British Upper Cretaceous Stratigraphy

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Chapter 4

Transitional Province, England

INTRODUCTION

From the Vale of Pewsey in Wiltshire to the north coast of Norfolk is a region known as the 'Transitional Province' (Figure 4.1), which is given this name because it contains elements of the litho- and bio-stratigraphy of both the Southern and Northern Provinces. The region is bounded to the south and south-west by the Vale of Pewsey, which has formed along a major fault structure (see p. 87, Chapter 3), and encompasses the Chalk hills from the Berkshire Downs, through the Chiltern Hills to East Anglia. Both the Berkshire Downs and the Chiltern Hills have a well-defined northerly-facing scarp with a dip-slope south-eastwards into the London Basin, where the Chalk is buried by Palaeogene sediments. At the northern end of the Chiltern Hills, there is another significant structural line, the Lilley Bottom structure (see Figure 1.15, Chapter 1), a probable fault-controlled monocline that seems to have exerted some control on sedimentation. This structure appears to follow the north-east edge of the deep-seated Midlands microcraton (Hopson *et al.*, 1996). Beyond that point there is still a Chiltern Hills scarp, but more subdued. The region then grades through the gently rolling Gog Magog Hills into East Anglia where any sort of feature in the Chalk is lost except for the Melbourn Rock feature at the base of the White Chalk Subgroup. Here the remainder of the outcrop is glacially degraded and largely drift-covered. This loss of features is related to lithological changes in the Grey Chalk Chalk Subgroup, to the complete loss of major hardgrounds forming the Chalk Rock and Top Rock lithologies, and to a very gentle dip of perhaps 0.5° to the east.

The Chalk of East Anglia overlies the northern extension of the buried Anglo-Brabant Massif

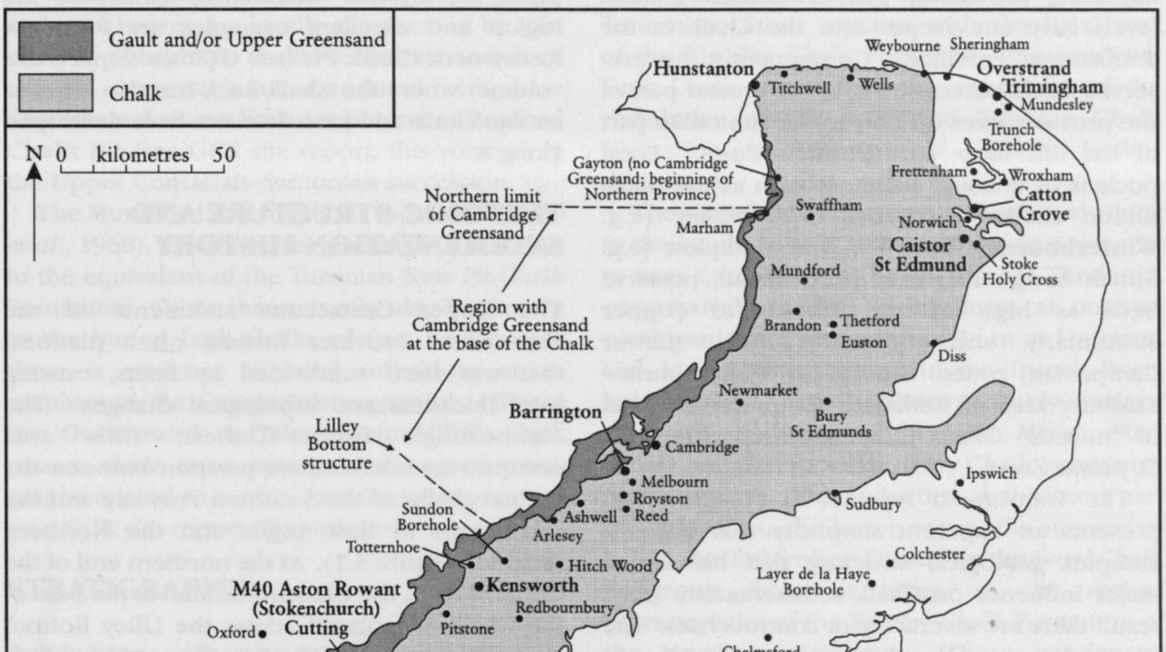


Figure 4.1 Location of GCR sites (bold type), and other sites also mentioned in the text, in the Transitional Chalk Province of England.

(Figure 1.8, Chapter 1), and the western margin of the North Sea Basin. A positive area in north Norfolk, has been related to the existence of an inferred igneous intrusive body at depth (Figure 1.15, Chapter 1; Smith, 1985; Gallois, 1994), and is considered to be the cause of the condensed successions that are developed there.

The northern boundary of the province in East Anglia shifted over time. It appears to have been particularly well marked during Turonian and Early Coniacian times, when it lay in the vicinity of Swaffham. Here it is expressed by the change from the black, burrow-form flints of the Southern and Transitional provinces, to the grey, tabular and semi-tabular flints, within well-bedded chalks, that characterize much of the flinty succession in the Northern Province. In contrast, the higher part of the succession in northern East Anglia has a more Southern Province character.

Apart from East Anglia, in contrast to the adjoining provinces, post-Cretaceous erosion levels have cut deeper into the Chalk in the Transitional Province. Consequently the preserved Chalk succession over the greater part of the province goes up only to the Santonian part of the *Micraster coranguinum* Zone. Local pockets of unusual sediment such as the phosphatic chalks north-east of Newbury (e.g. **Winterbourne Chalk Pit**) and at Taplow (e.g. **South Lodge Pit**) near Maidenhead, preserve beds as high as the *Marsupites* (Upper Santonian) and *Offaster pilula* (Lower Campanian) zones. Around the Winterbourne–Kintbury area of Berkshire the preserved level of 'normal' Chalk is somewhere within the *O. pilula* Zone.

The Transitional Province is a region that presents an apparent simplicity that belies a complex geological structure that has had a major influence on Chalk sedimentation. As a result there are several major controversies. The first relates to the lithostratigraphical subdivision of the Chalk for geological mapping, notably the extent to which the standard mapping stratigraphy of the Southern Province can be applied in the Transitional Province. The second controversy is the representation of the facies changes that occur towards adjoining regions, and the third is the age and correlation of the component hardgrounds and associated marl seams of the Chalk Rock in relation to the basinal successions of the Southern Province. The relationship between the Chalk Rock of the type area and the Spurious Chalk Rock of the Isle of Wight and Dorset is not entirely resolved.

Post-Cretaceous geological history of the region involved sub-Palaeogene erosion, Palaeogene sedimentation, tectonic movements, weathering to form Clay-with-flints and glacial and periglacial processes. A long-running controversy has been the cause of apparently 'out-of-place' Chalk blocks with anomalously dipping Chalk at the northern end of the Chiltern Hills around Reed and Barkway. Hopson (1995) has recently interpreted the origin of these blocks as the result of excavation by ice and subsequent rafting. One result of weathering has been the development of 'Sarsen' stones, which include the stone-runs of the Marlborough Downs, the Hertfordshire Pudding Stone and the more than 80 tonne-blocks excavated during construction of the M40 through the **Aston Rowant Cutting** (see GCR site report, this volume). Dissolution pipes are another weathering feature of the region and excellent examples are found at **Kensworth Chalk Pit** (see GCR site report, this volume) where the Chalk Rock has also acted as an aquiclude and karst features have developed along it.

TECTONIC STRUCTURE AND SEDIMENTATION HISTORY

The Upper Cretaceous sediments of the Transitional Province formed on a platform that was itself subdivided by faults, causing local thickness and lithological changes. The Marlborough Downs–Chiltern Hills area occupies an intermediate position between the basinal chalks of the Southern Province and the successions in East Anglia and the Northern Province (Figure 4.1). At the northern end of the Chiltern Hills, the Glauconitic Marl at the base of the Chalk is replaced across the Lilley Bottom structure by the Cambridge Greensand, which can be traced thence eastwards into East Anglia.

Compared with those of the Southern Province, the Grey Chalk Subgroup successions in the Chiltern Hills and in the southern part of East Anglia (Cambridgeshire, Suffolk) are characterized by thick basal Chalk (West Melbury Marly Chalk Formation). In contrast, from about mid-Cenomanian times, the entire Berkshire Downs–Chiltern Hills area intermittently constituted a structural high on which developed thin condensed calcarenitic successions such as the Totternhoe Stone in the Grey Chalk Subgroup (Middle Cenomanian), and, in the Turonian–Coniacian strata, extremely condensed successions with hardgrounds such as the Chalk Rock and Top Rock. The Marlborough Downs in Wiltshire constitute the type area for the Chalk Rock, for it is here that it attains its maximum development. The area immediately to the east of the Chiltern Hills is the type area for the Melbourn Rock, a unit of hard chalks, at the base of the traditional Middle Chalk, incorporating the Cenomanian–Turonian boundary transition.

Other aspects of the lithology, related to the broad tectonic setting, include flints at the top of the Holywell Nodular Chalk Formation over an area extending from the central Chiltern Hills (Ivinghoe-Aston Pit, Totternhoe) to the east of Hitchin. In the southern Chiltern Hills, the equivalent succession is not known to be flint-bearing. The Upper Santonian–Lower ampanian successions (crinoid zones to *Offaster pilula* zones inclusive) are locally represented by thin units of phosphatic chalk. Channels and deep troughs ('cuvettes') are associated with these deposits and slump beds are present at **Boxford Chalk Pit** (see GCR site report, this volume) in the Upper Coniacian–Santonian succession.

The Mundford investigations in Norfolk (Ward *et al.*, 1968), illustrated the presence of channels in the equivalent of the Turonian New Pit Chalk Formation. Other channels may also be present in the buried high chalks of East Anglia since there is evidence of local anomalous stratigraphies in the Campanian succession. Within the **Overstrand to Trimingham Cliffs** chalk masses there is an internally disrupted stratigraphy related to to intra-Late Cretaceous events (see GCR site report, this volume).

STRATIGRAPHY

Subdivision of the stratigraphy of the Transitional Province into formations, members and beds follows the scheme now established in the Southern Province (Figure 3.3, Chapter 3; Bristow *et al.*, 1997; Rawson *et al.*, 2001) for the greater part of the region up to the northern end of the Chiltern Hills. The Northern Province stratigraphy applies in the most northerly part of East Anglia around the Wash at **Hunstanton Cliffs** (Figure 5.3, Chapter 5). In between, the stratigraphical units are gradational. There are several distinct features of the stratigraphy, such as the presence of the Totternhoe Stone in the Grey Chalk Subgroup.

Grey Chalk Subgroup

The Grey Chalk Subgroup of the Chiltern Hills has been traditionally divided into four standard lithostratigraphical units, namely the Chalk Marl, Totternhoe Stone, Grey Chalk and Plenus Marls. The Plenus Marls Member is now included in the White Chalk Subgroup. In this area, the Totternhoe Stone provides a simple means of delimiting the traditional Chalk Marl from the Grey Chalk. Recent stratigraphical schemes have treated the Totternhoe Stone either as a unit intercalated between the Chalk Marl and the Grey Chalk (e.g. Shephard-Thorn *et al.*, 1994), or as the basal unit of the Grey Chalk (e.g. Horton *et al.*, 1995). The Chalk Marl, as developed in the Chiltern Hills, represents the preserved remnant of the West Melbury Marly Chalk Formation of the Southern Province. The Totternhoe Stone equates with the basal part of the Zig Zag Chalk Formation, the overlying Grey Chalk constituting the equivalent of the remainder of the redefined Zig Zag Chalk Formation (see Rawson *et al.*, 2001 for further discussion).

The Grey Chalk Subgroup, still relatively thick in the southern part of East Anglia (e.g. over 70 m near Cambridge and *c.* 40 m near Thetford), progressively reduces in thickness at outcrop northwards to a minimum of 14 m at Heacham and 11 m in the subcrop in the Trunch Borehole. Both the latter localities probably overlie a structural high that influenced Albian (Red Chalk) and Cenomanian (Grey Chalk Subgroup) sedimentation. This reduction in thickness particularly affects the lower part of the succession below the Totternhoe Stone. As the Grey Chalk Subgroup thins, it takes on the typical characteristics of the Ferriby Chalk Formation of the Northern Province. These condensed successions have very well-defined bedding and contain lower diversity faunas than successions in southern England. Ammonites, in particular, are relatively uncommon, whereas echinoids become more significant. The succession is closely similar to the equivalent, but thicker, successions in northern Germany (cf. Ernst *et al.*, 1983, 1996; Ernst and Rehfeld, 1997; Kaplan *et al.*, 1998). As in Germany, the condensed successions in eastern England are marked by a sequence of lithostratigraphical and/or biostratigraphical events, which provides a useful framework for correlation.

Glauconitic Marl Member and Cambridge Greensand

The basal beds of the Chalk Group in the western part of the Transitional Province and in the southern Chiltern Hills constitute a thin unit of glauconite-rich marls, the Glauconitic Marl Member, which is locally thick enough to be mapped. To the north, in the area of Totternhoe and Sundon, the Glauconitic Marl locally disappears, and only a few grains of glauconite are found at the contact between the Grey Chalk Subgroup and the Upper Greensand (Shephard-Thorn *et al.*, 1994). Even farther to the north, near Barton-le-Clay, where the Chiltern Hills scarp weakens significantly and changes to a generally east–west direction, thin Glauconitic Marl is replaced by the Cambridge Greensand. This is a unit of micaceous, glauconitic marls rich in phosphatized pebbles, including many fossils reworked from the (Albian) Gault mudstones, on which it rests with erosive contact (Morter and Wood, 1983). The replacement of the Glauconitic Marl by the Cambridge Greensand is apparently structurally controlled, and takes place in the vicinity of a NW–SE fault or monoclinal structure (Lilley Bottom structure), with a downthrow in the Chalk of up to 10 m to the north-east (Shephard-Thorn *et al.*, 1994; Hopson *et al.*, 1996). This structural line also marks the south-west edge of the so-called 'Anglian Trough', a depositional low revealed by the isopachytes of the Plenus Marls Member at the base of the White Chalk Subgroup (Hart, 1973, fig. 1). Although the Cambridge Greensand development is concentrated in this 'trough', it actually extends as far north as Ely and east into the East Anglian subcrop.

West Melbury Marly Chalk Formation (Chalk Marl)

The lowest part of the West Melbury Marly Chalk Formation (Figure 4.2) in the Chiltern Hills comprises relatively dark grey, silty sediments, which, apart from their different macrofossil content, are not always easy to distinguish from the underlying Gault when wet. These beds are characterized by a low-diversity fauna dominated by small, predominantly crushed, thin-shelled bivalves belonging to the genus *Aucellina*, and are known informally as the 'Aucellina Beds' for this reason (Figure 4.3).

In East Anglia, the lowest part of the Chalk, above the Cambridge Greensand, comprises buff-coloured, rather chalky beds, many metres thick, with a low-diversity fauna dominated by the bivalve *Aucellina*. These so-called 'Porcellaneous Beds' (Morter and Wood, 1983) correlate with the basal Cenomanian Aucellina Beds of the Channel Tunnel boreholes and the Chiltern Hills. Towards the top, they yield poorly-preserved assemblages of ammonites, including heteromorphs such as *Algerites*. The Porcellaneous Beds thin and become more lithified when traced northwards; a little to the south of the **Hunstanton Cliffs** GCR site they condense to a unit, less than 0.5 m thick, of intensely hard limestone, the 'Paradoxica Bed', with several superimposed glauconitized hardgrounds penetrated by *Thalassinoides* (formerly *Spongia paradoxica*) burrows. Throughout much of East Anglia, these basal beds are overlain by two units of inoceramid bivalve shell-detrital chalk, each with an erosional base (the Lower and Upper Inoceramus Beds), separated by a bed without shells. These beds also become thinner, more lithified and better defined towards Hunstanton Cliffs. Once the Porcellaneous Beds have passed into the Paradoxica Bed there is a standard (Northern Province) Ferriby Chalk succession.

Within the higher part of the West Melbury Marly Chalk Formation, above the Aucellina Beds, two variably cemented, highly fossiliferous limestone beds provide useful marker horizons. The lower of these, named the 'Doolittle Limestone' after a locality near Totternhoe in the northern Chiltern Hills (Shephard-Thorn *et al.*, 1994), is locally feature-forming and may equate in part with the spring-forming, so-called 'Marl-Rock' of the earlier literature. This bed contains abundant specimens of well-preserved three-dimensional ammonites, predominantly *Schloenbachia*, associated with *Inoceramus crippsi* Mantell. It has also been informally called the 'Crippsi Limestone' (e.g. Wood, 1996, fig. 23), and it equates with a similarly fossiliferous bed in the **Folkestone to Kingsdown** section (see GCR site report, this volume; marker horizon M3 of Gale, 1989), where it marks the top of the Lower Cenomanian *Sharpeiceras schlueteri* Subzone (Gale, 1996) of the *Mantelliceras mantelli* Zone. Figure 4.3 shows that this marker horizon can be used to

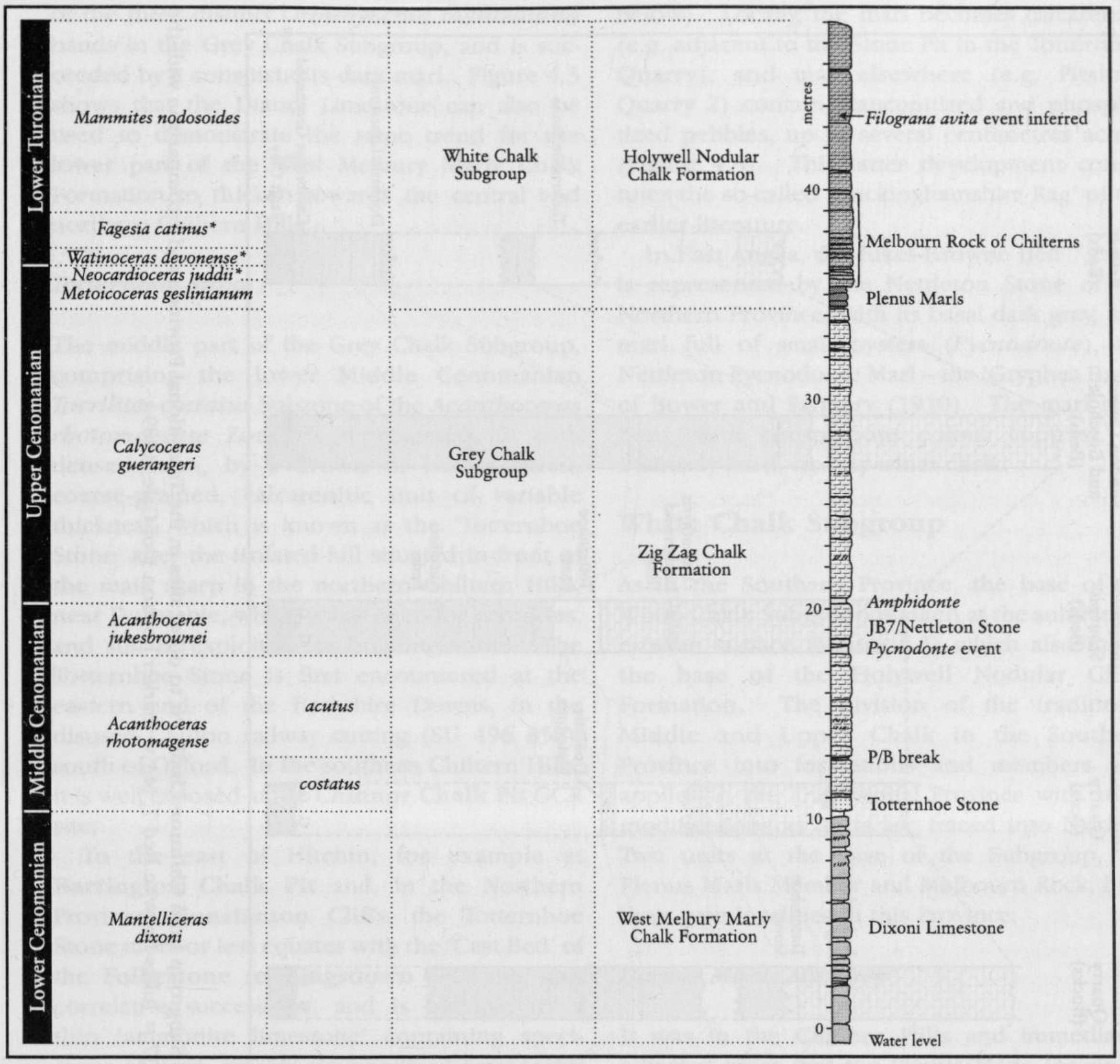


Figure 4.2 Chalk succession exposed in **Chinnor Chalk Pit**, Oxfordshire (* = inferred zones based on other sections and associated fossils). (After Sumbler and Woods, 1992.)

demonstrate how the underlying part of the West Melbury Marly Chalk Formation thickens from the **Folkestone to Kingsdown** GCR site (*c.* 12 m) to **Chinnor Chalk Pit** (15 m), to the north of which (Pitstone, Totternhoe, Sundon), this unit increases dramatically in thickness to *c.* 35 m. The northern limit of this thickening also appears to be linked to the position of the Lilley Bottom structure.

The higher of the two cemented limestones is known informally as the 'Dixoni Limestone', because it locally (but only rarely in the Chiltern Hills) yields well-preserved specimens of the Lower Cenomanian ammonite zonal index fossil *Mantelliceras dixoni* Spath. This bed is characterized by the occurrence of abundant large specimens of *Inoceramus virgatus* Schlüter, commonly with the valves articulated, associated with subordinate *I. crippsi*. It equates with a closely-spaced pair of thin spongiferous limestones (marker horizon M6 of Gale, 1989) in the **Folkestone to Kingsdown** standard section, and it similarly marks the top of a unit, some 3 m thick, of rather calcareous beds containing common *I. virgatus*. As in Kent, the Dixoni Limestone is overlain by marly beds with small brachiopods, including *Orbirhynchia mantelliana* (J. de C. Sowerby), constituting the lowest

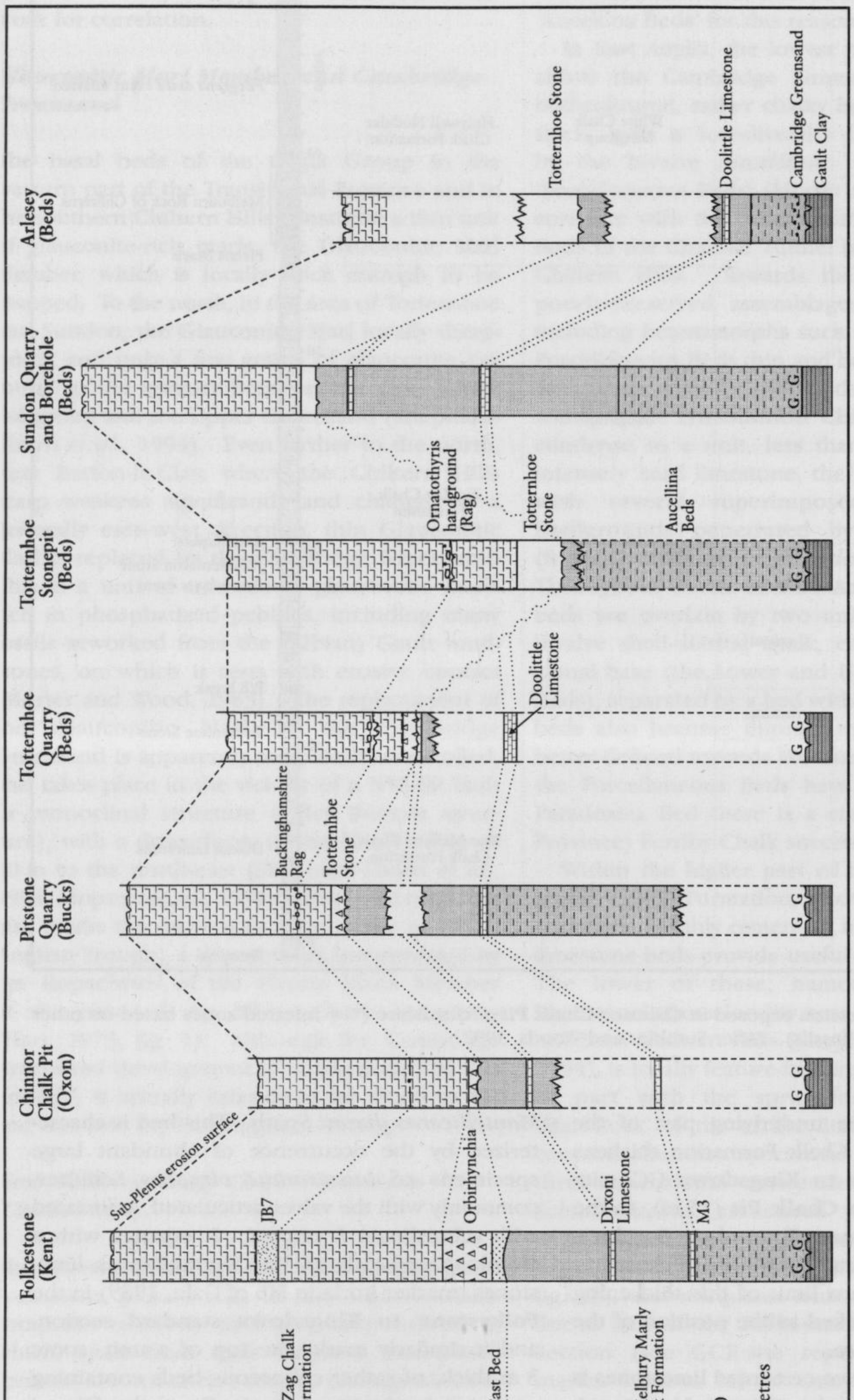


Figure 4.3 Correlation of the Cenomanian Grey Chalk Subgroup from Chinnor Chalk Pit to other sites in the Transitional Province and a comparison with the Folkestone standard section. (G = Glauconitic Marl; JB7 = Jukes-Browne Bed 7; M3 = marker horizon 3 of Gale, 1989.)

of the three distinct *Orbirhynchia mantelliana* bands in the Grey Chalk Subgroup, and is succeeded by a conspicuous dark marl. Figure 4.3 shows that the Dixoni Limestone can also be used to demonstrate the same trend for the lower part of the West Melbury Marly Chalk Formation to thicken towards the central and northern Chiltern Hills.

Totternhoe Stone

The middle part of the Grey Chalk Subgroup, comprising the lower Middle Cenomanian *Turrilites costatus* Subzone of the *Acanthoceras rhotomagense* Zone, is represented, in condensed form, by a brown or buff-coloured, coarse-grained, calcarenitic unit of variable thickness, which is known as the 'Totternhoe Stone' after the isolated hill situated in front of the main scarp in the northern Chiltern Hills, near Dunstable, where it has been for centuries, and still is, exploited for building stone. The Totternhoe Stone is first encountered at the eastern end of the Berkshire Downs, in the disused Chilton railway cutting (SU 496 858), south of Oxford. In the southern Chiltern Hills, it is well exposed at the **Chinnor Chalk Pit** GCR site.

To the east of Hitchin, for example at **Barrington Chalk Pit** and, in the Northern Province, **Hunstanton Cliffs**, the Totternhoe Stone more or less equates with the 'Cast Bed' of the **Folkestone to Kingsdown** GCR site, and correlative successions, and is overlain by a thin 'ammonite limestone' containing specimens of large, weakly glauconitized ammonites *Parapuzosia* (*Austiniceras*), together with *Orbirhynchia mantelliana*, which represents the third and highest of the three *Orbirhynchia mantelliana* bands of the Southern Province.

Jukes-Browne Bed 7/Buckinghamshire Rag

In the Chiltern Hills, Jukes-Browne Bed 7 (upper Middle Cenomanian *Acanthoceras jukesbrownei* Zone) of the Southern Province is represented by a poorly-developed equivalent of the Nettleton Stone of the Northern Province. This bed typically (e.g. **Chinnor Chalk Pit**; part of the Totternhoe Quarry complex) has a thin marl containing small pycnodonteine oysters at the base, which rests on a burrowed surface. The marl is the correlative of the Nettleton Pycnodonte Marl of the Northern Province (see below). Locally, the marl becomes calcarenitic (e.g. adjacent to the Stone Pit in the Totternhoe Quarry), and may elsewhere (e.g. Pitstone Quarry 2) contain glauconitized and phosphatized pebbles, up to several centimetres across (Figure 4.3). This latter development constitutes the so-called 'Buckinghamshire Rag' of the earlier literature.

In East Anglia, the Jukes-Browne Bed 7 event is represented by the Nettleton Stone of the Northern Province, with its basal dark grey, silty marl full of small oysters (*Pycnodonte*), the Nettleton Pycnodonte Marl – the 'Gryphea Band' of Bower and Farmery (1910). The marl rests here, with conspicuous colour contrast, on intensely hard, creamy-white chalk.

White Chalk Subgroup

As in the Southern Province, the base of the White Chalk Subgroup is taken at the sub-Plenus erosion surface (Figure 4.3) which also marks the base of the Holywell Nodular Chalk Formation. The division of the traditional Middle and Upper Chalk in the Southern Province into formations and members also applies in the Transitional Province with some modifications as units are traced into Norfolk. Two units at the base of the Subgroup, the Plenus Marls Member and Melbourn Rock, have their type localities in this Province.

Plenus Marls Member

It was in the Chiltern Hills and immediately adjacent areas that the Plenus Marls (originally called the 'Belemnite Marls' after the occurrence, in the higher part of the unit, of the belemnite now known as *Praeactinocamax* (formerly *Actinocamax*) *plenus* (Blainville)), were first recognized (Hill and Jukes-Browne, 1886). Throughout the Chiltern Hills, for example at the **Chinnor Chalk Pit** GCR site, Pitstone Quarry 2 RIGS site (SP 949 148) and Sewell Quarry (SP 9945 2236) near Totternhoe, the standard sequence of eight beds established in the Southern Province by Jefferies (1963), can be recognized without difficulty, but significant changes appear near Hitchin. Here the marly Bed 2 may virtually disappear, while the limestone (Bed 3) and the overlying silty Bed 4 may locally become merged to produce the conglomeratic, so-called 'marbled rock' of the earlier literature (e.g. Hill and Jukes-Browne, 1886), which incorporates reworked fossils from both lower (*Orbirhynchia multicostata* Pettitt, *Pycnodonte*) and higher (*Praeactinocamax plenus*) assemblages (see Hopson *et al.*, 1996). In addition, the occurrence in the Plenus Marls of terebratulid brachiopods (*Ornatothyris*), possibly associated with the sub-Bed 2 erosion surface (Jefferies, 1962) here, and throughout eastern England, suggests a change to a shallower water, higher-energy environment. This area falls well within the 'Anglian Trough' (Jefferies, 1963; Hart, 1973) of increased Plenus Marls thicknesses, but some of the sections around Hitchin are highly condensed (see Hopson *et al.*, 1996, fig. 12), and contradict the evidence for this thickness trend.

The Plenus Marls Member thins steadily northwards from Cambridge to **Hunstanton Cliffs** (see GCR site report, this volume). With increasing condensation, the succession (particularly the upper part) becomes more and more difficult to interpret (cf. Jefferies, 1962, fig. 3; 1963, fig. 10). Bed 2 tends to disappear, and Bed 3 retains the nodular character first seen at Hitchin. At Marham (TF 702 078), a conglomeratic bed at the base of Bed 3 contains abundant specimens of *Ornatothyris*, and a thin rusty marl, 0.15 m above the top of Bed 3, is inferred to represent Bed 8. Where most condensed, for example at Hillington Quarry (TF 723 244), SSE of Hunstanton, the Plenus Marls are represented by a marly unit, only a few centimetres thick, resting on a hardground corresponding to the sub-Plenus erosion surface and containing sediment-filled pockets with a fauna of *Ornatothyris latissima* (Sahini), *Orbirhynchia multicostata* and small, depressed forms of the echinoid *Camerogalerus cylindricus* (Lamarck).

Melbourn Rock

In its type area in south Cambridgeshire and north Hertfordshire, the Melbourn Rock crops out on the crest of a prominent feature that was used to survey the newly defined Lower–Middle Chalk boundary on the earliest [British] Geological Survey maps of the region (Penning and Jukes-Browne, 1881). Because part of the Plenus Marls (notably Jefferies' Bed 3) may be extremely indurated in this area, the 'Belemnite Marls' were included in the original concept of the Melbourn Rock, but were later (Hill and Jukes-Browne, 1886) excluded, when the distinctive, essentially marly, character of the Belemnite Marls elsewhere became apparent.

The original named localities were Melbourn (Cambridgeshire), as well as a quarry at Ashwell, and Hitchin railway cutting (TL 196 295). Of these sections, only the Ashwell section (TL 2687 3945) (Hopson *et al.*, 1996, fig. 13) remains, and it is now taken as the stratotype (see discussion by Hopson *et al.*, 1996). The lower part of the type Melbourn Rock includes the group of three intensely cemented marl–limestone rhythms that overlies the Plenus Marls in the Southern Province (the 'Sussex Melbourn Rock' of Mortimore, 1986a; or the Ballard Cliff Member of Gale, 1996).

Although the Melbourn Rock is recognizable thoughout the Chiltern Hills, the upper limit in the earlier literature was applied inconsistently to the west and south of the type area. However, the Melbourn Rock was generally perceived to be poorly fossiliferous, with its top being marked by a gradation to fossiliferous chalks containing inoceramid bivalves (*Mytiloides*) and rhynchonellid brachiopods (*Orbirhynchia cuvieri*). Using the sections in **Chinnor Chalk Pit** and the Pitstone Quarry 2 RIGS site as links, it has proved possible, on a basis of lithostratigraphical and macrofaunal criteria, to correlate the stratotypic Melbourn Rock at Ashwell with successions in the lower part of the Holywell Nodular Chalk Formation at Dover and Eastbourne (Wood, 1993). This correlation shows that the Melbourn Rock represents, in highly condensed form, the terminal Cenomanian strata (upper *Metoicoceras geslinianum* and *Neocardioceras juddii* ammonite zones) and the basal part of the Turonian succession (*Watinoceras devonense* and *Fagesia catinus* ammonite zones).

Holywell Nodular Chalk and New Pit Chalk formations

In the Chiltern Hills and East Anglia the Holywell Nodular Chalk Formation is readily recognizable, albeit relatively condensed, as it is in the North Downs and at Dover. There is, likewise, the usual lithological change at the top of the Holywell Nodular Chalk Formation, marked by the sharp upper limit of shell-detrital chalk. Locally (northern Chiltern Hills and north Hertfordshire) highly flinty chalk is present at the top of the Holywell Nodular Chalk and base of the equivalent of the New Pit Chalk

Formation. In the type area of the Chalk Rock, the sub-Chalk Rock succession (e.g. the **Fognam Quarry** GCR site) can be broadly assigned to the New Pit Chalk Formation, although it is much more flinty than in correlative Southern Province successions (cf. Gale, 1996, fig. 5).

To the east of Hitchin, the most shell-detrital part of the Holywell Nodular Chalk, incorporating the equivalent of the beds at, and immediately below, the *Filograna avita* event of the Anglo-Paris Basin (Gale *et al.*, 1993; Gale, 1996), becomes highly cemented, and comparable in its degree of induration with the Melbourn Rock, with which it has been confused by quarry operators. This distinctive unit, which is delimited by marl seams, and which in the Chiltern Hills is relatively friable, has been formally designated the 'Morden Rock' by the British Geological Survey after the type locality at the Steeple Morden Plantation Quarry (TL 298 402), near Ashwell (Hopson *et al.*, 1996). The overlying succession, up to the top of the Holywell Nodular Chalk Formation, is characterized in the central Chiltern Hills, for example at the Ivinghoe-Aston Pit (SP 960 176), Totternhoe, and in north Hertfordshire (Steeple Mordern Plantation Quarry), by a remarkable development of flint, producing flinty (albeit shell-detrital) chalks that are reminiscent of parts of the traditional Upper Chalk. The flinty chalk begins above a marl seam (the Aston Marl) that is named after the Ivinghoe-Aston Pit and locally includes a more strongly developed flint (Morden Flint) that preserves valves of *Mytiloides*. This occurrence of flinty chalk is demonstrably structurally controlled, for it is absent from the thinner, more condensed, successions developed over minor anticlines (cf. Hopson *et al.*, 1996, fig. 14). The flinty chalk in this area continues into the overlying basal part of the equivalent of the New Pit Chalk Formation of the Southern Province.

With the exception of the Holywell Nodular Chalk at the top of the Grey Chalk Subgroup escarpment, the Holywell Nodular Chalk and New Pit Chalk formations are poorly exposed in East Anglia, where they occupy mostly low-relief ground. The full succession, and also the lower part of the Lewes Nodular Chalk, was penetrated in cored boreholes and shafts at Mundford, south Norfolk and the composite section proved there provides a standard stratigraphy (Ward *et al.*, 1968) that is applicable throughout East Anglia. This comprises a framework of laterally persistent marl seams, fossil horizons and variably developed beds of flint. The marl seams have been tentatively correlated with marl seams in other depositional areas. In ascending order, the Mount Ephraim, Twin Marls, Grimes Graves Marl and West Tofts Marl of Mundford can be equated with the Southerham Marl 1, Caburn Marl, Bridgewick Marl 1 and Lewes Marl of the Southern Province succession; and with the Melton Ross Marl, Deepdale Marl 1, North Ormsby Marl and Ulceby Marl of the Northern Province succession (cf. Mortimore and Wood, 1986, figs 2.3, 2.6). Correlation of the marl seams below the Mount Ephraim Marl (e.g. Pilgrims Walk, Denton Lodge), with named marl seams elsewhere is more controversial. The Northern Province stratigraphy, rather than that of the Transitional Province applies in north Norfolk (e.g. see **Hunstanton Cliffs** GCR site report, this volume).

Lewes Nodular Chalk Formation

In the Transitional Province, the Lewes Nodular Chalk Formation with its nodular beds and/or coarse, gritty chalks can be traced through the Chiltern Hills into southern East Anglia. Within the region are the type localities for both the Chalk Rock and the Top Rock. The development of both the Chalk Rock and the Top Rock varies to such an extent that the Lewes Nodular Chalk Formation is, in places, only a few metres thick, and in others expands up to several tens of metres.

