Chapter 1 The Upper Cretaceous rocks of the British Isles

Introduction

Probably the two most conspicuous rocks in Europe are chalk and flint (Figure 1.1), and both formed during the Late Cretaceous Epoch. Chalk and flint have been familiar partners in the history of human activity for many millennia. Pre-historic flint tools gave way to flints for military muskets and tinder-boxes in the latter part of the second millennium. Flint has been used extensively as a building material and chalk has been quarried and mined for agricultural and building lime; a carpenters 'chalk' was a familiar item in the 19th and early 20th centuries in England. Chalk caves were even used as secret stores to avoid taxes in Roman-ruled Judea for commodities such as olive oil.

Chalk is indirectly important in other ways. It is the main aquifer for potable groundwater in England (Brighton taking 98% of its water supply from the local Chalk). It is a major oil reservoir in the North Sea (the giant Ekofisk field is expected to keep producing until the year 2028), and is the deposit in which many major civil engineering works are undertaken (e.g. the Channel Tunnel (Harris *et al.,* 1996a), the Channel Tunnel Rail Link (CTRL)).

Other rocks of Late Cretaceous age are also economically important. In the Morvern area (Argyll and Bute), the Lochaline Sands are so pure that they provide a major source of glass sands for the manufacture of high grade optics.

Stratigraphically, 'the Chalk', used as a proper noun with a capital letter, is taken to be equivalent to the Upper Cretaceous Series, reflecting the dominance of the chalk rock-type in Upper Cretaceous strata. Stratigraphy has been an important tool in helping to locate and select types of chalk for whitings and the types of flints for tools, gun-flint and building.

Uplift of former Chalk seabeds formed the vast landscapes that stretch from the English Downland, through the Champagne plains on the northern edge of the Cote de l'Ile-de-France in the Paris Basin to the Chalk hills of Crimea, Kazakhstan and the Judean Desert. Because of its wide extent across Europe and Middle Asia, Huxley (1868) described the chalk as '… no unimportant element in the masonry in the Earth's crust, impressing its own peculiar stamp on the landscape. The undulating Downs and rounded coombs, covered with sweetgrassed turf, … have a peacefully domestic and mutton-suggesting prettiness, neither grand nor beautiful'. Whilst acknowledging Huxley's generality, there is no doubting the grandeur of the White Cliffs that form the coastlines of Flamborough Head, Dover, Beachy Head, the Needles and the Dorset and east Devon coasts.

Naturally, a book on the Upper Cretaceous stratigraphy of the British Isles will be primarily about the history of the English Chalk, but it is important not to forget the relatively small outcrops of richly fossiliferous sandy deposits in south-west England and the less fossiliferous deposits of the Inner Hebrides in Scotland. Nor must it be forgotten that a unique Upper Cretaceous Chalk succession is preserved beneath the basalts of Antrim in Northern Ireland.

Definition of the Upper Cretaceous series

It is from the white Chalk of the Anglo-Paris Basin that the Cretaceous System takes its name (*creta* = Latin for chalk), introduced by the Belgian geologist, Omalius d'Halloy (1822). It was not until the late 20th century, however, that a Lower and Upper division was formalized at the base of the Chalk (strictly, at the base of the Cenomanian Stage, see below; see also (Figure 1.2) and the Appendix, this volume).

Global geological setting

During the Late Cretaceous Epoch, 100–65 million years (Ma) ago, the supercontinents of Laurasia and Gondwanaland were breaking up and sea levels reached their maximum for the whole of the last 600 Ma, leading to chalk deposits forming on many continental regions of the world, including the British Isles (Figure 1.3). The causes of these geological events have been related to:

1. bulging ocean basins (the Late Cretaceous 'super-plume'), which expelled sea water onto continents;
2. carbon dioxide levels being about four times greater than today, keeping continental interiors and polar regions much warmer during winter (DeConto *et al.,* 1998);
3. little or no water being trapped as polar ice, contributing to high sea levels (Hays and Pitman, 1973; Jenkyns, 1980).

Hancock (1975a,b, 1990) and Hancock and Kauffman (1979) considered the Upper Santonian *Marsupites* Zone as the period when the maximum peak of transgression occurred in the Late Cretaceous Epoch, with a gradual tailing off from that point to a low at the end of the Cretaceous Period. Subsequent studies of sea-level curves and coastal onlap ('Vail') curves, show a much more complex picture in the Late Cretaceous Epoch, and suggest that the maximum transgression occurred at or about the beginning of the mid-Turonian (Vail *et al.,* 1977a,b; Vail and Mitchum 1977; Haq *et al.,* 1987, 1988).

A combination of high sea levels and warm, less oxygenated, sea water compared to the present day also gave rise to three periods of black shale formation in the Cretaceous succession known as 'Oceanic Anoxic Events' (OAE of Schlanger and Jenkyns, 1976; Jenkyns, 1980). Two of these OAEs occurred in the Late Cretaceous Epoch, the first at the Cenomanian–Turonian (C/T) boundary (Figure 1.2), resulting in the Plenus Marls and Black Band lithologies 93.3 million years ago.

By the close of the Cretaceous Period, over a very short time period of perhaps only 200 000 years, huge changes had taken place on Earth that led to the disappearance of many fossil groups including the dinosaurs, ammonites, belemnites, inoceramid and rudistid bivalves and many of the chalk-forming calcareous nannoplankton. This extinction event marked the end of the Secondary Era, the Mesozoic. The suggested causes of these cataclysmic changes are controversial, and include inferred meteorite impact(s) in the Yucatan peninsula, Mexico (Chicxulub Crater) and Bombay area, India (Shiva Crater), preceded and followed by exceptional volcanic activity (the Deccan Traps), leading to a 'nuclear winter'. Until now, the Late Cretaceous rocks of the British Isles contributed little to the arguments because all of the sedimentary evidence at the Cretaceous–Palaeogene ('K/P') boundary, at the time the meteorite impact is believed to have occurred, was thought to have been removed by erosion. It is possible, however, that the small remnants of rock beneath the basalts in the Inner Hebrides at Gribun (Mull) and Beinn Iadain (Morvern) may preserve the evidence at the boundary. Of particular interest would be the presence of an iridium anomaly, a key indicator of the K/P boundary, which is used as evidence for a bolide impact.

Upper Cretaceous palaeogeography, climate and sea-level curves

The distribution of sediments and fossils in the Upper Cretaceous strata of Britain has been influenced by the existence of two major biogeographical provinces termed the 'Boreal Realm' and Tethyan Realm' respectively (e.g. Kauffman, 1973; see also (Figure 1.4)). A third influence from the opening of the Atlantic Ocean in the west may have become increasingly important towards the end of the Cretaceous Period and was also partly responsible for oceanic changes leading to black shale formation at the C/T boundary. The northern Boreal Realm, of presumed colder water, covered the area of the North Sea and northern Europe east to the Crimea and beyond. Most researchers have envisaged the Boreal Realm as the place where belemnites flourished, arriving in the 'British' area either during short-term migrations southwards with pulses of colder water, or during phases of shallowing. This distribution of fossils makes application of a Boreal (or German) stage, substage or zonal scheme, using belemnites, more difficult in southern England, but a scheme of this type works well in the more northern (Yorkshire, Northern Ireland, Inner Hebrides), and shallower shelf areas (East Anglia) of the British Isles.

Many groups of fossils, including ammonites and the unicellular group of microfossils, the planktonic foraminifera, are common in Tethyan Realm deposits, providing an international standard biostratigraphy. The majority of these Tethyan planktonic microfossils were, however, absent in the Boreal Sea (except for short-term invasions with warmer water) and, as a result, two distinct biostratigraphies have been developed that are only tenuously correlated at many levels. The general absence of abundant planktonic foraminifera has led to the development of a zonal scheme based on benthic species in the UK area (Figure 1.5).

The Upper Cretaceous deposits of the British Isles reflect these biogeographical influences and are divided into several depositional and faunal provinces (Figure 1.6) based on differences in rock type and the fossils they contain. Two distinct 'chalk' provinces are the Southern Province, which links south-eastwards through the Paris Basin to the Tethyan Realm; and the Northern Province, which is more closely related to the northern Boreal Realm. Between these two provinces there is a region in which the diagnostic lithologies and fossils interdigitate, a truly Transitional Province (Mortimore, 1983). For each province, standard sections have been identified and described. Within these broad regions, subprovinces can be identified, such as the shelf areas of south-west England, which link westwards into the developing Atlantic Ocean; and the Chalk Rock areas of Wiltshire and Berkshire, containing condensed and fossil-rich deposits (Figure 1.6). Northern Ireland and the Inner Hebrides provinces are separated from each other and from the main outcrop in England. For the purposes of this review the Upper Cretaceous rocks of the Inner Hebrides are treated as belonging to a single province (see Chapter 6 and (Figure 1.7)), but it is recognized that there are strong structural controls dividing the region into separate basins (Figure 1.8).

Upper Cretaceous tectonic setting in Europe

The Late Cretaceous Epoch was a time of major tectonic change on a global scale as well as one of exceptionally high sea levels globally. The supercontinents were breaking up, and Africa was beginning to under-ride and laterally shear along the southern edge of Europe. These global plate tectonic movements caused a change from primarily tensional tectonics to a compressional stress field (Subhercynian tectonic phases), transmitted as strike-slip fault movements across the European Platform on ancient Variscan structures (e.g. Ziegler, 1990). Such plate tectonic stresses, translated along planes (Allen and Allen, 1990), can be used to explain both the geometry of sedimentary bodies in the chalk (e.g. shelf marginal onlap), and the apparently anomalous stratigraphies found in all the provinces and related to erosional channels, slumping and major hiatuses. Such tectonic processes can also explain rhythmic packages of chalk sediment (parasequences) and episodic sedimentation.

Many of the litho- and biostratigraphical events recorded at the GCR sites appear to coincide with the sequence boundaries illustrated on the sea-level curve of Haq *et al.* (1987, 1988). The dating on the curve, however, particularly in the Santonian–Campanian interval, is not as accurate as the dating from the field exposures in the Chalk. Some of these events also coincide with tectonic events discussed below. Tectonically-enhanced sequence boundaries appear to be the best explanation for this, and one that combines evidence for both sea-level changes and tectonic movements.

The rocks of the Upper Cretaceous Series

Upper Cretaceous rocks of the British Isles (Figure 1.7) include the Chalk of England and Northern Ireland, and the greensands, chert beds and phosphate-rich deposits of the shelf and marginal areas of south-west England, parts of Northern Ireland and the Western Isles and north-west Highlands of Scotland.

Chalk

Chalk is generally considered to be a soft, very pure white limestone. It is formed from millions of submicroscopic marine algae (nannoplankton), which bloomed in the surface waters of seas and oceans and whose skeletal remains found their way to the seabed. It was T.H. Huxley who introduced the name 'coccolith' for these minute calcareous algae that he observed as objects in deep-sea sediments dragged from the floor of the Atlantic Ocean. Sorby (1879, p. 78) recognized that chalk was primarily composed of coccoliths with few of the typical constituents of a deep-sea ooze. Nevertheless, Sorby considered that the chalk must have formed originally as a lime-mud on a deep-sea floor because of the absence, in very pure chalk, of fragments of land-derived rocks or volcanic rocks. The depth at which chalk formed on a sea or ocean floor occupied considerable discussion until the latter part of the 20th century. It is now generally agreed that the Chalk formed at depths between 100 and 500 m across the UK, with the depth varying from shallower shelf areas where tidal channels might have been present to deeper parts of the basin. The Chalk of northern England is considered by many researchers to be a deeper water deposit than the equivalent age chalks of southern England.

Surprisingly, through most of the early 20th century, the work of Huxley and Sorby was forgotten and it was Black (1953) who re-introduced the idea that chalk was an organic deposit, using carbon replicas of coccoliths to investigate chalk with the transmission electron microscope (Hancock, 1980). The chalk-forming coccoliths are the remains of single-celled, planktonic calcareous, golden-brown algae (coccolithophorids), which comprise a skeleton of calcitic plates or rings (coccoliths; see (Figure 1.9)) formed into a coccosphere coated with a carbonaceous organic material (Jordan *et al.,* 1995; Young *et al.,* 1997; Bown, 1998). The resulting chalk-ooze is an extremely fine-grained, pure, often soft, low-magnesium calcite limestone (micrite). Silicates have also been found as post-depositional coatings on coccoliths (Glasser and Smith, 1986) and these may have a profound effect on the properties of chalks. Other important calcitic microfossil components include the calcispheres and foraminifera (Figure 1.10).

Chalk is unusual in two ways. Firstly, unlike many limestones, chalk is entirely planktonic (and biogenic) and the evolution of calcareous nannoplankton in Mesozoic times was required before such sediment could form; coccolithic chalk is not, therefore, found in Palaeozoic rocks. Secondly, the planktonic, coccolithic origin of the sediment in the top 40 m of sea or ocean water means that the resulting carbonate rock is very widespread and not restricted, as is the case with most limestones, to stable platforms.

Marly chalk and marl seams

The Chalk in England changes composition upwards through the rock column. In the Grey Chalk Subgroup (see p. 20) there is much more clay (e.g. Destombes and Shephard-Thorn, 1971) and the mixture of chalk and clay produces marl. In contrast to the Grey Chalk Subgroup, the White Chalk Subgroup, on average, is greater than 98% pure calcium carbonate and this purity is related to the great distance from land of the British area, caused by the Late Cretaceous transgression of the sea onto the continents. Marl seams are more horizon-specific concentrations of clay (Figure 1.11), forming conspicuous marker beds traceable in the field and borehole cores as well as being recorded on geophysical borehole logs (Mortimore and Pomerol, 1987; Barker *et al.,* 1984).

It was long suspected that many marl seams in the Chalk were of volcanic origin (i.e. that they were decomposed volcanic ashes). This idea has turned out to be correct. Wray's work on the trace-element chemical fingerprinting of the marls (Wray and Gale, 1993), and the identification of some of them as vulcanogenic (Wray, 1995, 1999),. is of great importance in supporting stratigraphical correlations from expanded to condensed sections, and in lithostratigraphical and biostratigraphical correlation between the Chalk provinces (e.g. Mortimore and Wood, 1986; Mortimore and Pomerol, 1987).

