) of borehole logs and related geophysics. This means karst features observed in boreholes and road cuttings can placed within a robust lithostratigraphical framework.

In East Sussex, eight out of the nine Chalk Group formations can be recognised and mapped; the Portsdown Chalk being cut out by the basal Palaeogene erosion surface (Figs 3 and 4). The dip is generally towards the south or south-southwest, but locally interrupted by several west–east-trending folds, notably a syncline just north of Seaford Head, the Kingston Anticline between Lewes and Brighton, and the Hollingbury Dome (Mortimore 1986).

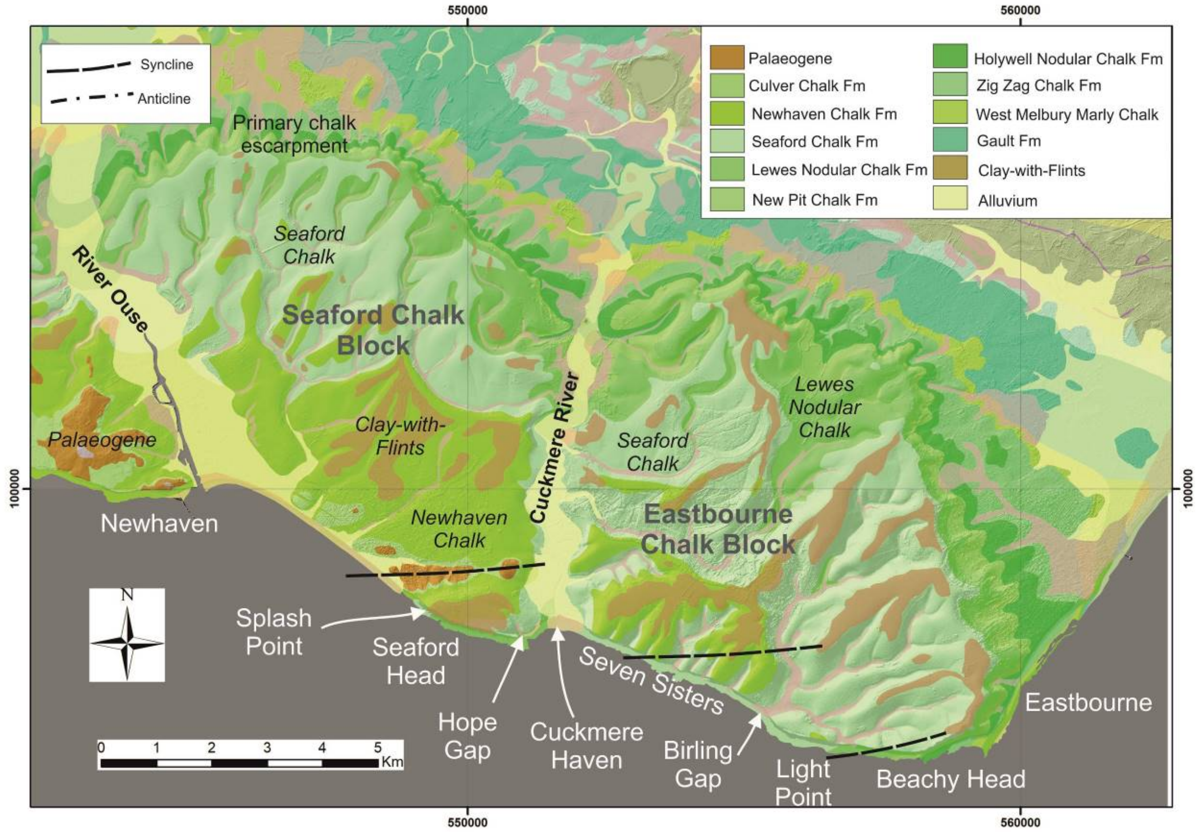

Figure 3. Geology of the Seaford and Eastbourne chalk blocks. Geology is BGS Geology 1:50,000 scale bedrock and superficial data. British Geological Survey © UKRI 2021. NEXTMap® Britain elevation data from Intermap Technologies. For a more detailed key, see https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

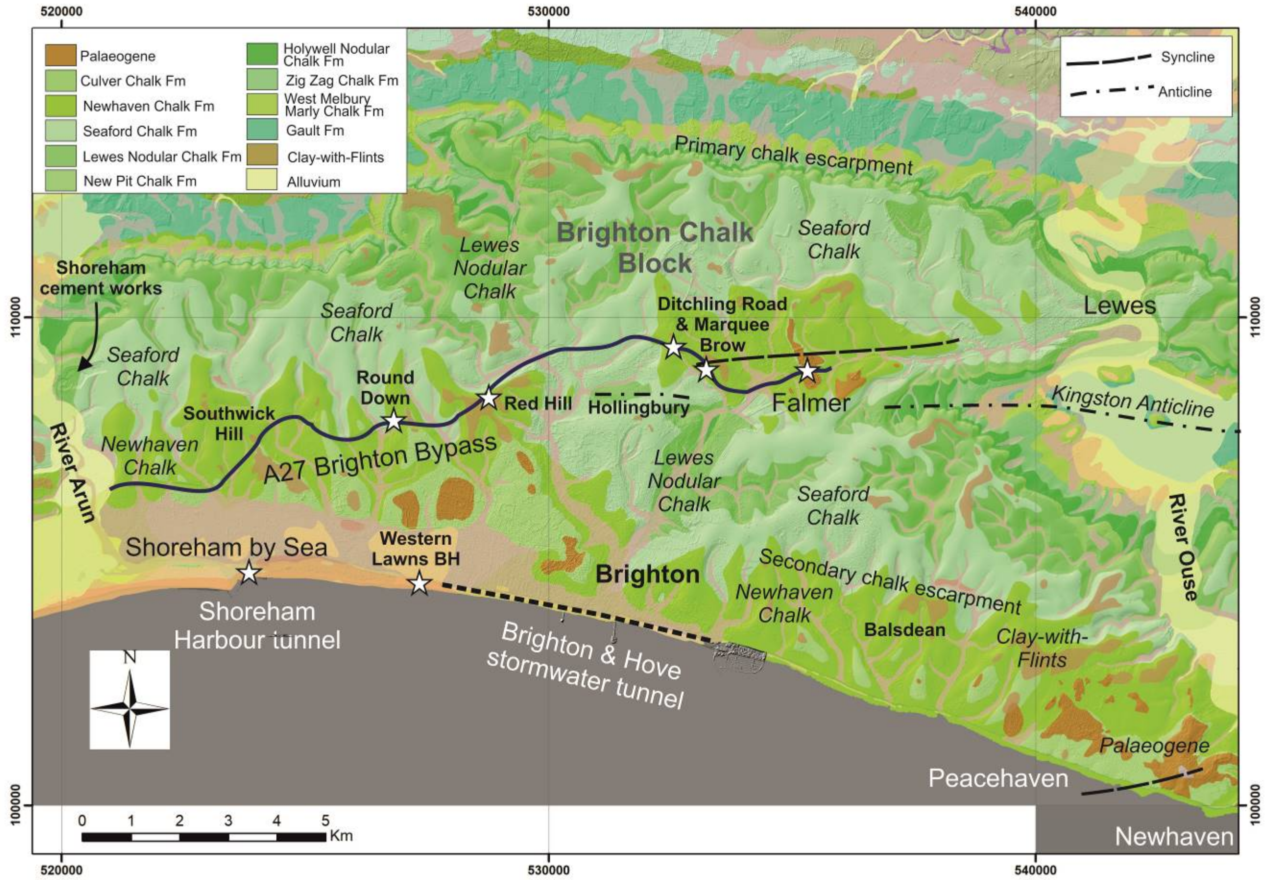

Figure 4 Geology of the Brighton chalk block. Geology is BGS Geology 1:50,000 scale bedrock and superficial data. British Geological Survey © UKRI 2021. NEXTMap® Britain elevation data from Intermap Technologies. For a more detailed key, see https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

The Gault Formation and Grey Chalk Subgroup crop out along the north side of the South Downs at the base of the main scarp; the Upper Greensand Formation being largely absent in this area except around Eastbourne. The main face of the South Downs escarpment is formed by the Holywell Nodular Chalk, New Pit Chalk and Lewes Nodular Chalk formations, with the Holywell Nodular Chalk forming a prominent topographical bench near the base. The Seaford Chalk caps the majority of the escarpment and much of the dip-slope to the south and west, with the Lewes Nodular Chalk locally forming re-entrants and inliers in the upper reaches of the dip slope dry valley networks. Overlying the Seaford Chalk is the Newhaven Chalk, which crops out in the south of the region, forming a secondary escarpment between Shoreham and the Cuckmere valley. The crest of the secondary escarpment is capped by the younger Culver Chalk Formation, commonly cropping out as outliers on the interfluves between the dry valleys near the coast. The Palaeogene Lambeth Group locally overlies the Chalk Group unconformably, cropping out farther south along the coast around Newhaven, Peacehaven, between Brighton and Shoreham-by-Sea, and farther east in the core of a syncline just north of Seaford Head.

Much of the succession is well exposed on the coast between Brighton and Eastbourne. The Eastbourne to Beachy Head section exposes the succession from the base of the Chalk Group at Eastbourne rising stratigraphically westwards through the Grey Chalk Subgroup, the Holywell Nodular Chalk and New Pit Chalk formations to the Lewes Nodular Chalk Formation at Beachy Head.

The upper Lewes Nodular Chalk and the Seaford Chalk formations descend to beach level between Beachy Head and Cuckmere Haven, forming the spectacular cliffs known as the Seven Sisters. To the west of Cuckmere Haven, the upper part of the Chalk succession from the Hope Gap hardground (upper Lewes Nodular Chalk) to the top of the Newhaven Chalk Formation is exposed around Seaford Head (Hampton et al., 2007). The upper Newhaven and Culver Chalk formations form the cliffs between Newhaven and Brighton.

Superficial deposits, notably the Clay-with-Flints on the interfluves, head, and alluvium in the valleys, locally overlie the Chalk. The Clay-with-Flints is a remanié deposit, comprising reddish-brown clay with stained flints, typically a few metres thick, derived from the overlying Palaeogene strata. Its outcrop marks the extent of the Palaeogene erosion surface. Locally river terrace deposits are present in some of the larger valleys. The thickness and distribution of the superficial deposits have an important influence on the distribution of karst features.

Chalk karst

Karst features occur quite widely on the Chalk (MacDonald et al., 1998; Edmunds, 2008; Maurice et al., 2021; Reeve, 2021), with surface dolines, buried dolines (dissolution pipes), dry valleys, stream sinks, large springs and caves all being recorded. Tracer test and other hydrogeological data indicate instances of rapid groundwater flow and high transmissivities typical of karst aquifers (Atkinson and Smith, 1974; Banks et al., 1995; Robins et al., 1999; Maurice et al., 2006, 2010). In East Sussex, although stream sinks and large springs are absent, there is still plenty of evidence of karst, both at the surface and in the subsurface.

Surface karst

There are many surface depressions across the Chalk outcrop in East Sussex, but field evidence and interpretation of LiDAR data (Figure 5) suggest that the majority of these are anthropogenic. The large size, irregular shape, and steep sides of many of these depressions suggests that, rather than being dolines, they are likely to be old chalk pits dug for agricultural purposes. They are unlikely to be collapse dolines (Waltham et al., 2005) as they are much larger than the largest known subsurface voids in the chalk, which are rarely more than a few metres across. Larger solution and suffosion dolines (Waltham et al., 2005) can form without the need for large subsurface voids, but in the Chalk, they tend to be rapidly infilled by sediment as they develop, creating buried dolines or dissolution pipes. The largest commonly occur close to the margins of the overlying Palaeogene deposits, such as those on Southover Heath in Dorset (Waltham et al., 1997), particularly where the Palaeogene deposits are sand-rich. In East Sussex, the lack of Palaeogene outliers and the relatively small extent of the Clay-with-Flints precludes extensive doline formation. Those that do occur are typically much smaller, more subdued features. They can be hard to distinguish from old pits that have been ploughed in.

Chalk pits are scattered across the region, but clusters occur in and around the Clay-with-Flints outcrop, where chalk was dug to neutralise the acidic clay soils. Some of the smaller, more subdued, depressions may be natural; however, there have been few site-specific investigations, and many may simply be old pits that are now ploughed in. A few features identified on LiDAR data are dewponds, distinguishable by their raised rims. Previous geological field mapping (BGS, 2006) suggests there are very few, if any, natural surface dolines in the area. Neither the Applied Geology Natural Cavities database (Farrant and Cooper, 2008; Cooper et al., 2011), nor the Chelsea Spelaeological Society databases have records of dolines in the area.

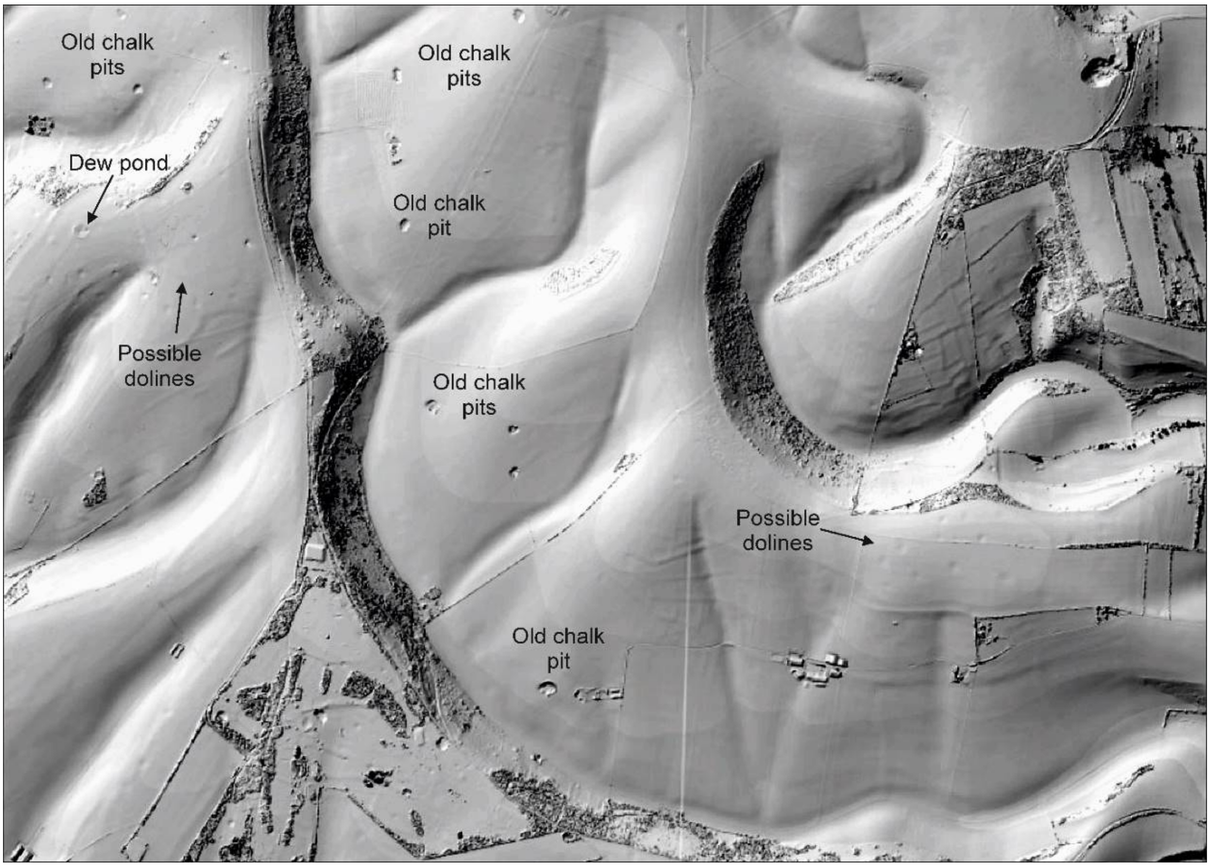

Figure 5. LiDAR image of part of the Seaford chalk block, showing numerous surface depressions, most of which are old chalk pits. LiDAR data ©Environment Agency.

