THE STRATIGRAPHY OF THE UPPER GREENSAND (CRETACEOUS) OF SOUTH-WEST ENGLAND

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The Upper Greensand Formation, in part capped by the Chalk, forms a broad, highly dissected plateau in east Devon and south Somerset. The formation is poorly exposed inland, but the coastal cliffs between Sidmouth and Lyme Regis provide the most extensive and most complete exposures of the Upper Greensand in Britain. De la Beche divided the formation in Devon into three parts, in ascending order the Cowstone Beds (or Sands), Foxmould and Chert Beds. A recent survey has confirmed two of these subdivisions (redefined here as members) and has added a third. Each of the three proposed members is separated by a major erosion surface that marks a change in overall lithology. The proposed type sections for all three are exposures in cliffs on the east Devon coast. The Foxmould Member, which includes the Foxmould and Cowstones of De la Beche, consists of weakly cemented sandstones that crop out mostly on steep slopes below precipitous cliffs formed by the higher parts of the formation. The Chert Beds of De la Beche have been divided into two members, the Whitecliff Chert Member and the overlying Bindon Sandstone Member. Both are markedly more calcareous than the Foxmould Member and give rise to extensive sections that reveal marked lateral variations, reflecting high-energy, shallow-water, marine environments. The ages of the lowest and highest parts of the formation are well constrained by ammonite assemblages. However, much of the middle part of the succession, in particular the Whitecliff Chert Member, although locally rich in bivalves, gastropods and foraminifera, has yielded few *in situ* age-diagnostic fossils.

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INTRODUCTION

The Upper Greensand crops out over an area of about 30 km by 30 km in east Devon, west Dorset and south Somerset where it forms a highly dissected plateau that stretches northwards from the Devon coast to the Blackdown Hills (Figure 1). The formation is poorly exposed throughout most of this region, with the notable exception of the sea cliffs between Sidmouth, east Devon and Lyme Regis, west Dorset where the whole of the formation, locally protected by a capping of Chalk, is well exposed (Figure 1). Almost complete sections, in which the upper part of the formation is affected by dissolution, occur west of Sidmouth at Peak Hill and High Peak, and east of Lyme Regis at Black Ven, Stonebarrow and Golden Cap.

The formation can be divided into two roughly equal parts, a less lithified lower part that gives rise to steep slopes on the coast, and a calcareously cemented upper part that gives rise to precipitous cliffs. The lower part of the formation is generally poorly exposed, but more or less complete sections occur from time to time in Dunscombe Cliffs, below Hooken Cliffs, at White Cliff (Whitecliff on older maps) and at Culverhole Point. The higher, more calcareous part of the formation is well exposed, but mostly in less accessible cliffs. Unweathered sections occur in Dunscombe, Weston and Hooken cliffs, and in the back faces of the Undercliff Landslip complex between Seaton and Lyme Regis. Complete sections occur at beach level beneath Beer Head and adjacent to White Cliff.

Much of the inland outcrop of the Upper Greensand Formation is overlain by a thick (up to 15 m) unit of clay-with-flints that is largely derived from what was originally a continuous cover of Chalk. The higher, more calcareous part of the formation is commonly extensively decalcified beneath the clay-with-flints, and karstic features are well displayed in those coastal sections where the Upper Greensand is not protected by an overlying layer of Chalk (Gallois, 2004). The presence of large amounts of chert in the clay-with-flints, referred to as "Clay with Flints and Chert" on the older Geological Survey maps of the region (Woodward and Ussher, 1911; Ussher, 1906), indicates that much of the upper part of the Upper Greensand has been lost to dissolution. Over much of the Blackdown Hills, the younger part of the formation is now only represented as derived cherts in the drift deposits.

The Upper Greensand of the east Devon and west Dorset coastal area was divided by De la Beche (1826) into three divisions, in ascending order the Cowstone Beds (or Sands), Foxmould and Chert Beds. Jukes-Browne and Hill (1900) noted a chert-free "Calcareous Sandstone" at the top of the formation: this was subsequently named the Top Sandstones by Smith (1961a). The Foxmould, Chert Beds and Top Sandstones were defined as members of the Upper Greensand Formation by Williams (1991).

Attempts to map out the boundaries of these divisions during the resurvey of Geological Survey Sheet 326 (Sidmouth) proved largely unsuccessful. Early descriptions of the Cowstone Beds refer to them as grey sands with calcareous sandstone doggers (up to 2x2x1 m) that weather out to form extensive beach aprons. Their name, which can be traced back to the 13th century, derives from the imagined similarity of the beach accumulations to a herd of resting cows. The doggers occur within glauconitic sands that are indistinguishable from the overlying Foxmould, and the whole succession weathers to a similar foxy brown sand. The Foxmould itself contains lenses, doggers and discontinuous tabular beds of calcareous sandstone. De la Beche's (1826) original division into Cowstone Beds and Foxmould seems to have been based on unweathered sections on the coast east of Beer Head. Westwards from there, calcareously cemented beds are common at this stratigraphical level, but the distinctively shaped 'cowstones' are much less common. The boundary between the Cowstone Beds and Foxmould is not clearly defined even in the coastal exposures, is laterally impersistent, and cannot be recognised in weathered sections.

The Chert Beds, or more precisely the calcareous sandstones and calcarenites that enclose them, form a distinctive steep,

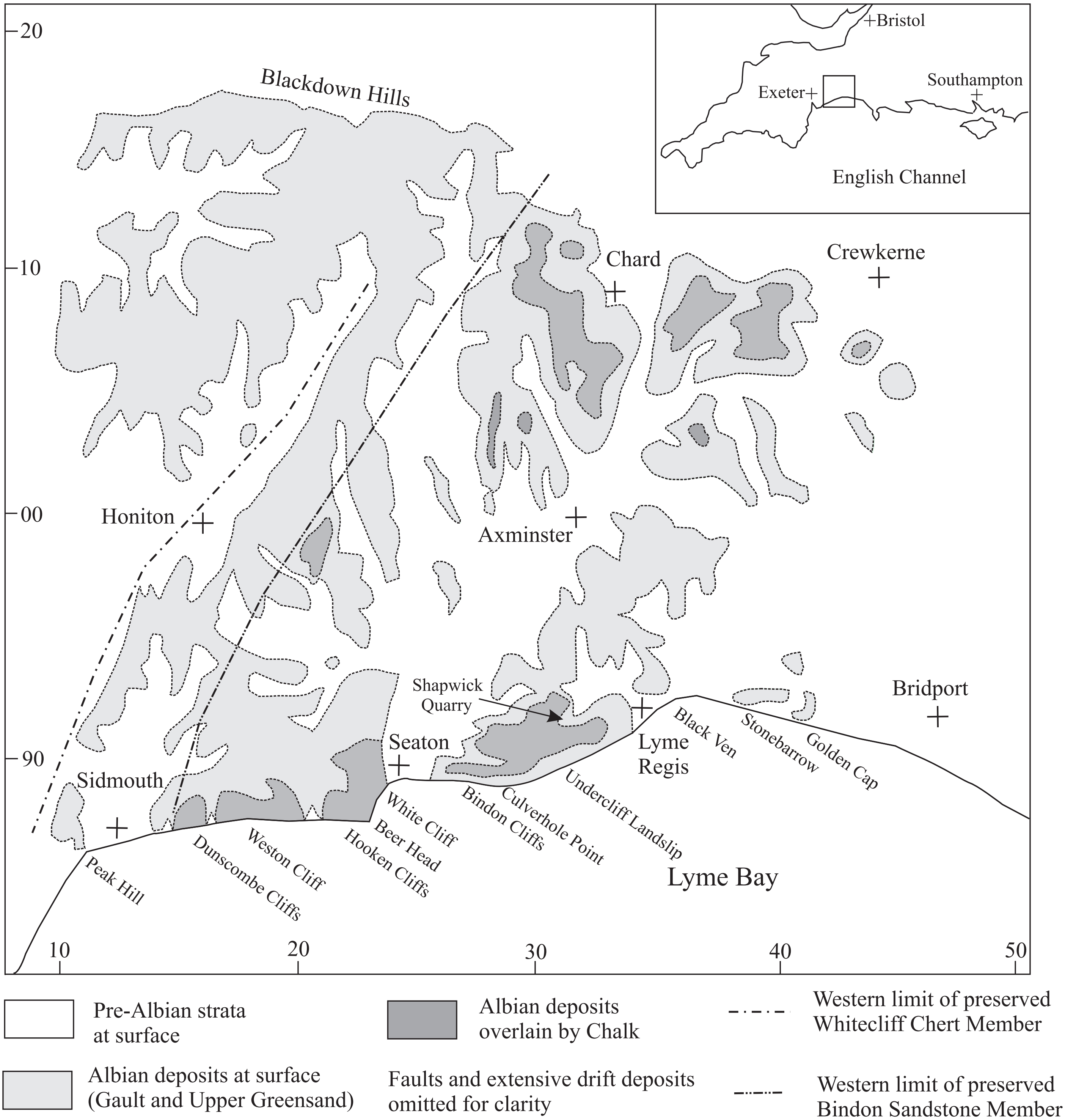


Figure 1. *Geological sketch map showing the positions of the outcrop and subcrop of the Upper Greensand Formation in south-west England, and localities referred to in the text. Outcrop linework after British Geological Survey (1956).*

commonly afforested, inland feature that has a sharp base marked by springs and seepages. This is readily mappable where not obscured by decalcified sands derived from the higher parts of the division. The top of the feature is marked by a sudden lessening of slope angle and change of soil type at the base of the Chalk. The absence of chert in the highest part of the formation is not a stratigraphically persistent feature and cannot be used to distinguish the 'Top Sandstones' from the underlying Chert Beds (see below).

