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LARGE-SCALE PARTIAL DISSOLUTION OF THE CHALK OF THE DEVON COAST AND ITS ENGINEERING SIGNIFICANCE

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Numerous site investigations have described 'reconstituted', 'putty', 'soft' and 'rubbly' chalks which have generally been grouped together for geotechnical description purposes as 'structureless', to distinguish them from 'structured' (bedded and jointed) *in situ* chalks. Structureless chalks have mostly been assumed to be redeposited materials or materials that have been intensely mechanically reworked in place. They include sludge (Head), partially water-sorted (Coombe), fluvial (Dry Valley and Nailborne) and cryoturbation (Head) deposits.

Recent surveys of the east Devon coast have shown that an extensive, thick chalk deposit, which in small exposures or in cored boreholes could be mistaken for redeposited material, has formed *in situ* by the partial dissolution of a particular type of chalk. The best exposures, in the cliffs at and adjacent to Beer, Devon [SY 230 890], show a 15 m- to 30 m-thick layer of partially decalcified, nodular chalk that is underlain and overlain by intact clay-rich chalks. The boundaries of the decalcified unit are stratigraphically controlled and sharply defined. It contains angular to rounded, granule to boulder sized lithorelics in a degraded, chalk-fines matrix. Blocks of intact, largely unweathered chalk up to tens of metres thick occur as detached masses 'floating' in the partially decalcified unit, and even larger masses have settled down into it. Some of these contain the youngest Chalk preserved in Devon.
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INTRODUCTION

Throughout much of the east Devon coastline between Salcombe Regis [NGR SY 151 877] and Devonshire Head [NGR SY 332 914], the Chalk crops out in the highest part of the cliffs, above the relatively stable Upper Greensand. Few major cliff falls have been recorded in this area in recent years, and none was initiated in the Chalk. Between Beer Head and Beer the Chalk is brought down to sea level in the core of a syncline and gives rise to a 1.2 km-long coastal section of vertical and near-vertical cliffs that are mostly 40 to 70 m high. Collapses of up to 50,000 tonnes have been common after prolonged periods of high rainfall (Figure 1). All the larger falls have been initiated in and been largely confined to a thick (up to 30 m) layer of partially dissolved chalk that is substantially weaker than the underlying and overlying intact chalks. Collapses of the type described by Mortimore *et al*. (2004a) as 'plane', 'wedge' and 'toppling' failures that involve complex sets of conjugate joints have also occurred in this area, but have involved much smaller volumes of material.

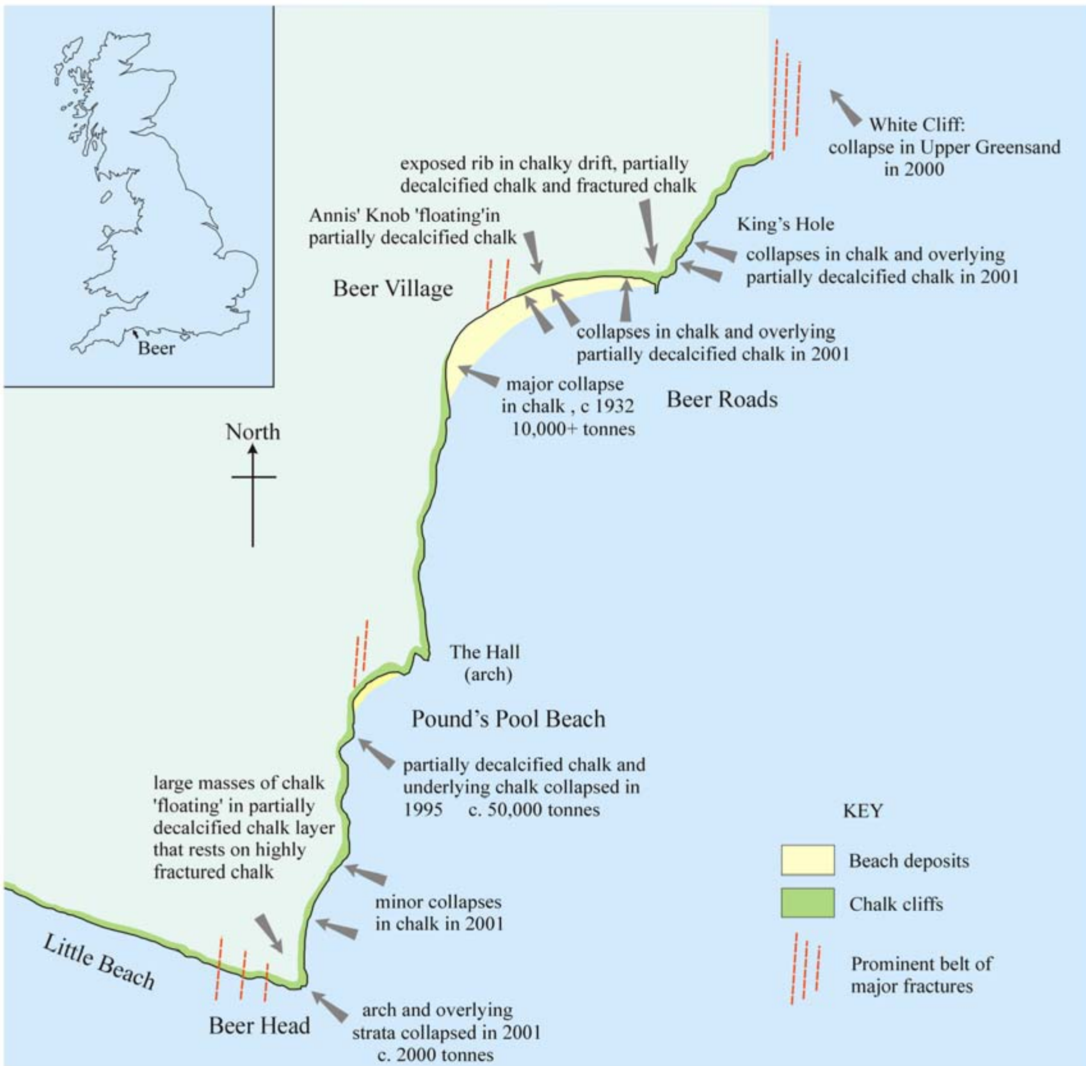


Figure 1. *Sketch map of the coastal strip in the Beer area showing the positions of localities and cliff falls referred to in the text.*

