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The stratigraphy of the mid Cretaceous (Albian) Upper Greensand Formation of the Wessex Basin and South West England, UK

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ABSTRACT:

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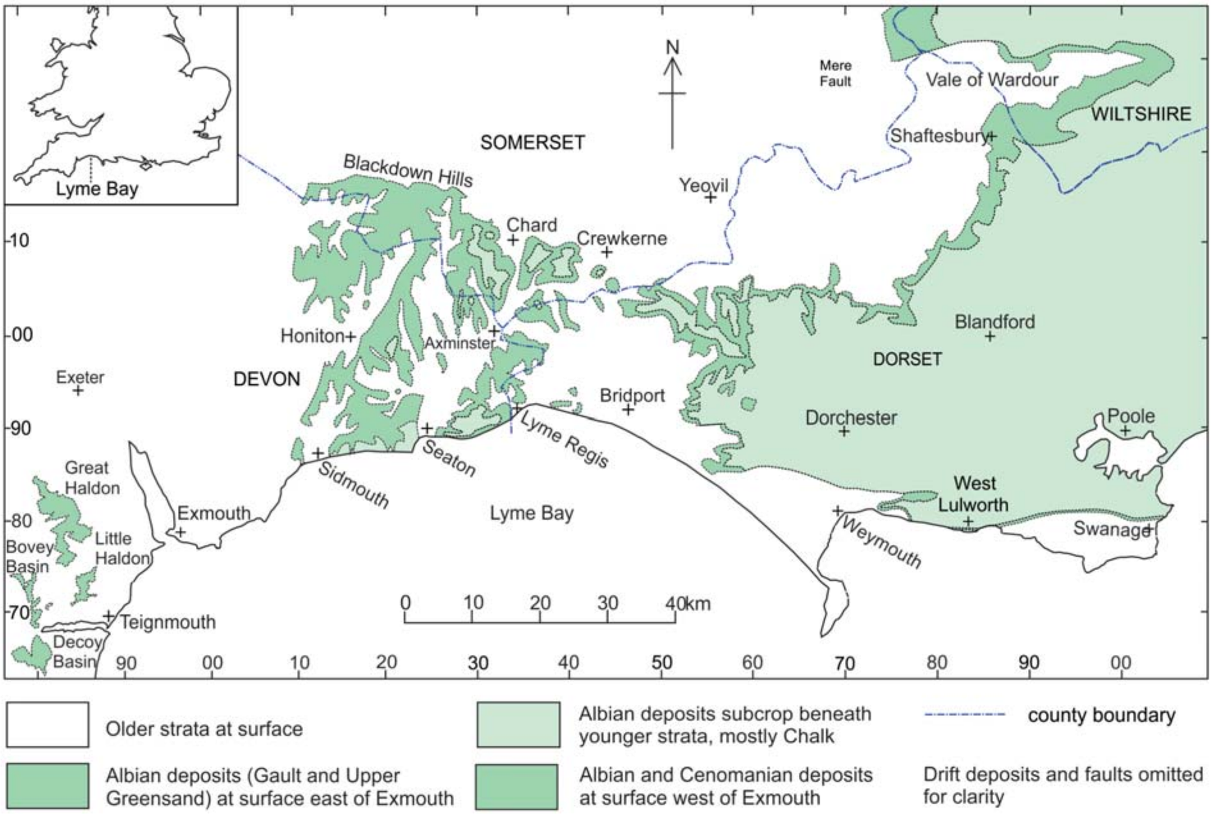
The Upper Greensand Formation, mostly capped by the Chalk, crops out on the edges of a broad, dissected plateau in Devon, west Dorset and south Somerset and has an almost continuous outcrop that runs from the Isle of Purbeck to the Vale of Wardour in south Wiltshire. The Formation is well exposed in cliffs in east Devon and the Isle of Purbeck, but is poorly exposed inland. It comprises sandstones and calcarenites with laterally and stratigraphically variable amounts of carbonate cement, glauconite and chert. The sedimentology and palaeontology indicate deposition in marginal marine-shelf environments that were at times subject to strong tidal and wave-generated currents. The formation of the Upper Greensand successions in the region was influenced by penecontemporaneous movements on major fault zones, some of which are sited over E-W trending Variscan thrusts in the basement rocks and, locally, on minor faults. Comparison of the principal sedimentary breaks in the succession with the sequence boundaries derived from world-wide sea-level curves suggests that local tectonic events mask the effects of any eustatic changes in sea level. The preserved fauna is unevenly distributed, both laterally and stratigraphically. Bivalves, gastropods and echinoids are common at some horizons but are not age-diagnostic. Ammonites are common at a few stratigraphically narrowly defined horizons, but are rare or absent throughout most of the succession. As a result, the age of parts of the succession is still poorly known.

Key words: Stratigraphy; Upper Greensand Formation; Cretaceous; Devon; Dorset; Wessex; Albian Stage; Cenomanian Stage; Sequence stratigraphy.

INTRODUCTION

As a result of widespread earth movements in the late Jurassic and early Cretaceous, the mid Cimmerian Event of the North Sea (Glennie and Underhill 1998), much of southern Britain was reduced by mid Albian times to a peneplain cut in Permian to early Cretaceous rocks. A series of widespread transgressive events expanded the area of marine deposition in the Aptian and Albian Stages and culminated in the late Cretaceous when the whole of NW Europe was occupied by a single shelf sea (Hancock 1969). As the sea expanded westwards across southern England, the mudstones of the Gault Formation of East Anglia and the SE region passed westward into the shallow-water, glauconitic sandstones and calcarenites of the Upper Greensand Formation in Dorset and east Devon and into sands and gravels in mid Devon as the western margin of the depositional basin was approached. High contents of glauconite and the clay



Text-fig. 1. Geological sketch map of the Upper Greensand outcrop and subcrop in the western Wessex Basin and SW England

mineral smectite in the Upper Greensand may be related to penecontemporaneous volcanic activity in the southern North Sea and possible in the Western approaches (Jeans *et al*. 1982).

The Upper Greensand Formation crops out over a large part of the Wessex Basin and SW England, mostly on steep slopes beneath a plateau capped by Chalk or, in more westerly areas, by deeply weathered Tertiary and Quaternary deposits that are collectively referred to as "drift deposits" (Text-fig. 1). The Formation comprises sandstones and calcarenites with laterally and vertically variable amounts of glauconite and chert that were deposited in shallow marine environments. It is sparsely fossiliferous except at a few levels where ammonites are sufficiently common to show that the Formation is essentially of late Albian age. In the eastern part of the Wessex Basin the Upper Greensand passes down into the argillaceous Gault Formation which rests unconformably on older strata when traced westwards, ranging in age from Lower Cretaceous in the Isle of Purbeck to early Jurassic at Lyme Regis (Gallois and Owen in press). Westwards from there the Gault passes laterally into the arenaceous Upper Greensand which rests on late Triassic strata in east Devon and on Permian strata westward in the Haldon Hills (Hancock 1969). Throughout the Wessex Basin and adjacent regions the Upper Greensand is overlain unconformably by a highly condensed succession of glauconitic sandstones and limestones at the base of the Chalk Group.

Selected parts of the Upper Greensand in the study area were once extensively worked for building purposes, but many of the quarries were already no longer in use and/or degraded by the 1890s. Jukes-Browne and Hill (1900) described all the sections in southern England known at that time. Some of these were also described by Arkell (1947), Wilson *et al*. (1958), Tresise (1960, 1961), Drummond (1970), Kennedy (1970) and Carter and Hart (1977). The Upper Greensand outcrops in the Wessex Basin and SW England can be grouped into four principal areas. Those in the outliers of east and mid Devon, south Somerset and west Dorset; a continuous outcrop in west and mid Dorset; its continuation into south Wiltshire; and those in the Isle of Purbeck (Gallois and Owen 2017, in press). The thickest and most complete succession is that exposed on the east Devon coast. When traced westwards into mid Devon the succession becomes attenuated and coarser grained as the western margin of the depositional basin is approached. When traced northwards and eastwards into west Dorset and Wiltshire, the upper part of the succession contains major sedimentary breaks as a result of penecontemporaneous tectonic activity along fault zones that are associated with the reactivation of E-W trending Variscan faults in the pre-Permian basement rocks.

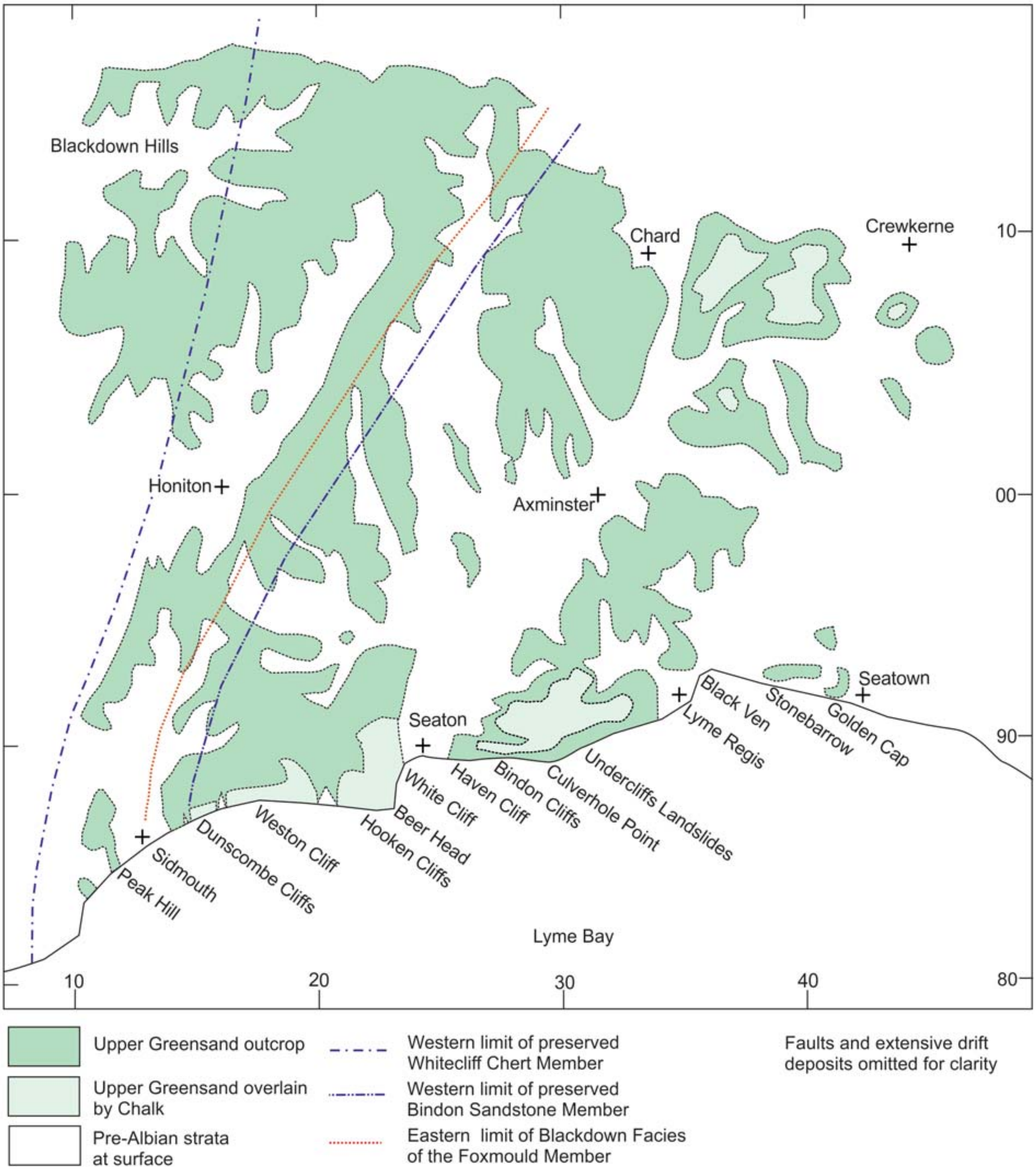
The zonal-subzonal scheme used in the present account is shown in Table 1. In addition to the standard scheme, two ammonite subzones can be recognised in the *inflatum* Zone (Owen in Gallois *et al.* 2016). An early *auritus* Subzone characterised by *Procallihoplites* with *P. auritus* (J. Sowerby) and *Inoceramus lissus* (Seeley), and a younger, as yet unindexed subzone, referred to as late *auritus*, is characterised by species of *Callihoplites* and in the later part by *Aucellina*.