Chalk Rock Member

The Chalk Rock is a complex of hardgrounds and condensed successions that varies stratigraphically from place to place. Its type locality is in the Marlborough Downs at Ogbourne Maizey, Wiltshire (SU 180 716) on the southern margin of the Transitional Province. Here the Chalk Rock comprises three groups of named hardgrounds, the so-called Bottom, Middle and Top suites (Bromley and Gale, 1982, fig. 3; Figure 4.4; Figure 3.41, Chapter 3). The pebble bed associated with the terminal hardground of the top suite, named the 'Hitch Wood Hardground' after a locality in Hertfordshire, yields the so-called '*reussianum* fauna' of well-preserved phosphatized and glauconitized moulds of originally aragonite-shelled molluscs (notably ammonites and gastropods) for which

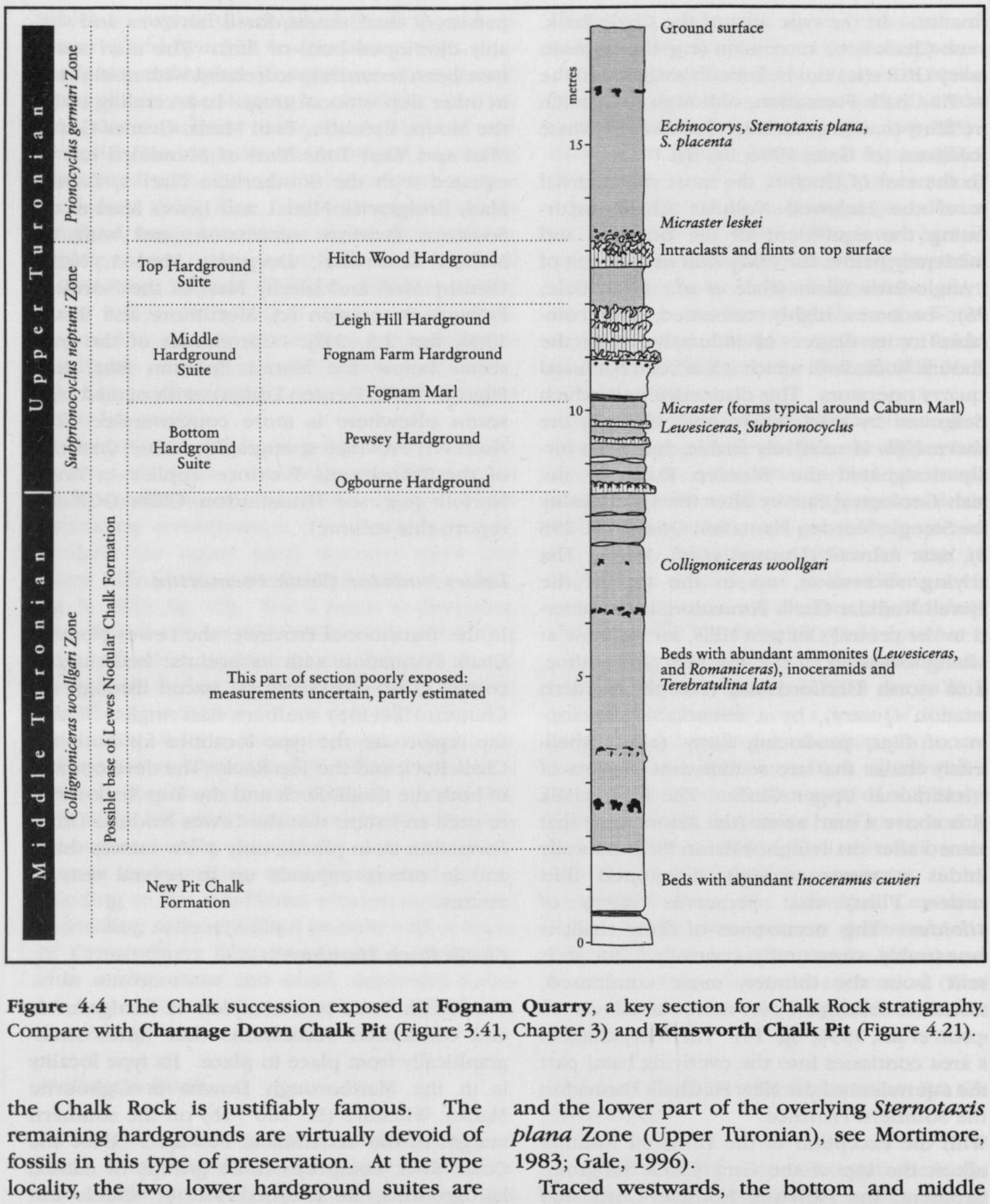


Figure 4.4 The Chalk succession exposed at **Fognam Quarry**, a key section for Chalk Rock stratigraphy. Compare with **Charnage Down Chalk Pit** (Figure 3.41, Chapter 3) and **Kensworth Chalk Pit** (Figure 4.21).

the Chalk Rock is justifiably famous. The remaining hardgrounds are virtually devoid of fossils in this type of preservation. At the type locality, the two lower hardground suites are separated by a conspicuous grey marl seam, the Fognam Marl, which is named after the type locality at **Fognam Quarry**. At its maximum development, the Chalk Rock Member represents, in a condensed form, the whole of the lower Lewes Nodular Chalk Formation and possibly part of the topmost New Pit Chalk Formation (i.e. a large part of the *Terebratulina lata* Zone (Middle and basal Upper Turonian) and the lower part of the overlying *Sternotaxis plana* Zone (Upper Turonian), see Mortimore, 1983; Gale, 1996).

Traced westwards, the bottom and middle hardground suites coalesce, occluding the Fognam Marl. On the other side of the Vale of Pewsey, at the western termination of Salisbury Plain, the top and middle suites also progressively coalesce and, at its extreme development on the Cley Hill outlier near Warminster (ST 839 447), the entire Chalk Rock condenses to a complex unit of chalkstones less than 1 m thick (Bromley and Gale, 1982, fig. 12; Gale, 1996, fig. 6).

To the east, in the direction of the Chiltern Hills, the bottom suite disappears, and the Chalk Rock comes to be represented only by the two higher suites, these being underlain in most localities by a marl seam that is generally inferred to be the Fognam Marl. Extreme condensation of the middle and top suites is found in the area around Henley, producing a unit, less than 1 m thick, of closely spaced hardgrounds that was termed by Hill (1886) the 'Henley Rock'. This type of development is seen in the nearby **Aston Rowant Cutting** GCR site.

Traced laterally into the Chiltern Hills, the middle suite of hardgrounds also disappears, and the Chalk Rock is eventually represented only by the top suite (i.e. the Hitch Wood Hardground and the subjacent chalkstone) underlain by several widely spaced marl seams, for example at **Kensworth Chalk Pit**, and the Hill End Pit, (TL 197 240). This type of development of the Chalk Rock is known as the 'Hitch Wood facies' (Hopson *et al.*, 1996). In north Hertfordshire, apparently under structural control, the complex phosphatized and glauconitized Hitch Wood Hardground, and its associated pebble bed, weakens and divides into two closely-spaced mineralized, fossiliferous hardgrounds; a glauconitized (green) hardground, followed by a phosphatized (brown) hardground. This development is termed the 'Reed facies', after the Reed Chalk Pit RIGS site (TL 359 371), where it is best seen (Bromley and Gale, 1982, fig. 13; Gale, 1996, fig. 7; Hopson *et al.*, 1996, fig. 17).

The Chalk Rock in the southern part of East Anglia is represented only by one or more closely spaced beds of patchily indurated nodular chalk containing small-sized elements of the characteristic *reussianum* fauna (Hewitt, 1924, 1935). The underlying giant grey flints (0.2–0.4 m thick) of the Grimes Graves and other flint mines in the vicinity of Brandon, constituting the so-called 'Brandon Flint Series' (Skertchly, 1879; Hewitt, 1935), and long exploited first for tools and latterly for gun-flints, were used by the British Geological Survey (Wood and Bristow in Bristow, 1990, fig. 8) to map the base of the traditional Upper Chalk. These flints are transitional in morphology between the large, black, irregularly shaped nodular flints associated with the Bridgewick Marls of the Southern Province (the 'Basal Complex') and the group of giant, predominantly tabular, grey flints (Ravendale, Triple Tabular and Ludborough) at the base of the Burnham Chalk Formation of the Northern Province (Mortimore and Wood, 1986, figs 2.3, 2.6; Wood, 1992; Figure 5.4, Chapter 5).

Swaffham railway cutting exposed a historically important section ranging from the higher part of the New Pit Chalk Formation to the upper Lewes Nodular Chalk Formation. The now extensively degraded, and partly backfilled, railway cuttings west of Swaffham (TF 799 094–TF 804 094), exposed key sections in the *T. lata*, *S. plana* and *M. cortestudinarium* zones, in ascending order, from west to east. There are no published sections of the cuttings, but descriptions by Rowe (in manuscript) refer to thick, semi-continuous tabular flints of Northern Province type and also to paramoudras. The characteristic Northern Province echinoid genus, *Infulaster*, is relatively common here in the Turonian strata. The easternmost cutting yielded rich faunas of Upper Turonian and, particularly, Lower Coniacian inoceramid bivalves, including specimens figured by Woods (1912), for example the zonal index fossil *Cremnoceramus crassus inconstans* (Woods) (Figure 2.18, Chapter 2) and of *C. waltersdorfenis waltersdorfensis* (Andert) (Figure 2.19, Chapter 2). The adjacent quarry, which presumably exposed a slightly higher Coniacian section, was the source of a mixed assemblage of southern and northern species of the echinoid *Micraster*.

Understanding of the relationship between the basinal chalk successions and the highly condensed successions (Bromley and Gale, 1982; Mortimore, 1983a; Mortimore and Pomerol, 1987; Gale, 1996) comprising the various developments of the Chalk Rock remains one of the major unsolved problems of English Chalk stratigraphy. The solution to this problem depends on successfully tracing the marl seams of the basinal successions, as they progressively disappear, via the transitional nodular chalk facies, into the condensed hardground facies of the platforms and structural highs. For example, the Lewes Marl is occluded throughout much of the North Downs and Chiltern Hills but is present in boreholes in the Thames, through Essex and through much of East Anglia.

Top Rock

In much of the Transitional Province the Chalk Rock forms the base of the Lewes Nodular Chalk Formation and is overlain by coarse-grained flinty chalks that can be assigned to the upper Lewes Nodular Chalk Formation. Beginning in the southern Chiltern Hills, condensation of the Navigation, Cliffe, Hope Gap and Beeding hardgrounds of the Southern Province forms the strongly glauconitized Top Rock hardground. In the northern Chiltern Hills and in Hertfordshire, the interval from the top of the Chalk Rock up to the top of the Top Rock is extremely condensed (< 3 m) and contains several glauconitized hardgrounds and nodular chalks, the Kensworth Nodular Chalk Member (Hopson *et al.*, 1996). The Top Rock of the Transitional Province, therefore, includes the greater part of the (Lower Coniacian) *Micraster cortestudinarium* Zone. The dominant hardground is overlain by glauconitized fossils including sponges in pebble preservation and internal moulds of echinoids, such as *Micraster* and *Echinocorys*.

The Top Rock is well exposed in the **Aston Rowant Cutting** and **Kensworth Chalk Pit** (see GCR site reports, this volume). The most northerly proved occurrence of the Top Rock is in the shafts near Mundford, Norfolk (Ward *et al.*, 1968), and it has been proved in road cuttings and trial pits as far east as Bury St Edmunds (Wood and Bristow, 1990). Some of the latter were remarkably fossiliferous: they yielded the same terebratulid brachiopods and Lower Coniacian inoceramid bivalves as the Top Rock at **Kensworth Chalk Pit** and Redbournbury Quarry, Hertfordshire (TH 123 103) (Figure 4.1, and p. 347), together with a diverse assemblage of sponges, corals, the rhynchonellid brachiopod *Cretirhynchia subplicata* (Mantell), echinoids and elements of a fauna of *reussianum* type, including moulds of small gastropods and bivalves. The sponges and the echinoids (*Echinocorys gravesi* (Desor), *Micraster cortestudinarium* (Goldfuss)) are heavily glauconitized, and tend to be concentrated on the terminal hardground, whereas the inoceramid bivalves, which include *Cremnoceramus* ex gr. *waltersdorfensis* (Andert), are variably phosphatized (for details see Wood and Bristow, 1990). Farther to the east, in the cored Stowlangtoft Borehole (TL 9475 6882), the Top Rock is represented by several beds of nodular chalk. There is no evidence of Top Rock in the essentially Northern Province-type succession in the Swaffham railway cutting. In the Trunch Borehole, a strongly glauconitized hardground overlain by chalks with the same inoceramid bivalves as occur in the Top Rock elsewhere is inferred (Wood *et al.*, 1994) to represent the Navigation Hardground of the Southern Province; here the extreme condensation represented by the Top Rock is not developed.

Overlying the Top Rock are rather coarse-grained, flinty and partly nodular chalks that can be assigned satisfactorily to the upper part of the Lewes Nodular Chalk Formation. The lithological change at this level to highly flinty chalks is particularly conspicuous. However, the highest part of the interval up to the correlative of the Shoreham Marls at the base of the Seaford Chalk Formation, although gritty, is not as nodular as its Southern Province correlative but it does contain the conspicuous Beachy Head Zoophycos Beds.

Seaford Chalk and Newhaven Chalk formations

Over much of the region, the sub-Palaeogene surface lies at a relatively high level in the Seaford Chalk Formation. For an apparently homogeneous soft, white chalk unit, the Seaford Chalk Formation is extraordinarily variable in the Transitional Province. In the vicinity of Newbury, higher chalks stratigraphically equivalent to the Newhaven Chalk Formation of the Southern Province are preserved beneath the Palaeogene sediments. In the same area, and near Maidenhead, deep channels cut into the Seaford Chalk, and presumably initiated under structural control, are filled by non-flinty phosphatic chalk. There are several conspicuous features including the presence locally of well-developed hardgrounds (e.g. Clandon Hardground) and the development of phosphatic chalks and slump folds.

Clandon Hardground

In an area stretching from the North Downs westward to the Berkshire Downs, a significant hardground is locally developed over structural highs at the boundary between the *Micraster coranguinum* Zone and the overlying crinoid zones. This strongly mineralized hardground, which is the indurated lateral equivalent of the Barrois' Sponge Bed of the **Thanet Coast**, forms the floor of the Chislehurst chalk caves in south London, and takes its name of Clandon Hardground (Robinson, 1986) from the West Clandon Quarry (TQ 038 508), east of

Guildford. The same hardground is inferred to correlate with the Whitway Rock, described by Hawkins (1918) from the area south of Newbury, and it is also found below the phosphatic chalks (see below) north of Newbury, and at **South Lodge Pit**, Taplow, near Maidenhead (see GCR site report, this volume).

Phosphatic chalks in the Newhaven Chalk Formation

In the Newhaven Chalk Formation of the Transitional Province (Upper Santonian–Lower Campanian crinoid zones to *Offaster pilula* Zone inclusive) several different lithologies are found. One lithology found in the east around Sudbury and Ipswich is a very strange, homogeneous, poorly flinty, creamy soft chalk. None of the usual marker beds are present and there may be evidence of severe truncation by channels (T. Wright, pers. comm.). In the Berkshire Downs (**Boxford Chalk Pit** and **Winterbourne Chalk Pit** GCR sites), and Chiltern Hills (**South Lodge Pit** GCR site), are highly condensed successions, only a few metres thick, of brown, flintless, highly fossiliferous chalks rich in pelletal phosphate. These phosphatic chalks are of only very limited areal extent, and they typically rest on a lithified erosion surface or on a glauconitized and/or phosphatized hardground. They have been compared with similar phosphatic chalks in northern France. On the northern edge of the Province on the Norfolk coast the Newhaven Chalk is represented by chalks with marl seams (Wells Quarry) which may correlate to both the Southern and Northern provinces.

The 'High Chalk' of East Anglia

Above the Top Rock in the Transitional Province, particularly in East Anglia, there are only discontinuous inland exposures of the overlying interval up to the Upper Campanian strata. There were formerly numerous small pits and quarries throughout East Anglia (see Peake and Hancock, 1961, 1970; Wood, 1988 for review and comprehensive references).

It is probable that at least the Seaford Chalk Formation will be mapped through this region in the future (but see comments above). The biostratigraphical equivalent of the Seaford Chalk, the *M. coranguinum* Zone, is known in several places. The basal beds of the *coranguinum* Zone are exposed in the partly filled Titchwell Parish Pit (TF 762 433): here flinty chalk with marl seams (equivalent to the Belle Tout Beds of the Southern Province), has yielded the basal Middle Coniacian inoceramid bivalve zonal index fossil, *Volviceramus koeneni* (Müller). This species was also identified in the Trunch Borehole (Wood *et al.*, 1994). A chalk pit (TL 895 776) south of Thetford, exposing chalk higher in the *coranguinum* Zone (upper part of the Belle Tout Beds and base of the overlying Cuckmere Beds), contains some of the most prolific Middle Coniacian inoceramid bivalve assemblages to be found anywhere in Britain. In addition to *Platyceramus mantelli* and *Volviceramus* spp., the assemblage includes undescribed forms that may be conspecific with coeval taxa described from North America. An important section of the top of the *coranguinum* Zone and, questionably, the base of the overlying *Uintacrinus socialis* Zone, is exposed east of Bury St Edmunds, at Stowlangtoft Quarry (TL 9475 6882) (Wood and Bristow, 1990, pp. 27–8, fig. 10). The Stowlangtoft Borehole, sunk in the floor of this pit, cored 211 m of Chalk down to the base of the Cambridge Greensand (Bristow, 1990).

Large, sparsely fossiliferous sections in almost flintless, very soft chalk inferred to span the boundary between the *Uintacrinus socialis* Zone and overlying *Marsupites testudinarius* Zone are exposed in Sudbury beneath the Palaeocene Thanet Beds (Pattison *et al.*, 1993). Parts of the Lower Campanian succession (*Offaster pilula* and basal *Gonioteuthis quadrata* zones) were reported to be formerly exposed in large quarries in and adjacent to the Gipping valley, north of Ipswich (Jukes-Browne, 1904; Boswell, 1913; Brydone, 1932a,b; Markham, 1967) but with the exception of Great Blakenham (TM 112 499) these have been backfilled. There are no detailed published sections of any of these quarries, and this part of the succession consequently remains poorly understood.

A key section of chalk with marl seams (Newhaven Chalk Formation), through the higher part of the *O. pilula* Zone and the basal part of the *quadrata* Zone is exposed in the abandoned quarry at Wells (TF 928 429). It yields the zonal index fossil *Offaster pilula* and, in the higher beds, common specimens of *Echinocorys* and *Gonioteuthis quadrata*. The section is also important because it includes an unnamed marl seam that was also found in the Trunch Borehole. This marl seam has previously been correlated on macrofaunal grounds (Wood *et al.*, 1994) with the vulcanogenic Old Nore Marl of the Southern Province and the M1 marl of the northern German standard succession at Lägerdorf (Schönfeld and Schulz, 1996). However, the microfaunal evidence (Swiecicki, 1980) suggests that this interpretation may be incorrect, and that the marl seam may perhaps correlate with a stratigraphically higher marl close to the top of the *pilula* Zone.

The *quadrata* Zone succession is very poorly exposed. The only complete succession is in the Trunch Borehole and this cannot readily be correlated with that in the south. Two closely spaced, weakly phosphatized hardgrounds at the top of the zone were inferred (Wood *et al.*, 1994) to reflect the same tectonic event (Peine) that is expressed, in southern England, by the Downend Hardgrounds at the **Downend Chalk Pit** GCR site (Mortimore and Pomerol, 1997; Mortimore *et al.*, 1998).

The Upper Campanian Chalk (traditional *Belemnitella mucronata* Zone) has been extensively worked in and around the city of Norwich in numerous pits and shallow mines. The early collectors of fossils recognized that these exposures yielded a rich, prolific and superbly preserved fauna that was distinctly different from that of the remainder of the English Chalk, and comparable with that of the Chalk of Meudon near Paris. This composite succession came to be known as the 'Norwich Chalk' (see Figure 4.5). Most of these sections are now backfilled, but there are discontinuous exposures of parts of the succession in the cliffs and foreshore between Weybourne Hope and Cromer.

Peake and Hancock (1961, 1970) divided the Norwich Chalk into several loosely delimited faunal units based largely on macrofossil collections and field observations made by Rowe (in manuscript) and a series of key papers by Brydone (1922, 1930, 1938). These were, in ascending order: Basal *mucronata* Chalk, Eaton Chalk, Weybourne Chalk, Catton Sponge Bed, Beeston Chalk and Paramoudra Chalk. This nomenclature was subsequently modified by Wood (1988) who, recognizing that the stratotype Eaton Chalk included the basal beds of the Weybourne Chalk, combined the Basal *mucronata* Chalk and Eaton Chalk to form the pre-Weybourne Chalk; and divided the Weybourne Chalk into three faunal belts and the Paramoudra Chalk into two. Johansen and Surlyk (1990) gave formal lithostratigraphical member status to the units from the Eaton Chalk upwards. The two 'Norwich Chalk' GCR sites (**Caistor St Edmund Chalk Pit** and **Catton Grove Chalk Pit**) provide a partial composite section through the highest part of the Weybourne Chalk and part of the Beeston Chalk Formation.

The onshore Maastrichtian Chalk (traditional *Belemnella lanceolata* Zone *sensu lato*) is exposed only in cliff and foreshore sections cut through isolated glacio-tectonic deformed erratic masses in the Anglian Till on the Norfolk coast **Overstrand to Trimingham Cliffs** GCR site. It is present *in situ* beneath the glacial deposits in the Trunch Borehole (Wood *et al.*, 1994), and it can be traced in the subcrop as far south as Wroxham (Whittlesea, 1991) and the valley of the Yare, east of Norwich (Arthurton *et al.*, 1994). The stratigraphically highest successions in the glacial erratics collectively constitute the informally named 'Trimingham Chalk' of earlier workers, and represent the youngest Chalk preserved onshore in England.

As in the case of the 'Norwich Chalk', the early workers appreciated the distinct nature of the Trimingham fauna, recognizing that many of the fossils had been described from the glacio-tectonic masses exposed in the cliffs of the island of Rügen in the Baltic. They inferred that the Trimingham Chalk lay above the Norwich Chalk. Belemnites are very common in the former, and extensive collections were made by Brydone. Jeletzky (1951) realized that these belemnites belonged not to the Upper Campanian zonal index fossil *Belemnitella mucronata,* as previously thought, but to the diagnostic Maastrichtian genus *Belemnella*, including forms related to the then standard European zonal index fossil *B. lanceolata*. He thereby broadly confirmed Brydone's own ideas (1900, 1906), based largely on bryozoa and serpulids, regarding the similarity between the Trimingham and the Lower Maastrichtian Rügen faunas.

Brydone (1906) subdivided the Maastrichtian succession into, in ascending order, the *Porosphaera* Beds; the Sponge Beds; the White Chalk without *Ostrea lunata*; the White Chalk with *Ostrea lunata*; and the Grey Beds. Wood (1967) split off the lower part of the

Stage		Southern England	Norfolk (Peake and Hancock, 1961, 1970)	Belemnites	Echinoids	Norfolk (Johansen and Surlyk, 1990)	Norfolk (Christensen, 1995, 1999)	
Maastrichtian	Upper	Not represented	Not represented	*Belemnella kazimirovensis*	Not represented	Not represented	Not represented	*Belemnella*
				Belemnitella junior				
	Lower		Grey Beds	*Belemnella licharewi*	*Echinocorys* aff. *limburgica*	Beacon Hill Grey Chalk		*Belemnella sumensis*
			White Chalk with *O. lunata*		*Echinocorys ciplyensis*	Little Marl Point Chalk Member		
			Sponge Beds	*Belemnella lanceolata*	*Echinocorys belgica*	Trimingham Sponge Beds Member	*Belemnitella minor* II [*minor* III]	*Belemnella obtusa*
			Porosphaera Beds					
			Sidestrand Chalk		*Echinocorys* passage forms	Sidestrand Chalk Member		*B. pseudobtusa*
Campanian	Upper		Paramoudra Chalk	*Belemnitella langei* dominant	*Echinocorys pyramidata* Portlock	Paramoudra Chalk Member	*Belemnitella minor* II	*B. lanceolata*
					?			
			Beeston Chalk		*Echinocorys conoidea* *Galerites roemeri-abbreviatus*	Beeston Chalk Member	*Belemnitella minor* I	
					Echinocorys aff. *conoidea* *Cardiotaxis ananchytis*			
			Catton Sponge Bed	*Belemnitella mucronata minor* and allied forms common	*Echinocorys ovata* auctt.	Catton Sponge Bed		
			Weybourne Chalk		*Echinocorys gibba* *M. stolleyi*	Weybourne Chalk Member	*Belemnitella woodi*	
					Echinocorys subglobosa fonticola			
		Highest Chalk Isle of Wight and Dorset						
		Belemnitella mucronata Zone	Pre-Weybourne Chalk [Eaton Chalk]	*Belemnitella mucronata* sensu stricto	*Echinocorys subglobosa* *C. heberti*	Eaton Chalk Member	*Belemnitella mucronata* sensu stricto	
					Echinocorys pyramidata auctt. var. *quenstedi*			
					Echinocorys marginata approaching *subglobosa*			
		Base of Zone in Hampshire	Pre-Weybourne Chalk [Basal Mucronata Chalk]		*Echinocorys lamberti*			
		-------(2)-------			*Echinocorys lata fastigata*			
	Lower (pars.)	*Gonioteuthis quadrata* Zone	*Gonioteuthis* Zone	*Gonioteuthis quadrata*	?			

Figure 4.5 The 'high' Chalk of Norwich and north Norfolk based on Peake and Hancock (1961, 1970); Wood (1988); Johansen and Surlyk (1990); and Christensen (1995, 1999).

Porosphaera Beds exposed in the glacio-tectonic masses at Overstrand as the pre-*Porosphaera* Beds. Johansen and Surlyk (1990), placed the entire succession in the glacio-tectonic slices that lay stratigraphically beneath the Sponge Beds, irrespective of whether or not it included Upper Campanian strata, into a formally defined 'Sidestrand Chalk Member'. In addition, they introduced the 'Trimingham Sponge Beds Member' for the Sponge Beds; the 'Little Marl Point Chalk Member' for the bipartite White Beds; and the 'Beacon Hill Grey Chalk Member' for the Grey Beds.

FOGNAM QUARRY, BERKSHIRE DOWNS, BERKSHIRE (SU 298 800)

Introduction

Fognam Quarry is a large abandoned chalk pit on the west side of the B4000 road, 3 km WNW of Lambourn (Figure 4.6). It is a key section through the Chalk Rock Member close to its type locality and area of maximum development. It is also the type locality for the (intra-Chalk Rock) Fognam Marl, and for the Fognam Farm Hardground, one of the component hardgrounds of the Chalk Rock. The succession below the Chalk Rock is crucial to resolving the continuing and contentious problem of the stratigraphical relationship between the Chalk Rock and the basinal Southern Province successions, and to determining the base level of sub-Chalk Rock erosion. It is also of importance to British Upper Cretaceous ammonite biostratigraphy because two of the international Middle Turonian zonal index ammonites, *Romaniceras* (*Yubariceras*) *ornatissimum* (Stoliczka) and *Collignoniceras woollgari* (Mantell), have both been collected *in situ*. The Fognam site has provided the lowest record in Britain of the ammonite genus *Subprionocyclus*, which has enabled the base of the international basal Upper Turonian *Subprionocyclus neptuni* ammonite Zone to be approximately identified in the lower part of the Chalk Rock standard succession.

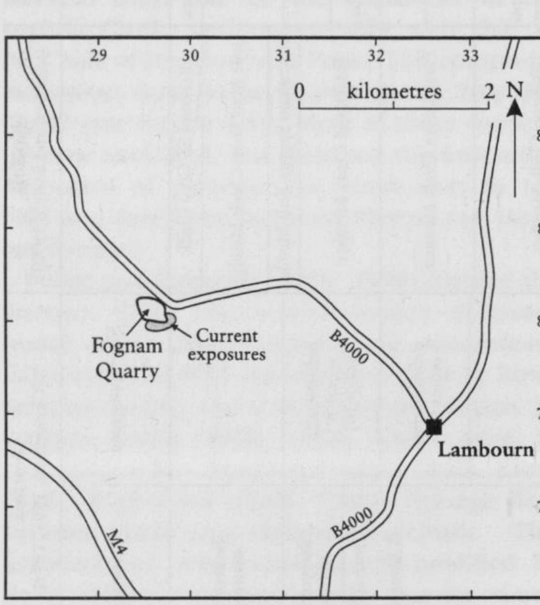


Figure 4.6 Location of Fognam Quarry (Fognam Farm), near Lambourn, Berkshire.

Description

The rapidly degrading faces of Fognam Quarry expose a section from 9 m below the Chalk Rock to some 3 m above the Chalk Rock. Details of the Chalk Rock succession were given by Bromley and Gale (1982). Mortimore (1987, fig. 5) correlated the section with geophysical downhole wireline logs of boreholes in the vicinity, and with other Chalk Rock localities including Beggar's Knoll Quarry and **Shillingstone Quarry** (see GCR site report, this volume). Wray and Gale (1993) described the clay mineral trace-element geochemistry of the Fognam Marl and the marl beneath the lowest hardground (Ogbourne) of the Chalk Rock, using this evidence to demonstrate a different interpretation of the correlation between the condensed Chalk Rock and expanded basinal successions from those of Bromley and Gale (1982) and Mortimore (1987). Wright and Kennedy (1981) gave a graphic log with macrofossil data down to the Ogbourne Hardground, and illustrations of Middle Turonian ammonites from the section beneath this hardground. Gale (1996) used the site as a key element in a sequence stratigraphical and cyclostratigraphical interpretation of the Turonian Stage, and discussed the significance of the ammonite biostratigraphy.

Lithostratigraphy

The lower part of the section (Figure 4.4) exposes *c.* 8 m of chalk with flints and marl seams, the lowest 2 m of which can be assigned to the New Pit Chalk Formation of the Southern

Province. Some of the flints have distinctively lilac-coloured cortices and grey-black cores. Above the highest flint band are found the two hardgrounds that constitute the bottom hardground suite (Bromley and Gale, 1982) of the Chalk Rock. Both of these hardgrounds are much less well cemented and mineralized, as well as showing a much lower relief, than the same hardgrounds in the Chalk Rock type section at Ogbourne Maizey (SU 180 716). The lower (Ogbourne) hardground is glauconitized and near-planar, and the subjacent chalkstone possesses a distinctive patchy orange coloration. It is overlain by weakly nodular, coarse-grained, highly fossiliferous, shelly chalk, which terminates in a poorly lithified thin, pink-coloured chalkstone and a near-planar pinkish-brown phosphatized surface. This higher (Pewsey) hardground is a poor development of the strongly phosphatized, highly convolute hardground of the type section. The chalk immediately above the hardground contains common brown phosphatized intraclasts, including small fossils such as internal moulds of inoceramid bivalves and ammonites.

The bottom hardground suite of the Chalk Rock is separated from the middle and top suites by an interval of flintless chalk containing a conspicuous 0.02–0.1 m thick silty greyish marl seam, the Fognam Marl, for which this is the type locality. The marl contains scattered glauconite grains and small phosphatized and glauconitized intraclasts, which also occur in the chalk immediately above and below. The hardgrounds and associated chalkstones that comprise the middle and top hardground suites are moderately well exposed. The lowest (Fognam Farm) hardground is strongly glauconitized, distinctively dark bottle-green in colour and overlain by a 0.1 m lag of even darker green pebbles. The hardground succession is essentially similar to that at Ogbourne Maizey, but the top hardground (Leigh Hill) of the middle suite is overlain here by a minor hardground, and the Hitch Wood Hardground is single rather than double, with a hummocky, instead of convolute, relief (see Bromley and Gale, 1982, fig. 12). There are also several unnamed glauconitized hardgrounds. The chalk immediately above the Hitch Wood Hardground contains glauconitized pebbles and small irregular carious burrow-form flints. The Chalk Rock is overlain by *c.* 3 m of white chalk containing a single flint band near the top of the section.

Biostratigraphy

The section extends from a level in the *Terebratulina lata* Zone to high in the *Sternotaxis plana* Zone. The diminutive zonal index brachiopod, *Terebratulina lata* R. Etheridge, occurs above the lowest conspicuous flint band and, together with the terebratulid brachiopod *Gibbithyris* sp. in the interval between the Ogbourne and Pewsey hardgrounds, where it is common. It is also common at the level of the Fognam Marl.

The inoceramid bivalve *Inoceramus cuvieri* J. Sowerby is particularly common below the marl seams at the base of the succession. The overlying flinty succession has yielded several in-situ specimens of the international Middle Turonian zonal index ammonite *Romaniceras (Yubariceras) ornatissimum* (e.g. Wright and Kennedy, 1981, pl. 15, fig. 1). The 2 m interval below the Ogbourne Hardground contains ammonites, including the Middle Turonian zonal index species *Collignoniceras woollgari*, as well as *Lewesiceras peramplum* (Mantell) and *Scaphites* sp.. Well-preserved inoceramid bivalves (some with the valves articulated), including *I. cuvieri*, are common at this level. In addition to indeterminate inoceramids, the phosphatized internal moulds above the Pewsey Hardground include the heteromorph ammonite *Sciponoceras bohemicum* (Fritsch) and a *Subprionocyclus* intermediate between *S. neptuni* (Geinitz) and *S. branneri* (Anderson) (Gale, 1996). Of particular interest is the occurrence of primitive forms of the echinoid *Micraster* in the interval from immediately below the Fognam Marl and the Fognam Farm Hardground. These have plate structures similar to those of *Micraster* from the Caburn Marl in Sussex.

The *reussianum* fauna of the terminal (Hitch Wood) hardground of the Chalk Rock at this locality is not particularly noteworthy, in comparison to its richness at **Kensworth Chalk Pit** (see GCR site report, this volume) and at the type locality, the Hill End Pit in Hertfordshire. The beds above the Chalk Rock contain the zonal index echinoid, *Sternotaxis plana* (Mantell) as well as *Sternotaxis placenta* (Agassiz), *Echinocorys* hexactinellid sponges, brachiopods, the spinose bivalve *Spondylus spinosus* (J. Sowerby) and *Micraster* sp. (Wright and Kennedy, 1981, fig. 6).

Interpretation

The succession at this site is critical to the understanding of the stratigraphical position of the Chalk Rock in relation to the expanded basinal successions of the Southern Province. Using a combination of flint band correlation and cyclostratigraphy (the succession of inferred precession-controlled marl–chalk couplets), Gale (1996, fig. 5) correlated the short section below the Ogbourne Hardground with the key section at Beggars Knoll Quarry, Wiltshire (ST 890 506) and with sections on the south coast, ranging from Ballard Head (part of the **Handfast Point to Ballard Point** GCR site) in Dorset, through the Isle of Wight **Compton Bay** GCR site and Culver Cliff, to the expanded section at Beachy Head, Eastbourne and the condensed section at Dover (part of the **Folkestone to Kingsdown** GCR site). All of these sections span the complete interval from the top of the Holywell Nodular Chalk Formation to the lithified erosion surface forming the Ogbourne Hardground and its inferred lateral correlative in the basinal succession. It should be noted that use, in the older literature, of the term 'Spurious Chalk Rock' (Rowe, 1901, 1908) for intra-*Terebratulina lata* Zone hardgrounds in the Dorset and Isle of Wight sections refers mainly (but not exclusively) to the glauconitized Ogbourne Hardground (see Bromley and Gale, 1982).

In Gale's interpretation, the marl seam *c.* 1 m below the Ogbourne Hardground at Fognam Quarry is the Round Down Marl (Robinson, 1986: Malling Street Marl of Mortimore 1983, 1986a) of the condensed section at Dover and the marl component of couplet F20 of the expanded successions. On this basis, he demonstrated (Gale, 1996, fig. 5) that pre-Ogbourne Hardground erosion had cut down more deeply into the New Pit Chalk Formation at Fognam Quarry than elsewhere. For example, an additional 16 couplets above F20 can be identified beneath the Ogbourne Hardground at Ballard Head, the hardground itself representing the lithification of the chalk component of couplet F36. Extending this interpretation to the expanded basinal section at Beachy Head, Eastbourne, Gale (1996, figs 2, 5) identified the Ogbourne surface at a level of weakly nodular chalk in the New Pit Chalk Formation, some 5 m below New Pit Marl 1. He also correlated (his fig. 6) the distinctively pink-coloured phosphatized Pewsey Hardground with a level of pink-coloured phosphates high in the interval between the Glynde Marls and Southerham Marl 1 and, consequently, equated the overlying Fognam Marl with Southerham Marl 1.

The corollary of Gale's interpretation is that an interval (20–40 m thick) in the basinal succession, from just above the Round Down Marl (Malling Street Marl) in the New Pit Chalk, to a level at or above the base of the Lewes Nodular Chalk Formation, may be missing at the Ogbourne Hardground surface at Fognam and correlative localities.

Gale (1996, fig. 8) additionally applied a sequence stratigraphical interpretation to the succession of hardgrounds that comprises the Chalk Rock in and adjacent to the type area. In his model, the two most strongly glauconitized hardgrounds, the Ogbourne Hardground at the base of the bottom suite, and the Fognam Farm Hardground at the base of the middle suite, represent major sequence boundaries. The variable position of the surface in the basinal succession that corresponds to the Ogbourne sequence boundary has been discussed above. Given that the Fognam Marl in the type area is the equivalent of Southerham Marl 1, the overlying Fognam Farm sequence boundary must relate to a surface in the interval of relatively nodular chalks between Southerham Marl 1 and the Caburn Marl. Erosion associated with both of the sequence boundaries has proceeded to a varying extent according to the depositional and/or structural position. Although the greater degree of erosion is associated with the Ogbourne sequence boundary, Gale (1996) noted that pre-Fognam Farm erosion had locally (e.g. at some localities in the Chiltern Hills) cut down to a level beneath the equivalent of Southerham Marl 1; at such localities, the sub-Chalk Rock 'Fognam Marl' was a Glynde Marl (cf. Wray and Gale, 1993) and not the correlative of the Fognam Marl of the type area. In contrast to the main glauconitized hardgrounds, the two main phosphatized (Pewsey and Hitch Wood) hardgrounds of the Chalk Rock are inferred (Gale, 1996, fig. 8) to represent transgressive (onlap) surfaces belonging to Turonian sequences 3 and 4 respectively.

Gale's interpretation of the Fognam Marl and the underlying weakly developed Pewsey Hardground at Fognam as the Southerham Marl 1 and pink phosphate horizon respectively of the Beachy Head succession appears to be well supported by the evidence. However, there are potentially serious problems with his interpretation of the Ogbourne Hardground and the underlying succession. In particular, the available biostratigraphical evidence from the site itself, taken in combination with the geophysical logs of water wells in the vicinity (Mortimore, 1987; Tate *et al.*, 1971), suggests that there is a considerable thickness of Chalk between the Ogbourne Hardground and the Plenus Marls Member in the immediate area. This thickness is far greater than is allowed for in Gale's (1996, fig. 5) inferred correlation between Fognam Quarry and the key Beggars Knoll Quarry succession. The abundance of *Inoceramus cuvieri*, rather than *Mytiloides* ex gr. *subhercynicus* (Seitz) beneath the supposed correlative of the Round Down Marl at both localities fits better with a level nearer the top than the base of the New Pit Chalk Formation.

The site is of key importance because of the occurrence of the ammonite *Romaniceras (Yubariceras) ornatissimum* in the succession below the Ogbourne Hardground. This occurrence, at two horizons beneath the inferred Round Down Marl (Gale, 1996, fig. 8) provides additional evidence for the existence in England of the international *R. ornatissimum* ammonite Zone/Subzone, which is recognized in France, Spain and North Africa (Wiese, 1997). Hitherto the only in-situ record of the index taxon was a specimen from the New Pit Marl 2–Glynde Marls interval in Sussex (Mortimore, 1986a; Lake *et al.*, 1987, fig. 19). The occurrence of the Middle Turonian index fossil *Collignoniceras woollgari* between the inferred Round Down Marl and the Ogbourne Hardground, and of definite *Subprionocyclus*, including forms between the basal Upper Turonian zonal index fossil, *S. neptuni* and the coarser-ribbed *S. branneri*, in the phosphates over the Pewsey Hardground, suggests that the boundary between the *woollgari* and *neptuni* zones should be placed either in the interval between the Ogbourne and Pewsey hardgrounds or at the Pewsey Hardground itself.

Fognam Quarry is hence the one locality where the Pewsey Hardground can be placed unequivocally at or immediately above the base of the Upper Turonian Substage. *Subprionocyclus (S. hitchinensis* (Billinghurst)) is also known from just above Southerham Marl 1 at Dover (Gale, 1996). The identification by Gale of the Pewsey Hardground phosphates and their associated pink-coloured chalkstone with a similar bed high in the Glynde Marls–Southerham Marl 1 interval at Eastbourne has therefore necessitated a downward revision of the base of the Upper Turonian succession to at least this level in the basinal succession. This latter datum may thus correspond to the transgressive surface of Gale's Turonian sequence 3. Wiese (1999) recommended that the Pewsey Hardground and its corresponding 'spike' in $\delta^{13}C$ curves could well serve as a marker for the base of the Upper Turonian Substage.

Conclusions

Fognam Quarry is a critical locality for the definition, correlation and interpretation of the Chalk Rock. This succession of hardgrounds and nodular chalk beds is the condensed equivalent of much of the lower Lewes Nodular Chalk Formation. Condensation has led to the loss of the key tephro-event marker marl seams of the more expanded basinal successions and in turn this has meant that correlations are difficult to prove and can be controversial. The fossils from the quarry, particularly Middle and Upper Turonian ammonites associated with inoceramid bivalve assemblages, provide the evidence for dating the Chalk Rock as a whole and the individual surfaces within the rock. This dating is essential to the various sedimentary models proposed for the origin of the Chalk Rock, the Lewes Nodular Chalk Formation, and interpretations of sequence- and cyclo-stratigraphy more widely in the Chalk.