The Chalk exposed in the east Devon cliffs is the most westerly preserved in the Anglo-Paris Basin. It contains evidence of shallower water environments than its more easterly correlatives in Dorset and Hampshire and is laterally more variable. Although lithologically different in detail from more easterly successions, many of the lithologies and individual marker beds used to divide the Chalk Group into formations (Mortimore *et al*., 2001) can be recognised throughout the east Devon outcrop. These enable the group to be divided on gross lithology into the standard southern England formations (Figure 2).

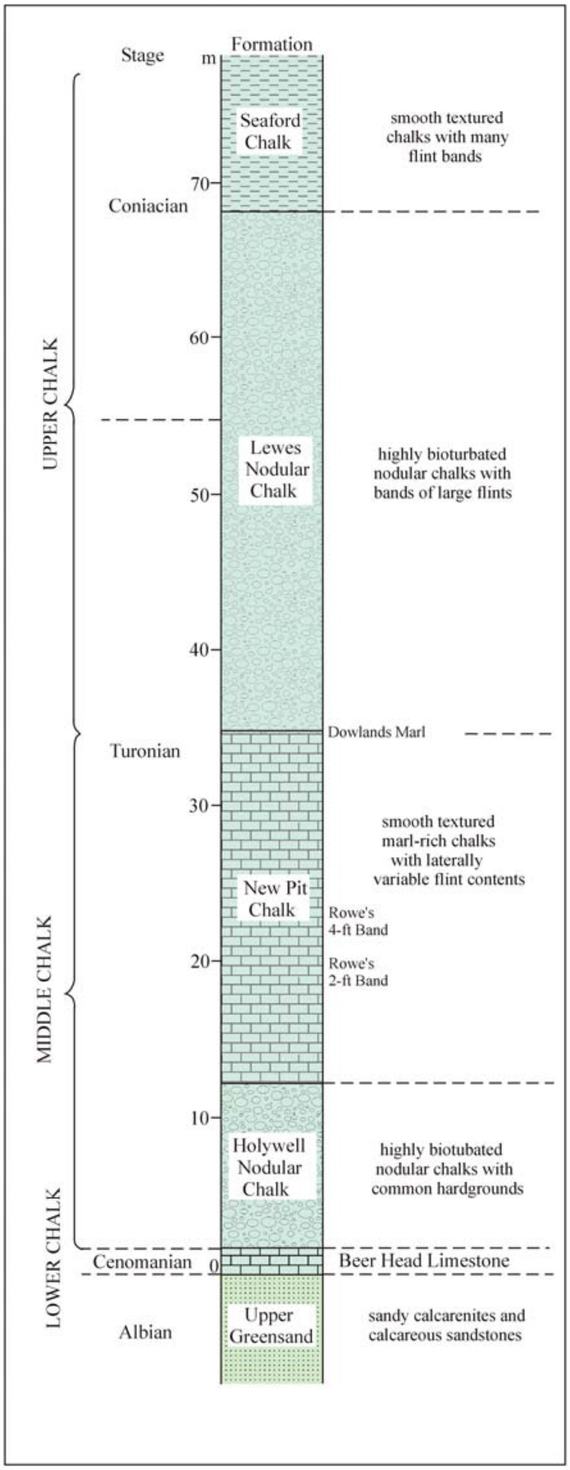


Figure 2. *Generalised vertical section for the Chalk of the Beer area*.

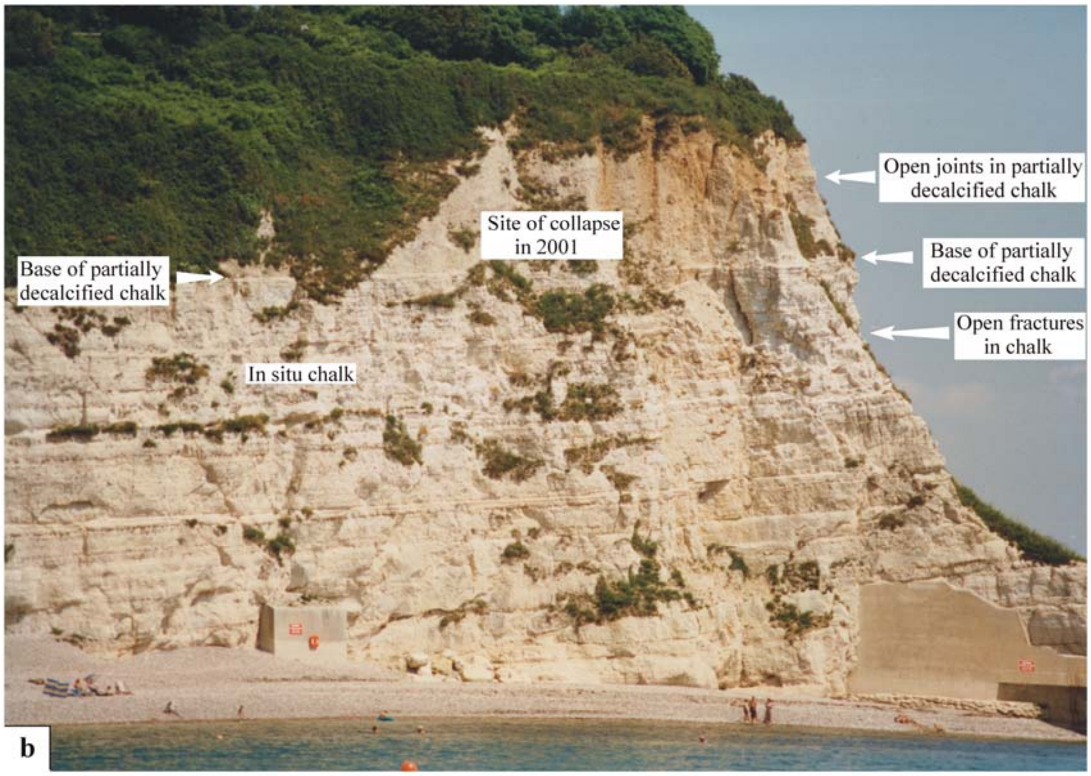
Much has been written about the close relationship of the stratigraphy of the Chalk to its properties and engineering performance with respect to slope and cliff stability, notably by Mortimore (2001) and Mortimore and Duperret (2004). The chalk cliffs at and adjacent to Beer provide a good example of the relationship between stratigraphy, bulk lithology and cliff profiles.