EAST DEVON-WEST DORSET COAST AND SOMERSET

The Upper Greensand crops out over an area of about 25 km by 30 km in east Devon and south Somerset where it forms a dissected plateau that stretches south from the Blackdown Hills to the coast (Text-fig. 2). To the east, there are small outliers at Stonebarrow and Golden Cap in west Dorset. The Formation is mostly poorly exposed inland except for a few deeply incised narrow valleys (goyles) where

			Haldon Hills, mid Devon	east Devon, Dorset, Wiltshire	Isle of Purbeck
Stage	Zone	Subzone	Member	Member	Member
Late Albian	*Stoliczkaia (Stoliczkaia) spp.*	*briacensis*	not recorded	Bindon Sandstone	White Nothe
		perinflata	not recorded	Bindon Sandstone	White Nothe
		rostratum	Telegraph Hill sands	not recorded	not recorded
		late *auritus*	not recorded	Whitecliff Chert	White Nothe
	Mortoniceras inflatum	early *auritus*	not recorded	Foxmould	Foxmould
	Hysteroceras varicosum	*choffati*	not recorded	Foxmould	Foxmould
		binum	Woodlands Sands	Foxmould	Foxmould
		orbignyi	not recorded	Foxmould	Foxmould
	Dipoloceras cristatum		not recorded	not recorded	not recorded
Middle Albian	*Euhoplites lautus*	*daviesi*	not recorded	not recorded	Some subzones represented by Gault Formation and/or 'transition beds'
		nitidus			
	Proeuhoplites loricatus	*meandrinus*			
		subdelaruei			
		niobe			
		intermedius		sandy 'Gault'	
	Hoplites dentatus	spathi			
		lyelli			

Table 1. Summary of the Albian zones and subzones proved in the successions described in the present account. Zonal-subzonal scheme after Owen (2012)



Text-fig. 2. Geological sketch map of the Upper Greensand outcrops in the Devon-West Dorset-Somerset outliers showing localities referred to in the text

streams cross the steeper escarpments. In contrast, the coastal cliffs between Sidmouth and Lyme Regis are the best exposed and most extensive and complete sections of the Upper Greensand in Britain. They are nominated here as the type section of the Formation.

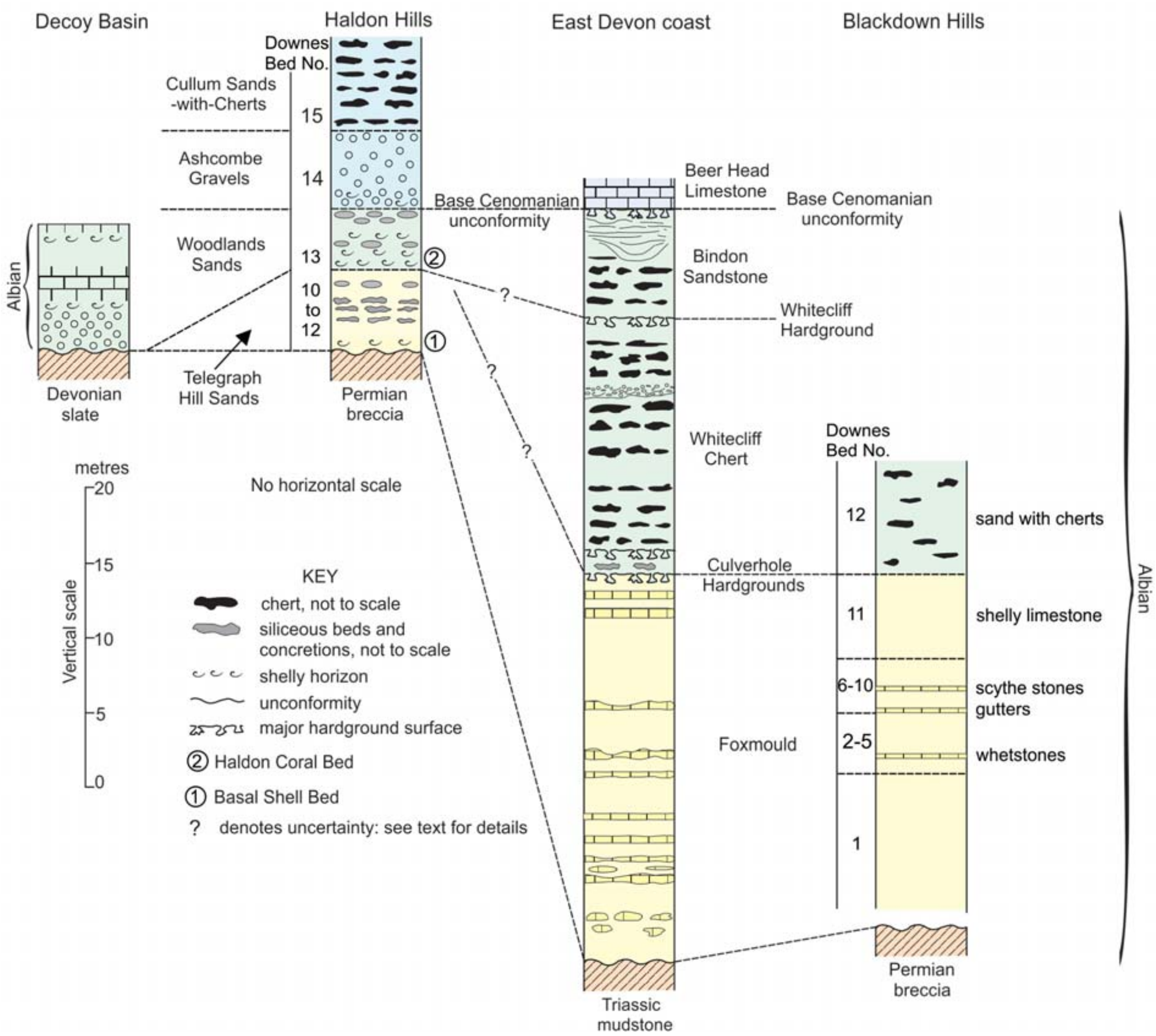
Where wholly preserved beneath a protective capping of Chalk in the coastal sections, the Upper Greensand is mostly between 50 and 55 m thick. Complete successions crop out on the cliffs between Sidmouth and Lyme Regis, and almost complete sections west of Sidmouth at Peak Hill and east of Lyme Regis at Stonebarrow and Golden Cap. Parts of the succession were formerly exposed in shallow pits dug for sharpening stones (siliceous sandstones) in the Blackdown Hills. The upper part of the Upper Greensand was locally preserved beneath a capping of Chalk in the Chard area in sand pits, quarries and road cuttings, but few of the sections described by Jukes-Browne and Hill (1900), Drummond 1970; Kennedy 1970; Smith and Drummond 1962) are now exposed.

The Upper Greensand in the region comprises fine-, medium- and coarse-grained calcareous sandstones and calcarenites composed of silica sand, glauconite, and comminuted calcite-shell debris with variable amounts of calcareous cement. Calcareously and siliceously cemented concretions and tabular beds are common in the lower part of the Formation and cherts are common in the upper part. The Formation has been divided into three Members, in ascending order the Foxmould, Whitecliff Chert and Bindon Sandstone, each of which is capped by a widespread sedimentary break marked by a prominent mineralised and burrowed erosion surface that is overlain by a glauconite-rich sandstone with phosphatic pebbles. The type sections for the Foxmould and Whitecliff Chert Members are White Cliff [SY 2344 8942]: that for the Bindon Sandstone Member is Bindon Cliffs [SY 275 894] (Gallois 2004). There are marked vertical and lateral variations and numerous sedimentary breaks within each member, but few of these can be traced over distances of more than a few kilometres. In contrast, the principal erosion surfaces that mark the boundaries between the members can be recognised throughout the region.

