The genesis and evolution of karstic conduit systems in the Chalk.

Andrew R Farrant (1), Louise Maurice (2), Daniel Ballesteros (3,4), Carole Nehme (3).

(2) British Geological Survey, Keyworth, Nottingham, NG12 5GG, United Kingdom.

(2) British Geological Survey, Crowmarsh Gifford, Wallingford OX10 8ED, United Kingdom.

(3) UMR 6266 IDEES, University of Rouen-Normandy/CNRS, Mont Saint-Aignan CEDEX, France.

(4) Departamento de Geodinámica, Universidad de Granada, Campus Fuentenueva s/n 18071 Granada, Spain.

Abstract

The Upper Cretaceous Chalk Group is renowned as a major aquifer, but the development of secondary porosity due to karstic conduits is poorly understood. Hydrogeological data and evidence from boreholes, sections, and tracer tests indicate that dissolutional conduits occur throughout the Chalk aquifer. Here, we assess the evidence for Chalk karst, and combine it with theoretical models of dissolution and cave formation to produce a conceptual model for the development of karstic conduits. Dissolution due to the mixing of saturated waters of contrasting chemistry along key lithostratigraphical inception horizons form extensive but isolated conduit networks. These form a significant proportion of the secondary porosity and enhance permeability. They prime the aquifer for the development of more integrated conduit networks formed by focussed recharge of unsaturated surface derived water. However, the porous, well-fractured nature of the Chalk means that the time needed to form large integrated cave systems is often longer than timescales of landscape change. Continued landscape evolution and water table lowering halts conduit development before they can enlarge into cave systems except where geological and geomorphological settings are favourable. Groundwater models need to consider the formation of secondary karst permeability as this has a major influence on groundwater flow.

The Upper Cretaceous Chalk Group of northwestern Europe (**Error! Reference source not found.**) is a major aquifer, covering over 160,000 km^2 and supplying more than 60% of the drinking water of northern France, southeast England, Belgium, Denmark and Netherlands (Price et al., 1993). The Chalk is a highly porous aquifer, with most (20-40%) of the porosity within pores 100-600 nm in size (MacDonald & Allen 2001; Faÿ-Gomord et al., 2016). Chalk matrix permeabilities are relatively low, between 10^{-4} and 10^{-2} m day^{-1} (Price et al., 1976) because the typical pore throat diameter of 0.1-1 µm is too small to permit efficient flow (Vázquez et al. 2016; Gaillard et al. 2018). Despite the chalk matrix having the combination of very low hydraulic conductivities and very high porosity values, in some areas transmissivity values are very high, commonly exceeding 1000 m^2 day^{-1} (Descamps et al., 2017). Much of the conductivity is within secondary porosity due to fracturing and/or dissolution (Zouhri et al., 2009; Mougin et al., 2011). Understanding the development of the secondary porosity, and how it affects permeability is of increasing importance as Chalk aquifers become stressed due to diffuse and point source pollution, increasing groundwater abstraction and climatic change.

Three main void types create most of the secondary porosity: fractures, fissures and conduits (Maurice et al., 2006). Fractures are any planar discontinuity in the Chalk that has a finite aperture. These include joints, including bed-parallel fractures, small faults and fractures associated with stratigraphical discontinuities. Where these have been enlarged by solution (karstic modification), but retain the generally planar geometry of unmodified fractures we use the term ‘fissure’. These have trace length to maximum aperture ratios greatly in excess of 10. These are distinct from ‘conduits’, which are tubular voids formed by solution which have a cross-sectional aspect ratio of ~1. Observed Chalk conduits tend to be ~ 10 mm to ~ 1000 mm in diameter and inferred to be tens of metres to kilometres in length. Where large enough to be enterable by humans, a conduit can also be termed a cave.

Determining how conduit systems develop and why they occur where they do is critical for developing robust conceptual models of aquifer behaviour. In this paper, we combine existing concepts and models of karst development with hydrogeological data and observations from sections, borehole data and chalk caves, together with an understanding of Chalk lithostratigraphy and landscape evolution to create a conceptual model for conduit genesis and evolution in the Chalk.

The Chalk

The Late Cretaceous Chalk Group of the Anglo-Paris basin crops out extensively in southern and eastern England, and much of northern France where it varies between about 200 and 700 m in total thickness (Figure 1). The composition of the Chalk is relatively uniform, mainly comprising pure fine-grained microporous limestones, although with important variations in clay content, hardness, texture, fossil content and occurrence of flint (Juignet, 1974; Ragot, 1988; Rawson et al., 2001; Hopson, 2005; Hoyez, 2008). 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; Gallagher et al., 2012; Gaillard et al., 2018). These include hardgrounds, marl seams, and various types of flint bands (semi-tabular, nodular and sheet-flints). Some are local in extent, sometimes arranged in complex 3D geometries; others are more regional scale or 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. They are especially important in low-dip settings. Evidence from cliff and quarry sections, boreholes, accessible chalk caves, adits and springs suggest these horizons play an important role in the development of conduit networks (Ballesteros et al., 2020).

Hardgrounds are characterized by nodular, bored chalk, often mineralized by carbonate, glauconite and phosphate (Kennedy and Garrison, 1975; Bromley and Gale, 1982, Quine and Bosence, 1991; Juignet and Breton, 1992; Amedro and Robaszynski, 2000). They are a common feature in certain parts of the succession, notably within the Turonian and Coniacian chalks (Mortimore 2011, 2019). They are particularly common in basin margin settings such as the Normandy area in northern France. Here, more than fifty hardgrounds are recognized in the Cenomanian to middle Turonian chalks (Juignet and Breton, 1992; Lasseur et al., 2009), with a further thirty hardgrounds in the upper Turonian to lower Campanian chalks (Hoyez, 2008). Fewer hardgrounds occur in the more basinal Chalk sequences of southeast England (Figure 2), concentrated in the Lewes Nodular Chalk and Holywell Nodular Chalk formations. Sponge beds are similar to hardgrounds in that they represent hiatuses in sediment deposition, enabling colonization of the sea floor by sponges (Quine and Bosence, 1991). They are characterized by indurated, often iron stained horizons with fossil sponge remains. In some areas, hardgrounds are associated with phosphatic chalks (Mortimore et al., 2017; 2019).

Marl seams are thin concentrations of terrigenous clay or in some cases bentonitic ash fall deposits (Wray, 1999) typically a few millimetres or centimetres thick. Some marls form distinctive marker beds across the Anglo-Paris basin (Figure 2) (Mortimore, 2018, 2019). Their occurrence and thickness varies both spatially and temporally through the sequence, thinning over structural highs.

Stratified flint bands are common in the Chalk Group and form nodules, semi-tabular bands and sheets. The most common are flint nodules typically 5-40 cm in diameter arranged in regularly spaced horizontal bands ~0.2-1.5 m apart through the succession from the early Turonian to the Campanian (Mortimore, 2018, 2019). In Normandy, Cenomanian chalk is also flinty (Quine and Bosence, 1991). Sometimes, flint forms semi-tabular bands, some of which represent identifiable basin-wide marker beds such as the Coniacian Seven Sisters Flint Band (Mortimore and Pomerol, 1991). Sheet-flints are semi continuous sheets of flint 1-10 cm thick formed by the silicification of shear planes and other sub-horizontal fractures during early diagenesis (Mortimore, 2011). These can extend laterally for hundreds of metres, and locally kilometres.

The stratigraphic disposition of the potential inception horizons, variations in the bulk lithology and lithologically influenced changes in fracture distribution and density can influence the distribution of conduit systems in the Chalk. In the UK, a high-resolution Chalk stratigraphy (Mortimore, 1986; Rawson et al., 2001; Hopson, 2005) provides a framework for understanding the lithostratigraphical influence on karst development (Figure 2), outlined below. A similar stratigraphy can be applied to the Chalk in northern France (Hoyez, 2008) which is part of the same Anglo-Paris basin. Each formation has differing hydrogeological properties resulting from variances in lithology, rock mass strength, fracture style and spacing, the presence or absence of marl seams, and the frequency and style of flint bands, hardgrounds and other stratigraphic discontinuities. Comparable stratigraphical frameworks can be applied to other Late Cretaceous Chalk basins in northern Europe. A similar approach can be used for other chalks globally.

Grey Chalk Subgroup

The oldest chalk is the Grey Chalk Subgroup (West Melbury Marly Chalk and Zigzag Chalk formations) comprises 65-80 m of alternating layers of low to medium density marls and thin limestone bands, passing up into a thicker marly chalk. In general, the chalk is rather marly and not conducive to karstic development. The limestone bands have open vertical joint sets, which may help concentrate flow on the underlying marls, giving rise to perched water tables, localised conduits and spring lines (Mortimore, 1993). In northern France, the equivalent strata (Rouen & St-Join formations) are very flinty with several significant hardgrounds.

White Chalk Subgroup

The Holywell Nodular Chalk Formation consists of medium to very high-density, shell-rich grainy, nodular chalks with many marl seams including the Plenus Marls Member, a thin alternating series of marls and chalk 1-3 m thick, at the base. The hard nodular chalk is extensively fractured by steeply inclined conjugate joints. The underlying Plenus Marls, which impede vertical water movement, are not jointed but dissipate stress sub-horizontally, so opening fractures in the rock above. Spring lines developed on the Plenus Marls have been exploited for water supply, for example at Holywell, near Beachy Head in Sussex (Mortimore 1993). The New Pit Chalk Formation, generally between 25 and 55 m thick, consists of massively bedded, low to medium density white chalks, with marl seams and rare flints. The Formation displays numerous well-developed conjugate joint sets, which often dissipate along marl seams. The overlying Lewes Nodular Chalk Formation comprises interbedded low to very high-density nodular chalks and hardgrounds interbedded with softer chalks up to 50 m thick. Marl seams, hardgrounds and flints are common, and in parts of southern England, the formation includes the ‘Chalk Rock’ (Bromley and Gale, 1982) a set of coalesced hardgrounds.

Of all the Chalk units in the UK, the Seaford Chalk Formation has by far the largest outcrop. It comprises 50-80 m of massively bedded, low to medium density chalk with regular orthogonal joints and abundant seams of large nodular and semi-tabular flints. Hardgrounds are locally developed in some areas, with a few marl seams at the base. Some of the large flint bands, notably the Seven Sisters Flint (Mortimore, 1986), form almost continuous seams. The Newhaven Chalk is composed of 50-75 m of blocky, low-density white chalks with numerous marl seams, discontinuous small flint bands, and well-developed conjugate joint sets. The marls thin to a few mm thick over syn-sedimentary positive features (Mortimore, 1986; Mortimore and Pomerol, 1987, 1991). The flints are generally much smaller and less continuous compared to the underlying Lewes Nodular Chalk and Seaford Chalk formations, and tabular and sheet flints are not so well developed. Synsedimentary channels with hardgrounds and phosphatic chalks occur locally within the Newhaven Chalk, notably at Stonehenge (Mortimore et al., 2017). The overlying Culver Chalk is composed of up to 60 m of low to medium-density white chalks with some very strongly developed nodular and semi-tabular flints (Mortimore, 1986). The formation lacks significant marl seams and sheet flints are less common. The Portsdown Chalk consists of relatively soft white chalk with common marl seams and some large nodular and paramoudra flints. It has a very limited outcrop.

Chalk fractures

The Chalk is well fractured. The dominant regional fracture set across northwestern Europe trends NW-SE, with a minor crosscutting NE trending set. The most common fracture styles are vertical extension joints, conjugate steeply inclined joints, and bedding parallel fractures (Bevan and Hancock, 1986; Price, 1987; Bell et al., 1999). The style of fracturing is influenced by lithology. Units with a high density of marl seams (Holywell Nodular Chalk, New Pit Chalk, Lewes Nodular Chalk, and Newhaven Chalk formations) are dominated by high angle (60–70°) conjugate fractures (Figure 3). The marl seams dissipate some of the stresses within the rock mass, inducing low angle shears and sub-horizontal bed parallel joints (Mortimore et al., 1996; Mortimore and Pomerol, 1997). In more homogeneous chalk with few marl seams (Seaford Chalk and Culver Chalk formations), vertical joint sets are typical (Figure 3). These fractures create potential flow pathways between stratigraphical inception horizons and form an important component of secondary porosity.

Fracture densities within the Chalk vary widely. Joint spacing is in the range of 0.07-1 m for bedding-parallel fractures and 0.1-2 m for bed-normal sets, with higher values being recorded in chalks without marl seams (Ward et al., 1968; Bevan and Hancock, 1986; Mortimore et al., 1996; Bell et al., 1999). Both the bedding parallel and high angle conjugate & vertical fractures approximate to lognormal distributions (Bloomfield, 1996), with geometric mean trace lengths of 0.15 m and 0.3 m, and spacing of 0.10 m and 0.12 m, respectively. The vertical fracture sets show a wide variability in trace length, most are less than 3 m in length and typically less than one metre long, reflecting the spacing between stratigraphical discontinuities and bedding parallel fractures. These values are likely to vary depending on lithology and weathering. However, some vertical fractures are pervasive, extending >50 m through the succession. Due to the presence of two orthogonal joint sets and the high joint density, connectivity is generally very high. By comparison, the fracture spacing in Carboniferous limestones in the Burren, western Ireland is much greater, ranging from 0.1 to >10 m (Gillespie et al., 2001) with a mean of 1.20 m (Odling et al., 1999).

Evidence of Chalk karst

The Chalk is a carbonate aquifer. The same dissolutional processes that operate in other carbonate aquifers such as the Carboniferous limestones in the UK also act on the Chalk. Yet, traditionally, the Chalk has not been viewed as karstic, and karst features are not usually included in groundwater models. The aquifer is typically modelled as a homogeneous porous medium (Le Vine et al., 2016; Zghibi et al. 2016), albeit with some variation in hydraulic conductivity with depth or multiple layers depending on the complexity of the model. The role of dissolution and the development of secondary karstic permeability is often not considered, or it is assumed to have a minor role in aquifer development (Roux et al., 2019). Yet karstic landforms including sinking streams, dry valleys, dissolution pipes and dolines, large springs, conduits and caves are locally common (Atkinson and Smith, 1974; Juignet P., 1988; Banks et al., 1995; Waltham et a;., 1997; MacDonald et al., 1998; Lamont-Black and Mortimore, 2000; Laignel et al., 2004; Maurice et al., 2012; El Janyani et al., 2014; Grube et al., 2017; Nehme et al., 2020; Farrant et al., 2021a). Groundwater geochemistry may display significant spatial heterogeneity (Barhoum et al., 2014).

Evidence from boreholes and adit systems in the Chalk indicate that most inflows are from discrete point inputs, some of which yield very large flows with discharges up to 174 l/s (Downing et al., 1993; Worthington et al., 2000). Analysis of downhole CCTV data, temperature and flow logs, and borehole dilution tests (Gallagher et al., 2012; Farrant et al., 2021a, 2021b, 2021c and unpublished data from South East Water and Affinity Water) indicates that the majority of water supply abstraction boreholes expose one or more dissolutional conduits ~5-20 cm in diameter, many of which are actively flowing. The data suggests small-bore conduits are ubiquitous in much of the aquifer, including confined parts of the aquifer. For example, CCTV data from a borehole near Aldershot proved flowing conduits in the Chalk at 60-70 m depth, beneath over 40 m of Palaeogene cover (Farrant et al., 2018).

