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The stratigraphy of the Upper Greensand Formation (Albian, Cretaceous) of the Isle of Purbeck, Dorset, UK

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ABSTRACT:

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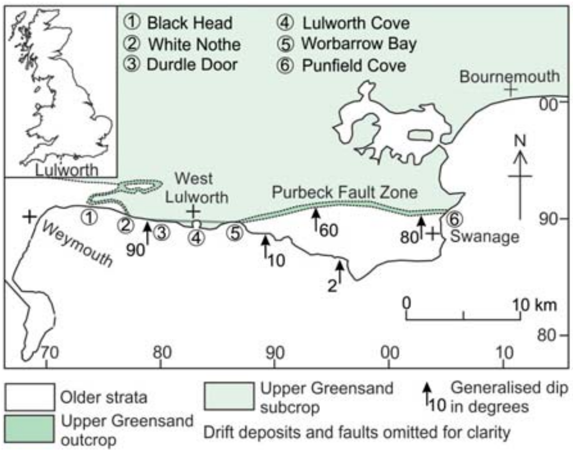
At its maximum development in the type area on the Devon coast, the Upper Greensand Formation comprises up to 55 m of sandstones and calcarenites with laterally and stratigraphically variable amounts of carbonate cement, glauconite and chert that were deposited in fully marine, shallow-water environments. The formation is divided into three members, in ascending order the Foxmould, Whitecliff Chert and Bindon Sandstone, each of which is bounded by a prominent erosion surface that can be recognised throughout the western part of the Wessex Basin. The full thickness of the formation, up to 60 m, was formerly well exposed in cliffs in the Isle of Purbeck in the steeply dipping limb of the Purbeck Monocline. The upper part of the succession is highly condensed in comparison with the Devon succession and exhibits lateral variations over distances of hundreds of metres that are probably related to penecontemporaneous fault movements. Much of the fauna is not age-diagnostic with the result that the ages of parts of the succession are still poorly known. However, the Isle of Purbeck sections contain diverse ammonite faunas at a few stratigraphically well-defined levels that enable the succession to be correlated with that of east Devon and west Dorset.

Key words: Upper Greensand Formation; Dorset; Isle of Purbeck; Cretaceous; Albian Stage; Stratigraphy; Palaeontology; Ammonites.

INTRODUCTION

The Upper Greensand Formation has extensive outcrops on the Devon and Dorset coasts between Sidmouth and Swanage where it comprises sandstones and calcarenites with laterally and stratigraphically variable amounts of carbonate cement, glauconite and chert that were deposited in fully marine, shallow-water environments. The sedimentology and palaeontology indicate deposition on a marine-shelf that was at times subject to strong tidal and wave-generated currents. The preserved fauna is unevenly distributed, both laterally and stratigraphically. It is dominated by bivalves, gastropods, echinoderms, brachiopods and serpulids, few of which are age-diagnostic. Except for the Ammonite Bed (Wright in Arkell 1947) near the top of the formation in the Isle of Purbeck, ammonites and other age-diagnostic fossils are rare at most stratigraphical levels, and much of the material in museum collections was found loose. However, there is sufficient ammonite and age-significant bivalve material to provide a biostratigraphical framework.

The formation was referred to as the “Greensand” by William Smith (1815), lying between the “Blue Marl” (Gault) and “Chalk”, and was included in the “Green sand formation” by Webster (1825) when it became apparent that the Gault was locally underlain and overlain by “greensands”. The name Upper



Text-fig. 1. Geological sketch map of the Upper Greensand outcrop in the Isle of Purbeck

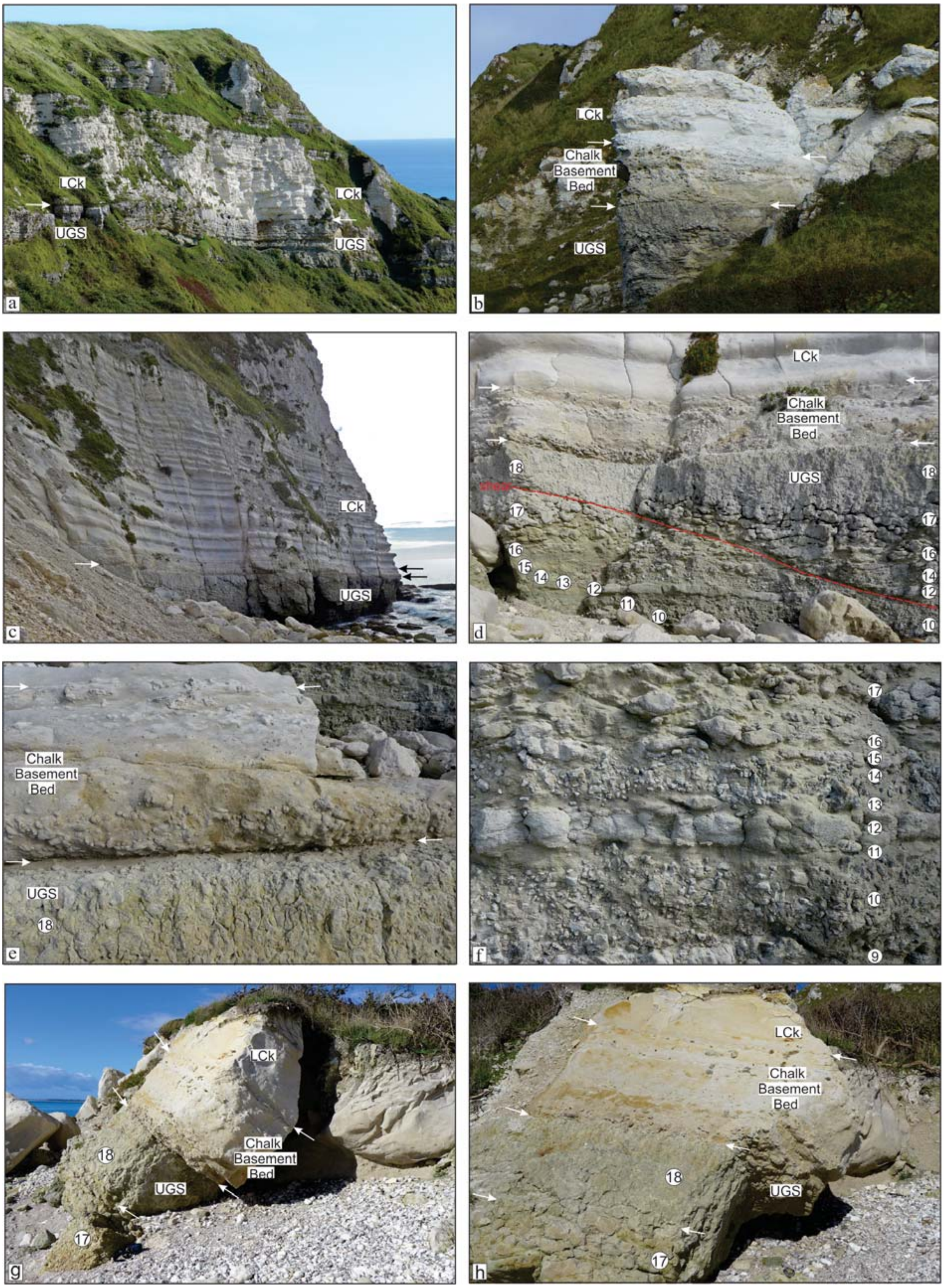
Greensand was formally adopted by the Geological Survey in 1839 (De la Beche 1846). De la Beche (1826) recognised three informal divisions in the coastal outcrops in East Devon, in ascending order the Cowstone Beds (glauconitic sandstones with ovoid calcareous concretions), Foxmould (glauconitic sandstones) and Chert Beds (glauconitic calcareous sandstones and calcarenites with cherts). Jukes-Browne and Hill (1900) used a similar nomenclature in their description of the same sections (Table 1). The Upper Greensand is also well exposed in the coastal cliffs adjacent to the Purbeck Fault Zone between White Nothe and Swanage, south Dorset (Text-fig. 1), c. 35 km ESE of the nearest west Dorset sections. Jukes-Browne and Hill (1900) divided the succession there into a lower Zone of *Ammonites rostratus* (c. 25 to 30 m thick between Worbarrow Bay and White Nothe) and an upper Zone of *Pecten asper* (c. 6 to 8 m thick) which they correlated with the Foxmould and Chert Beds respectively (1900, fig. 57).

Subsequent research showed that the ovoid calcareous concretions were not confined to the lowest part of the formation and that the "Cowstones" passed laterally into tabular cementstones and siliceous beds when traced westwards from Lyme Regis. The Cowstones and Foxmould of De la Beche were therefore included in the Foxmould Member in a revision of the stratigraphy of the formation (Gallois 2004). The distribution of the cherts in the Chert Beds was also shown to be laterally and vertically variable and not a useful criterion for defining the lithostratigraphy. However, the presence of prominent erosion surfaces marked by mineralised hardgrounds at the base of De la Beche's Chert Beds and in the upper part of the division enabled the formation to be divided into three members (Foxmould, Whitecliff Chert and Bindon Sandstone) that can be recognised throughout the region (Gallois 2004). The name Foxmould Member is applicable to the lower part of the Upper Greensand Formation in the Isle of Purbeck, but the succession above this is highly condensed with up to 8 major erosion surfaces that represent sedimentary breaks of unknown duration. It is sufficiently lithologically different from the successions elsewhere in the Wessex Basin for a new name, White Nothe Member, to be proposed here (see below).

