The development and origin of karst in the Upper Greensand Formation (Cretaceous) of south-west England

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The Upper Greensand of south-west England can be divided on bulk lithology into two roughly equal parts, each 25 to 30 m thick. The lower part, the Foxmould Member, consists of weakly cemented glauconitic sandstones with low carbonate contents. The member weathers, largely by oxidation, to soft, loose, yellow and foxy brown sands. In contrast, the overlying Whitecliff Chert and Bindon Sandstone members consist of calcareous sandstones and sandy calcarenites with numerous chert-rich horizons. Dissolution, particularly during the warm humid climates of the Eocene and the periglacial climates of the late Pleistocene, has been the dominant weathering process in these two members. Karstic features observed on the east Devon and west Dorset outcrops include widespread pervasive dissolution that has locally reduced the *in situ* thickness of the Whitecliff Chert and Bindon Sandstone members to less than half their original thickness, along with deep solution pipes, and at one locality, caves. These discrete solution features occur beneath a thick capping of Chalk that is not markedly affected by dissolution. Over much of east Devon and west Dorset, the residual loose sands and chert blocks derived from the dissolution of the Upper Greensand were remobilised during the late Pleistocene to form extensive Head deposits.

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Introduction

The Upper Greensand Formation in south-west England underlies a dissected plateau, capped by clay-with-flints and in part by Chalk, that covers an area of about 900 km^2 (Figure 1). Within this region the formation can be divided on bulk lithology into two roughly equal parts (Gallois, 2004). The lower part, the Foxmould Member, consists of weakly cemented glauconitic sandstones with low (mostly < 5%) carbonate contents. The member weathers, largely by oxidation, to soft, loose, yellow and foxy brown sands. In contrast, the overlying Whitecliff Chert and Bindon Sandstone members consist of calcareous sandstones and sandy calcarenites with significant amounts of chert at many levels. The carbonate content is made up of whole and broken shells (mostly bivalves and gastropods), unidentifiable shell sand and granules, along with secondary carbonate cements and concretions. The insoluble content consists of sand-grade quartz and glauconite, and cherts. Where not tightly cemented, both members have a high permeability, and both are cut by numerous bedding-related and steeply dipping joints. At outcrop they give rise to steep, free-draining slopes, with common strong springs at the base of the Whitecliff Chert Member.

The Upper Greensand Formation is overstepped westwards by an early Tertiary (probably Eocene) planation surface with the result that the two younger, more calcareous members are not preserved west of the Otter Valley. However, residual deposits of sand and chert derived from them are present in the clay-with-flints over the whole region. Dissolution, particularly during the warm humid climates of the early Tertiary and the periglacial climates of the late Pleistocene, is thought to have been the dominant weathering process in these two members (see below).

A number of early workers recognised the widespread occurrence of dissolution features in the Upper Greensand in the region, but did not described them as karstic features or comment on their possible genesis. Jukes-Browne and Hill (1900, p. 191), writing about the Upper Greensand Formation in east Devon and west Dorset, noted that "whenever the capping of Chalk has been completely removed from the tracts of Upper Greensand, the Chert-beds seem to have yielded very rapidly to the disintegrative effects of rain, frost, and percolating water". As examples, they gave the coastal sections at Black Ven [NGR SY 350 933], Stonebarrow [NGR SY 377 931], and Golden Cap [NGR SY 405 920], and inland gravel pits, all of which showed thick layers of cherts "which seem to have settled down as a mass, while much of the intervening sand has been carried away…by the soakage of rain and the suck of the springs". At most localities, the sand has remained in place and only the carbonate has been removed (Figure 2). In west Dorset, similar *in situ* chert-rich deposits on the outcrop of the Upper Greensand Formation were mapped out by Wilson *et al.* (1958) as 'angular chert drift'.

The karstic features described here can be grouped into three broad types: large-scale pervasive dissolution, solution pipes, and cave systems. One or more types may be present at any given locality and provide evidence of more than one phase of dissolution. All three types fall within Class kIII (mature karst) in the engineering classification of Waltham and Fookes (2003). The landforms generated by the karstic modification of the Upper Greensand Formation differ in detail from those developed over limestones because of the relatively high contents of insoluble silica. The degree to which the carbonate has been removed from the underlying solid deposits appears to have no surface expression, probably due to extensive reorganisation of the overlying clay-with-flints and Head deposits during periglacial climates in the Pleistocene. Over much of south-west England, the residual loose sands and cherts derived from the dissolution of the Upper Greensand Formation were remobilised during the late Pleistocene to form extensive Head deposits.