Data from single borehole dilution tests (Maurice et al., 2012) suggest these conduits are concentrated near the water table with densities of $\sim$0.3 m^{-1}, but are still present at depths of more than 40 m below the water table ($\sim$0.07 m^{-1}). Quantitative tracer test results suggest that groundwater flow may be through a complex combination of small conduits, typically 10 to 1000 mm in diameter and fissures with apertures of 1 to 50 mm (Maurice et al., 2006). Flow velocities measured from tracer tests can be >300-400 m h^{-1} (Maurice et al., 2006; Keim et al., 2012) and spring discharges in excess of 5 m^3 s^{-1} (Brenner et al., 2018). Some hydrogeological studies consider the Chalk as a triple porosity aquifer, with a combination of fracture and matrix porosity, and conduit permeability (Worthington, 1999; Pennequin et al., 2017). Others regard it as a karst aquifer in which karstification is less well developed than in other more massive and indurated limestones (Maurice et al., 2006; Slimani et al., 2009; El Janyani et al., 2012, 2014).

Chalk caves (i.e. those conduits that are large enough for a human to explore physically) are known to occur locally across the Chalk outcrop (Reeve, 1979), usually on coastal sections where cliff retreat has exposed the caves. Surveys of the cliff sections between Beachy Head and Seaford Head (Figure 1) in the South Downs (Farrant et al., 2021a,b,c) revealed over 60 karstic conduits, including the longest Chalk cave in the UK, Beachy Head Cave (Reeve, 1979; Waltham et al., 1997). The greatest concentration is at Seaford Head where 18 individual conduits developed on a sheet flint are mapped along a 400 m stretch of coast. Similar conduits occur at St Margaret's Bay near Dover including Canterbury Cave). These are all developed on sheet flints in the Lewes Nodular Chalk Formation at depths locally >100 m.

There is clear evidence from tracer tests and large springs for well-developed, fully integrated conduit systems elsewhere in southern England, especially close to the Palaeogene margin where point source allogenic recharge occurs (Atkinson and Smith, 1974; Banks et al., 1995; MacDonald et al., 1998; Maurice et al., 2012). Examples include the southern margin of the Vale of St Albans in the Chiltern Hills, the Newbury area, around Farnham in Surrey, parts of the North Downs, south Hampshire, and around Bedhampton and Chichester in the South Downs (Figure 1).

Karst and cave systems are particularly well developed in the Upper Normandy region of France (Figure 1), for example at Caumont and Petite Dalles (Rodet 1992, 2007; Rodet and Lautridou 2003; Nehme et al., 2020). Large karst springs at Norville, Radicatel and Yport near Fécamp are important public water sources (Roux et al., 2019). Over 50 cave systems have been recorded, with an aggregate passage length of over 10 km. The caves are typically relict conduit segments comprising complex anastomotic networks and branchwork systems. Discrete levels of cave development are preserved at elevations up to ~ 90 m above the present Seine River with the oldest, highest caves dating back to 1-1.2 million years (Nehme et al., 2020). Some, such as the cave system at Caumont near Rouen are still hydrogeologically active. This cave system, discovered and partially truncated during the excavation of an underground chalk quarry contains a 2.4 km long vadose stream passage (Rivière des Robots) with a discharge of 1-2 l/s. The stream feeds into the adjacent River Seine (Rodet and Lautridou, 2003). Many of the relict caves are choked with sand, silt and clay derived from the overlying Cainozoic sediments (Laignel et al., 2004; Rodet et al., 2006; Chédeville et al., 2015), and have only been discovered by excavation. The 1.4 km long Grotte de Petit Dales, near Fécamp consists of a sub-horizontal phreatic conduit 2-5 m diameter, which was almost completely infilled with loessic and other detrital sediments prior to excavation by cavers.

Understanding the genesis and evolution of karstic conduit systems in the Chalk is the first step to improve conceptual models of aquifer behaviour. Before discussing Chalk karst systems, and how they compare to more classical karst aquifers, it is first necessary to understand how karstic systems develop.

Conduit development in karst aquifers.

Conduit inception and karst development in carbonate aquifers has been extensively studied (Palmer, 1991; Dreybrodt, 1996; Palmer, 2002; Dreybrodt and Gabrovšek, 2002). Two interrelated process are dominant in the Chalk, epigenic carbonate speleogenesis by surface recharge of unsaturated CO_2 rich water, and speleogenesis due to mixing of saturated waters of contrasting chemistry, usually those differing in CO_2 or H_2S content, often at depth.

The permeability of a carbonate aquifer prior to karstification results from an interconnected network of small fractures including joints, faults, bedding plane partings and other stratigraphical discontinuities. For epigenic carbonate speleogenesis, initial flow pathways are distributed along these interconnected fractures, which are then subject to dissolution linked to the chemical kinetics of the system H_20-CO_2-$CaCO_3$ (Dreybrodt, 1987, 1988). The dissolution rate for calcite is largely dependent on the chemical under-saturation of the water, but only weakly on flow velocity, turbulence or viscosity (Dreybrodt et al., 2005). The dissolution kinetics is fast if the calcium concentration is far from saturation with respect to calcite (first-order kinetics) and slow (higher-order kinetics) if the concentration is close to saturation (Dreybrodt, 1996, Dreybrodt and Eisenlohr, 2000). When chemically aggressive surface derived water enters the aquifer via fractures, the initial rate of dissolution is rapid, but once the saturation ratio reaches a critical value (typically around 60-90% depending on temperature and CO_2 content), the rate of dissolution slows markedly.

Consequently, water entering the aquifer along fractures tends towards saturation, but never quite reaches it. This enables slow dissolution to take place along the entire length of a flow pathway from input to outlet. Where dissolution is rapid, the H_20-CO_2 solution tends towards equilibrium rapidly and thus cannot penetrate deeply into the aquifer without losing most of its solutional power (Kaufmann & Braun 1999; Romanov et al. 2003a). If dissolution rates are very low, then the time required for conduit development becomes geologically unfeasible. The initial phase of conduit development (conduit inception) occurs by the slow dissolution of the host rock by a small amount of water travelling slowly along fractures over long distances. This can take place throughout the aquifer over 10^3-10^6 year timescales (Kaufmann, 2009). As the system develops by gradual dissolutional widening of the fractures, preferred flow pathways evolve, which attract more and more flow (Siemers and Dreybrodt, 1998).

Once a flow pathway is enlarged sufficiently such that aggressive water can penetrate through to the outlet, typically once a conduit is large enough to permit turbulent flow, there is a sudden transition to rapid dissolution along the entire flow path. This transition, often termed 'breakthrough' is marked by a marked increase in the conduit enlargement rate to a maximum of ~0.1 cm per year (Palmer, 2007). Once a particular flow pathway has achieved breakthrough, it will rapidly enlarge, capturing flow from adjacent fractures and flow pathways (Dreybrodt et al., 2005). These alternative flow pathways then cease to enlarge, or become redirected towards the conduit that has achieved breakthrough. Over time, some of these redirected pathways also develop sufficiently to achieve breakthrough, leading to the self-organisation of an integrated conduit network (Worthington and Ford, 2009).

Using finite-difference modelling, Dreybrodt (1990, 1996) and Palmer (1991) showed that the breakthrough time needed for a fissure to reach its maximum growth rate decreases with the cube of the initial fissure width, and with roughly the 4/3 power of the hydraulic gradient and the -4/3 power of the flow distance (Audra and Palmer, 2011, 2013). Fracture aperture is particularly important. Under conditions of laminar flow, the rate of flow through a perfectly planar smooth-sided fracture with an aperture size a (m) follows a cubic law, $T = ga^3/12\mu$, where T is the transmissivity of the fracture (m^2/s), g is gravitational acceleration (m/s) and μ is the kinematic viscosity of the fluid (m^2/s). The most favourable flow paths for conduit development are those with the shortest breakthrough time, typically those with high discharges and short flow distance along fractures with a high initial aperture. In realistic scenarios, initial fractures 0.01-0.1 cm wide only require around 10^3-10^4 years to achieve the maximum enlargement rate.

The second important process in karst aquifers is mixing dissolution (Figure 4), particularly during conduit inception. When two H_2O-CO_2-$CaCO_3$ solutions, saturated with respect to calcite but with different chemical compositions mix, an under-saturated solution with renewed capability of dissolving $CaCO_3$ is generated (Bögli, 1964, 1980; Wigley and Plummer, 1976, Dreybrodt, 1981; Gabrovšek and Dreybrodt, 2000; Romanov et al., 2003b). This is a result of the non-linear relation between the calcium equilibrium concentration and the carbon-dioxide pressure. Differences in CO_2 concentrations of just 30% can initiate mixing dissolution. This can occur when water infiltrating vertically through the aquifer is, on reaching the saturated zone, forced to migrate sub-horizontally along a sheet flint or other lithological heterogeneity, mixing with water derived from other sources, for example water which has percolated through a different soil composition with high pCO_2 levels. Romanov (1993a) demonstrated that where different autogenic inputs that are >99% saturated, mixing corrosion behaviour and higher order kinetics cause very slow dissolution, creating conduits that can eventually reach metre-scale diameters without passing through a breakthrough stage (Faulkner, 2006). Mixing dissolution processes tend to form complex small-scale anastomosing conduits or upwards branching dendritic branchwork networks of dissolutional voids focussed along discontinuities. These often have a vuggy porosity sometimes referred to as 'spongework' or 'swiss cheese' texture (Palmer, 1991). Such features have been identified above stratigraphical discontinuities in the Chalk, where they have been termed 'dissolution tubules' (Lamont Black and Mortimore, 2000). The numerous small-bore anastomosing conduit networks observed on CCTV imagery from boreholes are likely to have formed by this process.

Mixing dissolution can occur at significant depths (~10^2-10^4 m) provided the groundwater flux enables mixing, although with increasing depth, thermal and other hypogene processes possibly become more important. Evidence of flowing conduits from downhole video logs of abstraction boreholes in the UK Chalk aquifer suggest mixing dissolution can occur at depths >100 m. The resulting dissolutional cavity can be completely independent from the surface and occur within confined parts of the aquifer beneath thick Palaeogene deposits (Farrant et al., 2018). This process can generate isolated conduits at depth even where sinking streams or other forms of point recharge are absent.

The rate at which epigenic and mixing dissolution conduit networks develop depends on dissolution kinetics, initial fracture aperture, fracture density and connectivity, saturation of water entering the aquifer and the style of aquifer recharge (Gabrovšek and Dreybrodt 2001; Kaufmann 2009; Dreybrodt et al. 2010). Conduits evolve through three stages, from initial inception, to gestation and rapid enlargement, followed by either abandonment, vadose modification or collapse (Figure 5). Conduit inception is the slow creation of small dissolutional voids along certain preferred horizons and discontinuities over a hundred thousand to a few million-year timescales (Lowe, 1992, 2000). Inception begins as soon as the pore space increases steadily due to dissolution processes (Filipponi et al. 2009). The inception process often starts at depth by mixing dissolution or by acids generated by the oxidation of pyrite or other sulphides, independent of surface environments. Gestation occurs when these begin to link up to form networks of small conduits prior to breakthrough. The transition from conduit inception to gestation is not defined by a change in the permeability of the rock mass but by the change of the hydraulic boundary conditions (Filipponi 2009), for example the increased prevalence of surface derived epigenic recharge. The gestation phase ends when the karst conduit is large enough to allow turbulent flow and breakthrough occurs. Dissolution then becomes more rapid. Numerical calculations suggest that for realistic values of initial fracture or discontinuity width (0.01 cm), flow length (~1 km) and hydraulic gradient (~0.01), the time taken to breakthrough is typically in excess of several million years. With larger initial fracture apertures, breakthrough times are much shorter; times in the order of hundreds of thousands of years are typical in epigenic caves (Audra, and Palmer, 2011, 2013). Epigenic conduit breakthrough times will be more rapid if mixing dissolution has increased initial fracture/discontinuity apertures. Under favourable conditions, a traversable conduit can form in around 10,000 years (Dreybrodt et al., 2005). The time for conduit enlargement after breakthrough is typically much more rapid, and conduits can reach human size (becoming caves) within a few thousands of years (e.g. White 1988; Dreybrodt & Siemers 2000; Palmer 2002). In a simulation of the Floridian karst aquifer, de Rooj and Graham (2017) were able to develop a well-connected conduit network in about 20,000 years.

Formation of conduit systems in the Chalk

Modelling of conduit development (Siemers and Dreybrodt, 1998) indicated that the time taken to achieve breakthrough and develop conduits is also influenced by the climate, lithology, geological setting, structure (fractures and folding), geomorphological setting and landscape evolution. Of these, the unusual lithology of the Chalk is especially significant, whilst the latter two are often overlooked when considering how the aquifer functions. The impact of these factors on the development of karstic conduits in the Chalk aquifer are discussed in more detail in this paper.

Role of Chalk lithology and fractures.

In many karstic aquifers, dissolution is focussed on certain stratigraphical discontinuities 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 and tabular flints (Maurice et al., 2012; Gaillard and Hauchard, 2018). All these laterally extensive inception horizons can facilitate initial dissolution through flow concentration and mixing of different saturated $CaCO_3$-H_20 solutions, even when the inputs are nearly saturated (Romanov, 1993a). Most of the known Chalk caves (i.e. those conduits large enough to physically enter) in southern England are developed on sheet flints (Figure 6), including those at Beachy Head and Seaford Head in Sussex (Reeve, 1979; Farrant et al., 2021a), and at St Margaret's Bay and Strood in Kent (Figure 1). Semi-tabular flints act in a similar way; the Seven Sisters Flint within the lower part of the Seaford Chalk also hosts conduits and caves, for example at Dieppe (Figure 7A & 7B). Thin marl seams are also important (Figure 7D), as witnessed from borehole CCTV data and coastal sections such as Beachy Head and the Isle of Thanet, notably in the New Pit Chalk, Lewes Nodular Chalk and basal Seaford Chalk formations (Farrant et al., 2021a). Marl seams can influence recharge processes significantly, creating horizons with high matric potential (Gallagher et al., 2012). In parts of the succession, hardgrounds are important inception horizons, notably the Chalk Rock in the Chiltern Hills and in Normandy where they host conduits and cave systems (Ballesteros et al., 2020) and springs (Figure 7C). The majority of the small solutionally enlarged conduits and dissolution tubules developed along these inception horizons are likely to be formed by mixing dissolution, locally enlarged by later epigenic dissolution. Most of these will develop in the saturated zone within ~50 m of the water table, but some occur at greater depths (>100 m) and within the confined zone.

Fractures also have an important role, both their density and disposition. They influence conduit gestation and enlargement, can significantly enhance fluid flow, and act as reservoir volumes (Price, 1987). Conjugate fractures are associated with marl seams, and can feed water between various inception horizons, focussing dissolution along the marl seams (Figure 7D). As discussed, fracture aperture is important for conduit inception. Several authors have derived vales for mean fracture aperture in chalk. Values range from 0.1-0.6 mm (Patsoules and Cripps, 1990) to 0.5 to 4.0 mm (Foster and Milton, 1974; Reeves, 1979). Younger and Elliot (1995) used radon modelling to infer fracture apertures in the range 0.45 to 0.9 mm. They concluded from fracture modelling that the high permeability zones of the Chalk are most likely to be characterised by conduits and fractures rather than classical dual porosity (fractures plus matrix) scenario.