East Devon			Isle of Purbeck	
De la Beche, 1826	Jukes-Browne and Hill, 1900	Gallois, 2004	Jukes-Browne and Hill, 1900	This account
Chert Beds	Chert Beds	Bindon Sandstone Mbr	Zone of *Pecten asper*, greensand, stone and chert	White Nothe Mbr
		Whitecliff Chert Mbr		
Foxmould	Foxmould Sands, sands with layers of stone	Foxmould Mbr	Zone of *Ammonites rostratus*, sands with layers of stone	Foxmould Mbr
Cowstone Beds				

Table 1. Comparison of the historical and current nomenclature of the Upper Greensand Formation exposed on the Devon-Dorset coast. Mbr. – Member

Text-fig. 2. Sections in the upper part of the Upper Greensand Formation (White Nothe Member) and the lower part of the Chalk Group.at and adjacent to White Nothe. a – *In situ* cliffs in the landslide backscarp above the Undercliffs Landslide; b – Detached block within the landslide; c – *In situ* sea cliff below White Nothe; d – Youngest part of the Upper Greensand and the basal beds of the Chalk in the sea cliff below White Nothe; e – Detail of the irregular highly bioturbated, mineralised nature of the junction of the Upper Greensand and Chalk in the sea cliff; f – Detail of the irregular interburrowed and erosional nature of the boundaries between Upper Greensand Beds 9 to 18 in the sea cliff. See text for details; g – Detached block on the beach below the landslide; h – Detail of the junction of the Upper Greensand and Chalk in the detached block. UGS – Upper Greensand Formation; LCk – Lower Chalk, Zig – Zag Chalk Formation in current nomenclature; arrows indicate major sedimentary breaks (hardgrounds) →


LCk
UGS
LCk
UGS
a
LCk
Chalk Basement Bed
UGS
b
LCk
UGS
c
LCk
Chalk Basement Bed
UGS
18
17
16
15
14
13
12
11
10
d
Chalk Basement Bed
UGS
18
e
17
16
15
14
13
12
11
10
9
f
LCk
Chalk Basement Bed
UGS
18
17
g
LCk
Chalk Basement Bed
18
UGS
17
h

Most of the early researchers (see Arkell 1947 for summary) who worked on the Upper Greensand Formation concentrated on the biostratigraphy of the sections with little emphasis on the sedimentology and the sedimentary breaks in the succession. The aim of the present study is to describe the lithostratigraphy and biostratigraphy of the key sections in order to correlate the Isle of Purbeck succession with that of the east Devon type area. The cliff sections at Worbarrow Bay lie within the Ministry of Defence Lulworth Gunnery Range. Those at beach level can be accessed during most weekends and public holidays: see https://www.gov.uk/government/publications/lulworth-firing-notice for details.

LOCALITIES

Between Black Head and White Nothe, almost horizontal Cretaceous rocks rest with marked unconformity on faulted and steeply dipping Kimmeridge Clay Formation and Portland Group. The lowest part of the Albian (Gault Formation) succession comprises montmorillonite-rich sandy mudstones that are prone to landslide failure. As a result the Gault and much of the lower, less lithified part of the Upper Greensand, the Foxmould, have collapsed and are poorly exposed.

Black Head to Osmington Mills

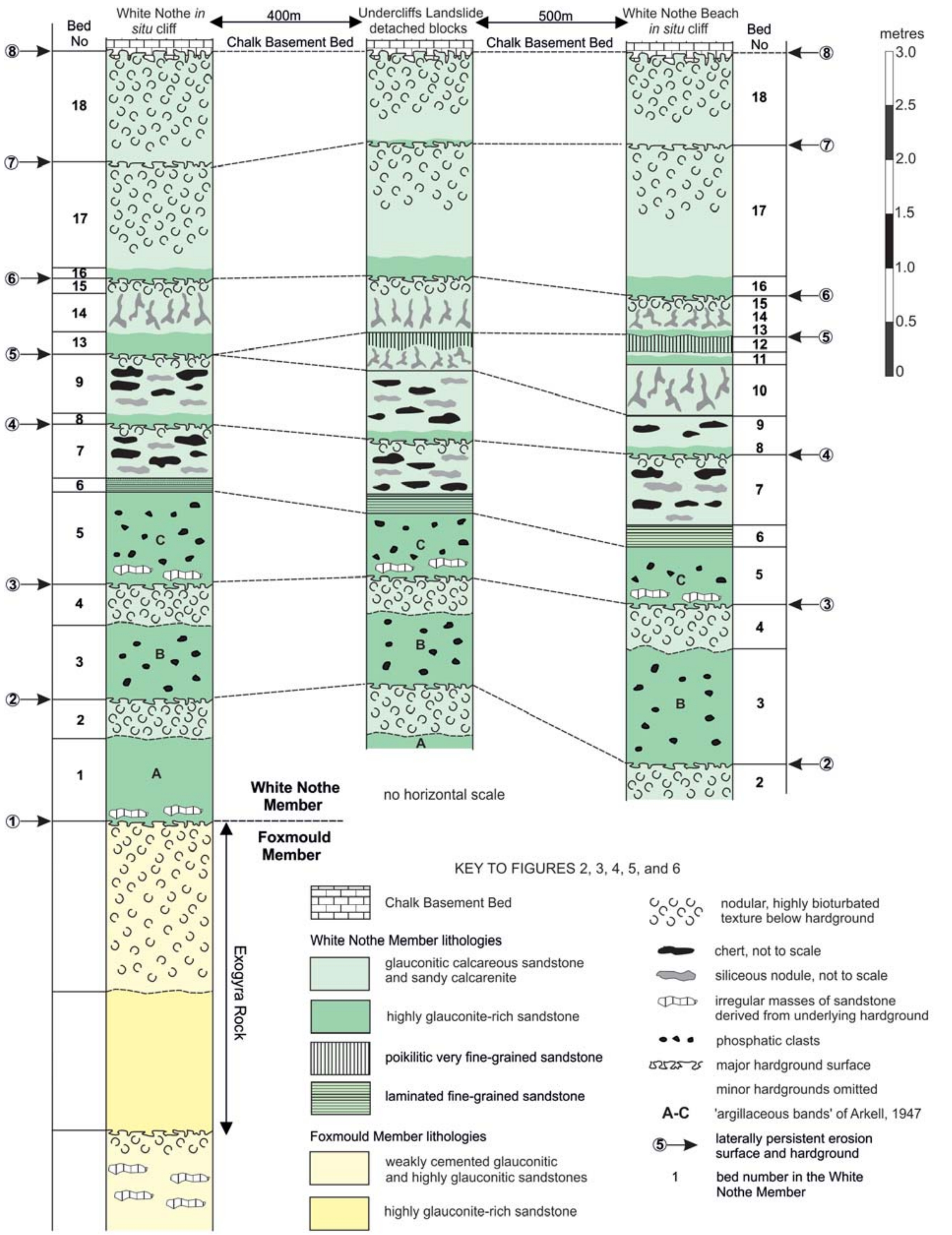
Strahan (1898) and Wright in Arkell (1947) noted that the whole of the Gault and Upper Greensand, comprising clays, sandy clay and sands with stone bands, was represented in the landslides between Black Head [SY 726 821] and Osmington Mills [SY 734 819]. The highest part of the formation, which contains strong calcareous sandstones and calcarenites, was formerly partially exposed *in situ* in the landslide back scarps and as loose blocks in the landslide debris. The sections are no longer visible except for small exposures of deeply weathered sandstone and calcarenite in a low cliff below Goggins Barrow [SY 733 818]. Even during Wright's time, the sections were incomplete and much of the fauna recorded was collected from loose blocks in the landslide. All the material collected from these sections is referred to in this account as Osmington.

White Nothe

An almost complete section through the Gault and Upper Greensand was measured by Strahan (1898) in the cliffs and lower slopes between Holworth House [SY 7670 8142] and White Nothe [7672 8135]. This comprised 12.5 m of Gault (sandy clays and clayey sands), 30.0 m of Foxmould (greensands with stone beds) and 6.1 m of Chert Beds (greensands and sandstones with cherts). Parts of the succession are exposed from time to time in the landslide debris, but the only permanent exposures are those in the cliffs in the highest part of the Foxmould and the Chert Beds (White Nothe Member of the present account). These are the most complete and tectonically undisturbed sections in the upper part of the Upper Greensand in the Isle of Purbeck. There, the whole of the upper part of the formation and the junction with the Chalk Group is exposed *in situ* in clean, air-weathered sections (Text-fig. 2a). Much of the same stratigraphical range of beds is also exposed *in situ* at beach level [SY 7712 8065] at the foot of White Nothe (Text-fig. 2b). In addition to the *in situ* exposures there are large detached blocks in the landslide (Text-fig. 2c) and on the beach [SY 7680 8085] (Text-fig. 2d). Many of these have broken off at weak, highly glauconitic sandstone beds in the upper part of the formation and at a bed of argillaceous chalk c. 1 m above the top of the Upper Greensand. They expose clean, unweathered sections in which the sedimentology of the highest part of the Upper Greensand and the junction with the Chalk can be examined in detail. Representative sections in the *in situ* outcrops and the detached blocks are shown in Text-fig. 3 in which Arkell's (1947) Exogyra Rock and "argillaceous beds" A to C, highly glauconitic sandstones (up to 50% glauconite) that preferentially weather out as slots in the cliffs, form laterally persistent marker beds.