In the weathered state, some of the 0.10 m to 0.15 m-thick marl seams display a distinctive foxy-brown colour, which contrasts with the surrounding off-white chalk, but in borehole cores they are usually coloured in shades of green and grey. Rare earth element (REE) analyses of the clay minerals of the Northern Province (Turonian–Coniacian) marl seams has permitted a differentiation into detrital marls, and marls of vulcanogenic origin derived from the argillization of air-borne volcanic ash (Wray and Wood, 1998). These marl seams, of whichever origin, are represented on downhole wire-line logs of boreholes by conspicuous 'spikes', which can be used for long-range correlation (Mortimore and Wood, 1986; Mortimore and Pomerol, 1987). The vulcanogenic marls are equivalent to the contemporaneous tuffs of north German successions (cf. Wray and Wood, 1995; Wray *et al.,* 1996), and are believed to correlate directly with them, and also with vulcanogenic marls of the Southern and Transitional provinces (Wray, 1999). This is now leading to the development of a Europe-wide framework of isochronous ashfall events, the so-called 'tephro-events' of event stratigraphy (Ernst *et al.,* 1983). Similar marl seams are present throughout the Newhaven Chalk and Flamborough Chalk formations, but have not yet been subjected to REE analysis (Figure 1.11) and (Figure 1.12).

Diagenetic effects: nodular chalks, chalkstones, hardgrounds, soft and hard chalks

Nodular chalks and hardgrounds represent syndepositional hardening of seabed sediment, and characterize particular lithological units such as the Lewes Nodular Chalk Formation. A lithification series can be recognized from incipient nodules to fully developed hardgrounds (Bromley, 1965, 1975a,b; Kennedy and Garrison, 1975). Because some hardgrounds formed by the lithification of erosion surfaces, one hardground may cut down to coalesce with another, giving rise to thicker units of 'chalkstone' such as the Chalk Rock of Wiltshire.

For stratigraphical studies, the potential loss of sediment (and hence stratigraphy) caused by dissolution is significant. Some researchers have suggested that up to 50% of the Yorkshire Chalk has been lost to pressure solution. A further curiosity, still not fully explained, is the softness of great thicknesses of chalk across Europe compared to other limestones. This has often been related to the stability of the low-magnesium calcite forming the coccoliths (Neugebauer, 1973, 1974; Scholle, 1974; Hancock and Scholle, 1975; Hancock, 1975a).

In England, there are both regional (Bloomfield *et al.,* 1995) and stratigraphical differences in hardness, density, porosity and strength (Mortimore *et al.,* 1990; Mortimore and Pomerol, 1998). In areas of generally hard chalk (Northern Ireland, the Northern Province and, in the Southern Province, parts of Dorset and the Isle of Wight), stylolites have developed as a result of pressure-solution.

Flints and trace fossil stratigraphy

One of the most conspicuous features of pure, white European chalks is the rhythmic layering of black flint (Figure 1.1). In contrast to chalk, flint is a very hard, brittle, siliceous material, formed in bands in the more carbonate-rich chalks. Bromley (1967) dissolved large blocks of chalk with flint in acid and found he was left with a branching network similar to the structure of modern crustacean (thalassinid) burrow systems in some shallow marine carbonates. Subsequently he illustrated the variety of animal burrowing, boring and feeding trace activity in the Chalk seabed that was preserved in flint. Submicroscopic studies of flint show that it has formed by replacing chalk in every detail, at a sufficiently early stage to preserve original, undeformed textures, fabrics and soft tissues (Clayton, 1986; Bromley and Ekdale, 1986). As a result, trace fossils are wonderfully preserved (e.g. Bromley and Ekdale, 1984a). Many of these preservation levels are horizon-specific (Figure 1.13), providing an additional stratigraphical tool for correlation (e.g. Mortimore and Pomerol, 1991b). Silicification of trace fossils produces many distinctive styles of flint including paramoudra (Bromley *et al.,* 1975) (Figure 1.14), *Zoophycos,* sheet-flint and the common thalassinid horn-flints (Figure 2.35), (Figure 2.36), (Figure 2.37), (Figure 2.38), (Figure 2.39), Chapter 2).

Flint styles are regionally, as well as stratigraphically, distributed, Northern Province flints presenting a quite different grey colour and form (with many tabular layers), compared to those of the Southern Province.

Greensands, chert beds and limestones

Transgression of the Upper Cretaceous sea onto the shelf areas of south-west England, East Anglia, Northern Ireland and the Inner Hebrides produced shallow-water deposits of glauconite-rich greensands, glauconitic marls, quartz sands and chert beds. In south-west England, instead of chalks, the Cenomanian strata are characterized by highly condensed successions, with limestones rich in ammonites (e.g. Hancock, 1969).

Upper Cretaceous stratigraphical framework

The last major review of the Upper Cretaceous stratigraphy in the UK was by Jukes-Browne and Hill (1903, 1904), and this classic memoir has now stood as a monument to geological research for nearly 100 years. Following this memoir, which established the Lower, Middle and Upper Chalk as the three main lithostratigraphical divisions throughout England, Chalk stratigraphical studies were largely biostratigraphical and the traditional macrofossil assemblage zones (Table 1.1) became the main reference for most researchers. Surprisingly, it was not until Hancock (1959) applied the international standard ammonite zones for the Cenomanian Stage from the Le Mans area of France that researchers began to look seriously at a zonation based on an international scheme. Subsequently, the International Stratigraphic Commissions have come into being and the Subcommission on Cretaceous Stratigraphy has defined the criteria for recognizing the stages of the Upper Cretaceous Series (Birkelund *et al.,* 1984; Rawson *et al.,* 1996; see also Appendix, this volume). The research to define these stages and their subdivisions is continuing, and the UK successions are critically important to this investigation.

For the purposes of the present review the Upper Cretaceous deposits of the UK are described in four chapters that correspond to the main depositional and preservational regions, i.e. to the provinces (Figure 1.6) and (Figure 1.7). The western margins of the outcrop in south-east Devon, Wessex, the Western Isles and north-west Highlands and Northern

Ireland are areas of shelving and condensation of sediments. The Anglo-Brabant Massif (Figure 1.8) also acted as a positive area where thin sediments and intra-Upper Cretaceous submarine channels were active. The condensed sediments in the shelf areas often contain a rich diversity of fossil remains and so, historically, exposures in these areas have attracted the most attention. The more basinal areas of south-east England contain more complete, thicker successions and are the sites of lithostratigraphical — and even some potential stage or substage basal boundary — stratotypes. The Upper Cretaceous GCR sites reflect these variations, with each site being linked to other locally important exposures to further illustrate the stratigraphy and sedimentology.

Upper Cretaceous lithostratigraphy in the British Isles

For nearly a century following Penning and Jukes-Browne (1881) and Jukes-Browne and Hill (1903, 1904), lithostratigraphy consisted of a simple threefold division of the Upper Cretaceous Chalk into Lower, Middle and Upper divisions, which, because they were the mapping units, were effectively three formations. Subdivision of these lithostratigraphical units employed biostratigraphy, mostly the macrofossil assemblage zones of Hebert (1874) and Barrois (1876), as modified and interpreted by Rowe (1900–1908), Brydone (1912) and Gaster (1924).

In the 1970s three areas were investigated quite independently and new lithostratigraphical divisions were recognized. The Geological Survey of Northern Ireland introduced a refined lithostratigraphy for the Ulster White Limestone Formation, which was divided into 14 members spanning the Santonian, Campanian and Maastrichtian stages (Fletcher, 1977). Within these members numerous lithostratigraphical marker beds were also recognized. In the Northern Province of England (Lincolnshire and Yorkshire), Wood and Smith (1978) found they could map four formations, with a fifth recognized in the subcrop (Figure 1.15), (Figure 1.16), and (Figure 5.3), Chapter 5). As in Northern Ireland, numerous marker beds of flint, marl and fossil-rich bands have been formally recognized.

The Southern Province Upper Cretaceous sediments, predominantly chalk, are more varied than those in the Northern Province, and a new lithostratigraphy took longer to develop (Mortimore, 1983, 1986a; Robinson, 1986). As mapping progressed in central Dorset, the relationship between lithostratigraphy, geomorphology and field brash enabled the British Geological Survey to establish a refined mapping stratigraphy. The informal Lower, Middle and Upper Chalk subdivisions were redefined as formations (Bristow *et al.,* 1997), and divided into nine mappable members. These members are based largely on the stratigraphy already established in Sussex (Mortimore, 1983, 1986a).

In November 1999 the UK Stratigraphic Commission of the Geological Society of London and the British Geological Survey agreed that the Upper Cretaceous Chalk Group in England would be divided into two subgroups within which the main mapping units would be formations (Rawson *et al.,* 2001). The Grey Chalk Subgroup is taken from the base of the Glauconitic Marl to the base of the Plenus Marls Member. The remaining Chalk from the base of the Plenus Marls to the top of the Chalk is placed in the White Chalk Subgroup. In the Northern Province the Grey Chalk Subgroup contains one formation only (Ferriby Chalk Formation). In the Southern and Transitional provinces the Grey Chalk Subgroup contains two formations (the West Melbury Marly Chalk Formation at the base and the overlying Zig Zag Chalk Formation). In south-west England the Grey Chalk Subgroup is represented by the highly condensed Wilmington Sands and the Cenomanian Limestone.

The White Chalk Subgroup has its base at the erosion surface beneath the Plenus Marls Member in the Southern and Transitional provinces, and beneath the variegated beds forming the 'Black Band' of the Northern Province. Within the condensed succession of south-east Devon this erosion surface lies at the base of Bed C (in most places) of the so-called 'Cenomanian Limestone'. The White Chalk Subgroup is divided into three Chalk formations in the Northern Province; the Welton Chalk, Burnham Chalk and Flamborough Chalk formations, with a fourth, the Rowe Formation, in the subcrop. In the Southern Province the succession extends well above that of the Northern Province and there are seven mapping formations; but here two of the four members are also mapped (Figure 1.15), (Figure 1.16) and (Table 1.1).

The use of formation status for the main mapping units allows greater flexibility in recognizing lateral changes in lithology. Where, for example, entry of flint along the south western margin occurs in the New Pit Chalk Formation, this can be recognized as a member subdivision (e.g. Beer Roads Member, Jarvis and Woodroof, 1984).

Cyclostratigraphy, episodic events and chemostratigraphy

In the Chalk, recognition of a background alternation of more and less calcareous layers ((Figure 2.2), Chapter 2) has been used to establish a cyclostratigraphy for parts of the Cenomanian and Turonian successions (Gale, 1990a, 1995, 1996). The cycles have been analysed using oxygen ($^{18}O/^{16}O$) stable isotope data of the carbonates to calculate an inferred seawater palaeotemperature difference of 4°C between the marl (cooler)-limestone (warmer) alternations at Folkestone (Folkestone to Kingsdown GCR site) and Southerham Grey Pit, southern England (Ditchfield and Marshall, 1989). Using absolute dating, it has been shown (Gale, 1989; Gale *et al.,* 1999) that the marl-limestone couplets of the Cenomanian succession reflect orbital forcing of sedimentation related to the precession cycle of the Milankovitch Band. Gale (1995) has developed a cyclostratigraphy for the Cenomanian succession based on Milankovitch cycles.

Volcanic ash beds (tuft), interbedded with marine sediments rich in fossil ammonites and inoceramid bivalves in the Western Interior Basin of North America, have been dated and provide the most reliable timescale for the Late Cretaceous Epoch (Obradovitch, 1993). Volcanic events are episodic rather than cyclic. The fossil assemblages, which are time-constrained by these episodic events, particularly the inoceramid bivalve assemblages, have been correlated to the English Chalk and provide a more controlled time-framework than fossil assemblages on their own.

The Chalk also contains geochemical signals related to oceanographic pulses, climate change and volcanic events. Conspicuous variation in the curves for the stable isotopes of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$), combined with peaks of manganese (Pomerol, 1976, 1983) and iridium (Pratt *et al.,* 1991) and strontium, are used as stratigraphical marker beds.

Upper Cretaceous biostratigraphy in the British Isles

By the middle of the 19th century there was sufficient knowledge of the distribution of fossils for d'Orbigny (1847, 1850, 1852) to produce lists of typical fossils for the subdivision of the Upper Cretaceous Series into stages. D'Orbigny's stage concepts came largely from the Chalk and marginal coarse bioclastic chalks of the Paris Basin, particularly the southern margins around Le Mans (Sarthe, Cenomanian) and Touraine (Turonian). The Senonian Stage was based on the Chalk around Sens in the Yonne and the uppermost stage, the Maastrichtian, originally distinguished by Dumont (1849), was based on the coarse, bioclastic chalks around Maastricht in the Netherlands.

The interval corresponding to d'Orbigny's broad Senonian Stage was further subdivided by Coquand (1856, 1857, 1858) into the Coniacian, Santonian and Campanian stages based on sections around Cognac, Saintes and Charante, in the Aquitaine Basin, France. It was not until 1983 that these latter subdivisions finally replaced the 'Senonian' as the accepted, formal stages of the Upper Cretaceous Series (International Subcommission on Cretaceous Stratigraphy; Birkelund *et al.,* 1984).

Subdivision of the Upper Cretaceous stages into macrofossil assemblage zones was also formalized in the Paris Basin Chalks by Hebert (1863, 1866, 1874, 1875) and Barrois (1875). The zones recognized in the Paris Basin were extended to the Kent coast by Hebert (1874) and, later, by Barrois (1876) to all of the Chalk of England and Northern Ireland. It was these zones that became the framework for Chalk studies in the UK up until the 1970s. The earliest [British] Geological Survey memoirs followed Barrois in listing fossils by zones (e.g. Reid, 1897, 1898, 1903) and this method was continued in the memoir by Jukes-Browne and Hill (1903, 1904) on the Cretaceous Rocks of England.

Detailed studies of the zones of the Chalk in England began with Rowe (1900–1908). Later, the zones were mapped in parts of England including Hampshire (Griffith and Brydone, 1911; Brydone, 1912), Sussex (Gaster, 1924–1951), and East Anglia (Hewitt, 1924, 1935; Peake and Hancock, 1961, 1970).

Monographs on each fossil group were published during the 20th century, but it is the work on two internationally important groups, the ammonites and inoceramid bivalves, that has revolutionized global correlation in the Upper Cretaceous succession. In this respect, the work of Kennedy (e.g. Kennedy, 1971) on the ammonites is of special note. However, apart from horizons of preservation such as hardgrounds, the originally aragonite-shelled ammonites are generally rare in white chalk facies. Because of this, zonal schemes, originally worked out in central Europe, using the calcitic shells of inoceramid bivalves (e.g. Tröger, 1989) have been increasingly applied to the zonation and long-range correlation of the English Chalk.

It was Jefferies (1963), however, who began the modern approach to Chalk biostratigraphy with his detailed collecting, bed-by-bed, in the Plenus Marls of England and the Paris Basin. A further development has been the recognition in Germany of bio-event horizons, where particular species are abundant at one level, and these abundance levels have been used to construct an event stratigraphy for the Chalk (Ernst *et al.,* 1983; Wood *et al.,* 1984) that can be used for long-range correlation.

