Feature

Geology of the Chiltern Chalk aquifer, southern England

The unique geological history which resulted in the evolution of the Chiltern Hills to the north of London, The United Kingdom, created the underlying foundations for everything that we see there on the surface today. The roots of the Chiltern Hills lie in their Chalk foundations. To understand the details of the way the chalk acts as an aquifer it is important to understand first the origins of the chalk sediment and how the subsequent geological history of the region has impacted on the rocks preserved today.

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The Chiltern Hills form the northern limb of the London Basin (Fig. 1) and, as such, provide a historic groundwater resource for the Chiltern region itself, as well as the United Kingdom's capital city. It is acknowledged that 65 percent of the water supply in southeast England comes from the Chalk. The geological history behind the formation of the Chiltern Hills is complex and needs to be understood if the chalk aquifer is to operate to its full potential, whilst still protecting the globally important and rare chalk streams which flow through these hills.

At a time when we have witnessed pollution of the chalk aquifer, as well as the impact of extensive tunnelling through it to construct a high-speed railway (HS2), it is critical that we understand how this multilayered chalk aquifer works and, more crucially, how we need to protect it if it is to continue to act as a sustainable resource. Throughout this article, 'Chalk' is used as the term for the stratigraphical unit, with 'chalk' the lithology.

Origins of the Chilterns Chalk

Deposition of the chalk occurred during a progressive series of sea-level rises, with sporadic, intervening sea level falls. These transgressions across the Cretaceous north-western European continental shelf probably started during the Late Albian, with the deposition of the Gault Clay. The Gault Clay comprises dark grey calcareous and silty mudstones, with occasional seams of phosphatic nodules, which probably mark minor non-sequences. This formation underlies the southern part of the Vale of Aylesbury and continues southwards beneath the whole of the London Basin (Fig. 2).

A regressive event marks the boundary between the Upper Cretaceous Chalk and the underlying Lower Cretaceous sediments. The latter are normally represented by the Gault Clay, although in several scattered locations around the base of the Chiltern escarpment patchy sandstones are recorded as the Upper Greensand. Approximately 3–4 m of unconsolidated dark glauconitic sand was recorded near to Aston Clinton in the late nineteenth century and similar deposits are known around Wendover. The onset of chalk deposition is marked by the initial deposits of calcareous clays and mudstones during the earliest Cenomanian Stage. These form the lower part of the Chiltern scarp slope.

The Chalk of southern England was traditionally split into three units, the Lower, Middle and Upper Chalk. Since the 1980s detailed studies have proven the existence of a series of Chalk formations which have been subsequently mapped across the country. However, the old threefold (Lower, Middle and Upper) geological mapping divisions of the Chalk perfectly reflect the Chiltern topography we see today. The newer Chalk formations are clearly recognized across the Chilterns and the variations which characterize them have a direct impact on the properties of the underlying groundwater aquifer. It is these formations which are discussed in greater detail below.

Whilst the clay-rich Gault Clay and Lower (Grey) Chalk provide the deep floor of the region, exposed

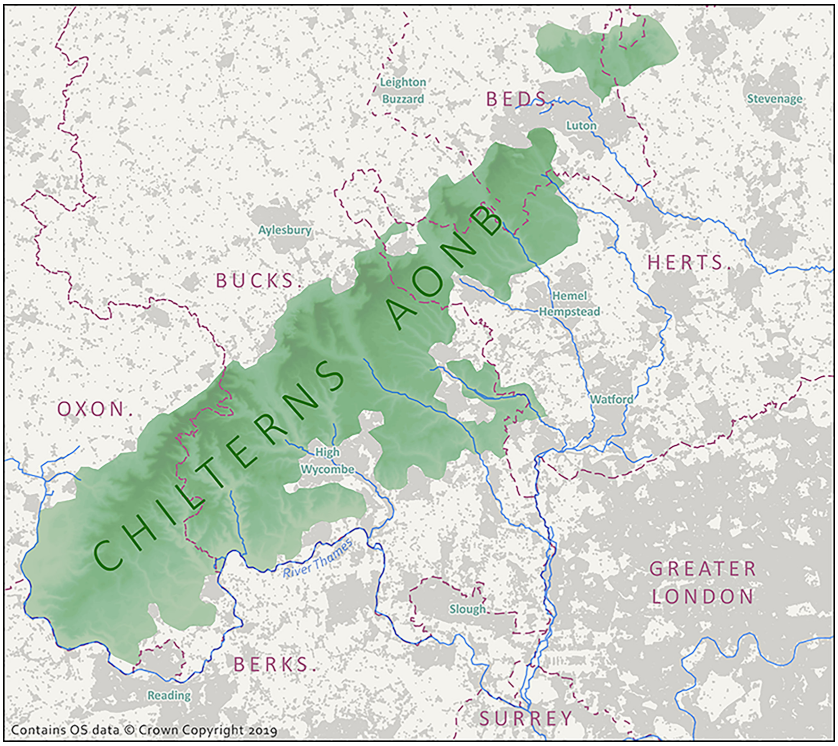

Fig. 1. Location map of the Chiltern Area of Outstanding Natural Beauty (AONB) (Courtesy of the Chiltern Conservation Board).

along the northern foot of the Chiltern escarpment, it is the relatively hard Middle Chalk which forms the scarp slope itself. This scarp is largely formed by the Holywell and New Pit formations and capped by the Lewes Nodular Chalk Formation. From oldest to youngest these are as follows.