EXPOSURES IN THE PARTIAL-DISSOLUTION BED

Beer Beach

The Chalk exposed in the cliffs at the back of Beer Beach can be divided on gross lithology into three parts (Figure 3). At the base, strong, widely jointed Holywell Nodular Chalk forms stable cliffs that rest on a hard wave-cut platform of Upper Greensand calcarenites. Above this, the more closely bedded and jointed, marl-rich New Pit Chalk forms near vertical cliffs that give rise to relatively infrequent block and toppling failures in which steeply dipping and sub-horizontal bedding-related joints combine to produce collapses. Two laterally persistent marl-rich beds, the 2-Ft and 4-Ft bands of Rowe (1903), give rise to prominent ledges and commonly form the termination of steeply dipping joints. The highest part of the cliff, steep (mostly 40° to 60°) and largely vegetated, is composed of partially decalcified Lewes Nodular Chalk. This material consists of angular to rounded lithorelics of chalk that range from granules to boulders, in a matrix of degraded chalk fines (Figure 4). The larger blocks are commonly joint bounded with solution-rounded edges. The smaller clasts are mostly well rounded, strong kernels of hard chalk (the nodular part of the original material) that could be mistaken in small exposures or borehole cores for fluvial gravel. Its high porosity (locally > 50%) and lack of interstitial cement have given rise to bulk failures on the Devon coast when the unit was saturated.

The partial dissolution process is almost certainly related to the marked differences in physical properties of the nodular and matrix components of the Lewes Nodular Chalk and lithologically similar chalks. In an extensive study of the physical properties of the chalks exposed along the Sussex and French coasts, Mortimore *et al*., (2004b) recorded typical values of 2.0 Mg/m^3 for the Intact Dry Density (IDD) and 10% for the Natural Moisture Content (NMC) of the ‘kernels’ (mostly mineralised burrow infills) in the Lewes Nodular Chalk, and 1.5 Mg/m^3 IDD and 30% NMC for the matrix.



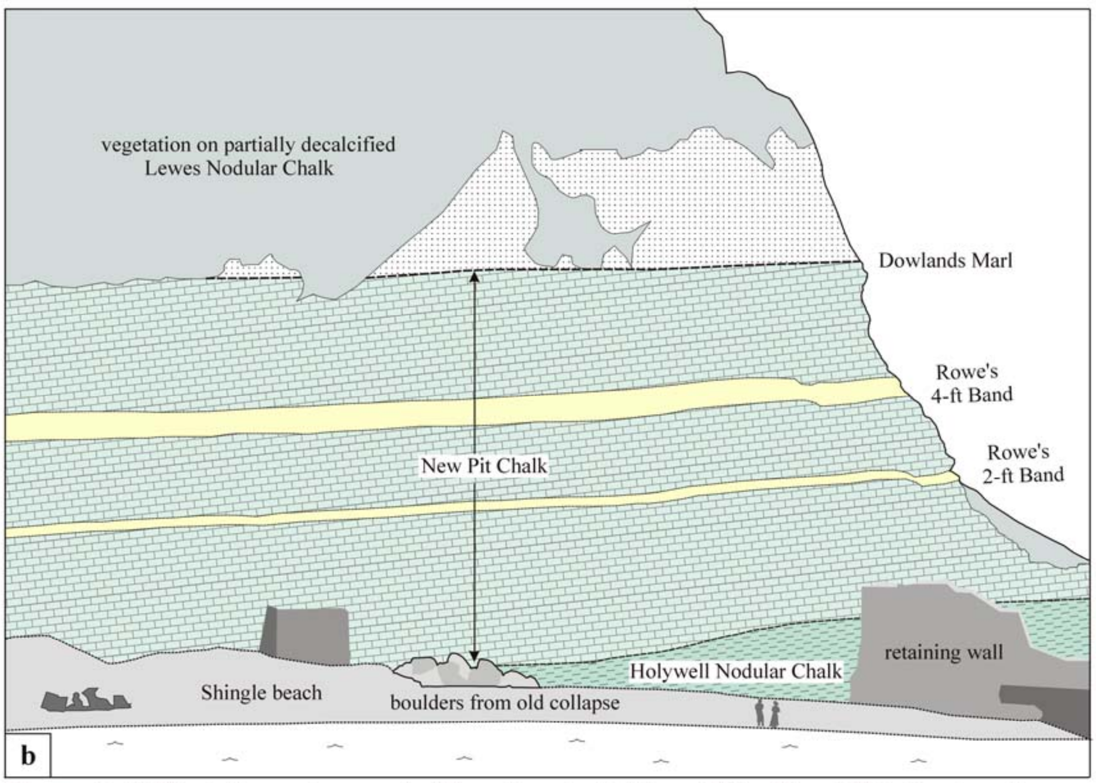


Figure 3. *Cliffs at the eastern end of Beer Beach: (a) the cliff in May 1996 showing the relationship of the stratigraphy and the partially decalcified to the cliff profile. (b) geological sketch section showing the principal marker beds.*