BOXFORD CHALK PIT, BERKSHIRE (SU 431 719)

Introduction

Boxford Chalk Pit is an abandoned and partly overgrown chalk pit situated 300 m NNE of Boxford Church, on the east side of a minor road (Figure 4.7). The site is of critical importance in demonstrating the effects of biostratigraphically well-constrained intraformational tectonism, erosion and slumping in the Chalk. It can be compared to the structurally complex **Downend Chalk Pit** GCR site, but the sedimentary anomalies there

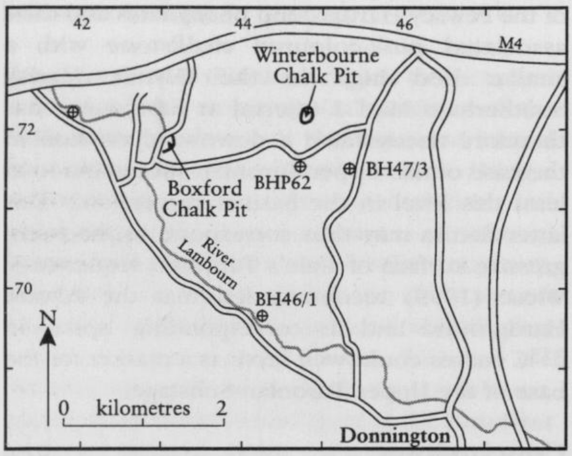


Figure 4.7 Location of Boxford Chalk Pit and **Winterbourne Chalk Pit** in the River Lambourn valley north of Newbury. (BH=Boreholes with geophysical logs that extend the stratigraphy to the Chalk Rock and below.)

result from a later phase of Late Cretaceous tectonism. Together with the nearby GCR sites of **Winterbourne Chalk Pit**, and **South Lodge Chalk Pit** at Taplow, near Maidenhead, Boxford Chalk Pit contributes towards an understanding of the distinctive, and highly fossiliferous, phosphatic chalk lithofacies. This facies is particularly strongly developed in local erosional channels in the Chalk of northern France, and the site in some respects provides a miniature analogue of one of the last extant French phosphatic chalk quarries.

Description

The succession at Boxford Chalk Pit comprises a relatively undisturbed (autochthonous) Lower Unit (Figure 4.8) of soft white flinty chalks with minor hardgrounds, which is itself capped by a pair of hardgrounds (Boxford Paired Hardgrounds). In contrast to the regional dip of only a few degrees to the SSE, the strata in the Lower Unit exhibit a significantly steepened, anomalous, dip of 25° in the same direction; evidence of this steepening of the dip is first seen 500 m to the north-east at Westbrook Farm Pit (SU 427 723), where dips of 5°–6° have been recorded. The autochthonous unit is overlain, above a basal slide-plane, by a highly disturbed and displaced (allochthonous) Upper Unit comprising components of the autochthonous unit (Figure 4.8). The highest part of the section exposes a hardground (Upper Hardground – a cemented channel floor) with phosphatic chalk above (Figure 4.8).

The initial description of the site (White and Treacher, 1906) was based on a largely overgrown exposure. Hawkins (1924) described a better exposed section after the pit had been re-opened and he made the first attempt to interpret the complex structure. Jarvis and Woodruff (1981) provided the first detailed stratigraphical log when the pit was excavated by the Nature Conservancy Council in 1980. Subsequently Gale (1990b) revised the Jarvis and Woodroof section and provided a new structural interpretation. The pit has recently (1999) been re-excavated by English Nature.

Lithostratigraphy

The succession (Figure 4.8) can be divided into three distinct units (Jarvis and Woodroof, 1981, figs 2, 3; Gale, 1990b, figs 2, 3).

The Lower Unit comprises a fossiliferous succession of soft white flinty chalk, which includes several hardgrounds and terminates in a closely spaced pair of hardgrounds. Jarvis and Woodroof (1981) recognized two poorly lithified glauconitized hardgrounds, 0.75 m apart, in the middle part of the succession,

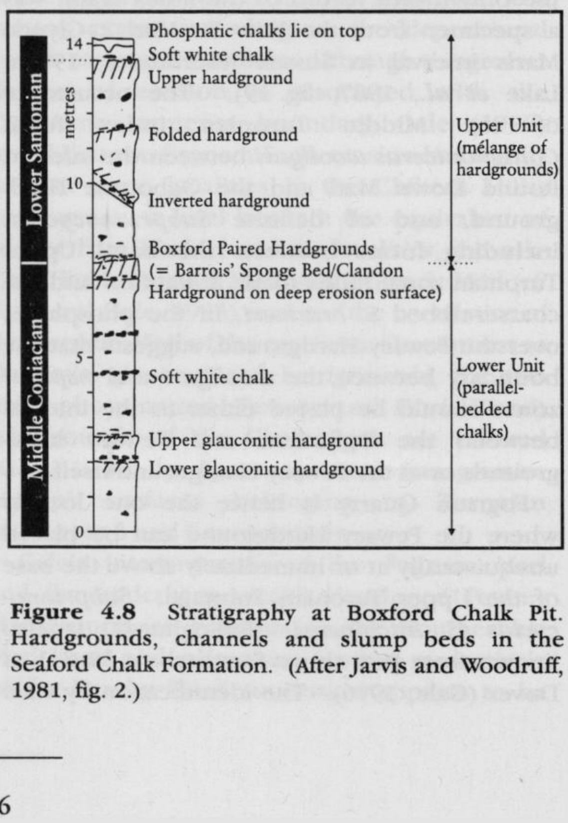


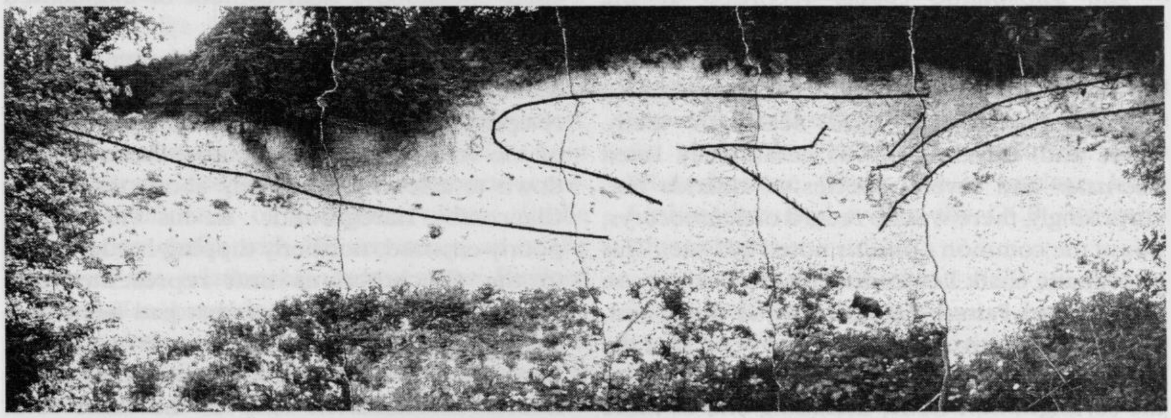
Figure 4.8 Stratigraphy at Boxford Chalk Pit. Hardgrounds, channels and slump beds in the Seaford Chalk Formation. (After Jarvis and Woodruff, 1981, fig. 2.)

which they termed the 'Boxford Lower Glauconitic Hardground' and the 'Boxford Upper Glauconitic Hardground' respectively. They reported that large pieces of inoceramid bivalve shell and a rich macrofauna occurred above the higher of the two hardgrounds. Gale (1990b, fig. 2) indicated that the lower, flint-strewn hardground was more clearly defined than the upper one and identified an additional mineralized surface (his horizon 2) some 2 m below. A trench in the talus at the extreme base of the section revealed a strongly lithified, 0.3 m thick hardground (Gale, 1990b, fig. 2, horizon 1); this is weakly glauconitized, with a patchy shiny phosphate veneer.

The lowest unit terminates in a pair of indurated and weakly glauconitized hardgrounds, 0.3–0.5 m apart, which Jarvis and Woodroof termed the 'Boxford Paired Hardgrounds'. These hardgrounds and the intervening chalks are strongly stained with limonite, the development of very closely spaced sub-horizontal Liesegang diffusion bands imparting a spurious appearance of primary sedimentary lamination. The interval between the hardgrounds progressively reduces towards the northern part of the quarry. The upper of the hardgrounds is much more strongly lithified than the lower. It has a planar surface with a light brown, polished phosphate skin, and is penetrated by a *Thalassinoides* burrow system with glauconitized and phosphatized walls.

The overlying Upper Unit (allochthonous unit), as interpreted by Gale (1990b), consists of the terminal portion of a slump, comprising a folded and partly overturned repetition of the beds of the lower unit, and terminating in a single hardground (upper hardground) with a brown phosphate skin (Figures 4.8 and 4.9). Distal to the essentially coherent, albeit fragmented slump, are disordered chalk and hardground fragments. The slump is incorporated in coarsely bioclastic chalk, which includes several high-angle to sub-vertical sheet-flints. The terminal upper hardground, which is exposed over a distance of about 6 m, was interpreted by Gale as representing a lateral equivalent of the paired hardgrounds of the lower unit, which here have coalesced.

The highest unit comprises a development of phosphatic chalk. Jarvis and Woodroof (1981) described this unit as occupying a 4 m wide broad concave channel at the top of the northern end of the face. The phosphatic chalk is concentrated in poorly defined burrows within a less strongly phosphatic chalk matrix. The channel is floored by the glauconitized upper hardground and is overlain by phosphatized and glauconitized intraclasts. The phosphatic chalk fill terminates in a minor, sub-horizontal, glauconitized hardground that partly spans the concavity of the channel, and is itself overlain by intraclasts and hardground fragments. Jarvis and Woodroof (1981) described this second hardground as being syndepositionally fractured, with the sub-vertical fracture surfaces encrusted by oysters. However, Gale (unpublished data) has recorded highly fossiliferous phosphatic chalks directly resting on the paired hardgrounds in a position



c. 10 m

Figure 4.9 Boxford Chalk Pit, Berkshire, showing the outlines of the slump-folded hardgrounds. Width of section illustrated, approximately 10 m. (Based on photographs kindly supplied by Professor A. Gale.)

distal to the toe of the slump constituting the Upper Unit. It is unclear how this occurrence relates to the channel described by Jarvis and Woodroof.

Biostratigraphy

The entire succession below the Boxford Paired Hardgrounds (Figure 4.8), including the glauconitic hardgrounds of the Jarvis and Woodroof section and the unnamed lowest hardgrounds in the Gale section, yields specimens of the inoceramid bivalves *Volviceramus* and *Platyceramus*. It therefore falls in the lowest (Middle Coniacian) part of the *Micraster coranguinum* Zone, the equivalent of the Belle Tout Beds of the standard Southern Province succession. Jarvis and Woodroof (1981) reported that large pieces of inoceramid shell and a rich macrofauna occurred above the Boxford Upper Glauconitic Hardground. *Micraster coranguinum* (Leske) itself was stated by White and Treacher (1906) to be common in the 2 m of chalk then exposed below the Paired Hardgrounds. They also noted that the surfaces of the large flints contained asteroid ossicles, as well as debris of regular echinoids and inoceramid shells. From the Paired Hardgrounds they recorded terebratulid brachiopods and siphonal tubes of the teredine bivalve *Teredo amphisboena* (Goldfuss). There is no evidence, either in the chalk below the Paired Hardgrounds, or in the hardgrounds themselves, of the basal Santonian event beds with the inoceramid bivalve *Cladoceramus undulatoplicatus* (Roemer).

The phosphatic chalks recorded at the northern end of the quarry are extremely fossiliferous, and have yielded common *Conulus*, as well as a rich, but unpublished, mesofauna of microbrachiopods and selachian teeth. White and Treacher (1906) additionally listed *Micraster* and several species of cidarids but, surprisingly, there was no record of *Echinocorys*, nor of the common *Conulus* noted by Gale. This phosphatic chalk lies in direct superposition on the Boxford Paired Hardgrounds at one point, and it can tentatively be inferred to represent the highly fossiliferous terminal (Santonian) part of the *coranguinum* Zone, including one or more horizons with abundant *Conulus*, that is found above the Barrois Sponge Bed of the Isle of Thanet and the Clandon Hardground in the North Downs respectively.

Interpretation

It can be inferred that the Paired Hardgrounds equate with the (Middle Santonian) Barrois' Sponge Bed of the **Thanet Coast** GCR site, and with the correlative, and much more strongly lithified Clandon Hardground of the North Downs (see p. 308). However, in marked contrast to the situation at West Clandon Quarry near Guildford, the type locality of the Clandon Hardground, where erosion prior to hardground formation cut down to a level a short distance above Whitaker's 3-inch Flint Band (Robinson, 1986), pre-hardground erosion has removed the greater part of the *coranguinum* Zone. The Boxford Paired Hardgrounds collectively represents a lithified surface within the Belle Tout Beds.

The initial description of the complex succession by White and Treacher (1906) was based on a largely overgrown exposure. They clearly identified the Boxford Paired Hardgrounds (their Bed 2), and some 2 m of the underlying autochthonous unit (Bed 1). The higher part of their descriptive log is less easy to interpret, although the coarse-grained, non-phosphatic chalks of their Bed 3 (*c.* 4 m) and the oyster-rich phosphatic chalks with angular brown and light green concretions of Bed 4 (*c.* 3 m) can be inferred to represent broadly the allochthonous slumped beds and the phosphatic chalks respectively. They additionally observed that the hardground was overlain by a thin seam of grey rubbly marl and that the basal part of the overlying chalk contained a high content of fragmented bioclastic debris.

Hawkins (1924) described the better-exposed section that was revealed when the pit was re-opened. He provided an accurate record of the lower part of the autochthonous unit, down to a level immediately above the Upper Glauconitic Hardground. In his view, some poorly exposed, northerly dipping hardgrounds in the allochthonous unit represented the southern part of a syncline that had been telescoped and forced northwards over the Paired Hardgrounds of the autochthonous unit, which formed the northern limb of the same fold. However, it is difficult to reconcile his section (Hawkins, 1924, fig. 34) of the allochthonous unit with those recorded by Jarvis and Woodroof (1981) and by Gale (1990b).

Jarvis and Woodroof (1981) recorded and illustrated (their fig. 3) several detached lengths of hardgrounds at various orientations within the displaced (allochthonous) Upper Unit, which they termed the 'inverted', 'inclined' and 'folded' hardgrounds respectively (Figures 4.8 and 4.9). They considered that the highest hardground (their upper hardground), situated high in the face, was entirely unrelated to any of the hardgrounds and hardground fragments below. Gale (1990b), on the other hand, re-interpreted their section on the basis of identifying several of the lengths of hardground as components of the autochthonous succession, and equated the single upper hardground with the otherwise similar Paired Hardgrounds. In his interpretation, the distinctive overturned 'folded' hardground of the Jarvis and Woodroof section represented the more strongly lithified (Lower) of the Glauconitic Hardgrounds (compare Jarvis and Woodroof, 1981, fig. 3, with Gale, 1990b, fig. 1), with the 'inverted' and 'inclined' hardgrounds representing lower hardgrounds within the same succession (Figure 4.8). Gale regarded the allochthonous unit as double, with the higher component, comprising the coalesced equivalent of the paired hardgrounds, together with the immediately underlying soft chalk, being separated by a slide-plane from the lower component, which was itself separated by a slide-plane (White and Treacher's 'grey marl') from the relatively undisturbed (autochthonous) Lower Unit (Figure 4.8).

Boxford Chalk Pit provides an analogue in miniature of the Beauval phosphatic chalk Quarry in Picardy, northern France. At the latter locality, the basal hardground below the phosphatic chalks locally contains *Cladoceramus* (e.g. Jarvis, 1992, fig. 2), demonstrating that erosion prior to hardground formation had cut down to the base of the Santonian succession. Elsewhere in the same quarry, erosion has cut considerably deeper, and the hardground represents lithification of a surface within Middle Coniacian chalks with *Volviceramus*, as in the case of the relationship between the Boxford Paired Hardgrounds and the underlying chalks.

The dating of the sedimentary anomalies at Boxford Chalk Pit is difficult to determine. It is also not easy to interpret them entirely in terms of the erosional channel (cuvette) model advanced by Jarvis (1980a, 1992) for other phosphatic chalk occurrences in the Anglo-Paris Basin. Westbrook Farm Pit exposes relatively gently dipping unfossiliferous standard flinty *coranguinum* Zone chalk (Upper Coniacian). Traced laterally from there towards Boxford Chalk Pit, the fossiliferous Middle Coniacian *coranguinum* Zone succession is incomplete, condensed and strongly dipping in the Boxford Chalk Pit autochthonous Lower Unit. A possible cause of this lateral change is the existence, close to Boxford, of an intra-Coniacian growth structure controlled by underlying faulting.

If the Boxford Paired Hardgrounds (Figure 4.8) are correctly interpreted as being the equivalent of the Middle Santonian Barrois' Sponge Bed/Clandon Hardground, then the depth of erosion at Boxford points to strong local structural control of this inter-regional intra-Santonian erosive event as well. Elsewhere the Clandon Hardground lithifies various levels within both the Santonian and Coniacian portions of the *coranguinum* Zone. The fact that the hardground is itself caught up in the allochthonous Upper Unit at Boxford Chalk Pit suggests that sliding of lithified sediment on a (structurally induced?) palaeoslope also took place at an even later date.

Structurally controlled anomalies of this type are typically associated with a position over or adjacent to NW–SE-aligned basement faults that were re-activated during the Late Cretaceous Epoch, following the switchover from a tensional to a compressive stress field. The anomalous sedimentation at Boxford Chalk Pit can be broadly placed within the sequence of Ilsede and early Wernigerode phases of Subhercynian tectonic events (Stille, 1924) recently described from both the European platform and from the Southern Province and Anglo-Paris Basin (see Mortimore and Pomerol, 1997; Mortimore *et al.*, 1998).

The structural and depositional relationship between the Boxford Chalk Pit succession and the phosphatic chalk succession of the nearby **Winterbourne Chalk Pit** is unclear, but is further discussed within the GCR site report (this volume).

Conclusions

Boxford Chalk Pit is unique in exposing Middle Coniacian to Lower Santonian major erosion surfaces and slump beds in the English Chalk. Abundant key index inoceramid bivalves and echinoids provide the evidence for detailed correlation of these events.

WINTERBOURNE CHALK PIT, BERKSHIRE (SU 448 722)

Introduction

Winterbourne Chalk Pit is an old farm quarry, situated 100 m south-west of Lower Farm and west of the track that joins Winterbourne Manor and Lower Farm (Figure 4.7). This is one of the few localities in the UK that exposes a section in the flintless phosphatic chalk lithofacies. As in the case of the **South Lodge Pit** GCR site at Taplow near Maidenhead, this site provides an excellent example of a biostratigraphically well-constrained condensed Upper Santonian–Lower Campanian phosphatic chalk succession that is comparable, in some respects, with the more extensive, and broadly coeval, phosphatic chalk developments exposed in abandoned quarries in northern France. The section is rich in macrofossils, particularly belemnites, which are otherwise rare in basinal equivalents. The site also shows that the development of phosphatic chalk, seen at the top of the nearby **Boxford Chalk Pit** GCR site, continued well into the Campanian Stage. This condensed flintless chalk succession, which includes four hardgrounds, can be correlated with part of the succession of hardgrounds that constitutes the so-called 'flintless belt' of the **Whitecliff** GCR site on the eastern side of the Isle of Wight, and likewise provides evidence of the effects on sedimentation of intra-formational tectonism developed over basement lineaments.

Description

The section at Winterbourne Chalk Pit, originally described at the beginning of the 20th century by White and Treacher (1906), had become seriously degraded and was re-excavated by the Nature Conservancy Council in 1978 to reveal a 6 m section (Figure 4.10), extending over 20 m (Jarvis and Woodroof, 1981). The beds dip at about 3° to the south-west. Jarvis and Woodruff additionally compared the section with sections containing phosphatic chalk at **Boxford Chalk Pit** and **South Lodge Pit**. The site was again re-excavated by English Nature in 1999.

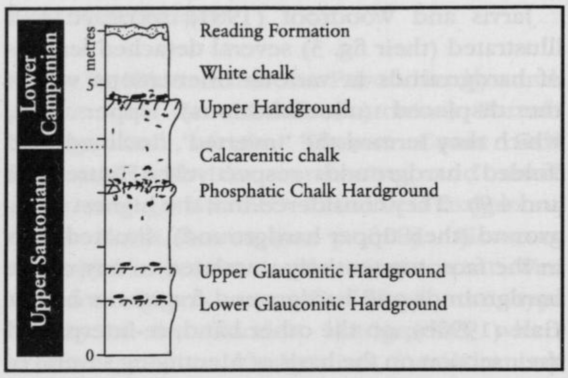


Figure 4.10 Chalk succession exposed at Winterbourne Chalk Pit near Newbury, Berkshire. (After Jarvis and Woodroof 1981, fig. 5.)

Lithostratigraphy

The initial description by White and Treacher (1906) related only to the higher part of the section, the lower beds being then obscured by talus. An excellent description of the re-exposed section, including glauconitized hardgrounds not seen by White and Treacher, was given by Jarvis and Woodroof (1981). The following account and log (Figure 4.10) draws extensively on both of these descriptions.

The succession includes four hardgrounds named by Jarvis and Woodroof (1981), in ascending order, the poorly lithified Winterbourne Lower Hardground and Upper Glauconitic Hardground, the more strongly lithified Winterbourne Phosphatic Chalk Hardground, and the very strongly lithified Winterbourne Upper Hardground. It must be emphasized that these hardgrounds do not relate in any way to hardgrounds with similar names described by those authors from the nearby **Boxford Chalk Pit** (see GCR site report, this volume), which belong to stratigraphically lower horizons. All of the hardgrounds are weakly glauconitized, the two higher ones being additionally limonite-stained, with the Upper Hardground being also locally phosphatized. The Phosphatic Chalk Hardground contains many limonitized hexactinellid sponges and is penetrated by a *Thalassinoides* burrow system; the hardground surface possesses a marked relief, with bosses up to 0.1 m high encrusted by pycnodonteine oysters. The Upper Hardground incorporates limonitized sponges as well as phosphatized and glauconitized intraclasts up to 0.1 m across; the hardground surface is of lower relief than that of the underlying hardground, and is encrusted by *Atreta* and *Spondylus*, in addition to oysters.

The white chalk at the base of the section contains scattered pelletal phosphate. Each of the lower hardgrounds is overlain by white chalk with scattered pelletal phosphate, similar in lithology to the lowest bed, with a thin basal lag of phosphatized and glauconitized intraclasts. The content of pelletal chalk and intraclasts increases upwards in the interval between the Upper Glauconitic and the Phosphatic Chalk Hardground. At the top of this interval, colour-contrasting grey, calcarenitic, pelletal phosphate-rich chalk is conspicuously piped down from above the hardground in *Thalassinoides* burrows. The chalk above the Phosphatic Chalk Hardground is overall greyish-white, very coarse-grained and rough-textured owing to a high content of fragmented and/or comminuted oyster and inoceramid shell material, and contains numerous phosphatized/glauconitized intraclasts. Pelletal phosphate occurs throughout, but is concentrated in the darker grey basal 0.1 m. Jarvis and Woodroof (1981) noted that the Upper Hardground is overlain by a basal concentration of pelletal phosphate chalk with phosphatized intraclasts, scattered glauconite grains and sporadic well-rounded quartz grains. Phosphatized intraclasts continue for another 0.3 m, above which the chalk becomes fine-grained, completely devoid of pelletal phosphate or phosphatized intraclasts, but contains instead dark specks of iron and manganese oxide.

Biostratigraphy

Calyx plates and arm ossicles of the Upper Santonian zonal index crinoid *Marsupites testudinarius* (Schlotheim) were reported by White and Treacher (1906) to occur throughout the section below the Phosphatic Chalk Hardground (their 'Bed 2'), but to become common in the topmost 0.3–0.6 m, where they noted that 'there are probably about a dozen plates per cubic foot of chalk'. They also recorded specimens of *Marsupites* in the Phosphatic Chalk Hardground itself, and in the overlying phosphatic chalk (their 'Bed 3'), where *Marsupites* plates were noted as being fairly common in the lowest part of the bed, becoming scarce some 0.2 m above the base, and disappearing altogether at about 0.75 m above the base. At the level where *Marsupites* first became scarce, White and Treacher (1906) reported a single specimen of the belemnite *Actinocamax verus* Miller and the appearance of the belemnite genus *Gonioteuthis*; the latter occurs sporadically throughout the remainder of the bed above this level. The reported Riedel Quotient (ratio of alveolar depth to the length of the belemnite) for the *Gonioteuthis* of between 5 and 7 places them within the range of populations of *Gonioteuthis granulata* (Blainville) from the *Marsupites* Zone of northern Germany (cf. Ernst, 1964). The shell-detrital phosphatic chalks also yield the distinctively pyramidate *Marsupites* Zone echinoid *Echinocorys scutata elevata* Griffith and Brydone and, particularly in the higher part of the bed, *Micraster rostratus* (Mantell) and less pyramidate *Echinocorys* morphotypes approaching *E. scutata tectiformis* Griffith and Brydone. The Upper Hardground contains common *Gonioteuthis* and *E. scutata tectiformis*, associated with a rich sponge fauna (of which the determinations cited by White and Treacher need revision), and also marks the first recorded appearance in the section of the small echinoid, *Offaster pilula* (Lamarck).

Resting on, or in, the basal 0.1 m of chalk above the Upper Hardground, *Echinocorys scutata tectiformis* and *Gonioteuthis* with a Riedel Quotient of 4.5 to 6 occur in flood abundance, together with common *Offaster pilula*. The belemnites were reported by White and Treacher (1906) to be even more abundant than in the 'Upper Brown (phosphatic) Chalk' unit of **South Lodge Pit** (see GCR site report, this volume). On the basis of their Riedel Quotients, the belemnites fall within the range of populations of *G. granulataquadrata* (Stolley) or *G. quadrata* (Blainville). The echinoids and belemnites become scarce about 0.3 m above the hardground, and are absent from the highest part of the section, from which White and Treacher (1906) recorded only biostratigraphically non-diagnostic oysters, '*Pecten cretosus*, *Spondylus latus* and *Rhynchonella plicatilis*'.

Interpretation

The macrofaunal evidence supports the interpretation given by Jarvis and Woodroof (1981), who considered that the boundary between the *Marsupites testudinarius* Zone and the overlying *Echinocorys scutata depressula* Subzone of the *Offaster pilula* Zone should be drawn at the disappearance of *Marsupites* within the shell-detrital chalk unit above the Phosphatic Chalk Hardground. The literature evidence that unequivocal *Marsupites* calyx plates, rather than merely crinoid brachials, which could include *Uintacrinus*, range right down to the base of the section, i.e. below the two glauconitic hardgrounds, needs confirmation. It is also possible that the lowest records refer to the lower of the two *Marsupites* calyx plate morphotypes (see p. 68, Chapter 2) that are known from expanded sections elsewhere.

The bioclastic sediments above the Phosphatic Chalk Hardground are clearly the equivalent of the non-phosphatic, but otherwise similar shell-detrital chalks that range in northern Germany (where they are known as the 'Grobkreide facies') from the top of the Upper Santonian *Marsupites* Zone into the lower part of the succeeding Lower Campanian *Gonioteuthis granulataquadrata* Zone (Ernst, 1963). The Grobkreide facies is relatively weakly expressed in equivalent Southern Province basinal chalks. At the **Newhaven to Brighton** and **Cuckmere to Seaford** GCR sites, it begins in the higher part of the *Marsupites* Zone, above the hardgrounds beneath the Brighton Marl, and extends a short distance above the *Uintacrinus anglicus* Zone. The Winterbourne Phosphatic Chalk Hardground and Upper Hardground can be inferred to equate, respectively, with the hardground(s) below the Brighton Marl and with the hardgrounds with common *Echinocorys scutata tectiformis* at the upper limit of the oyster-rich chalks (cf. Wood and Mortimore, 1988, fig. 18). The abundance of belemnites above the Upper Hardground is typical of phosphatic chalks elsewhere (Jarvis, 1980b), and is in marked contrast to their rarity in coeval basinal chalks. The absence of *Belemnitella praecursor* Stolley from the assemblage suggests that the succession does not extend up to the *praecursor* event at the base of the *Gonioteuthis quadrata* Zone, and that the associated *Offaster pilula* relate more to the lower rather than to the higher of the two *Offaster* belts in the *pilula* Zone (see also **West Harnham Chalk Pit** and **Newhaven to Brighton** GCR site reports, this volume).

It is also noteworthy that the two main hardgrounds appear to be at the same stratigraphical position as hardgrounds 1 and 2 respectively, of the so-called 'flintless belt' (Rowe, 1908) in the succession in the **Whitecliff** GCR site on the eastern side of the Isle of Wight (cf. Mortimore and Pomerol, 1997, fig. 9). This condensed succession, comprising an anomalous flintless belt with hardgrounds, reflects Late Santonian–Early Campanian structural control of sedimentation associated with the development of a pericline (the Sandown Pericline) over the northward extension of the major NW–SE Bray basement lineament of the Paris Basin. This interval of tectonic activity belongs to the Wernigerode Phase of Subhercynian tectonism (Stille, 1924) (see Mortimore and Pomerol, 1997; Mortimore *et al.*, 1998).

The relationship between the Winterbourne Chalk Pit section and the stratigraphically somewhat lower **Boxford Chalk Pit** succession is unclear, despite the mapping evidence presented by White and Treacher. Those authors suggested (1906, figs 3, 4) that non- or only very weakly-phosphatic chalk belonging to the *Uintacrinus socialis* Zone was intercalated between the phosphatic chalks of the two localities. They also showed (White and Treacher, 1906, fig. 2) that the Chalk succession in the Boxford–Winterbourne area formed a synclinal structure that was truncated by Tertiary strata. The Boxford and Winterbourne sites both show condensed and/or attenuated successions with hardgrounds, as well as units of relatively low-grade phosphatic chalk. The extent of the condensation at Winterbourne Chalk Pit is shown by thicknesses of 9 m and 6–7 m respectively for poorly flinty *Uintacrinus* Zone and *Marsupites* Zone chalk near Kintbury, only 8 km to the south-west (White, 1907). The *pilula* Zone in Winterbourne is also remarkably thin compared with the succession in the Layland's Green Chalk Pit, near Kintbury (SU 386 667) (White, 1907), where some 9 m of flinty chalk belonging to this zone were recorded below an indurated iron-stained bed that may well mark the boundary with the overlying *Gonioteuthis quadrata* Zone.

Occurrences of Santonian–Campanian phosphatic chalk are concentrated on the northern side of the Anglo-Paris Basin, and are typically associated with condensed successions preserved in single or stacked erosional troughs ('cuvettes') which have been incised into normal white chalks. The typical cuvette is floored by a basal hardground and is filled by pelletal phosphate-rich chalks that either pass up gradually into, or are relatively abruptly succeeded by, normal non-phosphatic chalks (Jarvis, 1980a, 1992). One or more additional cuvettes, each with its own fill of phosphatic chalk, may then be incised into the filled initial cuvette. Jarvis and Woodroof (1981) discussed the application of this model to the **Boxford Chalk Pit** and Winterbourne Chalk Pit occurrences and concluded that, unlike the situation at **South Lodge Pit** (see GCR site report, this volume), it was not possible to identify either the basal hardground or the position of a cuvette with any confidence. In particular, the mapping-based inference of normal or virtually normal soft, white, flinty, *Uintacrinus* Zone chalks (White and Treacher, 1906) intercalated between the phosphatic chalk of the two localities is difficult to reconcile with the need for a basal hardground to the Winterbourne Chalk Pit occurrences. In any case, the phosphatic chalks at the latter site are relatively low in phosphate (rarely reaching 5% (Jarvis and Woodroof, 1981)), compared with the more typical phosphate-rich chalk at **South Lodge Pit**. Jarvis and Woodroof (1981) suggested that Winterbourne Chalk Pit might possibly have been situated on the margin of a former (unidentified) cuvette, which subsequently was removed by erosion. Their preferred explanation, of intra-formational structural control of sedimentation, broadly agrees with the present authors' interpretation, but considerable further investigation is required in order to understand the structural and depositional relationships. In particular, it should be pointed out that condensed successions containing a hardground overlain by concentrations of *Echinocorys scutata tectiformis*, comparable with the Boxford Upper Hardground, are not restricted to the immediate Boxford–Winterbourne area, but are also found at Kintbury.

Conclusions

Winterbourne Chalk Pit is a key locality for studying the stratigraphy and sedimentology of phosphatic chalks in the Santonian Stage and Early Campanian Substage in England. The abundance of crinoids, echinoids and belemnites provides the evidence for correlation of the main hardground surfaces with the Isle of Wight and more widely in Europe.

SOUTH LODGE PIT, BERKSHIRE (SU 906 819)

Introduction

South Lodge Pit is an abandoned quarry cut into the southern end of the steep river cliff of the west-facing left bank of the river Thames, at Taplow, east of Maidenhead (Figure 4.11). As in the case of **Winterbourne Chalk Pit**, the site provides an excellent example of a biostratigraphically well-constrained condensed Upper Santonian–Lower Campanian phosphatic chalk succession, with up to 15% P_2O_5, that is comparable in some respects with the more extensive phosphatic chalk sections exposed in abandoned quarries in northern France. A pipe near the middle of the section contains derived, secondarily enriched, phosphatic sand with up to 30% P_2O_5, providing an analogue to the phosphatic sands formerly exploited in northern France and Belgium. Compared with coeval white, non-phosphatic chalks, the phosphatic chalks are extraordinarily rich in fossils, particularly zonally significant crinoids, echinoids and belemnites.

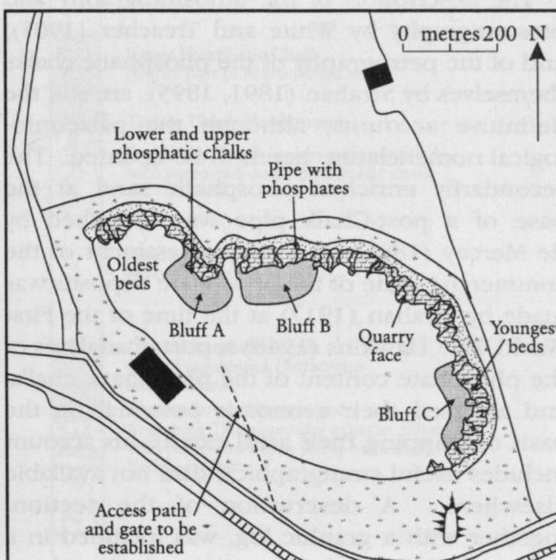


Figure 4.11 General geology in the vicinity of South Lodge Pit, Taplow.

Description

South Lodge Pit is generally known as the 'Taplow Pit' because of its proximity to the village of that name, and lies in private land in the grounds of Taplow Court estate. The quarry formerly exposed two beds of phosphatic chalk in an approximate dip section in a WNW–ESE face about 70 m long (Figures 4.12 and 4.13). The extensively overgrown section was partially re-excavated in 1999 (Figure 4.14). Two rather inaccessible air-weathered exposures remain, in the same part of the quarry, of the higher of the two phosphatic chalk units and the chalk above. These sections are separated by a Tertiary pipe filled with secondarily enriched phosphatic sand. This pipe has become progressively eroded back and the section seen today is virtually at its back wall. The highest beds of Chalk and the contact with the Palaeogene Reading Beds are rather poorly exposed in the eastern part of the quarry. The strata are variously recorded to dip at 4° or 5° at E10°S (Strahan, 1896); 5°– 8° approximately to the south-east (White and Treacher, 1905); and 3° SSE (Hawkins, 1948). Structural contours on the inferred position of the Chalk Rock in the subcrop (Willcox, 1953) also suggest a SSE dip.

The description of the lithostratigraphy and biostratigraphy by White and Treacher (1905), and of the petrography of the phosphatic chalks themselves by Strahan (1891, 1895), are still the definitive accounts, although the palaeontological nomenclature needs to be updated. The secondarily enriched phosphatic sand at the base of a post-Chalk pipe was described by de Mercey (1896). An early assessment of the commercial value of the phosphate deposits was made by Strahan (1917) at the time of the First World War. Hawkins (1948) reported analyses of the phosphate content of the phosphatic chalks and assessed their economic potential on the basis of mapping their areal extent; his account includes useful stratigraphical data not available elsewhere. A description of the section, together with a graphic log, was included in a general account of the origin of phosphatic chalks by Willcox (1953), but it is unclear how much of the detail derived from the literature, and how much was original. Jarvis, in an unpublished PhD thesis (1980c), described the section visible in 1979 in considerable sedimentological detail, and later (Jarvis, 1992, fig. 2) plotted his graphic log against the more important phosphatic chalk sections of northern France in a correlation diagram.

Lithostratigraphy

The succession (Figure 4.13), which is about 18 m thick, comprises three units. The lower one consists of white chalk, flinty only at the base of the section, and with a very low content of pelletal phosphate chalk (Figure 4.12). The two higher units of phosphatic chalk have strongly lithified, mineralized hardgrounds and lithified burrowed surfaces at their bases; and each unit passes upwards into less phosphatic white chalk. In the earlier description (White and Treacher, 1905; Willcox, 1953), the lower phosphate-rich parts of the phosphatic chalk units were termed Brown Chalk, the complex succession being simplified to comprise five parts, in ascending order, Division A, Lower White Chalk; Division B, Lower Brown Chalk; Division C, Middle White Chalk; Division D, Upper Brown Chalk; Division E, Upper White Chalk. In this account, a more sedimentological approach is adopted: the two lithified surfaces and their associated phosphatic chalks are here termed the 'Taplow Lower Hardground and Lower Phosphatic Chalk'; and the 'Taplow Upper Hardground and Upper Phosphatic Chalk', respectively. The published thicknesses of individual units differ considerably and there is evidence (e.g. Hawkins, 1948, fig. 5) of lateral variation within the pit and (based on boreholes) in the immediately surrounding area.

The Lower White Chalk contains a low content of pelletal phosphate and sporadic lightly phosphatized intraclasts. A nodular flint is variously reported 1.5 m (Hawkins, 1948) and 3.6 m (White and Treacher, 1905) below the Lower Hardground. The upper part of the unit is penetrated by phosphatic chalk-filled *Thalassinoides* burrows extending down from the hardground.

The chalkstone of the Taplow Lower Hardground is strongly lithified. The hardground itself is undulating, bored and penetrated by *Thalassinoides* burrows, which pipe the sediment of the Lower Phosphatic Chalk for 2 m into the Lower White Chalk. The surface is covered by adnate organisms such as agglutinating foraminifera, serpulids, *Crania* and bivalves including oysters, *Atreta* and *Spondylus*. Both the hardground and the adnate organisms are heavily encrusted with an irridescent skin of

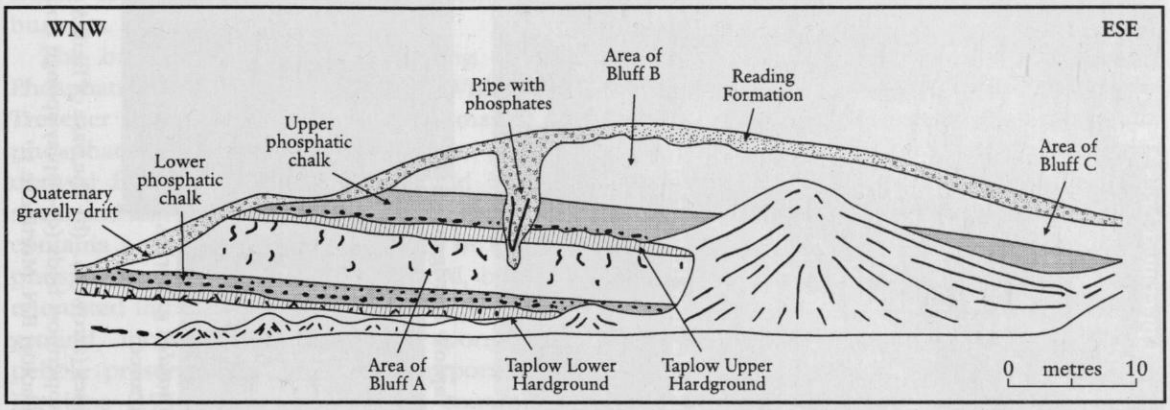


Figure 4.12 South Lodge Pit, Taplow, as exposed in 1905. (After White and Treacher, 1905, fig. 1.)