Buried dolines (Waltham et al., 2005), also known as dissolution pipes, have been recorded from numerous localities. These are formed by dissolution at the rock-head beneath overlying non-carbonate permeable deposits. In East Sussex, these are usually the Clay-with-Flints or river terrace deposits. Dissolution occurs at the contact between the sediment and the underlying chalk where aggressive recharge passing through the permeable superficial deposits meets the chalk, usually focussed below leakage points through the cover. This creates a void that gradually enlarges downwards. Sediment continues to slump into the void as the pipe develops, rather than being filled with sediment at a later stage. Dissolution continues, focussed on the base of pipe where aggressive water passing down through the sediment fill meets the chalk. The result is a cylindrical sediment-filled pipe typically a few metres across and up to 10-15 m deep. Most are known from road cutting and coastal sections, with just a few recorded elsewhere. This is partly due to a lack of observations, because most dissolution pipes present little or no surface expression. The construction of the A27 Brighton Bypass north of Brighton (Mortimore, 2012) revealed many buried dolines. Several clusters were noted, notably in the Falmer cutting, in the north abutments for the A27 Ditchling Road arch bridge, and beneath the interfluves at Red Hill, Round Hill and Southwick Hill (Figure 4). The presence of dissolution pipes and infilled derived from the Clay-with-Flints had an impact during the construction of the bypass, resulting in a 37% loss of suitable material for earthworks in the Red Hill cutting, and a 10% loss in the Round Hill cutting (Mortimore, 2012). At the Marquee Brow cutting, a cavity filled with cross-bedded sands floored by a sheet flint was exposed. Dissolution pipes exposed in the A27 Falmer cutting in the late 1970s began to fail soon after completion of the cuttings. To stabilise the slopes, the pipes had to be excavated and packed with rock-filled gabions (Mortimore, 2012). Taylor et al., (2018) described a sediment-infilled dissolution pipe/conduit at a site on the west-facing slope of an interfluve near Falmer, northeast of Brighton.

Many dissolution pipes occur beneath the Clay-with-Flints at Seaford Head (Figure 6), where they are exposed along the top of the cliff. A kilometre farther east, eroded remnants of dissolution pipes are scattered across the intertidal wave-cut platform between Hope Gap and Cuckmere Haven (Robinson, 2020). These pipes developed beneath fluvial river terrace deposits, which cap the adjacent cliff section. Secondary cementation of the chalk surrounding the dissolution pipes has made the chalk more resistant to erosion. Most of the pipes have since been exposed and largely removed by cliff retreat, leaving behind stubs of resistant chalk on the foreshore. This has created a series of chalk 'doughnuts' on the marine platform (Figure 7), with an eroded core where the sediment fill used to be. These observations indicate that dissolution pipes are common in areas underlain by superficial deposits, in particular the Clay-with-Flints and river terraces. It is probable that many dissolution pipes are present beneath the Clay-with-Flints elsewhere on the South Downs. These are likely to be up to ~10 m deep and contribute to a highly irregular rockhead. The spatial density of such features can range from as high as 265/ha to fewer than 30/ha (Robins and Dance, 2003).

Figure 6. Dissolution pipes infilled with reddish brown sediments developed beneath the Clay-with-Flints, forming an irregular rock-head at the top of the cliff, Seaford Head. Cliff height ~70 m.

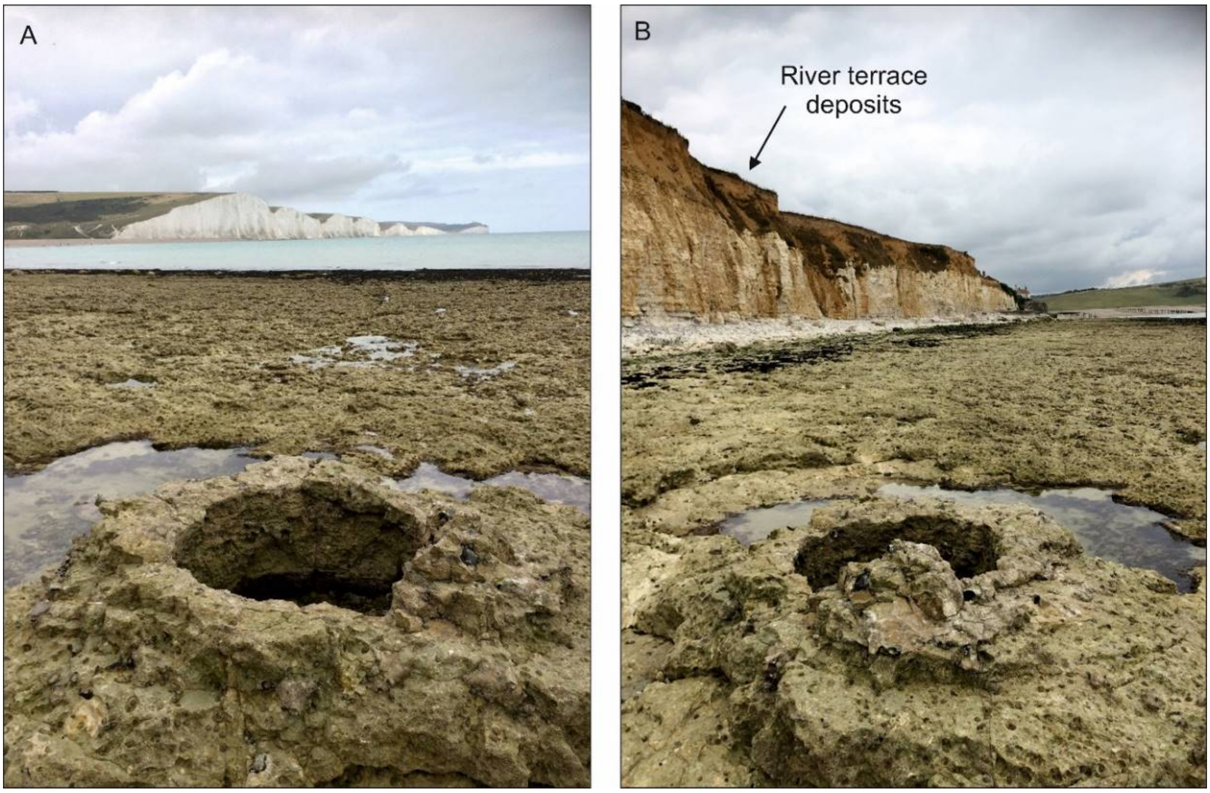

Figure 7. Eroded remnants of dissolution pipes exposed on the foreshore at Hope Gap. **A** is a view looking east to the Seven Sisters, with a relict dissolution pipe 'doughnut'. **B** is a similar feature, with the river terrace deposits exposed in the cliff behind. The pipes extended down from the base of these deposits to below the level of the current wave-cut platform.

Springs

Large springs are a common indicator of well-integrated conduit networks. Such springs are common in the South Downs (Edmunds, 1928), the largest being at Bedhampton near Portsmouth, at the eastern end of the Portsdown Anticline. These are among the largest groundwater springs in northern Europe. The average discharge for the entire group of springs is about 113,000 m^3d^{-1} (Jones and Robins, 1999). Tracer tests have proved links to stream sinks on the northern limb of the Chichester Syncline near Horndean (Atkinson and Smith, 1974; Maurice et al., 2021). However, relatively few large springs occur in East Sussex, partly because of the limited size of the Chalk outcrop, which is split into smaller topographical blocks, more-diffuse recharge and the extensive coastal outcrops, which allow groundwater to drain directly to the sea. Most springs occur at the base of the Chalk escarpment at the contact with the underlying Gault Formation. A few springs occur at the level of the Plenus Marls at the base of the Holywell Nodular Chalk, notably the eponymous Holy Well near Eastbourne. During a thermal infrared line-scan survey, Headworth and Fox (1986) recorded many springs along the foreshore within the intertidal zone, particularly on the wave-cut platform to the east of Brighton.

Caves and conduits

Members of the Chelsea Spelaeological Society identified several cave and karst features along the Sussex coast, including more than 20 caves between Birling Gap and the Beachy Head lighthouse (Reeve, 1977; Chelsea Spelaeological Society, 1979, 1982, 2012; Bradshaw et al., 1991; Reeve 2021; Maurice et al., 2021). Only the larger enterable caves were recorded and surveyed (Table 1).

Whereas topographically they are well surveyed, only limited stratigraphical information is included, and the sites do not have accurate grid references. Most of the caves recorded by the Chelsea Spelaeological Society occur at the base of the cliff between Seaford Head and Hope Gap, at Beachy Head, and around Splash Point near Seaford.

Cave	**Location**	**Length**	**CSS Vol**	**Comment**
Beachy Head Cave	Beachy Head	354 m	9, 11, 22.	Longest known English chalk cave.
Cave No. 1	Beachy Head			This cave is about 3 m above the beach and consists of two small chambers connected by a crawl
Beachy Head Cave No. 3	Beachy Head		9	
Beachy Head Cave No. 4 & 5	Beachy Head			Two cave entrances developed along the same vertical fracture.
Cave No.6a	Beachy Head		26	Passage parallel to cliff, now destroyed
Patrick's Rift	Beachy Head	28 m	9	Passage aligned along a strong joint inclined 10 degrees from the vertical
Seven Sisters Cave	Seven Sisters	1 m	22	Several fragments of a sediment filled cave running parallel to the cliff, now truncated by marine erosion.
Seaford Head Cave	Seaford Head	10 m	23	West side of Cuckmere Haven.
Cave at Seaford Head No. 1	Seaford Head	~14 m	9	
Cave at Seaford Head No. 2	Seaford Head	~22 m	9	Now destroyed. Possibly at Splash Point
Cave at Seaford Head 3A	Seaford Head	~16	9	Relict phreatic conduit
Cave at Seaford Head 3B	Seaford Head	~13 m	9	Relict phreatic conduit
Cave at Seaford Head No. 5	Seaford Head	~11 m	9	Relict phreatic conduit
Cave at Seaford Head No. 6	Seaford Head	~18 m	9	Conduit with two branches on sheet flint
Cave at Seaford Head No. 7	Seaford Head	~16 m	9	Was 24m in length, shortened by 8m after a cliff fall
Cave at Seaford Head No. 8	Seaford Head		9	Several small tubes on a sheet flint
Brian's Burrow	Birling Gap		9	A short phreatic cave about 10 m long to a blockage

Table 1. Significant caves recorded by Terry Reeve (pers. comm. 2017).

Of these, the longest, with over 350 m of surveyed passage, is Beachy Head Cave (Figure 8). It is located near the base of the cliff, approximately 200 m west of Beachy Head at ~5 m above sea level (Waltham et al., 1997; Reeve, 2021). The cave comprises a relict phreatic tube approximately 1 m in diameter, developed largely on a sheet flint in the Lewes Nodular Chalk Formation, 3-4 m above the Navigation Marl, with the passage zigzagging along the joints. Earthy sediments or flint nodules cover the passage floor. Cliff collapse has partially truncated the main passage, splitting the cave into two parts. Sharp changes in the level of the passages seem to coincide with displacement of the flint by minor faulting. The eastern end of the cave contains a small stream, which forms the end of the explored cave at a sump.

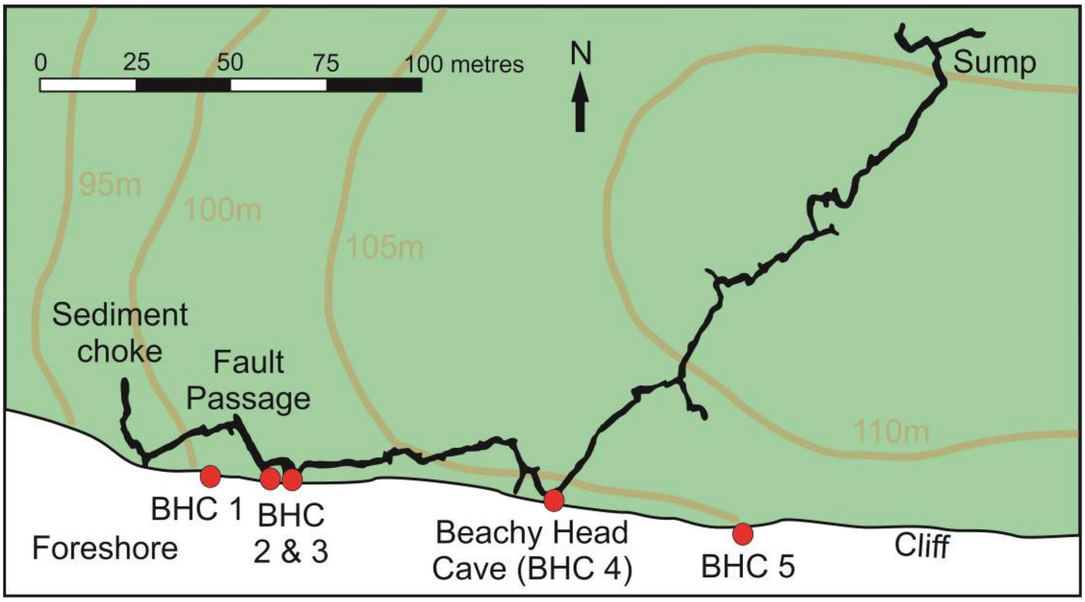

Figure 8 Survey of Beachy Head Cave (adapted from Waltham et al., 1997, after Reeve, 1979). Contains Ordnance Survey data © Crown Copyright and database rights 2021.

Other small caves occur elsewhere. In the northeast corner of the Shoreham Cement Works quarry near Upper Beeding, a series of relict phreatic conduits occur along a fault plane cutting through the lower Seaford Chalk. Most are sediment filled, but some are open voids up to c. 0.8 m in diameter, locally lined with speleothem. The largest void occurs where the fault cuts the Seven Sisters Flint in the lower Seaford Chalk.

Many of the caves and conduits seen in quarries and along the coast are associated with 'dissolution tubules' (Lamont-Black and Mortimore, 2000). These comprise complex anastomosing or dendritic networks of small dissolutional voids and conduits approximately 1-50 mm in diameter (Figure 9). They are common above major discontinuities such as sub-horizontal sheet flints, marl seams, hardgrounds and major fractures. They usually occur in a zone a few centimetres to a metre thick above the discontinuity, but extending laterally for tens to hundreds of metres. Larger, more integrated, anastomosing conduit networks and locally small caves occur embedded within these tubule zones (Figure 10). These small dissolutional openings form a highly porous, very transmissive spongework or 'Swiss cheese'-like texture in the Chalk. Numerous examples occur along the coast, in particular associated with the Hope Gap sheet flint and the Beachy Head sheet flint in the Lewes Nodular Chalk, and on marl seams. Construction of the A27 Brighton Bypass road cuttings in the Marquee Brow to Ditchling Road section revealed numerous examples (Mortimore, 2012). Similar examples occur in the Shoreham Cement Works quarry at Upper Beeding. Lamont-Black and Mortimore (2000) suggest that they form by mixing dissolution (Bögli, 1964) along stratigraphical inception horizons.