The lower limit of the partial-dissolution layer at Beer Beach, and westwards to Beer Head, is sharply defined by the Dowlands Marl at the junction of the New Pit Chalk and Lewes Nodular Chalk formations (Figure 2). This is a thin (5 to 10 mmthick), laterally persistent bed of argillaceous chalk (referred to in Chalk literature as 'marl') that forms an aquitard. Three kilometres east of Beer, at Haven Cliff, Axmouth [SY 897 260], the base of the partially decalcified layer rests on a stratigraphically lower horizon in the Chalk, but there too the bounding surface is a 'marl' a few millimetres thick.

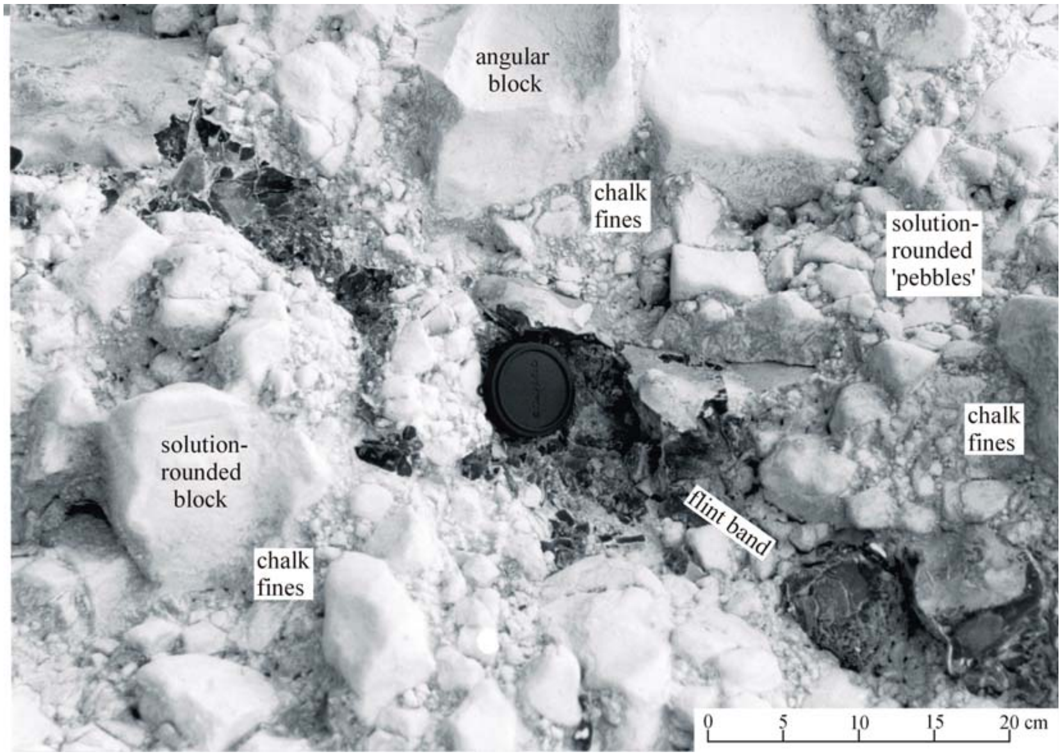


Figure 4. *Detail of the textures within the partially decalcified unit.*

Behind Beer Beach, a higher cliff known as Annis' Knob is the face of a large (15x50x80 m) block of intact Lewes Nodular Chalk that is a detached mass 'floating' in the partially decalcified layer. Comparison of the stratigraphical succession exposed in Annis' Knob with that in intact sections at Beer Head shows that the detached mass has subsided about 10 m, tilting seawards and westwards as it has done so (Figure 5A). Westwards from Beer, similar detached masses are common, culminating at Beer Head (see below) in blocks that preserve younger chalks (Seaford Chalk) than any *in situ* outcrop in Devon.

There have been several cliffs falls at Beer Beach in recent years. The largest of these, in January 2001, destroyed over 30 beach huts and caused the closure of a beach access path and the Coastal Path beneath Annis' Knob. The failure was initiated in the partially decalcified Lewes Nodular Chalk after a prolonged period of high rainfall, and incorporated a veneer of joint-bounded weathered material in the underlying New Pit Chalk (Figure 5B).