Durdle Door to St Oswald's Bay

The full thickness of the Upper Greensand has been exposed from time to time in the cliffs on the west [SY 8052 8030] and east (Man O'War Cove) [SY 8069 8030] sides of the ridge that leads to Durdle Door where the dip in the Upper Greensand increases northwards from c. 40º to vertical. The lower, less lithified part of the succession including the junction with the Gault is tectonically sheared, deeply weathered and mostly poorly exposed. Strahan (1898) recorded 6.7 m of "Gault" overlain by 25.6 m of "greensand" here. The more lithified upper part of the formation is also sheared and is probably reduced in thickness, but is otherwise well exposed. The succession, which comprises alternations of calcarenites and highly glauconitic sandstones separated by hardgrounds, as at White Nothe, is summarised in Text-fig. 4. The Exogyra Rock,



Text-fig. 3. Representative sections in the White Nothe Member at White Nothe. The distances between the sections are based on the assumption that the landslide blocks came from the *in situ* cliff directly above their present position

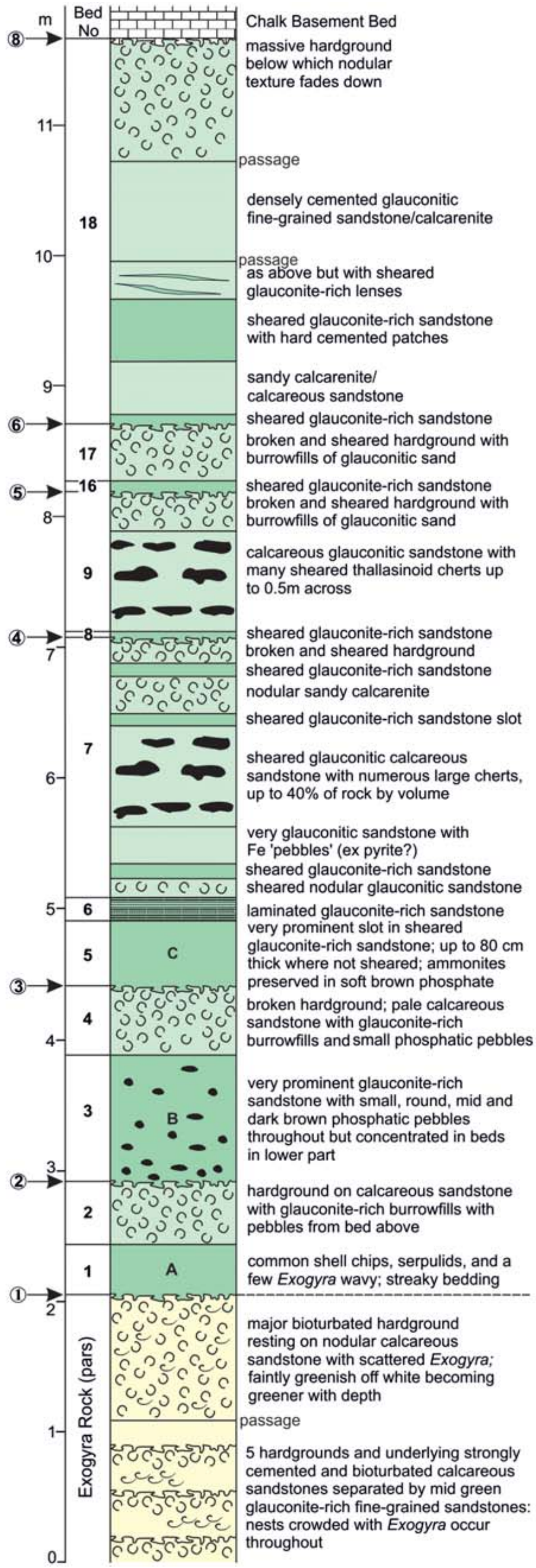
Arkell's (1947) beds A to C, and all except one of the eight hardground surfaces can be recognised in both sections (Text-fig. 5a, b). The highest part of the White Nothe Member and the junction with the Chalk is well exposed [SY 8145 8001] in St Oswald's Bay in the vertical limb of the monocline (Text-fig. 5d). Parts of the rest of the formation are poorly exposed in discontinuous sheared sections and displaced masses in landslide debris.

Lulworth Cove

The full thickness of the Upper Greensand was formerly exposed on the west side of Lulworth Cove [SY 8249 7998] where the dip of the formation increases northwards from 30º to >80º. Jukes-Browne and Hill (1900) summarised an earlier account by Barrois (1876) as 4.6 m of Gault (sandy clay), 23.5 m of Foxmould (sandstone, calcareous sandstone and greensand), and of 6.4 m Chert Beds (greensand and calcareous sandstone with cherts). The Gault and the junction with the Foxmould are now hidden beneath waterfront structures, but up 10 m of the Foxmould is well exposed, albeit deeply weathered (Text-fig. 5e). The whole of the White Nothe Member was exposed at beach level until 2013 when the lower part was covered by a landslide (Text-fig. 5f). The succession between the Exogyra Rock and the Chalk Basement Bed of Kennedy (1970), the White Nothe Member of this account, was described by Garrison *et al.* (1987, fig. 9). The correlation of the Lulworth succession with that exposed in St Oswald's Bay is shown in Text-fig. 6. Parts of the Foxmould and some of the harder beds in the highest part of the formation have been exposed from time to time on the NE side of Lulworth Cove [SY 8277 7999] in beds that are vertical to overturned. The junction with the Chalk is cut out by a bedding-parallel fault.

Worbarrow Bay

Large parts of the Upper Greensand are exposed in deeply weathered sections in the highest part of the cliff [SY 8659 8045] beneath Flower's Barrow on the east side of Worbarrow Bay (Text-fig. 7a, b) and in the landslides southwards from there. As elsewhere, the beds attributed by Strahan (1898) to the Gault comprise sandy clays and clayey sands. Parts of the Foxmould are moderately well exposed *in situ* and in slipped masses in the landslides. It comprises

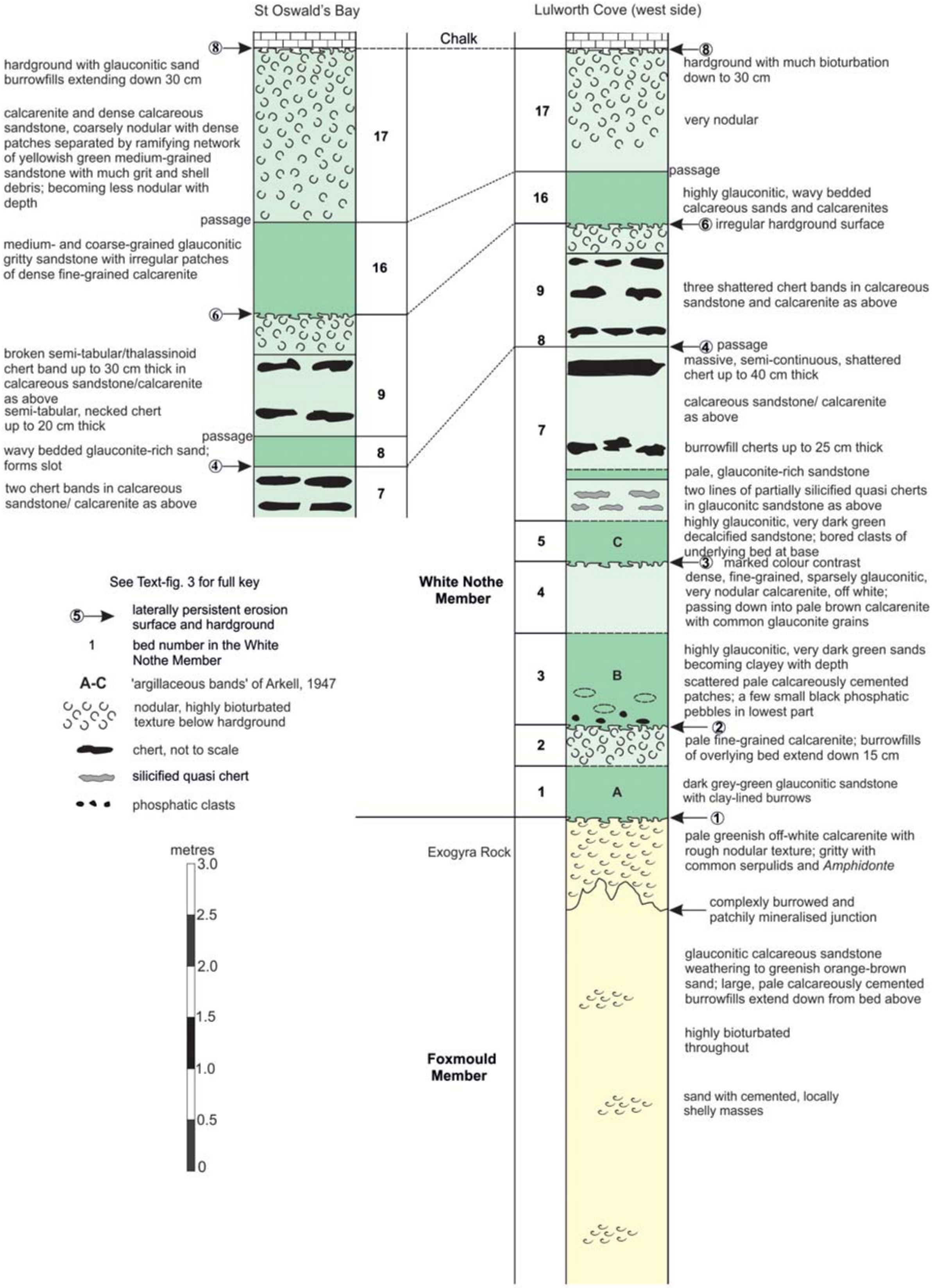


Text-fig. 4. Generalised vertical section for the White Nothe Member exposed at Durdle Door