The high fracture density, coupled with good connectivity influences conduit development by offering multiple potential flow pathways through the aquifer. This increases the time required for breakthrough as any dissolutional capacity is distributed along many competing pathways, rather than being focused on a few open fractures. In parts of the succession, the low dip and high fracture density favours the development of vertical joint-guided inputs in the unsaturated zone feeding recharge down to quasi-horizontal shallow phreatic conduits aligned along stratigraphical discontinuities or bedding plane partings within the saturated zone, akin to the idealised water-table caves of Ford, (1999).

Whilst virtually all of the permeability in the Chalk aquifer is associated with the development of secondary porosity, the primary porosity has a significant impact on dissolution rates and conduit development, both in the saturated and unsaturated zones. The reaction surface per unit volume of porous, highly fractured limestone is typically very large (de Rooj and Graham, 2017). Any infiltrating water entering the matrix tends towards saturation with respect to calcite far quicker than limestones with low primary porosity. However, modelling of conduit networks (Kaufmann, 2003; Bauer et al., 2003; and de Rooij and Graham, 2017) suggest that breakthrough times are faster in porous limestones. They suggest that as the conduit develops, the flow rate through the upstream parts of the conduit is not limited by the smaller conduit diameters downstream, as water can pass into the adjacent matrix. This allows more chemically aggressive water to enter the conduit from upstream (from an external source), increasing the dissolution rate. An analogy is a tap fed hosepipe with a blockage at the lower end; a leaky hose will have greater flow though it than one without any leaks. However, this is not the case in low permeability matrix limestones such as the Chalk, where flow into the matrix flow is severely limited by restricted pore throat sizes. The average hydraulic conductivity of the Chalk matrix in the UK is extremely low ($6.3x10^{-4}$ m/day; Allen et al., 1997), and is negligible with respect to the hydraulic conductivity of chalk fracture systems. The holes in the 'hosepipe' are simply too small to permit leakage. However, surface reaction rates are still high on the fine-grained chalk, which means that influent waters have plenty of opportunity to react with the rock mass via multiple flow pathways and by interaction with the matrix, and tend towards chemical saturation quickly. This increases the time required for breakthrough.

The combination of diffuse surface recharge via multiple fractures and the high porosity means little solutional activity is likely to occur within the saturated zone at depth under normal conditions, except by mixing dissolution. Intermittent bypass flow in wet weather can occur via a small number of open fractures within the unsaturated zone (Allshorn et al., 2007), feeding water more rapidly to the saturated zone at depth. This means any epigenic conduit enlargement is likely to occur mostly during flood events or where focussed recharge via stream sinks occurs. Moore et al., (2010) found that in the highly porous limestone aquifer in Florida, dissolution within a conduit was episodic, occurring only during 30% the time. During low flow conditions, carbonate saturated water flows from the matrix and small fractures to the conduit. When the hydraulic head within the conduit exceeds hydraulic head in the surrounding aquifer, under saturated allogenic water was lost to the surrounding aquifer.

Influence of time.

As discussed above, the high inter-granular porosity, high fracture density and easily dissolved nature of the Chalk means that much of the solutional aggressiveness is lost in the soil zone and epikarst within a few meters of the surface (Edmunds, 1987). Based on modelling experiments (Dreybrodt, 1996, Dreybrodt and Eisenlohr, 2000), these factors mean that it may take a significant amount of time (many hundreds of thousands to a few million years) to generate a fully integrated, epigenic conduit network in the Chalk (Figure 5) except where conditions are particularly favourable. This time span is greater than a typical glacial-interglacial cycle The readjustment of hydraulic gradients driven by continued landscape development (valley incision, base-level fall and erosion of low permeability Clay-with-Flints and Palaeogene deposits) may terminate conduit development before fully integrated conduit systems are formed (example C in Figure 5). This is exacerbated in low dip terrains, where a relatively small amount of valley incision can significantly change the location of a spring outlet, usually dictated by the lowest point where water can discharge from the aquifer. Similarly, the location of point source recharge (typically stream sinks draining the overlying Palaeogene sand and clay) can change. Consequently, epigenic conduit systems in the Chalk aquifer tend to remain relatively small (~0.01 to 1 m scale) reflecting their long gestation time. Moreover, changes in climate affect hydrogeological boundary conditions, further restricting conduit gestation, for example by changing the precipitation regime or enabling the development of permafrost during glacial periods. Changes in surface topography and boundary conditions are likely to have less impact on the development of mixing dissolution conduits at depth, but these are limited by low solute flux.

Role of geomorphology

The geomorphological setting can have a big impact on karst development, influencing aquifer recharge and introducing detrital sediments. In southern England, much of the Chalk outcrop is gently folded, forming prominent escarpments and rolling downland. The overlying Palaeogene strata is preserved in the core of large basins where the Chalk dips below the surface, such as the London Basin and in southern Hampshire (Figure 1), with outliers on the Chalk dip slopes. This topography affects the distribution of surface karst features. Maurice et al., (2012) divided the chalk outcrop into three broad karst zones. Karst features, notably sinking streams, are most prevalent in Zone 1 (Figure 8 and Figure 9), where allogenic recharge from adjacent low permeability deposits flows onto the Chalk. This usually occurs along the margins of the overlying Palaeogene sand and clay outcrops, but also where rivers flow onto the outcrop from adjacent older strata, for example the River Mole in Surrey (Adams, 2008). Small stream sinks are locally common along the margin of the Palaeogene outcrop, especially around the London Basin (Figure 1). Examples include the Water End swallow holes in the Chiltern Hills (Waltham et al., 1997; Cook et al., 2012), stream sinks in the Newbury area including the Pang catchment (Figure 8) (Banks et al., 1995; Maurice et al., 2010, 2012), dolines on Southover Heath in Dorset (Waltham et al., 1997), and in the Bedhampton springs catchment around Horndean (Atkinson and Smith, 1974). These areas are where there is extensive evidence for surface karst development (stream sinks, dolines) and epigenic conduit flow in the subsurface (McDonald et al., 1998).

Zone 2 comprises the outcrop at or close to the sub-Palaeogene erosion surface. This area is mantled by locally extensive deposits of Clay-with-Flints, a remanié deposit derived from the former Palaeogene cover. Zone 2 also includes areas where the Chalk is covered by river terrace and other relict fluvial deposits. Leakage through the superficial deposits can focus recharge into the underlying Chalk, creating a well-developed epikarst with dolines and sediment filled dissolution pipes (Edmonds, 2008; Valdes et al., 2014). This zone is characterised by numerous dissolution pipes, but few sinking streams (Figure 9). Karst development associated with former stream sinks when the Palaeogene cover was more extensive may also be present in the subsurface. Zone 3 comprises the Chalk escarpment and areas of the dip-slope eroded below the sub-Palaeogene erosion surface. In these areas, the superficial cover is very thin or absent, so dissolution and recharge to the underlying chalk appears to be predominantly diffuse. Surface karst features are poorly developed with few if any dolines or stream sinks.

The extent of connected networks of solutional fissures and conduits in Zones 2 and 3 is poorly understood, as there have been few investigations of subsurface karst in these areas. However high transmissivities (Allen et al., 1997), large springs (e.g. Grapes et al., 2006), saline intrusion at the coast (Jones and Robins, 1999), and some tracer tests (Ward et al., 1998) suggest that such networks can occur, despite the absence of surface karst. Similarly, evidence from CCTV images of boreholes, quarry and coastal sections (Waters and Banks, 1997; Waltham et al., 1997; Farrant et al, 2021a,b,c,d) indicate that solutionally enlarged conduits do occur at depth in Zones 2 and 3 (Figure 9).

The evidence suggests that subsurface karst can occur at depth even where surface karst features are absent. We suggest that many of the conduits observed in Zones 2 and 3 are formed by mixing dissolution at depth. Epigenic conduit formation from concentrated recharge via sinking streams and dolines becomes increasingly prevalent in Zone 1, locally overprinting existing mixing dissolution conduits (Figure 9). Therefore, the zonation map of Maurice et al., (2012) is appropriate for surface karst and epigenic conduits, but less applicable for mixing dissolution conduits at depth.

Role of landscape evolution

Groundwater flow and epigenic conduit development in the Chalk aquifer is intrinsically linked to base level lowering and valley incision, which influences discharge locations from the chalk aquifer.

This is driven by glacial-interglacial climatic variations, superimposed on regional scale Plio-Quaternary uplift. In karst areas, active incision interspersed with phases of fluvial gravel aggradation lead to the sequential development of cave levels and river terraces (Palmer, 1987; Bridgland and Westaway, 2008; Nehme et al., 2020). Data from river terraces (Lautridou et al. 2003; Antoine et al., 2007, Rose, 2009) and cave deposits (Nehme et al., 2020) indicate that the landscape of southern England and northern France has evolved over the last 1-1.5 million years, with spatially and temporally variable rates of valley incision. The process of valley incision changes local and regional base levels, forcing epigenic conduit systems to adjust to new hydrological regimes defined by the altitude of the spring. Existing conduits are progressively abandoned (and often infilled with sediment as discharges wane) in favour of new, lower, hydrologically more efficient routes, graded to the new base level. If the rate of landscape change (uplift and valley incision) is greater than the rate of conduit development, conduits may not form or will not transition from gestation to breakthrough and remain immature. If new conduits are able to form in the timescales available, a vertically stacked series of relict, conduits (possibly sediment filled) will develop over time in response to continued valley incision and progressive base level lowering. Former conduits may become re-activated during seasonal periods of high groundwater levels, potentially contributing to groundwater flooding, before eventually becoming relict.

Consequently, the landscape history of a region can influence where and to what extent karstic conduit systems develop and how they affect groundwater flow. Across much of northwestern Europe, continued Quaternary uplift and valley incision restricted the time available to develop conduits at any particular elevation and location. In some circumstances however, for example where springs are fed by deep, structurally confined conduits, a fall in base level at the spring will leave much of the conduit system unaffected, enabling conduit enlargement to continue uninterrupted. This is the case at the Bedhampton Springs, near Portsmouth (Figure 10), one of the largest groundwater sources in northern Europe, which are spatially constrained by the Portsdown anticline. Diffuse recharge on the South Downs, augmented by stream sinks on the northern limb of the Chichester syncline feed into a conduit system that passes beneath the Paleogene strata in the core of the syncline to emerge on the southern limb. Base level lowering at the spring will not truncate the conduit beneath the syncline, allowing continued conduit development over multiple glacial-interglacial cycles.

Role of sediment influx

In both southern England and northern France, the Chalk Group is often overlain by weak or unconsolidated Cainozoic sediments or Quaternary superficial deposits. Sediment eroded from these deposits is often introduced into the Chalk aquifer by sinking streams and ephemeral point source recharge directly into conduits. Sediment is also transported by soil piping failures and plug injections from doline collapses, soil wash-down via fractures, or by the slow subsidence of dissolution pipe infills (Herman et al., 2012). Influxes of sediment into a phreatic conduit system modifies the way it develops and changes the hydrological functioning of the karst aquifer by altering the way conduits behave and subsequently develop both in plan and long section (Ford and Ewers, 1978; Farrant and Smart, 2011).

Inputs of sediment into an active phreatic conduit can partially block it, covering the base of the conduit and forcing dissolution to be focussed on the walls and ceiling. Given stable or continued sediment influx the passage gradually evolves upwards over time eventually creating paragenetic conduits with a canyon morphology (Figure 11**Error! Reference source not found.**), terminating only when flow or sediment input ceases, or it reaches the water table. Under these conditions, sediment transport and accumulation are contemporaneous with dissolution and void development. Influxes of sediment can also lead to the development of bypass passages or floodwater mazes, thus altering the plan morphology of conduits. These typically develop where sediment accumulation causes an increase in hydraulic head across the obstruction, enabling alternative flow paths to open up. This can lead to the development of complex, partially sediment filled anastomotic conduit networks. Continued injection and flushing of sediment into and through a conduit system can alter flow paths on a seasonal to decadal timescale, and may help to explain the complex groundwater pathways revealed by tracer tests.

Many Chalk caves contain extensive sediment fills, often to the point of being completely infilled (Rodet et al., 2006; Chedeville et al., 2015). The majority of these contain evidence for paragenetic enlargement or modification (Farrant and Smart, 2011; Nehme et al., 2020). The processes associated with alluviation and paragenesis, for example, the change from a free-flowing open conduit to partly occluded one, kept open only by sediment flushing under flood conditions, can affect the hydraulic dynamics of a conduit and thus the hydrological functioning of the Chalk aquifer. This can temporarily restrict conduit transmissivity and thus change local hydraulic gradients, particularly under high discharge conditions, forcing groundwater levels to rise, and facilitating the development of bypass mazes. Sediment flushing can also affect public water supply boreholes by causing turbidity, and influencing contaminant transport. As such, turbidity at an abstraction can be a good indicator of karstic groundwater flow.

Conceptual model of conduit development in the Chalk

A conceptual model of conduit development in the Chalk, based on consideration of models of cave formation and the various factors discussed above is presented here. Initial conduits form by slow dissolution at depth by the mixing of saturated fluids along multiple inception horizons over timescales in the order of hundreds of thousands to a few million years. This can result in the formation of complex mixing dissolution conduit systems developed on certain stratigraphical discontinuities. These are generally formed close to the water table but frequently extending far below (Figure 9). They typically comprise an extensive network of small elliptical conduits a few mm to cm in diameter, and in exceptional circumstances, small cave passages (Figure 12) developed on an inception horizon. Often there is a zone of spongework or vuggy porosity ('tubule karst' of Lamont-Black and Mortimore, 2000; Farrant et al., 2021a) up to a metre thick, above. The formation of such mixing conduits are less susceptible to changes in surface topography, and not impeded by the rapid trend of influent waters toward saturation. Unlike typical epigenic systems fed by surface stream sinks, they can develop in isolation at depth, and need not form an integrated conduit system from surface inputs to a spring outlet. We argue here that many of the small-scale conduits seen in coastal sections (Figures 6 and 7) and in borehole CCTV imagery are likely to be formed by mixing dissolution. Their ubiquity and wide areal extent suggests they probably form a significant proportion of the secondary porosity in the Chalk.

The development of small-bore conduit networks at depth by mixing dissolution means that the Chalk aquifer is primed for more significant and integrated epigenic conduit development when the geomorphological setting becomes favourable. Price (1987) developed a model that suggests that dissolution is enhanced where flow concentration occurs towards the discharge zone of an aquifer (based on Rhodes and Sinacori, 1941) as more flow lines converge there. This solutional enhancement may then work up gradient through the aquifer. As we have discussed, the conduits feeding the springs are influenced not just by topography, but also a combination of lithology, geological structure and geomorphological history. Flow convergence may help to enlarge and link up pre-existing isolated mixing dissolution conduits in the sub-surface that are suitably disposed to the hydraulic gradient, to create more integrated conduit networks, particularly if the spring outlet is stable over long periods. Similarly, as valleys incise, deeper mixing dissolution conduits may be bought into play.