Holywell Nodular Chalk Formation

This indurated nodular chalk unit is flintless and is recorded as being ~15-m-thick across the Chiltern Region. The base of the unit is formed by the Melbourn Rock, an extremely hard unit originally described in chalk pits around Melbourn, Cambridgeshire. The formation is noted for the moderately spaced conjugate joint systems present which result in the unit having a locally good to high aquifer potential. Numerous water supply boreholes in the Chiltern region are drilled into the Holywell Nodular Chalk Formation as it provides the deepest resilient water source in the White Chalk Subgroup.

New Pit Chalk Formation

The New Pit Chalk Formation is described as a ‘massively bedded, non-nodular chalk, with fairly regularly developed marl seams and sporadic flints’. It is the presence of the marl seams which characterize this unit, as these argillaceous clay seams, frequently between 1 and 10 cm thick, are extremely widespread, being recognized across the whole of southern England and in a number of cases even across to Germany.

The most complete New Pit Chalk Formation section in the Chiltern area is that exposed in Kensworth Quarry near Dunstable (NGR TL015197). In the original description of this quarry 15 m of New Pit Chalk Formation were described; subsequent additional excavation by the quarry owners plus measurements at the Baldock bypass excavation have proven that

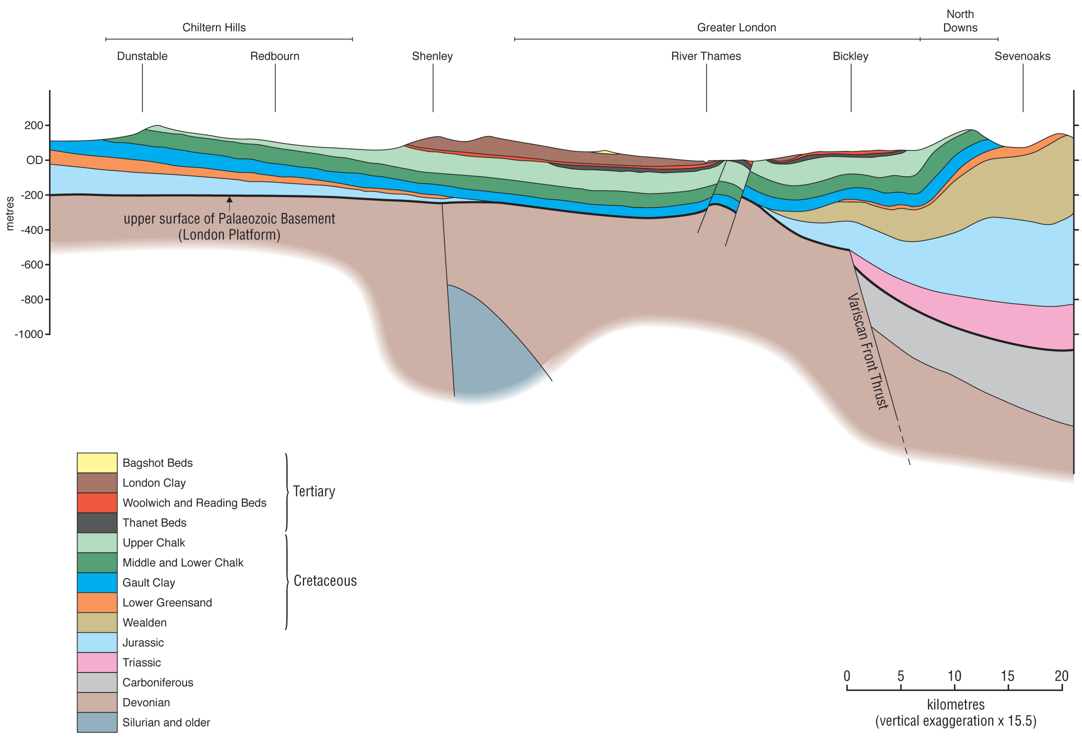

Fig. 2. Geological section across the London Basin and platform from northwest Hertfordshire to northwest Kent. Catt, J. 2010. Hertfordshire Geology and Landscape, Hertfordshire Natural History Society, with kind permission of the publishers.

Fig. 3. New Pit Chalk Formation, Kensworth Quarry, Dunstable, showing conjugate fracture system. Photo: Haydon Bailey.

double this amount of this formation is present along the line of the Chilterns. Forty-two metres of New Pit Chalk Formation are recorded in boreholes in the London Basin.