Text-fig. 5. a – Junction of the Upper Greensand and Chalk in the vertical limb of the monocline at Durdle Door; b – Detail of the highest part of the Foxmould Member and the lower part of the White Nothe Member at Durdle Door; c – View west from St Oswald's Bay towards Durdle Door of the Upper Jurassic and Cretaceous succession exposed in the steeply dipping limb of the monocline at Man O War Cove; d – Junction of the Upper Greensand and Chalk at St Oswald's Bay; e – Junction of the Foxmould Member and the White Nothe Member on the west side of Lulworth Cove; f – Junction of the Upper Greensand and Chalk on the west side of Lulworth Cove

fine- and very-fine grained glauconitic sands with ovoid calcareous doggers and tabular calcareously cemented beds at several levels.

The White Nothe Member consists of interbedded calcareous sandstones, sandy calcarenites and glauconite-rich sandstones as at White Nothe and Durdle Door, but with the notable absence of beds with cherts. All the more durable beds in the succession, including the junction of the Upper Greensand and Chalk, can be examined in fallen blocks on the



Text-fig. 6. Correlation of the successions exposed in the White Nothe Member at St Oswald's Bay and on the west side of Lulworth Cove beach (Text-fig. 7c, d). The succession is laterally variable over short distances largely due to erosion at the base of the Chalk Basement Bed (Text-fig. 8). The more southerly of the fallen blocks on the beach [SY 8032 to 8646] shows the highest bed of the White Nothe Member to be a massive, dense, highly bioturbated calcarenite capped by an intensely mineralized hardground surface (Text-fig. 7c) that is lithologically closely similar to the highest bed exposed in the *in situ* cliff below Flowers Barrow. In contrast, the most northerly blocks at Cow Corner [SY 8630 8028] (Text-fig. 7d) show the Chalk Basement Bed resting on the Exogyra Rock. Garrison *et al*. (1987, fig. 10) recorded the Upper Greensand-Chalk Basement Bed junction below Flower's Barrow and the section at Cow Corner in which the Chalk Basement Bed rests on the Exogyra Rock. They concluded that intra-Cretaceous erosion related to syn-sedimentary faulting had exposed the Exogyra Rock on the sea floor. The presence of the Chalk Basement Bed resting directly on Foxmould below the level of the Exogyra Rock in Mupe Bay (see below) supports this conclusion. The unusual section described by Strahan (1901) at Mupe Bay [SY 8468 8009] on the NW side of Worbarrow Bay, in which the White Nothe Member is cut out by an erosion surface and the Chalk Basement Bed rests on the Foxmould, was obscured by landslide debris at the time of Arkell (1947), but has been well exposed in recent years (Text-fig. 7e, f).

Punfield Cove

Much of the Gault and Foxmould overlain by a thin correlative of the lower part of the White Nothe Member were formerly exposed in discontinuous outcrops at the foot of the cliffs at Punfield Cove [SZ 0428 8114 to 0438 8116] in Swanage Bay. Strahan's (1898) section was interpreted by Jukes-Browne and Hill (1900) as Gault (27.8 m), Foxmould (16.8 m) and Chert Beds (3.0m). The highest part of the Foxmould and a highly condensed representative of the White Nothe Member are still well exposed *in situ* and in fallen blocks (Text-fig. 7g, h). The member comprises 0.4 to 0.5 m of highly bioturbated, calcareous glauconitic sandstones and sandy calcarenites bounded by complexly mineralised hardgrounds (Garrison *et al*, 1987, fig. 11) at the top of the Exogyra Rock and the base of the Chalk. Correlation of this part of the succession at Punfield Cove with those farther west is summarised in Text-fig. 9. The correlations shown are broadly similar to those of Cater and Hart (1977) and Garrison *et al*. (1987).

LITHOSTRATIGRAPHY

The base of the Upper Greensand and the junction with the underlying Gault has never been satisfactorily defined or described on the Devon-Dorset coast, except those described by Lang (1914) at Charmouth, for two principal reasons. First, the scarcity of *in situ* sections due to the presence of almost continuous landslides that formed along shear planes in the lower part of the Gault, and second because of the transitional nature of the boundary. None of the exposures in the Gault-Upper Greensand boundary beds described in earlier publications (e.g. Strahan 1898; Jukes-Browne and Hill 1903; Wright in Arkell 1947) are now visible, largely due to a much increased vegetation cover. Wright noted that the sections were poorer in his time than when Strahan saw them. In those sections in the Isle of Purbeck where the junction of the Gault and Upper Greensand boundary crops out close to the vertical limb of the Purbeck Monocline much of the succession is cut out by bedding-plane faults. An additional complication is that prior to the formalisation of stratigraphical nomenclature, the name Gault was commonly used in a biostratigraphical sense with the result that clayey sands with Middle Albian ammonites were referred to as Gault (e.g. Wright in Arkell 1947). Much of the upper parts of the successions attributed by Strahan (1898) to the Gault comprise sands and can best be described as transition beds in a succession that coarsens upwards over a thickness of tens of metres.

The lower part of the Upper Greensand *sensu stricto* in the Isle of Purbeck comprises up to 50 m of relatively poorly exposed, weakly calcareously cemented, fine-grained glauconitic sandstones with beds of calcareously cemented tabular beds and ovoid cementstones at several levels. The lithologies closely match the Foxmould of Devon as noted by Jukes-Browne and Hill (1900, fig. 57) who correlated the Foxmould with the "Zone of *Ammonites rostratus*" and "sands with layers of stone" in the Isle of Purbeck. They correlated the Chert Beds of Devon with "Sands with *Pecten asper*" in the Isle of Purbeck. This part of the succession includes strong calcareous sandstones and sandy calcarenites is the only part of the formation that is well exposed. The cliffs at and adjacent to White Nothe provide the best exposures in this youngest part of the Upper Greensand in the Isle of Purbeck. In addition, the beds are almost horizontal and tectonically undisturbed, in contrast to all the other sections. The lithological boundaries in the more steeply dipping (<45º) sections are commonly sheared and make it difficult to differentiate between


Head deposits
WN
Chalk
WN fallen blocks
Foxmould
cemented bed
a
Viewpoint for 8a
Chalk
WN
WN
fallen blocks
Foxmould
cemented bed
Head deposits
Foxmould
b
1.70 m
Chalk Basement Bed
Upper Greensand
c
Chalk Basement Bed
Exogyra Rock
d
Chalk Basement Bed
Foxmould
e
Lower Chalk
Chalk Basement Bed
Foxmould
f
Lower Chalk
Chalk Basement Bed
1-5
Exogyra Rock
g
Chalk Basement Bed
1-5
Exogyra Rock
h

a sharp lithological transition and an erosion surface marked by a hardground.

The White Nothe composite succession based largely on the *in situ* cliffs is shown below. All the sandstones are fine grained and glauconitic except where described otherwise. When fresh, colours range from dark green in the most glauconitic argillaceous sandstones to faintly green-tinged off-white in the more strongly cemented calcarenites.

White Nothe composite section

The thicknesses are based largely on the *in situ* sea cliff [SY 7712 8065] below White Nothe. The bed thicknesses are laterally highly variable between the western end of White Nothe Cliff and White Nothe sea cliff, but the hardground surfaces and lithological marker beds are present throughout. Some of the hardground surfaces are locally tectonically sheared out over distances of up to a few metres. The succession is as follows.