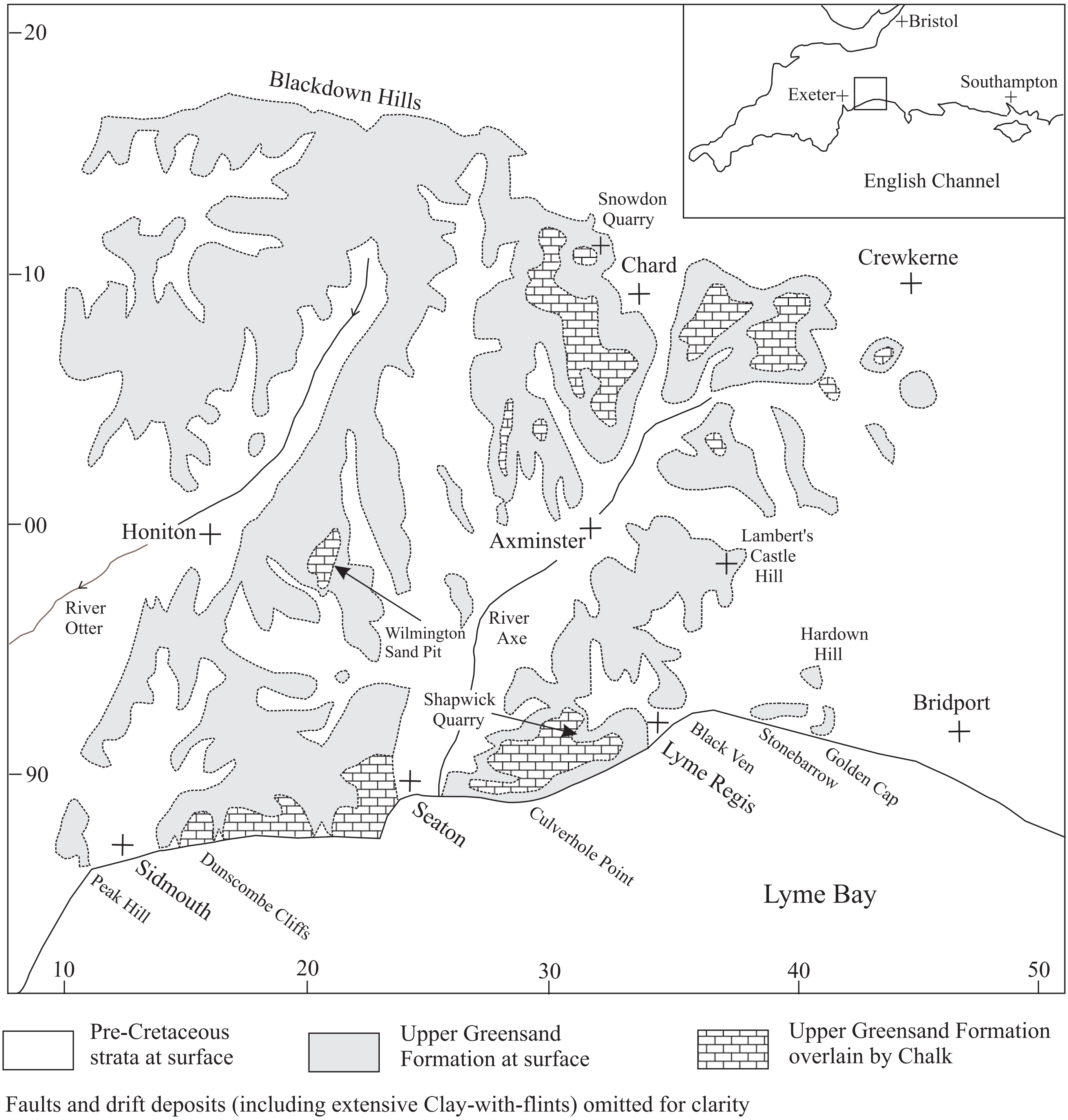