In addition to the characteristic marl seams and relatively low flint content, it is also important to recognize the distinctive fracture system frequently logged in the New Pit Chalk Formation. These are frequently recorded as 'inclined conjugate fracture systems' and have been recorded at Kensworth Quarry, at an angle of ~60° (Fig. 3). These fractures are key to the permeability of the New Pit Chalk, as water flow at depth will be concentrated along these fractures.

The New Pit is a major part of the Chalk aquifer because of the concentration of fractures present; however, within the Chiltern area it is often buried 40–50 m below the surface where water flow is concentrated horizontally in association with the semi-continuous marl seam levels.

Lewes Nodular Chalk Formation

The Lewes Nodular Chalk has very different characteristics to those described for the underlying New Pit chalk. The Lewes Nodular Chalk Formation comprises 'a hard nodular chalk, with conspicuous regularly developed flints, thin marls and hardgrounds'. The hard nodular chalks occur as a series of condensed hardgrounds, principally the Chalk Rock and the slightly higher Top Rock, both of which occur throughout the Chiltern area. These beds are extremely hard and were often used as quarry floors in old quarry workings regionally. The typical sequence seen throughout the Chiltern region, with minor variations in thickness, is that recorded at Kensworth Quarry and illustrated as Fig. 4. The hardness of the Chalk Rock unit where it occurs below the floor of the Colne Valley will provide a firm substrate into which piles can be driven, however, in this area the Chalk Rock could be as deep as 40–50 m below the surface.

The Lewes Nodular Chalk Formation has been described as 'characteristically hard, nodular, locally iron stained and flinty. Marl seams, up to 0.1 m thick, occur throughout. Hardgrounds occur locally, and at least some of the thickness variation in the Lewes Chalk may be caused by condensed sequences or depositional breaks at these horizons. Layers of flints are regularly spaced throughout the succession … At some horizons these flints almost interlock to produce laterally continuous bands'.

Joint systems are not as common in the Lewes Nodular Chalk Formation as the distinctive sets recognized in the New Pit Chalk Formation (see Fig. 8) and the 'well developed nodular chalk seams are interbedded with extremely soft to very soft chalks. Because of this variation in competency between layers, the more

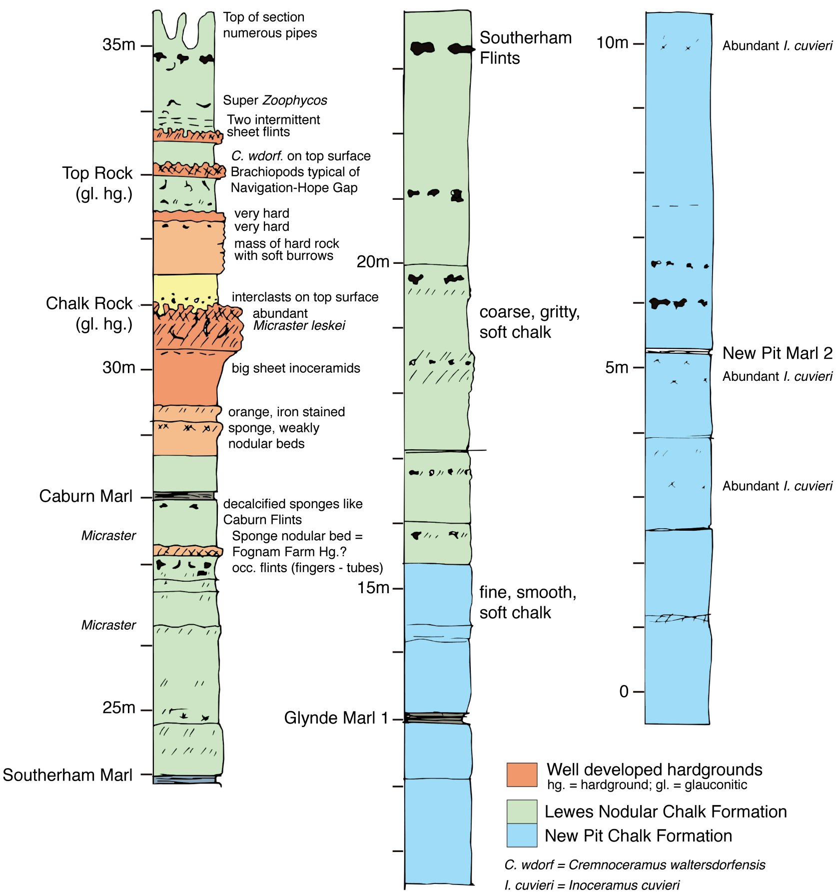

Fig. 4. Kensworth Quarry section, Dunstable (Bailey & Wood, 2010), illustrating the marl rich, flint poor, New Pit Chalk Formation and the overlying Lewes Nodular Chalk Formation with increased flint content and capped by thick indurated chalk beds (Chalk Rock). From Catt, J. 2010. Hertfordshire Geology and Landscape, Hertfordshire Natural History Society, with kind permission of the publishers.

brittle hardgrounds tend to be more densely fractured, presumably as the result of differential compaction'. This variation may well account for the lack of overt fracture systems in the Lewes Nodular Chalk Formation, although widely spaced conjugate joints are present in this formation.