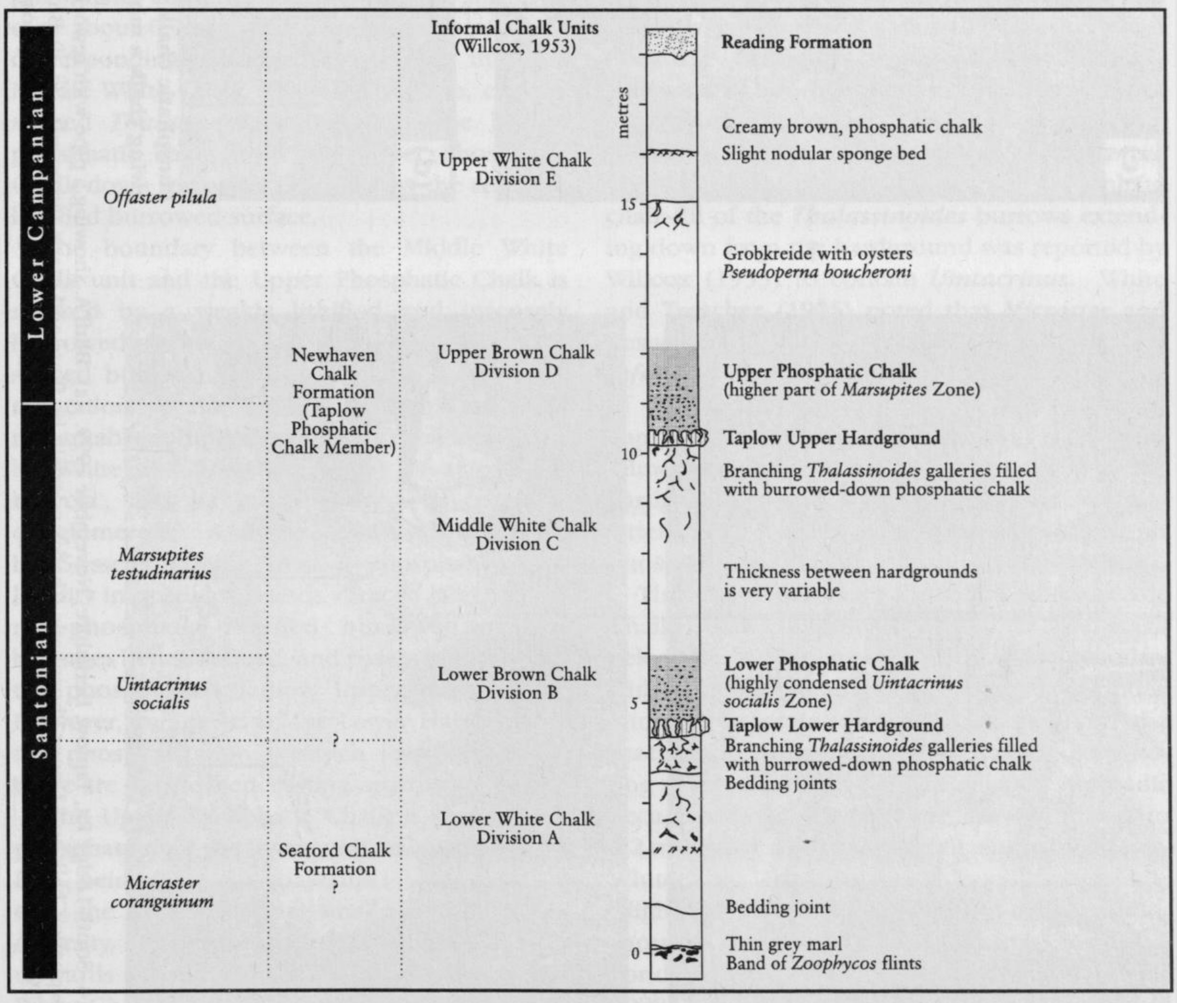


Figure 4.13 The Chalk succession at South Lodge Pit, Taplow.

Figure 4.14 South Lodge Pit, Taplow, Berkshire, November 1999. (a) Bluff A, showing a pipe with reworked phosphates (arrowed). (b) The base of Bluff A with Lower Phosphatic Chalk and Upper Phosphatic Chalk underlain by flints and marls (arrowed). (c, d) Bluff C. The uppermost beds (c) display sponge nodular horizons. The Upper (c) and Lower (d) Taplow Hardgrounds are orange-stained, glauconitized and phosphatized. (Photos: R.N. Mortimore.)

dark brown phosphate, up to 0.03 m thick, which locally caps the open *Thalassinoides* burrows.

The basal 0.15 m of the overlying Lower Phosphatic Chalk were described by White and Treacher (1905) as a sand composed mainly of phosphatized foraminifera, calcite prisms derived from comminuted inoceramid bivalve shell, and fish debris including teeth. This sand contains a variety of types and sizes of mainly phosphatized, and some glauconitized, bivalve-encrusted intraclasts, ripped up from the hardground, including *Micraster* and sponges in pebble preservation. An analysis reported by Hawkins (1948) gave a phosphate content of 15% P_2O_5. The higher part of the phosphatic chalk (*c.* 12% P_2O_5) has the texture of a friable sandstone. Above the lowest 1.8 m, the pelletal phosphate content reduces rapidly upwards over about 0.75 m, and the sediment becomes correspondingly much paler, passing into the Middle White Chalk. Towards the top, closely-spaced *Thalassinoides* burrows pipe brown phosphatic chalk from the Upper Phosphatic Chalk down for up to 2.5 m below the terminal lithified burrowed surface.

The boundary between the Middle White Chalk unit and the Upper Phosphatic Chalk is marked by a weakly lithified and intensely burrowed surface. The combination of closely spaced burrowing, early lithification and fragmentation of the sediment has produced a remarkably complex, nodular texture described by White and Treacher (1905) as a 'pseudo-breccia', and by Jarvis (1980c) as 'pseudo-conglomeratic'. A similar texture was described by Gosselet (1896), from a phosphatic chalk locality in northern France. Traced laterally, the non-phosphatic lithified burrowed surface becomes better defined, and passes laterally into the phosphatized Taplow Upper Hardground. However, compared to the Lower Hardground, the phosphatization is much less strong and there are very few encrusting organisms.

The Upper Phosphatic Chalk is less rich in phosphate than the lower unit, values of 9–13% P_2O_5 being quoted by Hawkins (1948). In addition, the foraminifera are smaller and of higher diversity. The phosphatic chalk grades rapidly upwards into the (relatively inaccessible) Upper White Chalk. The latter unit is soft in the lowest 1.2 m, with a small content of pelletal phosphate; the chalk becomes increasingly 'lumpy' upwards and, in the highest 0.9–1.2 m, near the junction with the Tertiary deposits, intensely indurated, with a subporcellaneous fracture and abundant dendritic MnO_2. It remains to be determined if this induration is wholly a secondary weathering effect, or if it is partly of primary origin. The thickness of 5.4 m of white chalk above the gradational top of the Upper Phosphatic Chalk found in a shaft sunk in the hillside above the pit (Strahan, 1891) suggests that no higher hardground exists at the top of the local succession.

Biostratigraphy

The white chalk below the Taplow Lower Hardground, particularly the top 2.4 m, contains a fauna (White and Treacher, 1905, nomenclature updated) of regular echinoids, for example *Temnocidaris sceptrifera* (Mantell) and *Tylocidaris clavigera* (Mantell) together with irregular echinoids such as *Conulus* sp., *Echinocorys* sp. (fragments only) and *Micraster coranguinum* (Leske). The beds below this yielded few fossils apart from *Inoceramus cuvieri* (i.e. *Platyceramus*?). The phosphate chalk-fill of the *Thalassinoides* burrows extending down from the hardground was reported by Willcox (1953) to contain *Uintacrinus*. White and Treacher (1905) noted that *Micraster* and hexactinellid sponges, including *Coscinopora infundibuliformis* Goldfuss and several species of *Ventriculites* (presumably *Rhizopoterion* spp.), were common both in the chalk immediately below the hardground and in the hardground itself, although the fossils in the latter tended to be preserved as rolled and phosphatized pebbles.

The basal 0.3 m of the Lower Phosphatic Chalk yield common examples of the small belemnite *Actinocamax verus* Miller together with calyx plates and brachials of the zonal index crinoid *Uintacrinus socialis* Grinnell and the brachiopod *Kingena lima* (Defrance), constituting a typical *socialis* Zone association. Sporadic occurrences of *Uintacrinus* are found up to 1.2 m above the base. From about this level, White and Treacher (1905) recorded a single 'slightly ornamented' calyx plate of *Marsupites* (housed in the Natural History Museum, London), which Prof. A.S. Gale (pers. comm., 1999) has identified as belonging to the stratigraphically older morphotype with simple ornament (see p. 68, Chapter 2). In the higher, poorly phosphatic, part of the unit, fossils are very scarce, the only species recorded as 'rather common' being the oyster *Pycnodonte vesiculare* (Lamarck).

The basal, phosphate-rich part of the Upper Phosphatic Chalk contains much inoceramid bivalve shell debris and yields abundant specimens of the belemnite *Gonioteuthis granulata* (Blainville), associated with oysters, including common *Pseudoperna boucheroni* (Woods *non* Coquand) as well as (largely fragmentary) ornamented calyx plates of *Marsupites testudinarius*. White and Treacher (1905) noted that the *Marsupites* occurred predominantly in the lowest 0.3 m, being rare above that level; the highest record was of a plate with 'blunt radial plication' 2.1 m above the base. The belemnites are so abundant that Willcox (1953) recorded collecting 100 complete specimens from a section 2.1 m high by 4.5 m long, having discarded the fragmentary specimens. Well-preserved, uncrushed tests of *Echinocorys*, of the morphotype characteristic of the higher part of the *Marsupites* zone, stand proud from the weathered face over an interval 0.6–2.1 m above the base.

Willcox (1953) noted the small zonal index echinoid *Offaster pilula* (Lamarck) at 1.8 m above the base of the Upper Phosphatic Chalk, i.e. still within the relatively phosphate-rich part of that unit. He inferred that the *pilula* Zone began at that level, despite the earlier record of a single *Marsupites* plate some 0.3 m higher. This record of *Offaster* is not confirmed by earlier accounts and, indeed, White and Treacher (1905) specifically emphasized that this species was not included in their faunal lists. The overlying beds up to the top of the section yielded relatively few macrofossils apart from inoceramid bivalves, oysters, including *Pseudoperna boucheroni* and *Gryphaeostrea canaliculata* 'var. *striata*' Rowe and incomplete *Gonioteuthis*. Professor Gale (pers. comm.) has additionally collected *Echinocorys scutata depressula* Brydone at this level. The belemnites become very scarce towards the top of the section and are not known from the hard porcellaneous beds.

Interpretation

The occurrence of phosphatic chalk at Taplow has been known since the 19th century. An interesting account of the history of ideas relating to it is provided by White and Treacher (1905). Whitaker (1889) described it as a grey gritty chalk resembling the (Cenomanian) Totternhoe Stone of the Chiltern Hills (see discussion of this unit under **Chinnor Chalk Pit** GCR site report), and broadly correlated it on the basis of the belemnites and oysters, with the 'Margate Chalk or Zone of *Marsupites*'. Strahan (1898) appreciated the lenticular nature of the deposit, but had a very unclear idea of its stratigraphical position. Because of the (incorrectly reported) occurrence of *Actinocamax quadratus* (i.e. *Gonioteuthis quadrata* (Blainville)), implying a higher horizon than the *Marsupites* Zone, de Lapparent (1900) actually placed the 'Taplow Chalk' in the Campanian Stage, between the (Santonian) Margate Chalk and the Norwich Chalk. The extremely limited fossil collections made by the [British] Geological Survey, which did not include the critical *Marsupites*, but did include *Conulus* from the base of the section, led to the seriously incorrect interpretation (Jukes-Browne and Hill, 1904) that the Taplow Chalk was a lateral equivalent of *Micraster coranguinum* Zone flinty chalk localities, such as Cliffe and Gravesend in north Kent. It was not until the outstandingly detailed investigation by White and Treacher (1905) that the true stratigraphical position of the deposit was properly appreciated.

The occurrence of *Conulus* places the chalk below the Taplow Lower Hardground broadly within the higher (Santonian) portion of the *coranguinum* Zone. The absence of flint from the top 3.6 m of the succession could be inferred to indicate a level above the equivalent of Whitaker's 3-inch Flint Band (but see further discussion of this point below). The fact that *Conulus* is cited as occurring, rather than common, tends to exclude the normally very fossiliferous highest beds of the *coranguinum* Zone. The Taplow Hardground itself occupies approximately the position of the Barrois' Sponge Bed/Clandon Hardground near the top of the *coranguinum* Zone. However, unlike the situation elsewhere, the hardground at Taplow is overlain by an extremely condensed (1.2 m) *Uintacrinus socialis* Zone in phosphate chalk facies, and there is no evidence of the highly fossiliferous *Conulus*-rich highest part of the *coranguinum* Zone that normally follows the hardground. Hawkins (1948), on the basis of a yellow hard-bed which he found in a nearby pit at Hitcham Park, actually inferred that the Whitway Rock of North Hampshire (i.e. the presumed equivalent of the hardground in question) was probably situated 4.5 m beneath the Taplow Lower Hardground. The occurrence of *Marsupites* at the top of the Lower Phosphatic Chalk, 1.2 m above the basal hardground, indicates unequivocally that the Middle White Chalk belongs to the lower part of the overlying *Marsupites testudinarius* Zone. This is contrary to the uncertainty expressed by White and Treacher (1905) as well as its placing in the *Uintacrinus* Zone by Hawkins (1948).

The Taplow lithified burrowed surface/Upper Hardground appears to be equivalent to the Phosphatic Chalk Hardground at **Winterbourne Chalk Pit** (see GCR site report, this volume) and, like that hardground, to correlate with the hardgrounds developed below the Brighton Marl in the higher part of the *Marsupites* Zone of the basinal successions (see Figure 3.89, Chapter 3). The relative abundance of oysters and fragments of inoceramid bivalves in the lower part of the overlying Upper Phosphatic Chalk suggests correlation with the oyster-rich shell-detrital Grobkreide facies. This facies is developed in the higher part of the *Marsupites* Zone, and the basal part of the overlying *pilula* Zone in normal white chalk successions (see also the phosphatic chalk above the Winterbourne Phosphatic Chalk Hardground).

A mean value of 6 for the Riedel Quotient (ratio of alveolar depth to the length of the belemnite) taken from data given by White and Treacher (1905) of the *Gonioteuthis* from the lower part of the beds above the phosphate-rich chalks (i.e. their Upper White Chalk), places the population on the boundary between *G. granulata* (Blainville) and *G. granulataquadrata* (Stolley). This suggests that this interval can be higher, if at all, than the *Marsupites* Zone, and certainly well below even the lower of the two *Offaster* events in basinal chalks. On this basis, the top of the succession does not extend as high as the Upper Hardground at **Winterbourne Chalk Pit**, unless the latter is reflected by the hard porcellaneous beds near the contact with the Tertiary deposits.

Apart from the fact that the lowest chalk in the section, i.e. below the Taplow Lower Hard ground, contains some pelletal phosphate, the South Lodge Pit provides a classic example, albeit on a minor scale, of a phosphatic chalk succession comparable to those formerly commercially exploited in northern France. Jarvis (1980b, 1992) has given a comprehensive account of the stratigraphy and possible mode of origin of these successions. The phosphatic chalks occupy narrow erosional troughs (cuvettes), up to 1 km in length, 250 m wide and 30 m deep, incised into the white chalk and filled with one or several units of phosphatic chalk separated by non-phosphatic chalk. The cuvettes are floored by a strongly lithified hardground, known as the basal hardground, which is typically glauconitized and heavily phosphatized, and overlain by a pelletal phosphate-rich sediment containing mineralized intraclasts. The hardground truncates the bedding of the underlying chalk and, towards the margins of the cuvette, passes laterally into a mineralized omission surface. Any higher phosphatic chalk units are also situated in erosional troughs, which may themselves be floored by a more or less strongly lithified and mineralized hardground.

The heavily phosphatized Taplow Lower Hardground, which is here tentatively inferred, on biostratigraphical evidence, to correlate with the Barrois' Sponge Bed/Clandon Hardground and, therefore, also with the Paired Hardgrounds of the **Winterbourne Chalk Pit**, could be taken to represent the basal hardground of a typical, multiple, phosphatic chalk-filled cuvette. However, it is difficult to apply this simple model to the South Lodge Pit succession, in view of the fact that the underlying chalk still contains a not insignificant proportion of pelletal phosphate, and even some weakly phosphatized intraclasts. White and Treacher (1905) noted, on the basis of intervening poor exposures, that there seemed to be a decrease in flint, and a gradual increase in phosphate content of the chalk, as the beds are traced 800 m down-dip in a southerly direction from the flinty coranguinum Zone exposure at the Root-House Pit (SU 9044 8264) to the South Lodge Pit. From this, it follows that the flintless nature of the highest chalk below the Taplow Lower Hardground could reflect some structural control of sedimentation intimately connected with the formation of the overlying packets of phosphatic chalk.

Although White and Treacher (1905) claimed that the Taplow Phosphatic Chalk occupied a tectonically, rather than erosionally induced, synclinal structure, truncated by the Tertiary Reading Beds, their arguments supporting this interpretation are inconclusive. All that the available evidence shows is that there are anomalously high dips at both the South Lodge Pit and the nearby Root-House Pit, with, according to White and Treacher (1905), a change in the dip direction from SSE to south-east. Furthermore, the basal contact of the Reading Beds dips at a lesser angle than the bedding of the Chalk and, outside the immediate area of the phosphatic chalk, appears to rest on various levels within the *coranguinum* Zone. Near Taplow Station, 1 km south-east of the South Lodge Pit, for example, Reading Beds were formerly exposed (SU 913 814) resting on the higher (Santonian) part of the latter zone. If the structural contour map on the inferred top of the Chalk Rock (Willcox, 1953) has any validity, it actually suggests the existence of a weak monoclinal structure near Taplow, rather than a syncline.

White and Treacher (1905) stated that the phosphatic chalk was limited to an area measuring less than 1 mile (1.6 km) from north-west to south-east, and less than 3.5 miles (5.6 km) from north-east to south-west, although they provided no data to substantiate the latter measurement. They noted that the extent of the phosphatic chalk to the south and east of the South Lodge Pit could not be determined due to the cover in those directions of alluvial gravels and Tertiary deposits respectively. To the west the phosphatic chalk occurrence is truncated by the valley of the Thames. However, Hawkins (1948) showed that phosphatic chalk (in part under Drift and Reading Beds cover) could be mapped over an area, 1 km wide near the South Lodge Pit, extending for at least 2.2 km to the north-east, and narrowing to a width of 0.7 km. The size of this area considerably exceeds that of the typical phosphatic chalk cuvette described from northern France.

Conclusions

South Lodge Pit exposes one of the few examples of Late Santonian phosphatic chalks in England, comparable to deposits in northern France. The phosphatic deposits and intervening chalks span the latest *M. coranguinum* Zone, a highly condensed *Uintacrinus socialis* Zone and the *Marsupites* Zone up to a point probably just below the equivalent of the Friars Bay Marl 1 of the basinal successions of the Southern Province. Mapping of the surrounding area provides a scale for channels in which phosphatic chalks form and indicates the relationship to tectonic structure.

ASTON ROWANT CUTTING, OXFORDSHIRE CHILTERN HILLS (SU 728 965–SU 740 965)

Introduction

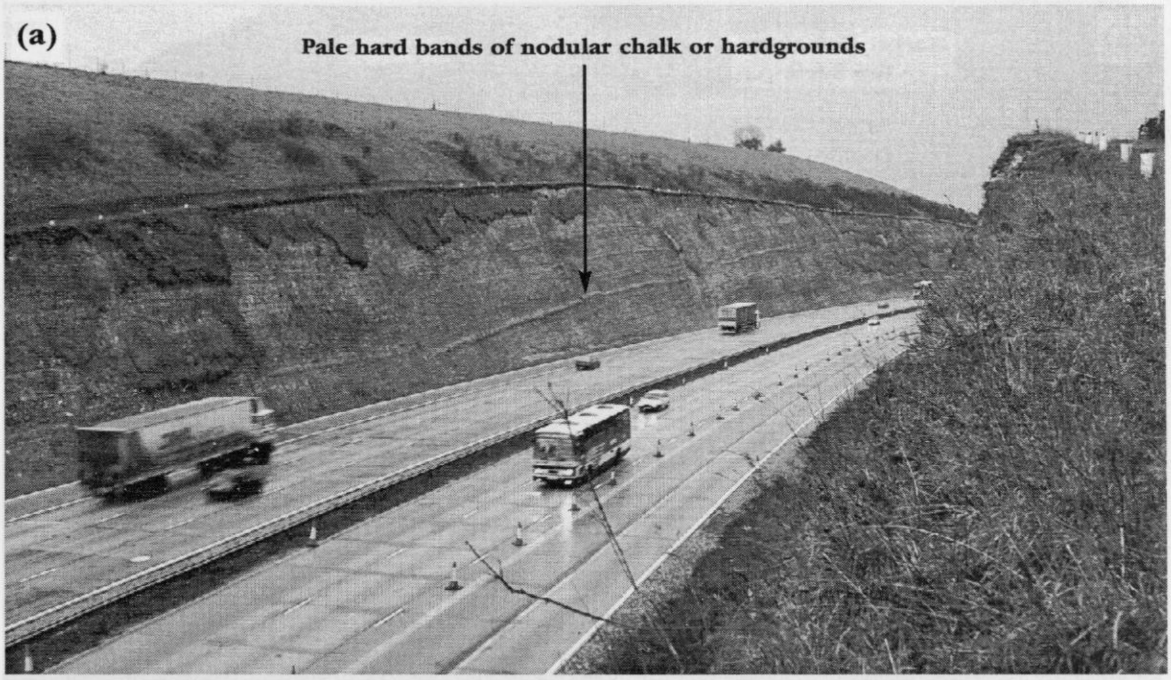
The M40 Aston Rowant (Stokenchurch) Cutting, some 700 m long (Figures 4.15–4.17), cuts through the southern part of the Chiltern Hills scarp and exposes a continuous, only partly accessible, 50 m section. This road cutting is one of the very few continuous exposures in the Chiltern Hills, where only small, discontinuous exposures are otherwise available, from below the Chalk Rock, through the Lewes Nodular Chalk Formation and into the basal Seaford Chalk Formation. The weathered faces pick out the key hard, nodular chalk horizons including the Chalk Rock, Top Rock and beds around the Light Point Hardgrounds. It is a key link section in the Chalk Rock and Lewes Nodular Chalk Formation stratigraphy between the Chalk Provinces.

Description

Apart from the basal succession, comprising the Chalk Rock and Top Rock (Bromley and Gale, 1982, fig. 13), no section for the Aston Rowant Cutting has been published. A short description of the section was given by Horton *et al.* (1995). The semi-skeletal section given here (Figure 4.18) is composite, based on sections measured by the British Geological Survey, supplemented by the present authors' own observations and section details kindly provided by Professors C.R.C. Paul and A.S. Gale as well as on information from the original site investigation by Wimpey and Company Limited.

Lithostratigraphy

The currently exposed succession (Figure 4.15a) extends from a over a metre beneath the Chalk Rock in its highly condensed 'Henley Rock' development (see p. 307; and Hill, 1886), to a level within the equivalent of the higher part of the Lewes Nodular Chalk Formation close to the Shoreham Marls and the Seaford Chalk. The thin Top Rock is situated about 4.8 m above the Chalk Rock, this interval being relatively nodular and, except at the top, devoid of flint. The succession above the Top Rock comprises gritty,



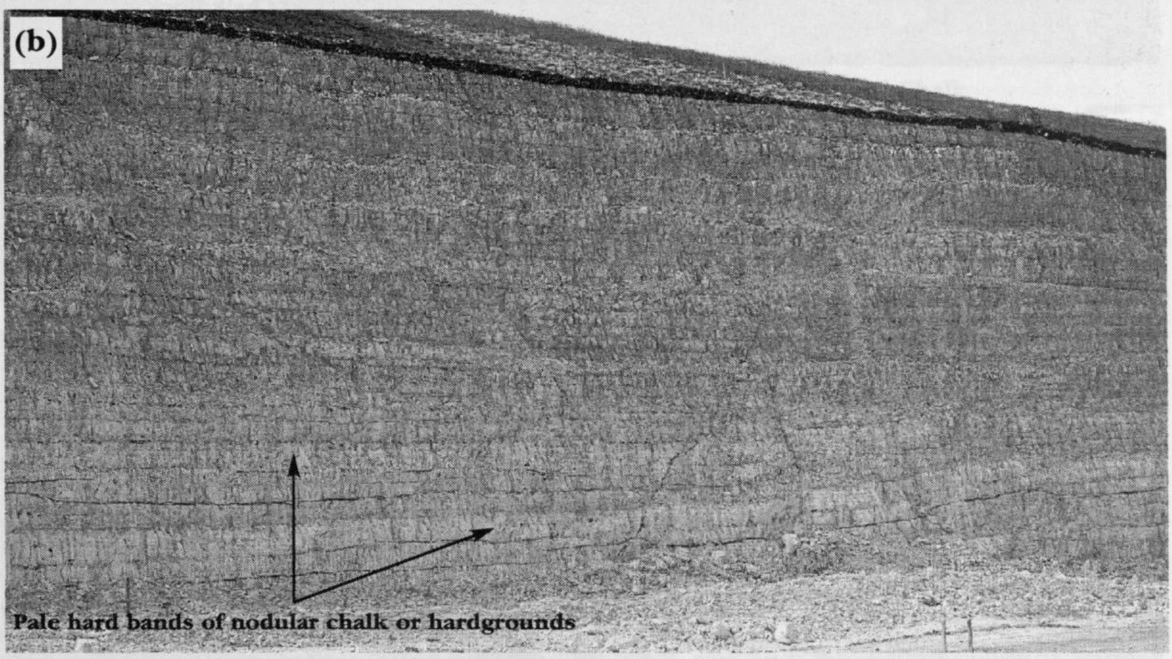


Figure 4.15 (a, b) Chalk geology exposed in the M40 Aston Rowant Cutting. (Photos: (a) R.N. Mortimore; (b) C.J. Wood.)

relatively soft off-white, very flinty chalks, with some more indurated nodular chalk horizons. A temporary section on the south side of the cutting at an earlier stage of construction, formerly exposed as much as 9 m of section below the Chalk Rock. This section (Figure 4.18), included, in addition to the sub-Chalk Rock 'Fognam Marl', an additional minor marl seam overlain by chalk with small flints that is not shown on the Bromley and Gale section (1982, fig. 13). In the highest part of the cutting, towards the

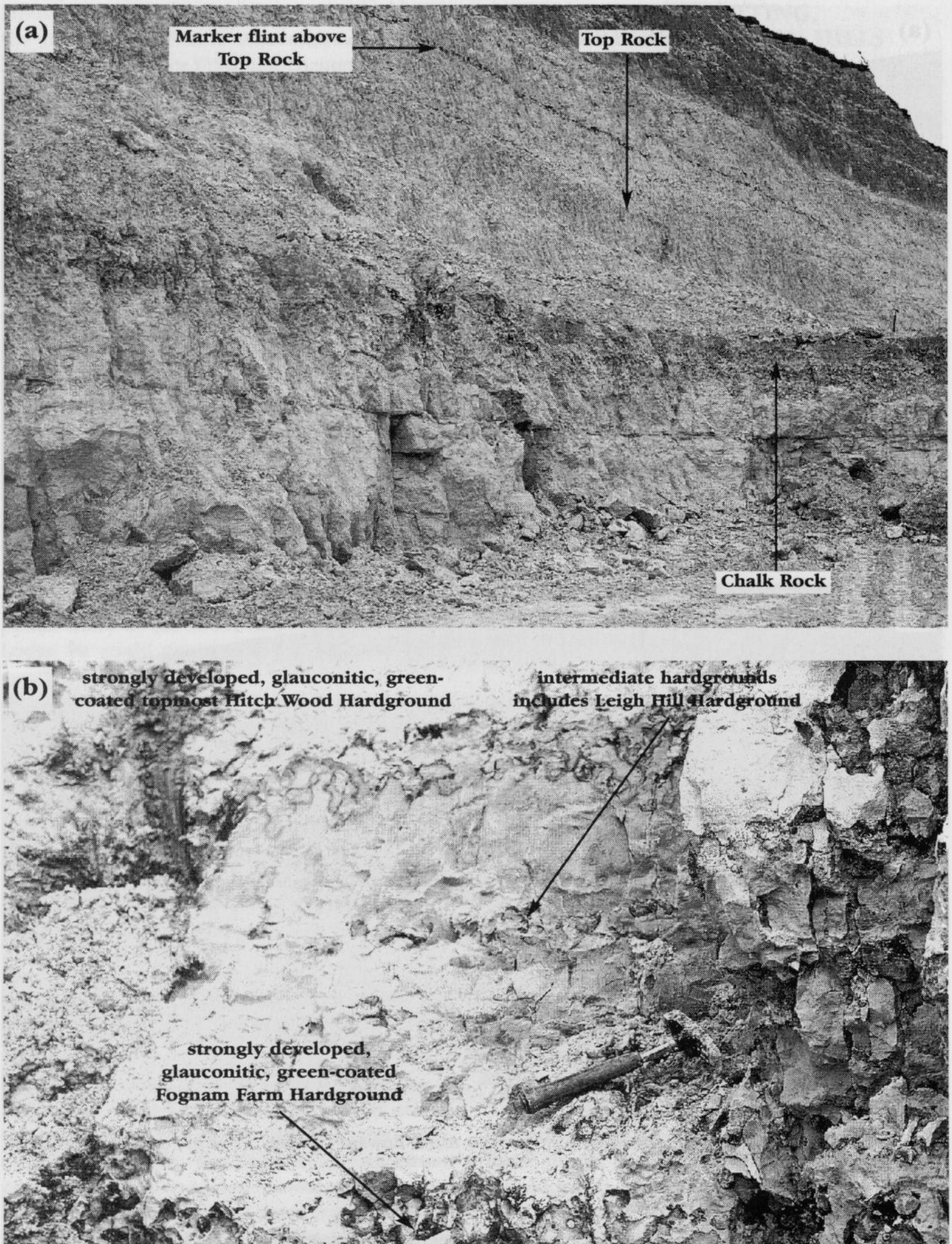


Figure 4.16 Aston Rowant Cutting, Chalk Rock. (a) Top Rock and the marker flint above Top Rock. (b) Details of the hardgrounds comprising the Chalk Rock in the Aston Rowant cuttings. (Photos: C.J. Wood.)

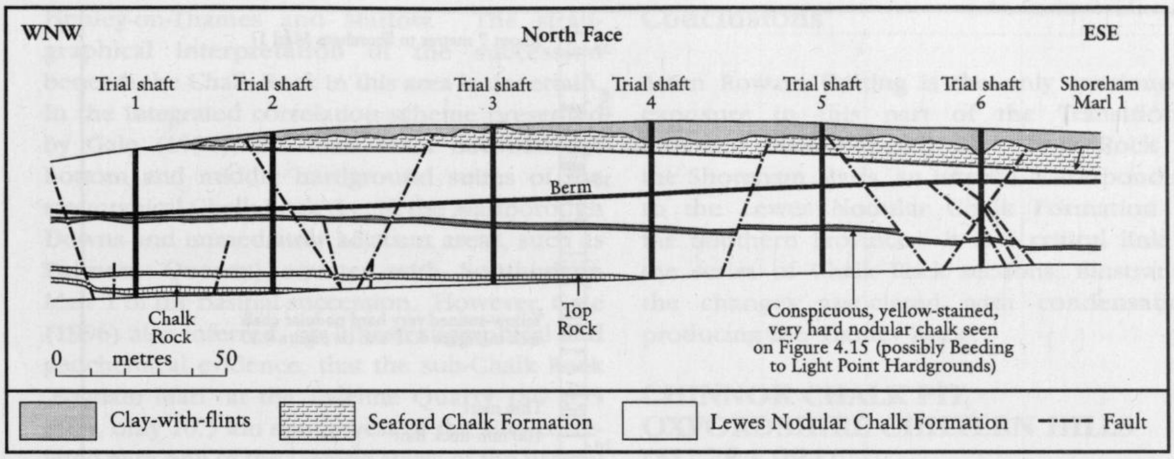


Figure 4.17 Simplified geological section of the M40 Aston Rowant Cutting, Oxfordshire, constructed from field measurements and depths to marker beds in the original site investigation trial shafts.

western end, the two Shoreham Marls, 4 to 5 m apart, were formerly exposed at and above the level of the berm. A marl seam, inferred to be the lower Shoreham Marl, could also formerly be seen in the low, eastern end of the cutting.

The succession above the Top Rock is traversed by numerous sub-horizontal and oblique sheet-flints, which emphasize shear-planes along which minor displacements have occurred. There are also several normal faults, involving displacements of over 1 m, as well as a reversed fault at the western end of the cutting. The extent of these various displacements, coupled with the relative inaccessibity of the higher parts of the succession, seriously hinders logging of the section, as a result of which no two sections agree in detail. However, in addition to the Chalk Rock and Top Rock, there are several particularly conspicuous flint bands, as well as one thick (0.6 m) prominent, yellowish hard-bed in the middle of the succession, which serve as marker horizons, and permit the construction of a generalized section. The marl seams at the top of the succession are situated several metres above the top of the measured sections and were recorded in the site investigation shafts only.

Although the succession largely comprises the equivalent of the Lewes Nodular Chalk Formation, overlain by the basal few metres of the Seaford Chalk Formation of the basinal succession, the chalks are relatively soft, with generally only a weak development of the nodularity that is diagnostic of the Lewes Nodular Chalk Formation. The Lewes Nodular Chalk retains, however, the coarse, gritty character that serves to distinguish it elsewhere from the overlying smoother Seaford Chalk.

Biostratigraphy

The higher part of the Upper Turonian *Terebratulina lata* Zone, and the lower part of the *Sternotaxis plana* Zone, are represented, in condensed form, by the Chalk Rock. The pebble bed of the Hitch Wood Hardground contains the usual *reussianum* fauna, but is not particularly fossiliferous. The interval from the Chalk Rock to the base of the Top Rock belongs to the higher part of the *plana* Zone and yields the echinoids *Echinocorys* sp., *Micraster* sp. and *Sternotaxis placenta* (Agassiz). No fossils have been collected from the Top Rock at this locality. It is likely, in analogy with the **Kensworth Chalk Pit** GCR site and the Redbournbury Quarry RIGS site in Hertfordshire, to contain small Lower Coniacian inoceramids of the *Cremnoceramus waltersdorfensis* (Andert) group, and to represent an extreme condensation of the lower part of the *Micraster cortestudinarium* Zone. The accessible part of the overlying higher *cortestudinarium* Zone succession contains common larger inoceramid bivalves (*Cremnoceramus crassus crassus* (Petrascheck)) and *Micraster*.

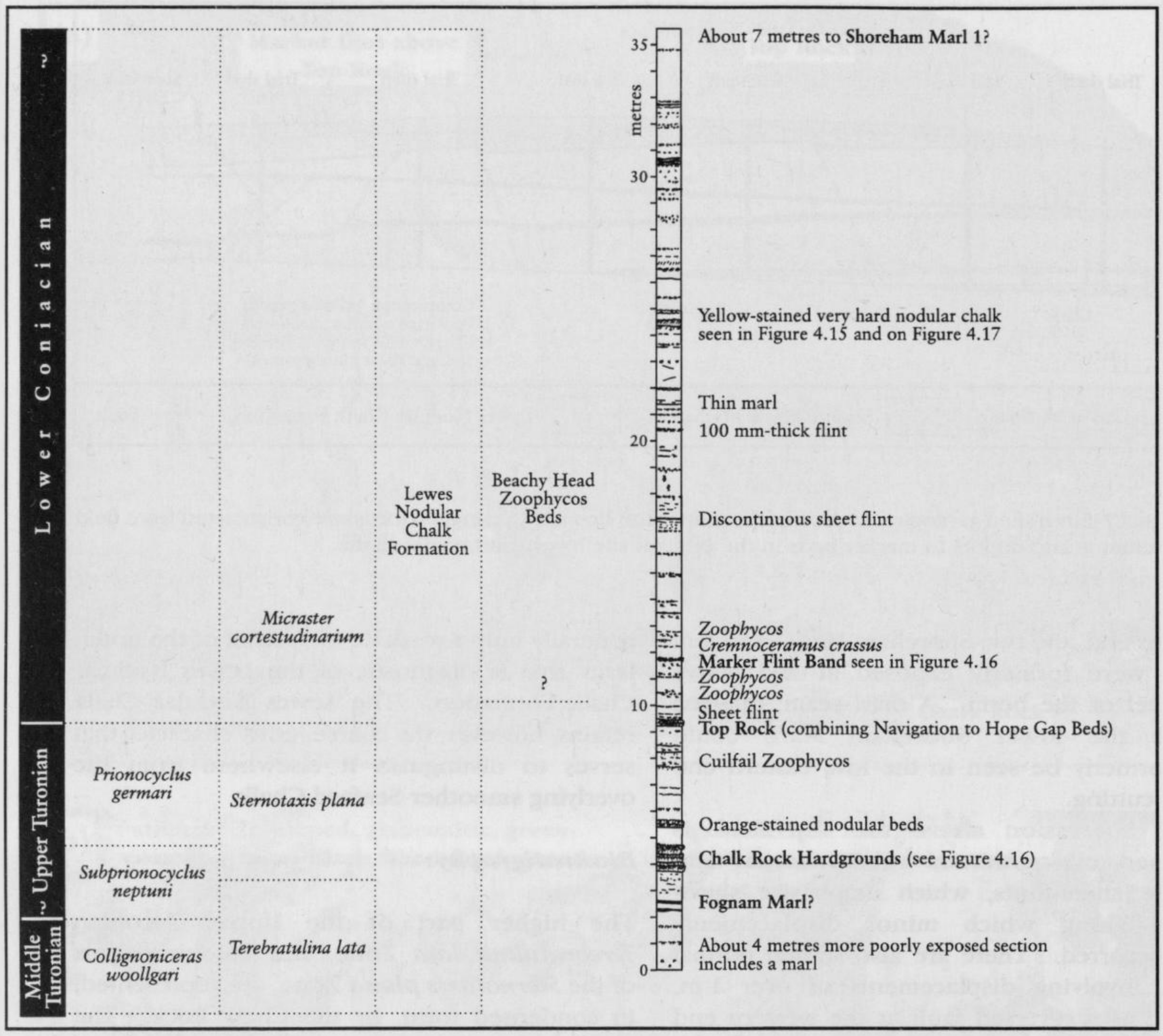


Figure 4.18 Chalk succession exposed in the M40 Aston Rowant (Stokenchurch) cutting.

Interpretation

The importance of the site is that it provides a continuous succession from below the Chalk Rock to the basal part of the Seaford Chalk Formation in part of the Transitional Province where only relatively small, discontinuous exposures are otherwise available. Shoreham Marl 2, in the highest part of the succession, links this section directly to the abandoned quarries in the Colne valley, between Uxbridge and Rickmansworth, where the same marl seam can be identified at the base of the *c.* 20 m thick lower *Micraster coranguinum* Zone succession, in the abandoned Summerhouse Lane Quarry.

The Chalk Rock (Figure 4.16) exhibits the extremely condensed 'Henley Rock' (Hill, 1886) development that characterizes this part of the Chiltern Hills. The bottom hardground suite is absent, and the middle and top suites are condensed into a complex unit, less than 1 m thick (Figure 4.16b), containing several internal glauconitized erosion surfaces corresponding to the individual main (Fognam Farm, Blounts Farm) and minor hardgrounds of the standard succession (see Bromley and Gale, 1982, fig. 13). This condensed unit is situated a short distance above a marl seam correlated with the Fognam Marl. The underlying succession, which includes an additional thin marl seam, and overlying chalk with small flints, that is not shown in the Bromley and Gale (1982, fig. 13) section, is virtually identical to that seen in the abandoned Medmenham Chalk Pit (SU 799 847), between

Henley-on-Thames and Marlow. The stratigraphical interpretation of the succession beneath the Chalk Rock in this area is uncertain. In the integrated correlation scheme presented by Gale (1996), the marl seam between the bottom and middle hardground suites of the stratotypical Chalk Rock (i.e. in the Marlborough Downs and immediately adjacent areas, such as **Fognam Quarry**) equates with Southerham Marl 1 of the basinal succession. However, Gale (1996) also inferred, on lithostratigraphical and geochemical evidence, that the sub-Chalk Rock 'Fognam Marl' at the Ewelme Quarry (SU 655 893), only 10.5 km south-west of the site, correlated with one of the Glynde Marls of the basinal succession, rather than with the equivalent of Southerham Marl 1. This implies that erosion prior to the lithification of the basal (Fognam Farm) hardground of the middle hardground suite had cut down to a level below Southerham Marl 1. It is entirely possible that a similar situation is to be found in the present site and in correlative sections in the southern Chiltern Hills.

The generally flintless succession between the Chalk Rock and the Top Rock (Figure 4.16) contains several minor indurated horizons with weakly developed terminal erosion surfaces. These supra-Chalk Rock indurated beds equate with the better-developed hardgrounds found in this interval at **Kensworth Chalk Pit**, which, together with the Top Rock, collectively constitute the Kensworth Nodular Chalk Member introduced by the British Geological Survey (see Hopson *et al.*, 1996). The highest of these surfaces is overlain by chalk with small flints and conspicuous *Zoophycos* traces, suggesting, as at Kensworth, the existence of the equivalent of the Cuilfail Zoophycos Beds of the basinal succession. The Top Rock has not been examined in detail, but it is inferred to be directly comparable to that at **Kensworth Chalk Pit**, i.e. to comprise a condensation of the lower part of the *Micraster cortestudinarium* Zone, the terminal hardground is phosphatized and overlain by small glauconitized pebbles.