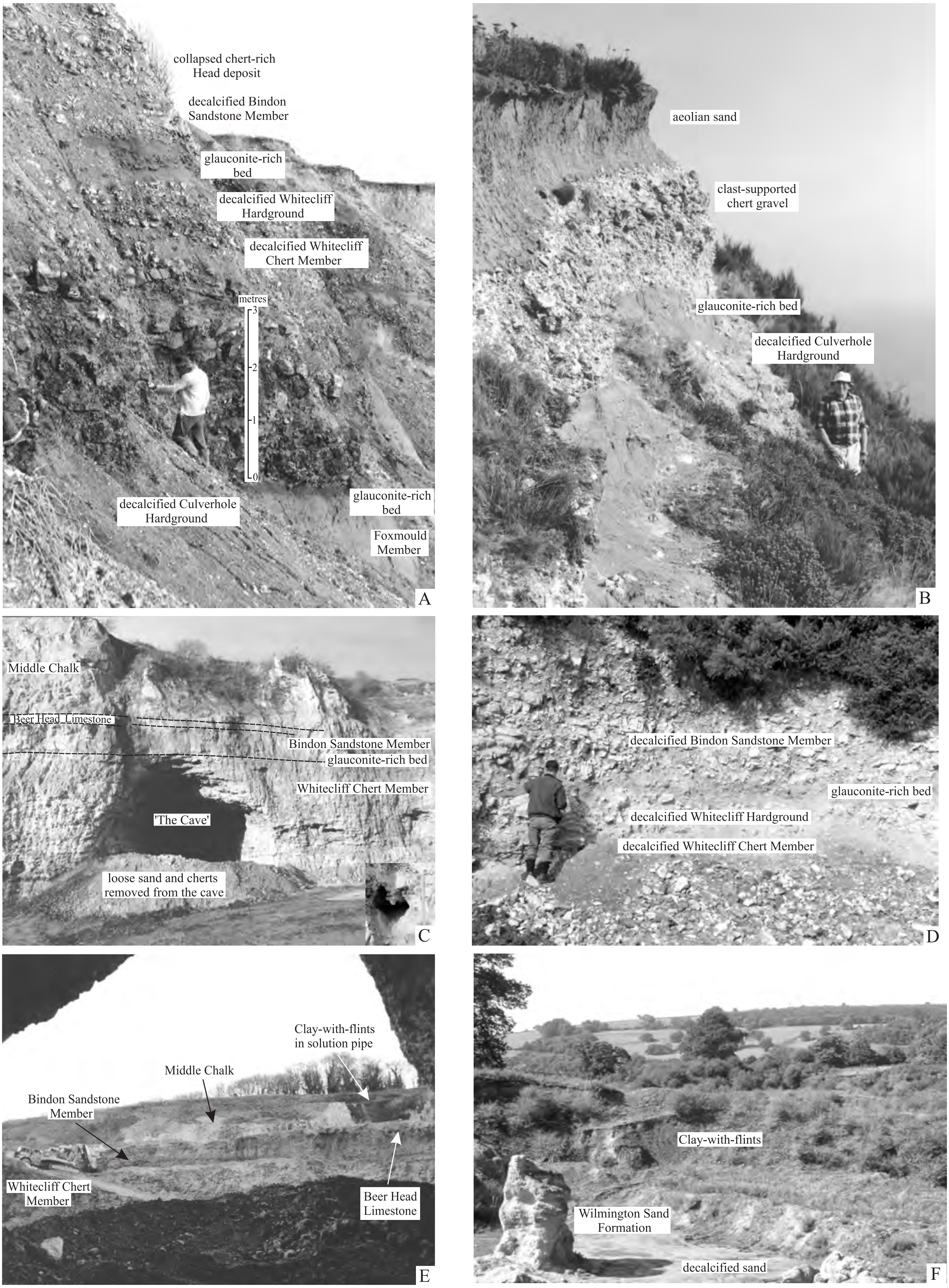