The steep Chiltern scarp slope is capped by the intensely 'indurated' (hardened) chalk which creates the 'hardgrounds' of the Chalk Rock complex that form the backbone of the Chiltern Hills (Fig. 5). These can be seen in the M40 motorway cutting at Aston Rowant and they stretch north-eastwards throughout the region. These hardgrounds represent a series of fossilized sea floors, ~90 million years old, which combine in some locations to create an important mapping feature within the Chalk forming a break in the local topography.

The Chalk Rock complex varies in thickness from 1 to 5 m between Aston Rowant and Great Missenden (Fig. 6). This suggests that deeper structure must have been moving during the time of this chalk deposition, some 89 million years ago, to account for this variation in thickness. These older structures are most likely in the form of re-activated New Pit Faults which can occasionally be recognized at the present-day surface. This is not easy in the Chilterns due to the lack of rock exposures, resulting from the wonderful agricultural soils and woodland areas present. These are not kind to the geologist who prefers clean rock faces to work on. Nevertheless, recent mapping by British Geological Survey (BGS) geologists working in the region, has established the existence of faults which run northwest–southeast through the Misbourne valley. Similarly, research studies carried out by members of the Hertfordshire Geological Society, indicates that the 'Tring Gap', at the top of the Bulbourne valley, is most likely underlain by a series of northwest–southeast trending faults. This northwest–southeast trend is a persistent structural alignment in the region and it is also seen in the Lilley Bottom fault line which is mapped at depth by the BGS from south of Northampton and south eastwards to the east of Luton.

The suggestion here is that breaks in the Chiltern escarpment, which are today the locations for Chalk stream river valleys, are much older than one might first suspect. Their origins could lie in structures which are Cretaceous in origin. These ancient lines of structural weakness in the Chalk have been exploited by later Pleistocene events which would eventually carve out the over enlarged river valleys we see today.

Seaford Chalk Formation

The youngest chalk recognized in the core area of the London Basin is the Seaford Chalk Formation. This is the more typical white chalk with regular flint bands that most people would consider to be a 'normal' chalk sequence. The Seaford Chalk is typically a 'soft, flinty chalk with local shell rich horizons' and 'the base of the Seaford chalk is marked by the Upper East Cliff Marl'. This marl is another of