Despite the enormous research effort on biostratigraphy and palaeontology over nearly two centuries, it was only in 1984 (Birkelund *et al.,* 1984) that Upper Cretaceous stages were finally recommended. The base of the Upper Cretaceous Series is currently defined in Europe and is taken at the base of the Cenomanian Stage. The basal marker is the first appearance of the planktonic foraminifer *Rotalipora globotruncanoides* in the basal boundary stratotype section at Mont Risou in the Vocontian Basin in south-eastern France, the candidate Global boundary Stratotype Section and Point (GS SP) (Tröger and Kennedy, 1996; see Appendix, this volume). This is virtually coincident with, but slightly lower than, the entry of the ammonite *Mantelliceras mantelli,* the zonal index fossil of the basal Cenomanian ammonite Zone (Figure 2.4) and (Figure 2.8), Chapter 2). In southern England, as in many areas of northern Europe, there is a hiatus representing perhaps 1 to 2 million years of sedimentation between the Albian and Cenomanian ages. In eastern England, for example the Hunstanton Cliffs GCR site and correlative sites on the East Midlands Shelf, such as the Melton Bottom Chalk Pit GCR site, the hiatus between the Albian and Cenomanian lies between the Hunstanton Red Chalk Formation and the Paradoxica Bed at the base of the Ferriby Chalk Formation (see Mitchell, 1995a, figs 11, 12). In the expanded section at Speeton Cliff; in the Cleveland Basin (Flamborough Head GCR site), there is an apparently continuous, unbroken succession, albeit without ammonites, but with the bivalve *Aucellina,* across the boundary ((Figure 5.25), Chapter 5). In this latter section, the lowest part of the Cenomanian succession is also in Red Chalk facies.

An 'Upper Cretaceous Series' divided into six 'stages' is now recognized (Figure 1.2). Each of the six stages of d'Orbigny (1847, 1850, 1852) and Coquand (1857) is made up of substages and zones based on a wide range of fossil taxa (Figure 1.5). Since the latest review of Upper Cretaceous stages (Rawson *et al.,* 1996), new research, particularly on inoceramid bivalves, has led to modifications of the taxa used to define the basal boundaries of stages and substages (Chapter 2, and Appendix, this volume). These new data are added to the appropriate site descriptions and further discussion of the stage concepts is given in the Appendix. Formerly, the basal boundary of a stage was generally marked by the base of a fossil zone. The selection of alternative criteria is now permitted, such as a palaeomagnetic reversal, a geochemical event, a cyclostratigraphical couplet or the first or last occurrence of a fossil.

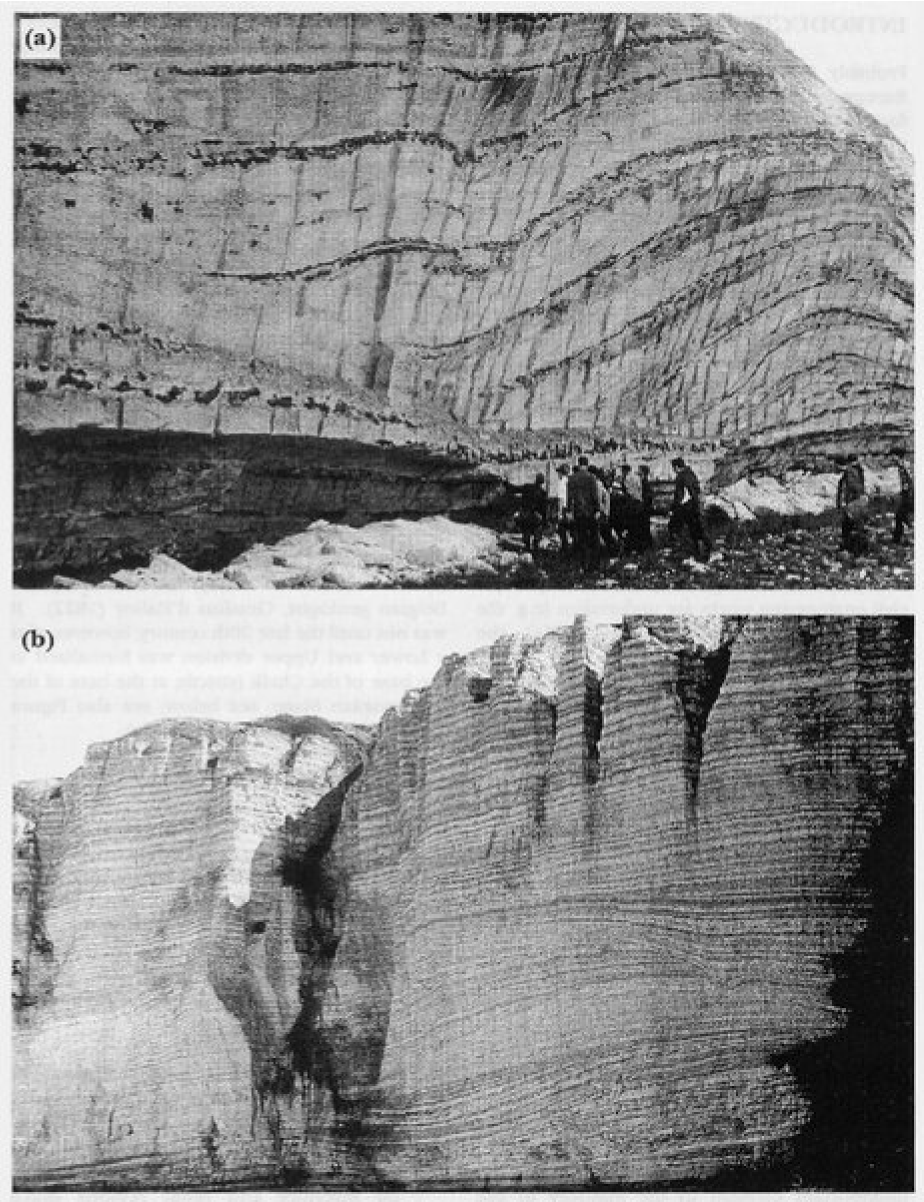
Correlation

The Chalk is unusual in that many individual beds can be correlated over great distances, for example the Upper Turonian marker marl seams that are traceable from Sussex northwards to Yorkshire, eastwards to Germany, and southwards through the Paris Basin. These marls form part of a tephro-event stratigraphy ((Figure 2.9), Chapter 2); the vulcanogenic Barton Marl 1 of the Northern Province is correlated with the Glynde Marl 1 of the Southern Province, and the Melton Ross Marl with the Southerham Marl 1 of southern England (Wray and Wood, 1998). These are inferred to correlate, respectively, with tuff T_c (Wray *et al.,* 1996) and with an as yet unclassified tuff in northern Germany (Figure 1.12). The conspicuous, black, detrital Grasby Marl of the Northern Province, which is inferred to correlate with the Mailing Street Marl of the Southern Province, probably equates with the thick M_0/MT_{EUTO} detrital marl (Wray *et al.,* 1996) of northern Germany. In contrast to the Southern Province, the thick, detrital, New Pit Marls ((Figure 2.9), Chapter 2) appear not to be developed in the north, unless one or other of them is represented by the Croxton Marl (Figure 1.12).

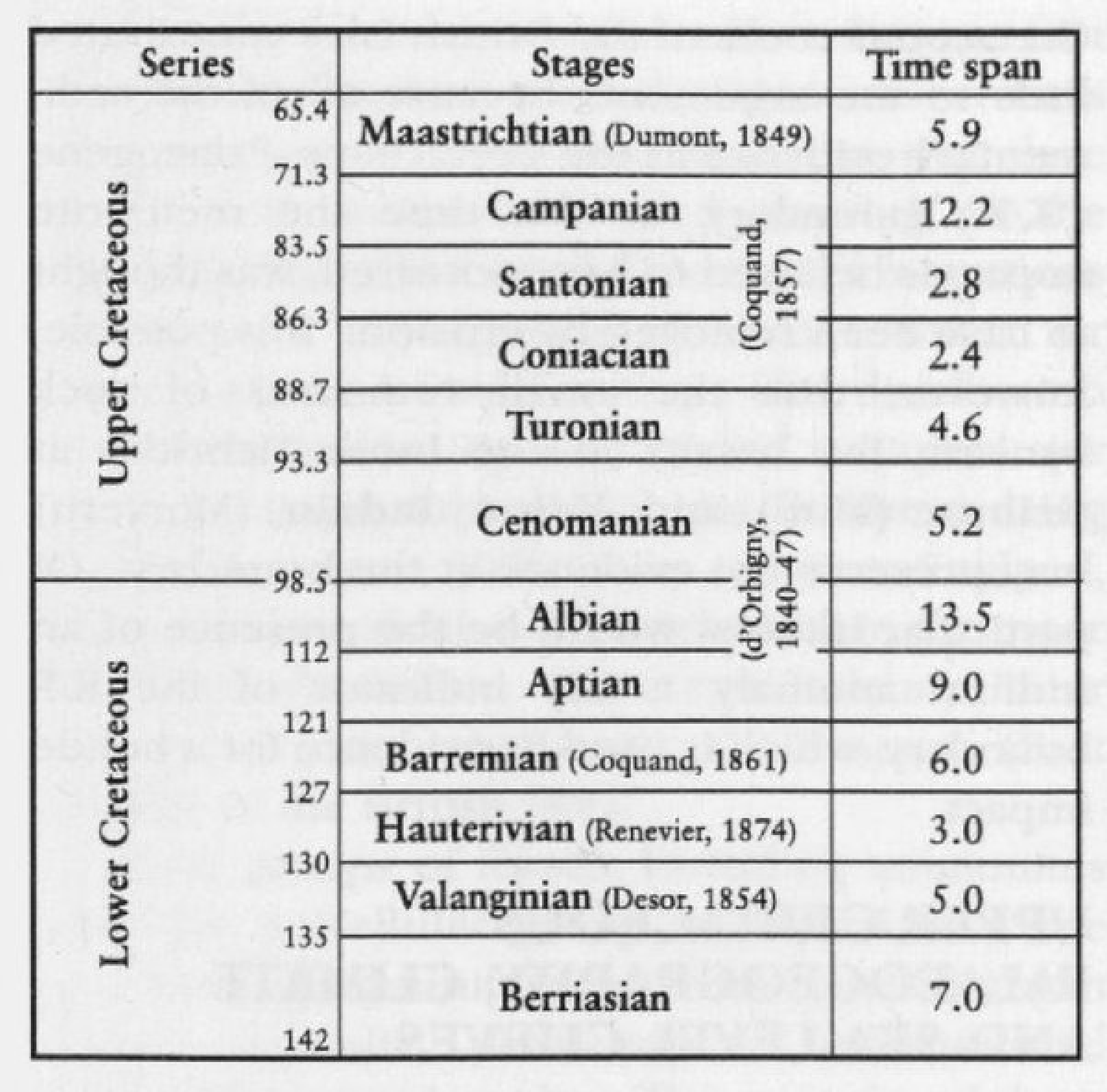
Another long-distance correlatable feature is the palaeomagnetic reversal from the long Cretaceous Quiet Zone, magnetochron 34N, to 33R ((Figure 2.3), Chapter 2) in the Lower Campanian strata beneath the Old Nore Marl (Barchi, 1995). However, Montgomery *et al.* (1998) regard this magnetic reversal as occurring lower, in the Santonian. Despite this apparent simplicity, the lateral correlations break down over major tectonic structures.

The preserved onshore Upper Cretaceous deposits of the British Isles are incomplete, generally ending in the Campanian Stage, except in Norfolk, where they end in the Lower Maastrichtian. Offshore, in the North Sea Basin, central English Channel, and Western Approaches basins the successions are more complete, different sedimentologically, and different lithostratigraphies apply (Figure 1.17). Here the Upper Cretaceous successions locally extend up to the Cretaceous–Tertiary boundary.

References

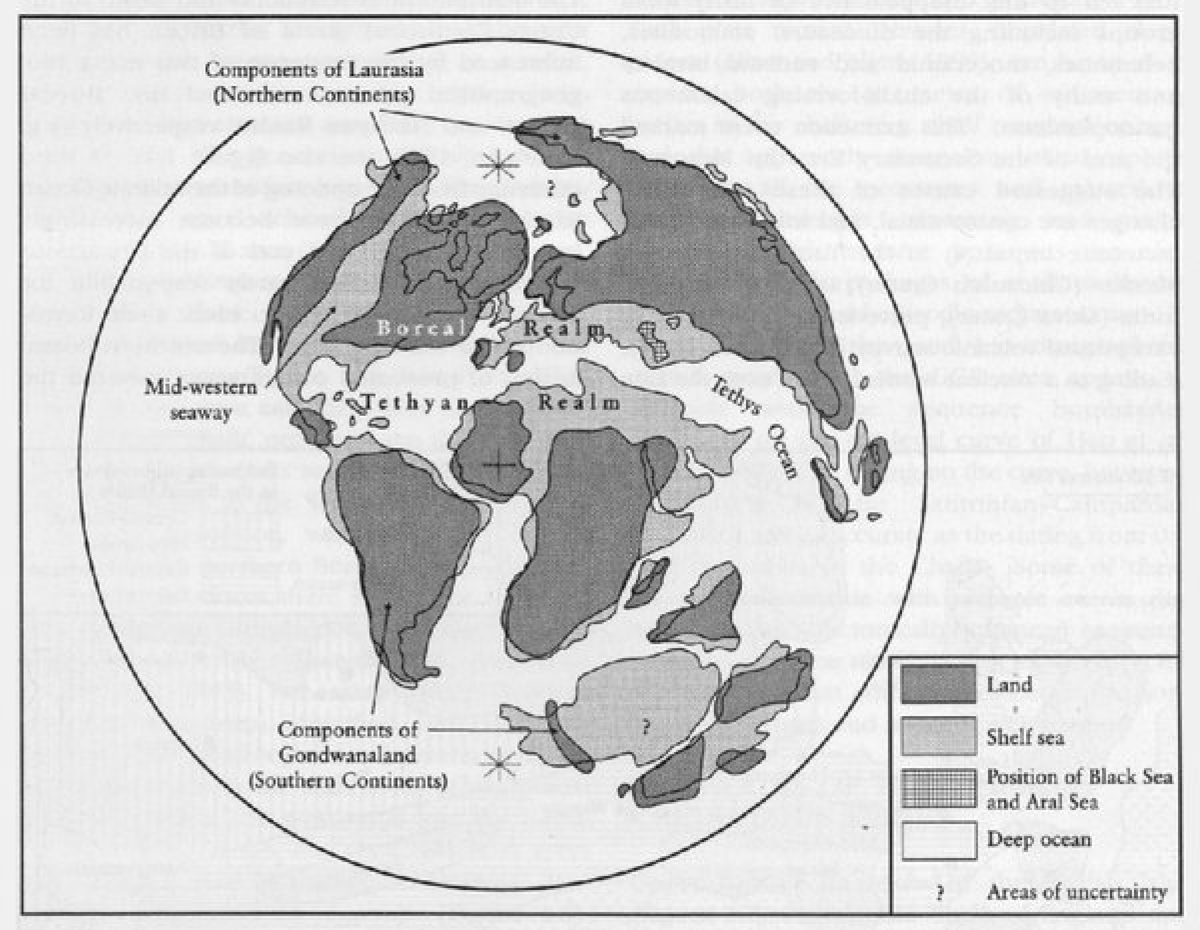


(Figure 1.1) Bedding in chalk picked out by flint bands. (a) Regular bedding in Maastrichtian chalk picked out by flint bands, overlain by irregularly bedded flint bands in the top section of the cliff (coral-bryozoan calcarenite bioherms; Danian, i.e. post-Cretaceous, in age), Stevens Mint, Denmark. (b) Irregular bedding in chalk picked out by flint bands and hardgrounds, overlain by regularly bedded flint bands in the top section of the cliff Etretat, Haute Normandie, France. (Photos: R.N. Mortimore.)