Foxmould Member

The Foxmould is well exposed in a few cliff sections, notably near Beer Head and at Seaton (Text-fig. 2), but elsewhere on the coast much of the outcrop is deeply weathered and vegetated. It comprises 25 to 30 m thick of highly bioturbated, fine- and medium-grained, weakly cemented glauconitic sandstones composed of variable amounts of quartz, glauconite, clay minerals and calcium carbonate. Secondarily calcareously cemented tabular beds and ellipsoidal concretions occur at several levels, but are not laterally persistent over large distances. The fauna and sedimentary structures indicate deposition in subtidal environments above storm wave base. There is a progressive lateral variation from east to west in the bulk composition of the member. From Beer eastward, all the harder tabular and concretionary beds in the Foxmould are calcareously cemented. West of Beer, these are progressively replaced by siliceously cemented beds until they are the only cemented beds present at Sidmouth and in the Blackdown Hills. They were referred to as the Blackdown Facies by Tresise (1960) (Text-fig. 2). Up to 25 m of Foxmould, comprising relatively soft, glauconitic sandstones with fossiliferous silicified beds at several levels, crops out in the western part of the Blackdown Hills between Culmstock [ST 102 136] and Corfe [ST 232 197]. There are now few exposures, but the siliceous horizons were extensively worked until late Victorian times for sharpening purposes (scythe-stones and whetstones) and yielded numerous well preserved fossils including ammonites and age-diagnostic bivalves. The composite succession, based on Downes (1882) is graphically summarised in Text-fig. 3. The junction with the underlying Mercia Mudstone Group was not recorded, but was thought to be close (< 1 m) below Bed 1.

The extensive museum collections of fossils from the Foxmould have almost all come from the siliceous beds in the western part of the outcrop. Downes (1882) recorded 196 species of fossils from the Blackdown Hills and plotted their occurrences against a measured section (Text-fig. 3), and Jukes-Browne and Hill (1900) recorded a similarly diverse fauna at Sidmouth. Less numerous and less diverse assemblages have been recorded at Lyme Regis and elsewhere along the coast, mostly in fallen blocks of calcareous sandstone. The preserved fauna of the Foxmould is dominated in numbers and variety by bivalves and gastropods. Taylor *et al.* (1983) recorded 76 bivalve species (representing 61 different genera) and 65 gastropod taxa from the Foxmould in museum collections from the Blackdown Hills. Jukes-Browne and Hill (1900) recorded 34 species of bivalve and 17 species of gastropod in siliceous beds at Sidmouth and similar, but less diverse, assemblages in calcareous sandstones at Lyme Regis. The remaining fauna includes annelids, echinoderms, brachiopods, crustaceans, polyzoans and plant debris. In addition to these, the siliceous beds of the Blackdown Hills have yielded well preserved ammonites. They include *Hysteroceras varicosum* (J. de C. Sowerby) and *H. binum* (J. Sowerby) indicative of the *binum* Subzone of the *varicosum* Zone, together with species of *Deiradoceras*, *Epihoplites*, *Euhoplites*, *Goodhallites* and "*Semenoviceras*". Downes (1882) thought that most of the ammonites came from his Beds 2–9, with one or two specimens of "*Ammonites varicosus*" from Bed 10. Taken together with the ammonites, the presence of *Actinoceramus sulcatus*



Text-fig. 3. Correlation of the Albian and earliest Cenomanian successions exposed in Devon and Somerset based on Sellwood et al. 1984 (Decoy Basin and Haldon Hills, Downes, 1882 (Haldon Hills and Blackdown Hills) and Gallois, 2004 (east Devon coast)

(Parkinson) in Downes (1882) Beds 1? to 5 Beds is indicative of the *orbignyi* Subzone of the *varicosum* Zone. The same species has been recorded from east Devon. A transitional interval in Bed 6 is followed by a well-developed *binum* Subzone fauna, particularly in Beds 7 and 8, with the *binum* Subzone form of *Actinoceramus concentricus* Parkinson and *binum* Subzone ammonites. The recorded occurrence of *A. concentricus* (Parkinson) suggests that Beds 9 and 10 also are of *varicosum* Zone age. The early *auritus* Subzone of the *inflatum* Zone is represented in Beds 11 and 12 by *Inoceramus lissus* Seeley and *Procallihoplites.* A similar faunal succession was recorded in the Sidmouth area (Jukes-Browne and Hill 1900) where it is represented by a less diverse fauna. Fundamentally, the Foxmould with its diversity of sediment types is of *varicosum* Zone age and early *inflatum* Zone throughout Wessex. Bed 12 in the Blackdown Hills contains cherts with *Neithea quadricostata*, but no ammonite has been recorded; hence its exact age is unknown. The possibility that this bed represents the local development of the Whitecliff Chert cannot be discounted. *Neithea quadricostata* is present also in the basal beds in the Haldon area (Downes 1882). When traced eastward to the Chard-Chardstock area, the well-exposed cherts at Snowdon Hill [ST 3118 0889] are the correlatives of those in the Whitecliff Chert on the Devon coast.

Whitecliff Chert Member

The Whitecliff Chert, 12 to 18 m thick, is wholly exposed in the upper parts of the cliffs between Sidmouth and Lyme Regis where the base of the member is taken at the lower of two prominently cemented and intensely burrowed erosion surfaces (Culverhole Hardgrounds) (Text-fig. 3). This marks an upward change in lithology and depositional environments from the Foxmould to strongly cemented, fine- to coarse-grained calcareous sandstones and sandy calcarenites with common cherts. The carbonate content is made up of whole and broken shells (mostly bivalves and gastropods), unidentifiable shell sand and grit, and secondary carbonate cements and concretions. The insoluble content consists of sand-grade silica and glauconite. Beds of nodular and tabular, translucent dark brown chert, mostly 0.15 to 0.3 m thick, are concentrated in the more carbonate-rich beds where they constitute up to 40% of the total volume of the rock.

Mineralised hardground surfaces occur throughout the member together with scour hollows infilled by clast-rich and shell-debris-rich channel-lag deposits. Garrison *et al.* (1987) described multiple phases of mineralisation and erosion associated with the more prominent hardgrounds. The lithologies 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 been shown to be laterally sufficiently persistent to be used as a stratigraphical marker bed. The number of sedimentary breaks increases in a westerly direction, and the number of chert horizons decreases in the same direction until west of Branscombe, chert is confined to the lower part of the member. This change is accompanied by an overall thinning of the member and evidence of deposition in shallower-water environments.

Notwithstanding the extensive outcrops and the number of readily accessible large blocks on the beaches, no *in situ* ammonite has been recorded from the Whitecliff Chert. A chert cast found in the landslide at Black Ven by Mr David Sole is a *Mortoniceras* (*M.*) *commune* indicative of the *auritus* Subzone of the *inflatum* Zone. It seems likely, on age grounds alone, to have come from the Whitecliff Chert rather than the overlying Bindon Sandstone (see below).

Bindon Sandstone Member

Where well exposed in the cliff sections between Sidmouth and Lyme Regis, the Bindon Sandstone comprises 3 to 8 m of glauconitic, fine- medium- and coarse-grained, glauconitic calcarenites and calcareous sandstones with cherts common in the lower part. The succession is laterally variable over distances as little as tens of metres, but can be divided into four lithologically distinct beds that can be recognised in all the coastal sections (Gallois 2004).

Bivalves, gastropods brachiopods, echinoids and rare ammonites that are presumed to have come from the Bindon Sandstone, have been recorded in the landslide debris below the cliffs between Beer and Seatown. Echinoids are relatively common and taxonomically diverse and include many of the forms described by Smith and Wright (1989–2012) from the Upper Greensand. The stratigraphically important ammonites include an *Arrhaphoceras* (Grimsdale Collection, Natural History Museum) found at Seaton, *Stoliczkaia* collected by Mr David Sole at Lyme Regis, *Stoliczkaia* and *Arrhaphoceras* from between Charmouth and Seatown (Spath 1926), and *Stoliczkaia* cf. *dispar* (d'Orbigny), *Durnovarites* cf. *subquadrata* (Spath), *Arrhaphoceras studeri* (Pictet and Campiche) and *Mariella bergeri* (Brongniart) from the same cliffs (Wilson *et al.* 1958). Taken together the ammonite assemblage is indicative of the *perinflata* Subzone of the *Stoliczkaia* spp. Zone. Ammonites collected *in situ* by the late Colonel O.T. Bayliss from the highest part of the Bindon Sandstone at Shapwick Grange Quarry [SY 3130 9190] near Lyme Regis include *Callihoplites*, *Discohoplites*, *Hyphoplites*, *Idiohamites*, *Stoliczkaia* and *Stomohamites* indicative of the *Praeschloenbachia briacensis* Subzone (Owen in Hamblin and Wood 1976).

HALDON HILLS AND BOVEY AND DECOY BASINS

Two small outliers of predominantly arenaceous and gravelly Albian and Cenomanian sediments that have been collectively referred to as Upper Greensand, cap the Haldon Hills in mid Devon, about 20 km SW of the nearest east Devon outcrop (Text-fig. 1). A maximum estimated thickness of 76 m of Cretaceous glauconitic, calcareous sandstones and gravels crops out in the Little Haldon and Great Haldon outliers (Selwood *et al.* 1984). Some of the deposits were formerly worked for building materials, but all the principal sections are now wholly degraded. Extensive temporary road cuttings across the Little Haldon outcrop in the 1970s, combined with the then extant sections, enabled Hamblin and Wood (1976) to divide the Haldon Hills succession into four members, in ascending order the Telegraph Hills Sands, Woodlands Sand, Ashcombe Gravels and Cullum Sands with Cherts (Text-fig. 3). Similar successions up to 20 m thick were formerly exposed father south in the Bovey and Decoy Basins, 9 and 18 km SSE respectively, in the Stickelpath fault belt (Selwood *et al.* 1984).

Downes (1882) compared the fauna found in the Blackdown Hills with that from the Haldon Hills and listed faunal elements common to both. These are mostly silicified bivalves and gastropods collected from the lower part of the succession which had not at that time been fully described. He concluded that the bivalves covered a similar range (in terms of species and diversity) to those of Beds 10 to 12 in the Blackdown Hills. However, he and later researchers (e.g. Hamblin and Wood 1976) noted that many of the specimens in museums labelled Blackdown Hills were from the Haldon Hills, and vice versa. The presence of four specimens of *H. orbignyi* in the Cunningham Collection (NHM 88681) and a *Hysteroceras* sp. juv. alleged to come from Haldon, but in a Blackdown Greensand preservation, suggests that the bulk of Haldon Hills Bed 12 is of *binum* Subzone age and corresponds to Beds 7–12 at Blackdown. The absence of a well-preserved, unequivocal *in situ* ammonite fauna in the Haldon Greensand makes it impossible to make a more detailed biostratigraphical correlation between the two localities.