De la Beche (1826, 1839), Fitton (1836) and Meyer (1874) recorded sections in the Upper Greensand on the East Devon coast and, in a comprehensive account, Jukes-Browne and Hill (1900) described all the principal sections that were accessible to them (notably those in the Undercliff Landslip, at White Cliff, Hooken Cliffs, Kempstone Rocks [NGR SY 162 881], Dunscombe Cliffs and Peak Hill). Tresise (1961) discussed the nature and origin of chert in the Upper Greensand Formation in south-west England, and introduced the term 'Blackdown facies' for the more siliceous variety of the Foxmould that crops out in the western and northern part of the region. Smith (1957, 1961a, 1961b) described aspects of the sedimentology of the highest part of the formation, mostly adjacent to Beer. Hamblin and Wood (1976) correlated the Upper Greensand succession of the Haldon Hills outlier with that of the east Devon coast. Williams (1991) made a detailed study of the stratigraphy and sedimentology of the Upper Greensand, based largely on coastal sections between Sidmouth and Beer, with particular respect to depositional environments and sequence stratigraphy. There have been few systematic studies of the biostratigraphy other than those by Hart and others (e.g. Hart 1970, 1973; Carter and Hart, 1977; Hart and Williams, 1990), although most of the above references describe occurrences of age-diagnostic ammonites.

LITHOSTRATIGRAPHY

Where completely preserved beneath a cover of Chalk on the east Devon coast, the full thickness of the Upper Greensand is between 50 m and 55 m. The boundaries of the formation are lithologically and biostratigraphically clearly defined throughout the region, except for two small areas. Westwards from Culverhole Point the formation rests with marked unconformity on Triassic rocks, mostly red mudstones. Eastwards from there it rests on Lower Jurassic mudstones. The Upper Greensand is overlain disconformably by the lithologically distinctive Cenomanian Beer Head Limestone Formation throughout the region. The junction of the two formations is marked by a distinct sedimentary break that includes evidence of uplift and desiccation (Ali, 1975). The two exceptional areas are eastwards from Lyme Regis, where the Upper Greensand passes down into sandy Gault clay (Wilson *et al*., 1958), and at Hooken Cliffs. There, the lower part of the Beer Head Limestone Formation passes locally into a glauconitic sandstone (Wilmington Sand Member) that is lithologically similar to the underlying Upper Greensand, but which is separated from it by a major erosion surface.

The Upper Greensand Formation has been divided in the present study into three members, in ascending order the Foxmould Member, Whitecliff Chert Member and Bindon Sandstone Member. Each of these is separated by a laterally persistent sedimentary break that is marked by one or more cemented (hardground) surfaces (Figure 2).

Foxmould Member

The proposed type section of the Foxmould Member is White Cliff, Seaton [NGR SY 2350 8963] where Fitton (1836) and Jukes-Browne and Hill (1900) measured the full thickness of the member. The latter described this as the "most complete and most accessible [Upper Greensand] section in Devon". In recent years the full thickness of the Foxmould, including the unconformable junction with the underlying Mercia Mudstone Group and the conformable junction with the Whitecliff Chert Member, has been exposed at different times. The Foxmould Member crops out there in the lower part of an unstable cliff with the result that the exposures change markedly almost every year. At any one time about half to two thirds of the member is well exposed, the lower beds being commonly covered by debris. All except the lowest few metres of the Foxmould Member are well exposed at the relatively accessible western end [NGR SY 148 878] of Higher Dunscombe Cliff and, close to beach level, at Under Hooken [NGR SY 221 879]. The upper half of the member is exposed at beach level at Culverhole Point [NGR SY 277 893] in a series of large, intact landslipped blocks. Williams (1991) proposed a type section for the Foxmould at and adjacent to Under Hooken [NGR SY 226 878]. However, the base of the member has not been recorded there for many years and the sections are discontinuous and difficult to correlate with one another.

The junction of the Foxmould Member with the Triassic rocks at White Cliff, and in temporary exposures westwards from there at Branscombe Mouth [NGR SY 211 880] and Littlecombe Shoot [NGR SY 182 882], is marked by a basal pebble bed that infills an irregular, burrowed surface cut into red mudstones. East of White Cliff, the junction is well exposed 500 m west [NGR SY 272 894] of Culverhole Point where the basal pebble bed rests on a burrowed and bored surface of White Lias limestone.

At outcrop on the east Devon coast the Foxmould Member comprises 25 to 30 m of fine- and medium-grained, weakly cemented sandstones composed of variable amounts of quartz, glauconite and calcium carbonate. The member appears to thicken eastwards into west Dorset where it is about 40 m thick at Black Ven and over 50 m thick at Golden Cap. The fauna and sedimentary structures indicate deposition in subtidal environments above storm wave base. When fresh, the sandstones range from soft to very hard depending on the amount of calcareous or siliceous cement, and from faintly greenish grey to bright green in colour. On weathering, all the lithologies break down to soft, grey, yellow or brown sands with residual clasts of calcareous and/or siliceous sandstone. Shell debris and broken shells, mostly oysters, pectinids and serpulids, are abundant at many levels, and weakly cemented (hardground) surfaces occur locally at a few levels in the upper part of the member.

There is a progressive lateral variation from east to west in the bulk composition of the member. At White Cliff and all localities east of there in east Devon and in west Dorset, all the harder beds in the Foxmould Member, whether tabular or concretionary, are calcareously cemented. The most easterly siliceously cemented beds recorded in the Foxmould Member in the present study are in the upper part of the member below Beer Head [NGR SY 224 879]. Westwards from there, although calcareously cemented horizons remain common as far west as Weston Cliff, they are less common than siliceously cemented beds at the western end of Dunscombe Cliffs and are absent at Salcombe Hill [NGR SY 140 877] and Peak Hill (Jukes-Browne and Hill, 1900).

Whitecliff Chert Member

The proposed type section of the member is White Cliff, Seaton which exposes the full thickness of the member and the junctions with the underlying Foxmould Member and the overlying Beer Head Limestone Formation. The higher part of the cliff face is difficult to access, but a low northerly dip brings the complete succession down to beach level at the adjacent King's Hole [NGR SY 233 891]. Williams (1991) proposed a type section at Under Hooken [NGR SY 226 878] and although the full thickness can be accessed between there and the foot of Beer Head [NGR SY 226 879], the White Cliff section has the advantage that it is continuous with the type section of the Foxmould Member. In addition to the sections at White Cliff and below Beer Head, the full thickness of the member can be accessed, with care, at Culverhole Point [NGR SY277 893] and the western end of Higher Dunscombe Cliff [NGR SY 149 878]. All but the lowest 1-2 m of the member has been exposed at Shapwick Quarry, Uplyme [NGR SY 313 918] in recent years.

The junction of the Foxmould and Whitecliff Chert members is wholly exposed and readily accessible at all four of the coastal localities listed above. The base of the Whitecliff Chert Member is taken at the base of a dark green, pebbly, glauconite-rich sandstone that infills an irregular erosion surface marked by cementation and intense burrowing. This sedimentary break marks a major upward change in lithology and depositional environments from weakly cemented sandstones that were deposited in relatively quiescent environments to strongly cemented calcareous sandstones and sandy calcarenites that were deposited in turbulent, shallow-water environments. At most localities, including the type section, the basal glauconite-rich sandstone is overlain by a second cemented (hardground) surface. Both hardgrounds are particularly well-exposed at Culverhole Point, from which they take the name Culverhole hardgrounds (Edwards and Gallois, 2004). In most of the east Devon cliff exposures the glauconite-rich bed weathers back to form a distinctive green slot. This distinctive bed and weathering feature was recognised by Jukes-Browne and Hill (1900) to mark the boundary between the Foxmould and Chert Beds throughout east Devon and west Dorset.