Chalk Group Thickness (cm)

Chalk Basement Bed (Chloritic Marl of authors). Sandstone, fine-grained calcareous glauconitic with small brown and black phosphatic clasts including hoplitid ammonites; passing laterally into glauconitic sandy chalks with scour hollows; cobbles of dense calcareous sandstone derived from the underlying hardground set in a partially re-sedimented matrix; *Holaster, Mantelliceras, Schloenbachia* and bivalves locally common; resting on an irregular phosphatised and glauconitised hardground surface that marks a major sedimentary break 50

Upper Greensand Formation, White Nothe Member

Bed 18. Sandy calcarenites and calcareous sandstone; densely cemented becoming less so with depth; coarsely nodular which complex network of glauconitic sandstone burrowfills descending from bed above; passing it down irregularly into 70 to 90

Bed 17. Sandstone, fine-grained, calcareous, glauconitic; sparsely nodular, passing down by the addition of glauconite into 130 to 150

Bed 16. Sandstone, fine-grained, glauconite-rich, weakly calcareous with broken and comminuted shells (shell grit), resting on irregular hardground surface 5 to 15

Bed 15. Sandstone, fine grained, glauconitic, densely calcareously cemented with glauconitic sand-filled burrows descending from bed above; passing down irregularly into 30 to 35

Bed 14. Sandstone, fine-grained, calcareous, glauconitic cut by ramifying network of off-white weathering silicified tubular and thalassinoid burrows; passing down by addition of glauconite into 20 to 30

Bed 13. Sandstone, fine-grained, glauconite-rich; sharp, gently undulating contact with bed below 5 to 10

Bed 12. Sandy calcarenite, very fine-grained with poikilitic cement; off-white, densely cemented; tabular bed with undulating lower and upper boundaries 5 to 20

Bed 11. Sandstone, fine-grained, glauconite-rich 20 to 25

Bed 10. Sandstone, fine-grained, calcareous, glauconitic cut by ramifying network of off-white weathering silicified tubular and thalassinoid burrows; locally with very glauconite-rich basal bed up to 5 cm thick 45

Bed 9. Irregularly interbedded calcareously cemented, glauconite-rich sandstones and lenticular cherts up to 120 cm long and 150 cm thick including thalassinoid burrow infillings 35 to 45

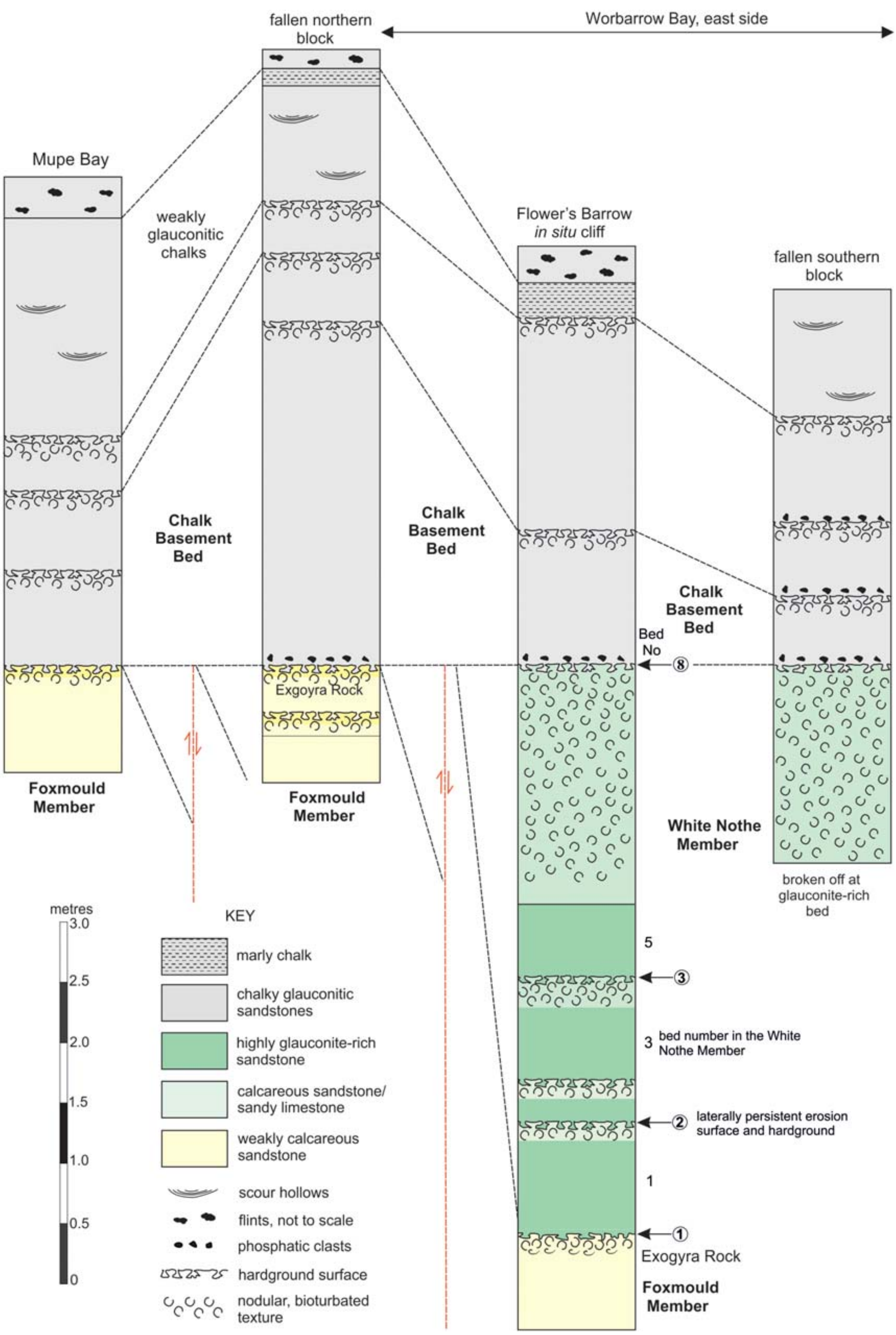
Bed 8. Sandstone, fine grained, argillaceous, glauconite-rich with wavy lamination; siliceous burrowfills; rests on a hardground surface 10 to 20

Bed 7. Complexly bioturbated nodular calcarenites and densely cemented calcareous sandstones with small and large cherts and siliceous concretions; laterally highly variable 50 to 60

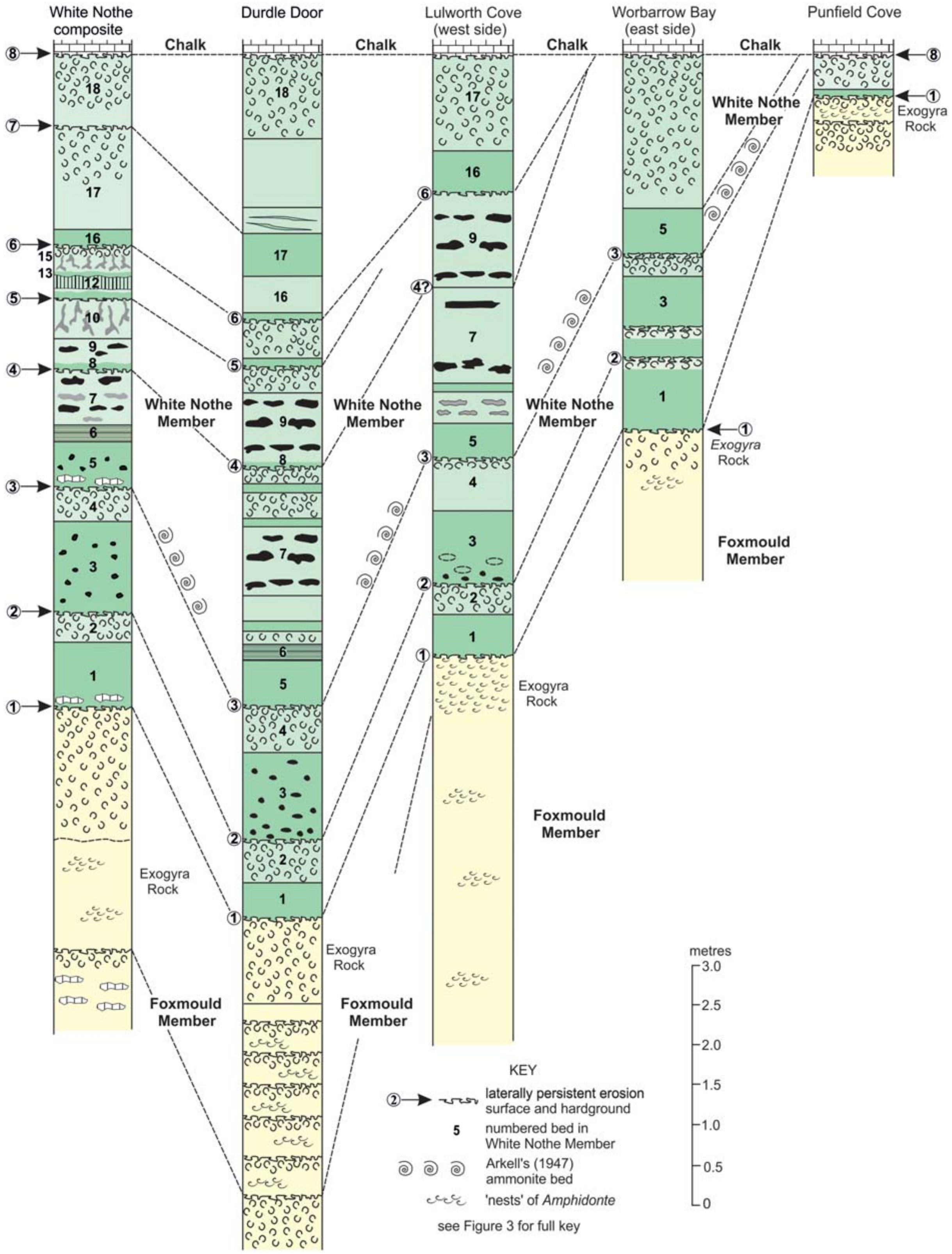
Bed 6. Sandstone, mid green argillaceous, highly glauconitic; distinctive planar and wavy lamination; a few small chert clasts and concretions that disturb the lamination; rests on a hardground surface 10 to 30