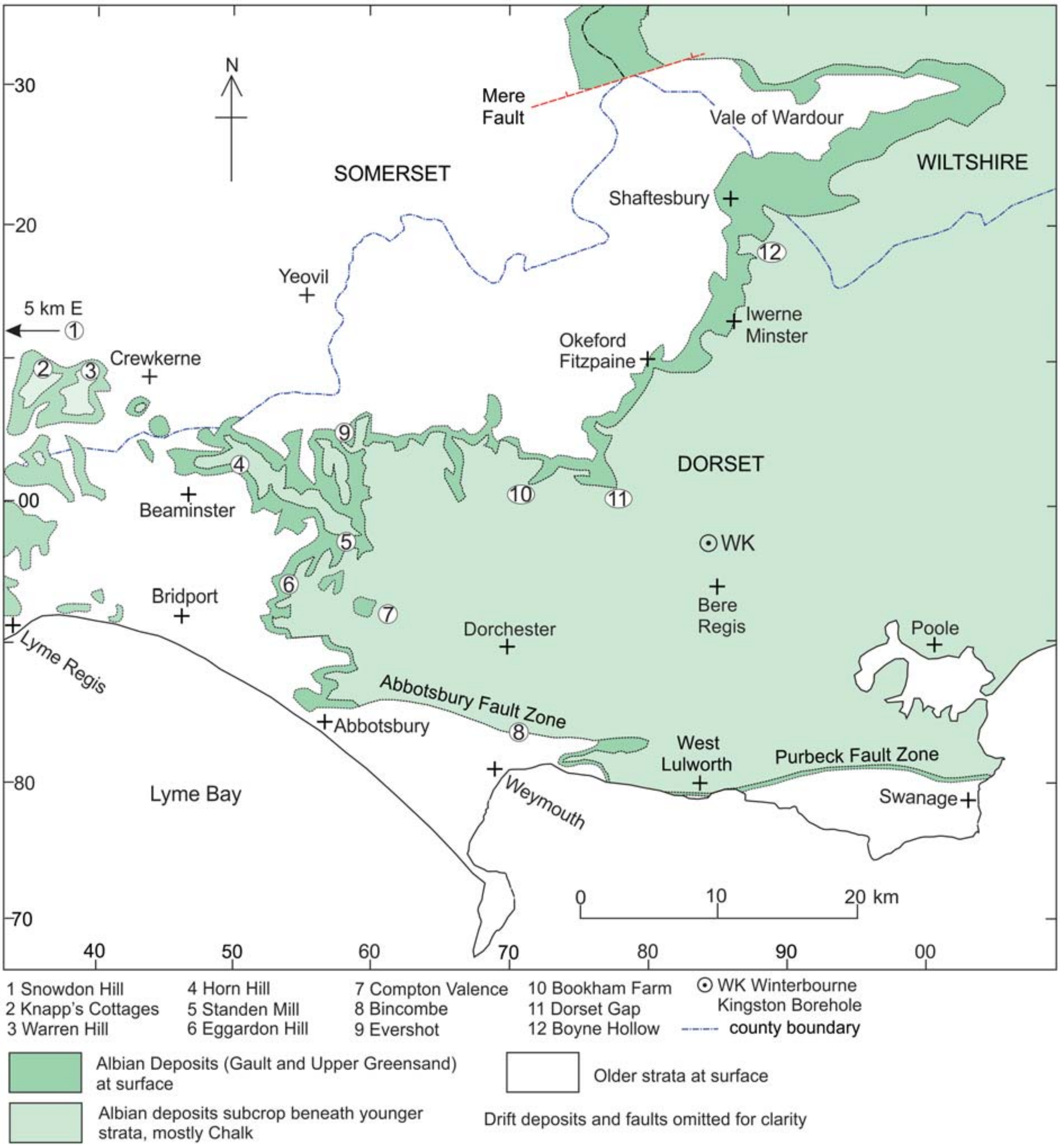
The Basal Shell Bed of the Telegraph Hill Sands (Beds 10 to 12 of Downes 1882) contains a diverse fauna that includes corals, brachiopods, bivalves, gastropods and orbitoline foraminifera which Sellwood *et al.* (1984) correlated with the Foxmould of the Devon coast. In the lower part of the Woodlands Sands the Haldon Coral Bed (Bed 13 of Downes 1882) contains bryozoans, brachiopods gastropods and echinoids together with corals and bivalves that are comparable with specimens from the type Cenomanian of France (Sellwood *et al.* 1984). However, these are mostly long-ranging forms that could be indicative of an Albian or Cenomanian age. A better indication of age might be given by two loose ammonite fragments which Hamblin and Wood (1976) thought were from the Coral Bed on lithological grounds. They were identified by Casey (in Hamblin and Wood 1976) as *Callihoplites* and *Mortoniceras* (*Cantabrigites*) suggesting either the late part of the *auritus* Subzone or the *rostratum* Subzone,

No fossil has been recorded from the Ashcombe Gravels, but ammonites preserved in cherts that are believed to have come from the Cullum Sands with Cherts include *Mantelliceras saxbii* (Sharpe) and *Paraturrilites* aff. *wiesti* Sharpe indicative of an age "up to a higher part of the *M. dixoni* Zone" (Woods *et al.* 2009). It raises the possibility that the Ashcombe Gravels could also be of earlier Cenomanian age.

The preferred correlation of the Upper Greensand successions in east Devon, the Blackdown Hills and the Haldon Hills/Bovey Basin based on the palaeontological evidence described above is summarised in Text-fig. 3. The correlation of the Foxmould with the Telegraph Hill Sands is broadly well established, but that between the Whitecliff Chert and Bindon Sandstone of east Devon with the Woodlands Sands and the Cullum Sands with Cherts interval is less certain. Hamblin and Wood (1976) concluded that the key to correlation of the Haldon Hills succession with that of the east Devon coast depended on three quartz-gravel beds in the Ashcombe Gravels. They correlated each of these with a specific bed in the coastal outcrops. The first is one of a number of laterally impersistent (10s to 100s of metres across) channel-lag deposits composed of shell debris and locally derived pebbles of calcareous sandstone in the upper part of the Whitecliff Chert at Kempstone Rocks [SY 161 881]. The second is the "coarse band" of Smith (1961), a glauconite-rich, medium-to coarse-grained sandstone (Bed 1 of the Bindon Member) that rests on the Whitecliff Hardground. They suggested that the third was either a sandstone at the top of the Bindon Member or a sandy limestone at the base of the Cenomanian Beer Head Limestone (Bed A1 of Jukes-Browne and Hill 1900). There is no sedimentological or other evidence to support these correlations. A more appropriate interpretation which fits in with the limited palaeontological evidence is that the rapid upward coarsening of the succession at the base of the Ashcombe Gravels marks an extension of the basal Cenomanian transgression that can be traced from east to west across the Wessex Basin.

DORSET AND WILTSHIRE, MAIN OUTCROP

The Upper Greensand has a continuous outcrop in the Isle of Portland, and northwards from Weymouth into west and north Dorset, south Wiltshire and beyond (Text-fig. 4). As in east Devon, the Formation can be divided into two lithologically distinct parts, the Foxmould and an overlying, laterally variable succession of calcareous sandstones and calcarenites locally with cherts and commonly with sedimentary breaks marked by hardground surfaces. The succession is well exposed in the cliffs in the Isle of Purbeck where the lithostratigraphy and palaeontology have been described in detail by Jukes-Browne and Hill (1900),



Text-fig. 4. Geological sketch map of the Upper Greensand outcrop and subcrop in the West Wessex Basin showing the locations of sections referred to in the text

Arkell (1947), Carter and Hart (1977) and Gallois and Owen (2017). The Foxmould and the transitional underlying beds down into the Gault are largely obscured by landslides on the coast and in many inland areas and have rarely been recorded in boreholes. Taken together, the coastal and inland data suggest that the Foxmould comprises 25 to 45 m of fine-grained glauconitic sandstones with subordinate calcareous concretions and tabular beds throughout the region.

Many of the road sections and abandoned small quarries recorded by Jukes-Browne and Hill (1900) in the upper part of the Upper Greensand in west and north Dorset were still visible, wholly or in part, until the 1980s but have become progressively more degraded and vegetated since that time. Wilson *et al*. (1958) and Smith and Drummond (1962) and Drummond (1967) described many of the extant sections, Drummond (1970) related lateral variations in the succession to penecontemporaneous earth movements, Kennedy (1970) described the stratigraphy of the youngest part of the Upper Greensand and the basal Chalk, and Carter and Hart (1977) described the stratigraphy of the Formation throughout the Wessex Basin. The successions in this region can be divided into two distinct areas, those in south Somerset and west Dorset between Crewkerne and Weymouth and those in north Dorset between Crewkerne and Iwerne Minster (Text-fig. 4). In many of the exposures throughout this region, the highest part of the Foxmould is lithologically distinctive calcareous sandstone with locally abundant *Amphidonte* (formerly *Exogyra*) that was referred to by Wilson *et al*. (1958) as the Exogyra Sandstone in west Dorset and by Arkell (1947) as the Exogyra Sandstone in the Isle of Purbeck. As in east Devon, this is capped by a mineralised and burrowed erosion surface, the correlative of the Culverhole Hardground, overlain by glauconite-rich sandstone with phosphatic pebbles and sandstone clasts.