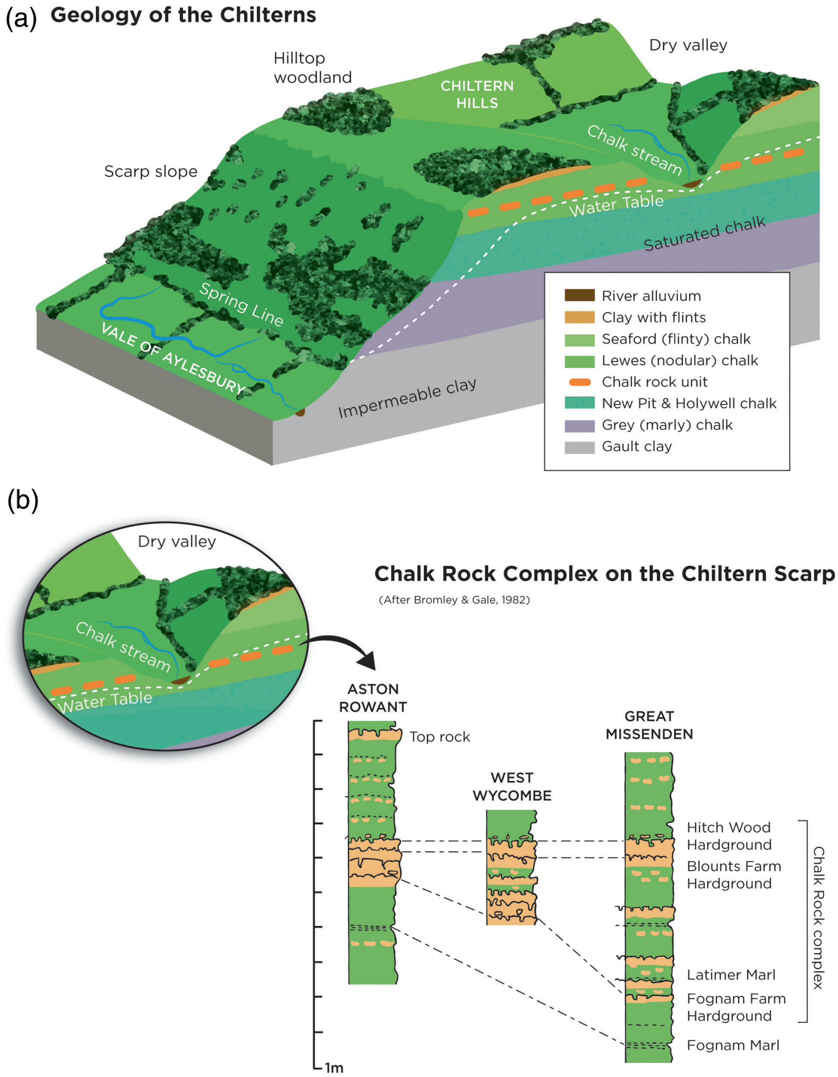

Fig. 5. (**a**) Block diagram of Chiltern Geology illustrating the importance of the Chalk Rock complex in the topography of the scarp slope. (**b**) Cross section illustrating thickness variation in the Chalk Rock complex (Bailey, 2019, courtesy of the Chiltern Conservation Board).

Fig. 6. Seaford Chalk Formation, Pinner Chalk mines, showing regular distribution of flint bands. Photo: Kirkman, K, 1992. Pinner Chalk Mines, Pinner Local History Society, with kind permission of the publishers.

the widespread clay seams recognized across much of southern England. The Seaford Chalk Formation comprises a uniform, very fine chalk with a relatively high microporosity, making it a major aquifer throughout southern England.

The uniform nature of the Seaford Chalk Formation again makes it more susceptible to fracturing and characteristic 70° fracture systems in the Belle Tout Member of the Seaford Chalk Formation are well described; this member being the oldest part of the formation and that present along the line of the Colne Valley.

The Seaford Formation is very rarely exposed in the region and probably the best examples nearest to the Chiltern area are the chalks of Pinner Chalk Mines (NGR TQ 115905). These mines are now closed to public access and were originally worked until the mid-Victorian period (Fig. 6). The chalk immediately underlying the Palaeogene unconformity at the Harefield Chalk Pit (Fig. 7) has been dated by Dr Liam Gallagher as earliest Santonian, thereby placing it into the upper part of the Seaford Chalk Formation.

The comparative ages of the two rock units (Upnor Formation and Seaford Chalk Formation) above and below the unconformity surface (in Fig. 7) are 56 Ma and 85 Ma, respectively. Therefore, this burrowed surface represents a time gap of ~29 Ma. During this extensive period the formation of the London Basin, due to the subsidence of older underlying rocks commenced. Chalks younger than the Seaford Chalk Formation, which are believed to have been deposited across southern England between 85 and 65 Ma, were subsequently eroded away. This took place during the next 8–9 Ma covering much of the Paleocene Epoch.

It is also worth noting that the Colne Valley was the site of a major 'Ice age' river (see below) and that the chalk below this riverbed will have been broken up and disaggregated due to the action of water and freeze/thaw during this period. The normal structural qualities and integrity of this formation may therefore have been damaged during this time.

Deposition of the Chalk ceased ~66 Ma ago and as much as 500 m of chalk may well have been eroded from the Chiltern region over the next 10 Ma, caused by major regional structural uplift. The youngest post-Chalk sediments recognized in the region are sands and clays of the Lambeth Group which were deposited between 55 and 56 Ma ago. In the southern extremes of the Chiltern region there are occasional outcrops of Eocene London Clay, representing the youngest phase of Paleogene sedimentation in the Chiltern region. All these Palaeogene sediments have all been affected by a further major chapter in the geological story of the Chilterns–the Pleistocene Ice Ages.

Fig. 7. Unconformity surface between the Seaford Chalk Formation and the overlying Upnor Formation, Harefield Chalk Pit (NGR TQ 049898), showing common crustacean burrows (*Glyphichnus harefieldensis*) down into the chalk. Photo: Haydon Bailey.

Influence of freezing and thawing—Anglian Glaciation

There were a series of glacial periods during the Pleistocene with intervening thaws or inter-glacials, but perhaps the most important period given its impact on the Chiltern escarpment was the Anglian Glaciation, which lasted from 480 to 425 ka ago. Glacial ice sheets spread southwards from the north and northeast, and these struck the north-eastern edge of the Chilterns around Royston and spread south and south eastwards over the existing line of the Chiltern escarpment.

During the cold periods the repeated freeze/thaw cycles would have broken down the chalk at the surface and conversely, during the relatively warmer inter-glacial times, melt-water erosion would have taken place. It was during these periods that the creation of the deep incised valleys which characterize the Chiltern dip-slope started to occur. A further effect of the Anglian ice sheet was to push the river which later became the Thames, onto a more southerly course, from the southern margins of the Central Chilterns to its present-day route through London.

One of the effects of the repeated glacial periods, both during and since the Anglian phase, has been the breakdown of the Palaeogene sands and clays overlying the Chalk into mixed sediments now often called Plateau Drift on the local geological maps. Beneath this, a layer of clay with flints, the latter derived from the underlying chalk, has also been formed; this is inevitably referred to as the 'Clay with flints' on most geological maps in the region.