Figure 9. Dissolution tubules above a sheet flint, upper Lewes Nodular Chalk, Hope Gap, Seaford. Hammer head is c. 20 cm for scale.

Figure 10. View looking vertically up at the underside of a chalk bed overlying a tabular sheet flint, which has fallen away revealing a spongework zone with many dissolution tubules developed immediately above. A complex network of anastomosing conduits is embedded within the zone of dissolution tubules. Lewes Nodular Chalk, Beachy Head.

Some site investigation works on major infrastructure projects have revealed active conduits. Mortimore (2012) describes groundwater flow horizons associated with karstic conduits exposed during construction of the Brighton and Hove Stormwater Tunnel (Figure 4). Several major ingresses of water occurred during the construction of seven access shafts sunk to facilitate the excavation of the tunnel. In the Black Rock Shaft, face logs indicated many slightly open (20-30 mm) conduits developed along sub-horizontal joints, with the main ingress of groundwater from a sub-horizontal sheet flint in the upper part of the Seaford Chalk (Haven Brow beds). In the Madeira B Shaft, the presence of open (20 mm) sub-horizontal joints in the basal Newhaven Chalk Formation led to major inflows that required four submersible pumps working at an estimated rate of 9600 l min^{-1} to keep the shaft from flooding. Similarly, in the Norfolk Shaft, most inflows were associated with open conduits up to 35 mm high at the junction between inclined conjugate fractures/minor faults and marl seams in the basal part of the Newhaven Chalk Formation, particularly at 20-30 m depth, causing flooding of the shaft. During construction, a sudden influx of brown, sediment-laden, water occurred at the base of the shaft, attributed to the interception of a sediment-filled cavity. Observations indicated an inflow of water of 7560 l min^{-1} to the shaft (Mortimore, 2012). The groundwater flows measured in the shafts bore little resemblance to those anticipated from the results of packer testing during the site investigation.

Saline intrusion

The coastal setting of the Chalk in East Sussex and the intensive use of the aquifer make it susceptible to saline intrusion (Jones and Robins, 1999). Many groundwater abstraction and observation wells in the Brighton–Seaford area record elevated conductivity values associated with the ingress of salt water. Some boreholes show a simple rise and fall in salinity according to the tides, others display complex patterns demonstrating rapid movement of saline water through the aquifer, probably via karstic conduits. Analyses of the data from boreholes (Robins et al., 1999) suggest that there is no conventional Ghyben–Herzberg interface between fresh and salt water along the coast. The data suggest that the salinity response is particular to each borehole, depending upon its connectivity to the sea, which is influenced by the distribution of fractures and conduits to which it is connected. Consequently, the susceptibility to saline intrusion of an inland borehole might be greater than that of a borehole nearer the coast. Some respond almost instantly to changes in the tides, indicating the presence of rapid flow pathways. Moreover, large variations in fluid conductivity can occur between boreholes only a short distance apart, again suggesting that fracture and conduit connectivity are important.

Logging of individual boreholes suggests saline intrusion occurs along specific fractures. Jones and Robins (1999) give several examples. In the Western Lawns Borehole in Brighton, conductivity logs indicated that saline water enters the borehole at high tide via an enlarged fracture at 130 m depth, probably leaving the borehole via a fracture at 66 m. Reverse flow occurs during the falling tide, with fresh water leaving via the fractures at 114 and 130 m depth. Similarly, in the east of the Brighton block, pumping at the Balsdean Source, about 2.5 km from the sea, induces a rapid salinity response particularly at high tide. This suggests there is likely to be a direct connection between Balsdean and the sea (Warren, 1967), probably along a karstic conduit or open fracture. In the Seaford chalk block, an abstraction site 2.5 km inland has suffered very high chloride concentrations (up to 6300 mg l^{-1}) in the past (Jones and Robins, 1999).

Transmissivity values and hydraulic gradients.

Jones and Robins (1999) provide details of the transmissivity distribution across the South Downs. Values range from less than 50 to over 5000 m^2 per day. The Seaford Chalk block in particular has unusually high transmissivities. This area also has a notably flat hydraulic gradient; groundwater levels recorded in boreholes close to the centre of the block over 4 km from the coast are only 1 to 2 m above sea level. This implies rapid groundwater outflows and short ground-water retention times. The high transmissivity and flat hydraulic gradient suggest that a well-integrated network of dissolutionally enlarged fractures and conduits is present. The combination of low hydraulic gradients and large variations in Chalk topography can create an unsaturated zone more than 100 m thick in interfluve areas.

Borehole data

Analysis of downhole CCTV data, temperature and flow logs, and borehole dilution tests from abstraction and groundwater observation boreholes (Jones and Robins, 1999; Gallagher et al., 2012; Farrant et al., 2021a, 2021b, Farrant et al, in press), indicate that the majority of water abstraction boreholes in the Chalk, including those in East Sussex, expose one or more dissolutional conduits ~5-20 cm in diameter. Borehole dilution tests, flow logging and downhole video data suggest that many of these are flowing actively. Similar discrete point inputs have been observed in adits dug for water supply. These can yield large flows with discharges up to 174 l/s (Downing et al., 1993; Worthington et al., 2000). The CCTV data coupled with geophysical logs suggest these flow horizons are commonly associated with particular stratigraphical horizons, especially sheet flints, marl seams and hardgrounds, or with open vertical or conjugate joint sets.

Coastal survey

To understand the spatial and stratigraphical distribution of karst features in the Chalk, a detailed survey of exposed caves and conduits along the coastal section between Seaford and Eastbourne was undertaken in July 2020. A total of 54 conduits (or groups of conduits) and caves were identified. A few additional features may be present beneath areas of rock-fall or buried by shingle. For each site, the location, plus details of the feature and the stratigraphical horizon are recorded. Some are the same features previously identified by Reeve (2021), but the lack of precise location data for these and the effects of coastal erosion make it difficult to correlate observed features with those identified previously.

The observed karst features occur in three distinct groups: those between Birling Gap and Beachy Head; those between Birling Gap and Cuckmere Haven; and those between Hope Gap and Seaford (Figure 1). Most of the features observed are small, relict, phreatic conduits (aligned on sheet flints or marl seams) or enlarged vertical or sub-vertical fractures (Figure 11).

Figure 11. Relict phreatic conduit c. 20 cm across developed at the intersection of the Navigation Marl and a minor fault, Lewes Nodular Chalk, Beachy Head. Smaller conduits guided by the marl occur on either side.

Caves and conduits between Birling Gap and Eastbourne

The section at beach level at Birling Gap is on a minor syncline in the lower part of the Seaford Chalk, just above the Seven Sisters Flint (Cuckmere Beds of Mortimore, 1986). Eastwards the section passes down into Belle Tout beds, the upper Lewes Nodular Chalk below the Belle Tout Lighthouse, and down to the basal Lewes Nodular Chalk at the Beachy Head Lighthouse. Twenty-eight conduits and small caves occur in this area (Figure 12), plus a small spring farther east at Holywell. These are listed below. Photographs of the features are available in the supplementary information on the BCRA website at xxx.

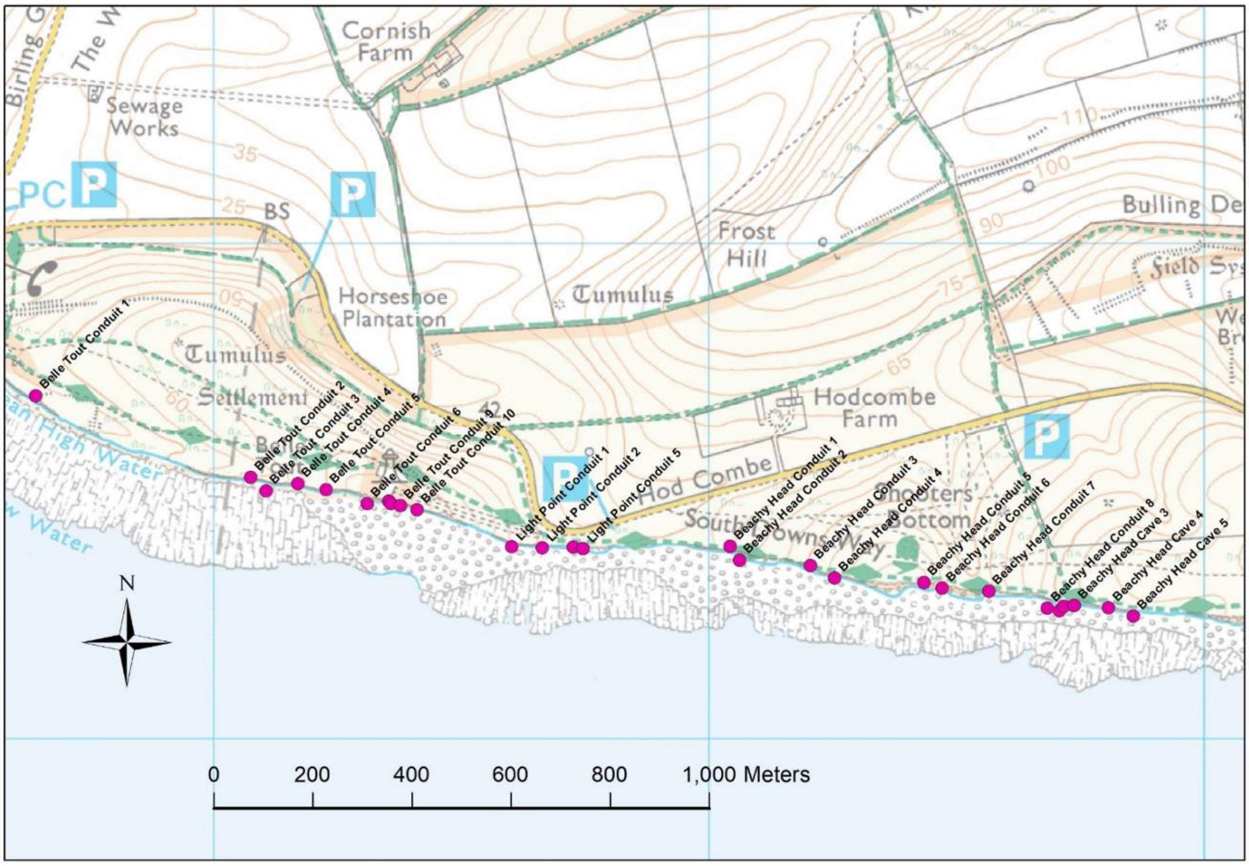

Figure 12. Conduits and caves between Birling Gap (left) and Beachy Head (right). Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.

Belle Tout Conduit 1. NGR 555641 95694. 860 m SE of Birling Gap, 270 m west of Belle Tout Lighthouse. This is a small conduit truncated by cliff retreat, developed on thin sheet flint in the Seaford Chalk, just above the Seven Sisters Flint. The conduit is ~0.3 m diameter, and is associated with a zone of dissolution tubules 0.3 m thick extending along the cliff for c. 10 m. Small conduits up to 0.1 m diameter occur within the tubule zone on the sheet flint.

Belle Tout Conduit 2. NGR 556075 95529, 860 m SE of Birling Gap, 270 m west of Belle Tout Lighthouse. This is a small phreatic conduit c. 0.4 m wide and 0.5 m high, developed on an inclined joint in the Belle Tout Beds (Seaford Chalk) just below the Seven Sisters Flint, 3 m above beach level. Smaller conduits occur on the same joint below the main cave. On the foreshore in front of the cave are the eroded remnants of a bifurcating conduit, with evidence of secondary cementation and hardening along the conduit walls in a 2-3 cm-thick zone with dissolution tubules.

Belle Tout Conduit 3. NGR 556106 95502, 900 m SE of Birling Gap, 240 m west of Belle Tout Lighthouse. This is a series of small conduits at beach level 45 m east of Belle Tout Conduit 2, developed on the uppermost Belle Tout Marl, c. 4 m below the Seven Sisters Flint. Several small conduits occur over a 2 m stretch along the marl seam. The conduits are small, up to 0.2 m high, with well-defined dissolution tubules. The chalk surrounding the conduits appears to be secondarily cemented and slightly more resistant to erosion. The conduits might be associated with a prominent vertical fracture.

Belle Tout Conduit 4. NGR 556170 95516, 960 m SE of Birling Gap, 170 m west of Belle Tout Lighthouse. This is a series of small, probably interlinked, conduits up to 0.25 m high at beach level, again developed on the uppermost Belle Tout Marl, c. 4 m below the Seven Sisters Flint. The conduits occur over a width of about three metres. Around the conduits the chalk is slightly harder than the surrounding rock, appearing possibly to be secondarily cemented and slightly more resistant to erosion.

Belle Tout Conduit 5 (Patrick's Rift?). NGR 556227 95504, 990 m SE of Birling Gap, 120 m west of Belle Tout Lighthouse. This is a large rift about 6 m long, 1 m wide at base, and at least 4-5 m high developed on a significant joint. The rift is about 1 m wide at beach level, narrowing to 0.5 m wide higher up. The top of cave is at the level of the Seven Sisters Flint. Several small openings occur higher in the cliff face on the same fracture, one of which is c. 0.4 m in diameter. The cave is associated with smaller conduits aligned on the uppermost Belle Tout Marl, the same marl as other conduits to the west. These conduits are typically 0.2 m high and 0.1-0.2 m wide, and they occur in a zone 5-10 m wide along the marl seam. One conduit, 0.3 m in diameter but blocked by pebbles, occurs 2.5 m lower at beach level, developed on the next lower Belle Tout Marl. Considering that its roof is formed on the Seven Sisters Flint, this cave may be Patrick's Rift (Reeve, 2021).

Belle Tout Conduit 6. NGR 556310 95476, 1.08 km SE of Birling Gap, 60 m SW of Belle Tout Lighthouse. This is a series of small conduits 0.2-0.3 m diameter developed on a thin marl at beach level, the lowest of the three Belle Tout marls, stratigraphically a few metres lower than caves to the west. The conduits occur over a 5-10 m-wide stretch of cliff at 1-2 m spacing. The largest conduit is at the intersection of an inclined conjugate fracture with the marl seam. Small dissolution tubules occur in a thin zone immediately above the hanging wall of the fracture.

Belle Tout Conduit 7. NGR 556354 95481, 1.11 km SE of Birling Gap, 50 m south of Belle Tout Lighthouse. This rift cave is formed on a prominent vertical fracture that extends up to the top of the cliff. The enterable cave at beach level is c. 2-3 m long, 1 m wide at its base, but typically 0.4-0.6 m wide, and c. 6 m high. The lower Belle Tout Marl forms the base of the cave, with the choked rift (0.2-0.4 m wide) extending up to the Seven Sisters Flint. The fracture extends to the cliff top, with some evidence of dissolution and clay infill. There is evidence of horizontal dissolutional conduits 0.2-0.3 m in diameter on both of the upper two Belle Tout marls.

Belle Tout Conduit 8. NGR 556358 95476, 1.13 km SE of Birling Gap, 50 m SE of Belle Tout Lighthouse. This is a possible phreatic cave at beach level, choked with flint cobbles. The conduit is 0.3-0.4 m wide (widened by marine erosion), developed on the second Belle Tout Marl, c. 5 m below the Seven Sisters Flint. There is a minor vertical fracture with no dissolution above.

Belle Tout Conduit 9. NGR 556377 95472, 1.14 km SE of Birling Gap, 70 m SE of Belle Tout Lighthouse. This is a small phreatic cave 2.5 m above beach level, developed on the intersection of a conjugate vertical fracture and the second (middle) Belle Tout Marl. The conduit is c. 0.4 m wide and 0.6 m high, narrowing upwards. The cave is inaccessible from beach level, so the length is unknown.