Bed 5. Sandstone, dark and very dark green, argillaceous (Arkell's, 1947 Ammonite Bed); bioturbated and complexly bedded; whole and fragmentary calcitic shells common; bivalves and ammonites preserved in mid-brown phosphate common; angular black phosphorite clasts scattered throughout; marcasite concretions and calcareous sandstone clasts

← Text-fig. 7. a – *In situ* section of the upper part of the Upper Greensand in the cliffs below Flowers Barrow; b – Detail of the Upper Greensand succession exposed in the cliff below Flower's Barrow; c – Junction of the Upper Greensand and Chalk in a fallen block on the beach below Flower's Barrow; d – Detail of the junction of the Foxmould Member and the Chalk Basement Bed in a fallen block at Cow Corner; e – The junction of the Upper Greensand and Chalk at Punfield Cove, Swanage; f – Detail of the highest part of the Upper Greensand and the junction with the Chalk at Punfield Cove



Text-fig. 8. Correlation of the successions proved on the west side (Mupe Bay) and east side (Cow Corner and below Flower's Barrow) of Worbarrow Bay



Text-fig. 9. Correlation of the Upper Greensand sections exposed in the Isle of Purbeck between White Nothe and Punfield Cove derived from bed below up to 20 cm across common in lowest part of bed; irregular highly bioturbated erosion surface at base 55

Bed 4. Calcarenite and densely cemented calcareous sandstone; nodular texture due to bioturbation, secondary calcitic and glauconitic cementation and networks of sand-filled burrows that descend from the bed above; very irregular passage down into 30 to 50

Bed 3. Sandstone, fine-grained, calcareous, argillaceous, glauconitic cut by ramifying network of off-white weathering silicified tubular and thalassinoid burrows; prominent pale chalk-like burrowfills 70 to 90

Bed 2. Sandstone and calcarenite, very pale grey, densely cemented with mineralised hardground at top; passing down into 50

Bed 1. Sandstone, fine-grained, calcareous, highly glauconitic, dark green; bioturbated and with wavy and streaked bedding (re-sedimented?) common shell chips, serpulids and a few *Exogyra*; lenses of sheared, off white densely calcareous fine-grained sandstone in upper part; rests on hardground surface 60

Foxmould Member, Exogyra Rock

Sandstone, fine-grained, calcareous and glauconitic sandy limestone; highly bioturbated with burrows of softer highly glauconitic green sandstone giving rise to nodular texture; contains abundant *Amphidonte obliquata* (Pulteney) (= *Exogyra conica* J. Sowerby), *Rhynchostreon columba* (Lamarck), *Neithea* fragments and serpulids; passing down with irregular bioturbated junction into 45

Sandstone, glauconitic and highly glauconitic, green and dark green; highly bioturbated with calcareously cemented *Thalassinoides* and other burrows; common oysters and serpulids; concentration of oysters at base resting on an irregular surface 160 to 180

Sandstone, glauconitic with patchy dense calcareous cement giving rise to nodular texture; highly bioturbated with traces of cross bedding; lower limit of abundant *E. conica* in lower part of bed 90

BIOSTRATIGRAPHY

The preserved fauna of the Gault and Upper Greensand Formations is unevenly distributed in the exposures on the Devon-Dorset coast where, with the exception of a few well-marked horizons, ammonites and age-diagnostic bivalves are of scattered stratigraphical occurrence or found loose. The zonal scheme used here is that of Owen (2012). The Albian zones and subzones recorded in the Isle of Purbeck and in the correlative succession in East-Devon-West Dorset is summarised in Text-fig. 10. In the Isle of Purbeck Wright (in Arkell 1947; Owen 1971) recorded ammonites indicative of the *spathi, intermedius* and *nitidus* Subzones in "Gault" facies. In the Foxmould, the *orbignyi* and *binum* Subzones have been identified in the lower to middle parts and the *choffati*-early *auritus* transitional interval has been recognised in the highest part. With the notable exception of Arkell's (1947) Ammonite Bed, the preserved fauna of the White Nothe Member is less abundant and less diverse than that of the Foxmould. This is probably a reflection of the abrasive high-energy environments and a coarser matrix that is less suitable for preservation rather than due to less favourable habitats. Whole and fragmentary exogyrine oysters, pectinid bivalves and the serpulid *Rotularia concava* (J. Sowerby) are abundant at some levels. Brachiopods and echinoids have also been recorded. The Albian ammonites recorded from the Isle of Purbeck can be divided into three groups: those from the Gault, mostly preserved in muddy siltstones and muddy fine-grained sandstones that are markedly more arenaceous overall than the correlative Gault mudstones of eastern England; those from the Foxmould Member, mostly preserved in fine-grained glauconitic sandstones and calcareous sandstone concretions; and those from the Ammonite Bed in the White Nothe Member, mostly preserved in phosphates in a highly glauconitic sandstone. Much of the material collected from the Gault and Foxmould came from disturbed sections within landslides, was collected loose, or in the case of the Foxmould from stratigraphically poorly defined levels within the c. 30 m thick succession. Many therefore provide only an indication of age.

The most comprehensive fossil collections from the Albian rocks of Devon and Dorset, including the Isle of Purbeck, are those of R.H. Cunnington, T.F. Grimsdale and C.W. and E.V. Wright which are housed in the Natural History Museum (NHM). The following account is based largely on these collections and is therefore not comprehensive. It augments that provided by Wright (in Arkell 1947), and illustrates the need for further patient *in-situ* collection of age-diagnostic fossils in of the coastal sections.

Middle Albian

Gault of Middle Albian age has been reported from sandy mudstones with sandstone beds ("tran-

		Isle of Purbeck			East Devon-West Dorset	
Stage	Zone	Subzone	Member	Locality	Subzone	Member
Late Albian	*Stoliczkaia (Stoliczkaia) spp.*	*briacensis*		not recorded	*briacensis*	Bindon Sandstone
		perinflata	White Nothe	OM WN DD LC WB PC	*perinflata*	Bindon Sandstone?
		rostratum		not recorded	*rostratum*	not recorded
	Mortoniceras inflatum	*auritus*	Foxmould	OM WN WB PC	*auritus*	Whitecliff Chert? Foxmould?
	Hysteroceras varicosum	*choffati*	Foxmould	OM	*choffati*	
		binum	Foxmould	OM WN WB PC	*binum*	Foxmould?
		orbignyi	Foxmould	OM WB	*orbignyi*	Foxmould? sandy 'Gault'?
	Dipoloceras cristatum			not recorded	*cristatum*	not recorded
Middle Albian	*Euhoplites lautus*	*daviesi*	Subzones in **bold** represented by Gault Formation and 'transition beds' in the Isle of Purbeck		*daviesi*	
		nitidus			*nitidus*	
	Proeuhoplites loricatus	*meandrinus*			*meandrinus*	
		subdelaruei			*subdelaruei*	
		niobe			*niobe*	
		intermedius			*intermedius*	sandy 'Gault'?
	Hoplites dentatus	***spathi***			*spathi*	
		lyelli			*lyelli*	

OM...Osmington Mills WN...White Nothe DD...Durdle Door LC...Lulworth Cove
WB...Worbarrow Bay PC...Punfield Cove ?...based on *ex situ* specimens

Text-fig. 10. Summary of the Albian zones and subzones proved in the Upper Greensand Formation of the Isle of Purbeck (after Wright in Arkell 1947) and East Devon-West Dorset (after Owen in Gallois 2004) with additions based on a re-examination of the exposures and faunas. Zonal-subzonal scheme after Owen (2012)

sition beds") in the Isle of Purbeck, but the typical Gault mudstone facies is restricted to the Isle of Wight where it contains ammonites indicative of Middle Albian the *Lyelliceras lyelli* and *Hoplites spathi* subzones (*Hoplites dentatus* Zone) and the *Paranahoplites intermedius* Subzone (*Proeuhoplites loricatus* Zone) Owen (1971).