The correlation of the various beds in the interval between the Top Rock and the Shoreham Marls is unclear at present. As at **Kensworth Chalk Pit**, *Zoophycos* chalks are conspicuous in the lower part of this succession. These probably correlate with the Beachy Head Zoophycos Beds. The main hard-bed marker horizon probably correlates with the Light Point Hardgrounds of the basinal succession.

Conclusions

Aston Rowant Cutting is the only continuous exposure in this part of the Transitional Province from beneath the Chalk Rock to the Shoreham Marls, an interval corresponding to the Lewes Nodular Chalk Formation of the Southern Province. It is a critical link in the series of Chalk Rock sections, illustrating the changes associated with condensation producing the 'Henley Rock'.

CHINNOR CHALK PIT, OXFORDSHIRE CHILTERN HILLS (SU 754 994)

Introduction

The Chinnor Chalk Pit site comprises Chinnor Quarry 3 (Figure 4.19), the most south-eastern, and most extensive, of the complex of quarries belonging (until 1999) to Rugby plc. The site exposes a continuous, fossiliferous section at the southern end of the Chiltern Hills through the greater part of the Grey Chalk Subgroup, as well as the lower part of the Holywell Nodular Chalk Formation at the base of the White Chalk Subgroup. Together with other quarry sections in the Chiltern Hills and **Barrington Chalk Pit**, near Cambridge (see GCR site report, this volume), it provides a key link between the basinal Grey Chalk Subgroup successions of the Southern Province and the condensed Ferriby Chalk Formation successions of the Northern Province. The Grey Chalk Subgroup section is important for its extensive exposure of the Totternhoe Stone, only 30 km south-west of the type locality. Together with **Southerham Grey Pit**, Folkestone (**Folkestone to Kingsdown** GCR site), and Beachy Head, Eastbourne, it is one of the most intensively studied Grey Chalk Subgroup sections in the Southern and Transitional provinces in respect of micropalaeontology (foraminifera and ostracods) and stable isotope stratigraphy. The Holywell Nodular Chalk Formation succession is critical, in conjunction with the Pitstone Quarry 2 RIGS site section to the north and that at Shakespeare Cliff, Dover, in establishing the correlation of the Cenomanian–Turonian boundary and basal Turonian successions between the Chiltern Hills and the Southern Province.

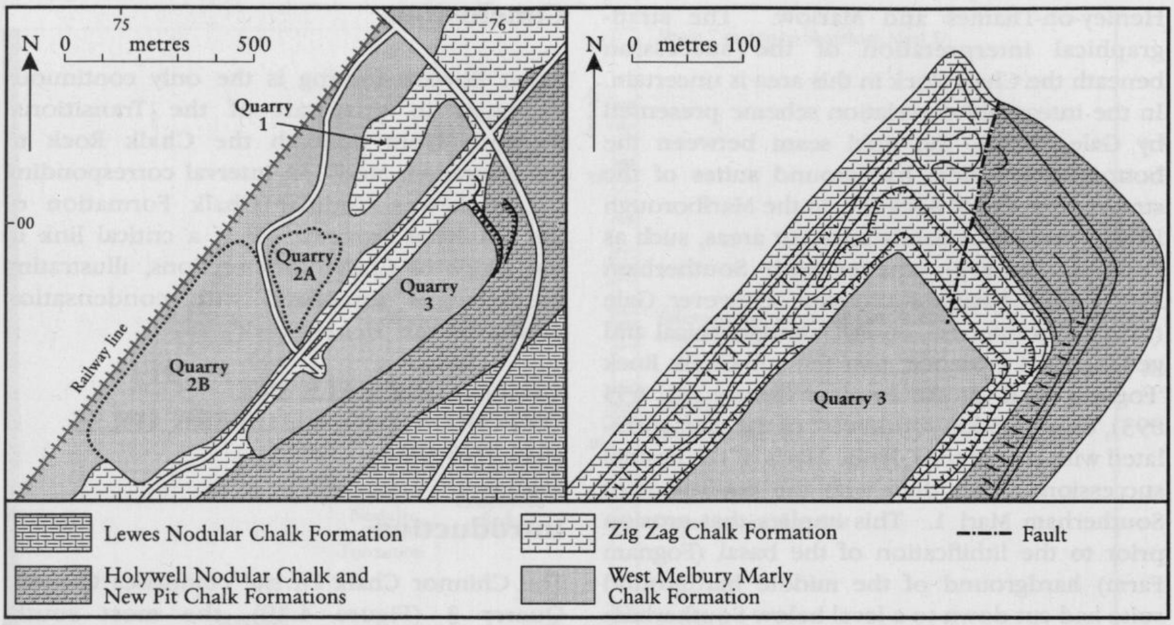


Figure 4.19 The Chinnor quarries, Oxfordshire, exposing the Grey Chalk Subgroup and basal units of the White Chalk Subgroup.

Description

Chinnor Chalk Pit (Quarry 3) is a narrow, deep quarry, 950 m long, orientated NE–SW, situated between the Icknield Way and the lower slope of the Chiltern Hills scarp. Access is through a tunnel beneath the Icknield Way. The quarry is *c.* 100 m wide at the south-west end, which is partially flooded, and *c.* 200 m wide at the north-east end, where there are seven faces, each 5–6 m high, separated by benches. The orientation of the quarry is such that the faces expose approximately dip- and strike-sections. The quarry exposes *c.* 35 m of the Grey Chalk Subgroup, which is known from borehole evidence to be *c.* 60 m thick here, and the lowest *c.* 14 m of the Holywell Nodular Chalk Formation at the base of the White Chalk Subgroup.

The following details are largely taken from the account by Sumbler and Woods (1992). The structure is simple, the regional dip, and the overall dip of the succession exposed in the quarry, being only *c.* 0.5°– 1° to the south-east; however, the higher beds exhibit opposite dips (up to 8°– 11°) to the north-west. Only minimal faulting can be observed in the strike-sections, but the dip-section at the north-east end is extensively affected by closely spaced normal faults, both oblique and sub-parallel to the face. The Plenus Marls Member is affected by normal faults orientated approximately north–south, with displacements of 0.5 m to over 2 m to the east. The only fault that can be traced throughout the north-east faces has a throw of 2 m in the Plenus Marls, reducing to 0.4 m at the level of the Totternhoe Stone.

The Grey Chalk Subgroup section was mentioned by McKerrow and Kennedy (1973). Gale (1990b) provided a log of the lowest beds in the present quarry. Descriptions of the stratigraphy and structure of the entire succession were given by Sumbler and Woods (1992) and Horton *et al.* (1995). A 210 m long tunnel, 5 m in diameter, was bored into the Grey Chalk close to the site in 1974 in order to evaluate methods of investigating ground conditions for the future Channel Tunnel (Varley, 1996). The lithostratigraphy, micropalaeontology and stable isotope stratigraphy of the Cenomanian succession in comparison with that of the standard **Folkestone to Kingsdown** succession was documented by Moghadam and Paul (2000).

Lithostratigraphy

The succession (Figure 4.2) extends from a level in the West Melbury Marly Chalk Formation of the Grey Chalk Subgroup, 13.5 m beneath the Totternhoe Stone, up to the beginning of the shell-detrital chalks in the Holywell Nodular Chalk Formation, near the base of the White Chalk Subgroup. This figure is a composite of data from the British Geological Survey log (Sumbler and Woods, 1992, fig. 2), fig. 4 in Moghadam and Paul (2000), a log of the succession beneath the Totternhoe Stone (Gale, 1990) and an unpublished log of the Holywell Nodular Chalk kindly made available by Professor Gale. The Moghadam and Paul log shows an additional 2.5 m beneath the base of the British Geological Survey log, different details of the highest beds beneath the Totternhoe Stone, and a measurement of *c.* 21 m, from the base of the Totternhoe Stone to the base of the Plenus Marls Member, as against 24 m.

Grey Chalk Subgroup

The Lower Chalk of Chinnor was recently divided by the British Geological Survey (Sumbler and Woods, 1992; Horton *et al.*, 1995) into the four traditional lithostratigraphical units applicable in the Chiltern Hills. These were the Chalk Marl (*c.* 11 m exposed), Totternhoe Stone (*c.* 1 m), Grey Chalk (*c.* 23 m) and Plenus Marls (*c.* 1 m). The same scheme was also adopted by Moghadam and Paul (2000). However, as noted by Bristow *et al.* (1997), the Chalk Marl in the Chiltern Hills represents the part of the West Melbury Marly Chalk Formation of the Southern Province that is preserved beneath the sub-Totternhoe Stone erosion surface. The Totternhoe Stone itself equates with the basal part of the Zig Zag Chalk Formation, the overlying 'Grey Chalk' constituting the remainder of the formation. In this account the Southern Province lithostratigraphical terminology will be used.

The preserved West Melbury Marly Chalk exhibits the typical succession of well-differentiated marl–limestone precession couplets that is seen in the standard Southern Province sections. Moghadam and Paul (2000, fig. 4) showed that there was a marked upward change, at *c.* 9 m below the Totternhoe Stone, from white chalks to grey chalks, which was not observed by Sumbler and Woods (1992). The thin (*c.* 1 m) brown-coloured, calcarenitic, sandy Totternhoe Stone, developed here in shelf facies, rather than channel facies, stands proud in the faces and can be followed throughout the length of the quarry. The base of the stone, particularly in the south-western part of the quarry, rests with sharp, undulating, and slight erosive contact on the underlying beds. The coarse-grained sediment is piped down in a *Thalassinoides* burrow system for up to 0.5 m below the contact. Phosphatized and glauconitized pebbles, including internal moulds of ammonites, are concentrated at the base, and small phosphatic intraclasts and fish debris are found throughout. The main mass of the stone contains the trace fossil *Teichichnus*. The top of the stone is gradational and is marked by the upper limit of phosphatic intraclasts. An interesting and hitherto unpublished record from here is a find by Dr M. Oates (BG group) of a pebble of arkose, 80 × 40 × 30 mm.

The overlying beds of the Zig Zag Chalk Formation cannot be readily examined in the steep faces. The sediments of the lowest 2 m above the Totternhoe Stone are silty and distinctly pale brown in colour, with scattered pyrite nodules. The greater part of the overlying succession comprises poorly differentiated and relatively inconspicuous alternations of thin, slightly darker coloured, bioturbated marls and thicker units of off-white chalk. A massive bed, 2 m thick, of slightly silty chalk with scattered pyrite nodules (Sumbler and Woods' Bed E1), with a 0.50 m thick marl (F4) at its base, *c.* 7 m above the Totternhoe Stone, and overlain by a closely spaced marl-pair (E2, E4), is inferred to equate with Jukes-Browne Bed 7 of the basinal successions. In the highest 4 m beneath the Plenus Marls the differentiation into marls and chalks becomes more noticeable; although Moghadam and Paul (2000) found no evidence for this. Sumbler and Woods (1992) suggested that the wavy basal contact between their beds D2 and D3, *c.* 4 m beneath the Plenus Marls, may represent a scoured surface, or even a regional erosion surface.

White Chalk Subgroup

The relatively dark-coloured Plenus Marls Member forms a conspicuous marker horizon in the higher part of the quarry and emphasizes the effects of the faulting. Compared to its development in sections in the central and northern part of the Chiltern Hills, the member is extremely thin here (up to 1 m, depending on the degree of compaction), and the standard eight beds (Jefferies, 1963), particularly beds 4–8 inclusive, cannot always be readily identified. Burrows extend down from the undulating sub-Plenus erosion surface for up to 0.5 m, but are concentrated in the top 0.1 m.

There is an excellent exposure of the basal beds of the Holywell Nodular Chalk Formation above the Plenus Marls section, and inaccessible exposures of even higher beds in the same formation. The highest beds appear to belong to the interval, two-thirds of the way up this formation, that is composed of the most shell-detrital-rich sediments. The section log given here (Figure 4.2) differs somewhat in detail from the published British Geological Survey log (Sumbler and Woods, 1992, fig. 2; Horton *et al.*, 1995, fig. 23).

Biostratigraphy

The lowest beds exposed, which are best seen at the south-west end of the quarry, lie in the lower part of the Lower Cenomanian *Mantelliceras dixoni* Zone. Even lower beds, formerly exposed in deep trenches at the base of Quarry 2, yielded an ammonite assemblage dominated by *Mantelliceras saxbii* (Sharpe) with subordinate *Mariella lewesiensis* (Spath) and *Schloenbachia* sp.. This important material, which is housed in the University Museum, Oxford (McKerrow and Kennedy, 1973), must have its provenance in the *Mantelliceras saxbii* event bed in the higher part of the underlying *Mantelliceras saxbii* Subzone of the *Mantelliceras mantelli* Zone. Sumbler and Woods (1992) inferred that this bed equated with a bed, *c.* 15 m above the base of the Grey Chalk Subgroup, that had been mapped in the surrounding area.

In the lowest part of the section, a cemented limestone (Sumbler and Woods Bed H15) containing common three-dimensional *Inoceramus* ex gr. *virgatus* Schlüter with the valves associated, represents the Dixoni Limestone marker horizon of sections in the northern Chiltern Hills (Shephard-Thorn *et al.*, 1994). This bed correlates with a pair of closely spaced spongiferous limestones in the **Folkestone to Kingsdown** section (marker M6 of Gale, 1989), which likewise, marks the top of an interval in which the inoceramid assemblage comprising *I.* ex gr. *virgatus* with subordinate *Inoceramus crippsi* Mantell, is increasingly dominated upwards by *I.* ex gr. *virgatus*. The Dixoni Limestone at Chinnor is very fossiliferous, having yielded, in addition to the inoceramid bivalves, serpulids, the long-ranging bivalves *Plagiostoma globosum* J. de C. Sowerby and *Plicatula inflata* J. de C. Sowerby, and the stratigraphically relatively restricted small brachiopod *Monticlarella? rectifrons* (Pictet and Campiche). The only ammonite recorded so far is a large unidentified *Acompsoceras* sp. (Sumbler and Woods, 1992).

A 0.3 m bed of spongiferous limestone, some 3 m beneath the base of the Totternhoe Stone, yielded three specimens of the heteromorph ammonite *Turrilites scheuchzerianus* Bosc (Gale, 1990b), enabling correlation with the *scheuchzerianus* event bed at **Southerham Grey Pit** (see GCR site report, this volume). This marker horizon is not readily identifiable in the published section, but may, contrary to the interpretation by Sumbler and Woods (1992), equate with the lower part of Bed H21, rather than with the slightly silty Bed H23. As a result of sub-Totternhoe Stone erosion the basal Middle Cenomanian ammonite Zone of *Cunningtoniceras inerme* appears to be completely missing (see below).

The Totternhoe Stone is very fossiliferous (collecting is best from fallen blocks) and is well known to local collectors for its vertebrate remains, including (M. Oates, pers. comm., 1997) bones of flying reptiles (pterosaurs) and large vertebrae of lamnid sharks. A turtle humerus was collected from this bed in the Pitstone Quarry. The Totternhoe Stone at Chinnor also yields abundant teeth of sharks, including *Cretolamna appendiculata* (Agassiz) and species of *Notidanus* and *Squalicorax*, with smaller numbers of ray teeth (*Ptychodus*). The Totternhoe Stone is inferred to represent, in condensed form, the *Turrilites costatus* Subzone of the Middle Cenomanian *Acanthoceras rhotomagense* Zone. The base of the stone here contains well-preserved three-dimensional phosphatized internal moulds (steinkerns) of ammonites, including *Acanthoceras rhotomagense* (Brongniart), *Cunningtoniceras* sp., *Schloenbachia coupei* (Brongniart), *Sciponoceras baculoides* (Mantell) and *Turrilites costatus* Lamarck (McKerrow and Kennedy, 1973). The Totternhoe Stone also yields poorly preserved unphosphatized composite moulds of large ammonites such as

Acanthoceras and *Parapuzosia* (*Austiniceras*), which represent indigenous faunal elements. As in other localities in the Chiltern Hills, the small, coarsely ribbed rhynchonellid brachiopod *Orbirhynchia mantelliana* (J. de C. Sowerby) occurs in profusion throughout the Totternhoe Stone, and a rich indigenous fauna of bivalves (notably *Plagiostoma globosum*, *Plicatula inflata*, various oysters and the thin-shelled pectinacean *Entolium orbiculare* (J. Sowerby)) and terebratulid brachiopods is found concentrated at the base. The geographically widely distributed, but stratigraphically restricted belemnite, *Praeactinocamax* (formerly *Actinocamax*) *primus* (Arkhangelsky) also occurs.

The beds immediately overlying the Totternhoe Stone contain the terebratulid brachiopod *Concinnithyris subundata*, (J. Sowerby), which elsewhere characterizes the succeeding *Turrilites acutus* Subzone. The higher beds are relatively poorly fossiliferous. The marls immediately overlying the inferred equivalent of Jukes-Browne Bed 7 contain small oysters (*Amphidonte* sp.), some with atttachment areas moulding the inoceramid bivalve *Inoceramus pictus* J. de C. Sowerby. However, the thin marl with sparse small pycnodonteine oysters that is found elsewhere in the Chiltern Hills (e.g. Totternhoe Quarry) at the base of this bed has not so far been identified. This oyster horizon may be represented by part of the interval of marly chalk with marls comprising beds F3 to F5 (of Sumbler and Woods, 1992), or it may be situated in the immediately overlying obscured part of the section at the foot of the next face. *Amphidonte* sp. together with common specimens of the thin-tested echinoid *Sternotaxis gregoryi* (Lambert), are also found some metres higher, in Bed D1.

Although well exposed, the very condensed Plenus Marls Member has yielded only a limited fauna. As usual, small to medium-sized oysters (*Pycnodonte*) and the large rhynchonellid brachiopod *Orbirhynchia multicostata* Pettitt are common in the basal marly Jefferies' Bed 1, and the eponymous belemnite, *Praeactinocamax* (formerly *Actinocamax*) *plenus* (Blainville) can be collected from the silty Jefferies' Bed 4.

The extremely indurated (topmost Cenomanian) limestones overlying the Plenus Marls Member (Sussex Melbourn Rock of Mortimore, 1986a; the Ballard Cliff Member of Gale, 1996) are readily accessible and, as elsewhere, contain the straight heteromorph ammonite *Sciponoceras bohemicum anterius* Wright and Kennedy and spines of the regular echinoid *Hirudocidaris hirudo* (Sorignet). Rhynchonellid brachiopods are characteristically absent from this interval everywhere. The re-appearance of *Orbirhynchia* in a silty bed (Sumbler and Woods Bed C20), 1.8 m above the Plenus Marls, is an important Lower Turonian bio-event that can be used for correlation with sections in the Southern Province (see below). The highest beds in the quarry are shell-detrital chalks rich in fragments and complete valves of the inoceramid bivalve *Mytiloides*.

Interpretation

The preserved thickness of the West Melbury Marly Chalk Formation below the Totternhoe Stone is inferred from boreholes to be between 36 and 40 m. This thickness compares with a similarly inferred thickness of *c.* 50 m at Pitstone Quarry, 23 km to the north-east, and, in the northern part of the Chiltern Hills, the 54 m proved below the Totternhoe Stone by the British Geological Survey Sundon Borehole (TL 0405 2724) in the base of Sundon Quarry (Shephard-Thorn *et al.*, 1994). To place this expansion in context, the thickness of the entire formation in the **Folkestone to Kingsdown** cliff section is only of the order of 34 m (Figure 4.3). The greatest expansion in the West Melbury Marly Chalk Formation in the Chiltern Hills is actually found in the succession below the Dixoni Limestone and, particularly, in the succession below the Doolittle Limestone, including the basal beds with *Aucellina*.

The occurrence at Chinnor in Quarry 2, at a lower stratigraphical level than the lowest beds exposed in Quarry 3, of the event bed with *Mantelliceras saxbii* is noteworthy. This bed must fall in the interval between the Dixoni Limestone and the Doolittle Limestone. Chinnor Chalk Pit is one of only three localities in England where this bed, situated in the higher part of the *Mantelliceras saxbii* Subzone of the *Mantelliceras mantelli* Zone has been recognized, the other localities being **Southerham Grey Pit**, Lewes, and **Compton Bay**, Isle of Wight. Elsewhere, this bed has either been removed by the erosive event that preceded the deposition of the overlying *Mantelliceras dixoni* Zone sediments, or it is not sufficiently cemented to preserve ammonites.

The distinctive event bundle, within the *Mantelliceras dixoni* Zone, comprising the strongly cemented, sponge-rich Dixoni Limestone, an overlying bed of marly chalk with small brachiopods (locally including *Orbirhynchia mantelliana*), and a conspicuous dark marl, is readily recognizable near the base of the section. The brachiopod bed equates with the lowest of the three horizons with *Orbirhynchia mantelliana* in the Grey Chalk Subgroup of the Southern Province, and with the lower of the two horizons in the condensed Ferriby Chalk Formation of the Northern Province. However, in contrast to the other Chiltern Hills sections, *Orbirhynchia mantelliana* has not so far been found here in this bed. The dark marl, seen particularly well in the Folkestone section (cf. Gale, 1989, fig. 3), is an excellent marker horizon throughout the Chiltern Hills. The composite event bundle enables Chinnor Chalk Pit to be directly correlated with standard Southern Province successions (e.g. **Folkestone to Kingsdown**) and with sections in the northern Chiltern Hills, for example Sundon Quarry (TL 041 267) and Barton-le-Clay Quarry (TL 079 296) (Shephard-Thorn *et al.*, 1994).

Two developments of the Totternhoe Stone can be distinguished in the region around Chinnor Chalk Pit. The first is a thin (less than 1 m thick), highly fossiliferous bed, with numerous *Orbirhynchia mantelliana* and small phosphatic intraclasts scattered throughout (the 'shelf facies'). The second is a much thicker, relatively poorly fossiliferous, 'channel facies', characterized by the trace fossil *Teichichnus* (Shephard-Thorn *et al.*, 1994; Hopson *et al.*, 1996). It is the 'shelf facies' that is found at Chinnor Chalk Pit. The channel facies is up to 4.7 m thick at the type locality in the Totternhoe Stone Pit, within the Totternhoe Quarry (SP 988 222), and it is separated from the shelf facies elsewhere in the quarry by a distance of 200 m or less (Shephard-Thorn *et al.*, 1994, fig. 25). North of Hitchin, at Arlesey (Green Lagoon Pit) (TL 1978 3486), the channel facies comprises a complex succession, *c.* 6 m thick, of calcarenites overlain by calcisiltites, whereas the shelf facies in the adjacent Blue Lagoon Pit (TL 1972 3444), only 300 m away, consists of only *c.* 1 m of calcarenites (Hopson *et al.*, 1996, fig. 10). The channel facies always involves a greater extent of pre-Totternhoe Stone erosion than the shelf facies: in the Totternhoe Stone Pit, erosion has cut down into the higher part of the Aucellina Beds (Figure 4.3).

The Totternhoe Stone section at Chinnor Chalk Pit can be linked in a network to several other sections in the Chiltern Hills. These include the type locality, Totternhoe Lime Quarry (TL 980 22), where both the shelf and channel facies are developed (Shephard-Thorn *et al.*, 1994, fig. 25), Houghton Regis Quarry (TL 005 236), Barton-le-Clay Quarry (Shephard-Thorn *et al.*, 1994), the two adjacent sections at Arlesey, Green Lagoon and Blue Lagoon which exhibit the channel and shelf facies respectively (Hopson *et al.*, 1996, fig. 10), and **Barrington Chalk Pit**. At Chinnor Chalk Pit, the basal contact of the Totternhoe Stone is situated *c.* 5 m above the Dixoni Limestone, and only *c.* 3 m above the event bed with *Turrilites scheuchzerianus*, which is found elsewhere (e.g. **Southerham Grey Pit**) in the higher part of the *Mantelliceras dixoni* Zone. This means that the basal beds of the Middle Cenomanian (*Cunningtoniceras inerme* Zone), and the highest part of the Lower Cenomanian *dixoni* Zone (an interval of *c.* 6–7 m in the Southern Province sections), are missing at Chinnor Chalk Pit. Farther to the north (Figure 4.3), pre-Totternhoe Stone erosion has cut down much deeper, for example in the Totternhoe Quarry, where the base of the shelf facies of the Totternhoe Stone rests on the Dixoni Limestone itself, while in the nearby Stone Pit the channel facies rests on a level near the base of the Grey Chalk Subgroup. The sub-Totternhoe stratigraphy at Houghton Regis is somewhat dificult to interpret, but at Barton-le-Clay Quarry, the basal contact is only 3.5 m above the Dixoni Limestone.

Moghadam and Paul (2000, fig. 4) show a $\delta^{13}C$ curve that does not exhibit the double-peaked positive excursion that is found above and below the Cast Bed at Folkestone and correlative localities (Paul *et al.*, 1994). They use this absence to suggest that the Totternhoe Stone has eroded down from above the Cast Bed. They also identified (their fig. 6) a sudden increase in the proportion of planktonic foraminifera in the assemblage at the higher of two conspicuous marl seams *c.* 3 m above the base of the Totternhoe Stone and correlated this with the so-called 'P/B break', identified by Carter and Hart (1977a) in the Southern Province. On this basis, the boundary between the *Turrilites costatus* and *T. acutus* subzones of the *Acanthoceras rhotomagense* Zone must lie at, or slightly higher than, this level.

Sumbler and Woods' Bed E1, which has a slightly gritty texture, corresponds to the Chiltern Hills equivalent of Jukes-Browne Bed 7 of the Southern Province or, alternatively, to a very poorly lithified and ill-defined development of the Nettleton Stone of the Northern Province. It is underlain by three marls from which Moghadam and Paul (2000) recorded the oyster *Pycnodonte*, confirming the position of the *Pycnodonte* event of northern European event stratigraphy, and it is overlain by a pair of marls containing the oyster *Amphidonte*. This latter oyster occurrence appears to correlate with the lower of two *Amphidonte* events (Ernst *et al.*, 1983) recognized in Westphalia, northern Germany (Kaplan *et al.*, 1998) at this level. The higher *Amphidonte* occurrence, associated with the inoceramid bivalve *Inoceramus pictus* and the thin-tested echinoid *Sternotaxis gregoryi*, in Bed D1, probably correlates with the higher of the two German *Amphidonte* events. The glauconitized/phosphatized pebble bed in a coarse-grained chalk matrix (the 'Buckinghamshire Rag' of the earlier literature), that is locally developed at this horizon to the north-east in Pitstone Quarry 2 and, associated with abundant thick-shelled terebratulid brachiopods (*Ornatothyris sulcifera* (Morris)), in the Totternhoe Lime Quarry (Shephard-Thorn *et al.*, 1994) and the former Grove Mill Quarry, Hitchin (Hopson *et al.*, 1996), is not found at Chinnor.

In marked contrast to the relative expansion in the Chiltern Hills of the preserved West Melbury Marly Chalk Formation, the Zig Zag Chalk Formation, particularly the interval from the base of the Totternhoe Stone to the base of the equivalent of Jukes-Browne Bed 7, is conspicuously thinner than in Southern Province successions. This is largely due to the strong condensation represented by the Tottternhoe Stone itself. The interval from the top of the Jukes-Browne Bed 7 equivalent to the sub-Plenus erosion surface (i.e. the White Bed of the North Downs), on the other hand, retains a more or less constant thickness of the order of 15–16 m from the North Downs to Chinnor Chalk Pit. At the former Butler's Cross Quarry (SP 843 070), 11 km to the north-east of Chinnor, the interval from the base of the Plenus Marls Member to the inferred correlative of the Buckinghamshire Rag, is only some 5 m in extent (Jefferies, 1963). This could be interpreted as the result of pre-Plenus Marls erosion. However, at the Pitstone Quarry 2 RIGS site, where the Buckinghamshire Rag is locally developed, the sub-Plenus erosion surface is situated less than 1 m above a hardground.

The 13 m section in the Holywell Nodular Chalk Formation above the Plenus Marls Member is potentially of importance in establishing the correlation with the relatively condensed succession in the North Downs and the more expanded succession at Beachy Head, Eastbourne, using the marker horizons documented by Gale (1996). Compared with Dover, the basal beds (Gale's Ballard Cliff Member) are only 0.7 m thick as against 1 m. The lowest two couplets belong to the highest part of the *Metoicoceras geslinianum* Zone, and the remainder of the unit can be inferred to belong to the overlying terminal Cenomanian *Neocardioceras juddii* Zone (Figure 4.2). The top of this unit marks the approximate position of the Cenomanian–Turonian boundary, and the inferred base of the *Watinoceras devonense* Zone. The calcarenitic bed that is used in the Chiltern Hills and the Hitchin area as a correlative of the base of the Holywell Marl 2–Holywell Marl 3 interval (Wood, 1993; Hopson *et al.*, 1996) can be identified 1.8 m above the Plenus Marls Member. This bed marks the first occurrence of *Orbirhynchia* in the Holywell Nodular Chalk above the Plenus Marls Member and, by extrapolation from Dover, the base of the *Fagesia catinus* ammonite Zone. The interval up to 5 m above the Plenus Marls is rather inaccessible and incompletely exposed. These beds were assigned to the Melbourn Rock by Horton *et al.* (1995); however, the upper limit chosen by those authors is probably significantly higher than the top of the Melbourn Rock as identified by Hopson *et al.* (1996) at Ashwell Quarry (TL 2687 3945), in the single extant locality of the three original type localities, namely Melbourn, Ashwell, and Hitchin railway cutting quarry.

The 0.10 m intraclastic marl, and the 0.05 m flaser marl overlying indurated nodular chalk, at 5 m and 6 m above the Plenus Marls Member respectively, are inferred to correlate with the Gun Gardens Marls in the sense of Gale (1996). The base of the lower of these two marl seams was taken by Horton *et al.* (1995) to mark the top of the Melbourn Rock. The extremely shell-detrital-rich chalks above and below a marl seam 8.3 m above the base are tentatively correlated with the beds associated with the Gun Gardens Marls as originally described by Mortimore (1986a) and by Mortimore and Pomerol (1996). The *Filograna avita* horizon, which occurs towards the top of this interval (Gale, 1996), and is approximately coincident with the most shell-detrital chalk in the Holywell Nodular Chalk Formation, has not so far been identified at Chinnor, but its inferred position is shown on Figure 4.2. It is known to be present near the top of the Pitstone Quarry 2 RIGS site section, 24 km to the north. The latter locality is the most northerly section where this important bio-event is seen in its normal development.

The highest beds at Chinnor Chalk Pit consist of some 2 m of shell-detrital chalks underlain by a marl seam. It is possible that this latter marl seam is the equivalent of the Aston Marl (see p. 305), which is seen farther to the north in the Ivinghoe-Aston Pit (SP 960 176) and at the top of the Totternhoe Quarry 2A. This marl seam marks the lowest level at which flint is developed in the Holywell Nodular Chalk in the central and northern Chiltern Hills. If this correlation is correct, it suggests that the top of the preserved Chalk at Chinnor Chalk Pit may be relatively close to the top of the Holywell Nodular Chalk. However, there is no evidence of flint at this level in this part of the Chiltern Hills.

Conclusions

The site exposes one of the most important successions in the Transitional Province, spanning the greater part of the West Melbury Marly Chalk, the Totternhoe Stone (which is particularly fossiliferous here), the Zig Zag Chalk Formation and the Holywell Nodular Chalk Formation. It is one of the most intensively researched Grey Chalk Subgroup sites in the UK in respect of integrated macrofossil and microfossil biostratigraphy, as well as stable isotope stratigraphy, and it can be used to link the Transitional Province to the standard Southern Province successions in the **Folkestone to Kingsdown** and **Southerham Grey Pit** GCR sites.

KENSWORTH CHALK PIT, BEDFORDSHIRE CHILTERN HILLS (TL 015 197)

Introduction

Kensworth Chalk Pit (TL 015 197) is a large working quarry located 1 km south of Dunstable, adjacent to Whipsnade Zoo, in the Dunstable Downs, northern Chiltern Hills (Figure 4.20). The pit exposes a continuous, 40 m section through the higher part of the New Pit Chalk Formation and the Lewes Nodular Chalk Formation up to the Beachy Head Zoophycos Beds. This corresponds to a stratigraphical range from the Middle Turonian *Collignoniceras woollgari* Zone to the Lower Coniacian *Micraster cortestudinarium* Zone. It thus provides a unique standard section for the Transitional Province. It is best known for the Chalk Rock, which, in some parts of the quarry, is extremely fossiliferous, and it is one of the three most important extant sources of Chalk Rock ammonites, including figured material. The marl seams beneath the Chalk Rock at this locality provide the key to the interpretation of the relationship between the basinal chalk facies and the marginal, condensed Chalk Rock hardground facies. The interval between the Chalk Rock and the Top Rock is more condensed than elswhere, and contains several unnamed hardgrounds. This hardground succession, together with the Top Rock, is termed the 'Kensworth Nodular Chalk Member' by the British Geological Survey, with the Kensworth section being taken as the stratotype. The Top Rock is particularly well exposed and, compared with other localities, relatively fossiliferous, yielding basal Coniacian inoceramid bivalves critical to long-range correlation.

Description

The Kensworth Chalk Pit section (Figure 4.21) extends from a level 30 m below the Chalk Rock to some 5 m above the Top Rock. The strata dip at *c.* 3° to the south-east. Faulting is minimal, and there are few faults with displacements in excess of 1 m. The chalk is worked in several faces, separated by wide benches. In the near future it is intended to extend quarrying to an even greater depth than at present. A recently opened section, 3 m high, exposing the Chalk Rock in about the middle of the face, and some

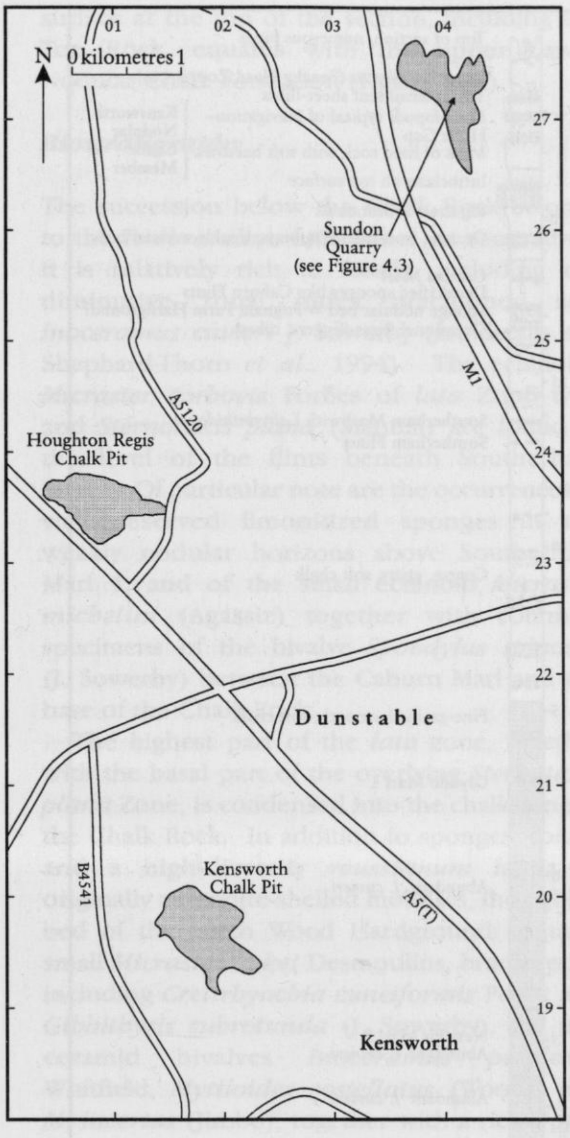


Figure 4.20 Location of Kensworth Chalk Pit, Bedfordshire, and adjacent sections.

distance from the present worked faces, will be retained as a GCR site after the remainder of the quarry has been restored by landscaping.

Various parts of the Kensworth section, notably the Chalk Rock and the underlying marl seams, have been discussed in the literature (Bromley and Gale, 1982; Mortimore and Wood, 1986; Wray and Gale, 1993; Hopson *et al.*, 1996; Gale, 1996), and the entire section has been described and illustrated in detail by the British Geological Survey (Shephard-Thorn *et al.*, 1994). Chalk Rock ammonites from here were illustrated by Wright (1979) and by Kaplan *et al.* (1987).

Lithostratigraphy

The succession (Figure 4.21) below the Chalk Rock comprises relatively soft, coarse, gritty chalks with several minor flint bands, as well as some weakly indurated horizons preserving sponges emphasized by pale orange-yellow limonite. This succession also includes several conspicuous, widely spaced marl seams up to 0.10 m in thickness. The uppermost two marl seams, 6 m and 2 m below the base of the Chalk Rock, equate with the Southerham Marl 1 and Caburn Marl of the Southern Province basinal succession respectively (Mortimore and Wood, 1986). One or more of the underlying marls are tentatively correlated with elements of the Glynde Marls group.

The Chalk Rock is represented by a prominent chalkstone unit 0.7 m thick, which comprises only the top suite of the standard succession. Although apparently a single, massive, homogeneous bed, it is in fact composite and contains two minor phosphatized surfaces (cf. Bromley and Gale, 1982, fig. 13). The chalkstone is penetrated by an extensive *Thalassinoides* burrow system, mostly filled either by friable, granular chalk or else empty of sediment. The Chalk Rock chalkstone terminates in the convolute Hitch Wood Hardground, which here is heavily glauconitized and phosphatized; its associated pebble bed is locally highly fossiliferous (see below). This is a typical development of the so-called 'Hitch Wood facies' (Hopson *et al.*, 1996), in which the terminal (Hitch Wood) hardground has not yet split into the succession of mineralized hardgrounds and nodular chalks (Reed facies) that characterize successions in eastern Hertfordshire and areas to the east.

The interval between the Chalk Rock and the base of the Top Rock is thinner here (*c.* 2 m), than in any other known section in the Chiltern Hills–north Hertfordshire area. This interval includes a chalkstone with a glauconitized and phosphatized hardground overlain by glauconitized pebbles, which is followed by three weakly glauconitized and poorly lithified hardgrounds. The chalk above the highest of these hardgrounds contains small *Zoophycos* flints. The hardground succession above the Chalk Rock up to the top of the Top Rock forms the stratotype of the Kensworth Nodular Chalk Member of the British Geological Survey (Hopson *et al.*, 1996, fig. 17). The Top Rock is double, comprising two hardgrounds welded together. The main

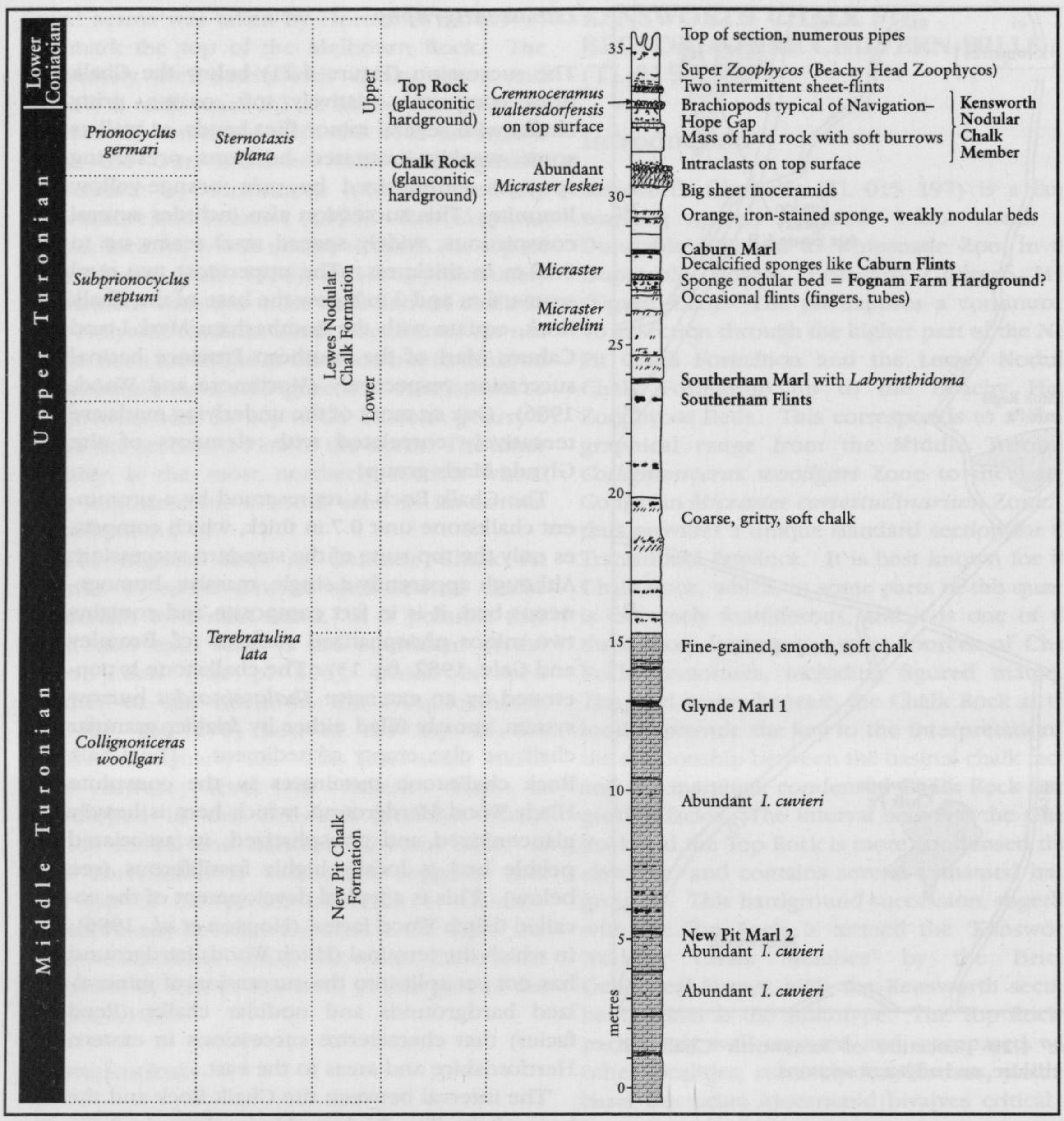


Figure 4.21 The Chalk succession at Kensworth Chalk Pit, where the inter-basinal Turonian marker marl seams are present and the northward change in development of the Chalk Rock and Top Rock is illustrated.

component is a massive, slightly pink-coloured chalkstone with a terminal convolute, dark-green glauconitized hardground, overlain by large glauconitized pebbles, several centimetres across, which include rolled hexactinellid sponges and echinoids. This is followed by a second, less strongly lithified and unmineralized hardground. The chalk above the higher of these hardgrounds contains conspicuous *Zoophycos* traces and small *Zoophycos* flints at the beginning of the Beachy Head Zoophycos Beds.