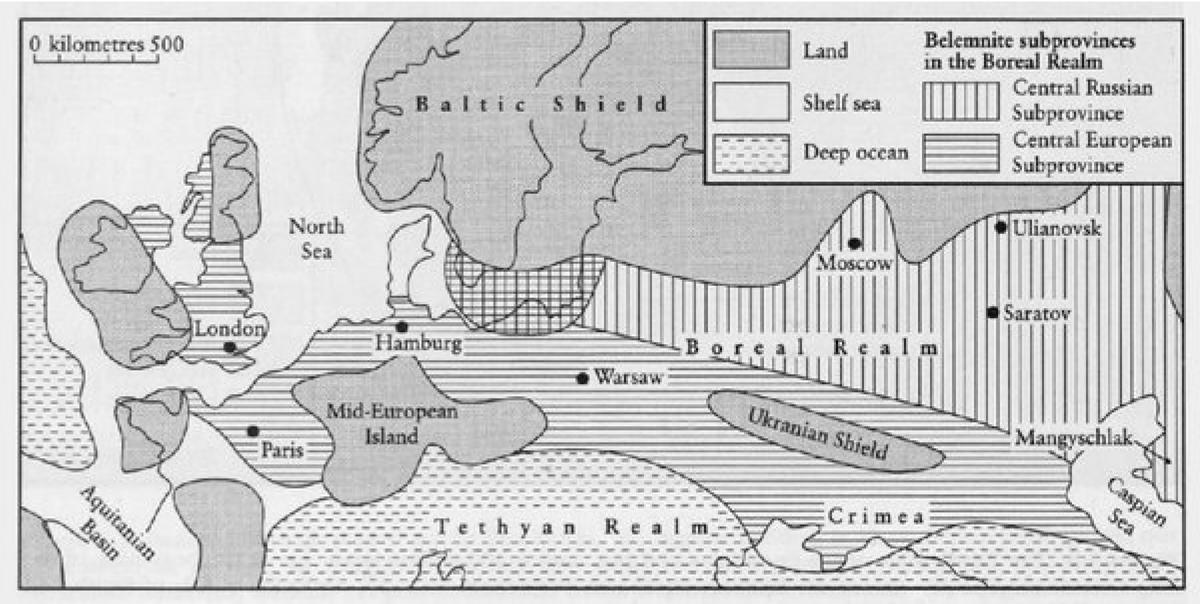


Series		Stages		Time span
Upper Cretaceous	65.4	Maastrichtian (Dumont, 1849)		5.9
	71.3	Campanian	(Coquand, 1857)	12.2
	83.5	Santonian		2.8
	86.3	Coniacian		2.4
	88.7	Turonian		4.6
	93.3	Cenomanian	(d'Orbigny, 1840–47)	5.2
Lower Cretaceous	98.5	Albian		13.5
	112	Aptian		9.0
	121	Barremian (Coquand, 1861)		6.0
	127	Hauterivian (Renevier, 1874)		3.0
	130	Valanginian (Desor, 1854)		5.0
	135	Berriasian		7.0
	142			

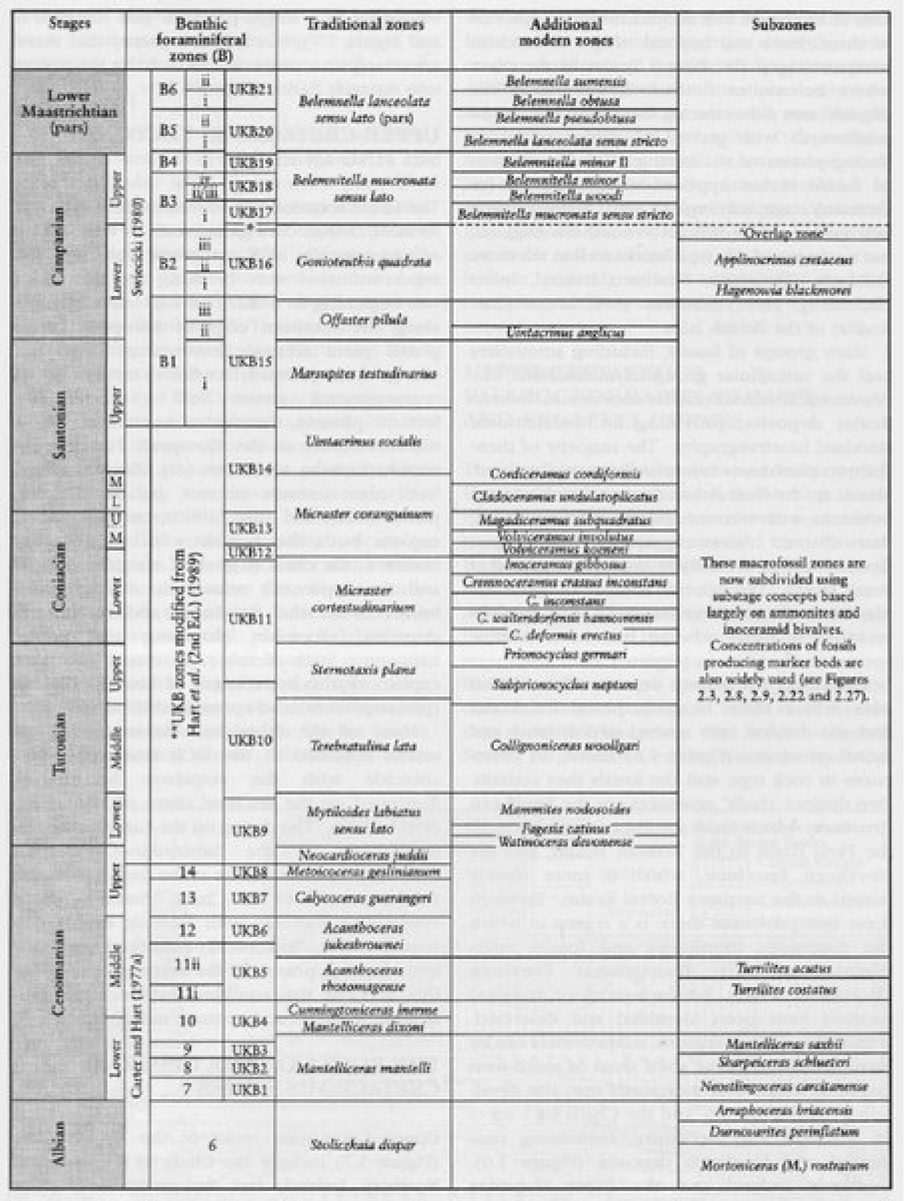
(Figure 1.2) Cretaceous (D'Halloy, 1822) series and stages (Birkelund et al., 1984). Age picks (Ma = million years) based on Obradovitch (1993) and Gradstein et al. (1999). (Dates obtained using $^{40}Ar/^{39}Ar$ laser fusion on 50–500 µg samples of sanidine from bentonites (volcanic ash/marls) interbedded with precisely dated fossiliferous marine sediments.)



(Figure 1.3) The distribution of the continents and the oceans 100 million years ago at the beginning of the Late Cretaceous Epoch. (Based on Lambert equal-area Projection, N = 43, Alpha-95 = 5.2; of Smith and Briden, 1977, p. 57, map 46.) (= Earth's axis of rotation.)*

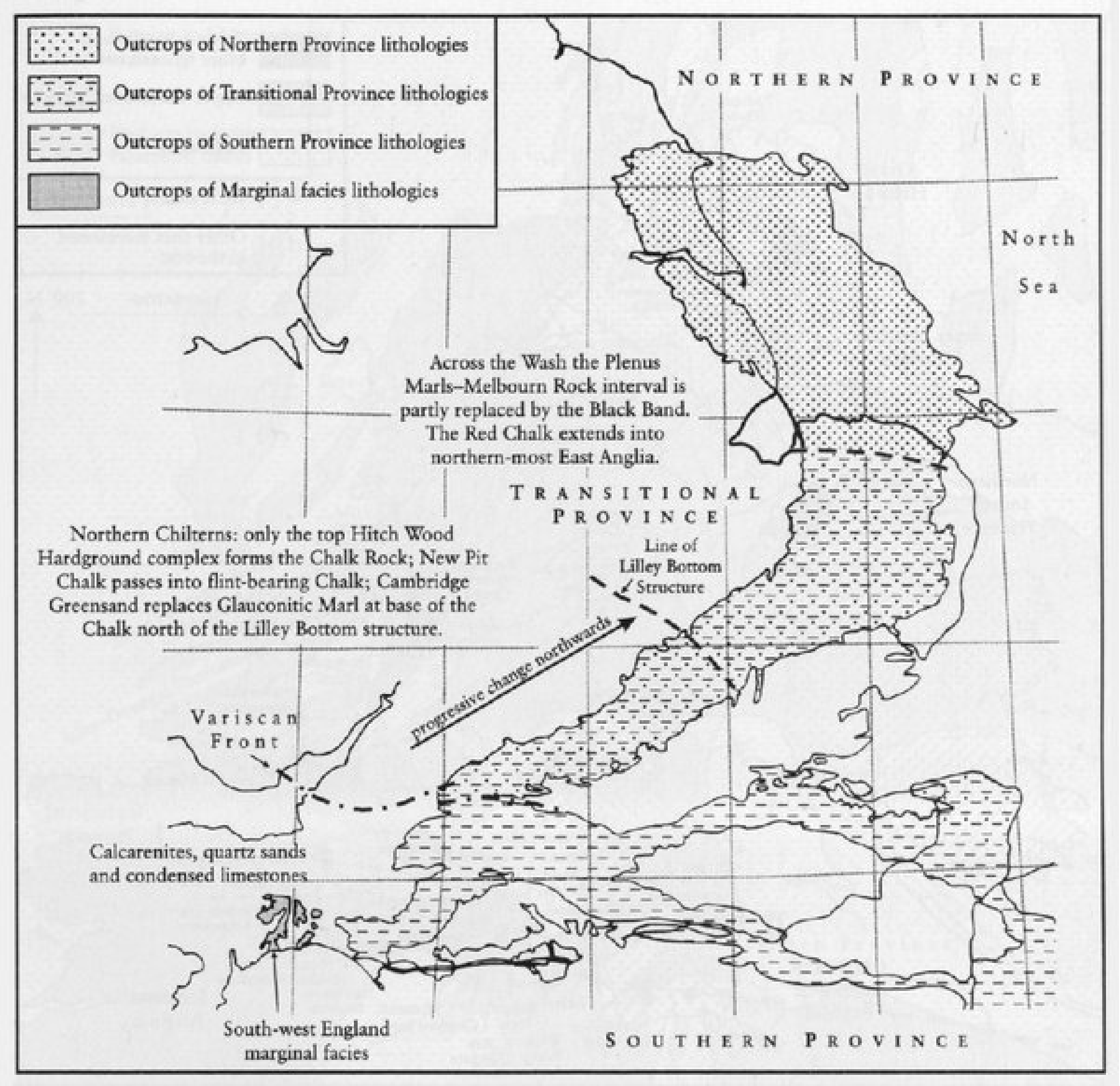


(Figure 1.4) Late Cretaceous biogeographical provinces in Europe. (After Christensen, 1984, fig. 3, p. 315.)