The Chalk aquifer and streams

The Chalk is an extremely important water storage system. Below the surface the microscopic pores within the chalk sediment hold the water in place, while major fracture systems provide conduits through which groundwater can flow both laterally and vertically. Where the water table intersects with the gradient of the chalk slopes, springs form; they arise higher up in the winter than summer, with some valleys dry throughout much of the year but with seasonal flowing water known as 'winterbourne' streams. To understand the importance of the fracture systems in the Chalk, the table below (Fig. 8) shows the variations in both hardness of the different Chalk formations together with an indication of the fracture density and the potential of each formation to act as an aquifer.

Studies carried out in the London Basin indicate that the youngest chalk in the region is the Seaford Chalk Formation. No younger chalks (Newhaven Formation and younger formations) have been proven. For the purposes of this study, it is deemed unnecessary to examine formations deeper that the Holywell Chalk Formation. Despite all being 'chalks', the Holywell, New Pit, Lewes and Seaford formations have very different lithological and hydraulic characteristics which may impact on water flow in the area, both above and below the surface.

Chalk hydrogeology

It has been stated that 'Chalk is hydraulically a highly complex aquifer. Its matrix has a high porosity, commonly of the order of 35%, but the pores are extremely small and thus the hydraulic conductivity of the Chalk is very low, with values averaging around 10^{-3} m/day. The ability of the Chalk to act as an aquifer is therefore due almost entirely to its fractured nature'.

To understand how the chalk behaves as an aquifer, it is important to recognize first that the chalk as a sediment is largely composed of microscopic fragments of microfossils or nannofossils (Fig. 9). These plate-shaped nannofossil fragments are frequently between 5 and 30 μ in size and consequently any pore spaces between them will be equally as small, if not consistently smaller.

A fluid would be held within the matrix porosity of the Chalk if the rock was uniform throughout, however, we have already noted that chalk is not a uniform sediment and because of this, the porosity varies and