Similarly, large injections of water from stream sinks can shorten the time to breakthrough, enabling existing conduits formed by mixing dissolution to develop into more extensive, integrated epigenic conduits and small cave systems within the timescale of an interglacial period (example B in Figure 5). Larger cave systems can form where local geological and hydrogeological conditions conjoin to facilitate conduit development over a shorter timeframe, or where dissolution can operate unimpeded over long timescales. Well-developed karstic systems can develop where input and in particular, outlet points (spring locations) are constrained to a particular location over multiple glacial-interglacial cycles. This may occur when the structural disposition of the bedrock is such that the spring outlet is constrained to more or less at the same location for a protracted length of time, as is the case at the Bedhampton Springs due the Portsdown anticline. Once an epigenic conduit system has developed, sediment influx can further modify the passage, either through upwards paragenetic dissolution (Figure 11**Error! Reference source not found.**) or by blocking the conduit, and forcing the development of alternative bypass conduits.

This model can explain the spatial heterogeneity in the distribution of cave and karst features in the Chalk. The relative abundance of karst in Normandy can be explained by the particular Chalk stratigraphy and geomorphological setting of the region. The Chalk in the Normandy area was deposited in a near-shore depositional environment close to the margin of the Anglo-Paris basin (Hoyez, 2008). This favoured the deposition of numerous hardgrounds (some dolomitised) and semi-tabular and sheet flints to act as inception horizons (Figure 2). The geological structure is generally favourable for karstification, with gentle dips and well developed jointing, as is the geomorphological situation, dominated by the deeply incised Seine River. Localised outliers of Palaeogene strata and thick Quaternary deposits serve to focus recharge into discrete stream sinks, ephemeral sinks or dolines. Over 9400 localities where rapid infiltration of runoff has occurred ('bétoires') have been identified (El Janyani, 2013; http://sigessn.brgm.fr). The extensive Chalk outcrop, deeply incised valleys and focussed recharge has enabled large karst catchments to develop.

In southern England, karst still occurs, but fewer cave systems are known. This is in part due to less favourable geology. The more basinal setting restricts the number of hardgrounds to certain parts of the succession (principally the Holywell Nodular Chalk and Lewes Nodular Chalk formations), and flint concentrations tend to decrease to the north and east reducing the number of potential inception horizons. The geological structure and the scarp & vale topography diminishes the potential for allogenic point source recharge to the margins of the outcrop (Figure 1). Moreover, the more dissected and dynamic nature of the landscape reduces the time available for conduit gestation. North of the Anglian glacial limit, the development of mature conduit networks may have been inhibited by the extensive reorganisation of the hydrogeological landscape following deglaciation. Epigenic conduit systems are likely to be spatially restricted to certain favourable locations, but mixing dissolution conduits can develop at depth in parts of the sequence where sheet flints, marl seams and hardgrounds promote mixing of saturated waters.

Conclusions

The Chalk is a carbonate aquifer. Like other carbonate aquifers, it is subject to dissolution and the formation of karst features and landforms, including conduits and caves. However, the Chalk typically lacks the large extensive cave systems that are characteristic of more classic karstic aquifers such as the Carboniferous limestones in the UK. Consequently, the Chalk has often been treated as a non-karstic aquifer. Despite the small number of known caves, karst features are widespread in the Chalk, with sinking streams, large springs, dolines, and evidence of rapid flow through conduits and high transmissivities. The style and distribution of conduit systems in the Chalk is linked to both the geological setting and the geomorphological history. Mixing dissolution along geological inception horizons at depth can aid the formation of extensive networks of small mm to cm scale dissolutional conduits, even where surface karst features are absent and in confined parts of the aquifer. These small-bore, but areally extensive conduits and tubules form a substantial proportion of the secondary porosity and significantly enhance permeability. They are critical in making the Chalk such a productive aquifer.

The lack of large cave systems can be explained by the high matrix porosity of the Chalk coupled with a dense network of fractures. This means that recharge tends towards saturation very quickly. This increases the time required for an epigenic conduit system to enlarge sufficiently to achieve breakthrough and then develop rapidly into a traversable cave system. Across much of the Chalk outcrop, the time needed for a cave system to form is typically greater than the rate of landscape change. Uplift and valley incision change the hydrological boundary conditions on glacial-interglacial timescales, rendering many conduits redundant before they can achieve breakthrough and rapidly enlarge. Consequently, most conduits remain in the gestation phase and do not develop into the large fully integrated cave systems that are characteristic of other karst aquifers.

However, larger, well-integrated conduit and cave systems on a par with those seen in more classic karst regions can form given suitable geological conditions and a favourable geomorphological history. These can develop where allogenic point source recharge from sinking streams occurs, where flow concentration occurs at discharge zones, or where conduits are able to develop uninterrupted over multiple glacial-interglacial cycles. Understanding the dissolutional processes that operate within the aquifer, combined with an appreciation of the geological setting and geomorphological history can lead to a better conceptual model of groundwater flow in the Chalk. This can be used to identify those parts of the aquifer where rapid karstic flow and hence potential contamination is more likely to occur. This has implications for groundwater modelling, aquifer protection and management.

Acknowledgements

We wish to thank colleagues at BGS, Rouen University, water companies (South East Water and Affinity Water) and the UK Environment Agency who have facilitated our understanding of Chalk karst. Farrant and Maurice publish with the approval of the Executive Director of the British Geological Survey. The paper benefited from comments by two anonymous reviewers.

References

Allen, D.J., Brewerton, L.J., Coleby, L.M., Gibbs, B.R., Lewis, M.A., MacDonald, A.M., Wagstaff, S.J. and Williams, A.T. 1997. *The physical properties of the major aquifers in England and Wales*. BGS Technical Report WD/97/34, Environment Agency R&D Publication 8. 312 pp

Allshorn, S.J.L., Bottrell, S.H., West, L.J. and Odling, N.E. 2007. Rapid karstic bypass flow in the unsaturated zone of the Yorkshire chalk aquifer and implications for contaminant transport. *Geological Society, London, Special Publications*, **279**(1), 111-122.

Amedro, F. and Robaszynski, F. 2000. Les craies à silex du Turonien supérieur au Santonien du Boulonnais (France) au regard de la stratigraphie événementielle. *Géologie de la France*, **4**, 39–56.

Antoine, P., Limondin Lozouet, N., Chaussé, C., Lautridou, J.P., Pastre, J.F., Auguste, P., Bahain, J.J., Falguères, C. and Galehb, B. 2007. Pleistocene fluvial terraces from northern France (Seine, Yonne, Somme): synthesis, and new results from interglacial deposits. *Quaternary Science Reviews*, **26**, 2701–2723.

Atkinson, T.C. and Smith, D.I. 1974. Rapid groundwater flow in fissures in the chalk: an example from south Hampshire. *Quarterly Journal of Engineering Geology*, **7**(2), 197-205.

Audra, P. and Palmer, A.N., 2011. The pattern of caves: controls of epigenic speleogenesis. Géomorphologie: relief, processus, environnement, 17(4), pp.359-378.

Audra, P. and Palmer, A.N. 2013. The vertical dimension of karst: controls of vertical cave pattern, in: Shroder, J.F. (ed) Treatise on Geomorphology, 6. Academic Press, 186–206.

Ballesteros, D., Farrant, A., Nehme, C., Todisco, D., Woods, M. and Mouralis, D. 2020. Stratigraphical influence on chalk cave development in Upper Normandy, France: implications for chalk hydrogeology. *International Journal of Speleology*. **49**(3)187-208.

Banks, D., Davies, C. and Davies, W. 1995. The Chalk as a karstic aquifer: evidence from a tracer test at Stanford Dingley, Berkshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, **28**(Supplement 1), S31-S38.

Barhoum, S., Valdès, D., Guérin, R., Marlin, C., Vitale, Q., Benmamar, J. and Gombert, P. 2014, Spatial heterogeneity of high-resolution Chalk groundwater geochemistry - Underground quarry at Saint Martin-le-Noeud, France. *Journal of Hydrology*, **519**, 756–768,

Bauer, S., Liedl, R. and Sauter, M. 2003. Modeling of karst aquifer genesis: Influence of exchange flow. *Water Resources Research*, **39**(10), 1285, doi:10.1029/2003WR002218.

Bell, F.G., Culshaw, M.G. and Cripps, J.C. 1999. A review of selected engineering geological characteristics of English Chalk. *Engineering geology*, **54**(3-4), 237-269.

Bevan, T.G. and Hancock, P.L., 1986. A late Cenozoic regional mesofracture system in southern England and northern France. *Journal of the Geological Society*, **143**(2), 355-362.

Bloomfield, J. 1996. Characterisation of hydrogeologically significant fracture distributions in the Chalk: an example from the Upper Chalk of southern England. *Journal of hydrology*, **184**(3-4), 355-379.

Boersma, Q., Prabhakaran, R., Bezerra, F.H. and Bertotti, G. 2019. Linking natural fractures to karst cave development: a case study combining drone imagery, a natural cave network and numerical modelling. *Petroleum Geoscience*, **25**(4), 454-469.

Bögli A. 1964. Corrosion par mélange des eaux. *International Journal of Speleology,* **1**(1), 61–70.

Bögli, A. 1980. *Karst Hydrology and Physical Speleology*. Berlin, Springer.

Bridgland, D.R. and Westaway, R. 2008. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon. *Geomorphology,* **98**, 285–315.

Bromley, R.G. and Gale, A.S. 1982. The lithostratigraphy of the English chalk rock. *Cretaceous Research*, **3**, 273–306.

Chedeville, S., Laignel, B., Rodet, J., Todisco, D., Fournier, M., Dupuis, E., Girot, G. and Hanin, G. 2015. The sedimentary filling in the chalk karst of the Northwestern Paris Basin (Normandy, France):

Characterization, origin and hydro-sedimentary behaviour. *Zeitschrift für Geomorphologie*, **59**(1), 79-101.

Cook, S.J., Fitzpatrick, C.M., Burgess, W.G., Lytton, L., Bishop, P. and Sage, R. 2012. Modelling the influence of solution-enhanced conduits on catchment-scale contaminant transport in the Hertfordshire Chalk aquifer. *Geological Society, London, Special Publications*, **364**(1), 205-225.

de Rooij, R. and Graham, W. 2017. Generation of complex karstic conduit networks with a hydrochemical model. *Water Resources Research*, **53**(8), 6993-7011.

Downing, R.A., Price, M. and Jones, G.P., 1993. *The hydrogeology of the Chalk of north-west Europe*. Clarendon Press.

Dreybrodt, W. 1981. The kinetics of calcite precipitation from thin films of calcarous solutions and the growth of speleothems: Revisited. *Chemical Geology*, **32**, 237-245.

Dreybrodt, W. 1988. Processes in karst systems-Physics, chemistry and geology. Springer Series in Physical Environments, Vol. 5. Springer.

Dreybrodt, W. 1990. The role of dissolution kinetics in the development of karstification in limestone. A model simulation of karst evolution. *Journal of Geology* **98**, 639–655.

Dreybrodt, W. 1996. Principles of early development of karst conduits under natural and man-made conditions revealed by mathematical analysis of numerical models. *Water Resources Research* **32**, 2923–2935.

Dreybrodt, W. and Eisenlohr, L. 2000. Limestone dissolution rates in karst environments. *In*: Klimchouk, A., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds) *Speleogenesis: Evolution of Karst Aquifers*. National Speleological Society, 136-148.

Dreybrodt, W. and Gabrovsek, F. 2000. Dynamics of the evolution of a single karst conduit. *In*: Klimchouk, A., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds) *Speleogenesis: Evolution of Karst Aquifers*. National Speleological Society, 184-193.

Dreybrodt, W. and Siemers, J. 2000. Cave evolution on two- dimensional networks of primary fractures in limestone. *In*: Klimchouk, A., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds) *Speleogenesis: Evolution of Karst Aquifers*, National Speleological Society, 201-211.

Dreybrodt W., Gabrovšek, F. and Romanov D. 2005. *Processes of speleogenesis: A modelling approach*. Lubljana, Karst Research Institute at ZRC SAZU, ZRC Publishing.

Dreybrodt, W., Romanov, D. and Kaufmann, G. 2010. Evolution of caves in porous limestone by mixing corrosion: A model approach. *Geologia Croatica*, **63**, 129–135.

Edmonds, C.N. 2008. Karst and mining geohazards with particular reference to the Chalk outcrop, England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **41**, 261–278,

Edmunds, W.M., Cook, J.M., Darling, W.G., Kinniburgh, D.G., Miles, D.L., Bath, A.H., Morgan-Jones, M. and Andrews, J.N. 1987. Baseline geochemical conditions in the Chalk aquifer, Berkshire, UK: a basis for groundwater quality management. *Applied Geochemistry*, **2**(3), 251-274.

El Janyani, S., Massei, N., Dupont, J.P., Fournier, M. and Dörfliger, N. 2012. Hydrological responses of the chalk aquifer to the regional climatic signal. *Journal of Hydrology*, **464–465**, 485–493.

El Janyani, S., 2013. Incidence des bétoires et de la karstogenèse des plateaux crayeux de la Haute-Normandie sur le fonctionnement hydrologique de l'aquifère de la craie Modélisation hydrogéologique des influences climatiques à différentes échelles spatio-temporelles (Doctoral dissertation).

El Janyani, S., Dupont, J.P., Massei, N., Slimani, S. and Dörfliger, N. 2014. Hydrological role of karst in the Chalk aquifer of Upper Normandy, France. *Hydrogeology Journal*, **22**, 663–677.

Farrant, A.R. and Smart, P.L. 2011. Role of sediment in speleogenesis; sedimentation and paragenesis. Geomorphology, **134**, 79–93.

Farrant, A.R, Maurice, L and Stuart, M E. 2017. Stream sink risk assessment for the Boxalls Lane and Itchells Chalk water supply sources, Farnham, Surrey. *British Geological Survey Commissioned Report*, CR/18/114. 60 pp.

Farrant, A.R., Maurice, L.D, Mathewson, E, Ascott, M., Earl, G., Wilkinson, D and Howe, S. 2021a. Caves and karst of the Chalk in East Sussex, UK: Implications for groundwater management. *Cave and Karst Science*, **48**(2), 65–83.

Farrant A R, Mathewson E, Ascot M J, Woods M A, Smith H & Maurice L. 2021b. An assessment of karst in the Seaford Chalk block. *British Geological Survey Commissioned Report*, CR/21/009. 25pp.

Farrant A R, Mathewson E, Ascott M J, Woods M A, Smith H & Maurice L. 2021c. An assessment of karst in the Eastbourne Chalk block. *British Geological Survey Commissioned Report*, CR/21/003. 25pp.

Farrant A R, Mathewson E, Ascott M J, Woods M A, Smith H & Maurice L. 2021d. An assessment of karst in the North Kent area (Charing to Faversham). *British Geological Survey Commissioned Report*, CR/21/016. 25pp.

Faulkner, T. 2006. Limestone dissolution in phreatic conditions at maximum rates and in pure, cold, water. *Cave and Karst Science*, **33**(1), p.11.

Faÿ-Gomord, O., Descamps, F., Tshibangu, J.P., Vandycke, S. and Swennen, R. 2016. Unraveling chalk microtextural properties from indentation tests. *Engineering Geology*, **209**, 30–43.

Filipponi, M., Jeannin, P.Y. and Tacher, L., 2009. Evidence of inception horizons in karst conduit networks. *Geomorphology*, **106**(1-2), 86-99.

Ford, D.C. 1999. Perspectives in karst hydrogeology and cavern genesis. In: Karst Modelling: Special Publication 5. The Karst Waters Institute Charles Town, West Virginia, pp. 17-29

Ford, D.C. and Ewers, R.O. 1978. Development of limestone cave system dimension of length and depth. *International Journal of Earth Sciences*, **10**, 213–244.