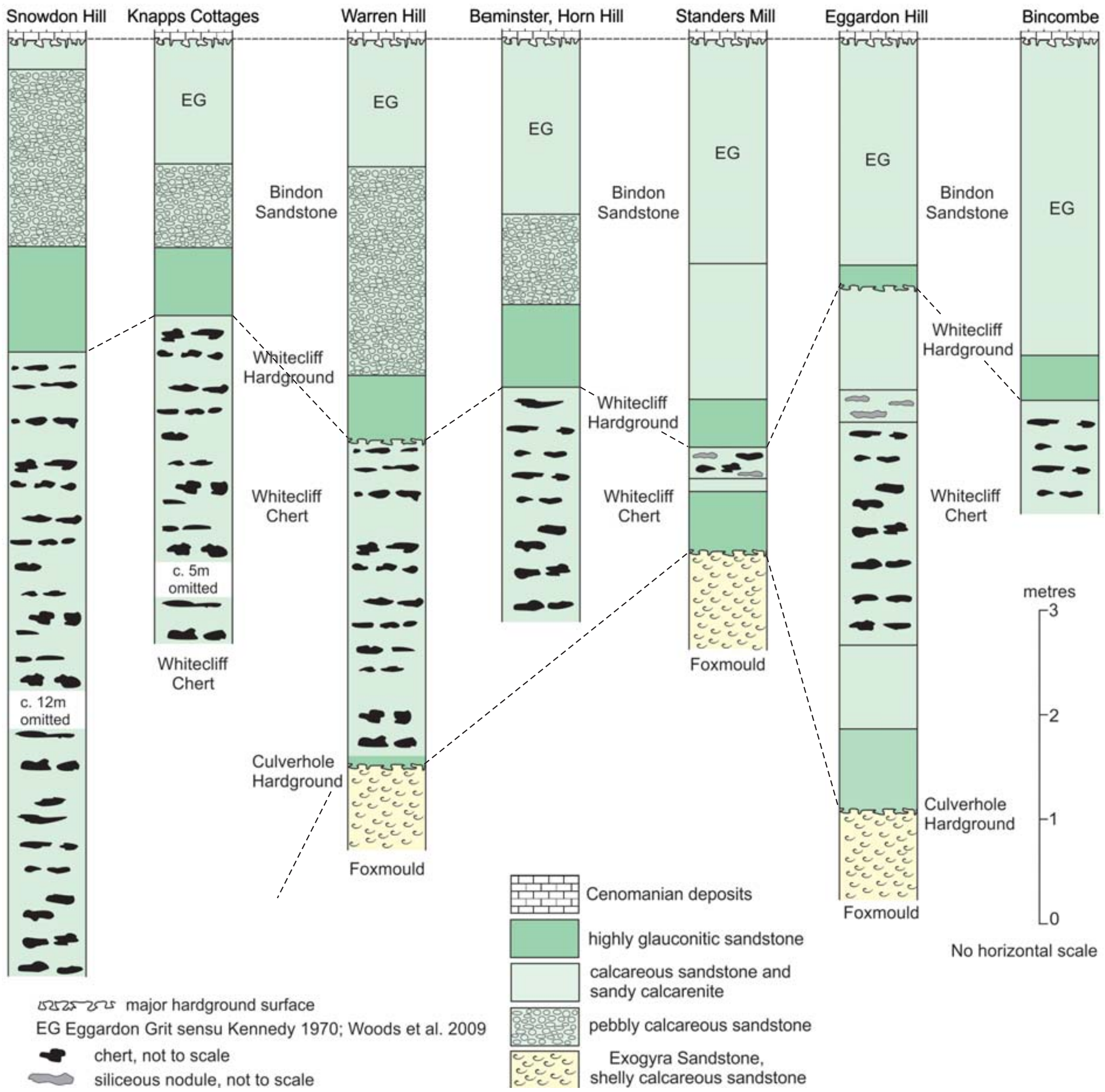
Jukes-Browne and Hill (1900), Wilson *et al*. (1958), (Kennedy (1970), Drummond (1970), Smith and Drummond (1962) recorded the successions in a series of road cuttings disused quarries and stream sections. A few of these are still sufficiently well exposed for comparison to be made with the published descriptions. They include Snowdon Hill [ST 312 089], Knapps Cottages [ST 362 099] and Warren Hill [ST 404 102] in the Chard area, and Eggardon Hill [SY 5341 9512], Compton Valence [SY 592 931] and Bincombe [SY 542 934] in Dorset.

Crewkerne to Weymouth

The succession in this area is similar to that in east Devon, but markedly more attenuated in the upper part (Text-fig. 5). The Foxmould is poorly exposed, but the limited borehole and exposure data show that the lithologies are similar to those farther west and that there is little lateral variation. Welch *et al*. (1974) recorded 31 to 49 m of "Foxmould" in west Dorset and Robbie *et al*. (1973) recorded 27 to 40 m of the same beds in the Crewkerne area. Wilson *et al*. (1954) divided the beds above the Foxmould in this region into Chert Beds, up to 10 m thick, overlain by glauconitic sands and sandstones capped by up to 3 m of calcarenite/calcareous sandstone. The Chert Beds are lithologically similar to the Whitecliff Chert and occupy the same stratigraphical position immediately above the correlative of the Culverhole Hardground at the top of the Foxmould (Text-fig. 5). The Chert Beds thin irregularly south eastwards, but are present in all the recorded sections between Crewkerne and Weymouth. Although poorly exposed, the presence of abundant cherts on a steep topographical feature above the Foxmould indicates that chert beds up to several meters thick are present at outcrop throughout this region.

Wilson *et al*. (1954) referred to all the beds between the highest chert and the base of the Chalk as the Eggardon Grit. At the type section at Eggardon Hill [SY 5341 9512] the top part of the Eggardon Grit crops out as small crags of sandstone/calcarenite at the top of the back scar of a series of landslides. Similar small crags in the highest part (Beds 3 and 4) of the Bindon Sandstone are locally present at the crest of steep slopes elsewhere in south and west Dorset and east Devon. Some later authors (e.g. Kennedy 1970; Woods *et al*. 2009) restricted the use of Eggardon Grit to the highest, crag-forming part of the succession. At most localities the lithologically distinctive "grit", a medium- and coarse-grained, sparsely glauconitic calcareous sandstone/calcarenite up to 3 m thick, is underlain by beds of pebbly/conglomeratic sandstone and glauconite-rich sandstone. In the current exposures at Warren Hill and Eggardon the latter rests on a burrowed and mineralised hardground close above the youngest cherts. The succession is similar to that at the junction of the Whitecliff Chert and Bindon Sandstone in the type area.

Few age-diagnostic fossils have been recorded from the Foxmould of the region. Wilson *et al*. (1958) recorded *Procallihoplites* aff. *auritus* (J. Sowerby) indicative of the lower part of the *Mortoniceras inflatum* Zone at several localities and *A. concentricus* from the "basal beds" of the Foxmould in a gully at Eggardon. There is no published record of fossils from the Chert Beds other than bivalves, gastropods and echinoids. The record of "*Pervinquieria* of the *stoliczkaia* type" by Spath (1926) from the "Chert Beds" near Charmouth, quoted in Wilson *et al*. (1958), almost certainly came from the cherts in the Bindon Sandstone (Gallois and Owen in press). *Stoliczkaia* cf. *dispar* (d'Orbigny), *Mortoniceras* (*Durnovarites*) cf. *subquadratum* (Spath), *Arrhaphoceras studeri* (Pictet and Campiche) and *Mariella bergeri* (Brongniart) indicative of the *perinflatum* Subzone of the *Stoliczkaia* spp. Zone have been recorded from quarries in the Eggardon Grit (Wilson *et al*. 1958). The highest part of the Eggardon Grit at Eggardon, in which Kennedy (1970) reported the apparent presence of indigenous

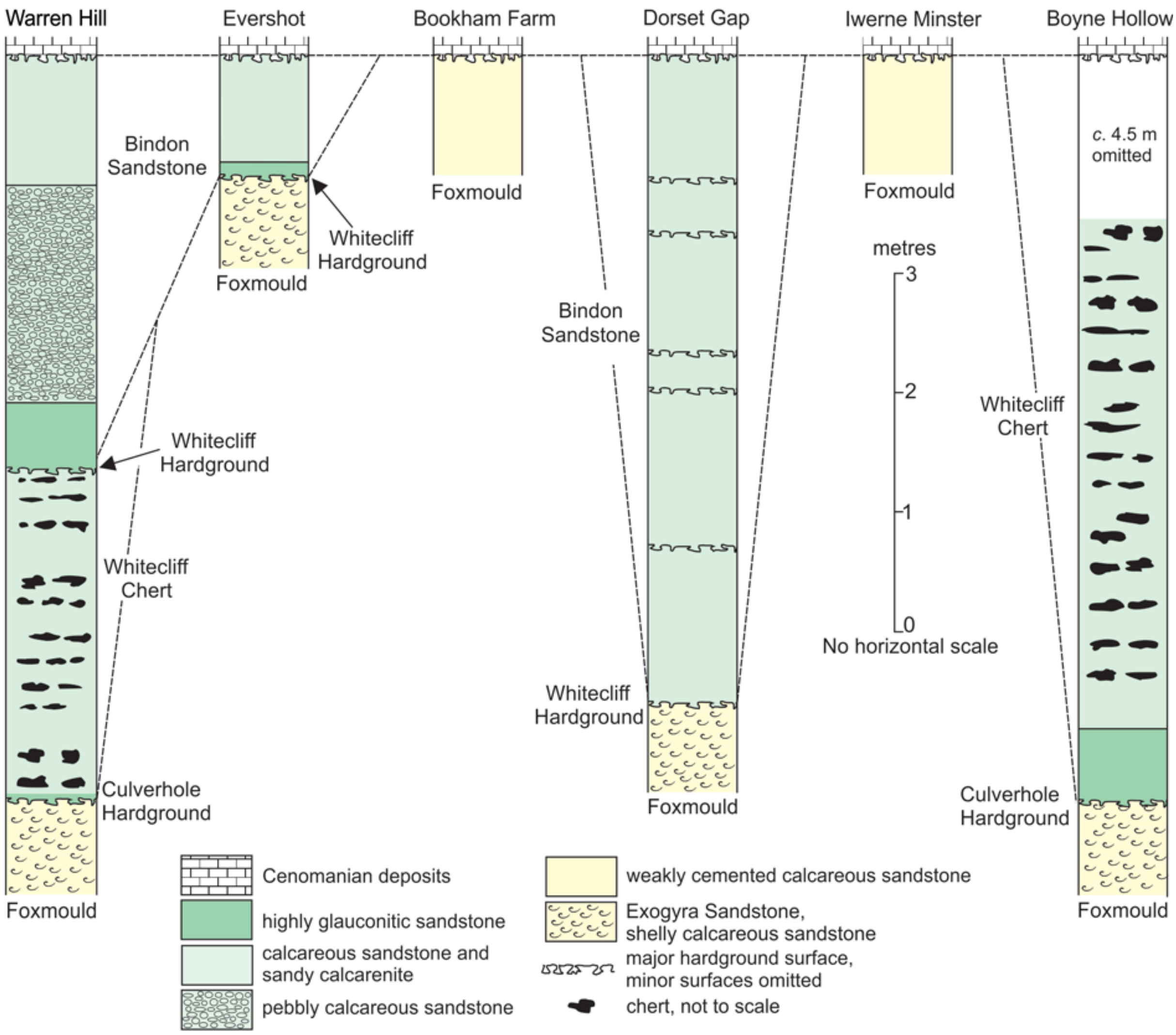


Text-fig. 5. Correlation of the upper part (Whitecliff Chert and Bindon Sandstone equivalents) of the Upper Greensand at outcrop in the Chard to Weymouth area

unphosphatised Cenomanian ammonites, was subsequently classified as the basal bed of the Chalk by Woods *et al.* (2009).