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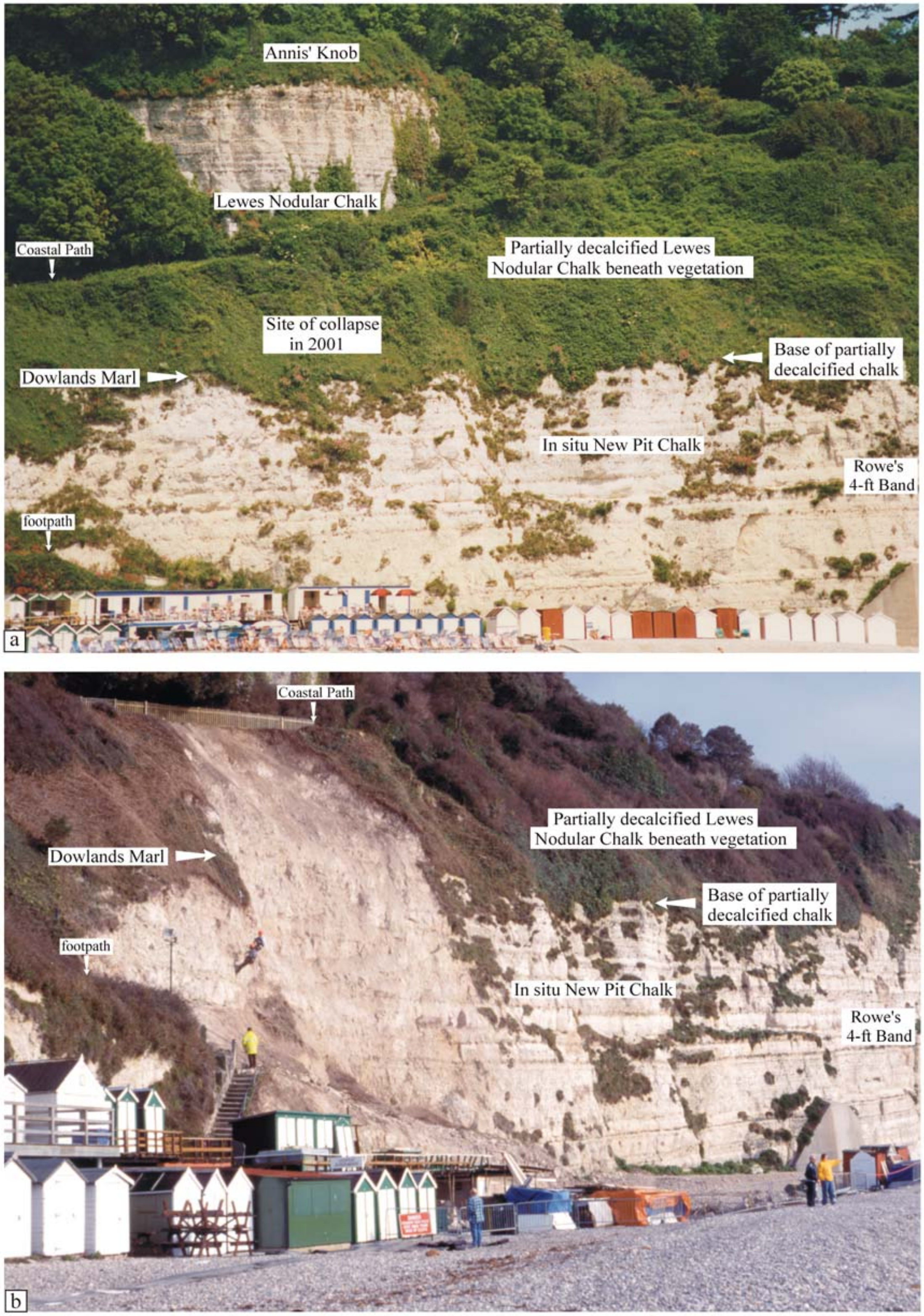

Figure 5. *Cliffs in the central part of Beer Beach. (a) In May 1996 showing the relationship of the partially decalcified bed to the underlying and overlying intact chalks. Note the discordance of dip in the main cliff and Annis' Knob outcrops. (b) Shortly after the collapse of January 2001.*

Pound's Pool Beach

A large collapse, which extended into the subtidal area, occurred at Pound's Pool Beach in August 1995 after a long period of above average rainfall. As at Beer Beach in 2001, the failure was initiated in waterlogged, partially decalcified Lewes Nodular Chalk, and its base was sharply defined by the Dowlands Marl (Figure 6). The application of a 'bulking factor' of 40% (Duperret *et al*., 2004) to the estimated volume of the fall, based on photographs taken shortly after the collapse, suggests that over 50,000 tonnes of material were involved. Unlike the Beer collapse, the fallen material included large angular blocks of intact Lewes Nodular Chalk that were derived from a subsided mass within the partially decalcified layer (Figure 6).