Foster, S.S.D. and Milton, V.A. 1974. The permeability and storage of unconfined Chalk aquifer. *Hydrological Sciences Bulletin*, **19**(4), 485-500.

Gabrovšek, F. and Dreybrodt, W. 2000. Role of mixing corrosion in calcite-aggressive H2O–CO2–CaCO3 solutions in the early evolution of karst aquifers in limestone. *Water Resources Research,* **36**(5), 1179–1188.

Gabrovšek, F. and Dreybrodt, W. 2001. A model of the early evolution of karst aquifers in limestone in the dimensions of length and depth. *Journal of Hydrology*, **240**, 206–224, Gaillard, T. and Hauchard, E. 2018. Les horizons kartogènes de la craie: apport de la stratigraphie aux écoulements de la Pointe de Caux (France). In: 22èmes journées techniques du Comité Français d'Hydrogéologie de l'Association Internationale des Hydrogéologues. « Hydrogéologie de la craie » Le Havre, Mai 2018.

Gaillard, T., Lasseur, E., Saïga, J., Dewez, T., Sizun, J.P. and Collin, P.Y. 2018. Sédimentologie et pétrophysique de la craie – Impact sur les écoulements actuels dans la Pointe de Caux (France). *Géologues*, **199**, 25–28.

Gallagher, A.J., Rutter, H., Buckley, D.K. and Molyneux, I. 2012. Lithostratigraphic controls on recharge to the Chalk aquifer of Southern England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **45**(2), 161-172.

Gillespie, P.A., Walsh, J.J., Watterson, J., Bonson, C.G. and Manzocchi, T. 2001. Scaling relationships of joint and vein arrays from The Burren, Co. Clare, Ireland. *Journal of Structural Geology*, **23**, 183-201.

Grapes, T.R., Bradley, C. and Petts, G.E. 2006. Hydrodynamics of floodplain wetlands in a chalk catchment: The River Lambourn, UK. *Journal of Hydrology,* **320**, 324-341.

Grube, A., Grube, F., Rickert, B.-H. and Strahl, J. 2017. Eemian fossil caves and other karst structures in Cretaceous chalk and succeeding Quaternary sediments covering the salt structure Krempe-Lägerdorf (SW Schleswig-Holstein, North Germany). *Zeitschrift der Deutschen Gesellschaft fur Geowissenschaften*, **168**, 263–284.

Herman, E.K., Toran, L. and White, W.B. 2012. Clastic sediment transport and storage in fluviokarst aquifers: an essential component of karst hydrogeology. *Carbonates and Evaporites*, **27**(3-4), 211-241.

Hopson, P.M. 2005. A stratigraphical framework for the Upper Cretaceous Chalk of England and Scotland with statements on the Chalk of Northern Ireland and the UK Offshore Sector. British Geological Survey Research Report, RR/05/01, Keyworth, Nottingham.

Hoyez, B. 2008. *Les Falaises du Pays de Caux: lithostratigraphie des craies turono-campaniennes*. Mont-Sain-Aignan, Publications des Universités de Rouen et du Havre.

Adams, B. 2008. The Chalk aquifer of the North Downs. British Geological Survey.

Jones, H.K. & Robins, N.S., 1999. The Chalk aquifer of the South Downs. British Geological Survey.

Juignet P., 1974. *La transgression crétacée sur la bordure orientale du Massif Armoricain, Aptien, Albien, Cénomanien de Normandie et du Maine ; Le stratotype du Cénomanien*. Tome 1. PhD Thesis Caen University, 807 pp.

Juignet P., 1988. *La craie normande - Prédisposition au karst*. Actes du colloque sur la craie du Museum de Rouen. 39–52.

Juignet, P. and Breton, G. 1992. Mid-cretaceous sequence stratigraphy and sedimentary cyclicity in the western Paris Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **91**, 197–218.

Kaufmann, G. 2003. A model comparison of karst aquifer evolution for different matrix-flow formulations. *Journal Hydrology*, **283**(1–4), 281-289.

Kaufmann, G. 2009. Modelling karst geomorphology on different time scales. *Geomorphology*, **106**, 62–77.

Kaufmann, G. and Braun, J. 1999. Karst aquifer evolution in fractured rocks. *Water Resources Research*, **35**, 3223–3238.

Keim, D.M., West, L.J. and Odling, N.E. 2012. Convergent flow in unsaturated fractured Chalk. *Vadose Zone Journal*, **11**(4): vzj2011.0146.

Kennedy, W.J. and Garrison, R.E. 1975. Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England. *Sedimentology,* **22**, 311–386.

Laignel, B., Dupuis, E., Rodet, J., Lacroix, L. and Masséi, N. 2004. An example of sedimentary filling in the chalk karst of the Western Parias Basin characterization, origins and hydrosedimentary beahviour. *Zeitschrift für Geomorphologie*, **48**, 219–243.

Lamont-Black, J. and Mortimore, R.N. 2000. Dissolution tubules: A new karst structure from the Engish chalk. *Zeitschrift für Geomorphologie*, **44**(4), 469–489.

Lasseur, E., Guillocheau, F., Robin, C., Hanot, F., Vaslet, D., Coueffe, R. and Neraudeau, D. 2009. A relative water-depth model for the Normandy Chalk (Cenomanian-Middle Coniacian, Paris Basin, France) based on facies patterns of metre-scale cycles. *Sedimentological Geology***, 213**, 1–26.

Lautridou, J.P. 2003. La datation du Quaternaire normand: tableau des elements de datation et de la chronostratigraphie. *Quaternaire,* **14**(1), 65–71.

Laxton, J., Serrano, J.J. and Tellez-Arenas, A. 2010. Geological applications using geospatial standards – an example from OneGeology-Europe and GeoSciML. *International Journal of Digital Earth*, **3** (sup1), 31-49.

Le Vine, N., Butler, A., Mcintyre, N. and Jackson, C. 2016. Diagnosing hydrological limitations of a land surface model: application of JULES to a deep-groundwater chalk basin. *Hydrological Earth System Sciences*, **20**, 143–159.

Lowe, D. 2000. Role of stratigraphic elements in speleogenesis: the speleoinception concept. *In*: Klimchouk, A.V., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds) *Speleogenesis: Evolution of Karst Aquifers*. National Speleological Society, 65–76.

Lowe, J. and Gunn, J. 1995. The role of strong acid in speleo-inception and subsequent cavern development. *Acta Universitatis Szegediensis: Acta Geographica*, **24**, 33–60.

MacDonald, A.M., Brewerton, L.J. and Allen, D.J. 1998. Evidence for rapid groundwater flow and karst-type behaviour in the Chalk of southern England. *Geological Society, London, Special Publications*, **130**, 95–106.

MacDonald, A.M. and Allen, D.J. 2001. Aquifer properties of the chalk of England. *Quarterly Journal of Engineering Geology and Hydrogeology,* **34**, 371–384.

Maurice, L.D., Atkinson, T.C., Farrant, A.R. and Williams, A.T. 2006. Karstic behaviour of groundwater in the English Chalk. *Journal of Hydrology,* **330**, 63–70.

Maurice, L.D., Atkinson, T.C., Barker, J.A., Williams, A.T. and Gallagher, A.J. 2012. The nature and distribution of flowing features in a weakly karstified porous limestone aquifer. *Journal of Hydrology*, **438–439**, 3–15.

Mortimore, R.N. 1986. Stratigraphy of the upper cretaceous white chalk of Sussex. *Proceedings of the Geologists' Association*, **97**(2), 97-139.

Mortimore, R.N. 1993. Chalk water and engineering geology. *In*: Downing, R.A., Price, M. and Jones, G.P. (eds) *The Hydrogeology of the Chalk of North-West Europe*. Oxford Science Publications, pp. 67–92.

Mortimore, R.N. 2011. A chalk revolution: What have we done to the Chalk of England? *Proceedings of the Geologists' Association*, **122**, 232–297.

Mortimore R.N. 2018. Late Cretaceous tectono-sedimentary events in NW Europe. *Proceedings of the Geologists' Association,* **129**, 392–420.

Mortimore, R.N. 2019. Late Cretaceous to Miocene and Quaternary deformation history of the Chalk: Channels, slumps, faults, folds and glacitectonics. *Proceedings of the Geologists' Association*, **130**, 27–65.

Mortimore, R.N. and Pomerol, B. 1987. Correlation of the Upper Cretaceous White Chalk (Turonian to Campanian) in the Anglo-Paris Basin. *Proceedings of the Geologists' Association*, **98**(2), 97–143.

Mortimore, R.N. and Pomerol, B. 1991. Upper Cretaceous tectonic disruptions in a placid Chalk sequence in the Anglo-Paris Basin. *Journal of the Geological Society*, **148**, 391–404.

Mortimore, R.N. and Pomerol, B. 1997. Upper Cretaceous tectonic phases and end Cretaceous inversion in the Chalk of the Anglo-Paris Basin. *Proceedings of the Geologists' Association*, **108**, 231–255.

Mortimore, R.N., Pomerol, B. and Lamont-Black, J. 1996. Examples of structural and sedimentological controls on chalk engineering behaviour. *In*: Harris, C.S., Hart, M.B., Varley, P.M. and Warren, C.D. (eds) *Engineering Geology of the Channel Tunnel*. Thomas Telford, pp. 436–443.

Mortimore, R.N., Gallagher, L.T., Gelder, J.T., Moore, I.R., Brooks, R. and Farrant, A.R., 2017. Stonehenge—a unique Late Cretaceous phosphatic Chalk geology: implications for sea-level, climate and tectonics and impact on engineering and archaeology. *Proceedings of the Geologists' Association*, **128**, 564–598.

Mougin, B., Branellec, M., David, P.Y., Zammit, C. and Bourgine, B. 2011. Atlas hydrogéologique régional de Haute-Normandie Cartes piézométriques de l'aquifère crayeux. BRGM, Orléans.

Nehme, C., Farrant, A., Ballesteros, D., Todisco, D., Rodet, J., Sahy, D., Grappone, J.M., Staigre, J.C. and Mouralis, D. 2020. Reconstructing fluvial incision rates based on palaeo-water tables in chalk karst networks along the Seine valley (Normandy, France). *Earth Surface Processes and Landforms*, https://doi.org/10.1002/esp.4851

Odling, N.E., Gillespie, P., Bourgine, B., Castaing, C., Chiles, J.P., Christensen, N.P., Fillion, E., Genter, A., Olsen, C., Thrane, L. and Trice, R., 1999. Variations in fracture system geometry and their implications for fluid flow in fractures hydrocarbon reservoirs. *Petroleum Geoscience*, **5**(4), 373–384.

Palmer, A.N. 1987. Cave levels and their interpretation. *National Speleological Society Bulletin*, **49**(2), 50-66.

Palmer, A. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin*, **103**, 1–21.

Palmer, A.N., 2002. Speleogenesis in carbonate rocks. Evolution of Karst: From Prekarst to Cessation: Ljubljana, Inštitut za raziskovanje krasa, ZRC SAZU, 43–59.

Palmer, A.N. 2007. *Cave Geology*. Dayton, Cave Books.

Patsoules, M.G. and Cripps, J.C. 1990. Survey of macro and micro faulting in Yorkshire chalk. In: Chalk: Proc. Int. Chalk Symposium, Brighton, 1989. Thomas Telford, 87–93.

Price, M., 1987. Fluid flow in the Chalk of England. *Geological Society, London, Special Publications*, **34**(1), 141–156.

Price, M., Downing, R.A. and Edmunds, W.M. 1993. The Chalk as an aquifer. In: Downing, R.A., Price, M. and Jones, G.P. (eds) The hydrogeology *of the Chalk of north-west Europe*. Clarendon Press, 14–34.

Quine, M. and Bosence, D. 1991. Stratal geometries, facies and sea-floor erosion in Upper Cretaceous Chalk, Normandy, France. *Sedimentology,* **38**, 1113–1152.

Ragot, J. 1988. *La sédimentation crétacée aux abords de l'accident Fecamp-Lillebonne-Villequier (Seine Maritime, France. Biostratigraphie et contrôle structural*. PhD Thesis Rouen University.

Rawson, P.F., Allen, P.M. and Gale, A. 2001. A revised lithostratigraphy for the Chalk Group. *Geoscientist*, **11**, 1.

Reeves, M. J. 1979. Recharge and pollution of the English Chalk: some possible mechanisms, *Engineering Geology*, **14**, 231–240.

Rhodes, R. and Sinacori, M.N. 1941. Patterns of groundwater flow and solution. *Journal of Geology*, **49,** 785–794

Rodet, J. 1992. La Craie et ses karsts. Groupe Seine et Centre Normand d’Etude du Karst et des Cavités du Sous-Sol Elbeuf, France.

Rodet, J. 2007. Karst de la craie et aquifère de Normandie. *European Journal of Water Quality*, **38**, 11–22.

Rodet, J. and Lautridou, J. 2003. Contrôle du karst quaternaire sur la genèse et l'évolution du trait de côte d'une région crayeuse de la Manche (Pays de Caux, Normandie, France). *Quaternaire,* **14**, 31–42.

Rodet, J., Laignel, B., Brocard, G., Dupuis, E., Massei, N. and Viard, J.-P. 2006. Contribution of a sedimentary study to the karstic evolution concept of a chalk cave of the Western Paris Basin (Normandy, France). *Geologica Belgica*, **9**, 287–296.

Romanov, D., Dreybrodt, W. and Gabrovšek, F. 2003a. Interaction of Fracture and Conduit Flow in the Evolution of Karst Aquifers. *Speleogenesis and Evolution of Karst Aquifers*, **1**(3), 2–7.

Romanov, D., Gabrovšek, F. and Dreybrodt, W. 2003b. The impact of hydrochemical boundary conditions on the evolution of limestone karst aquifers. *Journal of Hydrology*, **276**, 240–253.

Rose, J., 2009. Early and Middle Pleistocene landscapes of eastern England. *Proceedings of the Geologists' Association*, **120**(1), 3-33.

Roux, J.C., Gaillard, T. and Hauchard, E. 2019. Le système hydrogéologique karstique crayeux des sources d’Yport (Seine-Maritime). Évolution des connaissances et exploitation de la ressource. *Géologues*, **199**, 73–82.

Sauro, F., Zampieri, D. and Filipponi, M. 2013. Development of a deep karst system within a transpressional structure of the Dolomites in north-east Italy. *Geomorphology*, **184**, 51–63.

Siemers, J. and Dreybrodt, W. 1998. Early development of karst aquifers on percolation networks of fractures in limestone. *Water Resources Research*, **34**(3), 409-419.

Slimani, S., Massei, N., Mesquita, J., Valdés, D., Fournier, M., Laignel, B. and Dupont, J.P. 2009. Combined climatic and geological forcings on the spatio-temporal variability of piezometric levels in the chalk aquifer of Upper Normandy (France) at pluridecennal scale. *Hydrogeological Journal*, **17**, 1823–1832.

Valdes, D., Dupont, J.P., Laignel, B., Slimani, S. and Delbart, C. 2014. Infiltration processes in karstic chalk investigated through a spatial analysis of the geochemical properties of the groundwater: The effect of the superficial layer of clay-with-flints *Journal of Hydrology,* **519**, 23–33.