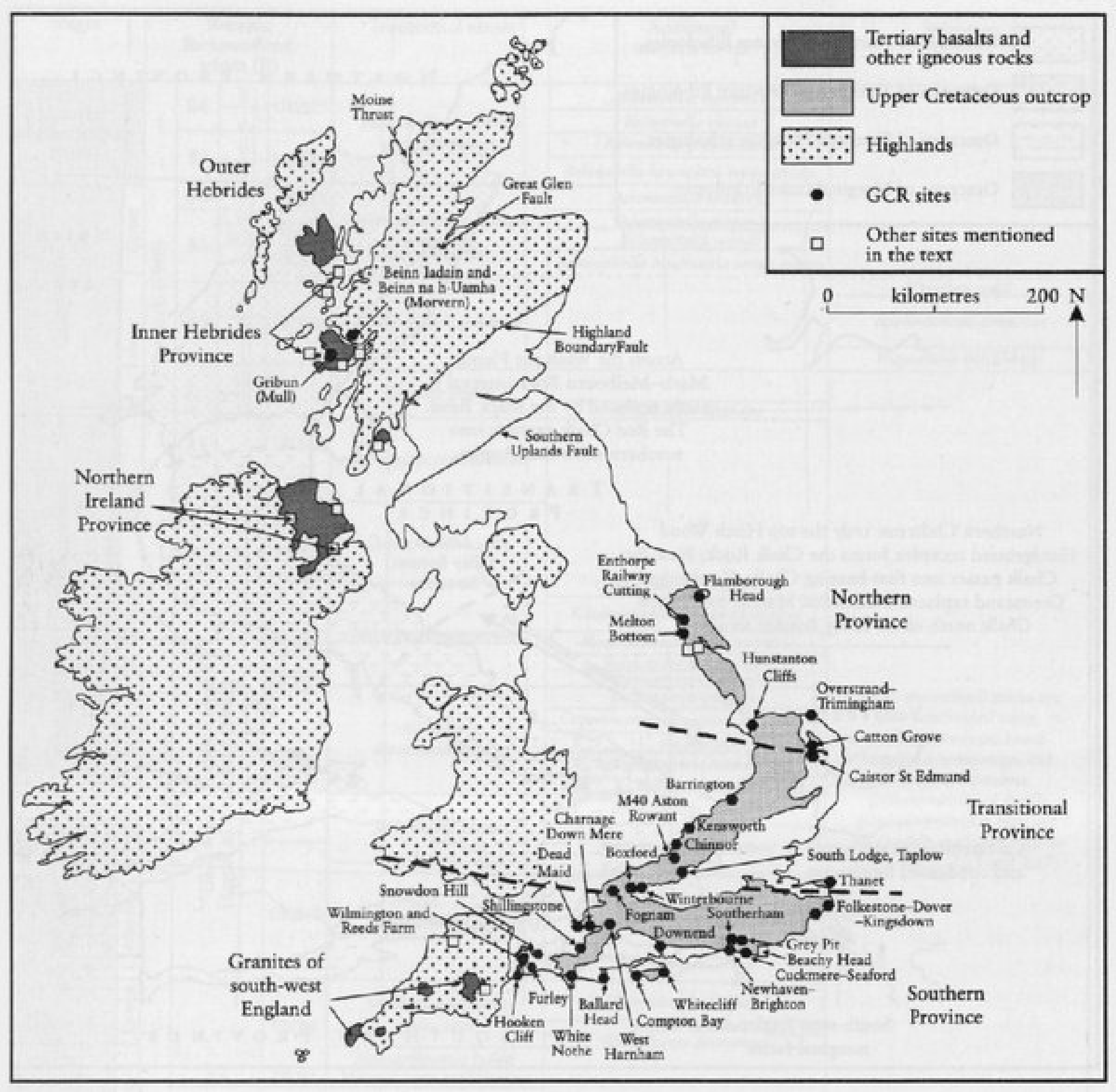


Stages		Benthic foraminiferal zones (B)				Traditional zones	Additional modern zones	Subzones
Lower Maastrichtian (pars)		Swiecicki (1980)	B6	ii	UKB21	*Belemnella lanceolata sensu lato* (pars)	*Belemnella sumensis*	
				i			*Belemnella obtusa*	
			B5	ii	UKB20		*Belemnella pseudobtusa*	
				i			*Belemnella lanceolata sensu stricto*	
Campanian	Upper		B4	i	UKB19	*Belemnitella mucronata sensu lato*	*Belemnitella minor* II	
			B3	iv	UKB18		*Belemnitella minor* I	
				ii/iii			*Belemnitella woodi*	
				i	UKB17		*Belemnitella mucronata sensu stricto*	
	Lower		B2	iii	*	*Gonioteuthis quadrata*		'Overlap zone'
				ii	UKB16			*Applinocrinus cretaceus*
				i				*Hagenowia blackmorei*
			B1	iii	UKB15	*Offaster pilula*		
				ii			*Uintacrinus anglicus*	
Santonian	Upper			i		*Marsupites testudinarius*		These macrofossil zones are now subdivided using substage concepts based largely on ammonites and inoceramid bivalves. Concentrations of fossils producing marker beds are also widely used (see Figures 2.3, 2.8, 2.9, 2.22 and 2.27).
		**UKB zones modified from Hart *et al.* (2nd Ed.) (1989)			UKB14	*Uintacrinus socialis*		
	M					*Micraster coranguinum*	*Cordiceramus cordiformis*	
	L						*Cladoceramus undulatoplicatus*	
Coniacian	U				UKB13		*Magadiceramus subquadratus*	
	M						*Volviceramus involutus*	
					UKB12		*Volviceramus koeneni*	
	Lower				UKB11	*Micraster cortestudinarium*	*Inoceramus gibbosus*	
							Cremnoceramus crassus inconstans	
							C. inconstans	
							C. waltersdorfensis hannovrensis	
							C. deformis erectus	
Turonian	Upper					*Sternotaxis plana*	*Prionocyclus germari*	
							Subprionocyclus neptuni	
	Middle				UKB10	*Terebratulina lata*	*Collignoniceras woollgari*	
	Lower				UKB9	*Mytiloides labiatus sensu lato*	*Mammites nodosoides*	
							Fagesia catinus	
							Watinoceras devonense	
Cenomanian	Upper					*Neocardioceras juddii*		
		Carter and Hart (1977a)	14		UKB8	*Metoicoceras geslinianum*		
			13		UKB7	*Calycoceras guerangeri*		
	Middle		12		UKB6	*Acanthoceras jukesbrownei*		
			11ii		UKB5	*Acanthoceras rhotomagense*		*Turrilites acutus*
			11i					*Turrilites costatus*
	Lower		10		UKB4	*Cunningtoniceras inerme*		
						Mantelliceras dixoni		
			9		UKB3	*Mantelliceras mantelli*		*Mantelliceras saxbii*
			8		UKB2			*Sharpeiceras schlueteri*
			7		UKB1			*Neostlingoceras carcitanense*
Albian			6			*Stoliczkaia dispar*		*Arrhaphoceras briacensis*
								Durnovarites perinflatum
								Mortoniceras (M.) rostratum

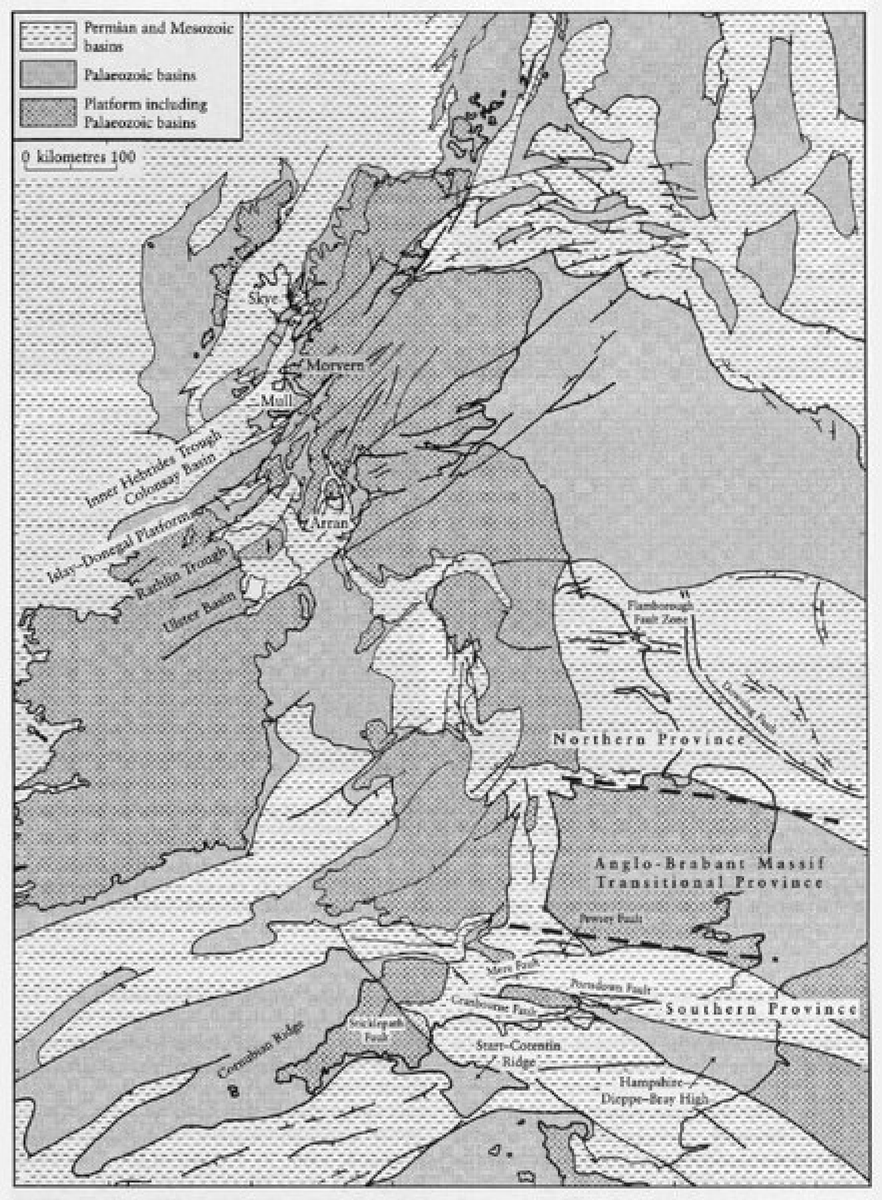
(Figure 1.5) Zones of the Upper Cretaceous Chalk. (= Gap in UKB scheme; ** = UKB zonal scheme modified for this book.)*



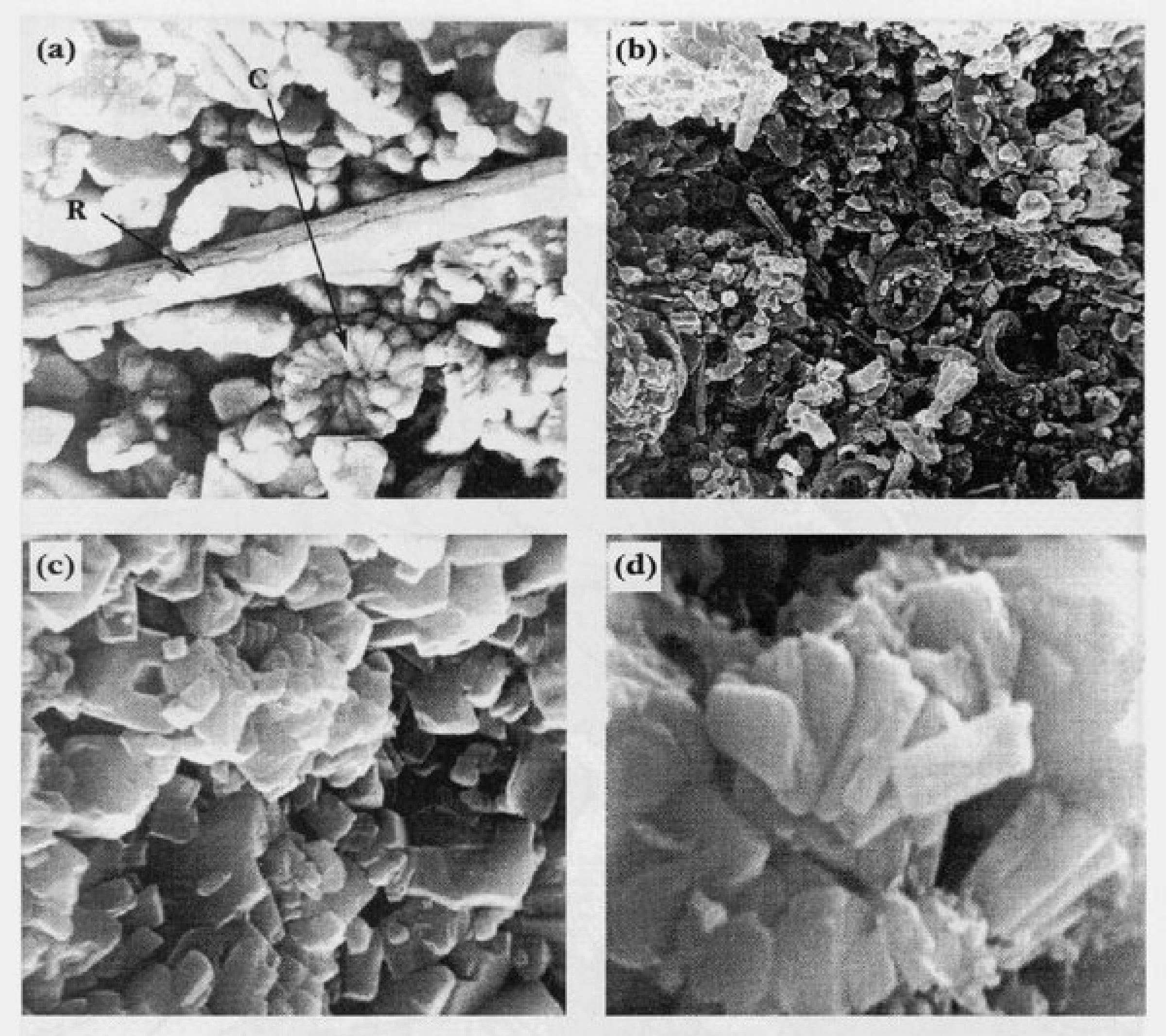
(Figure 1.6) Depositional and faunal provinces in the Chalk of England.



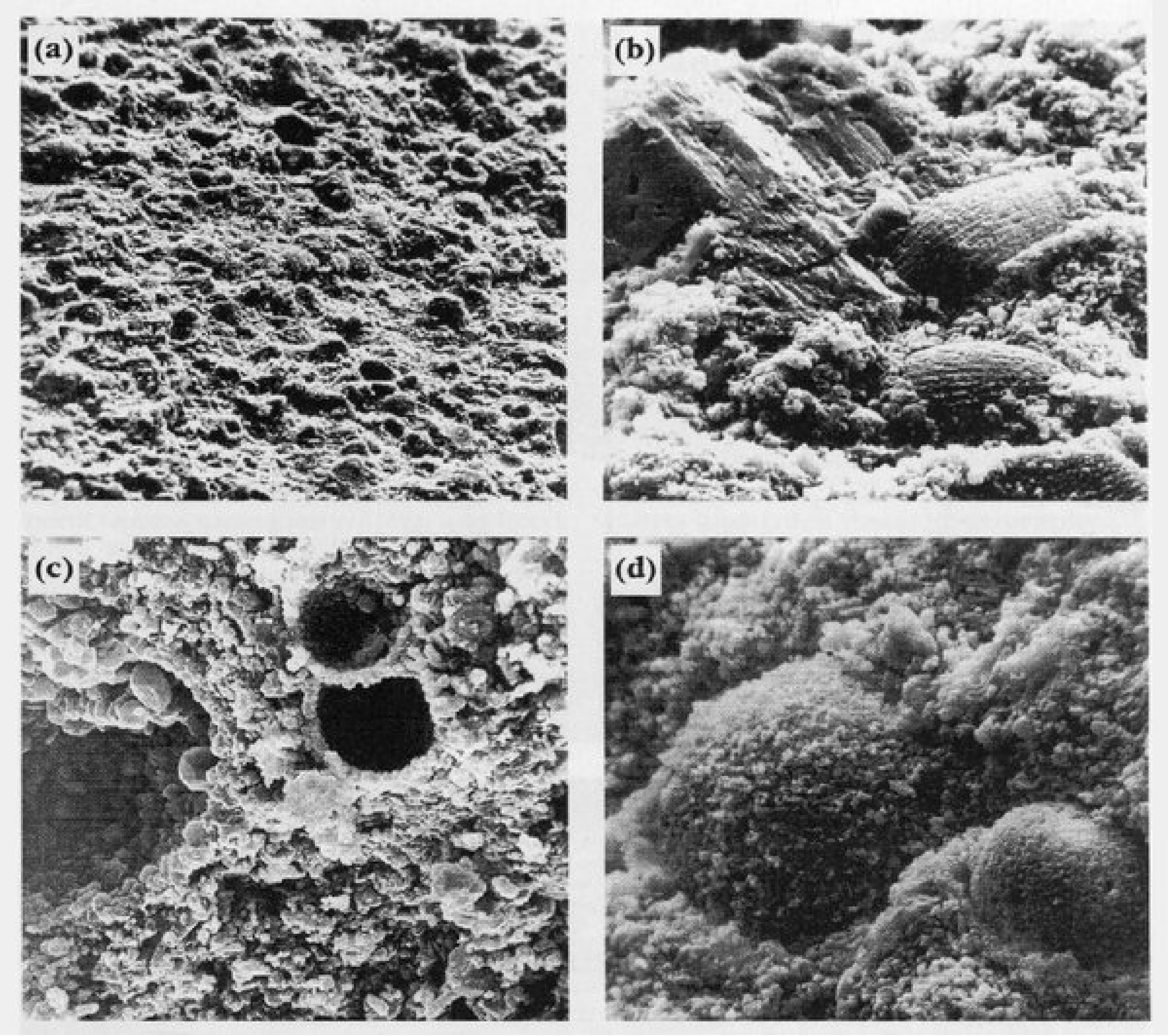
(Figure 1.7) Upper Cretaceous GCR sites in the British Isles.