The succession below and including the Glynde Marls group is the upper part of the New Pit Chalk Formation. The succession from above the Glynde Marls group, through the soft, gritty chalks up to and including the Chalk Rock, corresponds to the lower Lewes Nodular Chalk Formation. The interval from the top surface of the Chalk Rock up to the Quaternary erosion surface at the top of the section, including the Top Rock, equates with the upper Lewes Nodular Chalk Formation (Figure 4.21).

Biostratigraphy

The succession below the Chalk Rock belongs to the *Terebratulina lata* Zone. At some levels it is relatively rich in fossils, including the diminutive zonal index brachiopod and *Inoceramus cuvieri* J. Sowerby (for details see Shephard-Thorn *et al.*, 1994). The echinoids *Micraster corbovis* Forbes of *lata* Zone type and *Sternotaxis plana* (Mantell) are found at the level of the flints beneath Southerham Marl 1. Of particular note are the occurrences of well-preserved limonitized sponges in the weakly nodular horizons above Southerham Marl 1, and of the small echinoid *Micraster michelini* (Agassiz) together with common specimens of the bivalve *Spondylus spinosus* (J. Sowerby) between the Caburn Marl and the base of the Chalk Rock.

The highest part of the *lata* zone, together with the basal part of the overlying *Sternotaxis plana* Zone, is condensed into the chalkstone of the Chalk Rock. In addition to sponges, corals, and a high-diversity *reussianum* fauna of originally aragonite-shelled molluscs, the pebble bed of the Hitch Wood Hardground contains small *Micraster leskei* Desmoulins, brachiopods including *Cretirhynchia cuneiformis* Pettitt and *Gibbithyris subrotunda* (J. Sowerby), the inoceramid bivalves *Inoceramus perplexus* Whitfield, *Mytiloides costellatus* (Woods) and *M. incertus* (Jimbo), together with a rich Upper Turonian *Subprionocyclus neptuni* ammonite fauna. This assemblage enables correlation with the *plana* Zone Kingston Nodular Beds of the lower Lewes Nodular Chalk Formation of the standard Southern Province basinal succession.

The unnamed hardgrounds of the Kensworth Nodular Chalk Member have so far not yielded any diagnostic fauna, but they can be attributed on general stratigraphical grounds to the higher part of the *plana* Zone. The occurrence of *Zoophycos* in the chalks immediately above these hardgrounds points to a correlation with the terminal *plana* Zone Cuilfail Zoophycos Beds of basinal successions. The Top Rock contains common small uniplicate terebratulid brachiopods (*Concinnithyris*?) and recent collecting (1998) has yielded the topmost Upper Turonian–basal Lower Coniacian inoceramid bivalve *Cremnoceramus waltersdorfensis* (Andert). The glauconitized, pebble-preservation fossils resting on the lower hardground of the composite Top Rock include rolled hexactinellid sponges and echinoids, such as *Micraster cortestudinarium* (Goldfuss). The white, flinty chalks above the Kensworth Nodular Chalk Member contain common *Zoophycos* flints and larger, thick-shelled *Cremnoceramus* sp. typical of the Beachy Head Zoophycos Beds of the Southern Province.

Interpretation

The lower part of the succession at Kensworth Chalk Pit remains poorly understood, but it can be used to establish a tentative correlation (Mortimore and Wood, 1986, fig. 2.4), by means of marl seams and flint horizons, via the section in the Royston road cutting (TL 372 410) (Hopson *et al.*, 1996, fig. 16), to the successions in East Anglia.

Kensworth Chalk Pit is of particular importance because of the extensive 30 m succession, including marl seams, exposed beneath the Chalk Rock, which form part of the marl/tephro-event stratigraphy for north-west Europe (see Chapter 1). The two highest sub-Chalk Rock marl seams were originally named the 'Latimer Marl' and 'Reed Marl' by Bromley and Gale (1982) after a section near Latimer in the southern Chiltern Hills (TQ 005 993) and the Reed Chalk Pit (TL 359 371) in north Hertfordshire respectively. Of these two names, the Latimer Marl is unsatisfactory, because the type locality does not expose the relationship between the marl and the Chalk Rock. The Reed Marl, on the other hand, is well established as the marl seam that occurs below the Reed facies of the Chalk Rock. Mortimore and Wood (1986) showed that the 0.1 m 'Latimer Marl' at Kensworth Chalk Pit was closely comparable with the Southerham Marl 1 of the basinal succession and was, like that marl, full of the large foraminifer *Labyrinthidoma southerhamensis* Hart (formerly *Coskinophragmă*, see Hart (1993)) and underlain by the same distinctive vertical 'finger', tubular and nodular Southerham Flints. A similar development is found at the Great Chesterford Chalk Pit (Cambridgeshire), but there the marl in question is correlated with the Mount Ephraim Marl of the Norfolk succession (Ward *et al.*, 1968). Mortimore and Wood (1986) also suggested that the 0.05 m thick marl seam below the Chalk Rock was the equivalent of the Caburn Marl, and that certain of the marl seams beneath the Mount Ephraim/'Latimer'/ Southerham Marl 1 could be correlated with marl seams belonging to the Glynde complex. These correlations were substantiated by Wray and Gale (1993), on the basis of trace-element characterization studies of the clay minerals of the individual marl seams in the two areas.

Additional support for the Reed Marl–Caburn Marl correlation is provided by the macrofossils. The echinoid *Micraster michelini*, which is not uncommon here above the Reed/Caburn Marl (cf. the specimen figured by Stokes (1977, figs 4–6)), characterizes the interval between the Caburn Marl and the Bridgewick Marls of the basinal succession (Mortimore, 1986a). The record (Gale, 1996) of the zonal index ammonite *Romaniceras deverianum* (d'Orbigny) from a nodular horizon just above the same marl in a section near Luton railway cutting, agrees with finds of this species close to the Caburn Marl in Sussex.

Kensworth Chalk Pit is the sole locality where the relationship between the top hardground suite of the Chalk Rock and the marl seams of the standard basinal succession can be unequivocally demonstrated. On the basis of this correlation, the Bridgewick Marls and associated large nodular flints – the so-called 'Basal Complex' or 'High Turonian flint maximum' (Mortimore and Wood, 1986, fig. 2.2.) – must be condensed within the complex Chalk Rock chalkstone. An intermediate stage in this condensation is seen at Reed Chalk Pit (TL 359 371) in north-east Hertfordshire, where the relicts of the flints belonging to the Basal Complex are still preserved (Gale, 1996, fig. 7; Hopson *et al.*, 1996, fig. 17).

The relationship between the Chalk Rock succession at Kensworth Chalk Pit, which involves only the top hardground suite and the underlying marl seams, and the succession at the **Aston Rowant Cutting** GCR site, where the Chalk Rock comprises both the top and middle hardground suites and is underlain by a marl seam inferred to correlate with the Fognam Marl of the standard succession, is unclear. All of the attempts to satisfactorily interpret the correlation between these two key sections (cf. Bromley and Gale, 1982; Wray and Gale, 1993; Gale, 1996) are bedevilled by the absence of comparably extensive sections in the intervening ground. In any case, even the identity of the sub-Chalk Rock 'Fognam' Marl (Glynde or Southerham Marl 1?) in the **Aston Rowant Cutting** section (see GCR site report) is uncertain. In the present state of knowledge, it is impossible to state how the named hardgrounds (Fognam Farm, Blounts Farm) of the latter section are to be correlated with the incipiently nodular developments in the lower Lewes Nodular Chalk Formation at Kensworth.

The Hitch Wood Hardground pebble bed in the present working face is thin, and contains mostly relatively small fossils belonging to the *reussianum* fauna. Former Chalk Rock sections, much closer to the entrance to the quarry, yielded abundant fossils, notably ammonites, including large specimens of *Puzosia muelleri* de Grossouvre (*Austiniceras curvatisulcatum* Chatwin and Withers in the older literature). The recently cut preserved face is in this latter area and appears to expose Chalk Rock of this type. It is possible that these former sections intersected minor channels or depressions in the hardground surface, within which the larger material accumulated and was protected from erosion, and that the pebble bed elsewhere in the quarry was located on areas of high sea-floor relief, and consequently more exposed to erosion.

Kensworth Chalk Pit is particularly well known for the large number and taxonomic diversity of well-preserved ammonites belonging to the Upper Turonian *Subprionocyclus neptuni* ammonite Zone (Figures 2.9 and 2.11, Chapter 2) that have been collected from the Chalk Rock. Most of the 25 recorded species have been found here, and large collections, including specimens figured by Wright (1979) and by Kaplan *et al.* (1987), are preserved at the British Geological Survey, Keyworth. The only other Chalk Rock sections that have yielded comparably diverse ammonite faunas are the Hitch Wood (Hill End) and Reed chalk pits. The occurrence at Kensworth of the ammonites *Baculites undulatus* d'Orbigny, *Puzosia muelleri* and *Subprionocyclus normalis* (Anderson), associated with the inoceramid bivalve *Mytiloides incertus*, indicates that the Chalk Rock fauna here also incorporates elements from the highest of the three ammonite assemblages in the coeval Scaphiten-Schichten in Germany (Kaplan and Kennedy, 1996; Wiese and Kröger, 1998).

The main (lower) chalkstone of the Top Rock yields common small, uniplicate terebratulid brachiopods, as well as sporadic specimens of the topmost Turonian–basal Lower Coniacian inoceramid bivalve *Cremnoceramus waltersdorfensis*, which enable correlation with the standard European inoceramid zonal scheme (cf. Kauffman *et al.*, 1996; Walaszczyk and Wood, 1999b). Recent observations suggest that the intensely hard Top Rock at Kensworth, which hitherto has been considered to be relatively poorly fossiliferous, is probably broadly comparable with that exposed, in a weathered state, in a shallow trench at the Redbournbury Quarry RIGS site (TL 123 103), 14 km to the south-east. In addition to *C. waltersdorfensis*, the latter has yielded numerous specifically Lower Coniacian inoceramids, including *C. deformis erectus* (Meek) and *C. waltersdorfensis hannovrensis* (Heinz) (British Geological Survey collections). These inoceramids are found, in basinal successions, in the interval between the Navigation Hardground and Hope Gap Hardground, and are critical in establishing the stratigraphical equivalence of the Top Rock. Similar – but much more diverse – assemblages, including moulds of gastropods and the brachiopod *Cretirhynchia subplicata* (Mantell), occur in the Top Rock in various localities near Bury St Edmunds in East Anglia (Wood and Bristow, 1990). The fauna of the gritty chalk above this interval, containing abundant *Zoophycos* and examples of the large, thick-shelled inoceramid bivalve *Cremnoceramus crassus crassus* (Petrascheck) and the echinoids *Echinocorys gravesi* (Desor) and *Micraster* sp., is typical of the Beachy Head Zoophycos Beds.

Conclusions

Kensworth Chalk Pit is unique in the Transitional Province in providing a continuous section through the upper part of the New Pit Chalk Formation up to a horizon close to the top of the equivalent of the Lewes Nodular Chalk Formation. This is the only site where the identity of the marl seams beneath the Chalk Rock can be unequivocally established and it is, therefore, critical in interpreting the tephro-event stratigraphy and the stratigraphy of the Chalk Rock. The great diversity and richness of well-preserved Upper Turonian ammonites and other fossils from the Chalk Rock is also unique in the UK. The site provides the stratotype of the Kensworth Nodular Chalk Member of the British Geological Survey. Both the Chalk Rock and the Top Rock yield fossils that enable long-range correlation with successions and zonal schemes in northern Europe.

BARRINGTON CHALK PIT, CAMBRIDGESHIRE (TL 399 511)

Introduction

Barrington Chalk Pit is located south-west of Cambridge (TL 399 511) and consists of an enormous working quarry belonging to Rugby plc, which is cut into the hillside above the village of Barrington. The pit exposes a section from Gault mudstones below the Cambridge Greensand Member at the base of the West Melbury Marly Chalk Formation, to a level in the Zig Zag Chalk Formation, several metres above the Totternhoe Stone. It is thus the most extensive section of the lower part of the Grey Chalk Subgroup in the Transitional Province. It is also the better of the only two extant sections in the Cambridge Greensand Member, albeit not particularly fossiliferous compared with other former sections near Cambridge. It is important for showing a succession of the lower part of the West Melbury Marly Chalk Formation that is transitional between those of the Chiltern Hills and the condensed successions of the Northern Province Ferriby Chalk Formation. The base of the Totternhoe Stone is demonstrably erosive. The immediately overlying beds yield important inoceramid bivalve faunas that are older than the succeeding *Inoceramus atlanticus* assemblage of the *Acanthoceras jukesbrownei* Zone and which can be better collected here than elsewhere.

Description

The section at Barrington Chalk Pit has been considerably extended in recent years. At present, there are three main working faces, separated by benches, with the lowest beds under water. There is, surprisingly, no published log of this much-visited section, but considerable stratigraphical information, based on cored boreholes, is held by Rugby plc in a consultant's report. Because of the difficulty of logging the relatively inaccesible faces, the site (Figure 4.22) is illustrated by a panoramic photograph (Figure 4.23). A fault, or group of faults, affecting the Totternhoe Stone, can be seen in the centre of the main (second) working face.

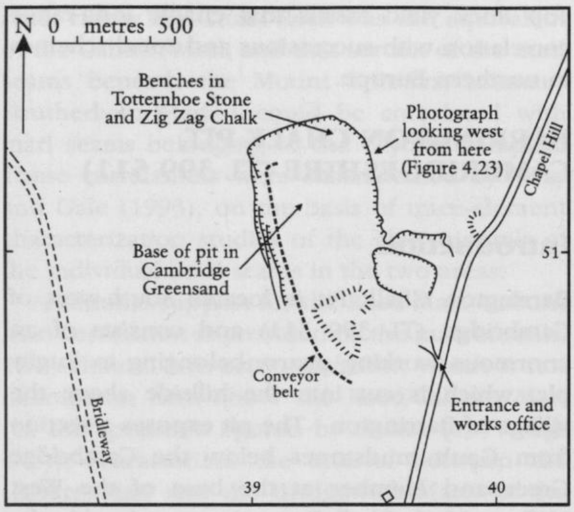


Figure 4.22 Barrington Chalk Pit, Cambridgeshire.

Lithostratigraphy

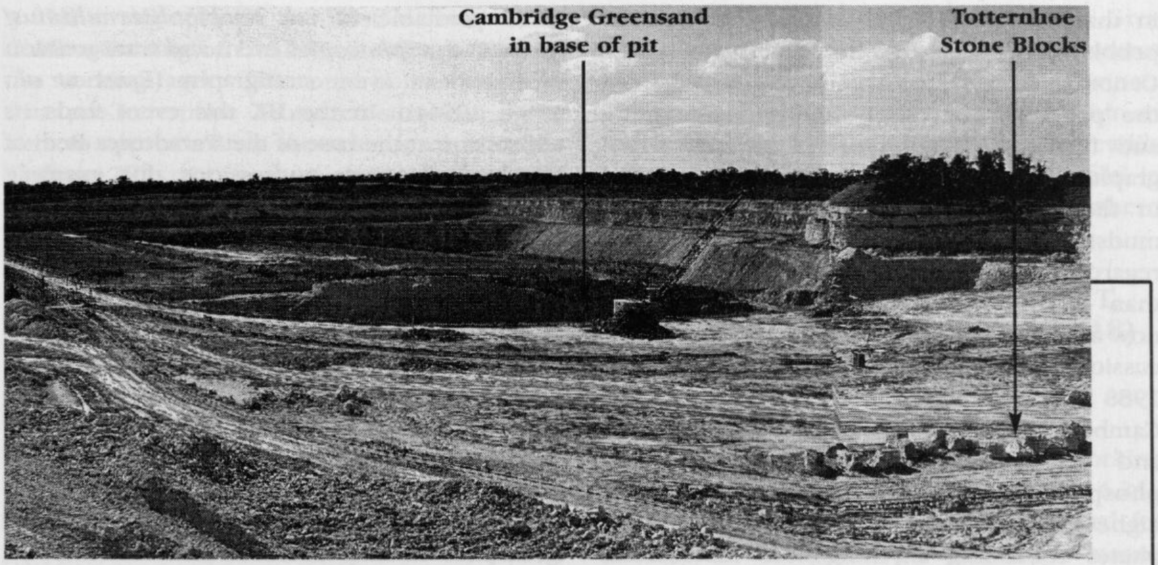
The exposed Chalk Group succession extends from the Cambridge Greensand Member, at the base of the Grey Chalk Subgroup, through the relatively incomplete West Melbury Marly Chalk Formation preserved beneath the Totternhoe Stone, up to a level, several metres above the Totternhoe Stone, in the lower part of the Zig Zag Chalk Formation. The higher part of the Zig Zag Chalk Formation is not exposed in the present working faces.

The Cambridge Greensand Member is exposed at the top of flooded excavations at the base of the quarry; and can be examined in the dumps of excavated material on the quarry floor. Detailed lithological descriptions, based on localities outside the Cambridge area, were given by White (1932) and Hopson *et al.* (1996). It consists of a silty, glauconitic, micaceous marl, rich in well-preserved coccoliths, with a basal concentration of phosphatized pebbles ('nodules') ranging in size from a few millimetres up to 0.15 m. The glauconite and phosphate content imparts a distinctive overall green colour, which contrasts with the paler grey of the Gault beneath. The pebbles, which were originally known as 'coprolites' (fossil faeces) and were exploited for agricultural phosphate, are typically bored, encrusted by small oysters and other bivalves (*Atreta nilssoni* (von Hagenow)), and exhibit various degrees of rolling and phosphatization. The extent of phosphatization can be seen from their colour, the most strongly mineralized being black, while the less mineralized are brown. Many of them are recognizable as reworked, variably abraded internal moulds of fossils; in some cases, notably the bivalve *Aucellina* and the larger terebratulid brachiopods, the shells are relatively well preserved and only the internal mould is partially or wholly phosphatized. The Cambridge Greensand also contains rare, rounded, angular and subangular erratic components, up to cobble size, of igneous and metamorphic rocks, such as granite, schist and gneiss, in addition to sedimentary rocks, which include greyish and greenish grits and greywackes, as well as red and purple sandstones of Old Red Sandstone and Lower Carboniferous aspect (Sollas and Jukes-Browne, 1873; White, 1932; Hawkes, 1943; Worssam and Taylor, 1969).

The overlying dark, poorly differentiated, marly beds are exposed in relatively inaccessible steep faces. They are rich in fragmented inoceramid bivalve shell debris. The interval from the Cambridge Greensand up to the base of the Totternhoe Stone was recorded as 90 ft (27 m) by Burnaby (1962), but this is known to be variable depending upon the extent of downcutting prior to the deposition of the Totternhoe Stone.

Biostratigraphy

The Cambridge Greensand contains one of the most diverse, albeit derived, Cretaceous faunas in the UK. Penning and Jukes-Browne (1881), summarized by White (1932), noted that the fauna comprised 200 species of invertebrates, including sponges, corals, serpulids, brachiopods, bivalves, gastropods, ammonites, crustaceans (crabs and lobsters) and echinoderms (regular echinoids and crinoids). Of even greater interest is the vertebrate fauna, which includes fish (mainly teeth of sharks), reptiles (ichthyosaurs, pterosaurs, turtles, crocodiles) and even birds (Seeley, 1869). Small phosphatized turtle skulls, up to 0.04 m long, are one of the more remarkable components (see illustrations and references in Collins, 1970). The macrofossil and microfossil biostratigraphy of the Cambridge Greensand is described in several key papers (Morter and Wood, 1983; Wilkinson and Morter, 1981; Wilkinson, 1988). Details of the derived Upper Albian ammonite faunas and their biostratigraphical significance were given by Casey (1965) and Spath (1943).



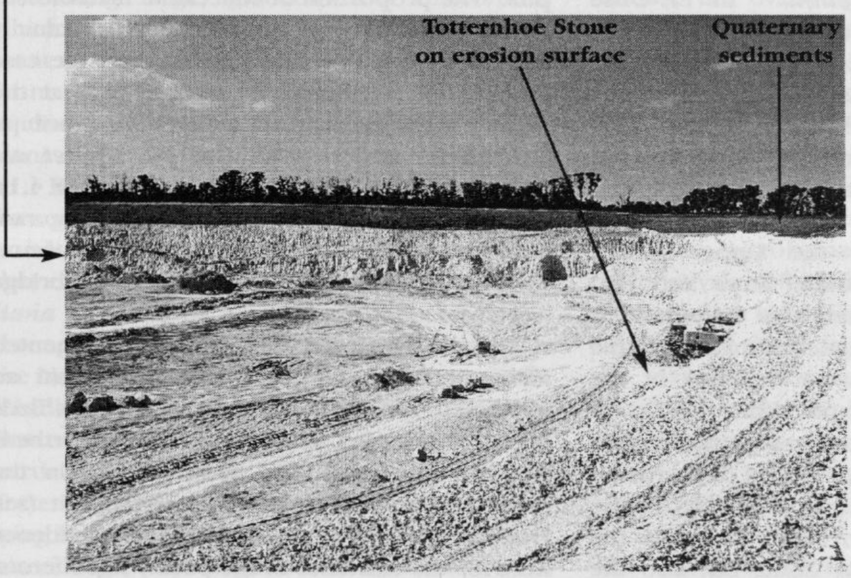


Figure 4.23 Barrington Chalk Pit, Cambridgeshire: a classic locality for the Cambridge Greensand and Totternhoe Stone. Photomosaic: R.N. Mortimore.)

Interpretation

The Cambridge Greensand first appears in the northern Chiltern Hills, where it relatively abruptly replaces the thin Glauconitic Marl Member at the base to the Chalk (seen in the British Geological Survey Sundon Borehole, Figure 4.3), in the vicinity of a fault or monoclinal structure known as the 'Lilley Bottom structure', which is inferred to follow the north-east edge of the buried Midlands Microcraton (Shephard-Thorn *et al.*, 1994; Hopson *et al.*, 1996). From the Cambridge area, it can be traced eastwards in East Anglia as far as the British Geological Survey Stowlangtoft Borehole, east of Bury St Edmunds (Bristow, 1990) and northwards to the British Geological Survey Marham Borehole, SSE of Kings Lynn. Farther to the north, where the Gault mudstones pass into the Red Chalk Formation, the basement bed of the Chalk becomes the 'Paradoxica Bed' of Northern Province successions (see **Hunstanton Cliffs** GCR site report, this volume).

The Cambridge Greensand is essentially a Chalk basement bed like the Glauconitic Marl Member of the Southern Province. However, it differs from the Glauconitic Marl Member in that the greater part of the phosphatized pebbles and fossils that it contains are not of Cenomanian age, but have been derived from the progressive erosion, repeated reworking and further mineralization of several, stratigraphically separated, 'phosphate nodule beds' in the underlying high Upper Albian Gault mudstones. In the past, opinion was divided regarding the age of the sediment itself, rather than that of the reworked fossils, but it is now accepted to be of Cenomanian age (for discussion see Morter and Wood, 1983; Wilkinson, 1988 and references therein). In fact, the Cambridge Greensand is composite (Morter and Wood, 1983), consisting of a lower phosphate and glauconite-rich part, and a higher part of greenish marls without phosphates containing an indigenous macrofauna dominated by small brachiopods and the thin-shelled bivalve *Aucellina*. In Ely-Ouse (Mildenhall) Borehole No. 6 (TL 6928 7307) this bipartite succession is actually underlain by a thin (Upper Albian) unit containing oysters and the belemnite *Neohibolites praeultimus* Spaeth (Morter and Wood, 1983). Ostracod evidence (Wilkinson, 1988) indicates that this lowest unit belongs to the *Mortoniceras rostratum* Subzone of the Upper Albian *Stoliczkaia dispar* ammonite Zone and that the remainder of the Cambridge Greensand is Lower Cenomanian in age, belonging to the *Neostlingoceras carcitanense* Subzone of the *Mantelliceras mantelli* Zone. Hart (1973), on the basis of foraminiferal evidence, suggests that there is a major non-sequence at the erosion surface that generally marks the base of the Cambridge Greensand, involving not only the highest part of the *dispar* Zone, but also the basal Cenomanian benthic foraminiferal Zone 7, which is co-extensive with the thin Glauconitic Marl Member in boreholes near Folkestone (see **Folkestone to Kingsdown** GCR site report, this volume).

The Cambridge Greensand is the type horizon for the biostratigraphically important bivalve *Aucellina gryphaeoides* (J. de. C. Sowerby *non* Sedgwick). Although the microsculpture of the shell of the neotype suggests that it comes from the lower (Cenomanian) part of the Cambridge Greensand (Morter and Wood, 1983), the age of this specimen and all other non-indigeneous *Aucellina* from this member cannot be determined. In conjunction with the belemnite *Neohibolites ultimus* (d'Orbigny), this bivalve gives its name to the *Neohibolites ultimus/ Aucellina gryphaeoides* event and transgression of European event stratigraphy (Ernst *et al.*, 1983, 1996). In the UK this event finds its expression at the base of the 'Paradoxica Bed' of Northern Province successions, for example **Hunstanton Cliffs**, and in the Rye Hill Sands in the area to the north of **Dead Maid Quarry**, Mere.

The Cambridge Greensand has long been famous for its fossils. The large numbers of these fossils, particularly ammonites, housed in museum collections – most importantly the Sedgwick Museum, Cambridge and the British Geological Survey, Keyworth – give a completely misleading impression of their relative abundance. In fact, most of the fossils were collected from piles of excavated sediment left to dry in the sun on the edges of the flooded coprolite pits. The proportion of collectable macrofossils to shapeless phosphatic nodules is actually extremely low, this being particularly the case both at Barrington Chalk Pit and also at the other extant exposure at Arlesey Pit, north of Hitchin (TL 1879 3476) (see Hopson *et al.*, 1996, pp. 34–35 and fig. 9; and Figure 4.1). Ammonites have always been extremely rare here, but there is evidence from museum collections that other sites nearer Cambridge were more fossiliferous.

The overlying silty marls rich in fragmented inoceramid bivalve shell debris represent an expanded version of the two Inoceramus Beds of the condensed successions in the northern part of the Transitional Province and in the Northern Province. As at the Arlesey Pit (see Hopson *et al.*, 1996, fig. 9), there is no evidence here for the existence of the poorly fossiliferous and pale-coloured 'Porcellaneous Beds', which, in East Anglia, are intercalated between the Cambridge Greensand and the Inoceramus Beds (Morter and Wood, 1983). There is also no evidence that the two inoceramid-rich units can be differentiated at Barrington Chalk Pit but, by extrapolation from the lower part of the Grey Chalk Subgroup at Abbot's Cliff, Folkestone, the lowest shell-detrital chalks can probably be assigned to the *Sharpeiceras schlueteri* Subzone. Microfaunal evidence (summarized by Wilkinson, 1988) places the basal beds of the West Melbury Marly Chalk Formation, above the Cambridge Greensand Member, in the *N. carcitanense* Subzone, which supports the above interpretation.

The stratigraphy of the West Melbury Marly Chalk at Barrington Chalk Pit is difficult to see in the working faces. The cored boreholes prove that pre-Totternhoe Stone erosion cut down here to approximately the same level as in the Chiltern Hills, i.e. a short distance above the lowest *Orbirhynchia mantelliana* Band (the *mantelliana* band in the middle of the Lower Cenomanian *Mantelliceras dixoni* Zone), but that locally it cut down to below this marker horizon.

In contrast to the sections in the Chiltern Hills (e.g. **Chinnor Chalk Pit**, Totternhoe, Houghton Regis), in which the *Orbirhynchia* of the third *Orbirhynchia mantelliana* Band (i.e. the band in the Middle Cenomanian *Turrilites costatus* Subzone) occur throughout the thickness of the Totternhoe Stone, the *Orbirhynchia* at Barrington Chalk Pit occur in a bed of chalky limestone containing large, glauconitized ammonites, which overlies the brownish arenaceous sediment of the Totternhoe Stone. The Totternhoe Stone here, and at all localities to the east, equates with the Cast Bed of the basinal successions of the Southern Province (e.g. **Folkestone to Kingsdown**, **Southerham Grey Pit**, **Compton Bay**) and the overlying bed corresponds to the group of marl–limestone couplets that comprises the third *Orbirhynchia mantelliana* Band. This type of succession is found throughout East Anglia, and also characterizes the Northern Province (e.g. **Hunstanton Cliffs**, Middlegate Quarry, South Ferriby, **Melton Bottom Chalk Pit**). The present site is of particular interest in that the bed above the Totternhoe Stone, and the immediately overlying beds, yield a distinctive inoceramid bivalve assemblage, including *Inoceramus tenuistriatus sensu* Keller (1982), which precedes the *Inoceramus atlanticus* assemblage of the lower part of the *Acanthoceras jukesbrownei* Zone.

Conclusions

Barrington Chalk Pit is of crucial importance to British Cretaceous stratigraphy in that it is one of only two extant sites exposing the Cambridge Greensand at the base of the Chalk. This greensand has long been famous for its derived phosphatized fossils, including, in addition to invertebrates (particularly ammonites), skeletal material of fish, turtles, flying reptiles and birds. The provenance and mode of transport of the exotic cobbles at the base of this bed remain highly controversial topics. The Grey Chalk Subgroup here shows transitional features to the successions in the Northern Province. The beds above the Totternhoe Stone contain an inoceramid bivalve fauna that cannot be readily collected elsewhere in England but is useful in long-range correlation to sections in northern Europe.

CAISTOR ST EDMUND CHALK PIT, NORWICH, NORFOLK (TG 238 048)

Introduction

Caistor St Edmund Chalk Pit is a working quarry, 4 km south of Norwich (Figure 4.24). The quarry was formerly largely exploited for Chalk, but latterly, as operations have moved eastwards towards the area with thicker overburden, the overlying sands and gravel have been worked at the expense of the Chalk. It provides the last remaining well-exposed inland section of part of the Beeston Chalk Formation of the Upper Campanian 'Norwich Chalk', and is the last inland section of any size in the Upper Campanian succession of the Transitional Province. It is rich in macrofossils, and well-preserved microfaunas can be extracted from the relatively soft chalks. The section includes the boundary between two of the informal local subzones of the *Belemnitella minor* I Zone of the standard northern European belemnite zonal scheme for the Upper Campanian succession (Figure 2.13, Chapter 2; Figure 4.5).

Description

The Caistor St Edmund Chalk Pit section was described by Peake and Hancock (1961) and by Wood (1988). Additional details were given by Pitchford (1991), Johansen and Surlyk (1990), and Christensen (1995). The palaeoecology, depositional environment and faunal analysis were documented by Godwin (1998). The geochemistry of the hollow 'potstone' flints and their chalk fill was used by Clayton (1986) in the development of a model for flint formation.

Lithostratigraphy

The quarry exposes a *c.* 13 m section (Figure 4.25) through the lower part of the Beeston Chalk. Peake and Hancock (1961, fig. 6) described 30 ft (9.14 m) of Chalk between the

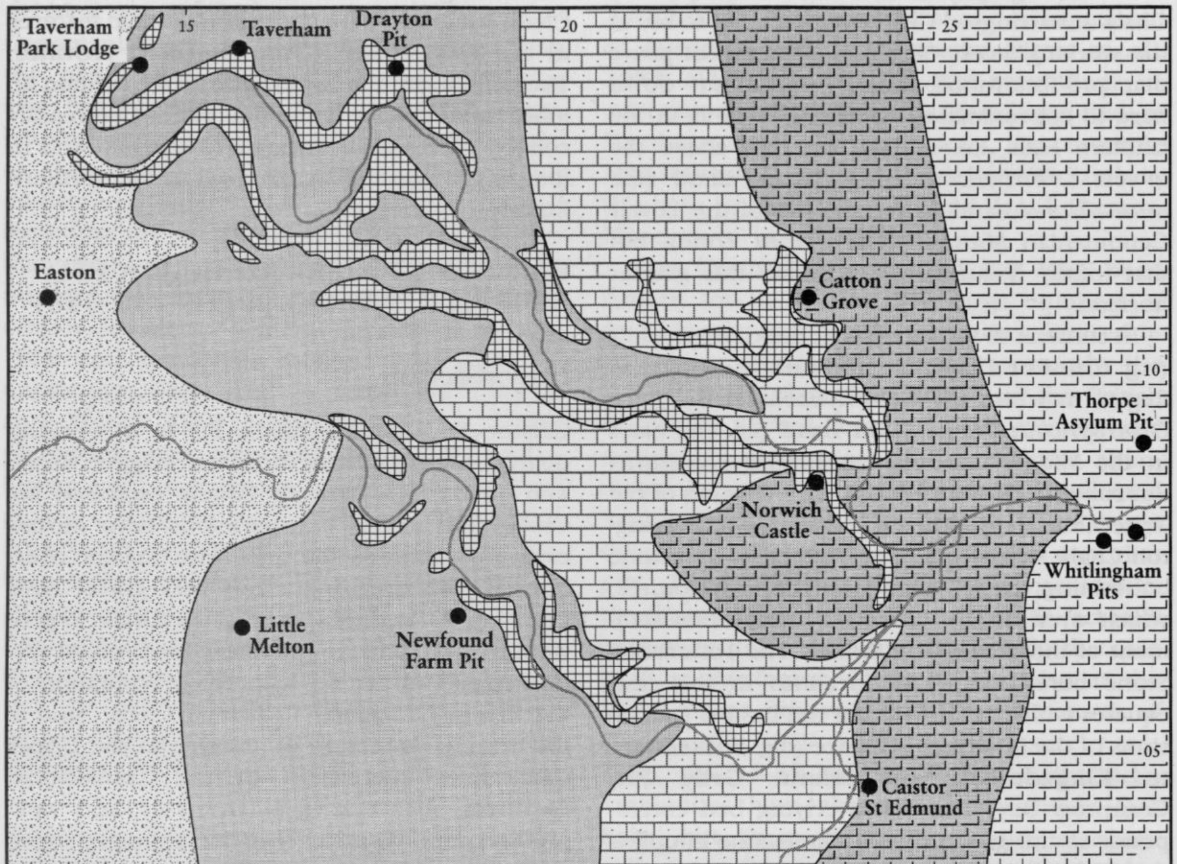


Figure 4.24 The location of Caistor St Edmund Chalk Pit and **Catton Grove Chalk Pit**, and other sections mentioned in the text, around Norwich, Norfolk. (After Cox *et al.*, 1989.)

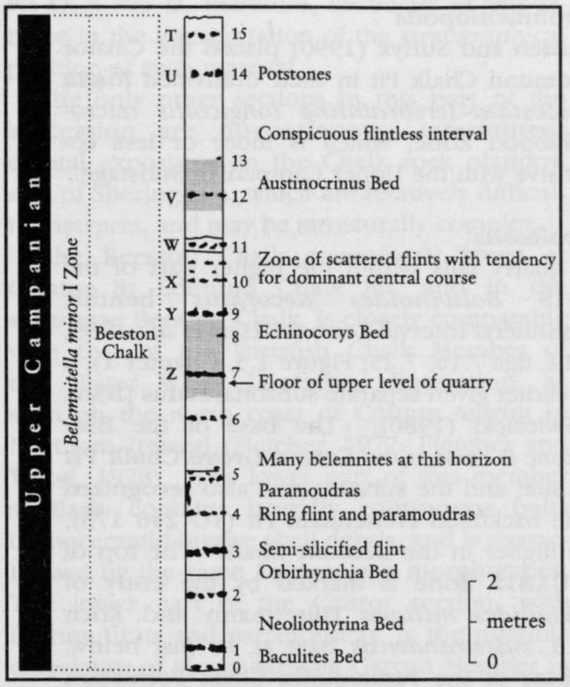


Figure 4.25 The Campanian Chalk (White Chalk Subgroup) at Caistor St Edmund Chalk Pit, Norwich (see Figure 4.24 for location). (Letters T–Z for flint bands are those of Peake and Hancock, 1961; numbers 1–15 are those of Wood, 1988.)

then working floor of the quarry and the base of the Norwich Crag. Wood (1988, fig. 8) recorded an additional 7 m of section in a deep part of the quarry that was normally flooded, giving a total exposed thickness of some 16 m. Additional graphic logs that also included the lowest beds, with the exception of the basal 1.7 m recorded by Wood, were published by Johansen and Surlyk (1990) and Pitchford (1991). Pitchford accurately logged the lateral variation of the flints over a standard 5 m-wide section, and recorded the distribution of the relatively weakly developed nodular chalk. Figure 4.25 is a modified version of Wood's log. The deepest part of the quarry is now largely filled with loose sand washed down from above the Chalk and is dangerous to approach.

The succession consists of relatively soft, distinctly yellow chalk that is to a greater or lesser extent flinty throughout, and entirely devoid of marl seams. The second flint from the bottom of the deepest section formerly visible is semi-tabular, and 0.15 m thick. The interval up to the conspicuous semi-continuous flint 7, at the base of the main face, includes a ring flint, 0.22 m thick, from which arise sporadic paramoudras. The Johansen and Surlyk log (1990, fig. 1) shows a paramoudra even higher in the succession. The chalk from immediately below flint 7 up to the next higher flint band (9) is replete with conspicuous large fragments of inoceramid bivalve shell. There is a similar concentration of shell debris in the interval from below flint 12 up to flint 13. Between the two belts of shell debris, and marking the top of an irregular grouping of three flint bands, there is a weakly indurated near-planar hardground, overlain by a concentration of echinoids (*Echinocorys*). At the top of the section, there is a conspicuous line of very large flints (14), including hollow potstones, above a virtually flintless interval, some 3 m thick.

Biostratigraphy

Macrofossils

The section is generally extremely fossiliferous, particularly the lower part, which contains the high-diversity fauna of well-preserved corals, brachiopods, bivalves, belemnites and echinoids that characterizes the Beeston Member (see Wood, 1988).

The succession falls into the higher part of the *Belemnitella mucronata* Zone of the traditional scheme. The quarry is very rich in belemnites. Extensive, bed-by-bed collections, particularly from here, and from other *mucronata* Zone sections in the vicinity of Norwich, and the exposures on the coast, enabled Christensen (1995) to establish a refined belemnite zonal scheme based on the genus *Belemnitella*. The succession falls within his *Belemnitella minor* I Zone, which is further subdivided into three informal local subzones defined by the co-occurrence, with the zonal index fossil, of particular additional belemnite taxa. The greater part of the succession belongs to Subzone 1, characterized by the occurrence of *Belemnitella 'langei'*. Large examples of the zonal index fossil are conspicuous in the lower belt of inoceramid shell-debris chalk. The base of the succeeding Subzone 2, marked by the entry of *Belemnitella najdini* Kongiel and *B. pauli* Christensen, is situated at the top of the lower belt of inoceramid shell debris.