Vázquez, P., Menéndez, B., Denecker, M.F.C. and Thomachot-Schneider, C. 2016. Comparison between petrophysical properties, durability and use of two limestones of the Paris region. *Geological Society, London, Special Publication*, **416**, 203–216

Waltham, A.C., Simms, M.J., Farrant, A.R. and Goldie, H.S. 1997. *Karst and caves of Great Britain*. Chapman and Hall. Joint Nature Conservation Committee.

Ward, W.H., Burland, J.B. and Gallois, R.W. 1968. Geotechnical Assessment of a Site at Mundford, Norfolk, for a large Proton Accelerator. *Géotechnique*, **18**(4), 399-431.

Ward, R.S., Williams, A. T., Barker, J. A., Brewerton, L. J. and Gale, I. N. 1998. *Groundwater Tracer Tests: a review and guidelines for their use in British aquifers*. British Geological Survey Report WD/98/19. 207pp.

Waters, A. and Banks, D., 1997. The Chalk as a karstified aquifer: closed circuit television images of macrobiota. *Quarterly Journal of Engineering Geology and Hydrogeology*, **30**(2), 143-146.

White, W. 1988. *Geomorphology and hydrology of karst terrains*. Oxford University Press.

Wigley, T.M.L. and Plummer, L.N. 1976. Mixing carbonate waters. *Geochemical and Cosmochimica Acta*, **40**, 989-995.

Woods, M.A. 2015. Applied palaeontology in the Chalk Group: Quality control for geological mapping and modelling and revealing new understanding. *Proceedings of the Geological Association*, **126**, 777–787.

Worthington, S.R.H. 1999. A comprehensive strategy for understanding flow in carbonate aquifers. *Speleogenesis and Evolution of Karst Aquifers*, **1**(1), 1-8.

Worthington, S.R.H. and Ford, D.C. 2009. Self-organized permeability in carbonate aquifers. *Groundwater*, **47**(3), pp.326-336.

Worthington, S.R.H., Ford, D.C. and Beddows, P.A. 2000. Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. *In*: Klimchouk, A.V., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (eds) *Speleogenesis: Evolution of karst aquifers*. National Speleological Soeciety, 463-472.

Younger, P.L. and Elliot, T. 1995. Chalk fracture system characteristics: Implications for flow and solute transport. *Quarterly Journal of Engineering Geology and Hydrogeology*, **28**(1), S39-S50

Zghibi, A., Zouhri, L., Chenini, I., Merzougui, A. and Tarhouni, J. 2016. Modelling of the groundwater flow and of tracer movement in the porous and fissured media: Chalk Aquifer (Northern part of Paris Basin, France). *Hydrological Processes*, **30**, 1916–1928.

Zouhri, L., Smaoui, H., Carlier, E. and Ouahsine, A. 2009. Modelling of hydrodispersive processes in the fissured media by flux limiters schemes (Chalk aquifer, France). *Mathematical and Computer Modelling*, **50**, 516–525.

Figures

Figure 1. The Chalk of southern England and northern France, with localities mentioned in the text. Areas with the potential for significant allogenic recharge are shown in southern England. UK Geology based on BGS and BRGM 1:1M-scale data (One Geology inspire data).

Figure 2. Chalk stratigraphy in the southeast England and Normandy (northern France), showing key lithostratigraphical discontinuities (hardgrounds, marl seams and the main semi-tabular and sheet flint bands) that can act as inception horizons. Many other smaller unnamed discontinuities and bedding partings are not shown.

Figure 3. Fracture styles in the Chalk. A Pervasive vertical joints in the Seaford Chalk, Seaford Head, Sussex, offering potential rapid bypass flow pathways through the unsaturated zone down to key inception horizons (Hope Gap Sheet flint). B. Conjugate fractures nucleated on marl seams, enabling transfer of groundwater between inception horizons and mixing dissolution.

Figure 4. Saturation concentration of calcite as a function of CO_2 concentration in volume of dissolved solid per litre. Mixing of two saturated calcite (chalk) solutions, for example A and B produces an under saturated solution (C). Subsequent dissolution follows line C-D.

Figure 5. Timescales of conduit development from inception to abandonment. Three examples are shown: A. Typical conduit/cave system in well-karstified limestones. B. Conduit system in a favourable setting in Chalk. C. Mixing zone conduit in the Chalk. Shaded area represents the period spent in the inception & gestation phase.

Figure 6. Dissolutional conduits formed by mixing dissolution above a sheet flint (arrowed). A. St Margaret's Bay, Kent. B. Detail looking up at the underside of a bedding surface (the sheet flint has fallen away) showing a conduit network embedded in a mesh of small dissolutional voids ('tubule karst' of Lamont-Black and Mortimore, 2000), Beachy Head, Sussex. C. St Margaret's Bay, Kent, D. Hope Gap, Seaford Head, Sussex.

Figure 7. Conduit development on inception horizons in the Chalk. A & B. Caves and sediment filled conduits developed on the Seven Sisters Flint, Dieppe, C. Spring (Pisseuses de Valaine) emerging from the Southerham Marl, just above the Tilleul hardgrounds (Plage du Tilleul, Etretat), D. Spring emerging on the Gynde 1 marl seam, Senneville, Normandy.

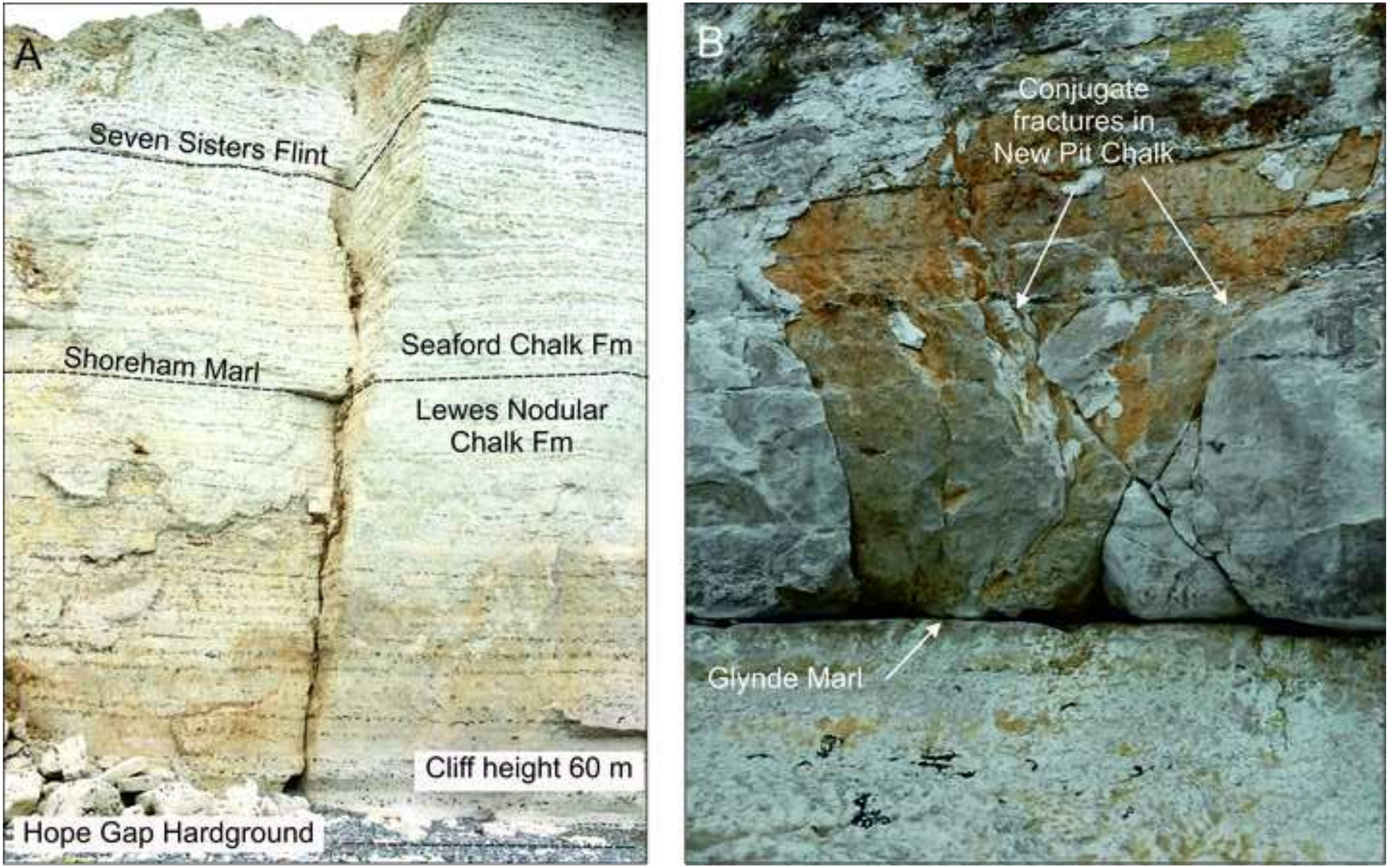
Figure 8. Surface karst zones in the lower Pang catchment, Newbury, southern England. Bedrock geology based on BGS Geology50. Shaded relief derived from NEXTMapTM Britain elevation data from Intermap Technologies.

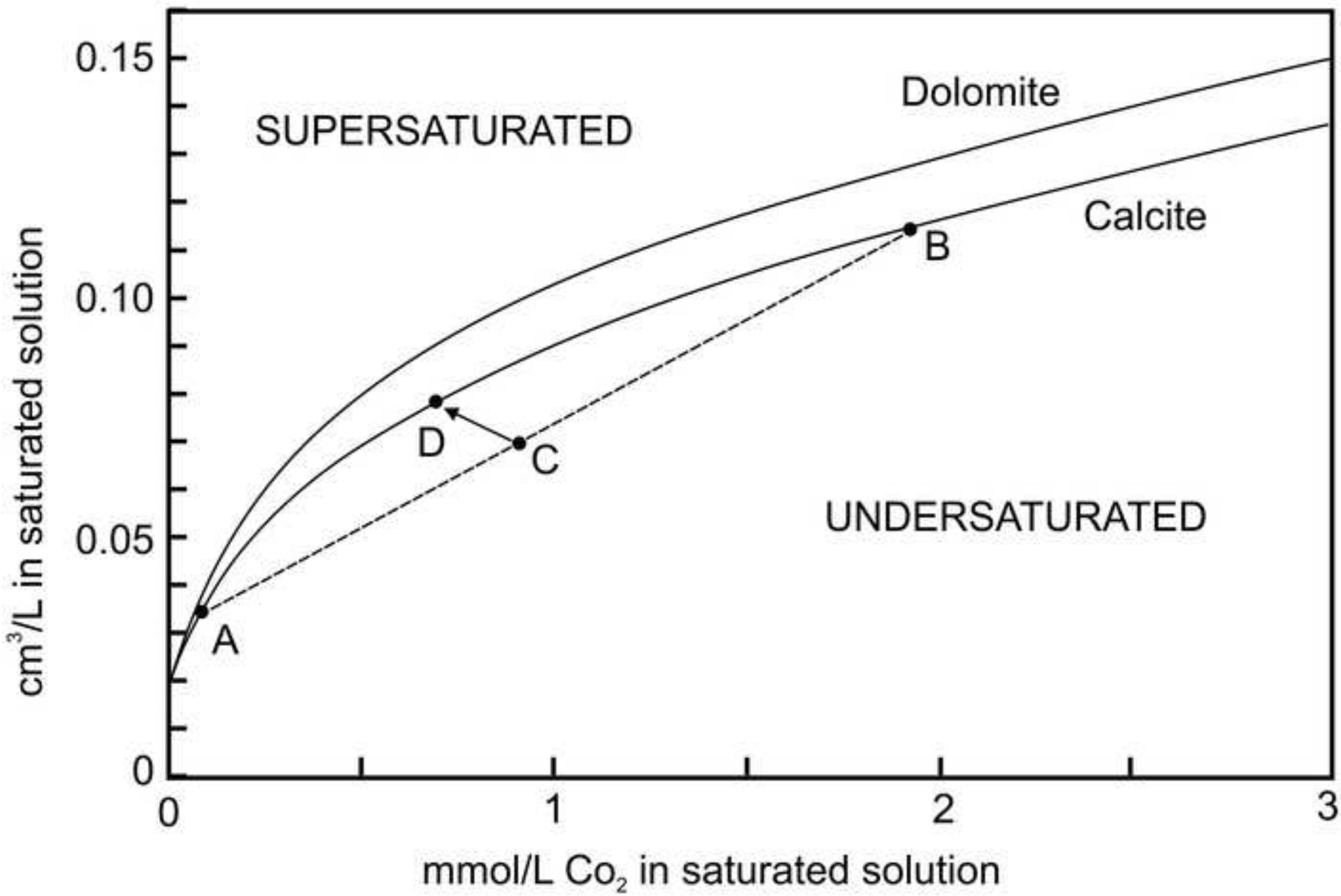
Figure 9. Conceptual distribution of conduit systems in the Chalk, with small-scale mixing zone conduits at depth, locally augmented by larger conduits and caves developed by epigenic allogenic recharge.

Figure 10. Schematic cross-section of the Bedhampton Springs conduit system across the Chichester Syncline, Portsmouth, modified from Maurice et al. (2017).

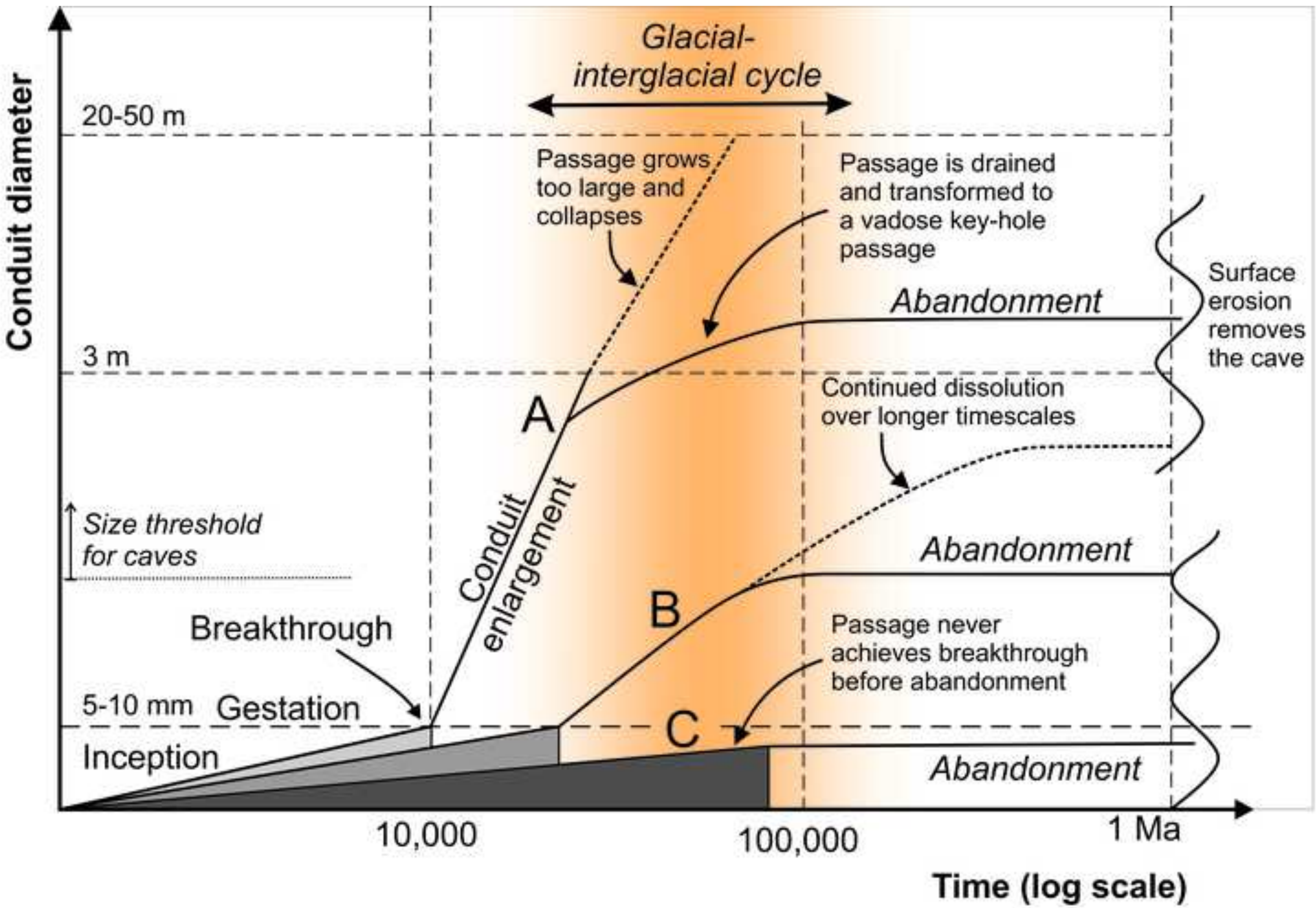
Figure 11. A. Upward evolution of paragenetic canyons (cross section and longitudinal view). B. Examples of sediment filled paragenetic canyons developed above inception horizons (Tilleul hardground), Tilleul Plage, Etretat (after Farrant and Smart, 2011).