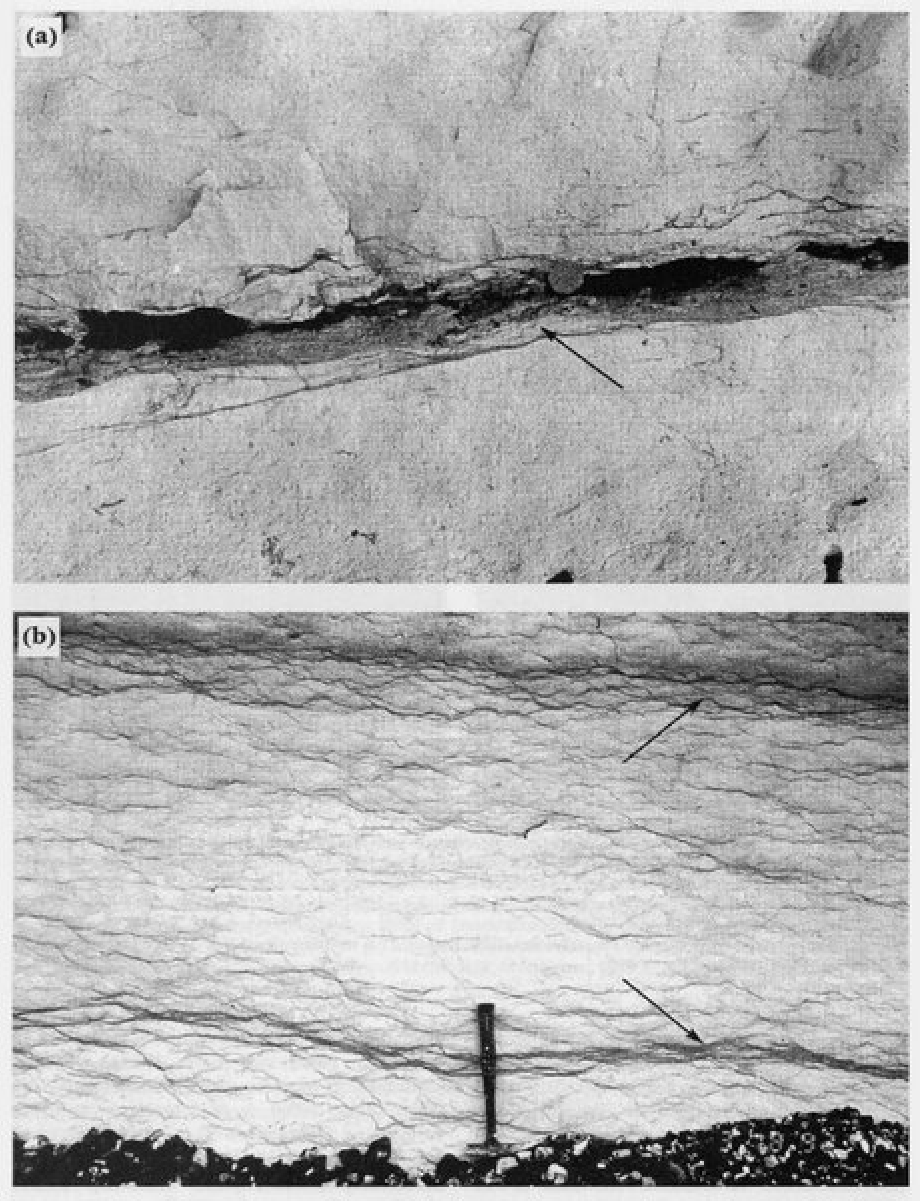
(Figure 1.8) Broad structural features affecting sedimentation of the Upper Cretaceous deposits in the British Isles. (Based on British Geological Survey 1:1 000 000 maps of the Geology of the UK, Ireland and Continental Shelf; North and South Sheets.)



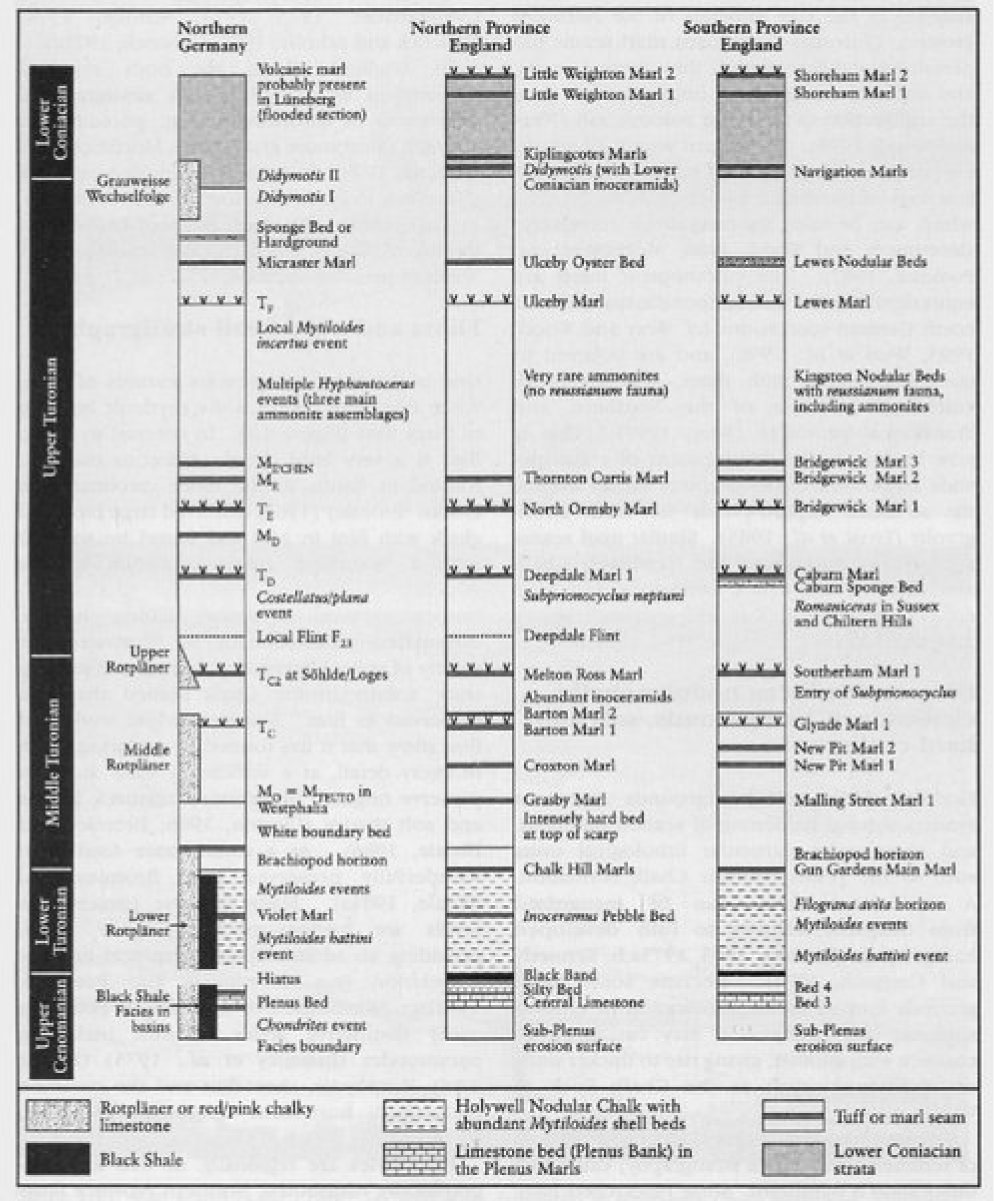
(Figure 1.9) Some common nannoliths in chalk illustrating the variety of grain shapes constituting different chalks, as seen under the Scanning Electron Microscope (SEM). (a) Rhabdoliths (R) and coccoliths (C) in the Newhaven Chalk Formation from Paulsgrove, Portsdown (magnification X 6000). (b) A soft, low density coccolithic chalk; Newhaven Chalk Formation from Arundel (BRESD9) (magnification x 2200). (c) A high density chalk from below the Brighton Marl, Seaford Head, Sussex; the blocky crystals are Micula, Newhaven Chalk Formation (magnification x 5500). (d) Nannoconus from Strahan's Hardground, Lewes, Sussex, a very high density chalk (magnification x 13 100). (Photos: R.N. Mortimore, 1979.)



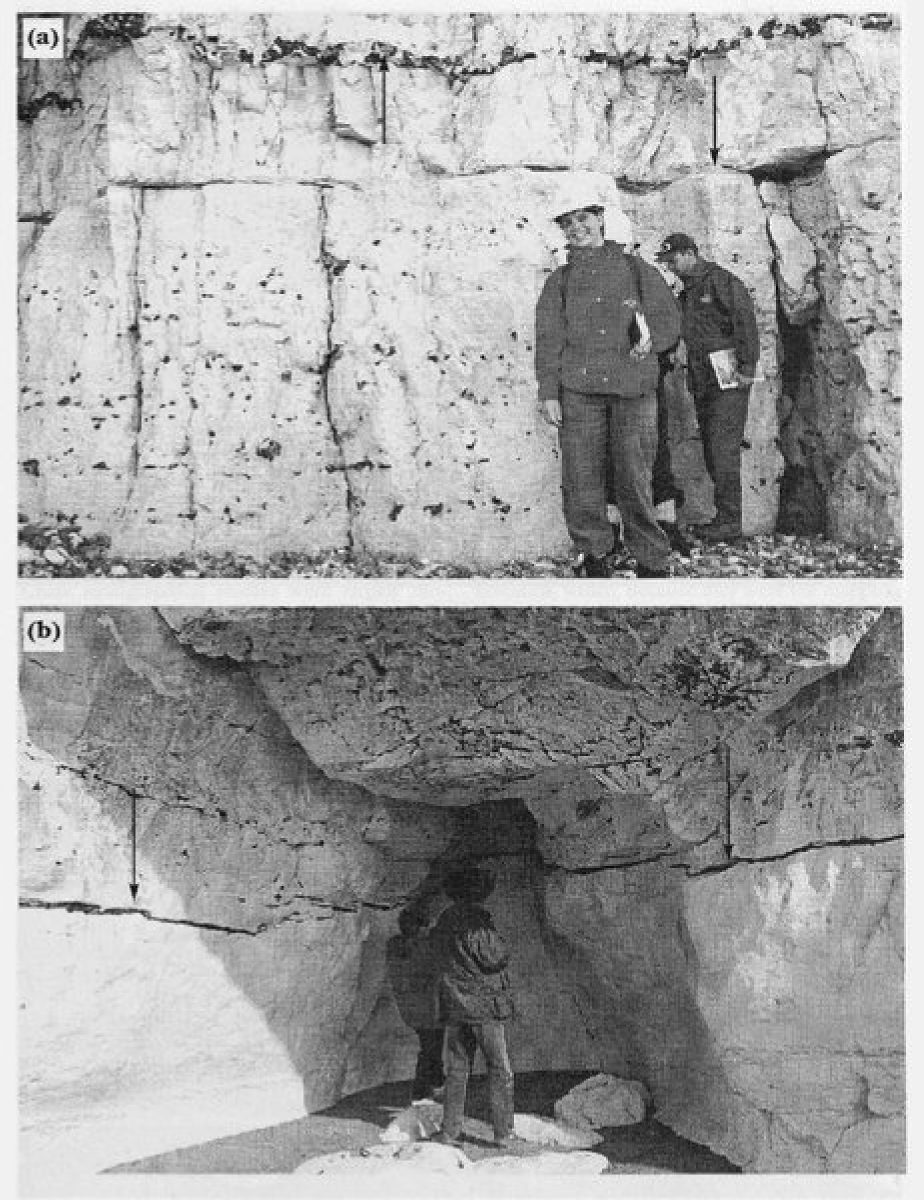
(Figure 1.10) Common components of chalk: calcispheres and foraminifera under SEM. (a) Calcisphere-rich, high density, nodular chalk (HG3) with Lewes Tubular Flints, South Portal, Lewes Tunnel (magnification x 205). (b) Oval-shaped Pithonella from a high-density hardground in the Lewes Nodular Chalk Formation, Lewes Tunnel, BH1, depth 24.2 m (magnification x 1050). (c) Foraminifera-rich (multi-chambered) coccolithic chalk, Grimes Graves Pit 15, Norfolk (magnification x 1100). (d) Calcisphaerula from a high-density nodular bed in the Lewes Chalk, Lewes Tunnel, BH1, depth 21.6 m (magnification x 1160). (Photos: R.N. Mortimore, 1979.)