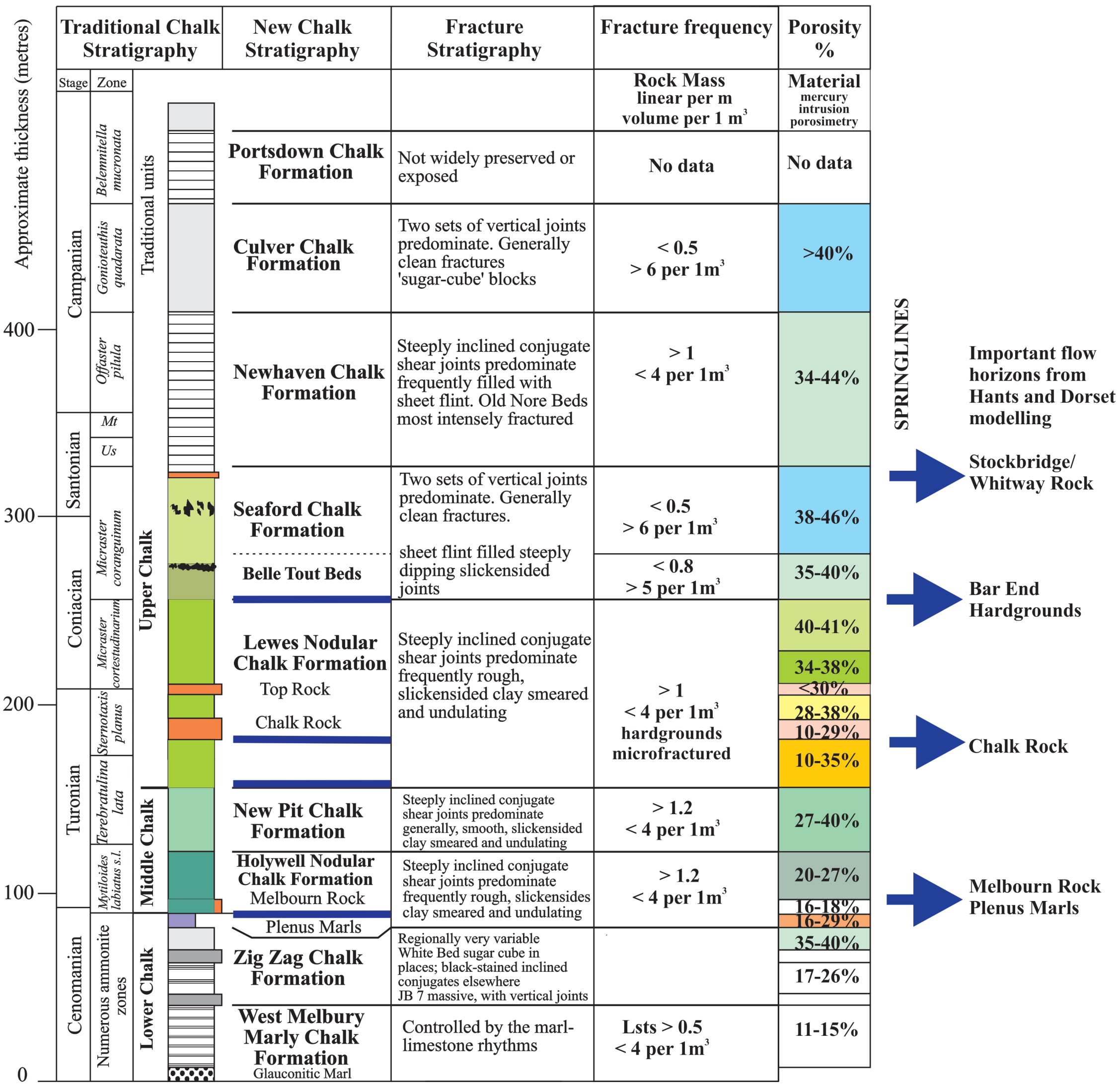

Fig. 8. A fracture stratigraphy related to the standard lithostratigraphy for the Southern Province Chalk (from Mortimore, in Soley *et al*., 2012) showing some of the key horizons associated with enhanced groundwater fissure flow and fracture/joint frequencies. From: R. W. N. Soley, T. Power, R. N. Mortimore, P. Shaw, J. Dottridge, G. Bryan & I. Colley, 2012. Modelling the hydrogeology and managed aquifer system of the Chalk across southern England. *Geological Society, London, Special Publications*, v.364, 129–154.

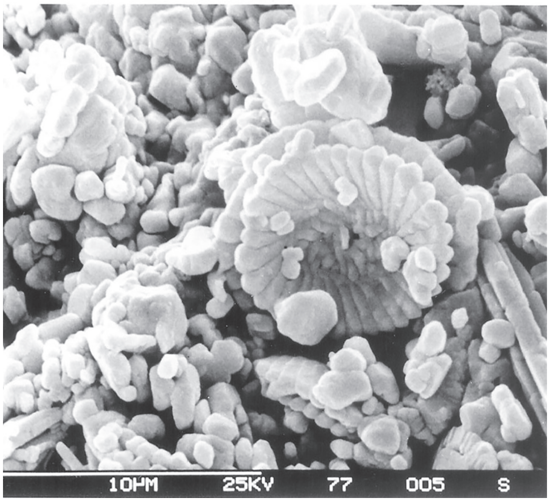

Fig. 9. Scanning electron micrograph of Seaford Chalk showing nannofossil plates and nanoscale porosity. Note 10 μ scale bar along lower border. Photo: Rory Mortimore, from Mortimore, R.N. 2014. *Logging the Chalk*. Whittles Publishing, Dunbeath. With kind permission of the publishers.

fluid flow through it will also vary. For considerable time the Chalk was assumed to behave consistently throughout with regards to fluid movement, however, since the recognition of the different chalk formations regional mapping has proven the persistent nature of lithological variations within the Chalk. These lithological variations are now recognized to be stratigraphically controlled and, as such, will exert controls on fluid flow within the formations.

Water flow through the chalk will be concentrated at certain levels. The location of these levels will be controlled by two important factors: (1) the presence of lithological barriers within the chalk, such as marl seams, flint bands (particularly continuous sheet flints) and hardgrounds; and (2) the presence of fracture systems. In the chalk succession identified in the study area all these factors can and will occur, so they are considered here on a formation-by-formation basis.

The *Seaford chalk Formation* has a uniform soft chalk lithology, but with common flint bands. The microporosity of this formation is high (ca. 35 percent) and there are numerous flint bands. Most of these comprise nodular flint bands allowing water flow through and between them, however, there are well known tabular flint bands present (e.g., Whitaker's 3″ band) in this formation which would preclude vertical fluid transfer, unless fractures were also present.

It is known that the lower part of the Seaford Chalk Formation has numerous fracture systems and that fracture systems tend to be most obvious in the upper few tens of metres below the surface. However, it is also noted that important water-bearing fractures have been shown to extend to depths of the order of 50m below the water table. This would also have been the case during glacial times and sediment-filled pipes have been recorded at least 55m below the surface at Kensworth Quarry in the Chilterns and there is the possibility that similar glacial karst generated pipes could exist elsewhere in the Chiltern region.

The *Seaford Chalk Formation* is closest to the surface in the southern part of the Chilterns, and it is likely to be highly fractured. It has also been exposed to freeze/thaw disruption during the Pleistocene ice ages which may well result in it becoming a 'soliflucted' deposit, or one which is 'structureless' as a result of these natural processes. This formation, which is up to 50-m thick in the Chiltern area, is likely to be the prime water-bearing unit within the aquifer due to the presence of common natural fractures. However, it has been exposed to superficial damage due to the natural processes described above and it should therefore be regarded as not being particularly robust, it is susceptible to pollution in the Chiltern area because of the intense fracturing recorded.