Belle Tout Conduit 10. NGR 556411 95464, 1.17 km SE of Birling Gap, 90 m SE of Belle Tout Lighthouse. This is a short cave at beach level (possibly widened by marine erosion), developed on a vertical fracture extending most of the way up the cliff. There is evidence of small dissolution conduits/tubules at various elevations, locally sediment-filled. The cave is estimated to be 2-3 m long, 0.4 m wide and 0.4 m high at beach level. It is choked with flint cobbles. The cave tapers upwards into an inaccessible fissure a few centimetres wide.

Light Point Conduit 1. NGR 556602 95389, 275 m SE of Belle Tout Lighthouse at Light Point. This is a dissolutionally enlarged vertical fracture c.10 m high and 10-15 m long forming part of the cliff face. There is evidence of extensive dissolution along the fracture surface, and a small cave at beach level

c. 2-3 m long and up to 0.5 m wide where the fracture enters the cliff. Associated horizontal conduits occur on a thin sheet flint and a marl seam just above beach level, probably the Shoreham Marl 2. These are associated with dissolution tubules. The sea has widened part of the conduit to create an obvious cave 3-4 m wide, 1.5 m high and 4 m deep, 1.5 m above beach level, the floor of which is on the Shoreham Marl 2. The back of the cave closes down to a series of small conduits along the marl.

Light Point Conduit 2. NGR 556664 95387, 335 m SE of Belle Tout Lighthouse at Light Point. Light Point Conduit 2 is a zone of many small, possibly interconnected, dissolution tubules developed on the Shoreham Marl 1 and Shoreham Marl 2 (c. 1.2 m apart). Notable dissolution tubule horizons up to 10 cm thick occur on the marls. These extend laterally several tens of metres along the cliff. Many small conduits 2-3 cm high and up to 20 cm wide are present within the zone of dissolution tubules, but there are no major enterable cavities.

Light Point Conduit 3. NGR 556726 95388, 400 m ESE of Belle Tout Lighthouse, 100 m east of Light Point. This is a small sediment-filled cave approximately 1 m high and wide, exposed c. 20 m up the cliff. The cave is located about five metres below the Seven Sisters Flint, probably on one of the Belle Tout marls in the lower Seaford Chalk. The cave is infilled with red-brown silt and clay overlying brecciated chalk, with no open void. The chalk around the cave is also highly brecciated. Some tubules a few metres to the west occur at the same stratigraphical level. The cave is inaccessible.

Light Point Conduit 4. NGR 556746 95385, 420 m ESE of Belle Tout Lighthouse, 140 m east of Light Point. Like the previously described conduit, Light Point Conduit 4 is a small cave exposed high up in the cliff, c. 5-8 m above the Seven Sisters Flint on a major inclined fracture, which extends down the whole cliff face. The cave is infilled with red-brown silt and clay, some of which has washed out to create the void. The cave is estimated to be 3-4 m high and 2-3 m wide, with a zone of highly brecciated chalk around it. Smaller cavities occur lower down on the same fracture, down to beach level, where there is a large wave eroded alcove. The cave is inaccessible.

Light Point Conduit 5. NGR 556746 95385, 420 m ESE of Belle Tout Lighthouse, 140 m east of Light Point. This is an extensive zone of dissolution tubules exposed high in the cliff about 5-10 m below the Seven Sisters Flint, probably on one of the Belle Tout marls in the lower Seaford Chalk. The zone is associated with localised brecciation. Red clay and silt infill a series of small cavities up to 0.5 m high (estimated). The zone of dissolution tubules extends laterally for about 100 m along the cliff face.

Beachy Head Conduit 1. NGR 557043 95390, 700 m ESE of Belle Tout Lighthouse, 430 m east of Light Point. This is a significant cave c. 8 m long, 5 m high and 0.9-1.2 m wide developed on a sheet flint just below Shoreham Marl at the top of the Lewes Nodular Chalk. The main phreatic tube occurs on the sheet flint, but locally the void extends c. 3-4 m up phreatic avens. Below the tube is a 1 m-deep vadose trench, which suggests the conduit was still active when the water table was at or just above the present sea level. The end of the cave becomes too narrow, but the void continues. Other small phreatic conduits 20-30 cm diameter are developed on the same sheet flint a short distance to the east and west, which probably link to the main cave. The dissolution tubule zone above the sheet flint is 0.5 m thick.

Beachy Head Conduit 2. NGR 557062 95362, 720 m ESE of Belle Tout Lighthouse, 460 m east of Light Point. Beachy Head Conduit 2 is a small phreatic conduit 2 m above beach level, 1.2 m wide, 0.3 m high and 1.5 m long, choked with cobbles a short distance farther east as Beachy Head Conduit 1, and on the same sheet flint just below the Shoreham Marl. The conduits are possibly linked. Above the sheet flint is a dissolution tubule zone up to 0.5 m thick.

Beachy Head Conduit 3. NGR 557205 95351, 870 m ESE of Belle Tout Lighthouse, 600 m east of Light Point. This is a major vertical fracture extending all the way up the cliff, cutting through the upper Lewes Nodular Chalk, the lower Seaford Chalk and into the middle Seaford Cuckmere Beds (Mortimore, 1986). There is evidence of dissolution throughout, with much orange-brown staining and localised pockets of sediment. Many small, localised cavities ~0.2-0.4 m in diameter (estimated) occur at intervals all the way down, and are visible on the fracture surface where it is exposed by rock-fall. A larger sediment-filled cavity 1-2 m wide and 10-15 m deep occurs near the top of the cliff (possibly a dissolution pipe?). Many small conduits extend laterally outwards from the fracture, along one of the Belle Tout marls to the east, showing the linkage between vertical fracture-dominated karst features and horizontal strata-bound conduits.

Beachy Head Conduit 4. NGR 557254 95326, 930 m ESE of Belle Tout Lighthouse, 650 m east of Light Point. This is a small, vertical phreatic tube exposed by rock fall, developed on a fracture just above beach level in the Upper Lewes Nodular Chalk, between the Shoreham and Navigation marls. The phreatic conduit is approximately 0.2 m in diameter extending from just above beach level 4-5 m up the cliff to a sheet flint. It meanders vertically along the fracture.

Beachy Head Conduit 5. NGR 557434 95317, 1.09 km m ESE of Belle Tout Lighthouse, 850 m west-northwest of Beachy Head Lighthouse. This is a well-developed phreatic conduit 30 cm in diameter with a small vadose trench, developed on a well-defined marl seam (the Navigation Marl, Upper Lewes Nodular Chalk) where it is cut by a minor fault. Many smaller conduits, typically 1-10 cm across and 1-3 cm high, occur along the marl to either side.

Beachy Head Conduit 6. NGR 557471 95305, 1.14 km m ESE of Belle Tout Lighthouse, 815 m west-northwest of Beachy Head Lighthouse. This is a well-developed phreatic conduit 2 m above the beach on a thick marl (the Navigation Marl) where it is cut by a minor fault. The passage is 0.6 m high and 1.2 m wide, with many dissolution tubules on the roof, but closes down to a series of smaller, impenetrable conduits on the marl seam. Many other dissolution tubules and small conduits 5-20 cm in diameter occur along the same marl to the east and west.

Beachy Head Conduit 7. NGR 557565 95299, 1.26 km m ESE of Belle Tout Lighthouse, 725 m west-northwest of Beachy Head Lighthouse. This is a well-developed conduit 3 m above beach level at the intersection of a major fracture and the Navigation Marl. The main cavity is on the marl seam, with the Navigation hardground just below. Clear dissolution tubules occur just above the marl seam. Many small (0.1-0.5 m-wide) cavities occur on the fracture at intervals all the way up to the cliff top. A second notable conduit, 0.5 m high and 0.4 m wide, occurs on the Navigation Marl 2 m to east. This also has dissolution tubules on its roof.

Beachy Head Conduit 8. NGR 557683 95265, 1.35 km m ESE of Belle Tout Lighthouse, 610 m west-northwest of Beachy Head Lighthouse. This is a series of enlarged voids developed along a major, near-vertical fracture extending the full height of the cliff, here about 95 m high. Cavities up to c. 0.5 m wide and 1-2 m high occur in the top two-thirds of the face, mostly within the Seaford Chalk. There is evidence of sediment fill near the top. The biggest cavity is where the fracture intersects the Seven Sisters Flint, with smaller voids below, possibly on the Belle Tout marls, but also on the Shoreham Marl.

Beachy Head Conduit 9. NGR 557708 95260, 1.39 km ESE of Belle Tout Lighthouse, 575 m west-northwest of Beachy Head Lighthouse. Like Beachy Head Conduit 8, this is a major vertical fracture or minor fault extending up the full height of the cliff, here approximately 100 m high. The fracture cuts through the Upper Lewes Nodular Chalk to the lower Seaford Chalk, with two significant cavities. The higher cavity is in the Belle Tout Beds (lower Seaford Chalk) and is estimated to be c. 4-5 m high and 0.5 m in diameter. The top of the cavity is c. 2-3 m below the Seven Sisters Flint. Lower down a second, smaller, cavity is about 10-15 m above beach level. An intermittent sheet flint at the base of the cliff is the westernmost visible extent of the sheet flint that is the inception horizon for Beachy Head Cave.

Beachy Head Cave – Entrance 1 (west). NGR 557717 95269, 1.38 km ESE of Belle Tout Lighthouse, 570 m west-northwest of Beachy Head Lighthouse. This conduit is the westernmost conduit/entrance associated with the Beachy Head cave system (Waltham et al., 1997; Reeve, 2021). The c. 1 m-diameter conduit is on a sheet flint 3-4 m above the Navigation Marl (in the upper part of the Lewes Nodular Chalk) where it is cut by a vertical fracture. It is associated with a well-developed tubule horizon about 0.5 m thick above the sheet flint. The sheet flint forms a sizable ledge 2-3 m above beach level, which might originally have formed part of the surveyed cave before being truncated by cliff retreat.

Beachy Head Cave – Entrance 2. NGR 557737 95270, 1.40 km ESE of Belle Tout Lighthouse, 550 m west-northwest of Beachy Head Lighthouse. A short distance to the east on the ledge described above is the second conduit associated with Beachy Head Cave. This is located on the same sheet flint as Entrance 1. This entrance is a phreatic tube approximately 1 m in diameter, developed on a sheet flint which here forms a sizable ledge some 3-4 m above the Navigation Marl. There is a well-developed tubule horizon above the flint. Other, smaller, conduits/entrances might be present on either side but not visible from beach level.

Beachy Head Cave – Entrance 3. NGR 557737 95270, 1.40 km ESE of Belle Tout Lighthouse, 550 m west-northwest of Beachy Head Lighthouse. This is the third entrance and is closely similar to Entrance 2 in that it is a sizable phreatic tube approximately 1 m in diameter. It is almost certainly part of the same conduit but truncated by cliff retreat. Like the other entrances, it occurs on a sheet flint 3-4 m above the Navigation Marl.

Beachy Head Cave – Entrance 4 (Original Entrance). NGR 557807 95266, 1.48 km ESE of Belle Tout Lighthouse, 480 m west-northwest of Beachy Head Lighthouse (approximate location; the cave was obscured by a rock-fall in July 2020). This is the original entrance to Beachy Head Cave. The cave is a phreatic conduit approximately 1 m in diameter revealed by cliff retreat. The passage occurs on the same sheet flint as Entrances 1-3 farther west. Two entrances currently exist about 3-4 m apart, which are part of the same passage but truncated by cliff retreat. These lead into the eastern and western branches of the system, which extends for over 350 m (Waltham et al., 1997). Both conduits are associated with an extensive dissolution tubule zone 1-2 m thick above the sheet flint, with many small, anastomosing, conduits. Several inaccessible sediment-filled caves occur in the cliff above, developed on the Seven Sisters Flint.

Beachy Head Cave – Entrance 5. NGR 557857 95249, 1.52 km ESE of Belle Tout Lighthouse, 430 m west-northwest of Beachy Head Lighthouse. This is the easternmost visible conduit associated with Beachy Head Cave. It is on the sheet flint, which here begins to rise higher in the cliff. A small conduit 0.5 m wide (estimated), partially infilled with sediment, is visible in the cliff. It might link into Beachy Head Cave but is too small to enter. Many small faults are present in the cliff in this area where the dip increases towards the east.

Birling Gap to Cuckmere Haven Section (the 'Seven Sisters')

The section immediately west from Birling Gap is in the middle Seaford Chalk (Cuckmere Beds of Mortimore, 1986) above the Seven Sisters Flint. This zone has no significant marl seams and few sheet flints. These beds crop out at beach level below the Seven Sisters, occupying the core of a minor syncline, with the lower Seaford Chalk (Belle Tout Beds) coming back up to beach level at Cuckmere Haven. The higher parts of the cliffs below each of the Seven Sisters extend up into the upper Seaford Chalk (Haven Brow Beds) and locally the basal Newhaven Chalk Formation. Ten conduits were noted in the cliff section between Cuckmere Haven and Birling Gap (Figure 13).

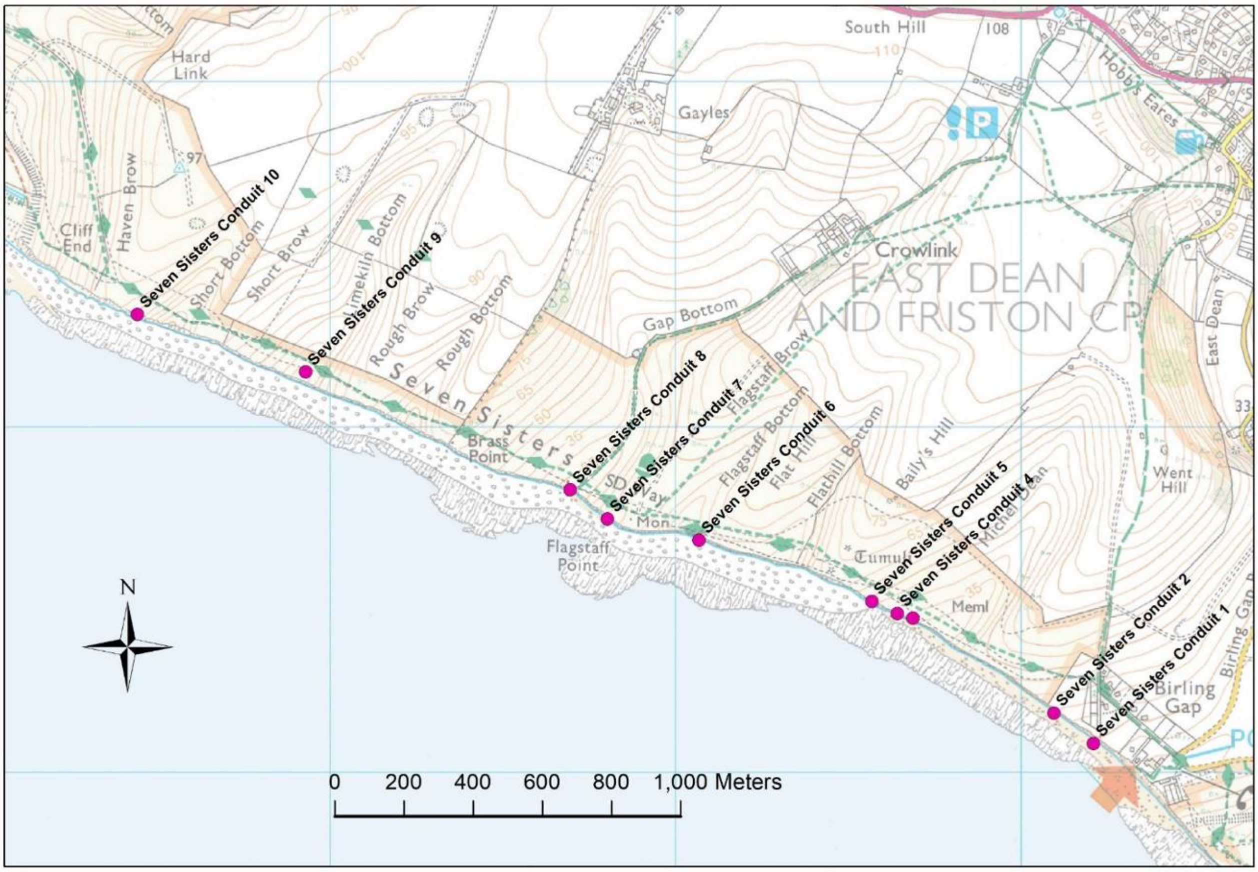

Figure 13. Conduits and caves between Birling Gap (right) and Cuckmere Haven (left). Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.