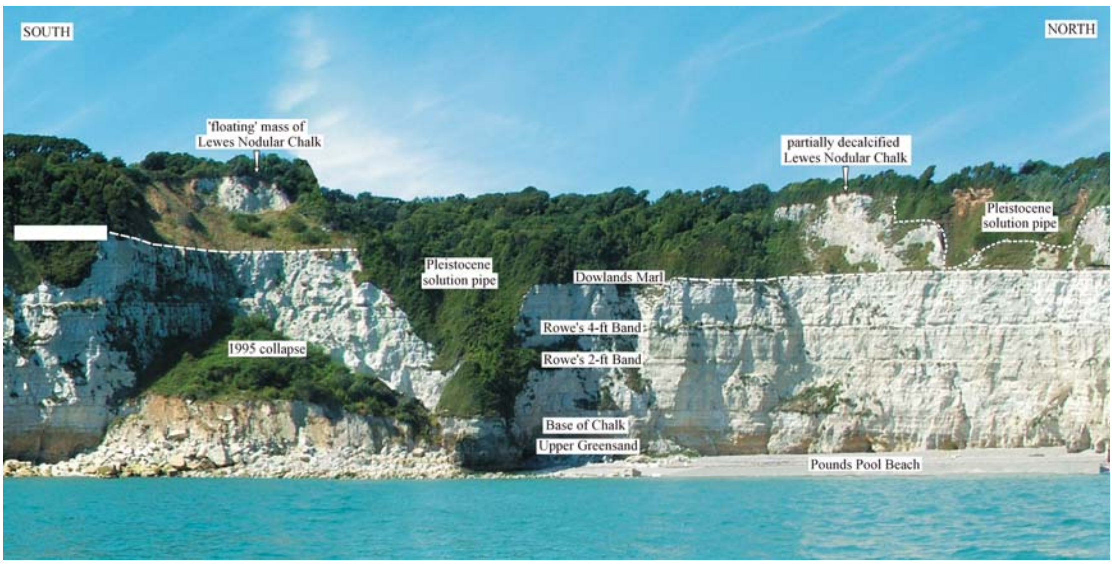

Figure 6. *Pound's Pool Cliff, December 2004 showing the relationship of the stratigraphy to the collapse of October 1995. Photo courtesy of Richard Edmonds.*

Beer Head

There has been no major collapse at or adjacent to Beer Head in recent years other than relatively small (a few thousand tonnes) block failures in the lower part of the cliff. The largest of these was the collapse of a sea arch [NGR SY 2368 8787] in 2002. However, the effects of the partial dissolution of the Lewes Nodular Chalk are more extensive (and more clearly demonstrable) at Beer Head at the present time than at any other locality. Large collapses will undoubtedly occur at the eastern end of the headland within the next 10 years if there are any long periods of higher than average rainfall.

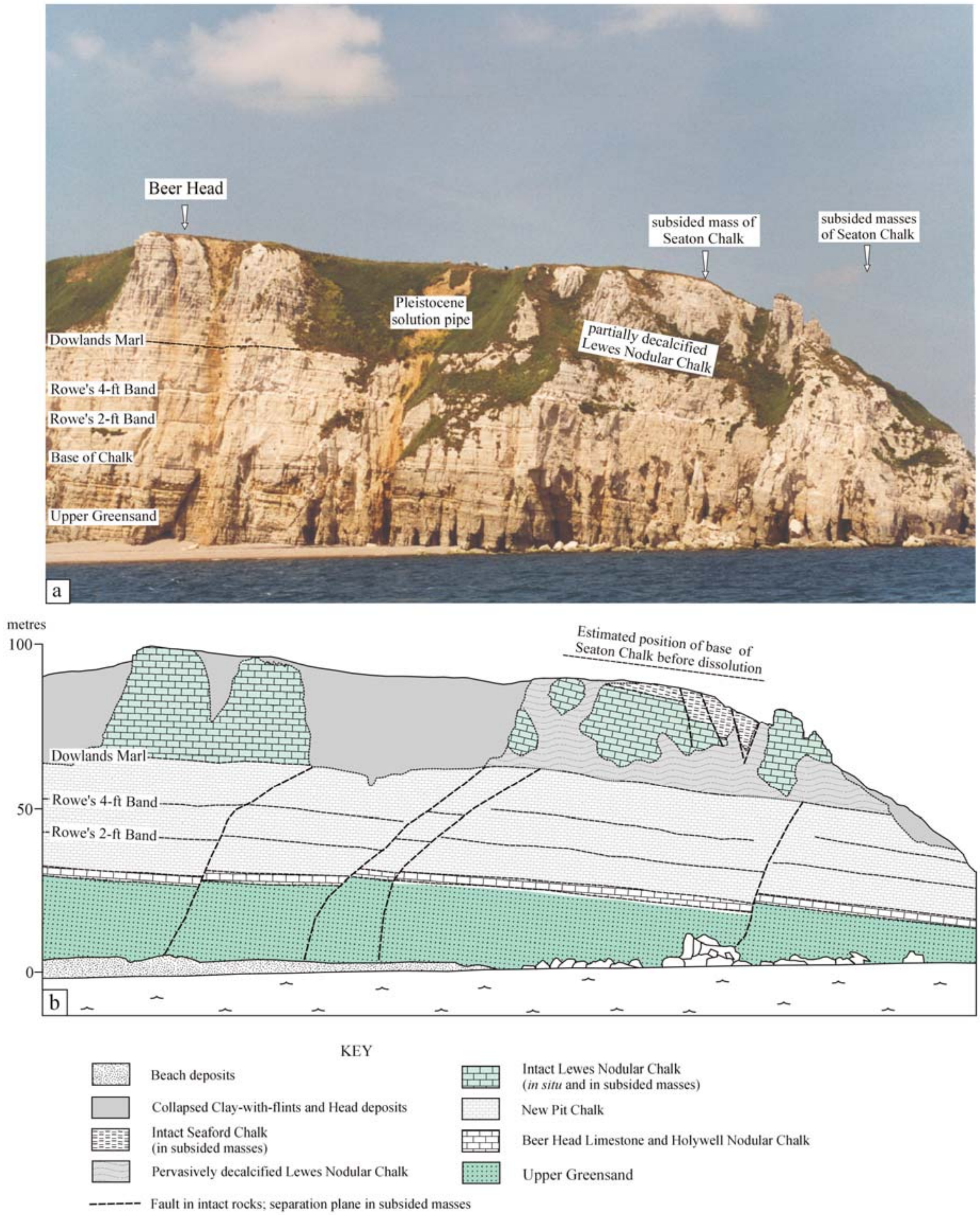

Figure 7. *Beer Head: (a) The relationship of the partially decalcified bed to the stratigraphy. (b) Geological sketch section showing the principal marker beds*.