Figure 1. *Outcrop and subcrop of the Upper Greensand Formation in south-west England showing the positions of sections referred to in the text. Outcrop linework after British Geological Survey (1956).*


collapsed chert-rich Head deposit
decalcified Bindon Sandstone Member
glauconite-rich bed
decalcified Whitecliff Hardground
decalcified Whitecliff Chert Member
metres
3
2
1
0
decalcified Culverhole Hardground
glauconite-rich bed
Foxmould Member
A
aeolian sand
clast-supported chert gravel
glauconite-rich bed
decalcified Culverhole Hardground
B
Middle Chalk
Beer Head Limestone
Bindon Sandstone Member
glauconite-rich bed
Whitecliff Chert Member
'The Cave'
loose sand and cherts removed from the cave
C
decalcified Bindon Sandstone Member
glauconite-rich bed
decalcified Whitecliff Hardground
decalcified Whitecliff Chert Member
D
Clay-with-flints in solution pipe
Middle Chalk
Bindon Sandstone Member
Whitecliff Chert Member
Beer Head Limestone
E
Clay-with-flints
Wilmington Sand Formation
decalcified sand
F

Left – Figure 2. *Examples of karstic features in the Upper Greensand Formation in south-west England.* ***A.*** *In situ decalcified Whitecliff Chert and Bindon Sandstone members, Black Ven, west Dorset. The total thickness of the two members here is 10.2 m, less than half that at the nearest unweathered section at Culverhole Point on the east Devon coast (see also Figure 4).* ***B.*** *Aeolian sand and residual chert gravel resting on the basal bed of the Whitecliff Chert Member at Golden Cap, west Dorset. Up to 2.5 m of clast-supported, cryoturbated chert gravel derived from the dissolution of the Whitecliff Chert Member rests on the basal glauconite-rich bed and the Culverhole Hardground.* ***C.*** *'The Cave' in the Whitecliff Chert Member at Shapwick Quarry, east Devon. Partially decalcified calcareous sandstones and calcarenites at the top of the cave collapsed to form a cone of loose sand and chert rubble. Solution conduits up to 0.6 m across and 0.6 m high (insert, lower right) are present at the base of the cave.* ***D.*** *Disused gravel pit, Lambert's Castle Hill [NGR SY 365 986], west Dorset. Cherts were worked for aggregate in numerous small pits dug into the edges of the east Devon-west Dorset high-level plateau. These deposits were described by earlier surveys as Angular Chert Gravel or as coarse lenses within the clay-with-flints. Many retain a stratigraphy that identifies them as the in situ decalcified upper part of the Upper Greensand Formation.* ***E.*** *View from within 'The Cave', Shapwick Quarry. A continuous bed of Middle Chalk (distance), up to 25 m thick, overlies the Upper Greensand Formation. The Chalk is penetrated by deep solution pipes infilled with clay-with-flints, but the body of the Chalk is not greatly affected by solution, and the pipes do not extend down to the Upper Greensand.* ***F.*** *Pillar of sandy calcarenite left by pervasive dissolution at Wilmington Sand Pit [NGR SY 210 998], east Devon. The pit worked loose sand in irregular pockets up to 15 m deep within the Wilmington Sand Member (of Cenomanian age but Upper Greensand lithology) and Bindon Sandstone Member beneath a thick cover of Clay-with-flints.*

Pervasive dissolution

The most widespread karstic feature in the Upper Greensand Formation in south-west England is pervasive dissolution of the Whitecliff Chert and Bindon Sandstone members. This appears to affect the whole of the outcrop of these members where they are not protected by a thick layer of Chalk or argillaceous clay-with-flints. At some localities pervasive dissolution is present beneath the Chalk, which is not itself affected by it. At others, complete dissolution has occurred within and beneath the Chalk to leave pillars and what appear in two dimensions to be detached masses of intact Chalk (Figure 3). The amount of dissolution in the Upper Greensand Formation can vary from a few percent to the whole of the carbonate content. Examples of the latter are well exposed in the cliff sections at Black Ven and Stonebarrow where the dissolution is complete, and at Golden Cap where, in addition, much of the sand content has been removed by rainwater leaching (Figures 2A, 2B and 4). Where incomplete, the solution-affected horizons tend to be concentrated along bedding features, and are more common in the chert-rich parts of the succession.

Most of the outcrop of the Cretaceous rocks in south-west England is covered by clay-with-flints that contains such a high proportion of chert that Ussher (1906) and Woodward and Ussher (1911) referred to these deposits as the 'Clay with Flints and Cherts'. This suggests that much of the pervasive dissolution was achieved as part of the process by which most of a continuous former sheet of Chalk was removed by dissolution.