This quarry, then much smaller, was one of Rowe's fossil collecting localities (Rowe, in manuscript; Norfolk locality 166). The fossils collected by him from here are preserved in the Natural History Museum, London. Although the succession contains fossils throughout, several particularly fossiliferous horizons have been named (Wood, 1988).

In the deepest, now inaccessible part of the section, the Baculites Bed yielded poorly preserved, weakly glauconitized specimens of baculitids and nautiloids. From this bed, or possibly from an even deeper level in a trial hole, the Goff collection (Norwich Castle Museum) additionally includes the hetero-morph ammonites *Neancyloceras bipunctatum* (Schlüter) and *Neocrioceras* (*Schlueterella*) sp.. The overlying Neoliothyrina Bed contained large (gerontic) individuals of the terebratulid brachiopod *Neoliothyrina obesa* Sahni.

The Orbirhynchia Bed, which overlies a slightly hardened omission surface, yielded an amazingly diverse macrofossil assemblage. The rhynchonellid *Orbirhynchia* makes up about 10% of the brachiopod assemblage. The remaining brachiopods are dominated by *Carneithyris carnea* (J. Sowerby) and *Cretirhynchia arcuata* Pettitt, with subordinate *Ancistrocrania parisiensis* (Defrance), *C. norvicensis* Pettitt, *Kingena* sp., *Kingenella* sp. nov., *Neoliothyrina obesa* and *Terebratulina chrysalis* (Schlotheim). The fauna additionally comprises 11 species of bivalves, including five pectinaceans, *Belemnitella 'langei'*, cirripedes, asteroid marginals, ophiuroid ossicles, cidarid spines and plates, and *Galerites roemeri* (Desor).

The Echinocorys Bed, at the top of the lower inoceramid shell-debris belt, contains predominantly crushed individuals of the morphotype (*Echinocorys* aff. *conoidea* Goldfuss) that characterizes the type Beeston Chalk. A smaller, more globose, morphotype is found on the minor hardground immediately above flint 11. The echinoids can also occur in nest-like accumulations at the level of the flint; a large flint in Norwich Castle Museum from this horizon contains 20 individuals.

The Austinocrinus Bed contains crinoid stem ossicles belonging to an *Austinocrinus* that is probably transitional between *A. rothpletzi* Stolley, and the *A. bicoronatus* (Hagenow) that characterizes the basal Maastrichtian of the **Overstrand to Trimingham Cliffs** glaciotectonic masses (see GCR site report, this volume). The bed also contains numerous small brachiopods, mainly small *Carneithyris carnea* and *Cretirhynchia arcuata*.

Microbrachiopods

Johansen and Surlyk (1990) placed the Caistor St Edmund Chalk Pit in their undivided *Rugia tenuicostata–Terebratulina longicollis* microbrachiopod Zone, which is more or less coextensive with the Upper Campanian Substage.

Microfossils

The quarry falls within the higher part of the UKB18 *Bolivinoides decoratus* benthic foraminiferal Interval Zone (cf. Hart *et al.*, 1989, p. 314, figs 7.16, 7.25; Figure 1.5, Chapter 1), a unit earlier given separate subzonal status (B3iv) by Swiecicki (1980). The base of the B3iv Subzone is seen at the **Catton Grove Chalk Pit** GCR site; and the subzone was also recognized in the backfilled Frettenham Pit (TG 246 173), even higher in the Beeston Chalk. The top of the UKB18 Zone is marked by the entry of *Bolivinoides miliaris* Hiltermann and Koch and *B. sidestrandensis* Barr at, or just below, the base of the Paramoudra Chalk Formation (Swiecicki, 1980).

Interpretation

The quarry provides the sole remaining useful inland section in the Beeston Chalk Formation in the higher part of the Upper Campanian succession of Norfolk.

The comparative field relationships of the Caistor St Edmund Chalk Pit and the nearby Halfway House (TG 2330 0268) and Stoke Holy Cross (TG 2536 0140) chalk pits suggests that the base of the quarry lies above the Catton Grove Chalk Pit–Stoke Holy Cross composite section. The absence, from the top of the Stoke Holy Cross section, of the basal semi-tabular flint 2 and the associated *Baculites* and *Neoliothyrina* Beds of the Caistor section (see above), as well as of *Belemnitella 'langei'*, precludes the possibility of an overlap between the two sections.

A similar, and presumably correlative, line of potstones above flintless chalk to that seen at the top of the quarry was exposed in trenches in the almost totally degraded sections (TG 2496 0683) cut into a glacially emplaced raft of Chalk at Crown Point Pit, Trowse Newton (Wood, 1988). The latter locality yielded much museum material labelled 'Trowse', including the types of the common Norwich Chalk brachiopod *Carneithyris carnea*. The Caistor St Edmund Chalk

Pit GCR site is, therefore, indirectly of importance in the interpretation of the stratigraphical position of such material.

The only other sections in this part of the succession are discontinuous, intermittent coastal exposures on the Chalk rock platform east of Sheringham, which are relatively difficult to interpret, and may be structurally complex.

The Beeston Chalk macrofossil fauna at Caistor St Edmund Chalk Pit, and in the stratotype Beeston Chalk, is closely comparable with that of the Portrush Chalk Member of the Ulster White Limestone Formation, as seen on the north coast of County Antrim in Northern Ireland (Fletcher, 1977; Fletcher and Wood, 1978). The lower part of this member similarly contains laterally continuous belts of inoceramid bivalve shell debris, and is characterized by the same *Echinocorys* morphotypes. The lower part of the Caistor section, with its ring flints and paramoudras, is the possible correlative of the underlying Garron Member in Northern Ireland.

The lower part of the section yields an extremely high-diversity fauna with well-preserved pectinacean bivalves, large brachiopods with colour banding and corals. This is inferred to be a warm-water fauna on the basis of the large size, strong ornament and colour-banding of the shells and the diverse coral fauna.

Conclusions

Caistor St Edmund Chalk Pit provides the last remaining well-exposed inland section of part of the Beeston Chalk Formation of the Upper Campanian 'Norwich Chalk', and is the last inland section of any size in the Upper Campanian succession of the Transitional Province. The equivalent strata on the Norfolk coast are poorly exposed and are to some extent structurally disturbed, rendering interpretation difficult. It is rich in macrofossils of all groups, and well-preserved microfaunas can be extracted from the relatively soft chalks. Collections of belemnites from here proved crucial to the development of the scheme of local belemnite zones originally recognized in Norfolk by Christensen (1995), and now part of the European standard belemnite zonal scheme. Of particular importance is the boundary between two of the informal subzones of the *Belemnitella minor* I Zone for the Upper Campanian succession. The pit is also well known for the hollow 'potstone' flints, which are conspicuous just below the top of the section and have been used in developing a model for the formation of flint.

CATTON GROVE CHALK PIT, NORWICH, NORFOLK (TG 229 109)

Introduction

Catton Grove Chalk Pit (also known as 'Campling's Pit') is a small quarry surrounded by a housing estate, situated to the east of the Sprowston Road, in the Catton area of Norwich (Figure 4.24). Access is by a track from the Sprowston Road. The site provides a section across the boundary between the Weybourne Chalk and Beeston Chalk formations of the Upper Campanian Chalk of Norfolk. It is also the stratotype for the Catton Sponge Bed, which is a hardground within a complex of hardgrounds that straddles this boundary. The succession here, and that at the stratigraphically higher **Caistor St Edmund Chalk Pit** GCR site, represents higher Campanian Chalk than is preserved in the **Whitecliff**, Isle of Wight and **Handfast Point to Ballard Point**, Dorset GCR sites. Catton Grove Chalk Pit and the nearby Attoe's Pit (TG 231 111), also now backfilled, were the source of many fossils, including ammonites, in museum collections; these came mostly from the Catton Sponge Bed and the immediately overlying beds, which are particularly fossiliferous.

The Catton Sponge Bed marks the boundary between two of the zones of the northern European Upper Campanian belemnite zonal scheme that now replaces the traditional *Belemnitella mucronata* Zone. It is a level of major macrofaunal change, which particularly affects the brachiopods, molluscs and echinoids. It marks the entry of certain benthic foraminiferal species that range up to and, in some cases, above the Campanian–Maastrichtian boundary, and is thus of particular relevance to the interpretation of the microfaunal biostratigraphy of the Chalk successions in the southern North Sea Basin. It reflects a European-wide regressive phase, which elsewhere is expressed either by a hardground or by a change in lithofacies to shallow-water sponge-rich siliceous marls with a high-diversity macrofauna.

Description

The previously exposed section at Catton Grove Chalk Pit has been backfilled, but the Catton Sponge Bed and the overlying basal Beeston Chalk, at the top of the pit, have been deliberately covered by soil and turfed within a semi-circular retaining wall of gabions, in order to preserve it.

Lithostratigraphy

In the 1960s, this pit exposed *c.* 10 m of the highest part of the Weybourne Chalk Formation, terminating in the Catton Sponge Bed; and overlain by the basal 1.8 m of the Beeston Chalk (Peake and Hancock, 1961, fig. 6). Those workers recorded six flint bands below the Catton Sponge Bed, and one band of huge flints up to 0.45 m thick above it. They noted that an additional 22 ft (6.7 m) of section had previously been visible down to a flint that formed the floor of the pit. When this flint, probably the thick semi-tabular flint T of the stratotype Weybourne Chalk succession (Peake and Hancock, 1961, fig. 5), was broken through, the lower part of the pit rapidly flooded and had to be backfilled. Wood (1988, fig. 7) recognized some additional flints, and published a revised log. Figure 4.26 is based on the two accounts quoted above.

The Catton Sponge Bed was named by Peake and Hancock (1961) to describe the 'hard yellow bed' or 'sponge bed' of the earlier literature that had been recorded in the chalk pits at Catton, and which Rowe (in manuscript) and Brydone (1938) regarded as marking a level of significant faunal change in the Chalk of Norfolk. Peake and Hancock's Catton Sponge Bed comprises two closely spaced beds of iron-stained, indurated chalk capped by hardgrounds (cf. Wood, 1988, p. 62, fig. 7), rather than the single hardground recorded by them. The two hardgrounds were designated hardgrounds I and II by Wood (1988, fig. 7), the higher (the Catton Sponge Bed proper of previous workers) being taken as the boundary between his topmost (Weybourne$_3$) subdivision of the Weybourne Chalk and the succeeding Beeston Chalk. Hardground I is patchily and relatively poorly

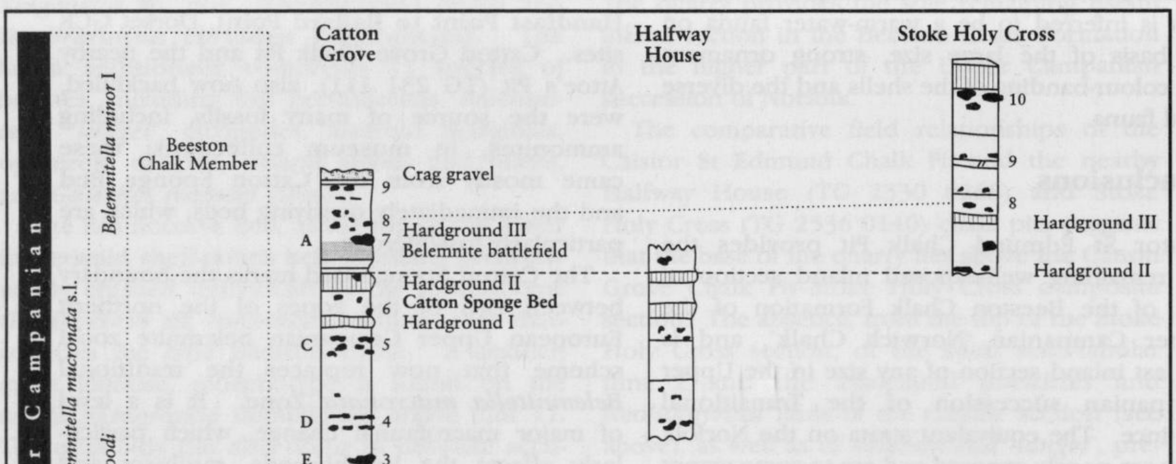


Figure 4.26 The Campanian Chalk (White Chalk Subgroup) at Catton Grove Chalk Pit, Norwich, and nearby exposures (see Figure 4.24 for locations). (Letters A–H for flint bands are those of Peake and Hancock, 1970; numbers 1–10 are those of Wood, 1988.)

indurated, but is capped by a well-defined, planar erosion surface. The Catton Sponge Bed (Hardground II) contains a rich assemblage of hexactinellid sponges, in limonitic preservation, together with moulds of originally aragonite-shelled bivalves and gastropods reminiscent of the *reussianum* fauna from the Hitch Wood Hardground of the Upper Turonian Chalk Rock. It is locally strongly indurated, and also terminates in a clearly defined erosion surface. This is overlain by soft glauconitized chalk pebbles and a concentration of large, reworked belemnites, which forms an excellent example of a so-called 'belemnite battlefield'. The Sponge Bed is penetrated by an extensive *Thalassinoides* burrow system, which in places contains belemnites 'piped down' from the overlying concentration. The huge flint A of the Peake and Hancock notation in the basal part of the Beeston Chalk is a section through a giant ring flint; it is underlain by chalk containing large pieces of shell of inoceramid bivalves, and is followed by weakly indurated chalk without an obvious erosion surface, which was designated by Wood (1988) as Hardground III.

Biostratigraphy

The section falls within the traditional *Belemnitella mucronata* macrofossil Zone, which covers the entire Upper Campanian Substage (Figure 1.5, Chapter 1; Figure 2.13, Chapter 2; Figure 4.5). There is a significant change in the belemnites, with *Belemnitella woodi* Christensen becoming extinct just below the Catton Sponge Bed, to be replaced by *B. minor* I Christensen in and above the Sponge Bed (Christensen 1995, fig. 6). The Sponge Bed marks the boundary between the *Belemnitella woodi* and *Belemnitella minor* I belemnite zones (Christensen, 1995, fig. 2; Figure 4.5). These zones, originally established as local zones in Norfolk, succeed the restricted *B. mucronata* Zone (Figure 2.13, Chapter 2; Figure 4.5), and have now been recognized in Belgium, the Netherlands and Germany (Christensen, 1999). The belemnites in the 'belemnite battlefield' on top of the Sponge Bed, and in the basal part of the Beeston Chalk, are exclusively *Belemnitella minor* I (Christensen, 1995, fig. 6). The absence of *B.* '*langei*', which is present at the base of the **Caistor St Edmund Chalk Pit**, places the Beeston Chalk at Catton Grove in the lowest of the three local subzones (Christensen, 1995) of the *B. minor* I Zone.

Records of ammonites (*Nostoceras* (*Bostrychoceras*) *polyplocum* (Roemer), *Baculites* sp. and *Menuites portlocki* (Sharpe)) can safely be inferred to have come from the Sponge Bed. However, other ammonites from the 'Norwich Chalk' in museum collections, particularly those preserved as glauconitized composite moulds, probably came from less well indurated ammonite-bearing horizons in the Beeston and Paramoudra Chalk. The non-ammonite molluscan fauna is largely undescribed, but includes species of the gastropod genera *Periaulax* and *Planolateralus*. The rich hexactinellid sponge fauna (details in Reid, 1968) is dominated by *Leptophragma striatopunctata* (Schrammen) with, in addition to another five species, *Aphrocallistes cylindrodactylus* Schrammen and *Lepidospongia rugosa* Schlüter. The latter two species also occur in the coeval strata in Northern Ireland.

There is a major macrofaunal change at the Sponge Bed, which especially affects the brachiopods, bivalves and echinoids. This was first noted by Rowe (in manuscript) and independently confirmed by Brydone (1922, 1938) (see review by Wood, 1988, pp. 19–39). Both workers compared this faunal change in the inland sections with the difference in faunal content between the (Weybourne) and (Beeston) Chalk successions to the west and east of Sheringham respectively. The rhynchonellid brachiopod *Cretirhynchia woodwardi* Pettitt, characteristic of the Weybourne Chalk, disappears abruptly at the top of the Sponge Bed, while the terebratulid *Carneithyris carnea* (J. Sowerby) and the rhynchonellids *Cretirhynchia arcuata* Pettitt and *C. norvicensis* Pettitt, all of which occur sporadically in the Weybourne Chalk, become abundant and represented by large-sized individuals in the Beeston Chalk. The large limacean bivalve *Plagiostoma marrotianum* (d'Orbigny) and the pectinacean *Mimachlamys mantelliana* (d'Orbigny) are apparently restricted to the pre-Sponge Bed succession. There is a striking change in the echinoids across the Weybourne Chalk–Beeston Chalk boundary, from an assemblage characterized by *Cardiotaxis heberti* Cotteau, *Micraster glyphus* Schlüter and *M. stolleyi* Lambert (the '*Epiaster*' of both Rowe and Brydone) to one characterized by *Cardiaster cordiformis* (S. Woodward) ('*Cardiaster* *ananchytis*') and *Galerites roemeri* (Desor), with only extremely rare *Micraster*.

There is an important change in the microfauna (ostracods and foraminifera) across the same boundary. Two very long-ranging species of the ostracod genus *Cytherelloidea* cut out a short distance above the the Sponge Bed, with other taxa entering at this level and continuing into the Maastrichtian strata (I. Slipper, pers. comm., 1998). Swiecicki (1980) recorded the extinction of some long-ranging benthic foraminiferal taxa, notably *Globorotalites micheliana* (d'Orbigny) at the Sponge Bed, and noted the abrupt entry of *Bolivina incrassata* Reuss, *Eponides beisseli* Schijfsma, *Globorotalites hiltermanni* Kaever, *Neoflabellina praereticulata* Hiltermann and *Reussella szajnochae szajnochae* (Grzybowski). These are species that range up to and, in some cases, above the Campanian–Maastrichtian boundary. There is also a significant drop in the planktonic foraminiferal content, in both numbers and diversity, at this level. The turnover in the benthic foraminifera constitutes a significant bio-event, potentially applicable to the interpretation of offshore wells, near the top of the UKB18 or *Bolivinoides decoratus* Interval Zone (cf. Hart *et al.*, 1989, p. 314, figs 7.16, 7.25). This higher part of the UKB18 Zone, given a separate subzonal status (B3iv) by Swiecicki (1980) (Figure 1.5, Chapter 1), is also recognized at the stratigraphically higher **Caistor St Edmund Chalk Pit**, and in the backfilled Frettenham Pit (TG 246 173), even higher in the Beeston Chalk. Its top is marked by the entry of *Bolivinoides miliaris* Hiltermann and Koch and *B. sidestrandensis* Barr at, or just below, the base of the Paramoudra Chalk Member in the section at West Runton confusingly labelled 'Sheringham' in the *Stratigraphical Index of Fossil Foraminifera* (Hart *et al.*, 1989, fig. 7.16).

Interpretation

South of Norwich, Hardground I and the Catton Sponge Bed were revealed in a trench in the now degraded Halfway House Chalk Pit (TG 2330 0268). The Sponge Bed was also exposed in a trench at or near the base of the now backfilled Stoke Holy Cross Chalk Pit (TG 2536 0140) (see Figure 4.26). The section at the latter locality, some 9.5 km to the south along the strike from the present site, extends the succession upwards by another 2 m. In this section an additional thin, weakly indurated chalk bed and a bed of large nodular flints occur just below a weakly developed softground (Wood, 1988, fig. 7). Hardground III in the Beeston Chalk is better developed here than at Catton Grove, with a well-defined erosion surface strewn with flattened glauconitized chalk pebbles. The relationship between the composite Catton Grove–Stoke Holy Cross succession and the basal beds of the **Caistor St Edmund Chalk Pit** remains unclear, but it is likely that only a very small thickness of chalk separates them.

The Catton hardgrounds were formerly also seen in intermittent foreshore exposures at Sheringham, where the old Lifeboat House (TG 153 436) is actually sited on the Catton Sponge Bed. Hardground III, which can be recognized from its echinoid fauna, crops out to the east, opposite the Two Lifeboats Hotel (Peake and Hancock, 1970, p. 339E); a second hardground, possibly Hardground I, crops out a short distance to the west. The Catton Sponge Bed was not recognized in the British Geological Survey Trunch Borehole (Wood *et al.*, 1994), probably as a result of poor core recovery, but its position can be inferred from the resistivity log.

Hardground I and the Catton Sponge Bed correlate with the North Antrim Hardgrounds of Northern Ireland, which comprise two closely spaced hardgrounds, the lower one weakly, and the higher strongly, hardened and glauconitized. The higher hardground is similarly succeeded by chalks with fragmented inoceramid shell and giant ring flints (Fletcher, 1977; Fletcher and Wood, 1978). Towards the depositional margins and over structural highs, the North Antrim Hardgrounds become even more indurated and more strongly mineralized. The Catton Sponge Bed and the North Antrim Hardgrounds reflect the '*polyplocum*' regression in northern Germany (Niebuhr, 1995; Niebuhr *et al.*, 1997), where it is marked by evidence of significant shallowing, including a high-diversity macrofauna with many baculitid ammonites, and the development of siliceous spongiferous marls (opoka facies), following marl–chalk rhythmites. This inter-regional regressive event, which can now be identified by correlative hardgrounds in Belgium and the Netherlands (Christensen, 1999) is interpreted as a sea-level lowstand, associated with a sequence boundary (Niebuhr *et al.*, 1997).

Conclusions

Catton Grove Chalk Pit is the type section and only remaining exposure of the Catton Sponge Bed, the other exposure on the foreshore at Sheringham having been permanently covered by the construction of a slipway. It forms the boundary between two of the belemnite zones of the standard northern European belemnite zonal scheme (Figure 2.13, Chapter 2), and is a level of major macrofaunal change. It marks the entry of certain benthic foraminiferal species that range up to and, in some cases, above the Campanian–Maastrichtian boundary, and is thus of particular relevance to the interpretation of the microfaunal biostratigraphy of the offshore Chalk successions in the Southern North Sea Basin. It reflects a European-wide regressive phase, which elsewhere is expressed by a significant change in lithofacies to shallow water, coarse-grained, partly siliceous sediments.

OVERSTRAND TO TRIMINGHAM CLIFFS, NORFOLK (TG 228 420–TG 306 375)

Introduction

The Overstrand to Trimingham Cliffs GCR site (Figures 4.27 and 4.28) comprises three components:

(1) foreshore exposures of in-situ Chalk west of Overstrand;
(2) cliff and foreshore exposures of glacio-tectonic masses of Chalk between Overstrand and Sidestrand (Figures 4.29–4.33);
(3) cliff and foreshore exposures of glacio-tectonic masses of Chalk between Trimingham and Mundesley (Figures 4.34–4.36).

To facilitate description, each of these components is treated as a separate locality, followed by an overall interpretative discussion of the entire composite succession. The exposures are continually changing over time as a result of marine erosion of the cliffs and foreshore. Historically, a continuous chalk platform was visible in the foreshore between Sidestrand and Trimingham (Taylor, 1824) but there is no evidence of this at present.

The Cretaceous Chalk masses within the Overstrand to Trimingham Cliffs are spectacularly rafted exotic blocks enclosed in Quaternary glacial tills and outwash deposits. Tertiary Crag and Quaternary lacustrine sands, silts and peats and outwash gravels are also present. The various glacio-tectonic masses of Chalk, commonly with a capping of Crag, provide a composite section through the highest Upper Campanian succession, and the lower part of the richly fossiliferous Lower Maastrichtian Chalk. High Upper Campanian Chalk is exposed *in situ* in intermittent foreshore exposures, from the western margin of the site as far east as Overstrand, beyond which point the easterly regional dip takes the Chalk below beach level. Most of the glacio-tectonic masses expose Lower Maastrichtian Chalk, although terminal Campanian Chalk is additionally found at the base of some of the Overstrand masses. In general, successively higher beds are incorporated in the masses from west to east. The highest preserved Chalk preserved onshore in the UK, the so-called 'Trim(m)ingham Chalk' of the early workers, is seen in cliff sections and intermittently exposed foreshore sections through masses near Trimingham and Mundesley.

Description

(1) Foreshore exposures of in-situ Chalk west of Overstrand

The so-called 'Thorpe Mass' (TG 230 420) consists of a reef composed of flints and blocks of highly fossiliferous Chalk, which is exposed at low tide seaward of the Cromer Lighthouse. It is presumed that in-situ Chalk is present immediately beneath the beach at this point. Loose echinoids (*Micraster* aff. *grimmensis* Nietsch, *M. ciplyensis* Schlüter and thick-tested *Echinocorys*) filled with hard chalk are common. The reef takes its name from the occurrence of a distinctive assemblage of echinoids associated with hard chalk that was formerly found in the Thorpe Asylum Pit east of Norwich (Peake and Hancock, 1970, pp. 339F–G; Wood, 1988). The association of hardgrounds and rich echinoid faunas at the latter locality characterizes the higher part of the Paramoudra Chalk (Paramoudra Chalk$_2$ of Wood, 1988).

To the east of the 'Thorpe Mass' there are no more foreshore exposures of Chalk until a point *c.* 150 m west of Overstrand (TG 242 414).

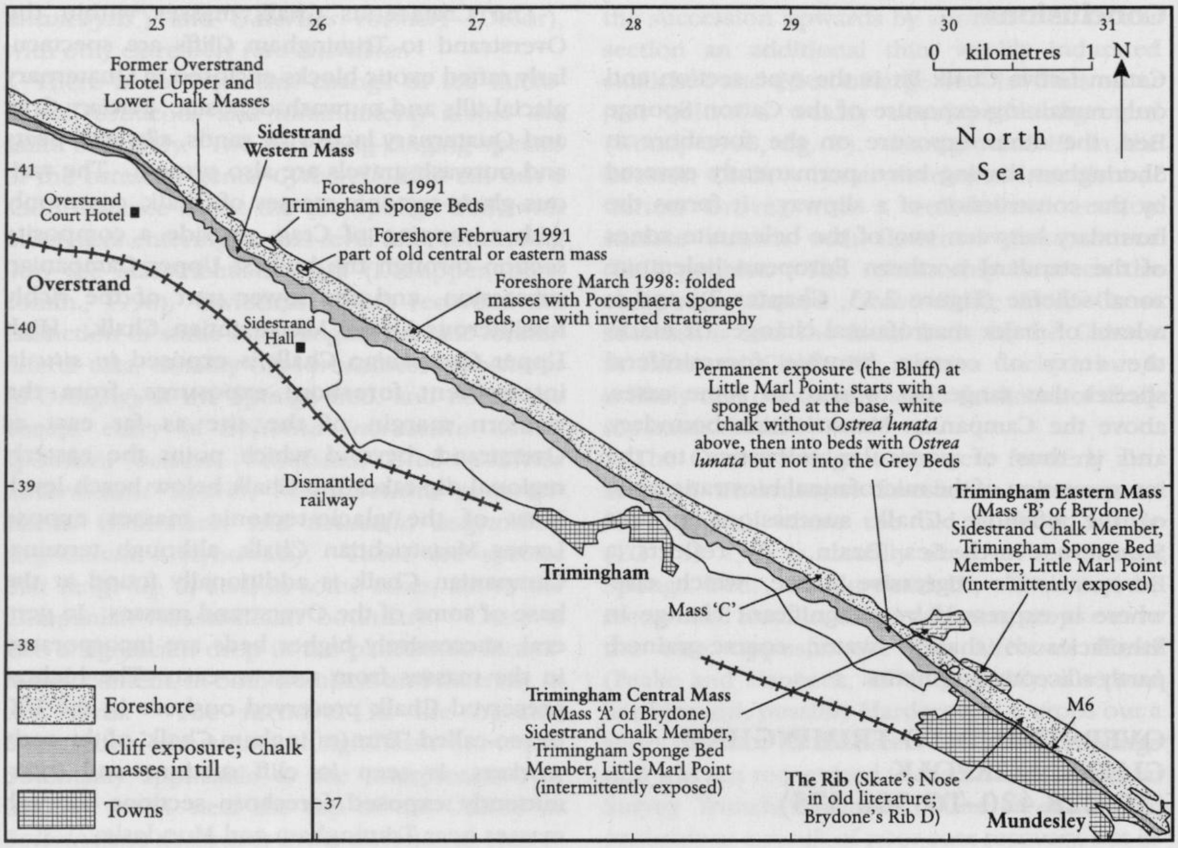


Figure 4.27 The Overstrand to Trimingham Chalk exposures in ice-rafted masses, north Norfolk coast.

There, at low tide, an intermittent foreshore accumulation can be seen of blocks of indurated chalk containing belemnites and large, closely packed echinoids (*Echinocorys pyramidata* Portlock). This hard chalk is informally known as the 'Pyramidata Hardground' and is generally presumed to represent the highest in-situ Chalk exposed on the Norfolk coast (Peake and Hancock, 1970, p. 339G).

(2) Cliff and foreshore exposures of glacio-tectonic masses of Chalk between Overstrand and Sidestrand

2a: Overstrand

Brydone (1906) stated that ten Chalk masses were formerly visible at the foot of the cliffs over a length of nearly half a mile at Overstrand. All but one of these rested on a bed of till. These sections were first discussed by Brydone (1908, 1938), who drew attention to the common occurrence in them, and in blocks of chalk on the beach at Overstrand, of the crinoid *Austinocrinus bicoronatus* (Hagenow), which linked his 'Overstrand Chalk' stratigraphically with the '*Porosphaera* Beds' at the base of the Trimingham succession.

The easternmost of these masses, the so-called 'Overstrand Hotel Lower Mass' (Wood, 1967; Mass 1 of this account), can still be seen in the cliffs (TG 253 408) below the site of the former Overstrand Hotel (Figures 4.29 and 4.30) from which it took its name. It exposes flinty chalk with several well-developed marl seams: in ascending order, the Overstrand Lower Marl, the Overstrand Upper Marl and the Sidestrand Marl, all of which are new names herein. An additional marl seam could formerly be seen at a lower horizon, but this is now buried. The Sidestrand Marl is named after the marl seam at the base of the Sidestrand Western Mass (see below; and Figures 4.31–4.33). The succession above the Sidestrand Marl includes a conspicuous paramoudra flint, above which there is a distinctive semi-tabular flint.

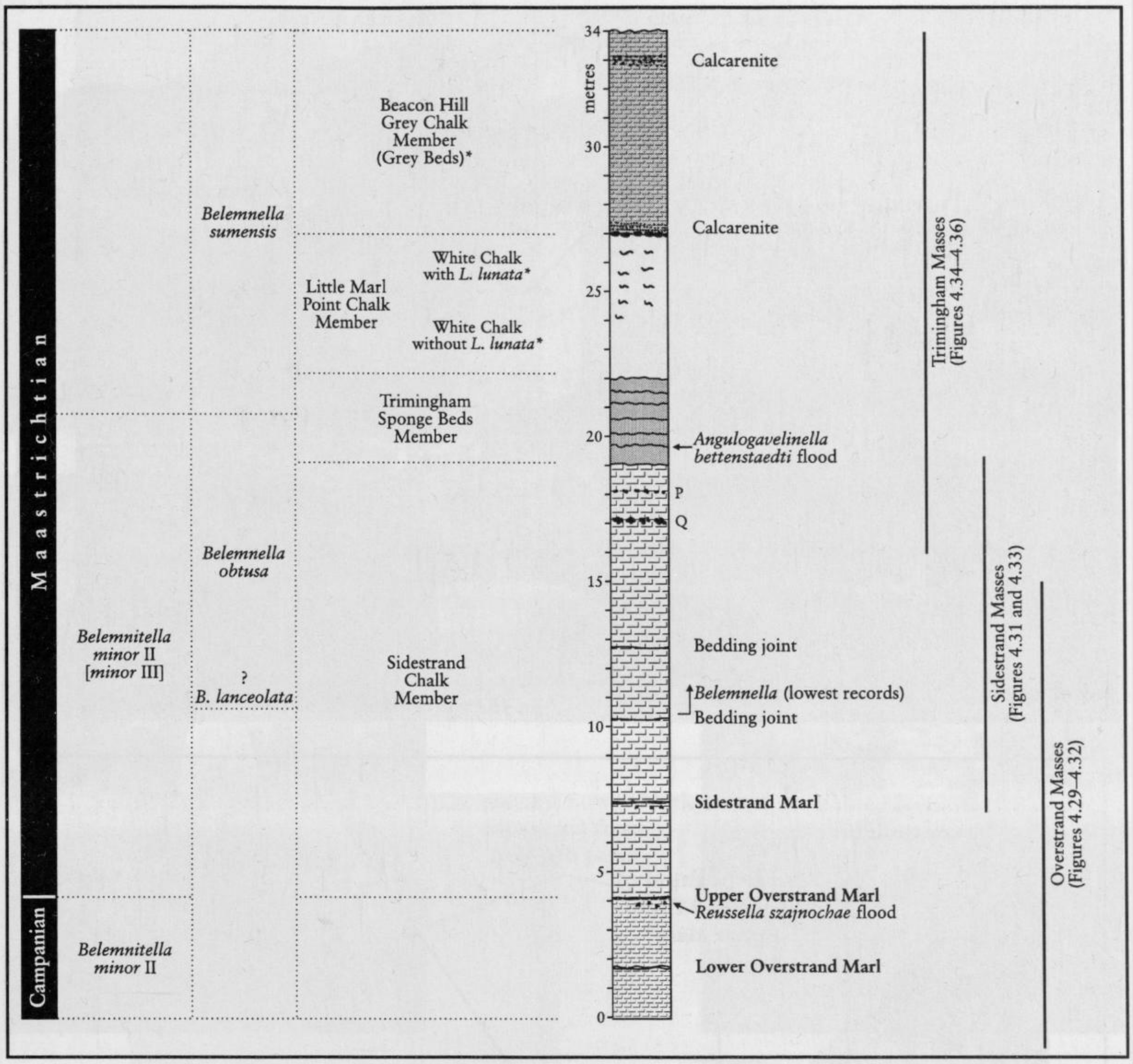


Figure 4.28 Composite, simplified section for the latest Campanian and Lower Maastrichtian of the Chalk between Overstrand and Trimingham, north Norfolk coast. (P and Q are marker flint bands of Peake and Hancock (1961, 1970); * = Brydone's terms.)

Above and slightly to the west of Mass 1, a highly fossiliferous 3 m section, termed by Wood (1967) the 'Overstrand Hotel Upper Mass', was formerly exposed at the extreme eastern end of an elongate Chalk mass (Mass 2). This key section has now slipped away and has broken up. However, the exposure of Mass 2, of which it formed a part, is better exposed than hitherto. The higher unit of the 'Lower Mass' (Mass 1), with its paramoudra flint horizon and basal Sidestrand Marl, is demonstrably an integral part of Mass 2, from which it has become detached. Some 2 m of beds are visible below the Sidestrand Marl in Mass 2, but the downward continuation is obscured by talus.

Farther to the east, adjacent to the construction road leading down to the sea defences, Mass 3 has the Sidestrand Marl at its base and exposes beds above the marl (Figure 4.29). Mass 4, on the seaward side of the construction road, exposes a Chalk succession partly truncated on the eastern side by a channel filled by flint cobbles with shell debris at the base. The succession in this mass includes a marl seam (inferred to be the Sidestrand Marl) which shows evidence of intra-Chalk folding.

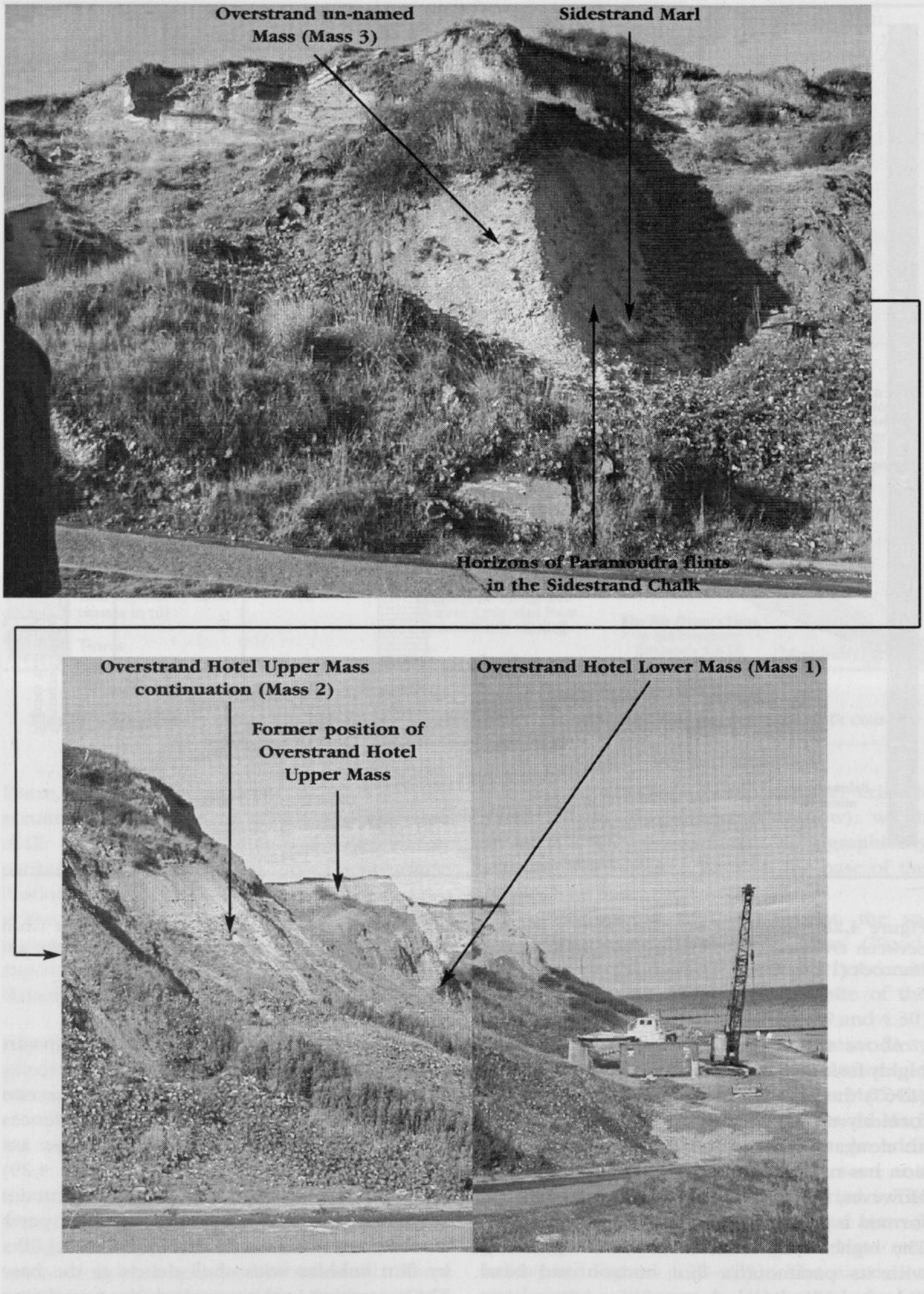


Figure 4.29 The Overstrand Hotel Chalk Masses, incorporated in Quaternary sediments and partly landslipped Overstrand Cliffs, north Norfolk coast. All the masses are in the Sidestrand Chalk Member. (Photomosaic: R.N. Mortimore.)

Figure 4.30 Mass 1 (Overstrand Hotel Lower Mass) containing the Overstrand and Sidestrand marl seams and the Campanian–Maastrichtian boundary. (Photos: R.N. Mortimore.)

Figures 4.32 and 4.33 show logs of the Overstrand Mass 1 and the Sidestrand Western Mass.

Lithostratigraphy

Wood (1967) split off the Overstrand Campanian–Maastrichtian succession as the pre-*Porosphaera* Beds, on the (faunal) basis of the co-occurrence in the Overstrand Hotel Upper Mass (Mass 2) of the belemnite genera *Belemnella* and *Belemnitella*, which had not been recorded from the *Porosphaera* Beds of the Sidestrand masses. Johansen and Surlyk (1990), placed the entire succession in the glacio-tectonic slices that lay stratigraphically beneath their Trimingham Sponge Beds Member (i.e. Wood's Pre-*Porosphaera* Beds + *Porosphaera* Beds), irrespective of whether or not it included Upper Campanian strata, into a formally defined Sidestrand Chalk Member, with its base taken at the Pyramidata Hardground. Accordingly, the Overstrand composite succession is included in this member.