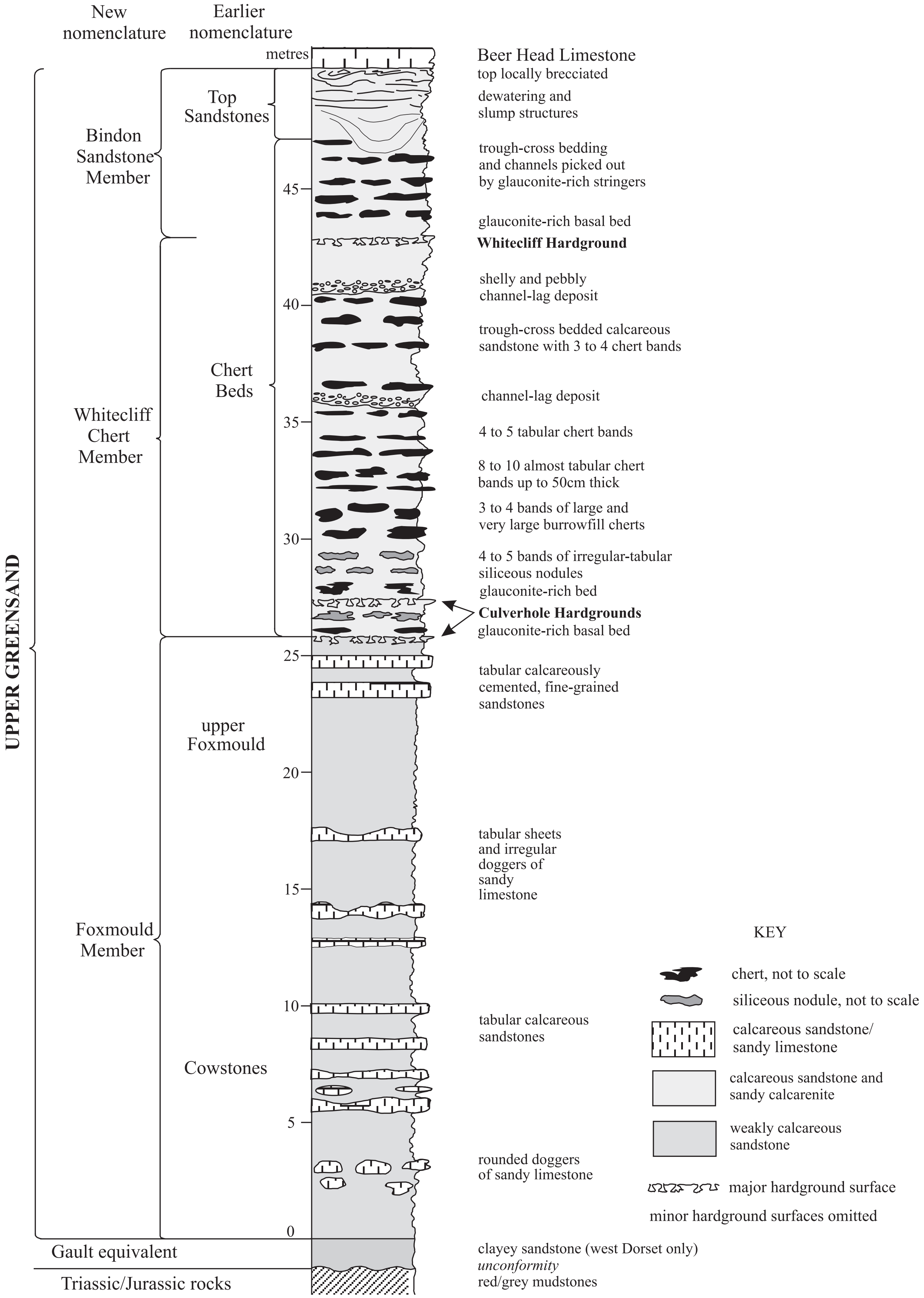


Figure 2. *Generalised lithostratigraphy of the Upper Greensand Formation based on coastal exposures between Beer and Lyme Regis. See text for details of lateral variations.*

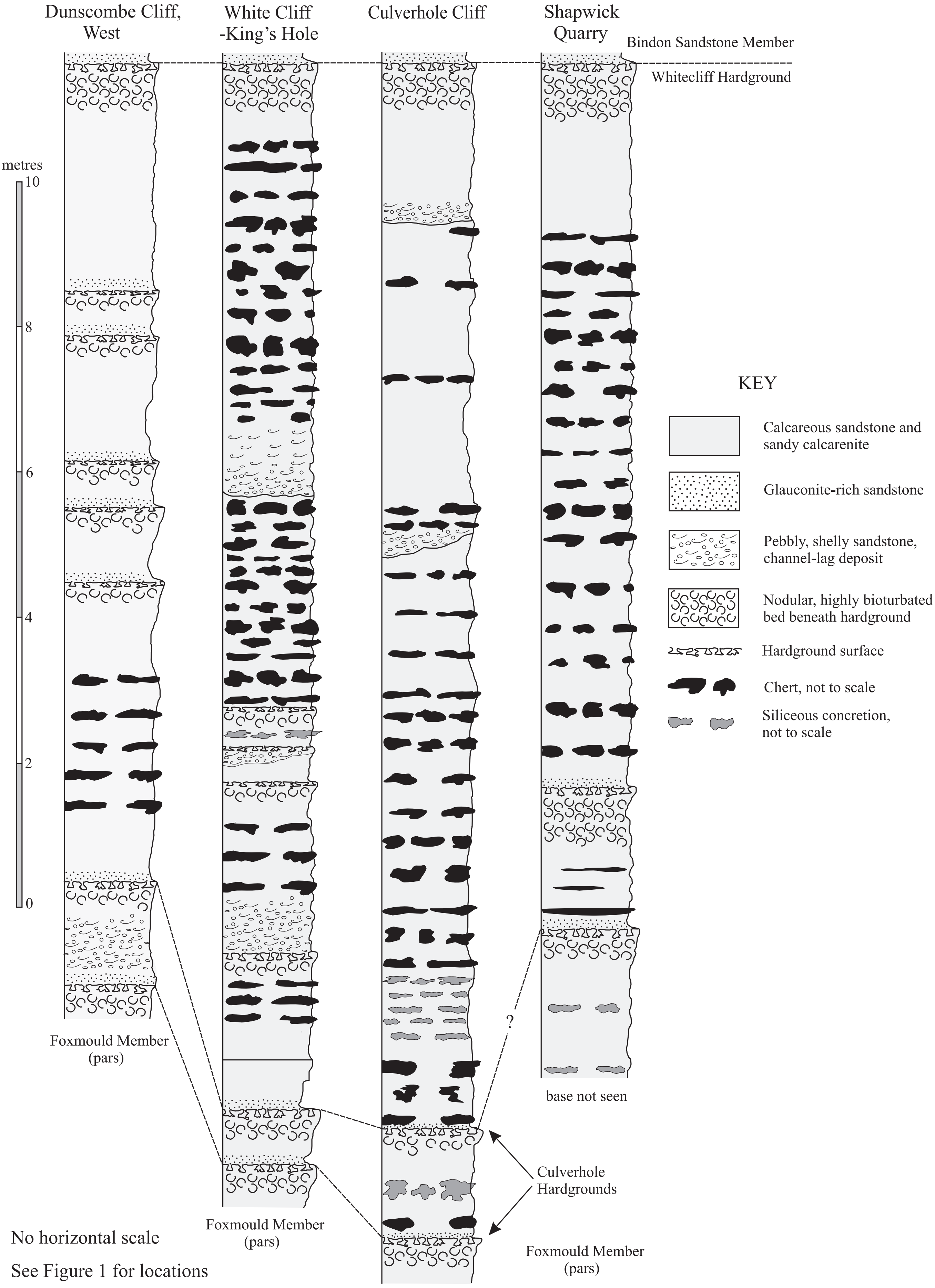


Figure 3. *Lateral variations in the Whitecliff Chert Member between Dunscombe Cliffs and Shapwick Quarry, Uplyme.*

Cherts are absent below the lower of the Culverhole hardgrounds, they may occur between the hardgrounds where two are present, and are everywhere abundant above the upper hardground. The lower chert layers are accompanied by one or more lines of lithologically distinctive quasi-cherts, pale coloured partially silicified sandstone masses commonly with dark chert centres.