Solutionpipes

Solution pipes and the associated phenomenon of joint widening are especially common in those areas where the Upper Greensand Formation is overlain by Chalk or by permeable, gravel-rich clay-with-flints. The phenomenon is especially well displayed in the cliffs between Sidmouth and Seaton and, less commonly, between Seaton and Lyme Regis. At many localities, joint-related solution pipes infilled with collapsed granular materials derived from the clay-with-flints extend down through the Chalk and up to 20 m into the Upper Greensand Formation, terminating in open, solution-widened joints at the base of the Whitecliff Chert Member (Figure 3). Inland, where there are few exposures in the Upper Greensand Formation, solution widening of joints is present through the full exposed thickness of the Whitecliff Chert Member at Axmouth [NGR SY 273 908] and Snowdon Hill, Chard [NGR ST 312 089].

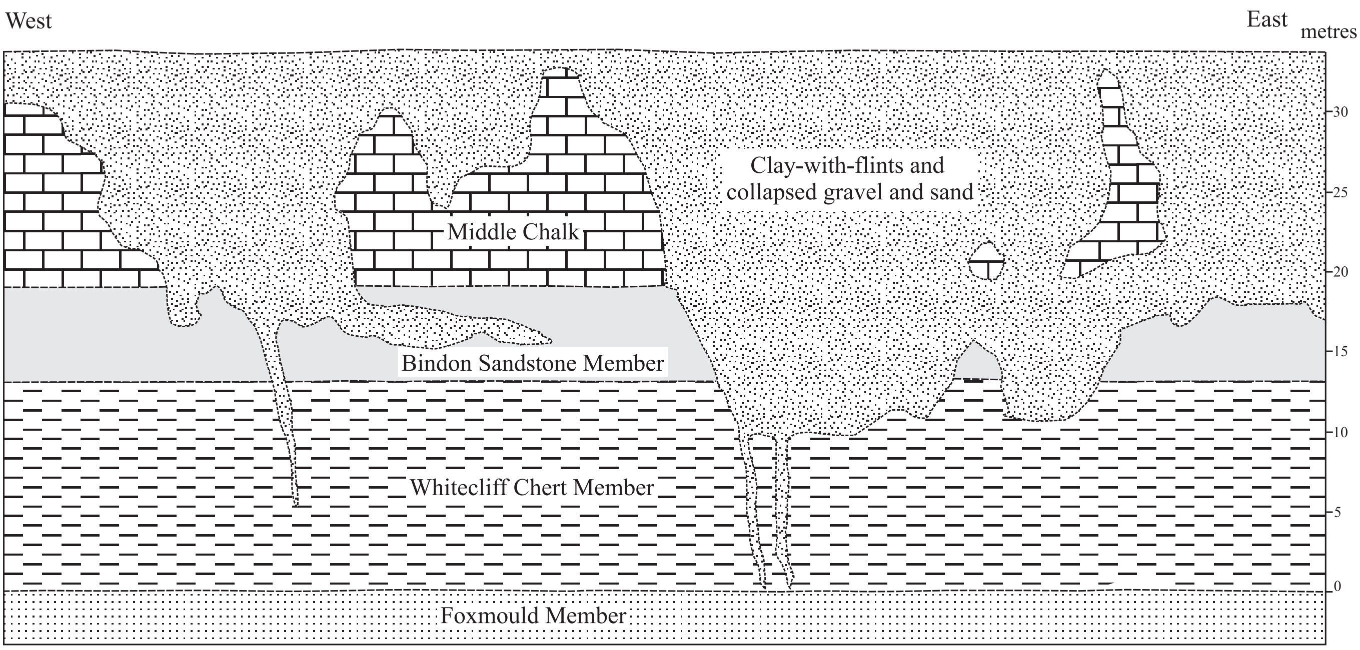


Figure 3. *Large-scale pervasive dissolution of the Middle Chalk and Bindon Sandstone Member at Higher Dunscombe Cliff [NGR SY 153 878], east Devon (based on a photograph). Joint-related solution pipes extend through the full thickness of the Whitecliff Chert Member.*