Seven Sisters Conduit 1. NGR 555210 96086, 190 m NW of Birling Gap. This is a suite of minor dissolutional conduits up to 0.3 m across and 0.1-0.2 m high developed on a thick sheet flint in the Cuckmere Beds just west of Birling Gap. Several small bedding-plane partings at beach level occur over a 3-4 m stretch of cliff.

Seven Sisters Conduit 2. NGR 555095 96174, 330 m NW of Birling Gap. This is a small dissolutional conduit 0.25 m wide and 0.15 m high on a thick sheet flint in the Cuckmere Beds west of Birling Gap.

Seven Sisters Conduit 3. NGR 554687 96449, 820 m NW of Birling Gap (Baily's Hill). This is an obvious large sediment-filled cave at beach level, at the eastern end of a minor embayment in the cliff. The cave is part of Reeve's 'Seven Sisters Cave' (Chelsea Spelaeological Society 2010). It is c. 3 m high and 2 m wide, infilled with thinly bedded and laminated reddish brown silt and clay, tapering upwards to a narrow rift. The cave is developed on a prominent inclined fracture/minor fault with a throw of c. 0.5 m trending parallel to the cliff. The cave is the eastern end of a fault-guided cave system trending parallel to the cliff face that has been intersected and partially truncated by cliff retreat. It is associated with (and once linked to) several other conduits 40 m to the west (Seven

Sisters Conduit 4 & 5). This site is noted by Reeve (pers. comm.) as 'Seven Sisters Sea Caves 2B' (Chelsea Spelaeological Society, 2010).

Seven Sisters Conduit 4. NGR 554642 96462, 870 m NW of Birling Gap (Baily's Hill). This is the western end of Reeve's 'Seven Sisters Cave' and comprises a series of large sediment-filled cavities. The cave is visible from Birling Gap. The main cave is c. 1 m in diameter, infilled with laminated and thinly bedded reddish brown silt, silty clay, and clay. The cavities are developed on a minor inclined fault with a throw of c. 0.5 m, dipping into, and trending parallel to, the cliff. The fracture extends to the top of the cliff and can be seen rising obliquely up the cliff face to the west. Several smaller cavities extend 4-5 m up the cliff in a zone of weathered, highly fractured chalk, linking to Seven Sisters Conduit 5 to the west. It is probably the cave noted by Reeve (pers. comm.) as 'Seven Sisters Sea Caves 2A'.

Seven Sisters Conduit 5. NGR 554568 96497, 950 m NW of Birling Gap (Baily's Hill). This is a series of small sediment-filled voids up to 2 m high developed on a vertical fracture/minor fault running obliquely up the cliff face from near beach level to close to top of cliff (40 m high). These voids are on the same fracture/fault as the two other cave features to the east (Seven Sisters conduits 3 and 4). The conduits are all part of a narrow, dissolutionally enlarged, steeply inclined fissure exposed by cliff retreat. The sediment fill is mostly reddish brown silty sandy clay with flint clasts.

Seven Sisters Conduit 6. NGR 554068 96674, 1.47 km NW of Birling Gap (Flat Hill). This is a sea cave 6 m long and 10 m high developed on vertical joints. There is little evidence of karst, but an impressive entrance. Some extensive dissolution tubules occur on a flint band 3-4 m above beach level just to the west of the main cave. The tubules are in a zone typically 0.2-0.3 m high over a 4-5 m stretch of cliff.

Seven Sisters Conduit 7. NGR 553803 96736, 1.73 km NW of Birling Gap (Flagstaff Brow). This comprises several small inaccessible sediment-filled conduits (estimated to be 0.3 m in diameter) developed on a flint band near the top of the cliff (here about 30 m high).

Seven Sisters Conduit 8. NGR 553695 96820, 1.85 km NW of Birling Gap (Gap Bottom). This comprises several small conduits in the cliff at beach level, close to the mouth of a dry valley. The largest conduit is c. 0.2-0.4 m wide and occurs in the cliff face about 5 m above beach level. This is developed on an inclined shear fracture. A few metres to the west are a few smaller, poorly developed, conduits on parallel shear fractures at beach level, typically <20 mm in diameter, and with no clear evidence of dissolution except a few dissolution tubules.

Seven Sisters Conduit 9. NGR 552929 97161, 2.71 km NW of Birling Gap (Gap Bottom). This cave is at beach level on a major fracture that extends to the top of the cliff. The fracture is typically just a few centimetres wide and infilled with clay, but has been widened out at beach level by marine action. There is no evidence of any bedding-parallel dissolution on inception horizons. Some marine caves developed on vertical joints cut through a buttress at the base of the cliff just to the west, but there is no evidence of any karst or dissolution tubules.

Seven Sisters Conduit 10. NGR 552442 97327, 3.21 km NW of Birling Gap (Gap Bottom). This comprises two small conduits about 0.2-0.3 m wide and 0.3 m high developed on the highest Belle Tout Marl in the lower Seaford Chalk. They are possibly part of the same conduit. Small dissolution tubules occur around each conduit.

Hope Gap to Seaford (Hope Gap and Seaford Head)

West of Cuckmere Haven, the upper Lewes Nodular Chalk is exposed at beach level, with the Hope Gap Hardground and sheet flint forming prominent marker beds at the base of the cliff as far west as Seaford Head. Many small conduits and caves occur at the base of the cliffs associated with the sheet flint just above the Hope Gap Hardground. Vertical dissolution-enlarged joints in the overlying Seaford Chalk occur around Seaford Head. The survey identified eighteen conduits, caves, or dissolution-enlarged joints around Hope Gap (Figure 14). The features between Hope Gap and Seaford are described from east to west.

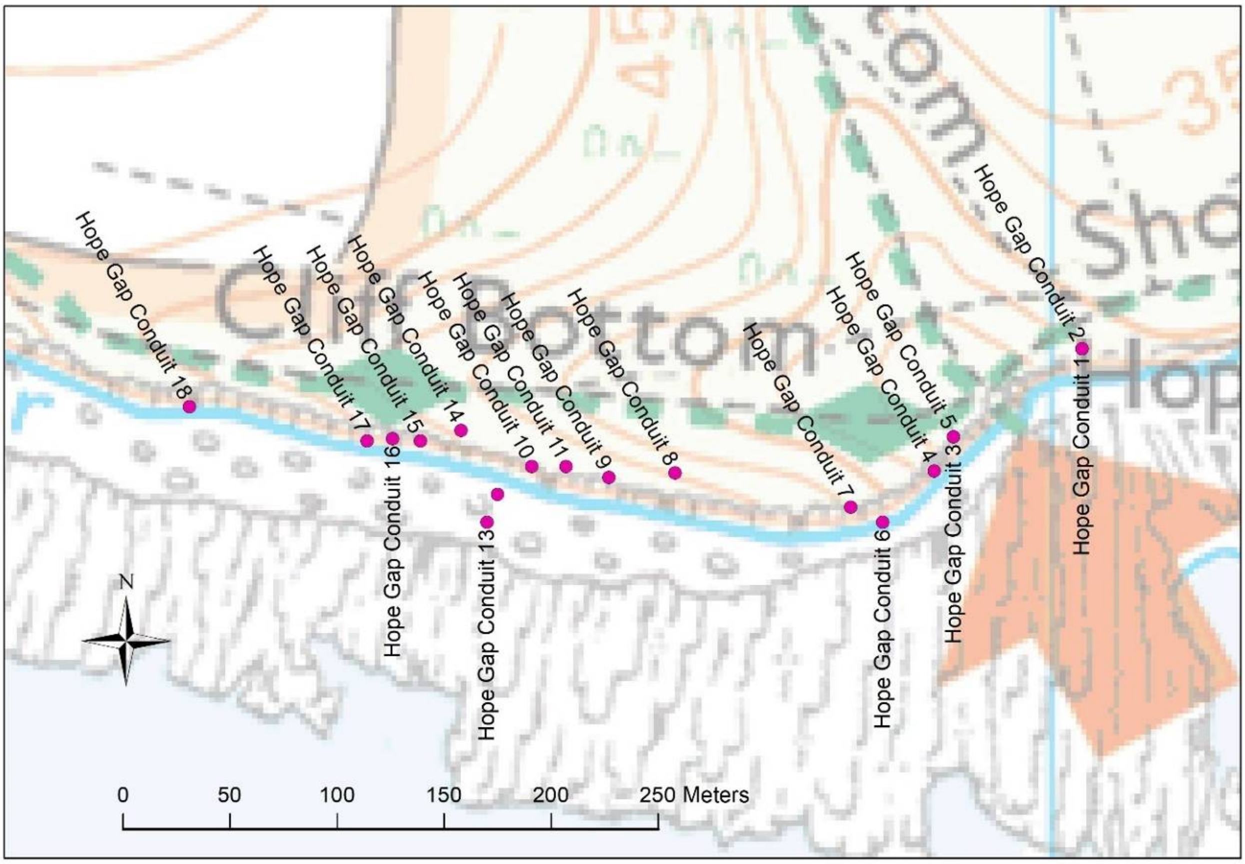

Figure 14. Conduits and caves around Hope Gap. Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.

Seaford Head Cave. Reeve (Chelsea Spelaeological Society 2012) describes a cave east of Hope Gap "on a 4 ft. high ledge in the chalk cliffs some 50 yards south of the new steps leading to the beach at the Seaford Head Nature Reserve by the mouth of the River Cuckmere" at NGR TV 514976. The cave is a relict phreatic conduit ending in a clay choke. The survey suggests the cave is developed on a tabular flint, almost certainly the Hope Gap sheet flint. This site was not visited during the coastal survey.

Hope Gap Dissolution Pipes. Numerous relict dissolution pipe 'doughnuts' occur on the foreshore between Hope Gap and Cuckmere Haven. Secondary cementation around the margins of the pipe makes the chalk more resistant to erosion. Marine erosion has since removed the sediment infill within the pipe and the surrounding weak chalk, creating a doughnut-shaped rampart on the foreshore.

Hope Gap Conduit 1. NGR 551014 97394, 50 m NE of the Hope Gap steps. The Hope Gap Conduit 1 is a zone with many small elliptical conduits, typically 30-40 cm across and 10-20 cm high, extending several metres along the cliff just east of the Hope Gap steps. These occur on top of a prominent sheet flint just above beach level, the Hope Gap sheet flint in the upper Lewes Nodular Chalk. The largest is at the intersection of a major joint and the sheet flint. The chalk in this area is heavily fractured and brecciated close to the Hope Gap dry valley.

Hope Gap Conduit 2. NGR 551014 97394, 30 m NE of the Hope Gap steps. This is a suite of sediment-filled, dissolutionally widened fractures in highly weathered brecciated chalk beneath the Hope Gap dry valley. The most prominent is a vertical fissure up to 0.4 m wide, infilled with red silt and clay that extends up to the top of the cliff. A large alcove has formed where the lower part of this fissure has been widened by marine action. The fissure itself has no open void. Immediately east of the alcove, two thin, sediment-filled, horizontal voids up to 5 cm high extend eastwards 10 m along the face in brecciated chalk just above the Hope Gap sheet flint. These appear to be developed on bedding-parallel joints.

Hope Gap Conduit 3. NGR 550954 97353, 30 m SW of the Hope Gap steps. This is a small conduit ~0.3 m in diameter developed on the Hope Gap sheet flint where it is cut by a minor fault (0.5 m throw) just west of the Hope Gap steps. Many small dissolution tubules occur just above the sheet flint, in a zone 0.2 m thick, extending along the flint band for several metres either side.

Hope Gap Conduit 4. NGR 550945 97337, 40 m SW of the Hope Gap steps. This section of cliff immediately to the west of the Hope Gap Conduit 3 contains many small elliptical conduits and dissolution tubules developed on the Hope Gap sheet flint. The conduits are typically 10-20 cm across and 5-10 cm high. The dissolution tubules extend across a zone 20-30 cm thick and 5-6 m long along the cliff face immediately above the Hope Gap sheet flint.

Hope Gap Conduit 5. NGR 550954 97353, 70 m SW of the Hope Gap steps. This is a well-developed phreatic conduit 0.8 m in diameter on the Hope Gap sheet flint. Well-developed dissolution tubules occur on the roof and on top of the sheet flint either side of the cave. The cave is at least 3 m long but choked with boulders at the inner end.

Hope Gap Conduit 6. NGR 550921 97313, 75 m SW of the Hope Gap steps. This is a small, 0.3 m-diameter, horizontal phreatic tube developed on the Hope Gap sheet flint 3 m to the west of Hope Gap Conduit 5. It is linked to a small vertical phreatic tube, 10-20 cm in diameter, rising 2-3 m along a joint above. Numerous small dissolution tubules occur on the sheet flint between the two main conduits.

Hope Gap Conduit 7. NGR 550906 97320, 85 m SW of the Hope Gap steps. This is a well-developed phreatic conduit, 0.3-0.4 m wide and 0.3 m high, on the Hope Gap sheet flint. Smaller conduits 10-20 cm across and 5-10 cm high occur all along the sheet flint on both sides. The conduit may extend through to the next alcove in the cliff to the west, where two small conduits can be seen on the same sheet flint.

Hope Gap Conduit 8. NGR 550824 97336, 160 m west of the Hope Gap steps. This is a vertical fracture widened by dissolution and with a red clay/silt fill extending >10 m up the cliff face. The fracture is typically 2-5 cm wide but gets wider towards the base of the cliff. Boulders block a possible cave at the base, at the level of the Hope Gap sheet flint.

Hope Gap Conduit 9. NGR 550793 97334, 195 m west of the Hope Gap steps. This is a small phreatic conduit, 0.3 m wide and 0.4 m high, choked with flint cobbles. The conduit, which occurs at the intersection of the Hope Gap sheet flint and a major joint, might extend through to the next alcove around the corner to the west.

Hope Gap Conduit 10. NGR 550757 97339, 205 m west of the Hope Gap steps. Hope Gap Conduit 10 is a series of three closely spaced conduits 0.3-0.4 m high on the Hope Gap sheet flint c. 2 m above beach level. The conduits have a well-marked phreatic morphology, with evidence of dissolution tubules.