The Whitecliff Chert Member exposed on the east Devon coast consists of 12 to 18 m of predominantly sandy medium-grained calcarenites, much of which are composed of comminuted shell debris, in which beds of nodular or tabular chert are concentrated in the more carbonate-rich beds. The cherts are mostly translucent dark brown, commonly with pale inclusions derived from shell material or burrow fills. In places, they enclose well preserved cross bedding and/or bioturbation. They mostly occur in crude beds within which the character and shapes of the individual cherts is relatively constant. In the more chert-rich parts of the succession the cherts, which are mostly 0.15 to 0.3 m thick but up to 0.5 m thick, make up 40% of the total volume of the rock.

Cemented (hardground) surfaces, commonly overlain by scour hollows infilled with clast-rich and shell-debris-rich sandstones, occur throughout the member. The clasts vary from well-rounded pebbles of glauconitic sandstone, mostly 50 mm to 300 mm in diameter, to angular sandstone blocks more than 0.2 m across. The lithofacies indicate deposition in shallow, strongly current agitated marine environments that at times might have been intertidal. In the absence of palaeontological control, none of these erosion surfaces has yet been shown to be sufficiently persistent laterally to be used as a stratigraphical marker horizon.

There is marked lateral change in the bulk lithology of the Whitecliff Chert Member when traced westwards in the east Devon cliffs. The number of chert horizons decreases westwards and chert is confined to the lower part of the member. This change is accompanied by an increase in winnowing and the number of sedimentary breaks represented by hardgrounds, and an overall thinning (Figure 3).

Bindon Sandstone Member

The junction of the 'Chert Beds' and the 'Top Sandstones' was defined by Smith (1961a) in the area west of Seaton as the base of a bed of pebbly greensand (which he named the 'Coarse Band') that weathers out to form a prominent recess in the cliffs. East of Seaton, where this bed was not recognised, he placed the base of the 'Top Sandstones' at the top of the highest bed of chert. Smith's (1961a) 'Coarse Band' is analogous to the basal bed of the Whitecliff Chert Member, a pebbly, glauconite-rich sandstone that infills irregularities in a prominent hardground surface. The hardground is prominently exposed at White Cliff and in all the coastal sections as far west as Higher Dunscombe Cliff and as far east as Golden Cap, and it has been recorded at inland sections throughout the region. Contrary to Smith's (1961a) description, the 'Coarse Band' does not separate beds with chert from beds without chert. Below Beer Head there is an abrupt lateral change in the succession within a distance of tens of metres in which cherts occur above (to the east) and below (to the west) the 'Coarse Band'. To the east, chert is everywhere present above the Whitecliff Hardground as far east as Golden Cap [NGR SY 405 921] and inland as far as Chard. Westwards, the highest chert occurs at progressively lower stratigraphical levels in the Whitecliff Chert Member until, at Higher Dunscombe Cliff, chert is confined to the lower part of the member. The presence or absence of chert is not, therefore, a stratigraphically diagnostic feature on its own. However, the Whitecliff Hardground, its associated erosion surface and the overlying glauconite-rich bed are stratigraphically consistent features throughout south-west England.

The name Bindon Sandstone Member has therefore been proposed for the beds between the Whitecliff Hardground and the unconformity at the base of the Beer Head Limestone Formation (Edwards and Gallois, 2004). The proposed type section is Bindon Cliffs [NGR SY 275 894] where the member, including its lower and upper junctions, is wholly exposed and accessible. The member is also fully exposed in the cliffs on the south side of Goat Island [NGR SY 277 895], where it reaches

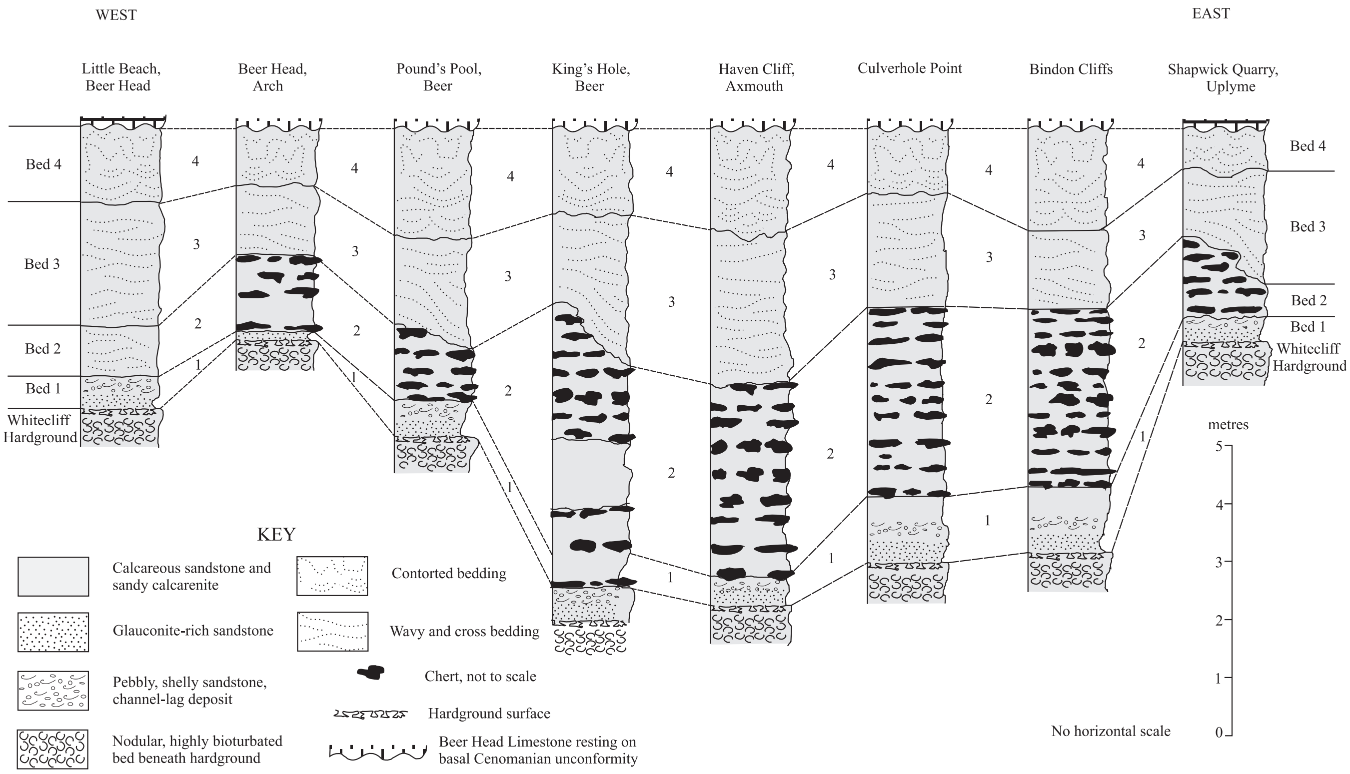
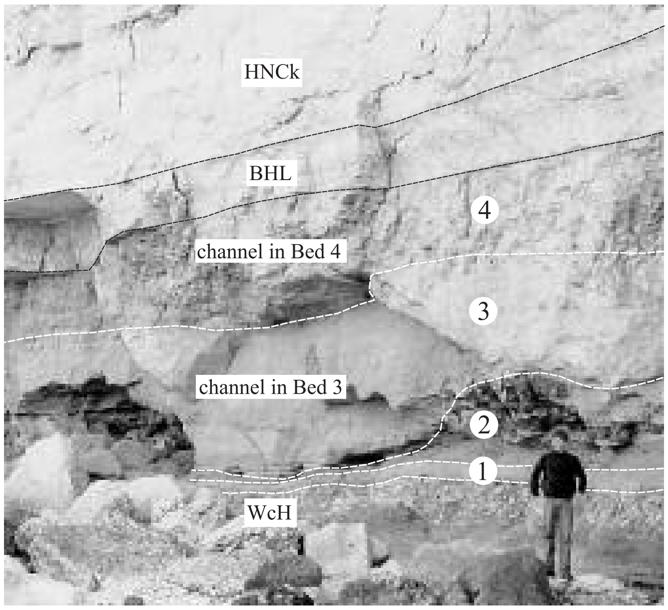


Figure 4. *Lateral variations in the Bindon Sandstone Member between Beer Head and Shapwick Quarry, Uplyme.*

its maximum recorded thickness of over 8 m, and in numerous cliff sections between Beer and Sidmouth, and at Shapwick Quarry.