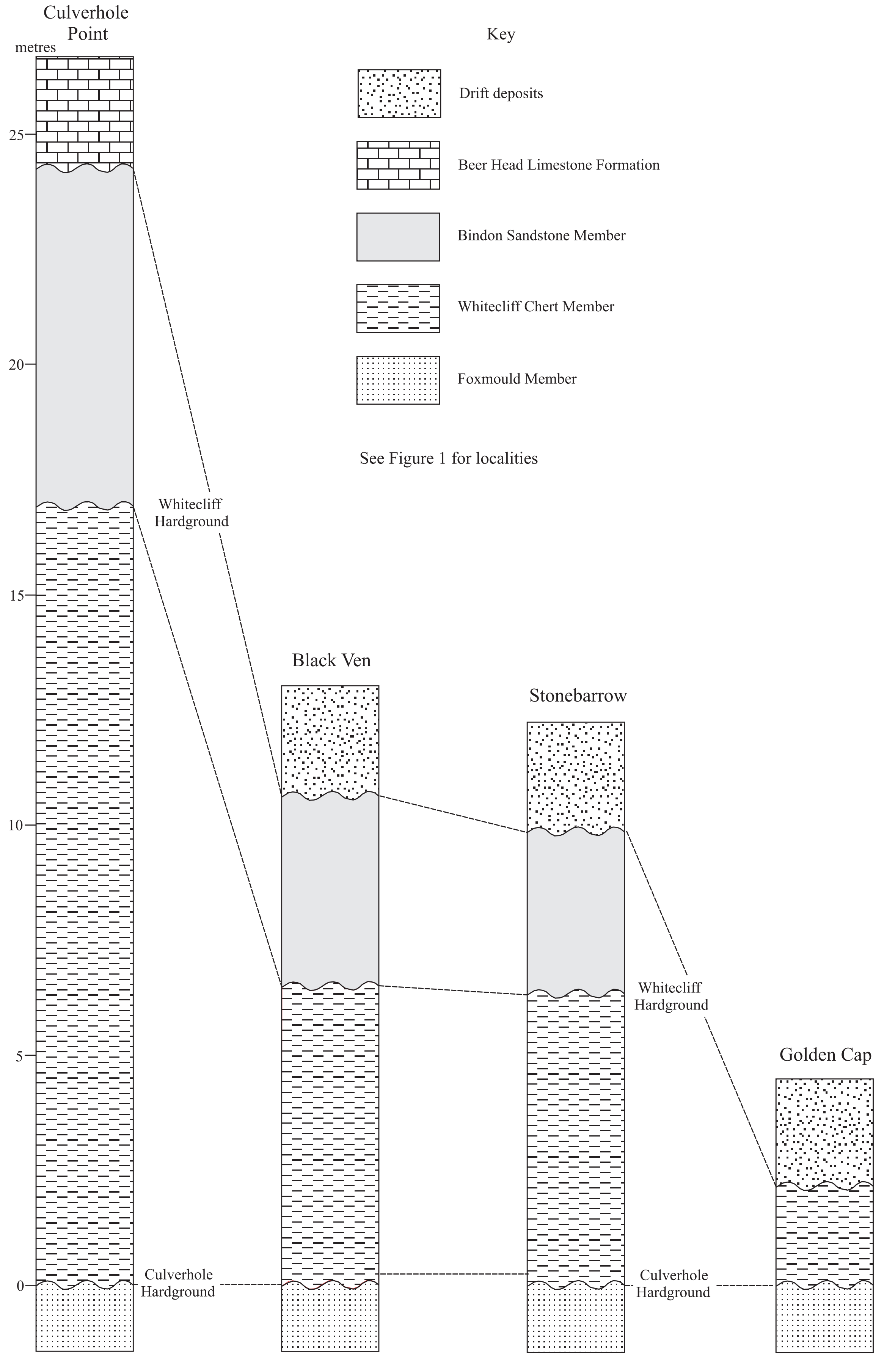


Figure 4. *Correlations between the unweathered section in the Whitecliff Chert and Bindon Sandstone members at Culverhole Point with the decalcified sections at Black Ven, Stonebarrow and Golden Cap.*