Figure 12. Plan view of a conceptual nested tubule—conduit—cave system formed by mixing dissolution system along a single stratigraphical horizon. Each conduit shown comprises an anastomosing network of smaller elliptical conduits 2-5 mm diameter. The cave plan is based on Beachy Head Cave, Sussex, UK, developed on a sheet flint in the Lewes Nodular Chalk Formation.


A
Seven Sisters Flint
Shoreham Marl
Seaford Chalk Fm
Lewes Nodular Chalk Fm
Cliff height 60 m
Hope Gap Hardground
B
Conjugate fractures in New Pit Chalk
Glynde Marl


0.15
0.10
0.05
0
0
1
2
3
SUPERSATURATED
Dolomite
Calcite
UNDERSATURATED
A
B
C
D
cm^3/L in saturated solution
mmol/L Co$_2$ in saturated solution

 Click here to access/download;figure;Farrant_Fig_5_Time_inception.jpg



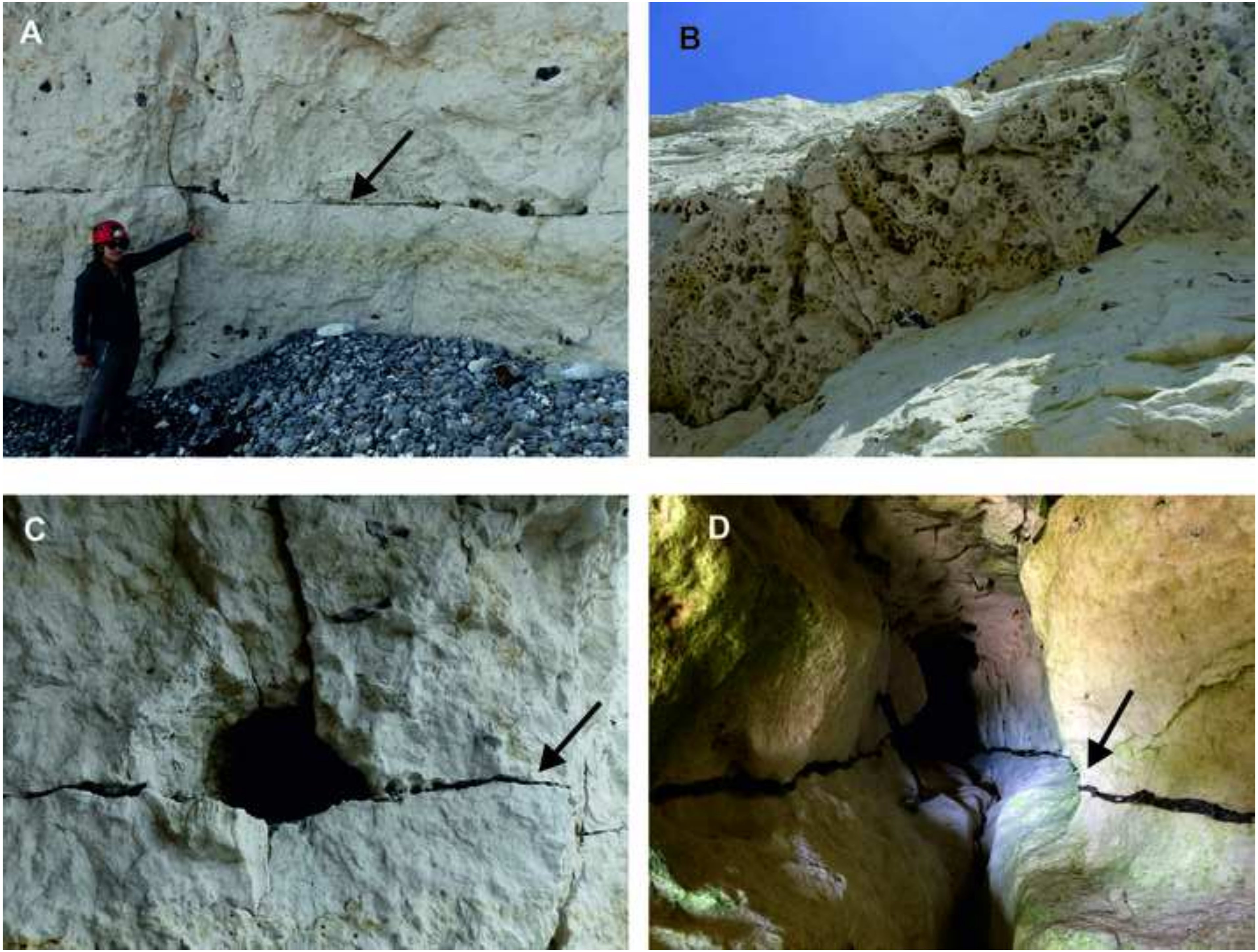
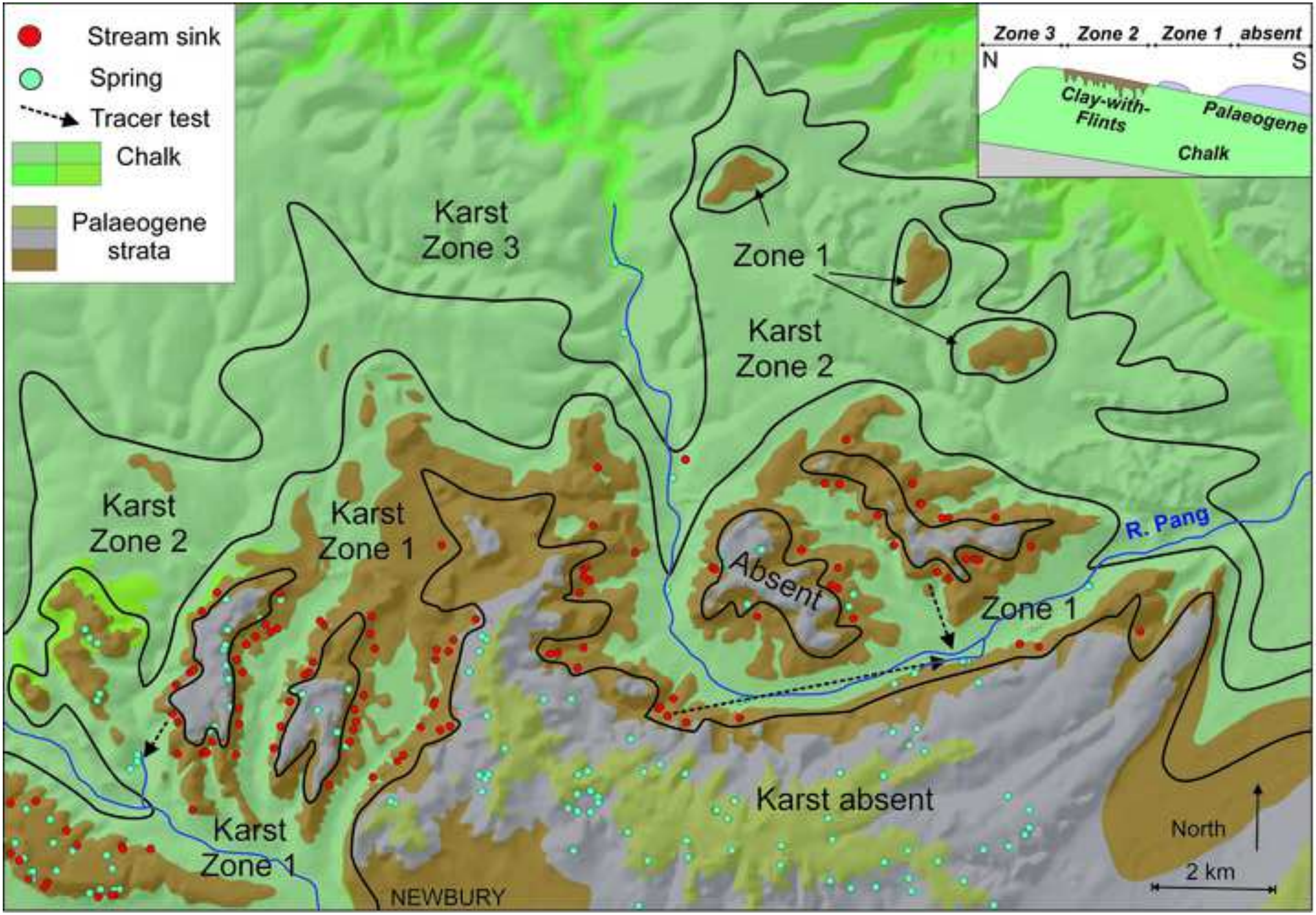

A
B
C
D

figure Click here to access/download;figure;Farrant_Fig_7_Conduit.jpg

figure

Click here to access/download;figure;Farrant_Fig_8_Karst zones.jpg



figure

Click here to access/download;figure;Farrant_Fig_9_Chalk_karst_conceptual model.jpg