Hope Gap Conduit 11. NGR 550773 97339, 200 m west of the Hope Gap steps. This is a tall, dissolutionally widened, sediment- and cobble-choked vertical rift, 10-15 m high and c. 0.5 m wide on a major joint in the cliff. A rock-fall blocks a possible cave at the base of the cliff. The rift is 0.5 m wide at the base (at the level of the Hope Gap sheet flint), tapering upwards near the top. The cave is infilled with reddish brown silty clay and chalk boulders.

Hope Gap Conduit 12. NGR 550741 97326, 225 m west of the Hope Gap steps. This is a conduit 0.7 m wide and up to 3 m high developed at the intersection of the Hope Gap sheet flint and a major joint. Prominent dissolution tubules occur on the joint face. The conduit may have been linked to Hope Gap Conduit 10, but has been breached by cliff retreat. A smaller conduit, 0.2 m diameter, occurs 1 m to the north in an alcove. The fracture continues higher into the cliff as a dissolutionally widened joint infilled with orange-brown clay. This may be the 'Seaford Head Cave No. 8' (Reeve, pers.comm. and Chelsea Spelaeological Society 2010).

Hope Gap Conduit 13. NGR 550736 97313, 225 m west of the Hope Gap steps. This is a small but well-formed phreatic conduit. 0.4 m high and 1.2 m wide, on the Hope Gap sheet flint. Several other, smaller, conduits occur on the same ledge between the main conduit and Hope Gap Conduit 12. These are almost certainly linked genetically, and are included as part of the Hope Gap Conduit 13.

Hope Gap Conduit 14. NGR 550724 97356, 230 m west of the Hope Gap steps. This is a well-developed relict phreatic cave previously identified by Reeve (pers. comm. and Chelsea Spelaeological Society 2010) as 'Seaford Head Cave No. 6'. The entrance is a sea cave with little evidence for dissolution that extends back c. 10 m and intersects a relict phreatic conduit, 0.7 m wide and 0.8 m high, on the Hope Gap sheet flint. The eastern branch of the conduit is >4 m long and probably links to the Hope Gap Conduit 12 or 13 on the other side of the bluff, whereas the northerly branch is >3.5 m long. The cave exceeds 18 m in length. A survey by Reeve (Chelsea Spelaeological Society 2010) indicates that the phreatic conduit segment has a length of c. 12 m.

Hope Gap Conduit 15. NGR 550705 97351, 270 m west of the Hope Gap steps. This is an enlarged bedding-parallel conduit, 4 m wide and 0.1 m high, on the Hope Gap sheet flint, possibly enlarged by wave action and extending back > 3-4 m. Some scallops and dissolution tubules are present on the roof.

Hope Gap Conduit 16. NGR 550692 97352, 290 m west of the Hope Gap steps. This is a large cave, at least 5 m high and 1.2 m wide, extending back >3-4 m at beach level. Fallen boulders currently block access. It is unclear how karstic it is, but it is located on a major joint at the level of the Hope Gap sheet flint. It might be the cave originally identified by Reeve (pers. comm. and Chelsea Spelaeological Society 2010) as 'Seaford Head Cave No. 3B'.

Hope Gap Conduit 17. NGR 550680 97351, 295 m west of the Hope Gap steps. This is a large cave, c. 14 m long, 2.2 m high and 1.2 m wide, developed on a joint trending into the cliff. The cave is on an inclined joint, but with evidence of dissolution, including well-marked dissolution tubules, at the level of the Hope Gap sheet flint. The cave is choked with flint cobbles. This may be what Reeve (pers. comm. and Chelsea Spelaeological Society 2010) identified as 'Seaford Head Cave No. 3'.

Hope Gap Conduit 18. NGR 550597 97367, 380 m west of the Hope Gap steps. This is a series of small conduits at beach level, approximately 0.3 m in diameter, associated with a hading (inclined), dissolutionally enlarged fracture that has been partially exposed by cliff retreat. The fracture trends obliquely to the cliff face, and extends vertically up the cliff for c. 10 m. There is evidence of phreatic conduit development along this exposed fracture at the level of the Hope Gap sheet flint c. 5 m above beach level (inaccessible). Higher up the fracture is infilled with sediment. Where the fracture surface has been exposed by cliff retreat, the whole cliff face has a dissolutionally fretted fracture surface. A series of phreatic tubes is exposed near the base, on the fracture surface extending up the cliff face above the Hope Gap sheet flint. These suggest that upward flow occurred from horizontal conduits on the Hope Gap sheet flint into conduits aligned along the vertical fracture.

Seaford Head

Approaching Seaford Head, the Hope Gap sheet flint passes below beach level. Six more conduits, caves or dissolution-enlarged joints occur around Seaford Head (Figure 15). In addition to these features, numerous dissolution pipes occur at the top of the cliff beneath the Clay-with-Flints that caps the headland. These pipes extend down to 10-15 m below the surface, and they are infilled with a characteristic dark orange-brown flinty clay. Between Seaford Head and Splash Point (a distinct promontory 300 m southeast from the end of the promenade at Seaford), the dip increases into a minor syncline, with the entire Seaford Chalk Formation passing down to beach level (Hampton et al., 2007) just east of Splash Point. Unfortunately, when visited, the area between Seaford Head and Splash Point was inaccessible due to tidal conditions and recent rock falls. The Newhaven Chalk succession comes to beach level between Splash Point and the promenade at Seaford.

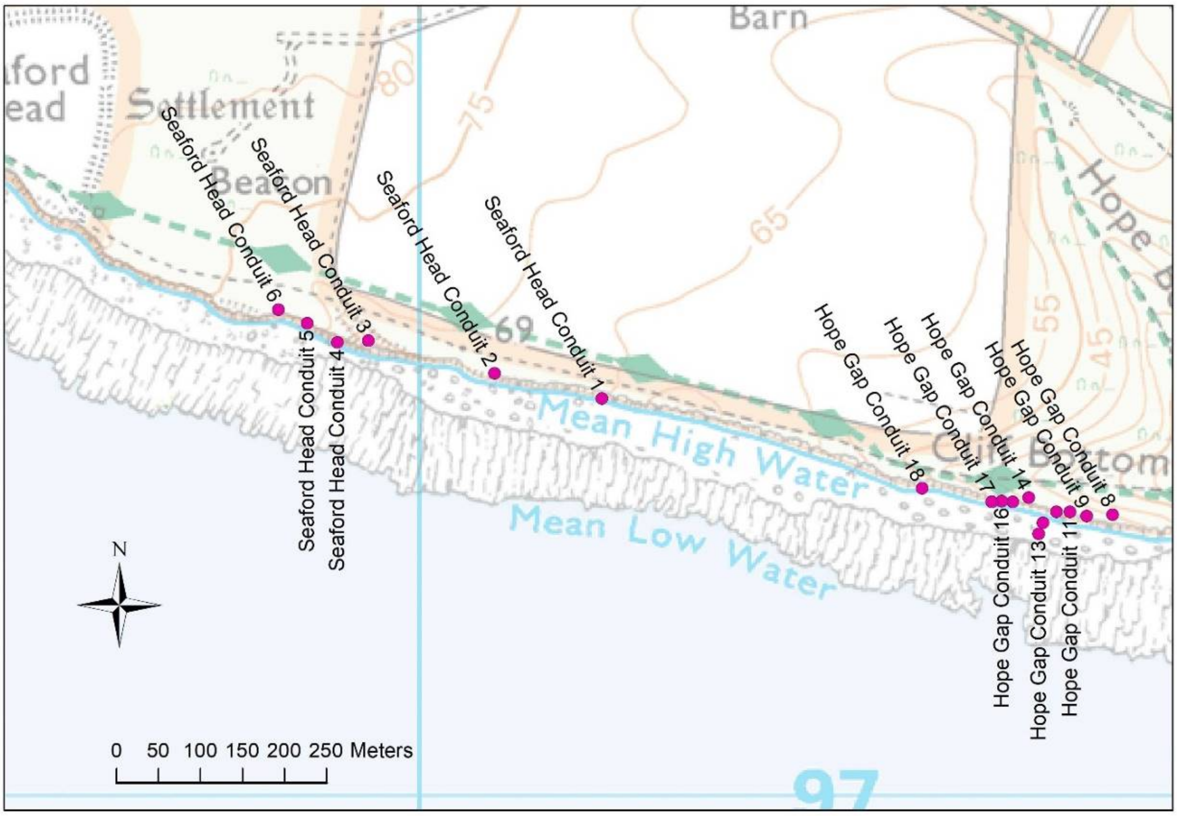

Figure 15. Conduits and caves around Seaford Head. Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.

Seaford Head Conduit 1. NGR 550216 97474, 770 m west of the Hope Gap steps. This is a series of small, 2-5 cm wide, dissolution conduits developed along a vertical fracture up 4 m high in the upper Lewes Nodular Chalk above the Hope Gap Hardground. In the same area, there are some minor dissolution tubules on a thin, intermittent, sheet flint some 3 m above beach level.

Seaford Head Conduit 2. NGR 550088 97504, 770 m west of the Hope Gap steps.
Stratigraphy. Upper Lewes Nodular Chalk & Seaford Chalk. Seaford Head Conduit 2 is a major solutionally enlarged vertical fracture extending nearly all the way up the cliff (60 m), from just above the Hope Gap sheet flint (here just below beach level) up to the lower Seaford Chalk. The fracture is 5-20 cm wide with evidence of solutional enlargement throughout. It is partially infilled with reddish brown silty clay and chalk fragments. At beach level, the base has been widened at the base by marine action. The top of the cliff is just above the Seven Sisters Flint.

Seaford Head Conduit 3. NGR 549938 97543, 1.06 km WNW of the Hope Gap steps. Seaford Head Conduit 3 is a small cave at beach level, c. 5-6 m long, 1.2 m wide and 1.2 m high, on a minor fracture, with evidence of dissolution rising by c. 8-10 m into the cliff above. The rift above is locally 5-10 cm wide. The entrance has probably been widened by wave action.

Seaford Head Conduit 4. NGR 549901 97541, 1.10 km WNW of the Hope Gap steps. This is a prominent vertical fracture extending to the top of the cliff (>60 m), with evidence of dissolution at intervals all the way up. The dissolutional voids, estimated to be around 5-30 cm wide, are partially infilled with reddish brown silty clay and chalk fragments. Some open voids are present; especially in the Belle Tout Beds (lower Seaford Chalk) between the Shoreham Marl and the Seven Sisters Flint, probably on the Belle Tout marls. At beach level the cave entrance has been enlarged by wave action. The top of the cliff is c. 10-12 m above the Seven Sisters Flint.

Seaford Head Conduit 5. NGR 549865 97564, 1.11 km WNW of the Hope Gap steps. This is another prominent dissolutionally enlarged vertical fracture a short distance to the west of Conduit 4 and cutting the same stratigraphy. It is 5-20 cm wide, partially infilled with reddish brown silty clay and chalk fragments and some open voids (especially in Belle Tout Beds just below the Seven Sisters Flint), extending to the top of the cliff (70 m above beach level). Like Seaford Head Conduit 4, the base has been widened by marine action. The top of the cliff is c. 10-12 m above the Seven Sisters Flint.

Seaford Head Conduit 6. NGR 549831 97580, 1.18 km WNW of the Hope Gap steps.
Seaford Head Conduit 6 is another major vertical fracture extending the full height of the cliff (here about 75 m) with a large dissolution pipe c. 10 m deep at the top infilled with Clay-with-Flints. The section comprises upper Lewes Nodular Chalk passing up into the Seaford Chalk (Belle Tout Beds to lower Cuckmere Beds). A small cave at beach level has been widened by marine action. Many small, sediment-filled, dissolution cavities occur at intervals along the fracture up the cliff.

Splash Point to Seaford

A few small karst features occur at the western end of the Seaford Head coastal section between Splash Point and the promenade at Seaford (Figure 16). In this area, the chalk dips northwestwards into a syncline. These conduits are in the Newhaven Chalk, which is above the Seaford Chalk stratigraphically. When visited, the section from just east of Splash Point to Seaford Head Conduit 6 was inaccessible due to tidal conditions and recent rock-falls.

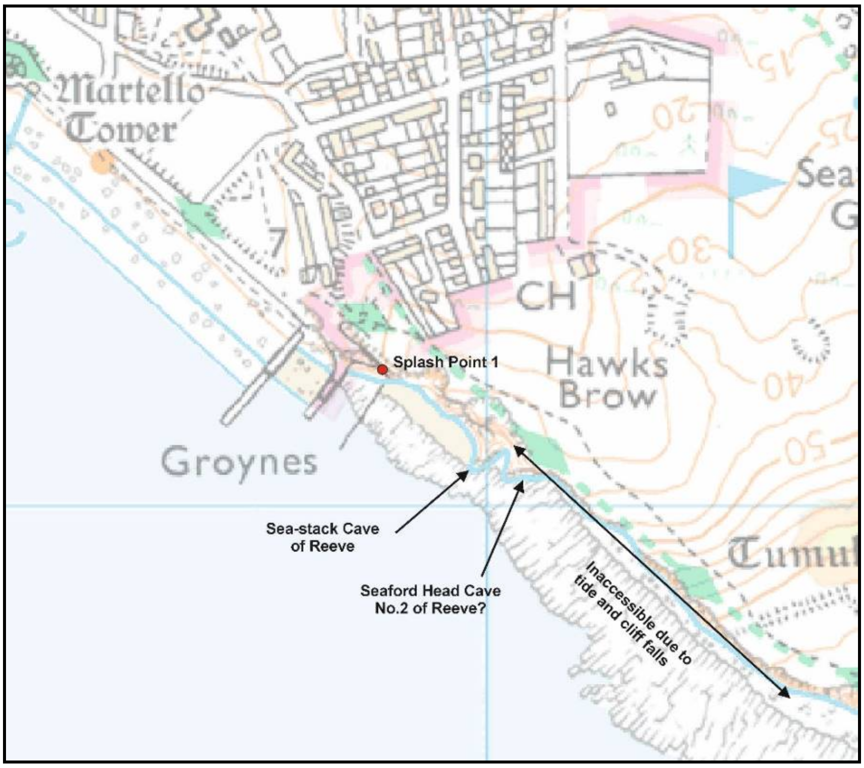

Figure 16. Karst features at Splash Point, Seaford. Base map contains Ordnance Survey data © Crown Copyright and database rights 2021.

Splash Point Conduit 1. NGR 54888 98146, at the eastern end of the promenade and coastal defences at Seaford. Several small dissolutional conduits were noted in the Newhaven Chalk at the base of the cliffs behind the coastal defence boulders. These are developed on thin marl seams (the Telscombe marls) and are typically small conduits, 1-2 cm high and 10-20 cm wide, over several metres of cliff section. They are commonly associated with dissolution tubules in a zone 10-20 cm thick. The chalk here dips at c. 5-10°, so the section of cliff associated with conduits at this stratigraphical horizon is restricted to a zone 20-30 m wide.

Newhaven

A detailed coastal survey was not undertaken between Newhaven and Brighton, but several karstic conduits and small caves occur in the cliffs below Castle Hill at Newhaven (NGR 5444 0999]. Relict phreatic tubes up to 1 m wide infilled with sediment, and some smaller cavities up to 30 cm wide occur associated with the Castle Hill marls at the top of the Newhaven Chalk Formation and in the basal Culver Chalk Formation. Networks of anastomosing, sediment-filled, conduits were observed on the underside of some bedding features in the cliff. In this area, the Chalk is overlain by Palaeogene strata. Small, 1-2 m deep, dissolution pipes occur along the Palaeogene/Chalk contact near the top of the cliff.

Conceptual model of karst in East Sussex.