In the east Devon coastal sections, the Bindon Sandstone Member comprises 3 to 8 m of glauconitic, fine-, medium- and coarse-grained calcarenites and calcareous sandstones. Inland, and on the west Dorset coast, the member is commonly reduced by dissolution to 1 to 2 m of chert-rich rubble (Gallois, 2004). The succession is laterally variable, but can be divided into four distinct beds throughout most of the region (Figure 4). Bed 1 comprises the pebbly, glauconite-rich basal bed referred to by Smith (1961a) as the 'Coarse Band'. Bed 2 is a glauconitic calcareous sandstone/calcarenite with up to six chert horizons, including individual cherts up to 0.6 m thick. The matrix of Bed 3 is lithologically similar to that of Bed 2 with wavy and low angle trough cross bedding picked out by glauconite-rich stringers, but chert is absent. The junction with Bed 2 is locally sharp and channeled to produce chert-free channel fills that cut out much or all of Bed 2 (Figure 5). Bed 4 is sedimentologically distinctively different from the underlying beds. It displays 'festoon' trough-cross bedding, and in its highest part contorted bedding due to slumping and/or de-watering is locally common. These highest beds contain concretionary shell accumulations rich in bivalves and gastropods, one of which has yielded the only ammonites found *in situ* to date in the Bindon Sandstone Member (see below).



HNCk.....Holywell Nodular Chalk Formation WcH.....Whitecliff Hardground
BHL.....Beer Head Limestone Formation 1 to 4.....Divisions of the Bindon Sandstone Member

Figure 5. *Channels in the Bindon Sandstone Member at Pound's Pool, Beer. Figure is 1.85 m tall.*

BIOSTRATIGRAPHY

Extensive faunal collections have been made from the Upper Greensand in south-west England, as evidenced by the collections of the British Geological Survey, the Natural History Museum in London, and those of Exeter, Taunton and other local museums. Taken together, the specimens show that the Upper Greensand Formation is fully marine at all stratigraphical levels and contains a rich and diverse fauna. However, the permeable nature of much of the succession makes it unsuitable for fossil preservation other than for robust calcitic shells, and the stratigraphical and geographical distribution of the preserved material is uneven. The siliceous preservation of the 'Blackdown facies' of the Foxmould Member has yielded particularly well-preserved specimens in which aragonite and calcite shells have been replaced by silica at an early stage of diagenesis, and ammonites are largely uncrushed. The calcareous lithologies of the Foxmould, Whitecliff Chert and Bindon Sandstone members of the east Devon coast have yielded much less material. The zonal and subzonal designations of the three members are summarised in Table 1.

The preserved fauna of the Upper Greensand is dominated in both abundance and diversity by bivalves and gastropods, with echinoderms, brachiopods and serpulids locally common. Jukes-Browne and Hill (1900) recorded over 50 species from Peak Hill in east Devon, probably all from the Foxmould, including 34 species of bivalve and 17 species of gastropod. Almost none of this material is age diagnostic. *In situ* ammonites are rare or absent in the middle and upper parts of the formation with the result that their ages are still not accurately known. Attempts to use foraminifera (Carter and Hart, 1977; Hart and Williams, 1990), locally common at these stratigraphical levels, to correlate with the standard ammonite zones, has so far proved to be of limited success.

The following summary of the ammonites from the Blackdown Hills housed in the Natural History Museum, London, and their stratigraphical significance, has been provided by Dr H. G. Owen. "The siliceous horizons in the Foxmould of the Blackdown Hills have yielded beautifully preserved ammonites and age-diagnostic bivalves, most of which are simply labelled "Greensand" or "Upper Greensand, Blackdown, Devon". Downes (1882) thought that most of the ammonites came from the lower concretionary beds (his beds 2-9), with one or two specimens of '*Ammonites varicosus*' from Bed 10. However, the principal distribution of the bivalve *Actinoceramus sulcatus* (Parkinson) suggest that beds 5 and 6 are of *Hysteroceras orbignyi* Subzone age. The distribution of *A. concentricus* (Parkinson) suggests that beds 8 to 10 are of *Hysteroceras varicosum* Subzone age in the European Faunal Province sense. Most of the ammonites from the Blackdown Hills are unequivocally of *varicosum* Subzone age and their preservation suggests Bed 10 of Downes (1882). They include species of *Hysteroceras*, including the zonally significant *Hysteroceras varicosum* (J. de C. Sowerby) and *H. binum* (J. Sowerby), together with species of *Epihoplites, Euhoplites, 'Semenoviceras', Mortoniceras* (*Deiradoceras*) and *Goodhallites*. The type specimens of *H. varicosum, 'Semenoviceras' gracilis* (Spath), *Mortoniceras (Deiradoceras) albense* Spath and *M.* (*D.*) *devonense* Spath came from this bed at Blackdown".

Far fewer ammonites, numerically and specifically, have been recorded from the Foxmould Member of the Devon coast, despite the extensive exposures. Most of those in museum collections are in calcareous sandstone preservation (commonly referred to as 'cowstone') and have been found *ex situ*. The earliest subzone recorded at Black Ven and more westerly exposures is that of *Hysteroceras varicosum*, with an ammonite assemblage that is closely similar in genera and species to that of the same subzone at Blackdown. Other ammonites recorded *ex situ* (Hancock, 1969; M. Foster *pers. comm.*, 2002) from the east Devon coast in what has been presumed to be Foxmould Member preservation include species of *Callihoplites* indicative of the *C. auritus* Subzone.

The recorded faunas of the Whitecliff Chert and Bindon Sandstone members are sparse in comparison with those of the Foxmould Member. This is probably more a reflection of their abrasive high-energy environments and less favourable preservation than the original abundance and diversity of their faunas. The fauna of the Whitecliff Chert Member is dominated by thick-shelled oysters, with other bivalves, serpulids, brachiopods and echinoderms the only other common fossils. No *in situ* ammonite has been recorded, but a few chert casts have been found in the landslip at Black Ven. One of these, collected by Mr D. Sole and identified as a *Mortoniceras (M.) commune* by Dr Owen (*pers. comm.*, 2003), is indicative of the *C. auritus* Subzone. It seems likely, on age grounds alone, to have come from the Whitecliff Chert Member. Specimens of

Locality	Member/Bed	Subzone	Zone
Devon coastal and inland sites	Beer Head Limestone Formation	*Neostlingoceras carcitanense*	*Mantelliceras mantelli* (pars)
Shapwick Quarry, Uplyme, Devon	Bindon Sandstone Member (Bed 4)	*Arraphoceras (Praeschloenbachia) briacensis*	*Stoliczkaia (S.) dispar*
	Bindon Sandstone Member? *ex situ*	*Mortoniceras (Durnovarites) perinflatum*	
	not recorded	*Mortoniceras (M.) rostratum*	
Devon coast	Whitecliff Chert Member? Foxmould Member? recorded *ex situ*	*Callihoplites auritus*	*Mortoniceras (M.) inflatum*
Devon coast and Blackdown Hills; Stonebarrow, Dorset	Foxmould Member sandy 'Gault'	*Hysteroceras varicosum*	
Blackdown Hills	Foxmould Member?	*Hysteroceras orbignyi*	
	not recorded	*Dipoloceras cristatum*	

Table 1. *Zones and subzones of the Upper Albian Substage and the basal Cenomanian Stage recorded in the Upper Greensand Formation in south-west England. Zonal/subzonal scheme based on Owen (1999).*

Stoliczkaia collected loose by Mr Sole and by Spath (1926) from the same area are indicative of the *S. dispar* Zone and probably came from the Bindon Sandstone Member (see below). A specimen of *Arraphoceras* (Grimsdale Collection, Natural History Museum Catalogue No. C41977) from White Cliff, east Devon is indicative of a *Mortoniceras (Durnovarites) perinflatum* Subzone age (Owen, *pers. comm.*, 2004). This also, seems more likely to have come from the Bindon Sandstone Member than from the Whitecliff Chert Member.

An indigenous ammonite assemblage indicative of latest Albian age was collected from an *in situ* concentration of shells in Bed 4 of the Bindon Sandstone Member at Shapwick Quarry [NGR SY 3130 9190] (Hamblin and Wood, 1976). It includes species of *Callihoplites, Discohoplites, Hyphoplites, Idiohamites, Stoliczkaia* and *Stomohamites* which, taken together, are indicative of the *Arraphoceras (Praeschloenbachia) briacensis* Subzone of the *Stoliczkaia dispar* Zone (Owen, *pers. comm.*, 2004). The proximity of this assemblage to the unconformity at the base of the overlying Beer Head Limestone (basal Cenomanian *Neostlingoceras carcitanense* Subzone age at this locality) makes it most unlikely that any part of the Upper Greensand there is of Cenomanian age.