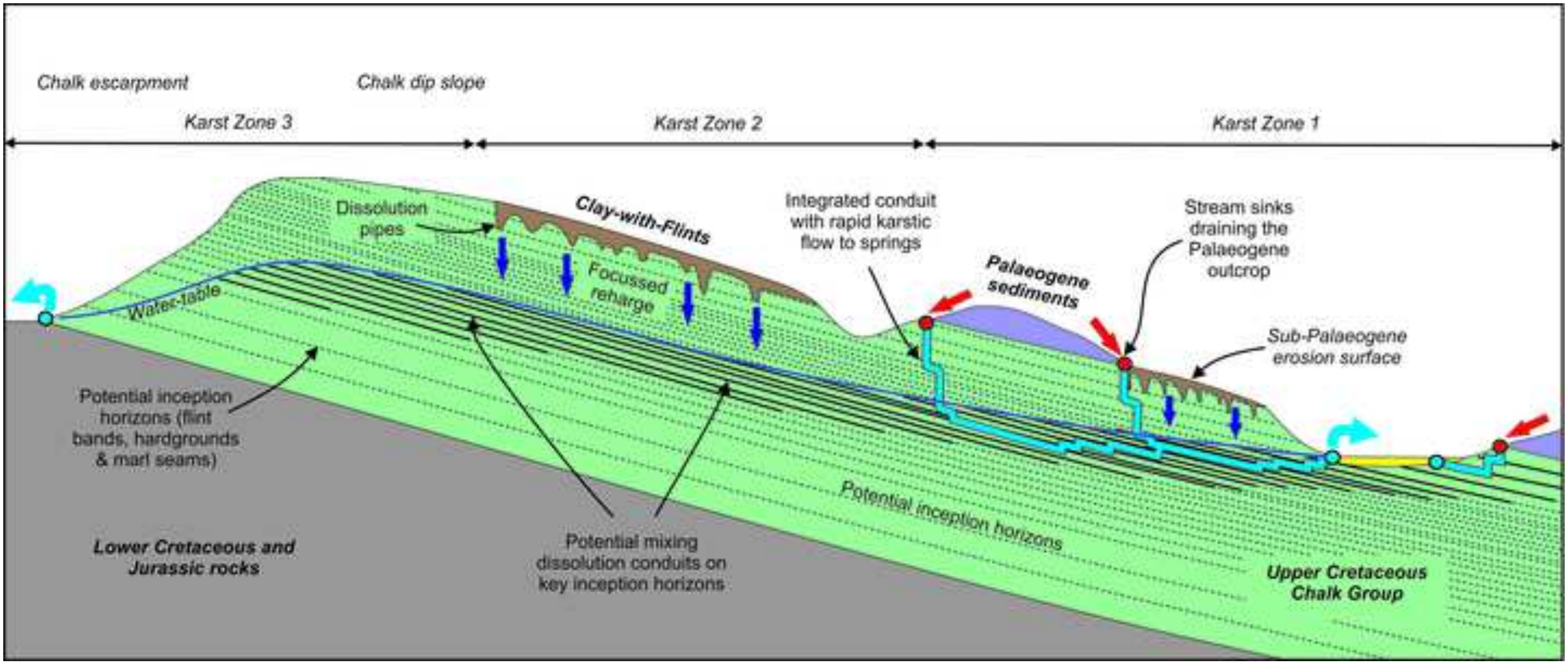


figure Click here to access/download;figure;Farrant_Fig_10_Bedhampton.jpg

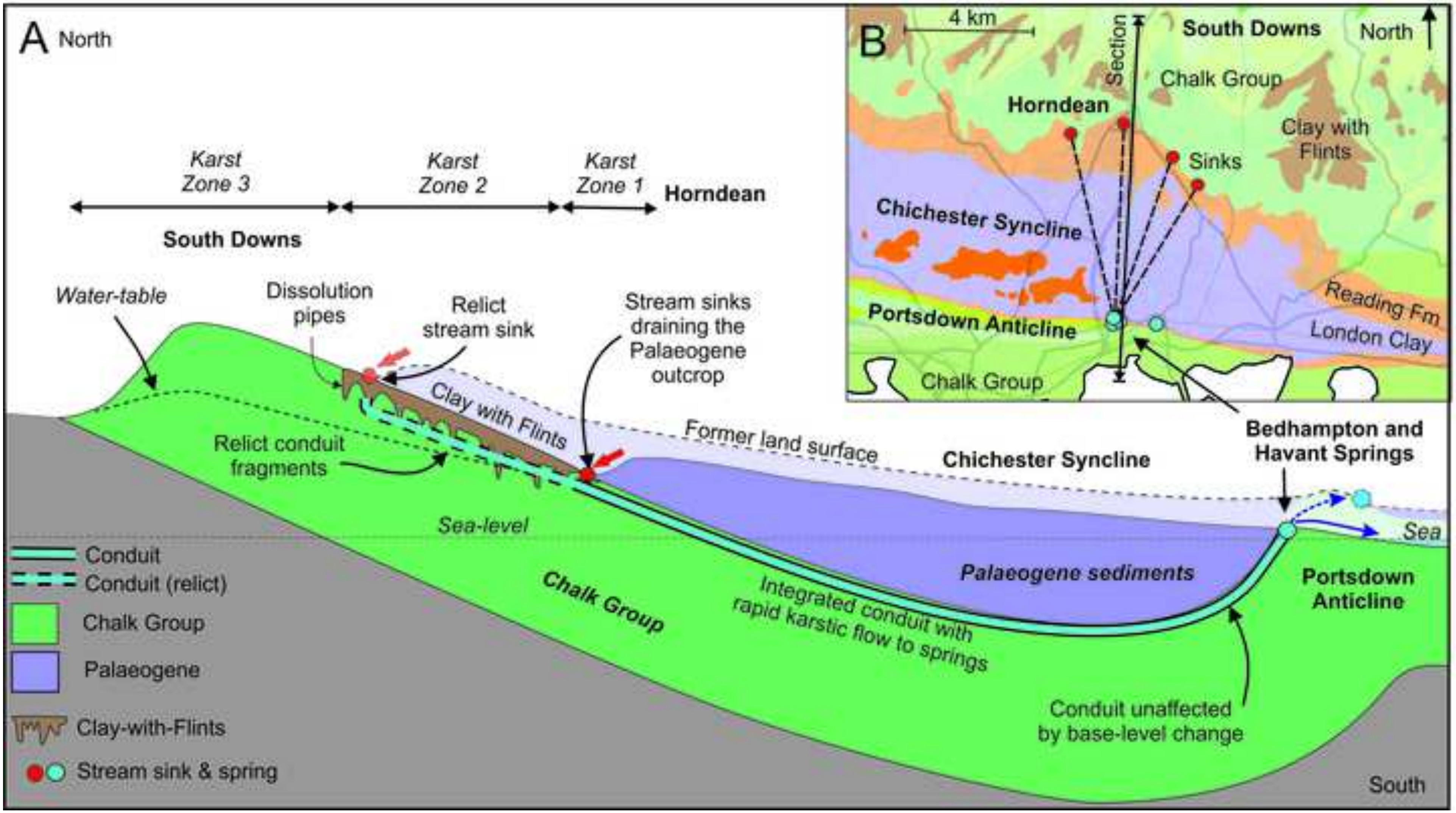
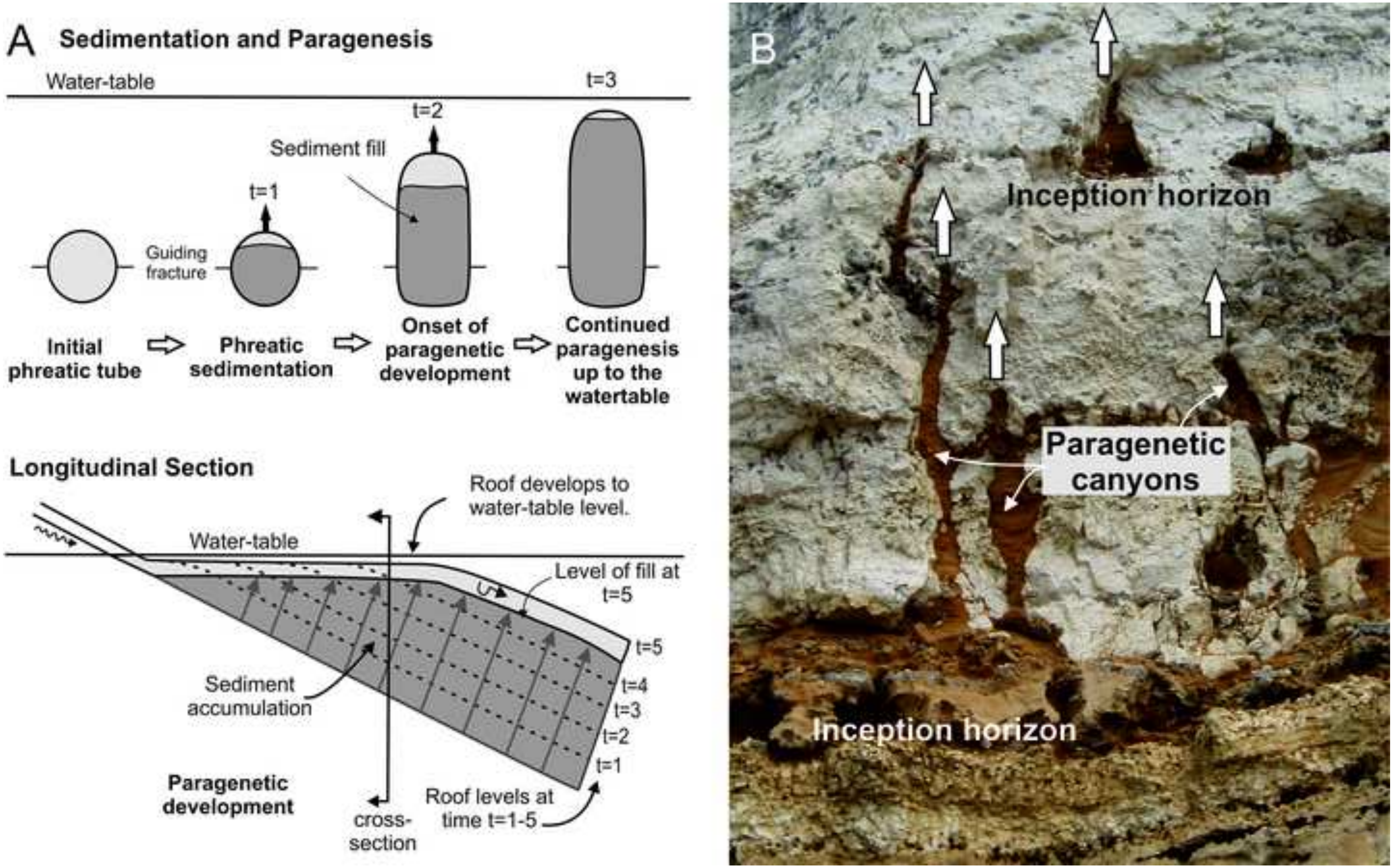
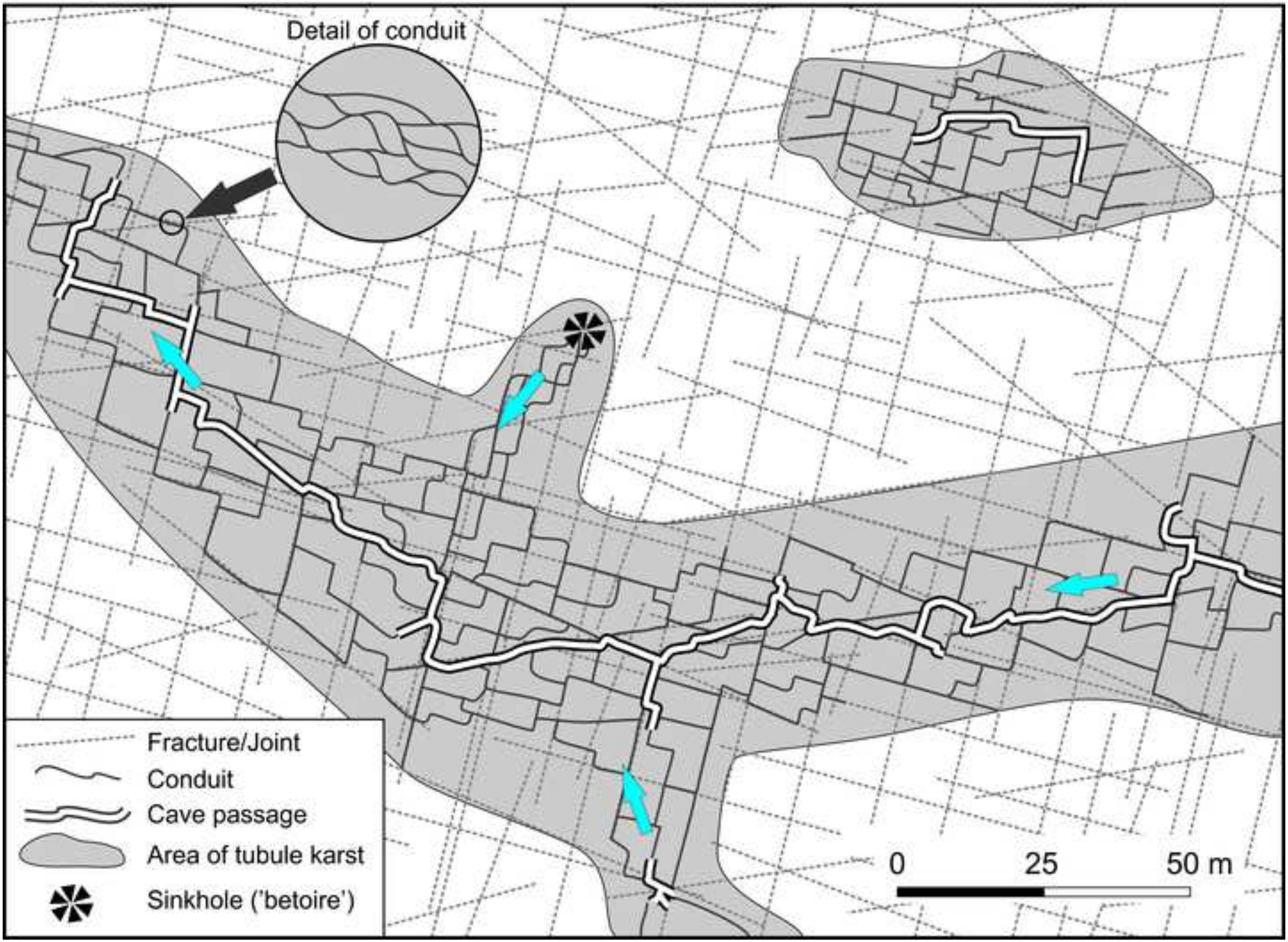


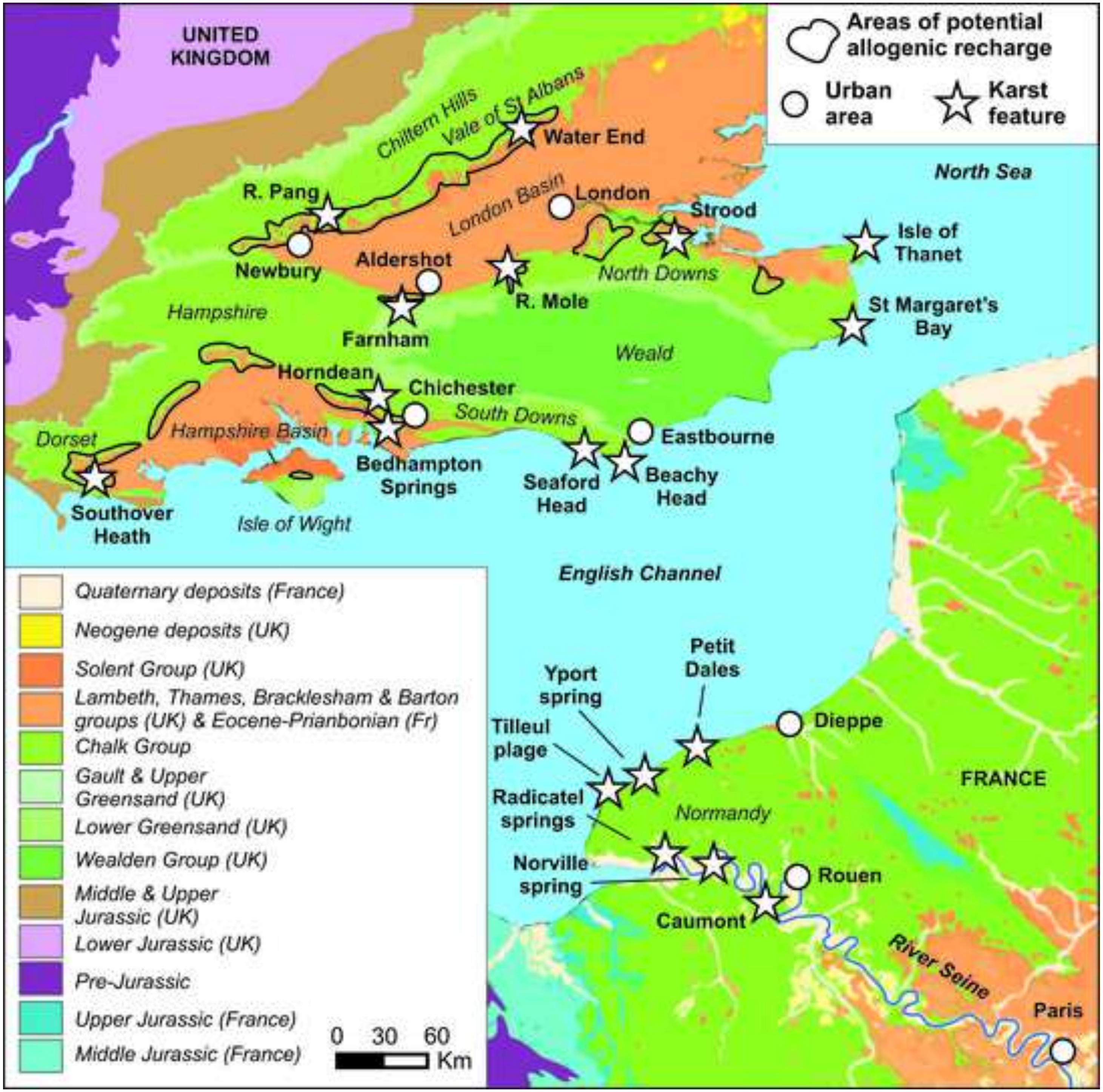
figure Click here to access/download;figure;Farrant_Fig_11_Paragenesis.jpg



figure

Click here to access/download;figure;Farrant_Fig_12_Chalk karst conceptual model plan.jpg




UNITED KINGDOM
Areas of potential allogenic recharge
Urban area
Karst feature
Chiltern Hills
Vale of St Albans
Water End
R. Pang
London Basin
London
Strood
North Sea
Isle of Thanet
Newbury
Aldershot
R. Mole
North Downs
Hampshire
Farnham
St Margaret's Bay
Weald
Horndean
Chichester
South Downs
Eastbourne
Dorset
Hampshire Basin
Bedhampton Springs
Seaford Head
Beachy Head
Southover Heath
Isle of Wight
English Channel
Quaternary deposits (France)
Neogene deposits (UK)
Solent Group (UK)
Lambeth, Thames, Bracklesham & Barton groups (UK) & Eocene-Prianbonian (Fr)
Chalk Group
Gault & Upper Greensand (UK)
Lower Greensand (UK)
Wealden Group (UK)
Middle & Upper Jurassic (UK)
Lower Jurassic (UK)
Pre-Jurassic
Upper Jurassic (France)
Middle Jurassic (France)
0 30 60 Km
Petit Dales
Yport spring
Tilleul plage
Dieppe
FRANCE
Radicatel springs
Normandy
Norville spring
Rouen
Caumont
River Seine
Paris

figure

Click here to access/download;figure;Farrant_Fig2_jpgformat.jpg