Evidence from coastal surveys, remote sensing interpretation, site investigation data and data from groundwater abstraction boreholes and adits combine to demonstrate the presence of karst groundwater flow in the Chalk of East Sussex. A clear distinction can also be made between surface karst features and those features recorded at depth.

Surface karst.

Surface karst features include dolines and dissolution pipes, dry valleys, stream sinks and large springs. Of these, the most common are dissolution pipes. Stream sinks occur most commonly around the margin of the overlying Palaeogene strata. However, in East Sussex, the Palaeogene outliers at Peacehaven, Seaford, Brighton and Falmer are too small or too thin to generate surface streams, so stream sinks are absent. Moreover, golf courses and urban development have tended to obscure any natural dolines that might exist around the outliers.

The distribution of surface karst can be divided into three broad zones (Figure 17, Maurice et al., 2006; 2012). Karst Zone 1 is where allogenic recharge from adjacent low-permeability deposits flows onto the Chalk. This generally occurs along the margins of the overlying Palaeogene sand and clay outcrops. The zone encompasses the featheredge of the Palaeogene outcrop and the area of Chalk around it, which may include some superficial deposits. In East Sussex, this zone is restricted to small areas near Newhaven and Seaford, but is more extensive in the South Downs farther east, particularly around Horndean and Chichester where stream sinks are more common (Atkinson and Smith, 1974). Where the Palaeogene is more than about five metres thick, it is deemed non-karstic.

Karst Zone 2 comprises the area underlain by Chalk at or close to the sub-Palaeogene erosion surface. The erosion surface is commonly marked by the Clay-with-Flints outcrop which is a remanié deposit derived from the former Palaeogene cover. Zone 2 also includes areas where river terrace and other relict fluvial deposits cover the Chalk. In both these areas, the superficial deposits serve to concentrate recharge via leakage points through the cover into the underlying chalk. The recharge, having passed through the permeable superficial cover (mostly clay, sand or gravel) is aggressive, creating a well-developed epikarst with dolines and sediment-filled dissolution pipes. This zone is characterised by numerous dissolution pipes, but few sinking streams.

Karst Zone 3 comprises the area of chalk where erosion has lowered the topography below the level of the sub-Palaeogene erosion surface. This is predominantly along the escarpment and along the valley networks on the dip-slope. In these areas, erosion and surface lowering has removed any remnants of the Palaeogene cover or the associated Clay-with-Flints. Consequently, the superficial deposits are generally thin or absent, with chalk exposed at the surface beneath a thin soil cover. Both dissolution and recharge to the underlying chalk is predominantly dispersed, with nothing to concentrate flow. Few if any dolines, dissolution pipes or stream sinks occur in these areas.

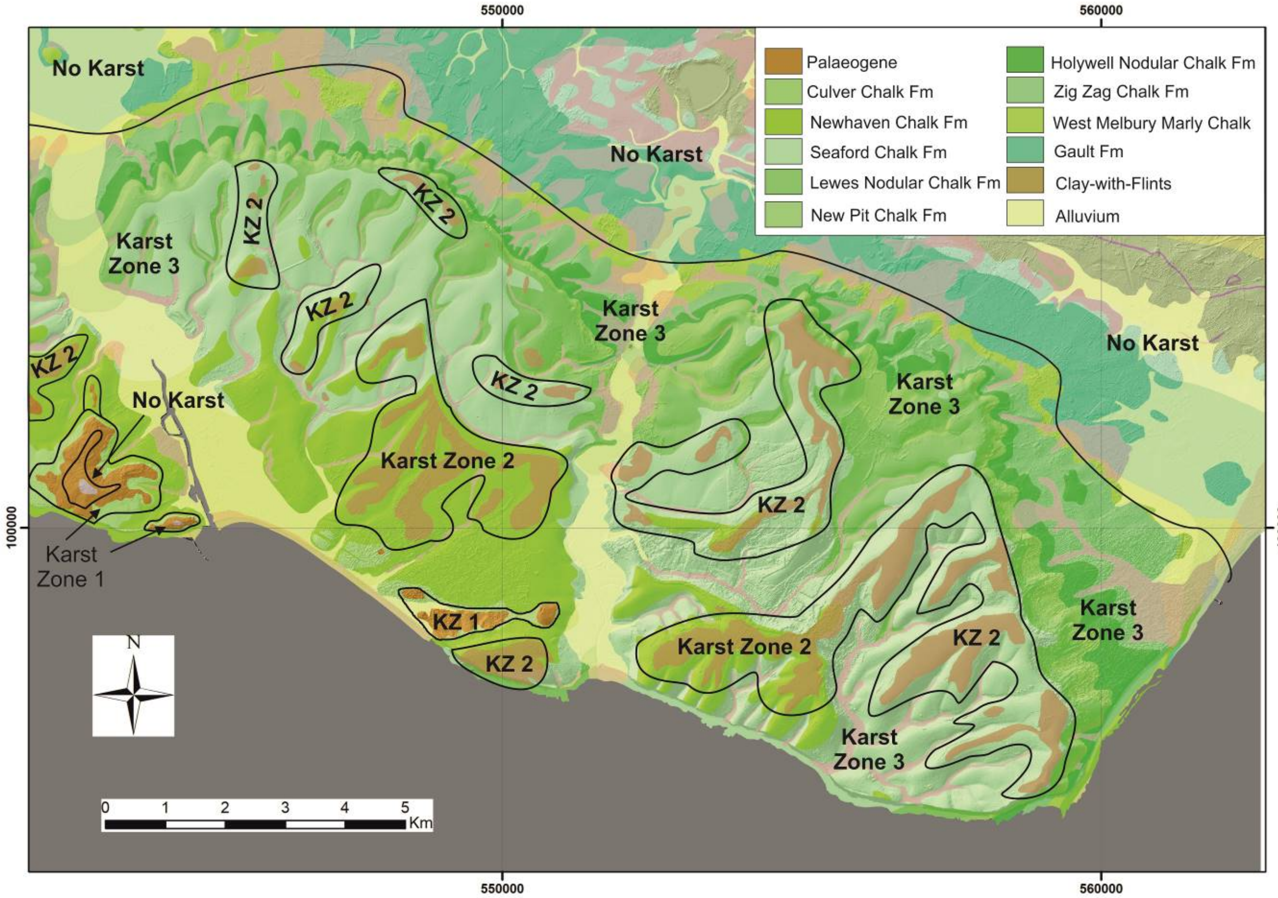

Figure 17. Example of karst zones in the Eastbourne and Seaford Chalk blocks. Geology is BGS Geology 1:50,000 scale bedrock and superficial data. British Geological Survey © UKRI 2021. NEXTMap® Britain elevation data from Intermap Technologies. For a more detailed key, see https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

In East Sussex, surface or near-surface karst features are likely to be restricted to dolines and dissolution pipes in Zone 1 and beneath areas of Clay-with-Flints (Zone 2). Dissolution pipes may occur outside these areas, but they are likely to be small and poorly developed. There are no point-sources of recharge via sinking streams feeding directly into conduits, and thus no stream sink-to-spring conduit systems that are currently active hydrologically. However, the lack of surface features and stream sinks does not preclude the formation of karstic conduits at depth.

Subsurface karst

Evidence from coastal and quarry sections, boreholes and site investigation data indicates that subsurface karst features are common in the Chalk of East Sussex. Typically these features constitute a hierarchy of forms, normally comprising a laterally extensive, stratigraphically constrained zone of spongework or vuggy porosity a few tens of cm thick (the 'tubule karst' of Lamont-Black and Mortimore, 2000) in which are nested numerous small-scale, elliptical, conduits a few mm to several tens of cm in size. In exceptional circumstances some of the conduits grow to cave dimensions; that is they are large enough for human access (Figure 10). The conduits occur typically along specific geological horizons that are, for various reasons, more susceptible to dissolution; these are known as inception horizons (Lowe, 2000; Lowe and Gunn, 1995; Filipponi et al., 2009; Sauro et al., 2013). In the Chalk, these are principally hardgrounds, marl seams, sheet flints and tabular flints (Maurice et al., 2012; Gaillard and Hauchard, 2018). Sheet flints in the upper Lewes Nodular Chalk are the pre-eminent inception horizons for the caves at Hope Gap and Beachy Head. Depending upon the geological setting, the zone of enhanced spongework or 'tubule' porosity may extend for more than several hundred metres along the inception horizon. In plan view, the embedded conduits are likely to form a complex 2D network of anastomosing flow pathways and locally, small caves (Figure 10 and Figure 18).

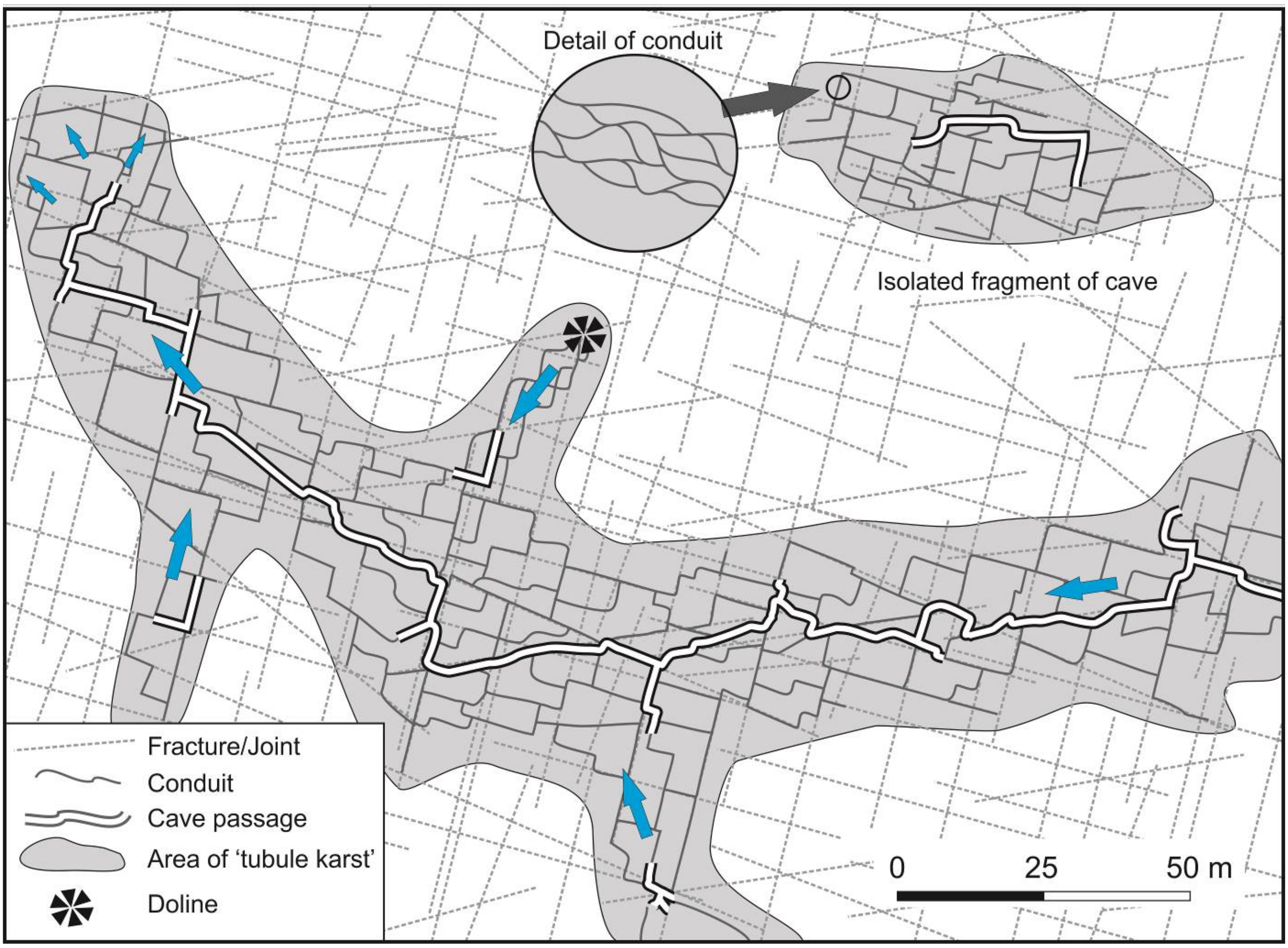

Figure 18. Plan view of a conceptual nested tubule—conduit—cave system formed by mixing dissolution along a single stratigraphical inception horizon. Flow can move in and out of the mixing dissolution conduits via vertical fractures. Based on the Beachy Head Cave system.

The conduits are likely to have been formed by dissolution resulting from the mixing of different saturated $CaCO_3$-H_20 solutions along sheet flints, marl seams and hardgrounds within the saturated zone (Bögli, 1964; Gabrovšek and Dreybrodt, 2000; Farrant et al., in press). The presence of dissolution tubules and conduits away from the coast and well above present sea-level rule out dissolution by mixing of seawater and groundwater. These inception horizons facilitate initial dissolution by promoting lateral flow and mixing of different waters, even when the input solutions are already close to saturation (Romanov, 1993). Mixing dissolution occurs most commonly close to the water table, where groundwater flux is greatest, but it can also occur along favourable inception horizons far below the water table and in confined aquifers. Unlike typical epigenic systems fed by concentrated recharge from the surface they can develop in isolation at depth over timescales of 10^5-10^6 years, and are not part of integrated conduit systems that link surface inputs to spring outlets. Consequently isolated fragments of conduit networks can develop, with water feeding into and out of these conduit segments via fractures and the matrix (Figure 18). Hence, this form of mixing dissolution can create zones of secondary karstic porosity and high transmissivity that are unrelated to surface karst features and surface topography.

In addition to the sub-horizontal mixing dissolution conduits developed along stratigraphical inception horizons, vertical or steeply inclined dissolutional fissures are locally common. Unlike dissolution pipes which are formed by dissolution around the margins of a sediment-filled surface depression, these are formed by water flow and dissolution along a joint or fault. It is possible some may be relict conduits fed by concentrated surface recharge such as former stream sinks. Many examples of vertical and conjugate fractures widened by dissolution and infilled with reddish brown flinty clay occur on the coast at Seaford Head and Beachy Head. Some extend the full height of the cliff, in places up to 95 m high (Figure 19). These can potentially transmit vadose recharge onto stratigraphical inception horizons at depth, particularly in wet weather when rapid 'bypass' flow may be activated (Allshorn et al., 2007). In the saturated zone, such fractures can feed water into and out of the mixing zone conduit networks, enabling water to pass between various inception horizons, and provide potential pathways to surface springs.