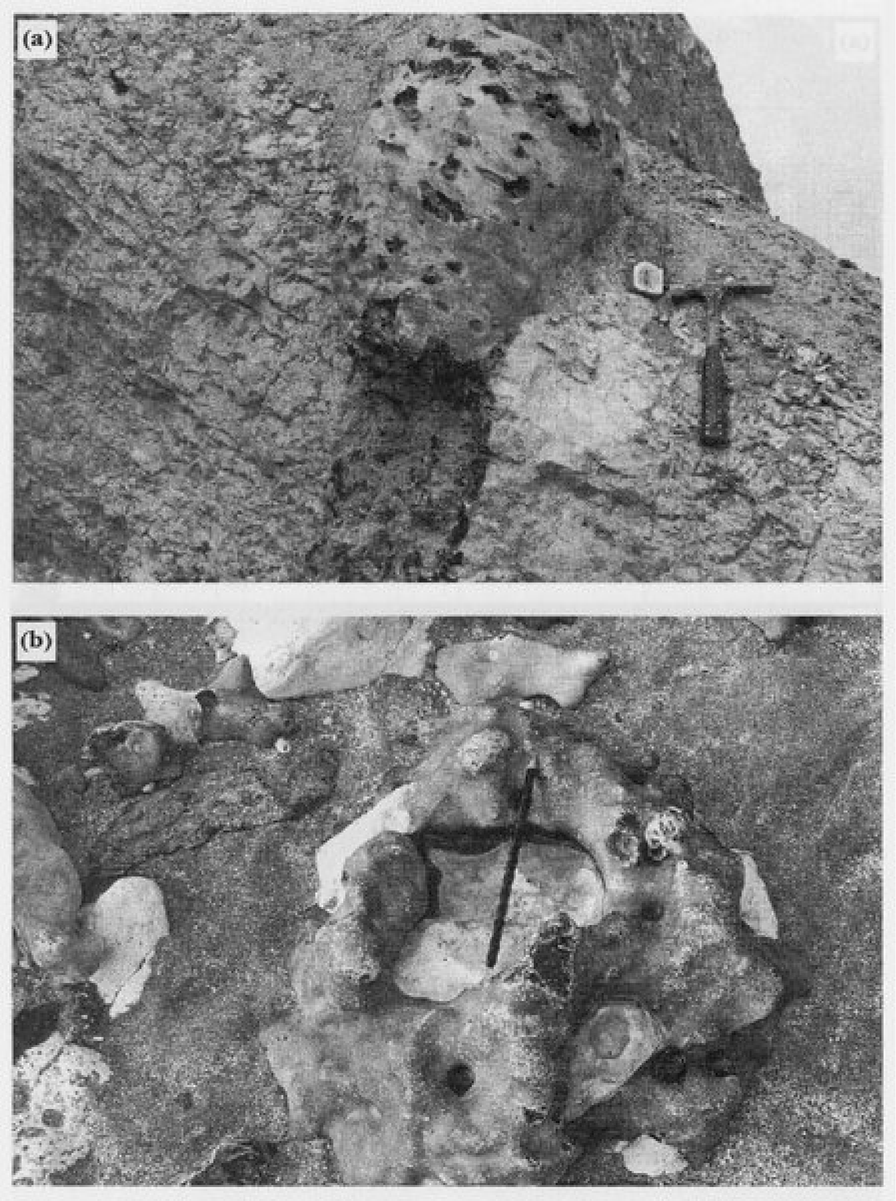
(Figure 1.11) Marl seams in the Chalk. (a) Marl seam (arrowed) in Newhaven Chalk Formation, Newhaven, Sussex, showing cavities developed on a former perched water table. The coin is about 25 mm in diameter. (b) Flaser marl seams (arrowed) forming a pair, New Pit Chalk Formation, Beachy Head, Sussex. The hammer is 130 mm long. (Photos: R.N. Mortimore.)



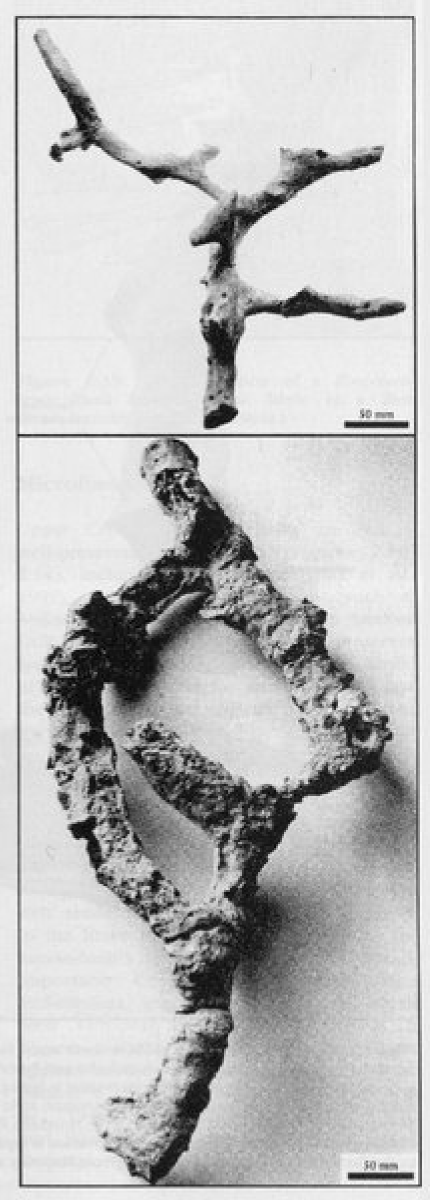
(Figure 1.12) Correlation of key marker marl seams and tephro-events in Europe.



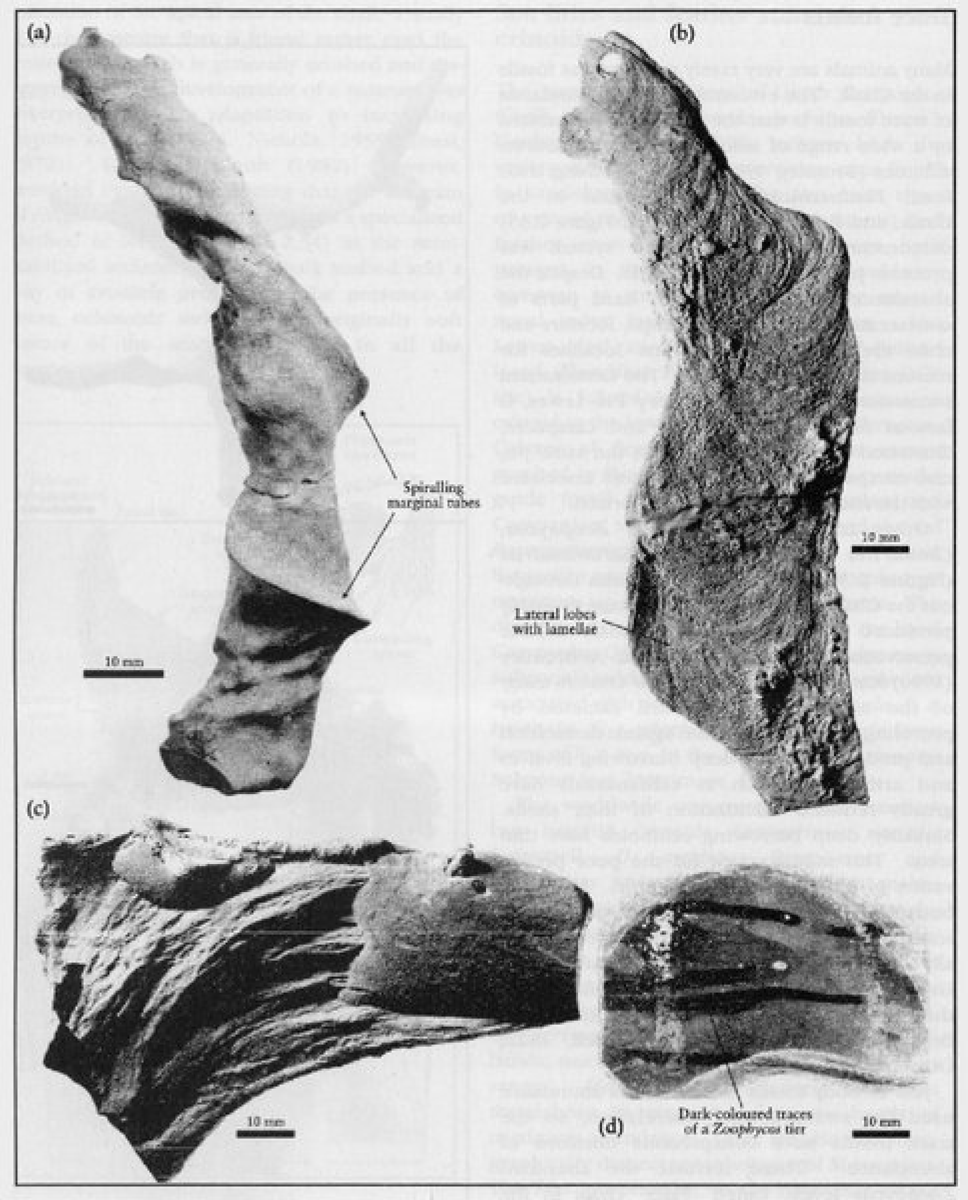
(Figure 1.13) Types of nodular and sheet-flint in chalk. (a) Semi-tabular flint bands (arrowed) above the Lewes Marl, with broad horizons of scattered nodular/tubular flints (Lewes Tubular Flints) below, beside the figures. (b) Sheet-flint forming in slip scars (arrowed), Newhaven Chalk Formation, Newhaven. (Photos: R.N. Mortimore.)



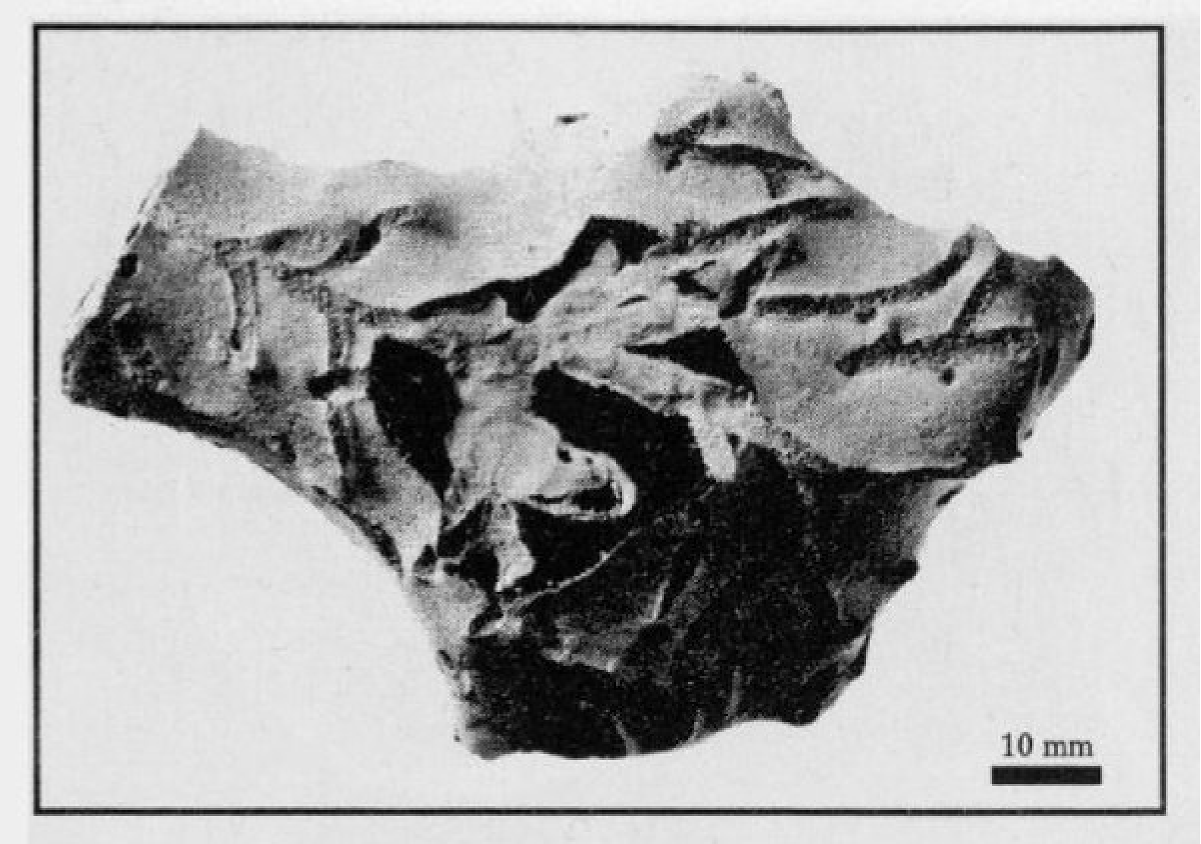
(Figure 1.14) Paramoudra flints. (a) Giant flint in the Sidestrand Western Mass, north Norfolk coast. The hammer is 320 mm long. (b) Paramoudra with internal, hardened chalk core, foreshore at Dumpton Gap, Thanet Coast, Kent. The pencil is 160 mm long. (Photos: R.N. Mortimore.)



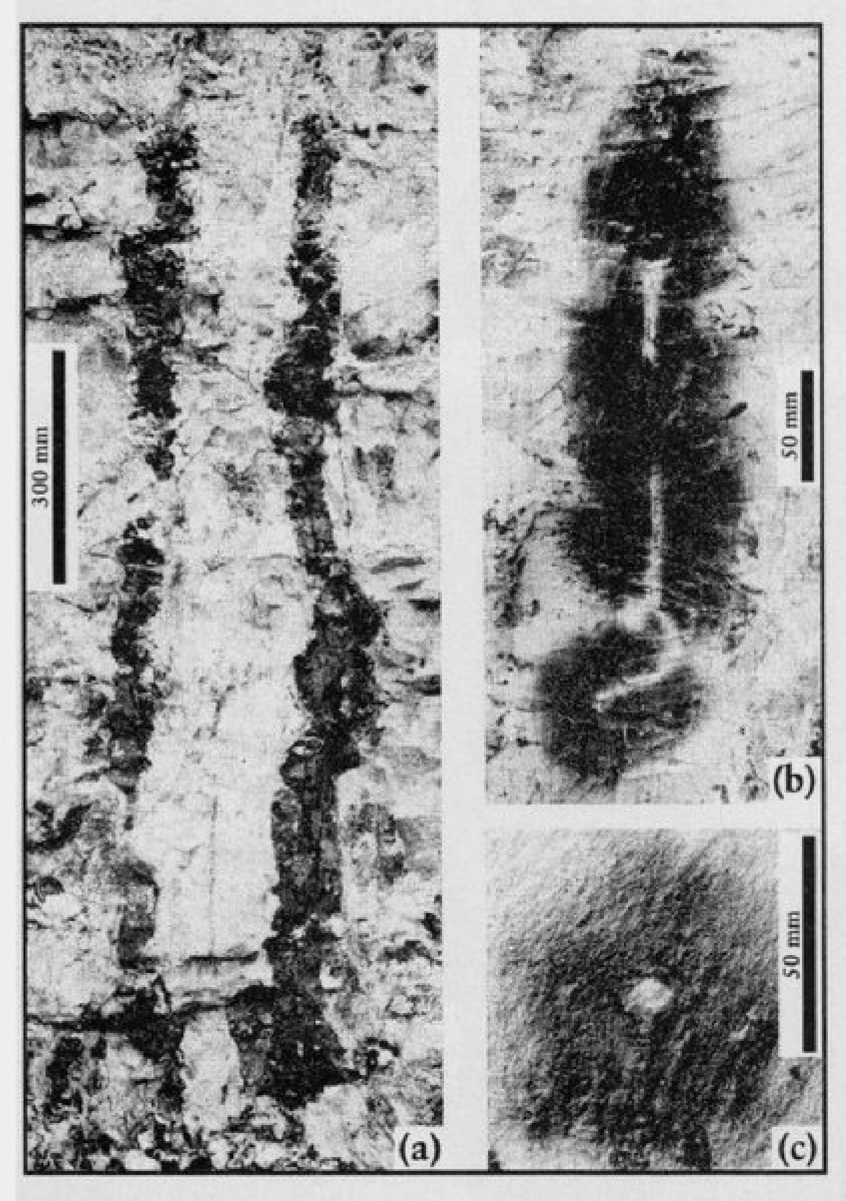
(Figure 2.35) Branching Thalassinoides burrow-replacement flints. (From Bromley and Ekdale, 1984a.)