Crewkerne to Okeford Fitzpaine

The lower (Foxmould) part of the Upper Greensand succession in this area is similar in thickness and lithology to that throughout the Wessex Basin, but the upper part is markedly more attenuated. A section at Evershot [ST 578 050] (Kennedy 1970) shows up to 1 m of glauconitic sandstone between the Exogyra Sandstone and the base of the Chalk, while at Buckland Newton [ST 703 051] (Kennedy 1970), Bookham Farm [ST 707 042] (Smart 1955; Kennedy 1970; Bristow *et al.* 1995), Okeford Fitzpaine [ST 804 102] (Drummond 1970; Kennedy 1970), Stour Bank [ST 846 106] (Kennedy 1970) and Iwerne Minster [ST 864 147] (Bristow *et al.* 1995) the basement bed of the Chalk rests on the Foxmould. In contrast, a series



Text-fig. 6. Correlation of the upper part of the Upper Greensand at outcrop in the Crewkerne to Shaftesbury area

of overlapping trenches dug at Melcombe Bingham [ST 755 024] (this account) proved c. 5 m of deeply weathered calcareous sandstone with 5 hardgrounds between the top of the Exogyra Sandstone and the base of the Chalk (Text-fig. 6).

North Dorset

The Upper Greensand thickens rapidly northwards from Okeford Fitzpaine reaching up to 55 m thick in the area around Shaftesbury (Drummond 1970). Bristow *et al.* (1995) divided the Formation in that area into four members; in ascending order the Cann Sand, Shaftesbury Sandstone, Boyne Hollow Chert and Melbury Sandstone. Taken together, the Cann Sand and Shaftesbury Sandstone are the correlative of the Foxmould of Devon and south and west Dorset. The boundary between the two members is based on a mapped topographical feature in the Cann area: there is no type section for either member. Similar topographical features are present at more than one stratigraphical level in the Foxmould outcrop in Devon and west Dorset where they relate to laterally impersistent thin (mostly < 0.3 m thick) tabular beds of calcareous sandstone. The Cann Sand and the Shaftesbury Sandstone comprise fine-grained, weakly cemented glauconitic sandstones up to 60m thick in total. The succession is capped by a well-cemented glauconite-rich calcareous sandstone (Bristow *et al.* 1995). This was extensively worked in the Shaftesbury area as a distinctive dark green building stone until the late 19th century, but none of the former quarry faces are now exposed. The type section of the junction of the Shaftesbury Sandstone and the overlying Boyne Hollow Chert is in a former quarry at Boyne Hollow [ST 8737 2227], Shaftesbury which is lithologically closely similar to the succession at the junction of the Foxmould and the Whitecliff Chert exposed on the Devon coast and elsewhere. The section has not been exposed for many years but was measured by Jukes-Browne and Hill (1900, p. 159) who recorded the following section (simplified and metricated here with the Devon type section nomenclature applied):

	thickness [m]
Soil and rubble	0.46
Whitecliff Chert	
Glauconitic sand and silty sand with siliceous cherty and siliceo-phosphatic concretions	3.28
Fine greyish sandstone with cherty concretions and hard calcareo-siliceous concretions some of which have centres of blue-grey chert	2.29
Massive layer of blue-grey chert with thick whitish rind	0.30
Greenish grey glauconitic and very glauconitic sand with a few brown phosphates	0.99
Foxmould capped by Culverhole Hardground	
Hard glauconitic semi-crystalline sandstone called "Rag"; many fossils at top	0.91
Firm compact glauconitic sandstone with calcite cement	1.37
Soft greenish grey glauconitic sand	0.61

White (1923) referred to the Rag as Ragstone and the underlying sandstone, which Jukes-Browne and Hill (1900) noted was used for building purposes, as the Freestone. Note that the traditional use of the name Shaftesbury Sandstone for the building stone (mostly 1 to 3 m thick) differs from that on British Geological Survey (BGS) maps (up to 30 m of sand and sandstone in the upper part of the Foxmould). Drummond (1970) correlated the Ragstone with the Exogyra Sandstone of west Dorset. Above this the glauconitic sand with brown phosphates rests on a mineralised hardground, the correlative of the Culverhole Hardground of more westerly areas. The full thickness of the chert-bearing beds in the Shaftesbury area has been estimated, in the absence of exposures, to be up to 15 m thick (Bristow *et al.* (1995). White (1923) recorded 7.6 m of chert-bearing beds in the same area overlain by up to 4.6 m of glauconitic sandstone overlain by the basement bed of the Chalk. There are no other published descriptions or current exposures in this highest part of the Upper Greensand so it is not known whether or not it includes correlatives of the Bindon Sandstone or Eggardon Grit. Chert is not, in the absence of other evidence, useful as stratigraphical marker bed. In addition to that in the Whitecliff Chert and Bindon Sandstone in west Dorset, Tresise (1961) referred to some of the siliceously cemented beds in the Foxmould in the Blackdown Hills, Somerset as chert, and chert has been recorded in the Cann Sand of the Shaftesbury area (Bristow *et al.* 1995). In contrast to the cherts in east Devon and west Dorset, many of the cherts in the Shaftesbury area have a thick (several cm) white rind. Others are siliceously cemented sandstones, with and without a chert core, and are lithologically similar to the siliceously cemented beds in the Blackdown facies of the Foxmould.

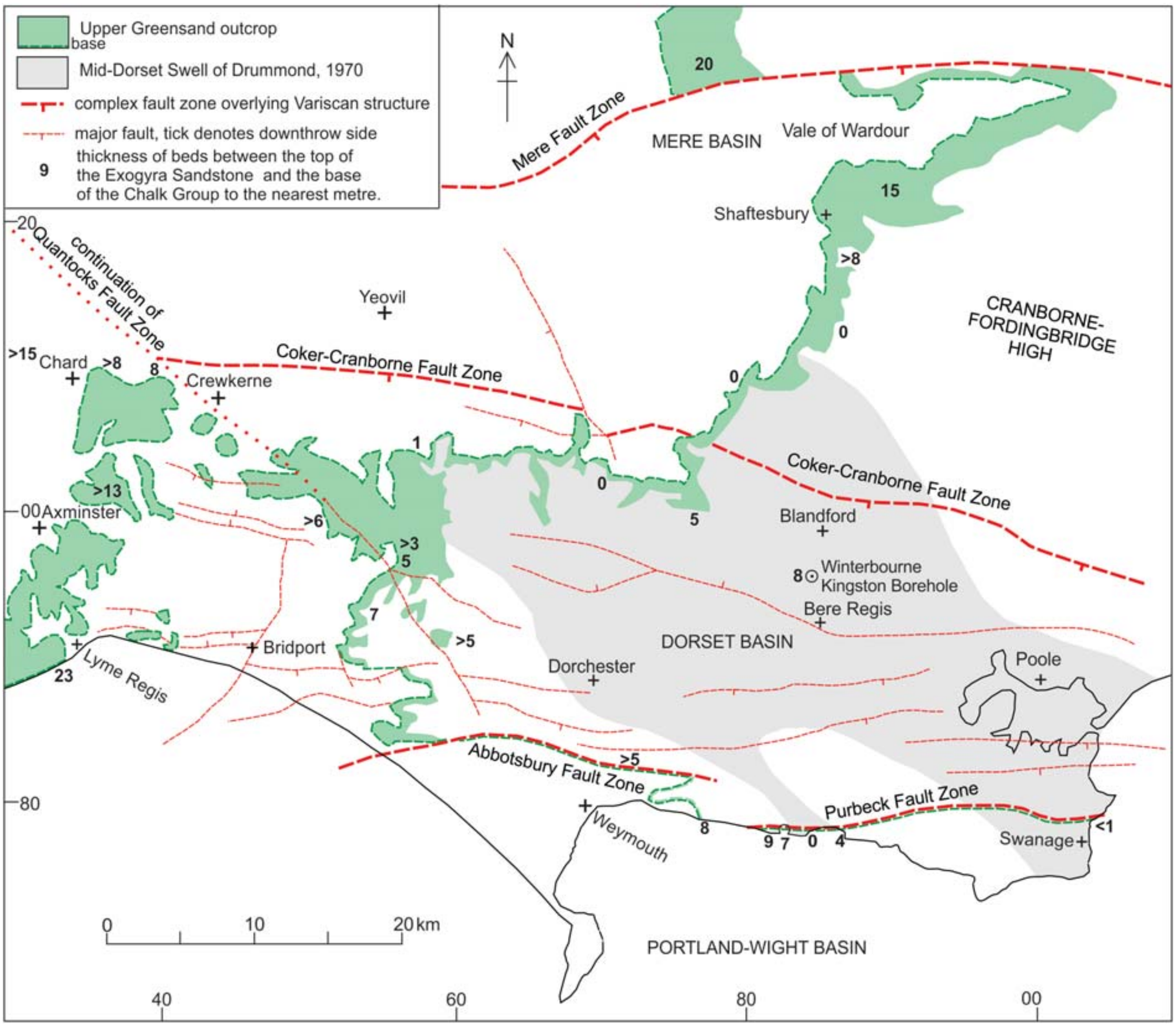
Jukes-Browne and Hill (1900) described a diverse bivalve fauna from old quarries in the Foxmould in the Shaftesbury area and these were added to by Bristow *et al.* (1995). The latter also recorded the ammonites *Mortoniceras* (*M.*) *cunningtoni*, *Anahoplites picteti* and *Idiohamites* sp., all indicative of the *binum* Subzone of the *varicosum* Zone, in loose sandstone debris in the same area. A specimen of *Goodhallites applanata* is thought to have come from the top of the Shaftesbury Sandstone, the correlative of the highest part of the Foxmould (Bristow *et al.* 1995).

A diverse assemblage of bivalves was recorded by Jukes-Browne and Hill (1900, p. 159) from the glauconitic sandstone with phosphates in the Boyne Hollow quarry. Farther east, at Fontmell Magna, the Foxmould passes into a fossiliferous sandy Gault facies; the Fontmell Magna Sands of *orbignyi* and *binum* Subzones age (Bristow and Owen 1991).

The Melbury Sandstone contains a derived, phosphatised Albian fauna and an indigenous early Cenomanian fauna including *Hyphoplites* spp. and *Mantelliceras* spp. (Kennedy 1970). It was interpreted by Mortimore *et al.* (2001) as a local, coarse basal bed of the Chalk Group and is not considered further here.