Beer Head itself, at 95 m, is one of the highest truly vertical cliffs in southern England. It exposes a complete, intact and *in situ* succession from the base of the Chalk to an horizon high in the Lewes Nodular Chalk (Figure 7). At the highest point on the headland unweathered chalk is overlain by a veneer (< 0.5 m thick) of chalky soil and subsoil. Immediately west and east of this point the whole of the Chalk down to the level of the Dowlands Marl has been removed by dissolution, a total thickness of about 30 m of material. The resulting void has been filled by collapsed Clay-with-Flints and Head deposits. It is probable that these and similar hollows along the adjacent coastline formed in two stages. Partial dissolution of the Lewes Nodular Chalk in the Tertiary left a permeable chalky deposit that was susceptible to dissolution by cold meltwater in the Pleistocene. This enabled frost wedges infilled with highly permeable chert- and flint-rich gravels to expand laterally and coalesce. The Tertiary and Pleistocene dissolution phases probably occupied a total period of several million years. Dissolution appears to have proceeded slowly enough for the overlying materials to subside rather than collapse into the voids created.

The results of the Tertiary subsidence are well exposed at the eastern end of the headland where a bed of partially decalcified Lewes Nodular Chalk up to 30 m thick contains large subsided masses of intact Lewes Nodular Chalk and Seaton Chalk (Figure 7). The latter expose younger Chalk than any recorded elsewhere in Devon, and the youngest Chalk exposed on the south coast west of White Nothe, Dorset [NGR SY 764 813]. The subsidence occurred unevenly with the result that individual blocks are separated by planar surfaces that were originally master joints.
As in the sections at Beer Beach and Pound’s Pool Beach, the base of the zone of dissolution is sharply defined by the Dowlands Marl (Figure 7).

Other areas in southern England

Karstic features are common in the Chalk of the Anglo-Paris Basin, especially in the unglaciated areas of England south of the River Thames and in northern France. Sperling *et al.* (1977) noted that solution collapse features (dolines) were rare (< 10 per 100 km^2) on the chalk downlands of East Anglia and Lincolnshire-Yorkshire, but were relatively common south of the Thames, reaching an observed maximum of 90 per 100 km^2 in south Dorset. Solution pipes and solution-widened fractures occur down to depths of 100 m or more, to the levels of former (mostly Pleistocene) water tables, in the chalk cliffs on both sides of the English Channel. However, no partially decalcified bed comparable to that exposed on the east Devon coast has been reported elsewhere from the outcrop of the Chalk, including 40 km of the Sussex cliffs and 120 km of the French cliffs that have been the subject of a detailed engineering study (Mortimore and Duperret, 2004).

Lithologically similar deposits to that decribed from east Devon occur beneath most chalk valleys in southern England, many of which are permanently or seasonally dry and subject to underground drainage. Sections through large and small dry valleys are well exposed at many cliff localities along the south coast, notably in the Lulworth area in Dorset, at Freshwater on the Isle of Wight and along the Sussex coast. These show partially decalcified chalks with chalk lithorelics of variable size in a partially reconstituted, chalk-fines matrix. As in the partially decalcified layer in east Devon, relict bedding (e.g. lines of flints) and jointing are commonly visible, indicating that the partially dissolved beds are *in situ*.

There is, however, a major difference between the east Devon occurrences and those elsewhere in southern England. The east Devon deposits occur as sheet-like, stratigraphically controlled beds, largely in nodular chalks, and are underlain and overlain by intact chalks. This difference is related to the timing and method of their formation. The principal period of dissolution in east Devon occurred in the early Tertiary, probably in a warm, humid climate following region-wide uplift of the Chalk in the mid Palaeocene to form a low-relief plateau (Hansen and Clausen, 2005). Elsewhere in England, the strongly solution-affected beds are confined to valley floors, and they die out at depth. They are largely independent of stratigraphy and lithology, having formed by the downward percolation of meteoric water during the Pleistocene.

ENGINEERING SIGNIFICANCE

The partially decalcified chalks described from Devon, and lithologically similar materials that underlie valleys on chalk in southern England, have markedly different properties from intact chalks. In particular, they have lower bulk densities and shear strengths and higher porosities and permeabilities. In Devon, where the solution affected beds crop out in the upper parts of cliffs, they give rise to collapses at relatively frequent (< 10 years) intervals. At valley sites they can give rise to foundation problems, and can provide pollution pathways that are more rapid than those predicted by fracture-flow models. Whilst the identification of pervasive solution effects in chalks and their probable 3-D distribution in the rock mass is relatively easy to determine in cliff exposures, it is difficult to identify at inland sites.

There are few published site-investigation records of large-scale, partially dissolved chalks in inland Britain. Those in valley floors are usually below the water-table and can only conveniently be explored by drilling. However, even continuous borehole cores rarely preserve the bulk textures that characterise *in situ* partial decalcification. Materials at such sites are commonly described as 'structureless', 'putty' or 'reworked' chalks with markedly different geotechnical (e.g. Bracegirdle *et al*., 1990) and hydrological (Lloyd *et al*., 1981) properties from those of nearby valley-side outcrops of chalk. It is important, therefore, that partially dissolved chalks should be described in a manner that is both consistent and related to their bulk properties.

The partially dissolved layer exposed in the Beer area falls outside the current engineering classifications of chalk. The two most widely used classifications for the description of the mechanical weathering of chalks, the Mundford (Ward *et al.*, 1968) and CIRIA (Lord *et al*., 1994, 2002) grades (Table 1), are inappropriate. Both contain descriptions of textures that can be loosely matched with those of the partial-dissolution bed, but they refer to mechanical weathering, not to the results of solution effects. The description of the most heavily altered category (Grade V) of the Mundford classification ("unweathered and partially weathered chalk blocks and fragments set in a matrix of deeply weathered remoulded chalk") is superficially similar to that of parts of the partial-dissolution bed of east Devon. However, the Mundford grade described Pleistocene *in situ* cryoturbation damage to the chalk fabric in an area of Norfolk that had undergone long periods of periglacial climate.