Conclusions

The Upper Greensand Formation throughout south-west England can be divided into three members, in ascending order the Foxmould, Whitecliff Chert and Bindon Sandstone, each of which is bounded by a sedimentary break marked by a prominent erosion surface. Notwithstanding their continuity over an area of several hundred square kilometres, there are marked lateral variations within each member. The Foxmould Member consists of relatively uniform fine- and medium-grained glauconitic sandstones, but with siliceous cements and concretions in the west and north (including the whetstone horizons of the Blackdown Hills) and calcareous cements and concretions (including the 'cowstones') in the east. In the Whitecliff Chert Member exposed on the Devon coast the proportion of chert decreases from east to west and the number of hardground surfaces increases in the same direction. Much of the chert in the higher part of the member is represented by calcareous concretions west of Branscombe, and chert is confined to the lower part of the member. The Bindon Sandstone Member shows a similar lateral variation in chert content, chert being ubiquitous east of Beer Head and absent to the west. Much of the important local building stone worked under the name Salcombe Stone came from this chert-free part of the Bindon Sandstone Member.

Acknowledgements

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References

ALI, M.T. 1975. Environmental implications of infillings in the Upper Greensand of the Beer district, south Devon. *Proceedings of the Geologists' Association*, **85**, 519-532.

BRITISH GEOLOGICAL SURVEY. 1956. *Geological Survey Ten Mile Map: South Sheet. First Edition (Solid)*. Southampton: Ordnance Survey.

CARTER, D.J. and HART, M.B. 1977. Aspects of mid-Cretaceous stratigraphical micropalaeontology. *Bulletin of the British Museum (Natural History), Geology*, **29**, 1-135.

DE LA BECHE, H.T. 1826. On the Chalk and sands beneath it (usually termed Greensand) in the vicinity of Lyme Regis, Dorsetshire, and Beer, Devonshire. *Transactions of the Geological Society, London*, **2**, 109-118.

DE LA BECHE, H.T. 1839. *Report on the geology of Cornwall, Devon and West Somerset*. HMSO, London.

DOWNES, W. 1882. The zones of the Blackdown Beds and their correlation with those at Haldon, with a list of fossils. *Quarterly Journal of the Geological Society, London*, **38**, 75-94.

EDWARDS, R.A. and GALLOIS, R.W. 2004. *Geology of the Sidmouth District - a brief explanation of the geological map Sheets 326 and 340 Sidmouth*. British Geological Survey, Keyworth.

FITTON, W.H. 1836. Observations on some of the strata between the Chalk and Oxford Oolite in south-east England. *Transactions of the Geological Society*, Series 2, **4**, 103-400.

GALLOIS, R.W. 2004. The development and origin of karst in the Upper Greensand Formation (Cretaceous) of south-west England. *Geoscience in south-west England*, **11**, xxx-xxx.

HAMBLIN, R.J.O. and WOOD, C.J. 1976. The Cretaceous (Albian-Cenomanian) stratigraphy of the Haldon Hills, south Devon, England. *Newsletters in Stratigraphy*, **4**, 135-149.

HANCOCK, J.M. 1969. Transgression of the Cretaceous sea in south-west England. *Proceedings of the Ussher Society*, **2**, 61-83.

HART, M.B. 1970. *The distribution of the Foraminiferida in the Albian and Cenomanian of South-West England*. Unpublished PhD thesis, University of London.

HART, M.B. 1973. Some observations on the Chert Beds (Upper Greensand) of south-west England. *Proceedings of the Ussher Society*, **2**, 599-608.

HART, M.B. and WILLIAMS, C.L. 1990. The Upper Greensand in East Devon: new data but old problems. *Proceedings of the Ussher Society*, **7**, 273-278.

JUKES-BROWNE, A.J. and HILL, W. 1900. *The Cretaceous rocks of Britain. Vol. I, The Gault and Upper Greensand of England*. Memoirs of the Geological Survey of the United Kingdom. HMSO, London.

MEYER, C.J.A. 1874. On the Cretaceous rocks of Beer Head and the adjacent cliff sections, and on the relative horizons therein of the Warminster and Blackdown fossiliferous deposits. *Quarterly Journal of the Geological Society, London*, **30**, 369-393.

OWEN, H.G. 1999. Correlation of Albian European and Tethyan ammonite zonations and the boundaries of the Albian Stage and substages: some comments. *Scripta Geologica*, Special Issue No. 3, 129-149.

SMITH, W.E. 1957. Summer field meeting in south Devon and Dorset. *Proceedings of the Geologists' Association*, **68**, 136-152.

SMITH, W.E. 1961a. The detrital mineralogy of the Cretaceous rocks of S. E. Devon, with particular reference to the Cenomanian. *Proceedings of the Geologists' Association*, **72**, 303-331.

SMITH, W.E. 1961b. The Cenomanian Limestone and contiguous deposits west of Beer. *Proceedings of the Geologists' Association*, **72**, 91-134.

SPATH, L.F. 1926. On the zones of the Cenomanian and uppermost Albian. *Proceedings of the Geologists' Association*, **37**, 430-432.

TRESISE, G.R. 1961. The nature and origin of chert in the Upper Greensand of Wessex. *Proceedings of the Geologists' Association*, **72**, 333-356.

WILLIAMS, C.L. 1991. *The sedimentology of the Upper Greensand of Devon*. Unpublished PhD thesis, University of Plymouth.

WILSON, V., WELCH, F.B.A., ROBBIE, J.A. and GREEN, G.W. 1958. *Geology of the country around Bridport and Yeovil*. Memoirs of the Geological Survey of Great Britain. HMSO, London.

WOODWARD, H.B. and USSHER, W.A.E. 1911. *The geology of the country near Sidmouth and Lyme Regis*. 2nd Edition. Memoirs of the Geological Survey. HMSO, London.

USSHER, W.A.E. 1906. *The geology of the country between Wellington and Chard*. Memoirs of the Geological Survey. HMSO, London.

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

R.W. Gallois

Gallois, R.W. 2004. The development and origin of karst in the Upper Greensand Formation (Cretaceous) of south-west England. *Geoscience in south-west England*, **11**, 00-00.

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.