Biostratigraphy

The composite succession includes the basal boundary of the Maastrichtian Stage and, on belemnite evidence alone, falls partly in the

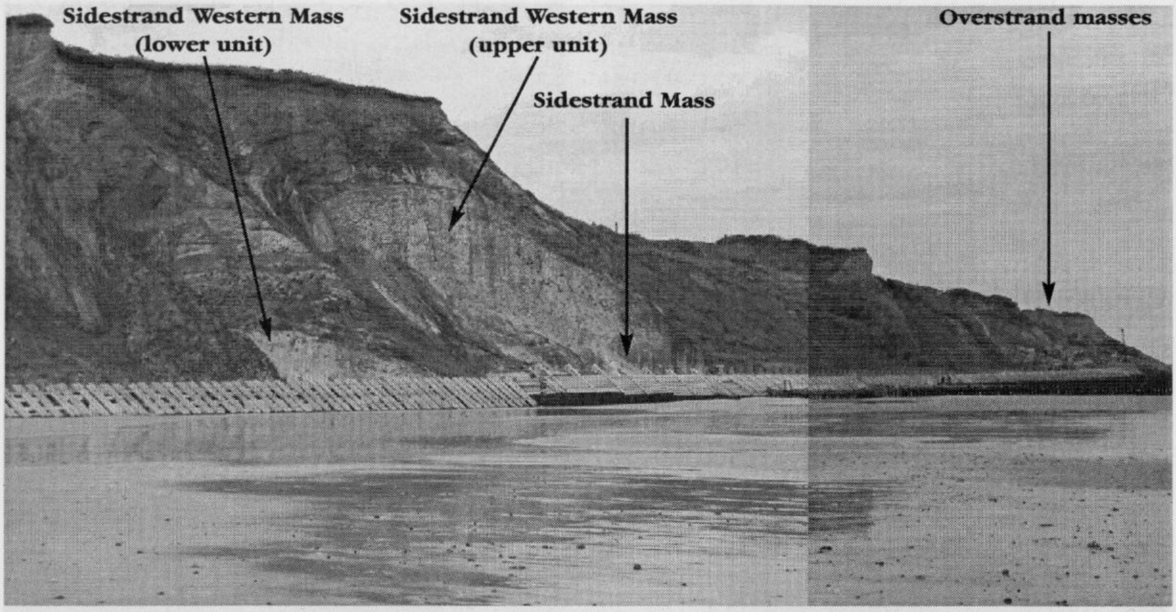


Figure 4.31 Two components of the Sidestrand Western Mass enfolded in Quaternary sediments, Sidestrand beach, north Norfolk coast. The upper part is thrust over the lower part and contains the Sidestrand Marl at its base. (Photomosaic: R.N. Mortimore.)

Belemnitella minor II Zone (which crosses the Campanian–Maastrichtian boundary (see Christensen, 1997), and partly in the basal Maastrichtian restricted *Belemnella lanceolata* Zone of the standard European belemnite scheme (Figure 2.13, Chapter 2). However, the identification of this boundary is unclear at present.

The Overstrand masses are very fossiliferous, yielding predominantly rhynchonellid and terebratulid brachiopods, large thick-tested echinoids (*Echinocorys* cf. *belgica* Lambert), the crinoid *Austinocrinus bicoronatus* and belemnites. There is a significant change in the belemnite assemblage in the highest part of the composite Overstrand succession above the Sidestrand Marl. Small *Belemnitella* sp. alone are found up to the semi-tabular flint above the paramoudra flint horizon near the top (Figure 4.32), at which level appears a mixed fauna of the long-ranging genus *Belemnitella* and the diagnostic Maastrichtian genus *Belemnella*, including *B. lanceolata* (Schlotheim). The *Belemnella* from the Overstrand masses were later assigned to the basal Lower Maastrichtian restricted *Belemnella lanceolata* Zone of the standard scheme (Schulz, 1982; Christensen, 1997). On this basis, at least the highest beds of the Overstrand succession belong in the Lower Maastrichtian Substage.

The boundary between the low, but not basal, Lower Maastrichtian *Rugia acutirostris*–*R. spinosa* Zone and the overlying *R. spinosa*–*Trigonosemus pulchellus* microbrachiopod Zone was reported to fall in the middle of the Overstrand Hotel Upper Mass (Johansen and Surlyk, 1990). From the stratigraphical interpretations presented here, this boundary must lie in the highest part of the composite Overstrand succession, i.e. in the unit above the Sidestrand Marl, and approximately at the level of the mixed belemnite assemblage.

The reported entry (Swiecicki, 1980) of the benthic foraminifer *Bolivinoides peterssoni* Brotzen just below the Overstrand Lower Marl marks the base of the UKB20 benthic foraminiferal Zone (Hart *et al*., 1989) (see Figure 1.5, Chapter 1). Swiecicki (1980) noted a fundamental change in the microfauna at the Overstrand Upper Marl. The foraminiferal assemblage below the marl was characterized by the occurrence (and upper limit) of the benthic taxa *Gavelinella monterelensis* (Marie), *Globorotalites hiltermanni* Kaever and *Reussella szajnochae szajnochae* (Grzybowski) (Figure 2.44, Chapter 2), the last occurring in increasing

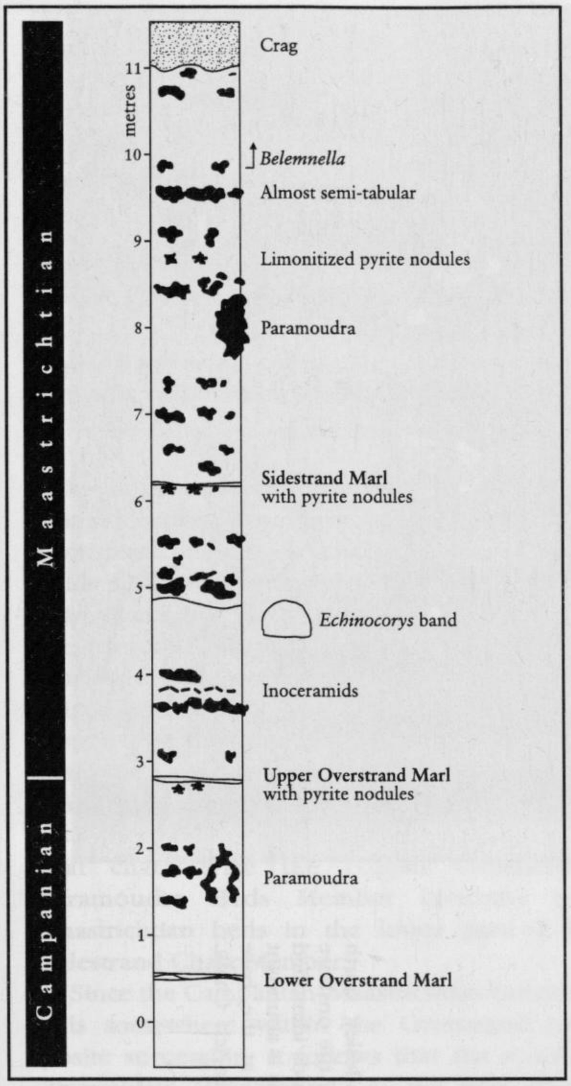


Figure 4.32 Stratigraphy of the Overstrand Hotel Lower Mass (Mass 1).

abundance up to a flood occurrence below the marl. For practical purposes, the ***Reussella s. szajnochae*** bio-event that is associated with the extinction of ***Globorotalites hiltermanni*** is taken as a marker in the offshore successions for the Campanian–Maastrichtian boundary (Bailey *et al.*, 1983; Hart *et al.*, 1989). Immediately above the Overstrand Upper Marl, ***Bolivina incrassata*** Reuss is present in flood abundance; ***Neoflabellina reticulata*** (Reuss) enters higher, above the Sidestrand Marl, overlapping with the top of the range of the long-ranging ***N. praereticulata*** Hiltermann.

Interpretation

The 'Overstrand Hotel Lower Mass' (Mass 1) has been considered by some workers (e.g. Peake and Hancock, 1961) to be composite, comprising several stacked thrust-slices, each repeating the same succession and separated by marl-filled thrust-planes containing Quaternary fossils. The highest of these supposed thrust-slices has been inferred to comprise the repeated succession overlain by higher beds. However, better exposure of the higher part of the mass has revealed that three of the supposed thrust-planes have the internal structure of primary marl seams and that the 'thrust-slices' are part of a normal Chalk succession, albeit one containing several well-developed marl seams.

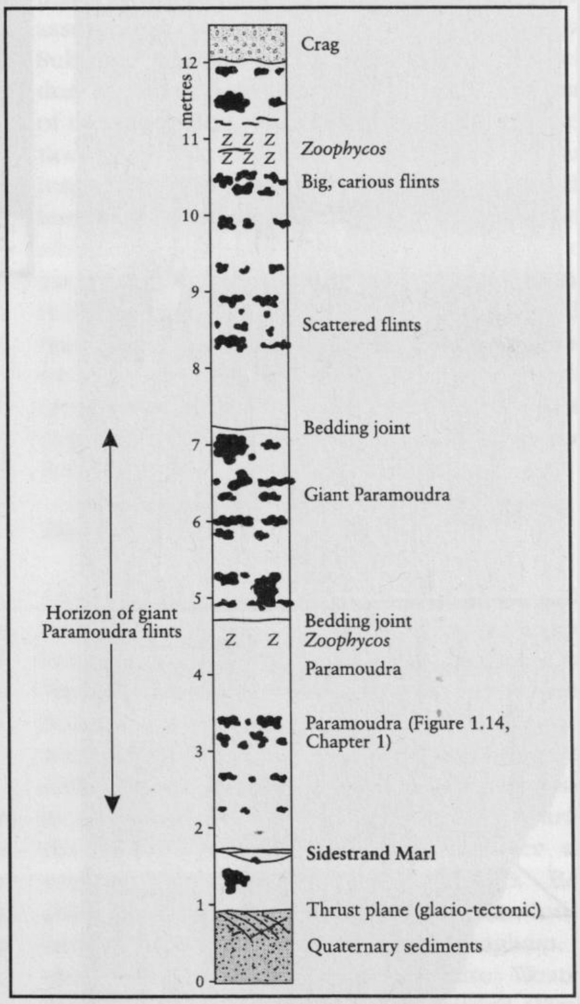
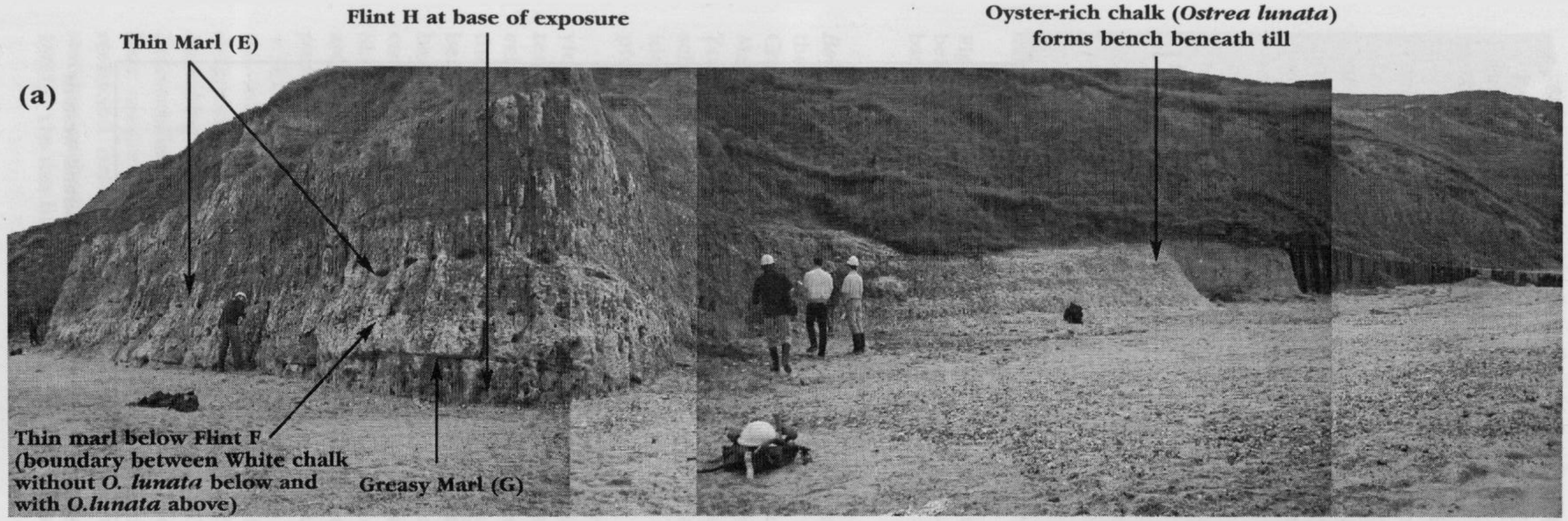


Figure 4.33 Stratigraphy of the Sidestrand Western Mass.



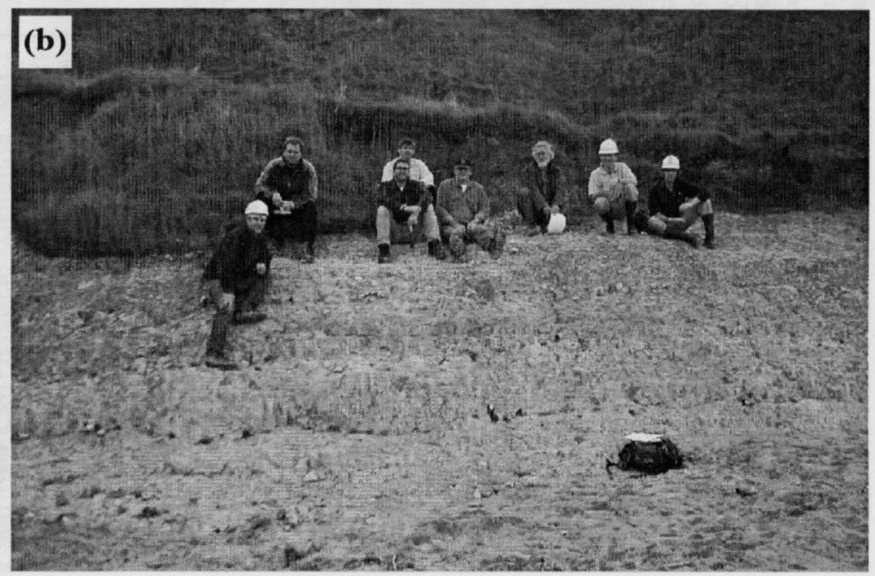


Figure 4.34 Little Marl Point, Trimingham near Mundesley, north Norfolk coast. The uppermost Maastrichtian exposed in the onshore succession (as an ice-rafted block). Letters refer to the beds identified by Peake and Hancock (1961, 1970). *Belemnella sumensis* is abundant throughout this exposure except in the sponge beds at the base of the section. (a) Composite photograph. (b) Oyster-rich Chalk. (Photomosaic: R.N. Mortimore.)

Figure 4.35 Folding picked out by flint bands within the rafted *Ostrea lunata* Chalk masses exposed in the foreshore at Trimingham, August 1949, north Norfolk Coast. (From Sainty, 1949, pl. 7.)

It is noteworthy that the Campanian–Maastrichtian boundary interval of the Overstrand masses is characterized by flinty chalk with well-developed marl seams, since no marl seams are known from the remainder of the (exposed) Upper Campanian succession of Norfolk. Thin marl seams are present in the Trimingham Sponge Beds Member, higher in the Lower Maastrichtian Substage, but these are associated with a condensed succession comprising closely spaced hardgrounds. It is also interesting that the large paramoudra flints that characterize the (Upper Campanian) Paramoudra Beds Member continue into Maastrichtian beds in the lower part of the Sidestrand Chalk Member.

Since the Campanian–Maastrichtian boundary falls somewhere within the Overstrand composite succession, it follows that the so-called 'Pyramidata Hardground', at the base of the Sidestrand Chalk Member, lies in the higher part of the Upper Campanian Substage rather than at the base of the Maastrichtian Stage. It is possible that this hardground marks the top of the in-situ Chalk and that it may have served as a plane of decollement for the successions in the glacio-tectonic masses to the east. However, there was no evidence of a hardground at this level in the British Geological Survey Trunch Borehole.

The belemnites in the composite Overstrand succession do not enable definite identification of the Campanian–Maastrichtian boundary. The diagnostic Maastrichtian genus *Belemnella* is already relatively common where it appears in the mixed *Belemnitella*/*Belemnella* assemblage. In view of the extreme rarity of *Belemnella* in the basal beds of the boreal standard basal boundary succession at Kronsmoor in northern Germany (Schulz, 1982), the mixed Overstrand assemblage is likely to be some distance above the base of the stage. This interpretation is supported by the microbrachiopod data, which place the horizon with the mixed belemnite assemblage within the Lower Maastrichtian Substage and not at the base. Unfortunately, due to the relative inaccessibility of this part of the succession, only limited belemnite collections have been made from the (Maastrichtian) interval between the Sidestrand Marl and the level with the mixed assemblage and it is impossible to know whether or not *Belemnella* is present. The evidence from foraminifera was, until recently, thought to support a lower level for the base of the Maastrichtian Stage. New evidence on the entry of the basal Maastrichtian index ammonite, *Pachydiscus newbergicus*, suggests that this boundary may be significantly higher, well above the entry of *Belemnella*.

2b: Sidestrand

Three complex glacio-tectonic masses, collectively known as the 'Sidestrand masses', and termed, from west to east, the 'Sidestrand Western Mass', 'Central Mass' and 'Eastern Mass', respectively (Peake and Hancock, 1961), were progressively revealed by erosion of the cliffs at Sidestrand (Figure 4.31). The succession in these masses terminates in the lower part of the Trimingham Sponge Beds Member and extends lower in the Porosphaera Beds (Sidestrand Chalk Member) than the lowest beds in the foreshore masses at Trimingham. Of these masses, only the composite Western Mass (Figure 4.33) is still well exposed (Figure 4.31); the Central Mass has now completely disappeared and the Eastern Mass has now been eroded right down to beach level,

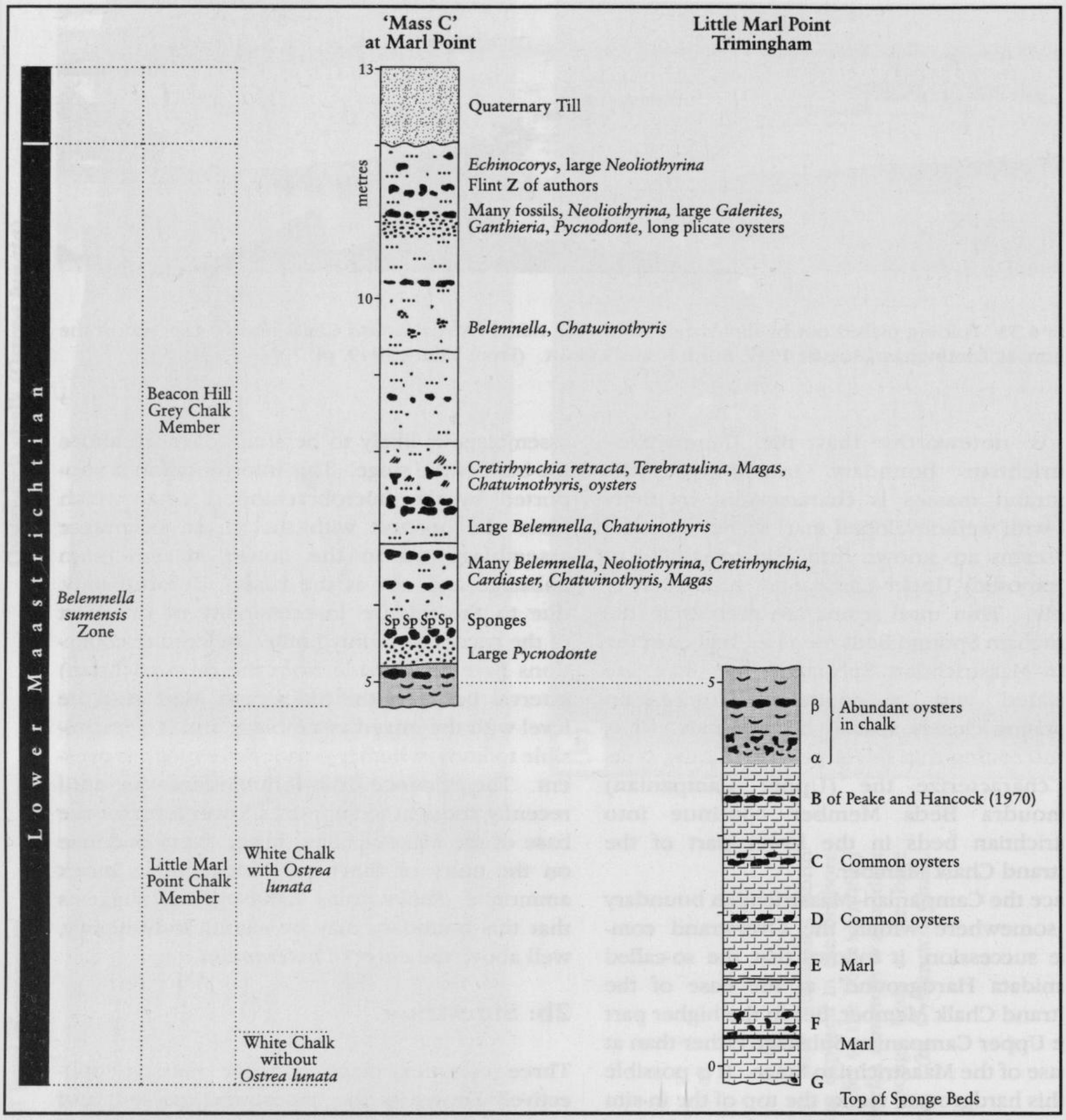


Figure 4.36 Sections in the highest onshore chalk in England at Trimingham.

where it is represented only by intermittent foreshore exposures at low water. Contrary to the statement in Peake and Hancock (1961), the Chalk masses at Sidestrand rest directly on, and are enclosed by, Quaternary deposits.

The Sidestrand masses can be correlated directly with the Overstrand masses by means of the Sidestrand Marl, which is situated just above the base of the western of the two component masses of the Western Mass (Figure 4.33). As in the Overstrand masses, the chalk above the Sidestrand Marl contains large paramoudra flints (Figure 1.14a, Chapter 1). The immediately overlying succession overlaps with the top of the composite Overstrand succession but it is difficult to correlate on a bed-by-bed basis. However, the broad correlation, which involves the recognition of a more or less flintless interval, is indisputable.

Biostratigraphy

The *Porosphaera* Beds have been assigned to the *Belemnella pseudobtusa* Zone and the overlying *B. obtusa* Zone, with the latter extending up to the top of the Trimingham Sponge Beds (Schulz, 1982). In view of the correlation between the top of the Overstrand composite succession and the base of the Sidestrand succession, the level in the restricted *B. lanceolata* Zone with the mixed *Belemnitella/Belemnella* fauna must be present at Sidestrand, even though it has not yet been identified.

The entry of the benthic foraminifer *Bolivinoides paleocenicus* (Brotzen) at the top of the Sidestrand Chalk Member (i.e. *Porosphaera* Beds), immediately beneath the Trimingham Sponge Beds Member, marks the base of the *B. paleocenicus* benthic foraminiferal Zone (UKB21, Figure 1.5, Chapter 1). Another benthic species *Angulogavelinella bettenstaedti* Hofker enters at the same level, and ranges up into the middle of the Sponge Beds, where it occurs in flood abundance before its upper limit. The *A. bettenstaedti* flood is an important bio-event in the Rowe Formation of the offshore succession, located a short distance above the *Reussella szajnochae szajnochae* acme (Lott and Knox, 1994).

The *Porosphaera* Beds are very fossiliferous and, in addition to common belemnites, they are particularly characterized by large simple corals (*Desmophyllum* sp.), the large rhynchonellid brachiopod *Cretirhynchia magna* Pettitt (a *Cyclothyris*?) and the smaller *Cretirhynchia retracta* (Roemer), together with very large, thick-tested *Echinocorys* ex gr. *belgica* Lambert and small *Galerites* sp.. Brydone's idea that this unit contains particularly abundant specimens of the small spherical calcisponge *Porosphaera*, is difficult to understand.

The overlying Trimingham Sponge Beds Member is poorly exposed today, but in previous years extensive bed-by-bed collections made by the British Geological Survey from the basal beds forming the relict Sidestrand Eastern Mass included large *Belemnella obtusa* and large *Galerites* sp.. The member takes its name from the numerous hexactinellid sponges with the skeletal meshwork picked out in pyrite that are found preserved in the harder beds. As in the case of the Catton Sponge Bed at **Catton Grove Chalk Pit**, the most indurated beds (the chalkstones beneath the hardgrounds) contain moulds of originally aragonite-shelled bivalves and gastropods, comparable with the so-called '*reussianum* fauna' of the Upper Turonian Chalk Rock (e.g. **Fognam Quarry** and **Kensworth Chalk Pit** GCR sites). Unfortunately no determinable ammonites have been collected from this level.

(3) Cliff and foreshore exposures of glacio-tectonic masses of Chalk between Trimingham and Mundesley

In the 19th century (cf. Lyell, 1833, 1852), and in the early years of the 20th century, there were extensive exposures through three, structurally complex, glacio-tectonic masses in the cliffs and foreshore at Trim(m)ingham (Figure 4.27). Some of these masses at the time stood high above beach level, but they became progressively eroded by the action of the sea. There are numerous sketches and photographs in the literature recording the erosion and eventual disappearance of these masses (Figure 4.35). The question of whether or not the masses represented in-situ, albeit glacially contorted, Chalk, glacially transported Chalk, or simply sea-stacks of in-situ Chalk, was the subject of considerable, often acrimonious, controversy, which filled the pages of the scientific journals at that time (see Peake and Hancock (1961) for a comprehensive review). From approximately west to east, the masses were known as the 'Western Mass', 'Central Mass' and 'Eastern Mass', these being subsequently termed by Brydone (1906), 'Mass C', 'Mass A' and 'Mass B', respectively. A rib of Chalk intermittently exposed on the foreshore, some distance to the east, was given the designation D. Today, only the cliff section at Marl Point, representing the termination of Mass A, can be seen, although foreshore exposures of Mass C can sometimes be observed at extreme low water under favourable tidal conditions when the wind is blowing offshore.

Although he produced no detailed logs, Brydone (1908) mapped the Trimingham exposures in great detail, tracing the succession from the cliff into the truncated foreshore exposures. The accuracy of his work was confirmed by photographs (Figure 4.35) of fortuitous exposures following storms (Sainty, 1949, pl. 7). Although Brydone failed fully to appreciate the structural complexity of the individual masses, and the structural inter-relationships between them, he neverthelesss had far better exposures available to him than the poor remnants that exist today. Moreover, he had a clear understanding of the overall succession, and of the biostratigraphy. In his classic 1908 paper he subdivided the Trimingham succession into five partly lithostratigraphical, partly biostratigraphical units that, albeit renamed, remain in use today.

Lithostratigraphy

In ascending order, Brydone's units were the *Porosphaera* Beds; the Sponge Beds; the White Chalk without *Ostrea lunata*; the White Chalk with *Ostrea lunata*; and the Grey Beds. Brydone also used the term 'General beds' to group the entire post-Sponge Beds succession. The *Porosphaera* Beds took their name from the remarkable abundance in them of the small spherical calcisponge *Porosphaera globularis* (Phillips). The overlying Sponge Beds, constituting a succession of hardgrounds, were named after the conspicuous large sponges that they contained. The term 'White Chalk with *Ostrea lunata* [now *Agerostrea*]' referred to chalks containing the eponymous thin-shelled oyster (Figure 2.28a, Chapter 2), at some levels in rock-forming quantities. The Grey Beds were so designated after the overall smoky grey colour of the flints. At that time, only the highest *Porosphaera* Beds were exposed in the cores of the truncated anticlinal structures, but lower parts of the succession subsequently became exposed in the glacio-tectonic masses farther to the west at Sidestrand. Brydone's informal units were given formal lithostratigraphical member status by Johansen and Surlyk (1990). They named the *Porosphaera* Beds, together with the underlying succession in the Sidestrand masses, the 'Sidestrand Chalk Member'; the Sponge Beds, the 'Trimingham Sponge Beds Member'; the White Chalk with and without *Ostrea lunata*, the 'Little Marl Point Chalk Member'; and the Grey Beds, the 'Beacon Hill Grey Chalk Member', respectively (Figure 4.28).

The cliff section at Little Marl Point extends from the top of the Trimingham Sponge Beds to a level inferred to be near the top of the oyster-rich beds of the Little Marl Point Member (Figure 4.36). The section given by Peake and Hancock (1961, fig. 7) is essentially correct up to their flint C, but the higher part of the section contains additional flint bands not shown by them. A fortuitous foreshore exposure of the Beacon Hill Member in Mass C was logged and collected in considerable detail by Mr A.A. Morter (then of the British Geological Survey) in 1976. He also later prepared a skeletal log, without measurements, of the immediately underlying beds, but it is difficult to correlate the highest flints recorded by him with the highest flints seen in the bluff. It is, likewise, difficult to accept the Peake and Hancock interpretation of the correlation between the bluff and foreshore exposures. Figure 4.36 is a composite section, in which the present authors, with the agreement of Mr Morter, attempt to link his unpublished logs with our log of the bluff. The top of Morter's Mass C section, which terminates against Quaternary till, can probably be inferred to represent the highest Chalk ever observed at Trimingham. These unpublished logs were used by Gale to produce a composite log for the entire Maastrichtian succession (Jenkyns *et al.*, 1994, fig. 9).

The sediments of the Beacon Hill Grey Chalk Member are overall relatively coarse grained, and include one or more beds that are true bioclastic calcarenites. These represent the closest approach in the English succession (albeit in the Lower Maastrichtian Substage) to the tuffeau lithology that characterizes the (Upper) Maastrichtian strata in the type area.

Biostratigraphy

The palaeontological richness and diversity of the fossils in the Chalk at Trimingham caught the attention of amateur and professional geologists. Taylor (1824) was the first to appreciate the distinctness of the Trimingham Chalk, and its superposition on the Norwich Chalk. In the Cromer Memoir (Reid, 1882), it was stated that the Trimingham belemnites included, in addition to *Belemnitella mucronata*, forms referable to *Belemnitella lanceolata* Schlotheim, although the biostratigraphical significance of this perspicacious observation was not understood for almost another seventy years. In fact, it was clearly stated then (Reed, 1882, p. 5) that all the fossils listed were 'Upper Chalk forms; none characteristic of higher zones, such as the Maestricht Chalk, having at present been found'. Jukes-Browne and Hill (1904) also appreciated the distinct nature of the faunas of the Trimingham Chalk, and the superposition of that unit on the Chalk of Norwich. Brydone, in a series of key papers on the Trimingham Chalk (1900, 1906, 1908, 1938), drew attention to the fact that both the bryozoans and the serpulids pointed to a much higher stratigraphical level than the 'Norwich Chalk', and suggested a correlation with the Chalk of the island of Rügen in the Baltic region. This interpretation was also supported by the evidence from the asteroids.

Belemnites are very common in the Trimingham masses, and extensive, albeit only broadly horizoned, collections were made by Brydone. These collections, now housed in the British Geological Survey collection at Keyworth, were studied by Jeletzky, who realized (Jeletzky, 1951) that the Trimingham belemnites belonged, not to the Upper Campanian zonal index fossil *Belemnitella mucronata* (Schlotheim), as previously thought, but to the diagnostic Maastrichtian genus *Belemnella*, including forms related to the then standard European zonal index fossil *B. lanceolata*. He thereby broadly confirmed Brydone's own ideas (1900, 1906, 1908), regarding the similarity between the (Lower Maastrichtian) Rügen and Trimingham faunas. He later plotted (Jeletzky, 1958, fig. 8) the inferred range of the Trimingham succession in terms of a much more refined European belemnite biostratigraphy, demonstrating that it belonged in the Lower Maastrichtian Substage, and pointing out that the basal beds of the Maastrichtian Stage were missing. He additionally noted that the genus *Belemnitella* was extremely rare, constituting about 2% of the total examined, with half the records coming from the lowermost *Porosphaera* Beds. He also observed that the *Belemnella* assemblages from the *Porosphaera* and Sponge Beds differed from those of the overlying beds, matching the general biostratigraphical succession elsewhere in Europe. Subsequently Schulz (1982) and, more recently, Christensen (1995) have revised Jeletzky's nomenclature while accepting his general conclusions, and have tentatively correlated the Maastrichtian succession with the standard belemnite zonal scheme.

The faunas of the Little Marl Point Member, dominated in the higher part (Brydone's 'White Chalk with *Ostrea lunata*') by rock-forming concentrations of the oyster *Agerostrea lunata* (Woods *non* Nilsson), are of relatively low diversity, contrasting markedly with the abundant and high-diversity faunas of the overlying Beacon Hill Grey Chalk Member. The latter is particularly rich in very well preserved echinoids, including *Cardiaster granulosus* (Goldfuss), the large irregular species *Gauthieria princeps* (Hagenow) and the distinctive small *Echinocorys limburgica* Lambert. Other important elements are the small pectinacean bivalve *Lyropecten* (*Aequipecten*) *pulchellus* (Nilsson) and oysters, notably *Gryphaeostrea canaliculata* (J. Sowerby) and, in the calcarenitic beds, very large *Pycnodonte vesiculare* (Lamarck). The brachiopod assemblage contains many terebratulids (large *Neoliothyrina obesa* Sahni in addition to smaller *Chatwinothyris* sp.), together with the rhynchonellid *Cretirhynchia limbata* (Schlotheim). Other brachiopods characteristic of this bed include *Magas chitoniformis* (Schlotheim), *Terebratulina gracilis* (Schlotheim) and *Trigonosemus pulchellus* (Nilsson). Extensive macrofossil collections made by Brydone and others are housed in the Sedgwick Museum in Cambridge and at the British Geological Survey, Keyworth.

The composite Trimingham succession (Figures 4.28 and 4.36) visible today, comprising the Little Marl Point bluff section and intermittent foreshore exposures of Mass C, spans the higher part of the *Belemnella obtusa* Zone and the *Belemnella sumensis* Zone of the standard European belemnite zonal scheme (Schulz, 1982; Christensen, 1995). The change from the large, obtuse ended, lanceolate *B. obtusa* Schulz in the Trimingham Sponge Beds, to the more cylindrical *B. sumensis* Jeletzky in the overlying beds, is conspicuous.

The Trimingham succession falls within the *Bolivinoides paleocenicus* benthic foraminiferal Zone (UKB21) (Swiecicki, 1980; Hart *et al.*, 1989). The entry of *Tappanina selmensis* (Cushman) at the base of the White Chalk with *Ostrea lunata* (higher part of the Little Marl Point Chalk Member) was taken by Swiecicki (1980) to mark the base of his B6ii benthic foraminiferal Subzone (Figure 1.5, Chapter 1).

The entry of *Trigonosemus pulchellus* (Nilsson) in the Grey Beds (Beacon Hill Grey Chalk Member) marks the base of the *T. pulchellus* microbrachiopod zone of the northern European scheme (Johansen and Surlyk, 1990).

Interpretation

The various masses in the Overstrand to Trimingham Cliffs site provide a composite succession through the highest onshore Upper Cretaceous strata in England (Figure 4.28; Figure 4.5), in highly fossiliferous soft chalks ideal for the collecting of macrofossils and the extraction of microfossils and nannofossils. The origin of these masses is controversial (e.g. Eyles *et al.*, 1989). Within the succession, there is evidence (Overstrand Mass 4) for internal, intra-Cretaceous slumping akin to some of the events recognized in the Central Graben structure in the North Sea Basin. It is noteworthy that the composite Lower Maastrichtian succession of the site spans virtually the same stratigraphical range as the in-situ Maastrichtian component (Port Calliagh and Ballycastle Chalk members) of the Ulster White Limestone Formation that is preserved in a synclinal structure beneath the Tertiary basalts on the North Antrim coast (see Wood, 1967; Fletcher, 1977; Fletcher and Wood, 1978). It follows that the highest onshore Chalk in Britain extends no higher than the lower part of the Lower Maastrichtian Substage (*Belemnella sumensis* belemnite Zone); higher Maastrichtian strata in the Southern North Sea Basin are first found to the east of the continuation of the Dowsing Fault (Figure 1.8, Chapter 1). The large *Belemnella lanceolata* from the Port Calliagh Member match those from the original Overstrand Hotel Upper Mass assemblage.

The three successions between Overstrand and Trimingham, particularly the Overstrand Hotel masses (Sidestrand Chalk Member), and the Trimingham Sponge Beds Member, are critical to the interpretation of the foraminiferal biostratigraphy of the offshore successions of the Southern North Sea Basin. Of particular importance is the identification ***in situ*** in the Overstrand Hotel Lower Mass (Overstrand Mass 1) of the *Reussella szajnochae szajnochae* flood event, indicative of the Campanian–Maastrichtian boundary (Schönfeld and Burnett, 1991), and, in the lower part of the Sponge Beds, of the *Angulogavelinella bettenstaedti* flood event. These events allow the onshore Maastrichtian strata to be placed in the Rowe Formation (Figure 5.3, Chapter 5) of the North Sea Chalk Group (Lott and Knox, 1994). The composite Overstrand–Trimingham succession has been placed within the standard European belemnite zonal scheme. The (now disappeared) Overstrand Hotel Upper Mass is older than most of the succession exposed in the Sidestrand masses, belonging to the restricted *Belemnella lanceolata* Zone, rather than to the *Belemnella pseudobtusa* and *obtusa* zones. This is supported by the micromorphic brachiopod evidence (Johansen and Surlyk, 1990), which places the Upper Mass in the low, but not basal Maastrichtian, *Rugia spinosa–Trigonosemus pulchellus* Zone. Although they reported that the basal Maastrichtian *Gisilina jasmundi–Rugia acutirostris* Zone was missing from the Overstrand masses, their sampling did not extend as low as the Campanian–Maastrichtian boundary determined on foraminiferal evidence. The anomalous succession of Lower Maastrichtian belemnite assemblages, which apparently involves two successive immigrations of *Belemnella* into the Norfolk area (Christensen, 1996), requires further investigation but may be partly explicable by the previous incomplete understanding of the stratigraphical relationships between the Overstrand and Sidestrand masses.

The Trunch Borehole (TG 2933 3455), which cored the entire Chalk succession, entered in-situ Chalk, beneath *c.* 45 m of Quaternary deposits, in the lower part of the Trimingham Sponge Beds Member, and proved the *Angulogavelinella bettenstaedti* flood event (Wood *et al.*, 1994). At this site, 3 km from Trimingham, which was deliberately chosen to intersect the top of the Chalk at a topographically high level, the higher part of the Trimingham sucession was actually missing, presumably as a result of erosion. The higher part of the core beneath the Sponge Beds consisted of remarkably soft chalk and recovery was very poor. There was no evidence for a hard-bed corresponding to the Pyramidata Hardground of the coast. The identification, at 61 m, of the *Reussella szajnochae szajnochae* flood-occurrence, *c.* 16 m beneath the Sponge Beds, almost exactly matches the composite stratigraphy in the Sidestrand and Overstrand masses (see Figure 4.28), where the corresponding interval from the Sponge Beds to the Sidestrand Marl is 15 m.

The Mundesley Borehole (TG 317 364) entered Chalk beneath 13.4 m of Pleistocene deposits and proved 1.7 m of highly fossiliferous calcarenitic chalk with grey flints before terminating. The lithology and fauna (Wood *et al.*, 1994) indicated that the highest (presumed in-situ) Chalk at this locality belonged to the Beacon Hill Grey Chalk Member. The succession here extends no higher than that in Mass C, implying that the Beacon Hill Grey Chalk Member marks the top of the onshore Maastrichtian succession. A tentative correlation of the Maastrichtian succession of the Norfolk coast and that proved in inland boreholes around Wroxham was shown by Pitchford (1991).

Conclusions

The three Chalk successions in the Overstrand to Trimingham Cliffs site at Overstrand, Sidestrand and Trimingham, are of great historical interest in the development of ideas on the stratigraphy of the highest part of the Upper Cretaceous succession in Britain. The origin of the masses, which are believed to have been detached by ice action from the floor of the North Sea, is controversial and is still being investigated. These masses provide a small-scale British analogue of the huge masses of Chalk incorporated in glacial deposits on the Island of Møn, Denmark and the German Island of Rügen in the Baltic. The Overstrand masses, in particular, are of key significance in the interpretation of the foraminiferal biostratigraphy of the offshore successions in the Southern North Sea Basin. They are thus of great importance in the search for oil and natural gas. The highly fossiliferous, soft chalks are ideal for collecting macrofossils as well as for the extraction of microfossils and nannofossils. Within the succession there is also evidence for internal, intra-Cretaceous slumping akin to some of the events recognized in the Central Graben, North Sea.