The Mid-Dorset Swell and structural considerations

The Upper Greensand in Wessex is largely covered by Chalk and younger formations and is mostly exposed only in the marginal areas where the Chalk has been eroded away. Within the outcrop, there are



Text-fig. 7. Geological sketch map of the western part of the Wessex Basin: fault pattern after Barton *et al*. (2011). See Text-fig. 4 for localities: Isle of Purbeck based on Gallois and Owen (2017)

indications that sedimentation was locally affected from time to time by the reactivation of tectonic structures. The locations and trends of these structures were formerly difficult to determine in the subcrop beneath the Chalk. Drummond (1970) postulated that the sedimentation of the Upper Greensand and Lower Chalk successions was interrupted by tectonic movements that resulted in erosion surfaces in late Albian and Cenomanian times throughout the Wessex region. The more important of these were phases of uplift in the late Albian *inflatum* Zone and in the Early and Middle Cenomanian. He identified a NW-SE trending area (1970, fig. 3) that ran from central Dorset to the Isle of Purbeck which he referred to as the Mid-Dorset Swell. The boundaries of this area were largely defined by comparing the attenuated Upper Greensand successions in the upper part of the Formation between the top of the Foxmould and the base of the Chalk between Evershot [ST 572 048] and Okeford Fitzpaine [ST 806 110] with those between Worbarrow Bay and Punfield Cove (Text-fig. 7).

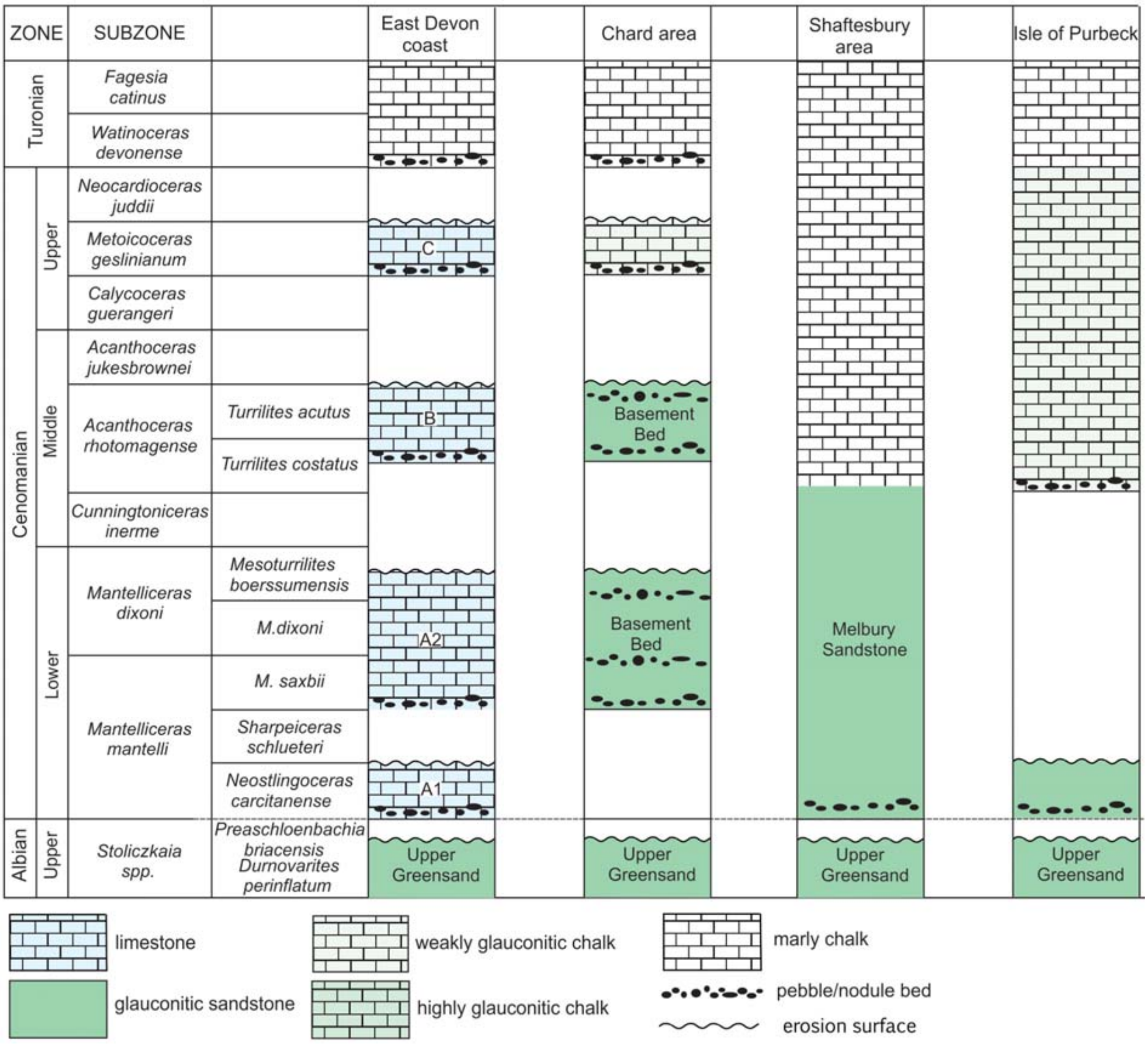
Bristow *et al*. (1995) interpreted the same southerly attenuation of the Upper Greensand in north Dorset as that used by Drummond (1970) to define the northern margin of the Mid-Dorset Swell, as the southern edge of an E-W trending Cranbourne-Fordingbridge structural high (Text-fig. 7). Since the research by Drummond (1970), deep boreholes and extensive seismic-reflection surveys studies carried out for hydrocarbon-exploration purposes have enabled much of the concealed tectonic structures that affected Upper Greensand sedimentation and erosion in the Wessex Basin to be identified (Chadwick and Evans 2005) (Text-fig. 7 herein). Throughout southern England, Caledonian and to a much greater extent Variscan faults in the Pre-Permian basement rocks were reactivated notably in the mid Cretaceous and at subsequent intervals until the Middle Pleistocene (Owen 2014). In the Upper Greensand, the effects of the re-activation were more pronounced in a westerly direction as the margin of the sedimentary basin adjacent to the Cornubian massif was approached.

With the possible exception of the partially cored Winterbourne Kingston Borehole [SY 8470 9796] (Morter 1981) there is no evidence in the subcrop between North Dorset and the Isle of Purbeck to determine the extent to which this part of the Upper Greensand is or is not attenuated.

Hart (1994) noted that Drummond's (1970) interpretation had subsequently been superseded by 3-D interpretations of the regional structure made possible by deep boreholes and seismic-reflection profiles (summarised by Chadwick and Evans 2005). He concluded that the lateral variations in the succession were such that they could not be satisfactorily explained by the Mid-Dorset Swell or by N-S extensional tectonics related to the reactivation of the E-W trending Variscan structures in the pre-Permian basement rocks. The most prominent structural features in the region are the complex Purbeck-Abbotsbury and Coker-Cranbourne fault zones. These, together with a south-easterly extension of the Quantocks fault zone suggested by Chadwick and Evans (2005) appear to have had a marked influence on the post-Foxmould Upper Greensand successions in the Wessex Basin. The thicker chert-beds successions are confined to the area west of the Quantocks Fault Zone, and the more attenuated successions are close to the other fault zones. The Purbeck-Abbotsbury Fault Zone marks the boundary between two different post-Foxmould successions. To the north, the Bincombe succession is similar to that at outcrop between there and Beaminster. To the south, the Isle of Purbeck successions between Osmington and Punfield Cove, Swanage can be closely matched with one another, but differ from that north of the fault zone. Superimposed on the regional pattern are marked local variations that appear to be related to local fault movements.

The lateral thickness variations in the successions between the erosion surface at the top of the Exogyra Sandstone, and that at the base of the Cenomanian can be explained by these intermittent penecontemporaneous fault movements in the latest Albian and early Cenomanian (Text-fig. 7). In the Isle of Purbeck, marked lateral variations in this part of the succession occur over distances of as little as a few hundred metres. They are well exposed in the cliffs where they have been interpreted as the result of intermittent movements on faults in the Purbeck Fault Zone (Garrison *et al.* 1987; House 1989; Gallois and Owen 2017).

Drummond (1970) showed that the earliest of the principal tectonic events that affect the Upper Greensand in the Wessex Basin occurred in the *inflatum* Zone where it is marked by the erosion surface at the top of the Exogyra Sandstone: the Culverhole Hardground in east Devon and the Dorset north of the Purbeck Fault Zone and the Durdle Door Hardground in the Isle of Purbeck. This interpretation is supported by the laterally persistent nature of the Foxmould in terms of lithology and thickness which is indicative of deposition in a tectonically quiescent period. This is further supported biostratigraphically by the apparent absence of later *auritus* Subzone and *rostratum* Subzone sediments throughout the region, sediments of these Subzones being preserved only north of the region in Wiltshire and Oxfordshire. In addition, Lott *et al.* (1980) noted from a study by heavy-mineral assemblages in cored boreholes in the English Channel between the Isle of Wight and the Western Approaches, that the Foxmould represented a distinctly different phase of sedimentation from that of the later part (now the Whitecliff Chert and Bindon Sandstone) of the Formation. The Foxmould assemblages indicate derivation from an Armorican source whereas those from the overlying beds indicate a Cornubian source following a period of tectonic uplift at the end of the *inflatum* Zone or in the early *Stoliczkaia* spp. Zone. Lateral variations in the thicknesses of the correlatives of the Whitecliff Chert and Bindon Sandstone agree with this interpretation. Drummond (1970) suggested that faulting was most active in the early Cenomanian. This is confirmed by the presence in the Buckland Newton-Dorsetshire Gap outcrop area of phosphatised latest Albian age ammonites present as clasts in sediments with indigenous Cenomanian ammonites. This indicates that sediments of the *perinflata* and *briacensis* Subzones were present formerly throughout the region. Lateral variations in the distribution of derived early Cenomanian phosphatised ammonites led Kennedy (1970) to conclude that the age of this derived material youngs from east to west with Cenomanian



Text-fig. 8. Comparison of the Cenomanian successions in selected parts of the Wessex Basin to illustrate variations in the preserved successions as a result of the reactivation of local faults

carcitanense and *saxbii* Subzone ammonites present in the east and *carcitanense* to *acutus* Subzone assemblages in the west.