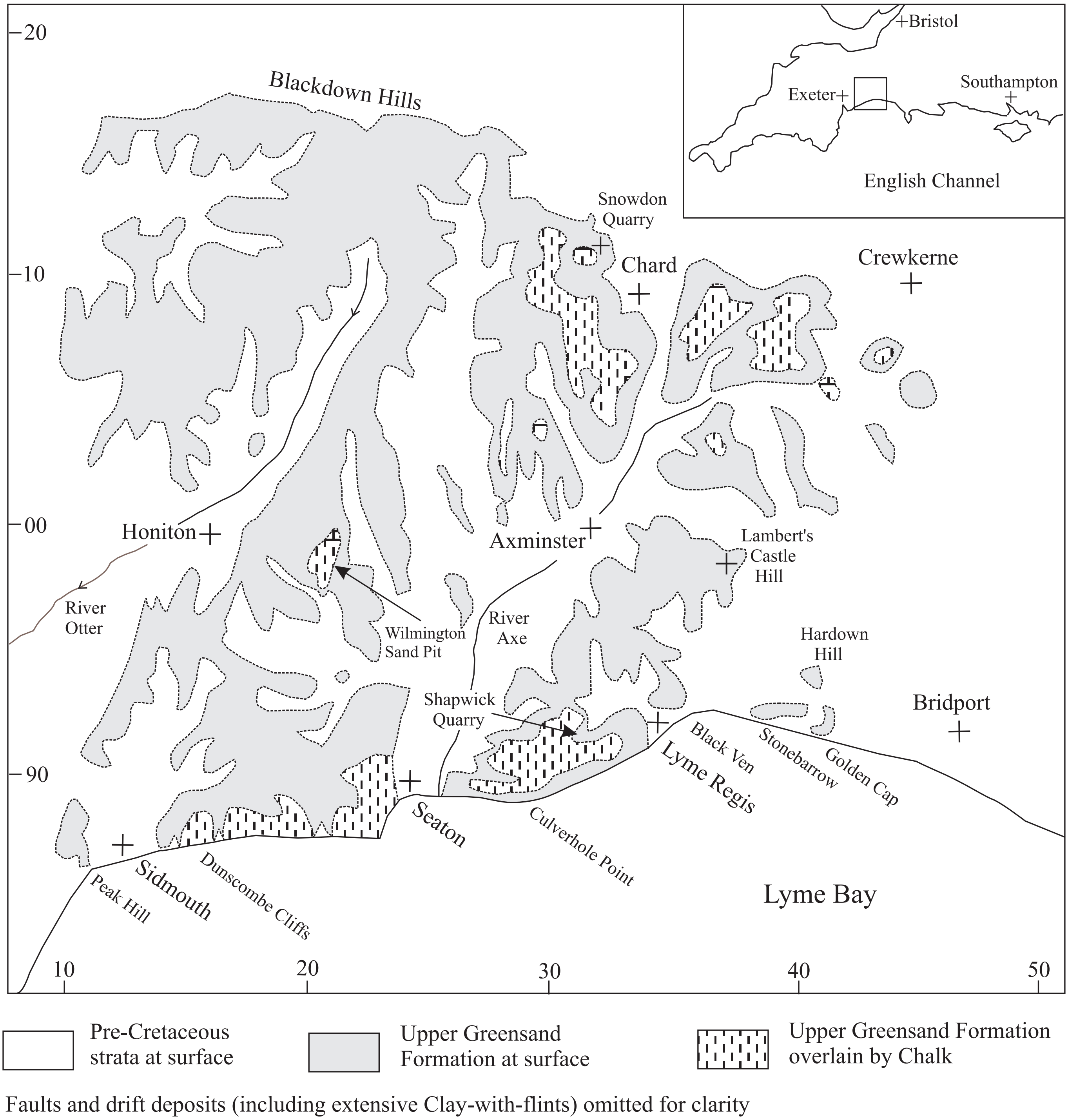
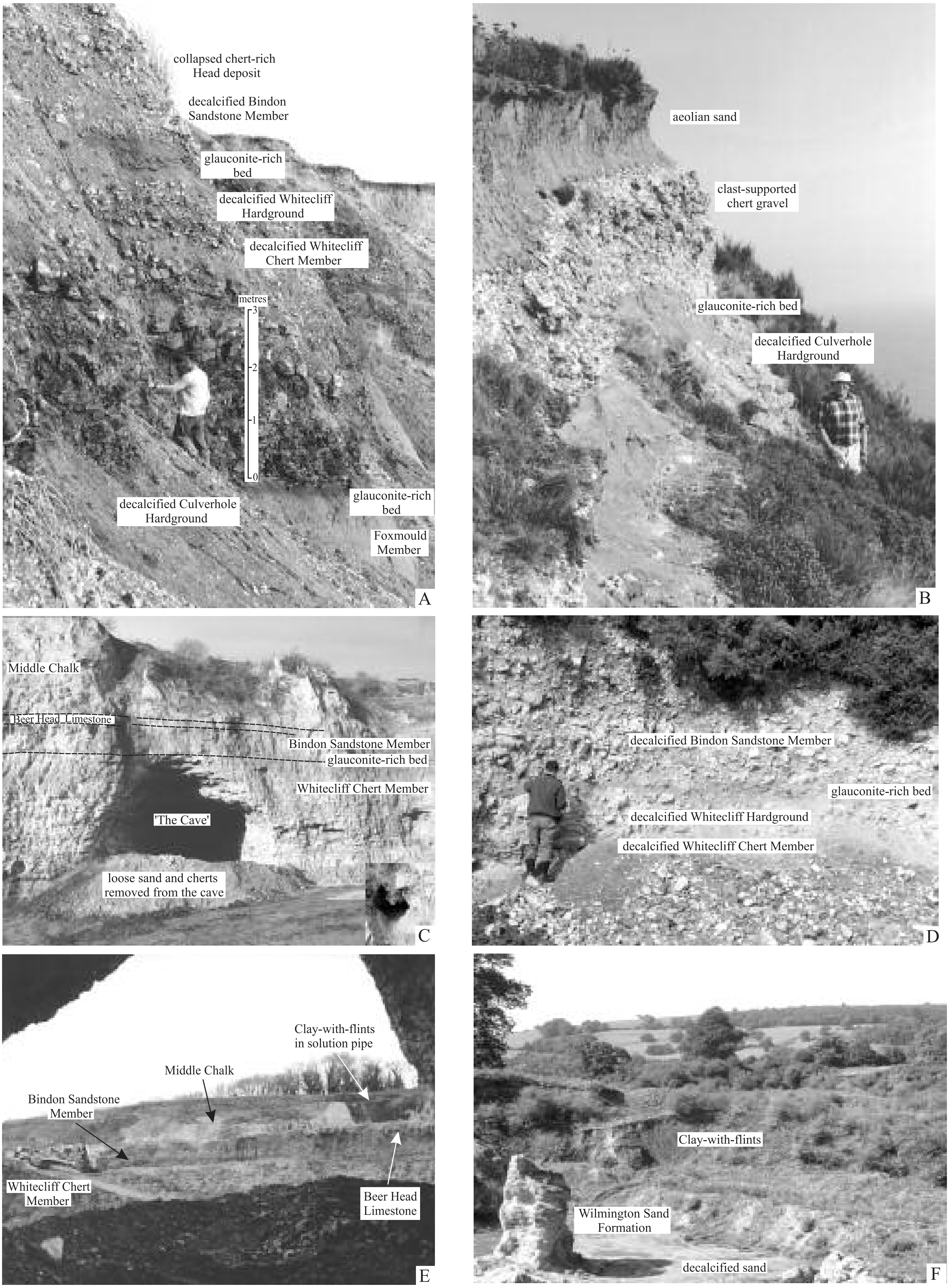


Figure 1. *Outcrop and subcrop of the Upper Greensand Formation in south-west England showing the positions of sections referred to in the text. Outcrop linework after British Geological Survey (1956).*


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.

Solution pipes

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].

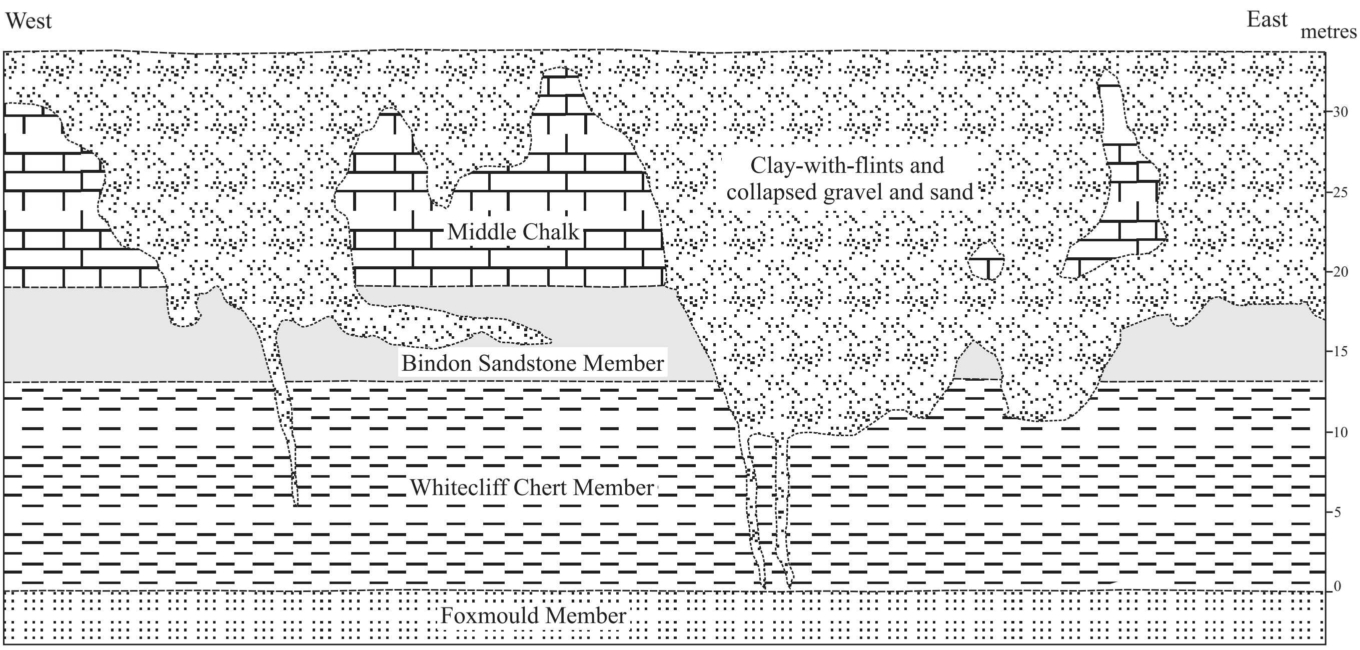


Figure 3. *Large-scale pervasive dissolution of the Middle Chalk and Bindon Sandstone Member at Higher Dunscombe Cliff [NGR SY 153 878], east Devon (based on a photograph). Joint-related solution pipes extend through the full thickness of the Whitecliff Chert Member.*