Other descriptions of highly altered chalks, such as Wakeling's (1970) addition of a Grade VI ("soft structureless chalk containing small lumps of intact chalk") to the Mundford classification are even less appropriate. This grade has been used almost exclusively for remobilised chalk sludges, with and without additional clastic material, that should be described separately as drift deposits (mostly Head).

In the CIRIA classification (Lord *et al*., 2002) the fundamental difference between the partially decalcified layer described here and material allocated to the CIRIA Dc and Dm grades (Table 1) is that they are only applicable to near-surface deposits. Many of these are remobilised or contain non-chalk materials and would be better classed as drift deposits. Except for rare examples where solution cavities are infilled with collapsed near-surface deposits, these are never overlain by intact, structured chalks (Grades A1 to Cg). In contrast, the partially dissolved chalks described here from east Devon are commonly overlain by thick beds of intact chalk. For example, Annis' Knob at Beer, composed of strong chalk with widely spaced joints (CIRIA Grade A1), overlies 20 m of partially decalcified chalk (Figure 3).

CIRIA Grade	**Mundford Grade**	Chalk type	Description
Dm	VI	Structureless fine soil, (mostly drift deposits)	Structureless CHALK composed of gravel and cobbles of weathered chalk with flint gravel and sand and clay
Dc	V	Structureless coarse soil	Structureless CHALK composed of uncompacted silt to gravel-sized chalks with voids
C5-A1	IV	Bedded/jointed chalk	Moderately weak CHALK with closely spaced joints
B3	III	Bedded/jointed chalk	Moderately strong CHALK with moderately spaced joints
A2	II	Bedded/jointed chalk	Moderately strong CHALK with widely spaced joints
A1	I	Bedded/jointed chalk	Strong CHALK with widely spaced joints

Table 1. *Comparison of the CIRIA (Lord et al., 2002) and Mundford (Ward et al., 1968 modified by Wakeling, 1970) chalk-grade classifications for engineering purposes.*

Descriptions of the state of chemical weathering of chalks (e.g. Mortimore *et al*., 1990) are also inapplicable to the deposits described here because they place a heavy emphasis on discoloration. This feature is absent from the partially decalcified layer in east Devon except along narrow zones where it is stained by groundwater draining from the overlying Clay-with-flints. The bulk of the material would therefore be described by the potentially misleading term "fresh" in these classifications.

Solution effects in Chalk are covered by the CIRIA recommendations (Lord *et al*., 2002) which refer (p. 59) to "chalk decay" in valley floors that produces "rounded fragments of chalk (clasts)" enclosed in a "putty chalk matrix of fines" in which crude layering (e.g. flint bands) can be picked out. Reference to this type of texture as

Mundford Grade V is potentially misleading because it has not resulted from mechanical weathering and disguises the true (solution weathering) nature of the deposit. The DEFR database of limestones and chalks in the U.K. (quoted in Lord *et al.*, 2002, pp.64-66) refers to three types of natural solution feature; caves, solution pipes and sinkholes. None of these describes the stratigraphically-controlled partial dissolution of the Chalk of east Devon.

SUMMARY AND CONCLUSIONS

The cliffs between Beer Head and Devonshire Head on the east Devon coast locally expose an *in situ* bed of partially dissolved chalk up to 30 m thick. This is underlain and overlain by intact chalks, and contains large subsided masses of intact chalk up to tens of metres thick as detached masses 'floating' in the partially decalcified layer. Those at Beer Head contain the youngest Chalk preserved in Devon. The boundaries of the decalcified layer are stratigraphically controlled and sharply defined.

Much of the outcrop of the partially decalcified layer between Beer Head and Beer Cliffs forms steep slopes (mostly >50°). These are heavily vegetated most of the time, but do not carry mature trees. This suggests that individual sections of the outcrop are stable for periods of tens rather than hundreds of years. The high permeability of the deposit and its position above an aquitard make it especially prone to instability after prolonged periods of heavy rain. Locally, deep gravel-rich pockets in the overlying Clay-with-flints act as natural soakaways that feed groundwater into the partially decalcified layer. When failures occur, they can involve large masses of intact chalk within the partially decalcified layer and give rise to collapses in excess of 50,000 tonnes.

The partially decalcified layer contains angular to rounded, granule to boulder sized lithorelics in a degraded, chalk-fines matrix. In small exposures or borehole cores such material could be mistaken for a drift deposit or a structureless soil. Current engineering classifications designed to describe the mechanical and/or chemical state of chalks are inappropriate for the east Devon partial dissolution unit. The bulk geotechnical properties of the deposit, including the intact chalk masses 'floating' within it, are so variable in three dimensions that they fall outside current engineering classifications of chalk weathering. It is therefore essential in any site investigation in these materials that the role of solution should be recognised at the earliest possible stage. This will avoid the use of mechanical or chemical weathering classifications that might lead to a false appraisal of the bulk geotechnical properties of the rock mass under consideration.

The age of formation of the partially decalcified layer in east Devon cannot be directly demonstrated. Its position as a stratigraphically bounded unit beneath the relatively impermeable Clay-with-flints suggests that it is older than or of similar age to the Clay-with-flints, a deposit that pre-dates the Miocene folding of the region (Woodward and Ussher, 1911). The partial dissolution of the Chalk described here was probably part of an early Tertiary dissolution 'event' that decalcified much of the Upper Greensand Formation (Gallois, 2004) of the region and removed a thick (possibly up to 500 m) cover of Chalk.

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