More precise evidence now available indicates several regional erosion phases which affected the Upper Greensand and Cenomanian deposits in Wessex. (1) an early *Stoliczkaia* spp. Zone pre-*perinflata* Subzone event which removed sediments of late *auritus* and *rostratum* Subzone age: an event which also affected much of Weald area of S.E. England and East Anglia (Owen 2012). (2) a latest Albian–earliest Cenomanian event which produced the Bookham Conglomerate and other conglomerates at the base of the Cenomanian deposits throughout the region (Text-fig. 8) with their derived *Stoliczkaia* spp. Zone (*perinflata* and *briacensis* Subzones) faunas. This event was contemporaneous with the formation of the Cambridge Greensand Member in East Anglia (Gallois *et al.* 2016). (3) further erosion of these sediments occurred on at least two occasions in the Early to Middle Cenomanian as indicated by erosion surfaces and phosphatic pebble beds in the *mantelli* Zone in east Devon, and in the Beaminster-Chard and Isle of Purbeck areas where *rhotomagense* Zone sediments rest directly on an eroded Upper Greensand surface (Text-fig. 8).

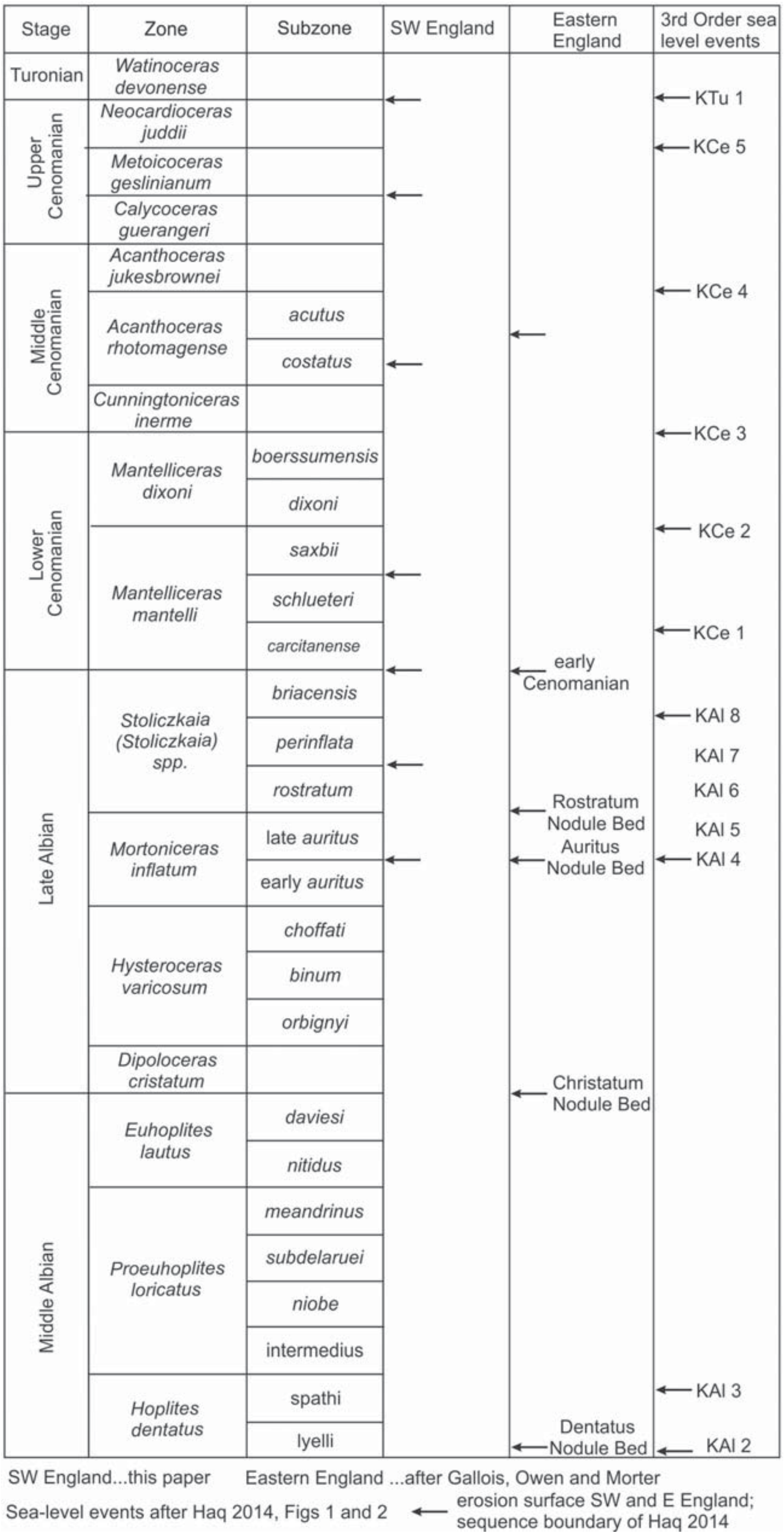
Sequence stratigraphy and sea-level changes

The transgression of Albian and Cenomanian deposits westwards across southern England onto progressively older rocks has been known since the 19th century. Subsequent accounts based on a more detailed knowledge of the biostratigraphy showed that the transgression was made up of a series of pulsed events that are represented by mineralised hardgound surfaces overlain by phosphatic nodule beds (e.g. Hancock 1969). The publication of the Exxon eustatic sea-level curve (Vail *et al.* 1977) and its correlation with the chronostratigraphical succession (Haq *et al.* 1988) led to attempts to correlate transgressive events (referred to as sequence boundaries) in the Albian and Cenomanian deposits of southern England succession with particular eustatic rises in sea level (Hart 1980; Hancock 1989; Hesselbo *et al.* 1990; Ruffell 1991). However, doubts were expressed about the validity of this type of correlation by Miall (1992) when he concluded that "the existence of a globally correlatable suite of third-order eustatic cycles, remains unproven" and that the correlation of local successions with the Exxon chart would almost always succeed because "there were so many Exxon sequence-boundary events from which to choose". There are also problems that arise from the difficulty of correlating the sea-level curves with radiometric dates and with chronostratigraphical and local biostratigraphical successions. In the case of the relatively shallow-water, near-shore Albian and Cenomanian sediments of southern England and northern France tectonic, palaeogeographical and probably climate factors make it unlikely that it will ever be possible to identify eustatic sea-level changes except in the broadest terms.

The long-term Cretaceous sea level curve shows a steady rise in global sea level in the Albian and Cenomanian culminating in a peak in the earliest Turonian when sea level was an estimated 250 m above present-day mean sea level. Superimposed on this long-term trend Haq (2014) recorded 8 Third Order Pulses and sequence boundaries in the Albian (KAl 1 to KAl 8) and 5 in the Cenomanian (KCe 1 to KCe 5). Comparison of these boundaries with the principal sedimentary breaks in the Gault and Upper Greensand and the Upper Greensand and Cenomanian deposits in Wessex and SW England (Text-fig. 9) shows few if any clear correlations. The principal sedimentary breaks in the Upper Greensand succession in the Wessex Basin and SW England occur at the top of the Foxmould (Culverhole Hardground), the top of the Whitecliff Chert (Whitecliff Hardground) and at the base of the Beer Head Limestone and its correlatives. The first of these, which separates Early *auritus* Subzone sediments from Late *auritus* Subzone sediments might be the correlative of KAl 4 or KAl 5. The correlation of the Haq (2014) curve with the European Albian succession used the zonal scheme of Amedro (2009) which is based on the successions in the Anglo-Paris and Mons Basins in NW Europe. The French succession is incomplete in comparison with that of southern England and this affects the ammonite zonation and the correlation of events used widely in the determination of sequences and erosional events. Thus, the dating of the Exxon curves with the boundaries, KAl 5 to KAl 7 are approximated here with the English succession. KCe 1 to KCe 5 have no obvious correlatives in either the Gault or the Upper Greensand.

SUMMARY AND CONCLUSIONS

The Upper Greensand in the Wessex Basin can be divided into several local successions, each of which is separated by a major fault zone (Text-fig. 7). Overall, the lithologies are more siliceous and indicative of shallower water, higher energy environments when traced westwards. The Haldon Hills and Bovey Basin successions (Text-fig. 1), adjacent to the Sticklepath Fault Zone, were deposited close to the western edge of the depositional basin and are condensed in comparison with those of more easterly areas. In east Devon, south Somerset and much of mid Dorset the Formation can be lithologically divided into two parts, the weakly cemented argillaceous sandstones of the Foxmould Member and the calcareous sandstones and sandy calcarenites of the Whitecliff Chert and Bindon Sandstone Members. The Foxmould retains its lithological character throughout the Wessex Basin with the exception of the lowest part in those more easterly areas where there is a transition via muddy sandstones and sandy mudstones into the underlying Gault. In contrast, the overlying beds exhibit marked lateral variations within what are interpreted here as fault-influenced regions. South of the Abbotsbury-Purbeck Fault Zone, in the Isle of Purbeck, the correlative of the Exogyra Sandstone at the top of the Foxmould is overlain by a succession of calcareous sandstones and sandy calcarenites with cherts that is lithologically different from that in any other part of the Wessex Basin. To the north of the fault zone and to the west of the presumed continuation of the Quantocks Fault Zone (Text-fig. 7) the successions in mid Dorset are similar to those in the Devon, west Dorset and the Somerset outliers. In contrast, east of the Quantocks Fault Zone



Text-fig. 9. Comparison of the principal sedimentary breaks in the Gault and Upper Greensand succession in England with the sequence stratigraphy and eustatic sea level events of Haq (2014) and close to the Coker-Cranbourne Fault Zone (Text-fig. 7) much of the succession above the Foxmould has been removed by erosion in the early and mid Cenomanian with the result that the Chalk locally rests of the Foxmould.

The preserved fauna of the Upper Greensand mostly comprises bivalves and gastropods and is stratigraphically unevenly distributed. Ammonites are relatively common at a few stratigraphically narrowly defined horizons where they are preserved in siliceous sandstones, as in the Blackdown Hills, or in phosphate as in the Isle of Purbeck. They are rare or unrecorded throughout much of the succession, and the great majority of those preserved in calcareous sandstone or chert in museum collections have been found loose. Nevertheless broad correlations can be made within the Wessex Basin although doubts remain about the age of parts of the succession, notably the Whitecliff Chert and the beds between Arkell's (1947) Ammonite Bed and the base of the Chalk in the White Nothe Member. The influence of penecontemporaneous faulting on the local successions is such that the principal sedimentary breaks (sequence boundaries) cannot confidently be correlated with the eustatic changes in sea-level recognised elsewhere in the Albian Stage.

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