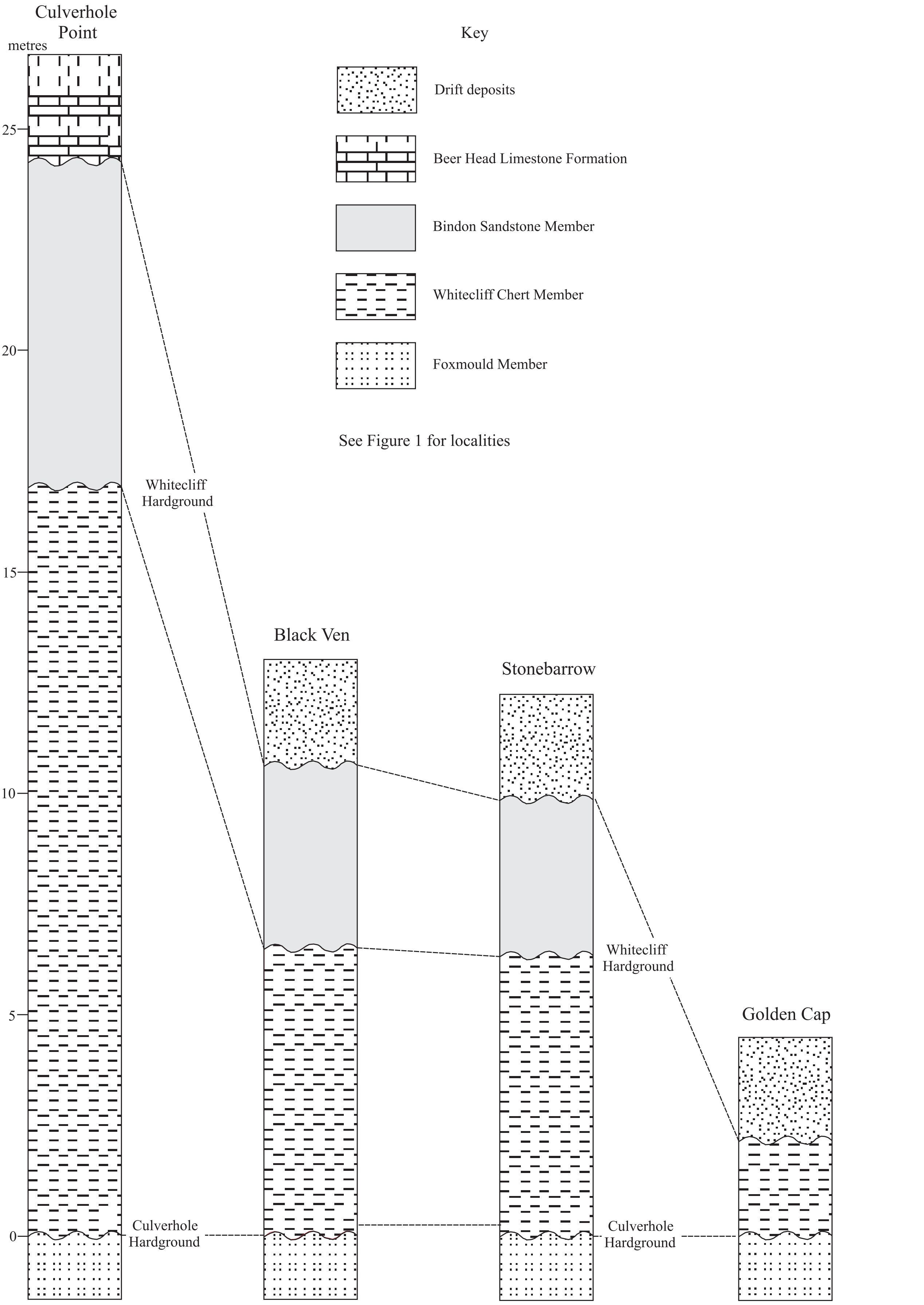


Figure 4. *Correlations between the unweathered section in the Whitecliff Chert and Bindon Sandstone members at Culverhole Point with the decalcified sections at Black Ven, Stonebarrow and Golden Cap.*

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.

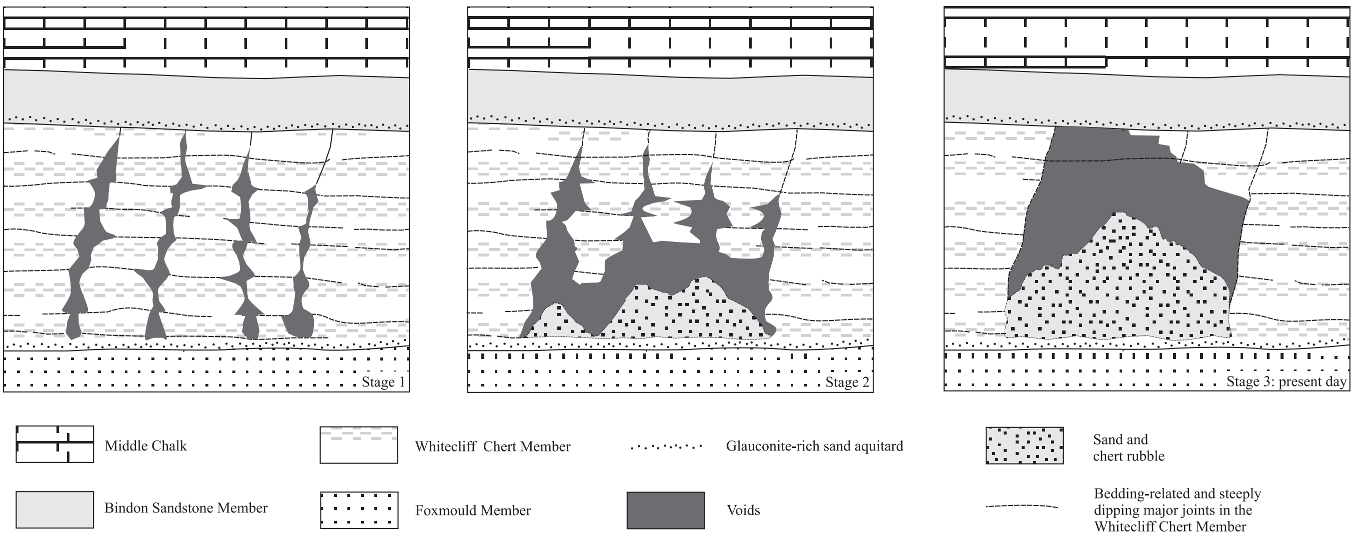


Figure 5. *Suggested mechanism for the formation of 'The Cave' at Shapwick Quarry, Uplyme, east Devon (Stage 3 based on Figure 2c).*

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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References

BRITISH GEOLOGICAL SURVEY. 1956. *Geological Survey Ten Mile Map: South Sheet. First Edition (Solid)*. Southampton: Ordnance Survey.

GALLOIS, R.W. 2004. The stratigraphy of the Upper Greensand Formation (Cretaceous) of south-west England. *Geoscience in south-west England*, **11**, xxx-xxx.

HAWKES, P.W., FRASER A.J. and EINCHCOMB, C.C.G. 1998. The tectono-stratigraphic development and exploration history of the Weald and Wessex basins, southern England. In: UNDERHILL, J.R. (Ed.), *The development, evolution and petroleum geology of the Wessex Basin*. Geological Society, London, Special Publications, **133**, 39-68.

JUKES-BROWNE, A.J. and HILL, W. 1900. *The Cretaceous rocks of Britain. Vol. I, The Gault and Upper Greensand of England*. Memoirs of the Geological Survey of the United Kingdom. HMSO, London.

WALTHAM, A.C. and FOOKES, P.G. 2003. Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology and Hydrogeology*, **36**, 101-118.

WILSON, V., WELCH, F.B.A., ROBBIE, J.A. and GREEN, G.W. 1958. *Geology of the country around Bridport and Yeovil*. Memoirs of the Geological Survey of Great Britain. HMSO, London.

WOODWARD, H.B. and USSHER, W.A.E. 1911. *The geology of the country near Sidmouth and Lyme Regis*. 2nd Edition. Memoirs of the Geological Survey. HMSO, London.

USSHER, W.A.E. 1906. *The geology of the country between Wellington and Chard*. Memoirs of the Geological Survey. HMSO, London.