The *Lewes Chalk Formation* has hardgrounds present in its upper part which shows the greatest concentration of subvertical fracture systems, and porosity in these harder units will also be reduced due to cementation and mineralization closing the original pore spaces. The Chalk Rock hardgrounds are frequently zones where open burrow systems are recorded. These are open tubular pipes often several centimetres across which can act as major groundwater conduits. There are also two key marl seams within the Lewes Chalk Formation, these being the Caburn and the Southerham Marls. Both marl seams show consistent thicknesses throughout the region of 0.08–0.10m and, because of these consistent thicknesses, they will act as significant permeability barriers, blocking vertical water movement.

Mineralization within the pore spaces in the Lewes Chalk is more common than that seen in the overlying Seaford Chalk and therefore the natural porosity will be reduced. This formation tends to act as a secondary aquifer in this region.

The *New Pit Chalk Formation* is a marl-rich chalk unit, and the most deeply buried formation being considered currently in the Chiltern area, potentially as much as 100m deep. As such, it is possibly less likely to act as a major aquifer. Marl seams are common, including the New Pit marl seams and the Glynde marl seams. These act as barriers to water flow, particularly to vertical fluid movement. Any water flow would be concentrated along lines of lateral movement particularly if joint/fracture systems which are known to occur commonly in the New Pit Formation, remain open. Flints are very rare within in this unit, and sheets flints will occur only sporadically in localized areas, as such these should not affect fluid flow.

The *Holywell Chalk Formation* is composed of clean, shelly, well-indurated chalk that is highly fractured and underlain by the argillaceous succession of the Plenus Marl Member. As a result of these two factors, water resources are concentrated in this unit and it is one of the prime targets for the water companies operating in the region.

Fractures

As already noted above particular levels within the Chalk succession are more susceptible to fracturing. These tend to be those levels where the chalk comprises a uniform very fine matrix. Within the Holywell to Seaford Formation succession this will tend to be within the Seaford Chalk Formation, the New Pit Chalk Formation and the Holywell Chalk Formation. The Seaford Chalk Formation is at or close to the surface in the study area and because of this any fracture systems have the potential to be open and therefore active as conduits for water flow.

The complex fracture system known to exist within the New Pit Chalk Formation may increase transmissivity within the chalk of the Chiltern area, although the depth of burial of this formation to the south may reduce fluid movement, whereas to the north there are likely to be zones of high-density open fractures. The Chalk streams, principally the Misbourne, the Chess and the Wye, provide unique ecosystems with indigenous plants and animals dependent on them. They are critically important to the ecological health and heritage of the region.

The overlying Palaeogene succession

The basal boundary between the Lambeth Group and the underlying Seaford Chalk Formation is illustrated in Fig. 7, which clearly shows the intensely burrowed unconformity surface, the burrows being described as of crustacean origin (*Glyphichnus harefieldensis*).

The Lambeth Group in the study area comprises a basal unit (0.3 m) of Upnor Formation (basal flint pebble conglomerate bed with glauconitic sand matrix) which is overlain by 1.2 m of sand and clay. This conglomeratic unit could be a lateral equivalent of the Hertfordshire Puddingstone. The nearest *in situ* example of this distinctive rock unit is probably that exposed in the shaft down into Pinner Chalk Mines.

The overlying Reading Formation (grey and brown clays and silty sands) has a total thickness in the order of 10 m. The boundary between these two formations may be difficult to determine. The overlying Thames Group sediments comprise a section of London Clay with a maximum thickness of 48 m around Northwood, Middlesex.

In the present study area Lambeth Group sediments are 'confined by the London Clay' and 'most of the sandy facies is unsaturated and only thin perched water tables and seepages at the interface with the underlying clay beds are present'. The Lambeth Group sediments are therefore unlikely to act as an aquifer locally and the overlying London Clay is an impermeable aquiclude.

Fig. 10. *Inoceramus lamarcki* Parkinson from a badger sett, Ibstone, in the Chilterns. Photo: Haydon Bailey (Courtesy of the Chiltern Conservation Board).

A final thought

Charles Rangeley–Wilson recorded in his book, centred around the River Wye, *Silt Road—The Story of a Lost River*:

> We now know that the chalk accreted at the rate of just one millimetre in a century, a centimetre every thousand years. A small lump of chalk such as the one I was holding on that hillside (Fig. 10) bearing the imprint of a long-dead Inoceramus represents a greater span of time than has elapsed since the last ice age. And this lump was to this landscape as ten thousand years is to the length of time it took chalk to accumulate.

Acknowledgements

Thanks go to a whole list of people for assisting with this manuscript, particularly John Gladwyn, Peter Brown, Keith Hoffmeister and Jim Conboy of the Chiltern Society HS2 Working Group, together with the Directors of Misbourne Environmental Protection Ltd. Thanks also go to Elaine King and Allen Beechey of the Chiltern Conservation Board for the very useful discussions. I would also like to acknowledge the editor of *Geology Today* for his patience, as well as Rory Mortimore for his assistance and his enduring friendship.

Suggestions for further reading

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