CAVES

At Shapwick Grange, Uplyme [NGR SY 313 918] chert, calcarenite and calcareous sandstone in the Whitecliff Chert and Bindon Sandstone members are worked for aggregate beneath the floor of a former chalk pit. Both members are locally partially decalcified. In 1999 the workings broke into 'The Cave', a 15 m-diameter by up to 15 m-high cavity in the Whitecliff Chert Member. The workings subsequently intersected two smaller voids (up to 4 m across), partially choked by collapsed debris, at the same stratigraphical level. A debris cone of loose sand and chert occupied about 50% of the volume of 'The Cave' (Figure 2C). The Bindon Sandstone Member forms the roof of the cavity and marks the upper limit of pervasive decalcification in the Upper Greensand Formation in this part of the quarry. The floor of the cavity, after removal of the debris cone, was an almost horizontal, bedding-controlled surface 1 m to 2 m above the base of the Whitecliff Chert Member. The cavity appeared, therefore, to be approximately bounded by the relatively impermeable beds of glauconite-rich sand that mark the bases of the Whitecliff Chert and Bindon Sandstone members. A suggested mechanism for the formation of 'The Cave' is shown in Figure 5 in which it is assumed that the shape of the cavity was controlled by the presence of bedding-related and steeply dipping joints.

A continuous layer of Chalk, up to 25 m thick, overlies the Upper Greensand Formation, and is itself overlain by a continuous layer of clay-with-flints 5 m to 12 m thick. Large solution pipes up to 15 m wide and 20 m deep extend down to within a few metres of the base of the Chalk. At the base of the Chalk, the Cenomanian Beer Head Limestone forms a continuous layer of tightly cemented limestone that is well-jointed but otherwise relatively impermeable (Figure 2E).

The workings at Shapwick Quarry are situated in a shallow dry valley above a present-day maximum water-table level that is close to the base of the Whitecliff Chert Member. The cave and associated partial dissolution features in the member are presumed to have been initiated and largely formed at times of high water discharge through the Cretaceous rocks. These are most likely to have occurred in the late Pleistocene, after the permafrost associated with the Devensian cold stage had thawed, but whilst there were still high winter snowfalls followed by rapid spring melts.

'The Cave' is the only recorded example of a large solution void in the Upper Greensand in south-west England. However, the scarcity of inland exposures and the absence of surface expression make it impossible to assess whether or not similar voids might be present elsewhere. Several cave-like features up to 3 m across are exposed in the Bindon Sandstone Member in the cliffs between Sidmouth and Beer, but these have probably been formed by the removal of a decalcified sand residue by the action of wind and rain.

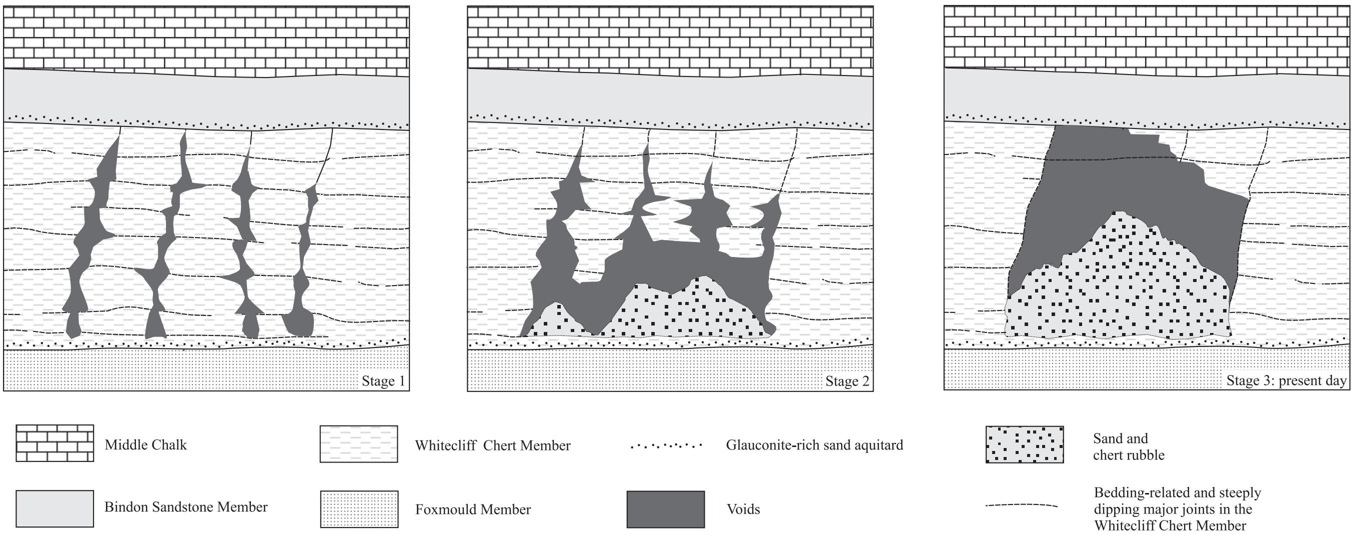


Figure 5. *Suggested mechanism for the formation of 'The Cave' at Shapwick Quarry, Uplyme, east Devon (Stage 3 based on Figure 2c).*