In the Isle of Purbeck, sandstone concretions close above the pebbly basal bed of the Gault contain a late *Hoplites spathi* Subzone (*H. dentatus* Zone) fauna and, slightly higher, similar concretions of early *P, intermedius* Subzone age Owen (1971). Sediments of *Euhoplites loricatus* Zone age (*Pseudhoplites niobe* to *Proeuhoplites meandrinus* Subzones) have not been recorded, but ammonites of *E. nitidus* Subzone age have been collected from Osmington Mills-Black Head and sections between there and Durdle Door (Man O'War Cove). All are preserved in dark to mid-grey, fine-grained sandstone typical of the lower part of the Foxmould. However, none were found *in-situ* so that their exact stratigraphical position is not known. The Osmington specimens of *nitidus* Subzone age include *Anahoplites planus* (Mantell), *Dimorphoplites biplicatus* (Mantell), *D. parkinsoni* Spath, *D. chloris* Spath, *D. parkinsoni* Spath, *Euhoplites lautus* (J. Sowerby), *E. lautus duntonensis* Spath and the Lower Gault form of *Actinoceramus concentricus* (Parkinson). This last is also associated with the *lyelli* and *spathi* Subzone ammonite occurrences referred to above and in the matrix of the *E. nitidus* Subzone ammonites at Osmington. *Dimorphoplites* sp. has been collected from Man O'War Cove.

Late Albian

There is currently no published record of sediments of *Dipoloceras cristatum* Zone age from the Dorset-Devon coast. The *Hysteroceras varicosum*

Zone (comprising in ascending order the *Hysteroceras orbignyi*, *H. binum* and *H. choffati* Subzones) is represented by thin patchily distributed, current-winnowed sediments. *Hysteroceras orbignyi* (Spath) preserved as a black phosphatic cast has been collected from Worbarrow Bay which may reflect the current-winnowed succession generally recorded from the *orbignyi* Subzone succession in England (Owen 1976, 2012). *H.* cf. *orbignyi* has been recorded at Osmington. Faunas of *binum* Subzone age are present in the lower part of the Foxmould throughout the area, but with the exception of Punfield Cove almost all the material in the NHM collections was found loose. The most diverse assemblage has been collected from Osmington. It includes *Anahoplites planus* (Mantell), *A. planus gracilis* Spath, *A.* cf. *picteti* Spath, *A.* sp., *Beudanticeras* cf. *beudanti* (Brongniart), *Deiradoceras cunningtoni* Spath, *Epihoplites gibbosus* (Spath), *E.* cf. *glyptus* Spath, *E. iphitus* Spath, *E.* sp., *Euhoplites* cf. *boloniensis* (Spath), *Goodhallites delabechei* Spath, *G.* sp., *Hysteroceras binum* (J. Sowerby), *H. varicosum* (J. de C. Sowerby), *H.* aff. *subbinum* Spath, *Mortoniceras pricei* (Spath) and *M.* sp. *Anahoplites* sp., *Epihoplites denarius* (J. Sowerby) and *Epihoplites* sp. have been collected from Punfield, *H. binum* from White Nothe, and *Anahoplites* sp. from Worbarrow Bay. The presence of undoubted *Hysteroceras choffati* Subzone sediments is indicated by the presence of *Epihoplites* aff. *iphitus* Spath transitional to *Procallihoplites* at Osmington.

The *Mortoniceras inflatum* Zone comprises two subzones, the *Procallihoplites auritus* Subzone *sensu stricto* ("early" *auritus* Subzone) followed by an as yet unindexed subzone referred to a "late a*uritus*". The Wright Collection contains *Hengestites* sp. from Worbarrow and a mortoniceratid and *Epihoplites* sp. from Osmington, all preserved in black phosphatic pebbles that might reflect the erosive event of the basal *auritus* Subzone known widely in southern England and present in the Lulworth section. The "early" *auritus* Subzone is well developed in the Upper Greensand of the Dorset and Devon coastal region where it occupies most of the upper part of the Foxmould. It has been recorded in all the coastal sections in the Isle of Purbeck where age diagnostic fossils include *Procallihoplites auritus* (J. Sowerby) (Worbarrow and Osmington), *P. strigosus* (Spath) and *P. strigosa cristata* Spath (Osmington), *Mortoniceras inflatum* (J. Sowerby) (Punfield Cove and Osmington), *M. fissicostatum* (Spath) (Punfield Cove) and *M. arietiforme* (Spath) (Osmington), and ?*Anahoplites (*Punfield Cove). Shell fragments of *Inoceramus lissa* (Seeley), a characteristic bivalve of this subzone, are present throughout. Whether sediments of the "late" *auritus* Subzone are present in the Isle of Purbeck is uncertain. Indigenous crushed specimens of *Callihoplites* occur c. 2 m below the Exogyra Rock at White Nothe (Wright in Arkell 1947)

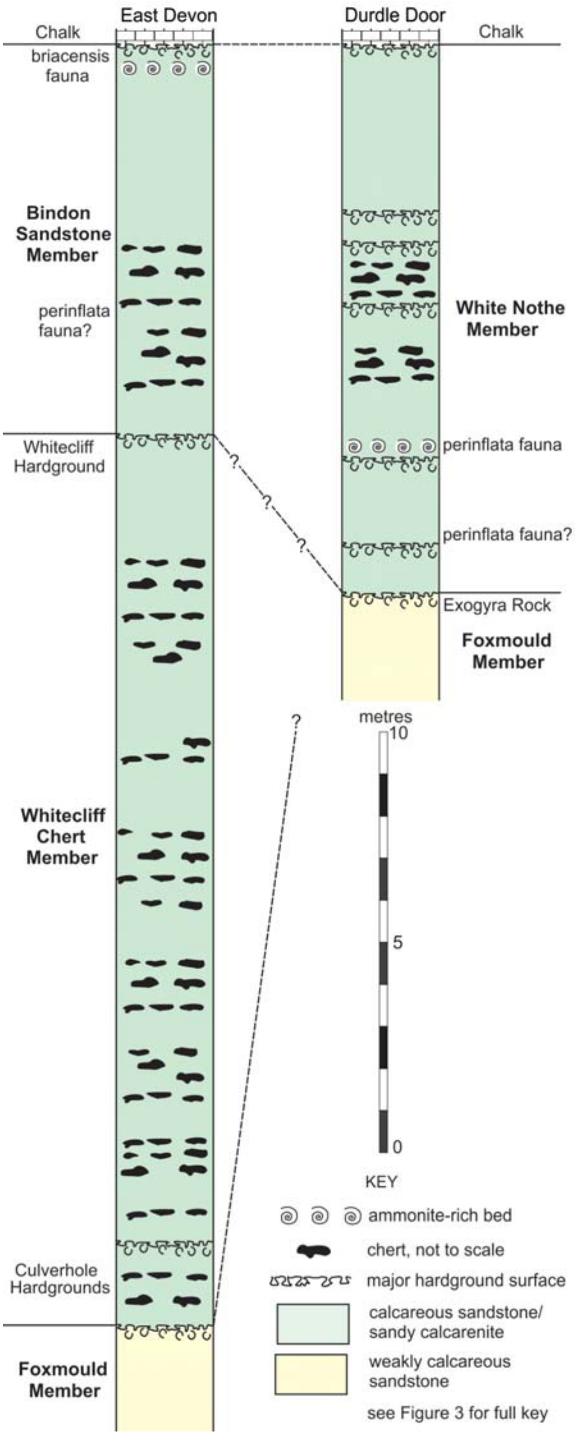
The *Stoliczkaia* spp. Zone comprises three subzones, in ascending order, *Mortoniceras rostratum*, *Durnovarites perinflata* and *Praeschloenbachia briacensis.* There is currently no evidence of sediments of *rostratum* Subzone age in the Isle of Wight or on the Dorset-Devon coast. Arkell's (1947) Ammonite Bed, Bed 5 of the White Nothe Formation in the present account, contains fragmentary ammonites and other fossils preserved in pale buff phosphate that show little sign of abrasion. They probably accumulated as the gentle winnowing product of former more calcareous sediments of *perinflata* and early *briacensis* Subzone age. The Ammonite Bed is present at all the localities shown in Text-fig. 9, and at Compton Bay [SZ 3630 8542] in the Isle of Wight, but has not been recorded elsewhere. Wright (in Arkell 1947) recorded "a few ammonites" lower in the succession at White Nothe (in Bed 3 of the present account). These are either not represented in the collections or are not listed separately. The ammonite fauna listed by Wright (in Arkell 1947, with corrections in the 1978 reprint) is revised and augmented here. It includes *Stomohamites virgulatus* (Brongniart?) Pictet and Campiche, *S. venetzianus* Pictet, *S. duplicatus* Pictet and Campiche, *S. subvirgulatus* Spath, *Lechites gaudini* Pictet and Campiche, *L. moreti* Breistroffer, *L. communis* Spath, *Sciponoceras skipperae* Monks, *Idiohamites dorsetensis* Spath, *I. elegantulus* Spath, *Anisoceras armatum* (J. Sowerby), *A perarmatum* (Pictet and Campiche), *A. picteti* Spath, *A. exoticum* Spath, *A. pseudoelegans* Pictet and Campiche, *A. campichei* Spath, *Mariella bergeri* (Brongniart), *M. miliaris* (Pictet and Campiche), *Ostlingoceras puzosianum* (d'Orbigny), *Turrilites* sp., *Puzosia* (*Puzosia*) *sharpei* Spath, *Lepthoplites falcoides* Spath, *L. cantabrigiensis* Spath, *L. proximus* Spath, *Callihoplites tetragonus* (Seeley), *C. vraconensis* (Pictet and Campiche), *C.* spp., *Arrhaphoceras studeri* (Pictet and Campiche), *A. substuderi* Spath, *A. precoupei* Spath, *Pleurohoplites subvarians* Spath, *Discohoplites subfalcatus* (Semenov), *D. simplex* Wright and Wright, *Savelievella valbonnensis* (Hébert and Munier-Chalmas), *S. dorsetensis* (Wright and Wright), *Spathoplites transitorius* (Spath), *S. anomalus* (Spath), *S. arkelli* (Wright and Wright), *Wrighthoplites pylorus* (Wright and Wright), *W. daedalius* (Wright and Wright), *Hyphoplites campichei* Spath, *Hyphoplites aurora* Wright and Wright, *Stoliczkaia dispar* (d'Orbigny), *S. dorsetensis* Spath, *S. notha inflata* Spath, *Engonoceras grimsdalei* Spath, *Durnovarites perinflata* (Spath), *D. quadratus* (Spath), *D. postinflatus* Spath, *D. subquadratus* Spath. The assemblage contains early *briacensis* Subzone material including discohoplitids similar to those recorded at the only *briacensis* Subzone succession recorded in southern England at Uplyme, Devon (see below), and the presence of *Callihoplites* with prominent raised venters and *Arraphoceras* with raised venters and depressed whorl sections foreshadows that seen in typical *Praeschloenbachia*. At Punfield Cove where the White Nothe Member is represented by a highly bioturbated deposit 0.5 m thick, the fauna includes that of the Ammonite Bed and Early Cenomanian ammonites in burrows that extend down from the Chalk Basement Bed.