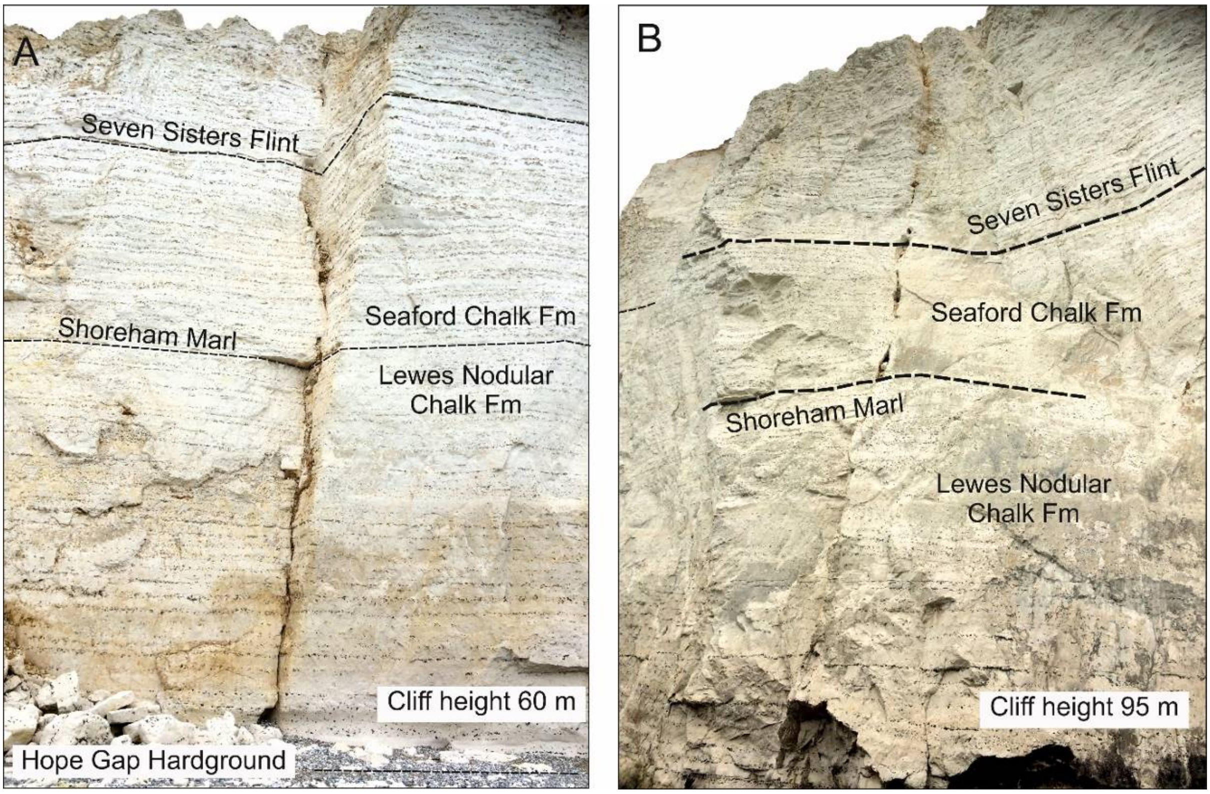

Figure 19. Examples of vertical fractures widened by dissolution to form potential rapid vertical flow pathways in the Seaford Chalk (A is Seaford Head Conduit 2, B is Beachy Head Conduit 8).

Various strands of evidence can be bought together to create a chalk karst conceptual model (Figure 20 and Figure 21). The shallow subsurface is characterised by localised areas of sediment-filled dissolution pipes, concentrated beneath the Clay-with-Flints on the interfluves and beneath river terrace gravels, and a very densely fractured, weathered, locally cryoturbated and de-structured chalk epikarst zone. Recharge is typically dispersed and feeds via the epikarst into the unsaturated zone via numerous fractures and the matrix. Flow is generally slow, but localised concentration of flow along major fractures (generally vertical joints in the Seaford Chalk or conjugate fractures in the New Pit Chalk and Lewes Nodular Chalk formations) or via relict karstic conduits, possibly from former stream sinks, permits some rapid bypass flow in wet conditions, especially in Karst Zones 1 and 2. Most groundwater is close to saturation with respect to $CaCO_3$ by the time it reaches the saturated zone. Within the saturated zone, the presence of marl seams, sheet flints or hardgrounds form localised barriers to flow. Groundwater flow is focussed along these horizons, enhancing lateral flow and forcing saturated waters to mix. This results in mixing dissolution, which generates zones of enhanced porosity, spongework and anastomosing networks of conduits and, more rarely, small caves. These can occur at multiple levels within the aquifer, including in confined settings. They are not necessarily connected to each other or to the surface. Conjugate and vertical fractures permit some cross-stratal flow between the various inception horizons. This flow can be in either direction and may vary temporally according to conditions within the aquifer.

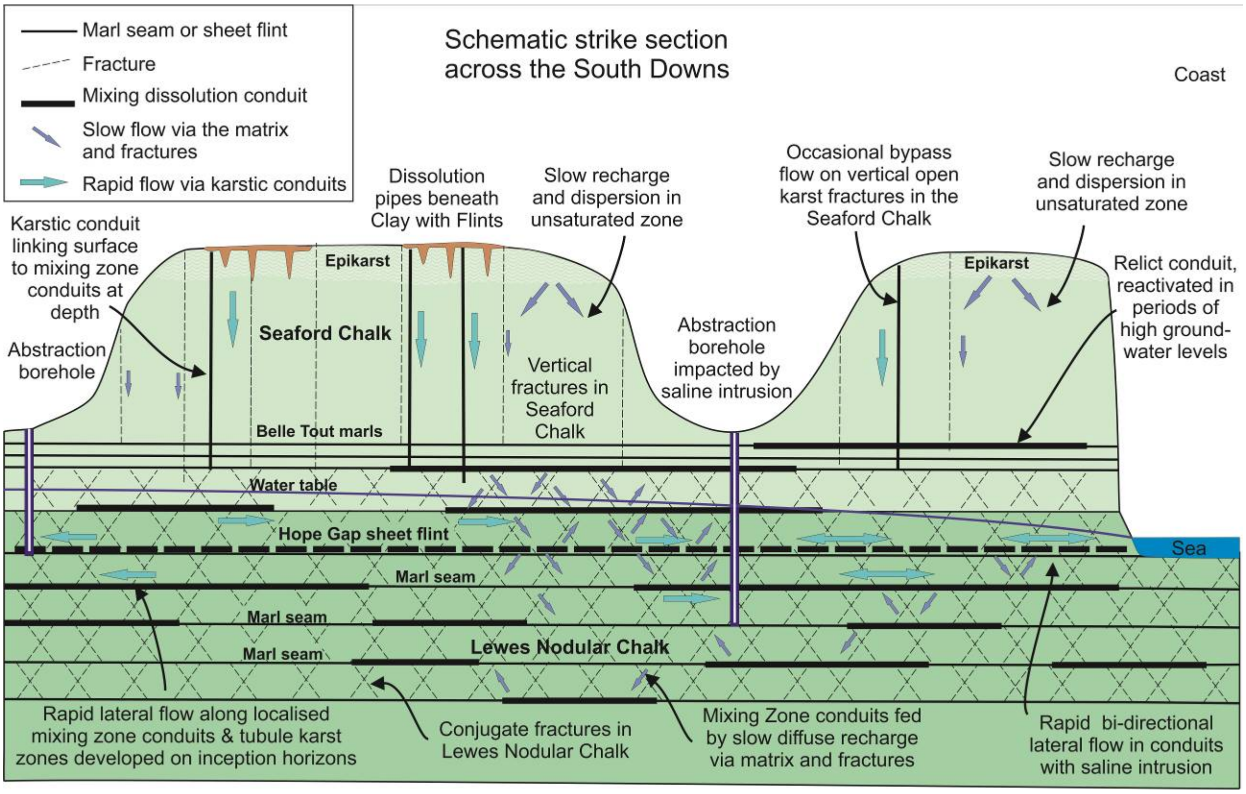

Figure 20. Conceptual model of chalk karst in the East Sussex area; strike section.

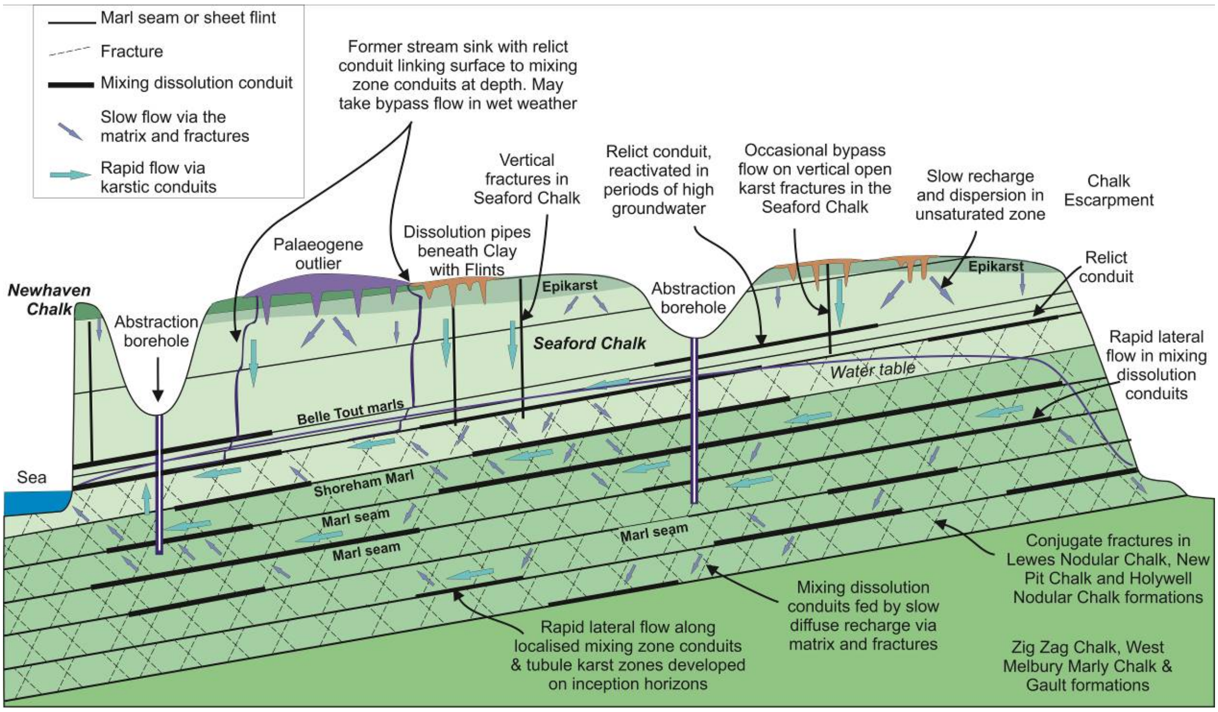

Figure 21 Conceptual model of chalk karst in the East Sussex area; dip section.

Implications for ground water management

The formation of laterally extensive mixing dissolution conduits and zones of tubule karst at depth has implications for groundwater management. The result is a highly heterogeneous aquifer with slow vertical flow in the unsaturated zone, via the matrix and unmodified fractures, feeding into lateral conduit systems and high-porosity spongework with more rapid flow at depth. The evidence for deeper karstic development shown by the coastal survey suggests there may be rapid flow paths in the saturated zone through integrated sub-horizontal conduit/fissure systems. Such rapid flow-paths, if present, have implications for pollutant transport and help explain the unexpectedly low hydraulic gradients across much of the East Sussex chalk aquifer.

They also have implications for Source Protection Zones (SPZs). The Environment Agency have established SPZs around all boreholes from which groundwater is abstracted for potable supply. SPZ 1 is defined by a 50 day travel time from any pollution source below the water table to the groundwater abstraction and has a minimum radius of 50 metres around the abstraction. SPZ 2 is similar but the area is defined by a 400 day travel time. SPZ 3 is defined as the area around a groundwater abstraction within which all groundwater recharge (whether derived from precipitation or surface water) is presumed to be discharged at the abstraction. The SPZ areas are derived from groundwater travel times calculated principally from groundwater models that assume the chalk is a single porous medium. This probably applies in the chalk matrix, but groundwater velocity in conduit/fissure systems will be two or more orders of magnitude faster. Catchment zones in karstic aquifers cannot be adequately resolved using methods assuming Darcian flow. Given the evidence for mixing dissolution conduits, it seems plausible that saturated zone groundwater flow might be possible in less than 50 days from areas outside the current Source Protection Zones 1 & 2. Tracer tests elsewhere suggest this may be commonplace (Maurice et al., 2006; 2010).

There is uncertainty regarding the spatial extent of such karstic conduit/fissure networks, but it is possible that they extend beyond the current modelled abstraction catchment areas. Once in the saturated zone, diffuse and point source pollutants may be able to travel long distances within conduit networks, potentially rapidly. Also, the presence of laterally extensive conduits means that there is the potential for rapid flow in the saturated zone from the coast to sites inland, giving rise to the potential for saline intrusion.

By their nature, conduits formed at depth by mixing dissolution are isolated from the surface and fed by slow matrix- and fracture-flow through the unsaturated zone. Consequently the potential for contamination from the surface is relatively low. However, intermittent bypass flow via a small number of open vertical fractures or conduits within the unsaturated zone (Allshorn et al., 2007) can feed water more rapidly to the saturated zone. Potential pathways include the dissolutionally widened vertical fractures observed in coastal sections (Figure 19), and conduits fed by stream sinks (where present). The latter represent the top end of an integrated karstic conduit system and thus pose the greatest contamination risk to groundwater abstractions. The fate of point-source pollutants at the surface will depend upon whether they are located above or close to such vertical dissolution fissures, enabling rapid transport through the unsaturated zone. If they are not located close to such features there will be considerable attenuation within the unsaturated zone, with dilution and dispersion (and diffusion for solute pollutants). Where rapid flow pathways connecting the surface to conduits at depth are present, there is a much greater risk of contaminants reaching the saturated zone with little or no attenuation. Where high infiltration rate soakaways, leaking pipes and sustainable drainage systems (SuDS) occur on areas with a high density of open fractures there is a potential for rapid flow to abstraction boreholes.

In the absence of obvious surface karst, assessing the locations and frequency of such pathways is extremely difficult, but detailed knowledge of the lithostratigraphy can provide a guide to the type of fractures likely to be present (Mortimore et al., 1996; Mortimore and Pomerol, 1997). High-angle (60°–70°) conjugate fractures are more typical of chalks with a high density of marl seams (the Holywell Nodular Chalk, New Pit Chalk, Lewes Nodular Chalk, and Newhaven Chalk formations). Their conjugate nature means they are less likely to cut through more than a few tens of metres of chalk. In more homogeneous chalk units with few marl seams (the Seaford Chalk and Culver Chalk formations), vertical joint sets are more typical, such as those shown in Figure 19. These fractures can be pervasive and cut through >50 m of chalk. Both types of fracture create potential flow pathways between stratigraphical inception horizons and form an important component of secondary porosity.

Conclusions

The Chalk of East Sussex has plenty of evidence of both surface karst (dolines, dissolution pipes) and subsurface conduits and caves, which impact groundwater flow through the aquifer. Evidence from a coastal survey and from other data sources including downhole CCTV imagery suggests that many karstic conduits (some large enough to be explored as caves) are present within the aquifer. Over fifty cave and karst features occur along the coast between Seaford and Eastbourne, including several caves. These are likely to have been formed by mixing dissolution along key stratigraphical inception horizons, in particular sheet flints and marl seams in the upper Lewes Nodular Chalk and Seaford Chalk formations. The presence of laterally extensive zones of highly transmissive porous chalk with small conduits and local caves enables rapid lateral groundwater flow to occur, resulting in a highly heterogeneous aquifer. They account for much of the secondary permeability of the Chalk aquifer. These highly transmissive zones permit saline intrusion and generate very low hydraulic gradients (1-2 m/km) within the Seaford and Eastbourne chalk blocks. The risk to groundwater from surface-derived contamination is likely to be quite low because these mixing zone conduits do not connect to the surface; they are fed by diffuse recharge through the unsaturated zone. The exception is where dissolutionally enlarged, open, vertical fractures or conduits fed by stream sinks or focussed surface drainage are present enabling rapid bypass flow to occur, particularly during wet periods. Recognising the presence of karstic conduits and highly transmissive zones developed along specific stratigraphical inception horizons is critical to enable development of more-accurate groundwater models.

Acknowledgements

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