AGE OF THE KARSTIC FEATURES

There is no direct evidence of the age of formation of the karstic features in the Upper Greensand Formation in south-west England, but their nature and distribution suggest two principal periods of formation. Much of the large-scale pervasive dissolution observed in the Upper Greensand Formation in the cliff sections is intimately associated with the dissolution 'event' that removed a thick (possibly up to 500 m) cover of Chalk from the region. The presence of large quantities of chert in the clay-with-flints in those areas where the Whitecliff Chert and Bindon Sandstone members are no longer preserved supports this origin. The pervasive dissolution clearly predates the formation of the solution pipes that are superimposed on it, and the extensive reworking of the clay-with-flints during the late Pleistocene. At localities in east Devon and along the west Dorset coast, the clay-with-flints locally contains abundant well-rounded quartz and quartzite pebbles that Woodward and Ussher (1911) and Wilson *et al.* (1958) presumed to be of early Tertiary (Eocene) origin. This presumption was supported by Ussher's observation (in Woodward and Ussher, 1911, figs 23 and 33) that the Tertiary planation surface and overlying clay-with-flints are extensively folded and faulted in east Devon. The last phase of tectonic activity on this scale in southern Britain was during the Miocene (Hawkes *et al.*, 1998). The pervasive nature of the dissolution is commensurate with deep weathering beneath a vegetated land surface in a warm, humid climate.

In contrast to the pervasive dissolution, the solution pipes and the cavities at Shapwick Grange (which are an extreme case of joint widening) were probably produced by repeated short phases of dissolution during periods of high groundwater flow. Their initiation pre-dates the late Pleistocene periglacial reworking of the clay-with-flints land surface, on which they have no effect, and the extensive spreads of chert-rich gravel that descend from that surface. They are most likely to have formed during the later parts of the penultimate and earlier cold phases in the Devensian Stage, at times of high meltwater runoff when the ground was not rendered impermeable by deep permafrost.

The upper part of the Upper Greensand Formation that caps the ridge that runs northwards from Black Ven to Lambert's Castle Hill can be seen to be decalcified at numerous localities, and to give rise to sheets of chert-rich Head deposits that extend for up to 2 km into the adjacent Char Valley. Similar extents of chert-rich Head in the valleys of the rivers Axe and Sid and their tributaries suggest that much of the Whitecliff Chert and Bindon Sandstone members is also pervasively decalcified in those areas. On the higher valley slopes much of this material consists of clast-supported, chert-rich breccias that pass down slope into matrix-supported, chert-rich sands. The most plausible explanation of their origin is that they were deposited rapidly as flow breccias under conditions of abnormally high pore pressure during spring meltwater phases in the late Pleistocene. On coming to rest, they rapidly drained and set to produce highly permeable, free-draining deposits that have been subject to little post-Pleistocene modification.

CONCLUSIONS

There is no published example of a collapse or engineering failure in south-west England that has been attributed to karstic features in the Upper Greensand Formation. However, the outcrop and subcrop of the formation are almost wholly agricultural, and over almost the whole of the Tertiary plateau area the formation is overlain by a thick layer of clay-with-flints. Few civil engineering works have penetrated the full thickness of the drift deposits. Site-investigations for improvements to the A30(T) road near Honiton and the A35(T) near Charmouth encountered deposits of loose chert-rich sand, but these were not attributed to dissolution. On the east Devon coast, between Sidmouth and Seaton, there are no discernible surface depressions related to the underlying karst even where the tops of pinnacles of Chalk up to 20 m high occur within 3 m of ground level adjacent to drift-filled depressions up to 25 m deep. This suggests that the karst process has progressed little since the late Pleistocene when the clay-with-flints and associated drift deposits were last extensively remobilised.

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