The Foxmould of the Blackdown Hills, Somerset has yielded a well preserved fauna of *Hysteroceras binum* Subzone age including *Hysteroceras varicosum* (J. de C. Sowerby), *H. binum* (J. Sowerby), *H. subbinum* Spath, *Goodhallites goodhalli* (J. Sowerby), *Mortoniceras* (*Deiradoceras*) *albense* Spath and *M.* (*D.*) *devonense* Spath, *Mortoniceras* (*Mortoniceras*) *pricei* Spath, *Epihoplites denarius* (J. de C. Sowerby), *E. gibbosus* Spath, *E. glyptus* Spath, "*Semenoviceras*" *gracilis* Spath, "*S.*" *glyptus* Spath, *Euhoplites* sp. The ammonite fauna suggests the earlier part of the Subzone. The outcrop of the member is contiguous with that of the Foxmould of the east Devon coast where ammonites indicative of the *orbignyi* to *auritus* Subzones have been recorded, but mostly *ex situ* (Owen in Gallois 2004). No *in situ* ammonite has been recorded from the Whitecliff Chert, but a *Mortoniceras* (*M.*) *commune* indicative of the *auritus* Subzone preserved in a loose chert at Lyme Regis is believed to have come from the member. *Ex situ* examples of *Arrhaphoceras studeri* (Pictet and Campiche), *Arraphoceras* sp., *Mariella bergeri* (Brongniart), *Mortoniceras* (*Durnovarites*) cf. *subquadratum* (Spath) and *Stoliczkaia* cf. *dispar* (d'Orbigny) (Spath 1926; Wilson *et al.* 1958) that are presumed to have come from the Bindon Sandstone of the Devon-west Dorset coast are indicative of the *perinflata* Subzone. The only ammonites recorded *in situ* in the Bindon Sandstone came from shelly lenses in the highest part of the member (Bed 4) at Uplyme [SY 313 918], Dorset. They include typical *Stoliczkaia dispar* associated with species of *Callihoplites* with elevated ventral areas, *Discohoplites*, *Hyphoplites*, *Idiohamites* and *Stomohamites* suggesting the early part the *Arraphoceras* (*Praeschloenbachia*) *briacensis* Subzone (Owen in Hamblin and Wood 1976). A similar assemblage is known as derived phosphatic pebbles in the Early Cenomanian Bookham Conglomerate in north Dorset together with indigenous Early Cenomanian ammonites (Kennedy 1970; Bristow *et al.* 1995). A typical *briacensis* Subzone fauna is also present in the mudstones of the Kirchrode Marls in the Hannover area (North Germany) (Wiedman and Owen 2001; Owen 2007).

CORRELATIONS WITH OTHER AREAS

The Upper Greensand succession in the Isle of Purbeck is a shallow-water, marine, deposit that is laterally and vertically variable over distances of a few hundred metres. It contains numerous erosion surfaces marked by hardgrounds that represent breaks in sedimentation of unknown duration, and two erosion surfaces that can be traced throughout southern England. In the Isle of Purbeck these last are represented by complex hardgrounds overlain by pebble beds at the base of the White Nothe Member and the base of the Chalk Group. Both mark an abrupt change in sedimentary facies. At the top of the Foxmould, the Exogyra Rock is a loosely defined succession of cemented glauconitic sandy calcarenites and calcareous sandstones interbedded with glauconite-rich, fine-grained sandstones with nests crowded with *Amphidonte* and *Rhynchostreon* at many levels. The top of the bed is sharply defined by a prominent hardground, but the base passes down into lithologically similar sandstones with the same oysters scattered throughout with the result that the thickness varies from 3 m thick at White Nothe to 0.5 m at Punfield Cove. The abundance of *Amphidonte* is not stratigraphically diagnostic, but is characteristic of current-swept, shallow-water environments.

The hardground at the top of Exogyra Rock marks a sudden upward change in all the Isle of Purbeck sections from weakly cemented glauconitic sandstones that are largely decalcified at outcrop to interbedded highly glauconitic argillaceous sandstones and strong calcareous sandstones and calcarenites with laterally impersistent beds of chert, siliceous concretions (quasi cherts), silicified thalassinoid and other burrow systems, and erosion surfaces marked by mineralised hardground surfaces overlain by glauconite-rich sandstones with phosphatic and sandstone clasts. A similar upward change is present on the Devon-west Dorset coast where the lower of the two Culverhole Hardgrounds separates the Foxmould from the Whitecliff Chert Member (Gallois 2004). The Whitecliff Chert Member is also separated from



Text-fig. 11. Correlation of the upper part of the Upper Greensand of the East Devon type area (after Gallois 2004) with that at Durdle Door, Isle of Purbeck

the lithologically similar Bindon Sandstone Member by a widespread sedimentary break, that marked by the Whitecliff Hardground (Gallois 2004).

Comparison of the limited ammonite evidence from the two areas suggests that the Foxmould Member is *varicosum* to *inflatum* Zone in age and that the Whitecliff Chert may not be represented in the Isle of Purbeck succession (Text-fig. 10). The

presence of a possible *perinflata* Subzone fauna in the Bindon Sandstone and in the White Nothe Member below the level of the Ammonite Bed suggests that the basal bed of both members are of similar age (Text-fig. 11). Alternatively, the presence of erosional breaks in the form of hardground surfaces and the absence of an *in situ* age-diagnostic fauna in the Whitecliff Chert might mean that the member is in part *rostratum* and/or *perinflata* Subzone in age.

SUMMARY AND CONCLUSIONS

The Upper Greensand of the Isle of Purbeck consists largely of fine-, medium- and coarse-grained sandstones, and calcarenites composed of variable amounts of silica, glauconite and calcium carbonate. It can be divided into two parts, a less lithified, finer grained, more siliceous lower part that gives rise to low-angle cliffs, and a more calcareous upper part that gives rise to precipitous cliffs. Glauconite is present throughout and is abundant at some levels, notably in condensed beds that overlie the more prominent erosion surfaces. Mineralised hardground surfaces are common in the upper part of the succession. Some of these are overlain by scour hollows infilled with clast-rich and shell-debris-rich sands in which 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 complex nature of the hardground surfaces was described by Garrison *et al.* (1987) who showed that they are commonly calcitised, phosphatised and glauconitised, brecciated, pervasively penetrated by burrow systems, and encrusted by bivalves and serpulids.

A marked feature of the upper part of the Upper Greensand of the Isle of Purbeck, the White Nothe Member of this account, is the presence of up to 8 prominent erosion surfaces that give rise to a marked thinning of the formation when traced from west to east (Text-fig. 9). Drummond (1970) compared this thinning with a southward attenuation of the upper part of the formation in north Dorset and attributed this to a 40 to 50km wide, roughly NW-SE trending tectonically positive area which he called the Mid Dorset Swell. This interpretation has been superseded by 3-D interpretations of the regional structure made possible by seismic-reflection profiles. These have shown the importance of the multiple fault reactivations associated with roughly E-W trending buried Variscan structures. 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 northern edge of an E-W trending Cranbourne-Fordingbridge High. This structure is contiguous with the Hampshire-Dieppe High of Chadwick and Evans (2005) who also identified an additional E-W trending post-Variscan structure, the Purbeck-Wight Disturbance, c. 20 km south of the southern margin of the high.

In the Isle of Purbeck, lateral variations in the White Nothe Member successions occur over distances of as little as a few hundred metres (Text-fig. 8). These were noted by Garrison *et al.* (1987) who interpreted them as the result of penecontemporaneous movements on faults in the Purbeck Fault Zone. This interpretation is supported by the present research which has shown that sedimentation of the Upper Greensand in the Isle of Purbeck was influenced not only by local variations in water depth and the strengths of tidal and storm-generated currents, but also by local fault movements in the late Albian.

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