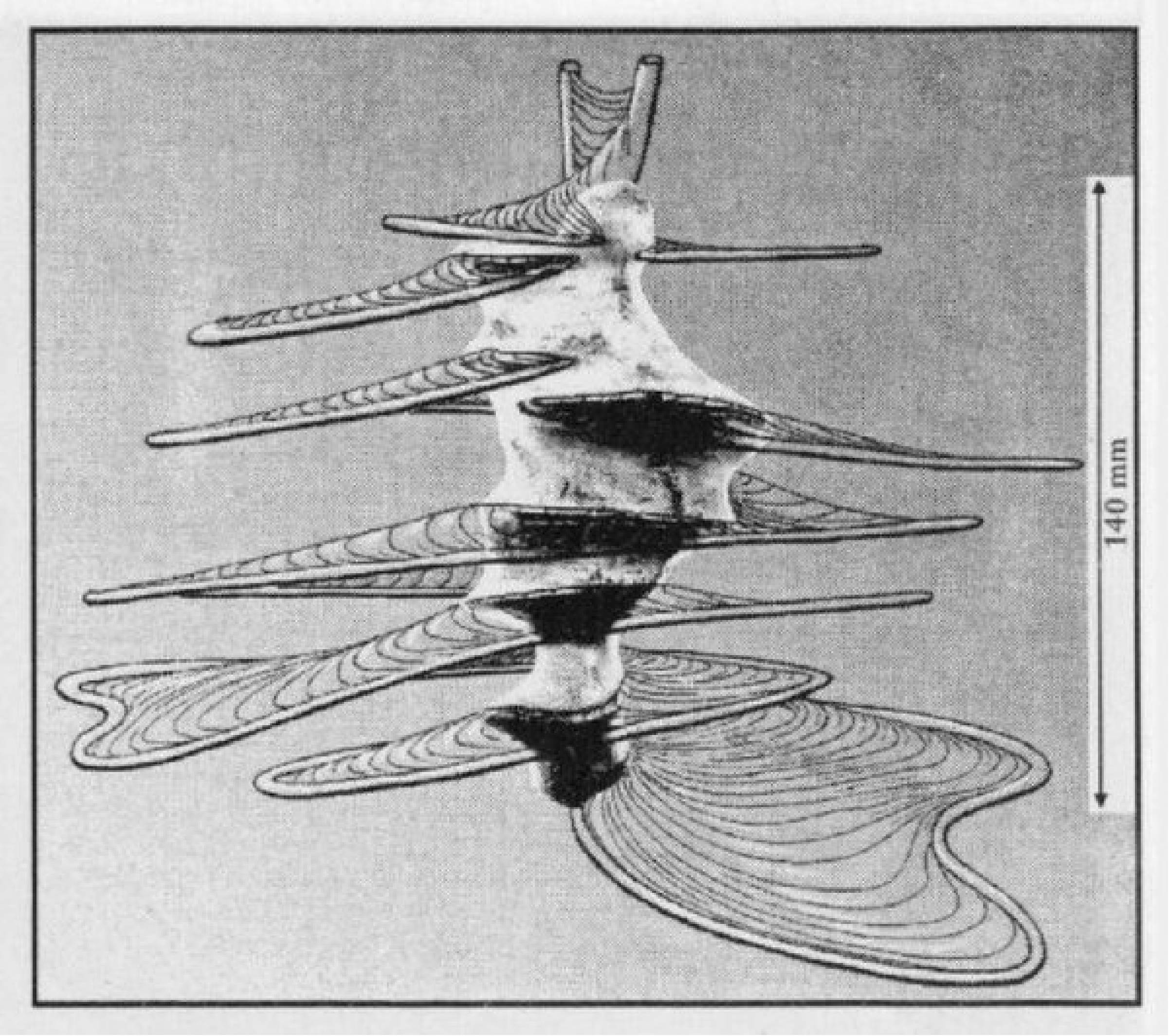
(Figure 2.36) Ecology of a soft chalk seabed: trace fossils in flint. (a) A spiral Zoophycos typical of many horizons such as the Tavern Flints, Portobello and Pricy Zoophycos. (b) Silicified lateral lobes with lamellae of a Zoophycos spreite. This type of preservation is typical of the Cuilfail and Beachy Head Zoophycos beds. (c) A lobe of a Zoophycos burrow with preservation style typical of the Asham Zoophycos at Southerham Pit, Lewes and the Sub-Plenus Zoophycos of the Northern Province. (d) Four tiers of a Zoophycos system within a Thalassinoides burrow. This style of preservation is typical of many horizons including the bands of Zoophycos in the Scottish Chalk at Gribun, Mull. (From Bromley and Ekdale, 1984a.)



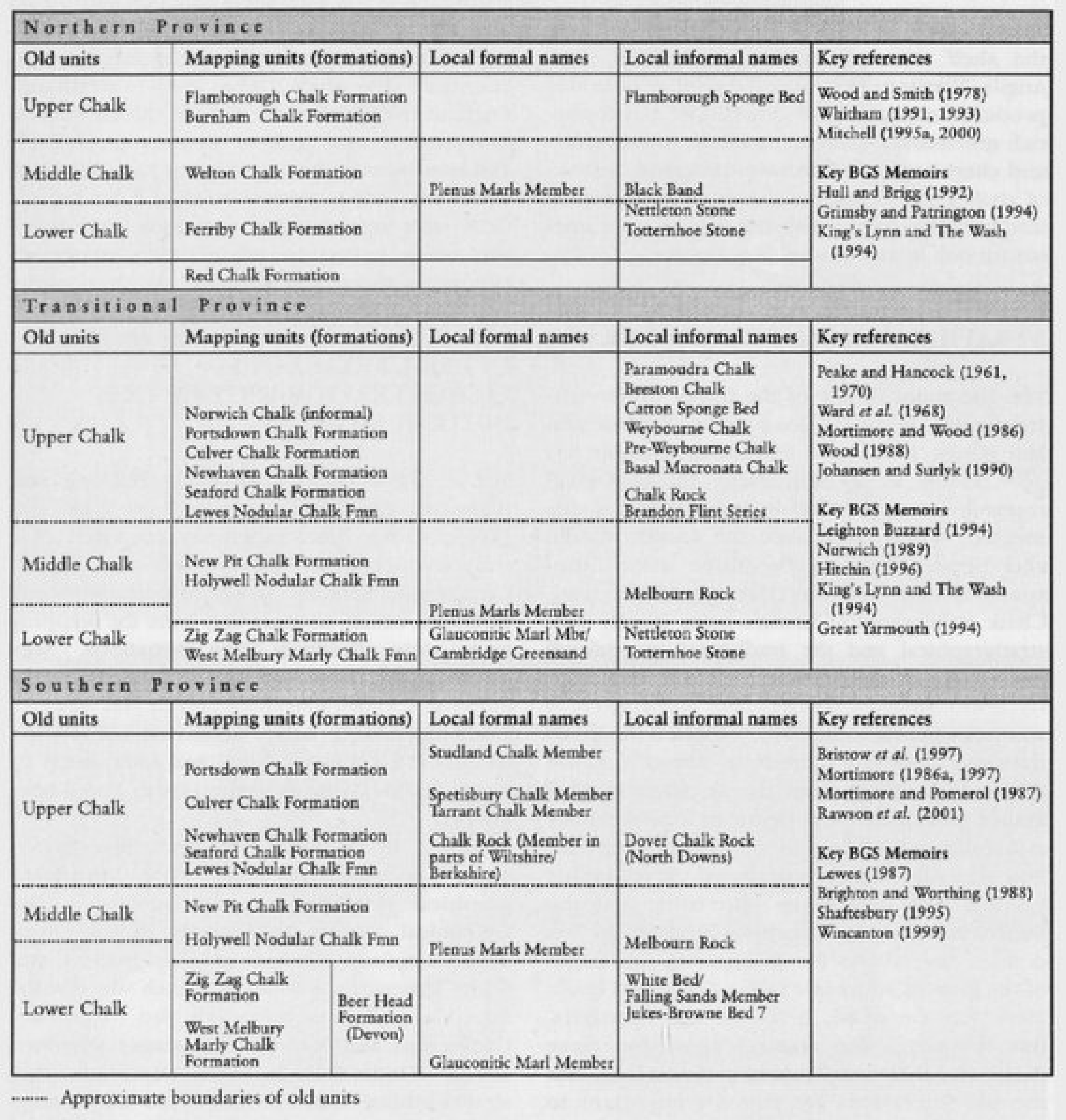
(Figure 2.37) A typical 'Chondrites' flint showing a branching Chondrites network in a Thalassinoides suevicus network. (From Bromley and Ekdale, 1984a.)



(Figure 2.38) Bathichnus paramoudrae in various forms. (a) A vertical cylinder of flint (Paramoudra) at Caistor St Edmunds Chalk Pit, Norwich. (b) Dark pyritic aureole around the trace fossil (vertical section). (c) Horizontal section of (b). (From Bromley et al., 1975.)



(Figure 2.39) Reconstruction of a Zoophycos trace fossil from a spiral fabric in a flint. (From Bromley and Ekdale, 1984a.)



Northern Province

Old units	Mapping units (formations)	Local formal names	Local informal names	Key references
Upper Chalk	Flamborough Chalk Formation Burnham Chalk Formation		Flamborough Sponge Bed	Wood and Smith (1978) Whitham (1991, 1993) Mitchell (1995a, 2000) **Key BGS Memoirs** Hull and Brigg (1992) Grimsby and Patrington (1994) King's Lynn and The Wash (1994)
Middle Chalk	Welton Chalk Formation	Plenus Marls Member	Black Band	
Lower Chalk	Ferriby Chalk Formation		Nettleton Stone Totternhoe Stone	
	Red Chalk Formation			

Transitional Province

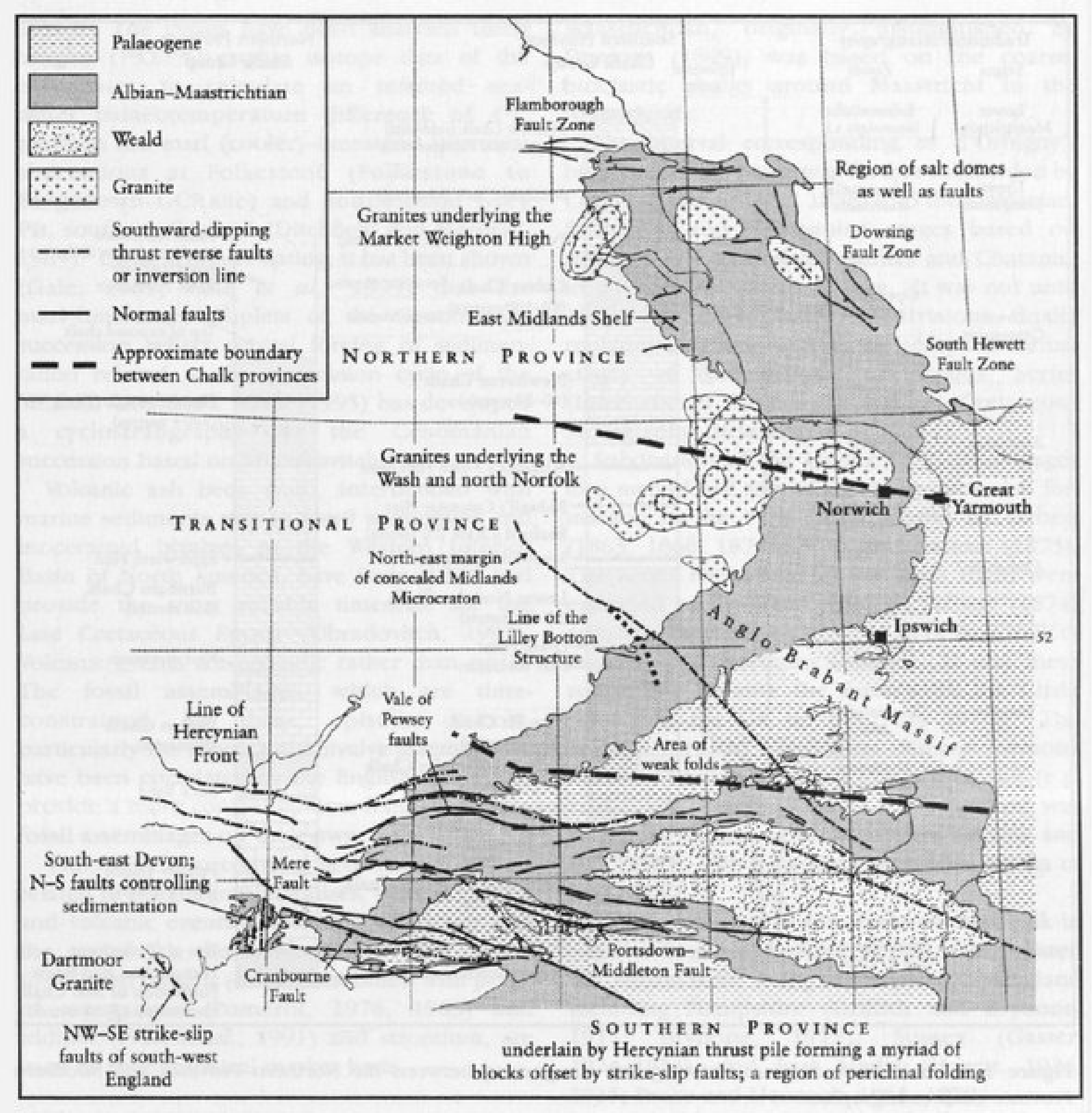
Old units	Mapping units (formations)	Local formal names	Local informal names	Key references
Upper Chalk	Norwich Chalk (informal) Portsdown Chalk Formation Culver Chalk Formation Newhaven Chalk Formation Seaford Chalk Formation Lewes Nodular Chalk Fmn		Paramoudra Chalk Beeston Chalk Catton Sponge Bed Weybourne Chalk Pre-Weybourne Chalk Basal Mucronata Chalk Chalk Rock Brandon Flint Series	Peake and Hancock (1961, 1970) Ward *et al.* (1968) Mortimore and Wood (1986) Wood (1988) Johansen and Surlyk (1990) **Key BGS Memoirs** Leighton Buzzard (1994) Norwich (1989) Hitchin (1996) King's Lynn and The Wash (1994) Great Yarmouth (1994)
Middle Chalk	New Pit Chalk Formation Holywell Nodular Chalk Fmn	Plenus Marls Member	Melbourn Rock	
Lower Chalk	Zig Zag Chalk Formation West Melbury Marly Chalk Fmn	Glauconitic Marl Mbr/ Cambridge Greensand	Nettleton Stone Totternhoe Stone	

Southern Province

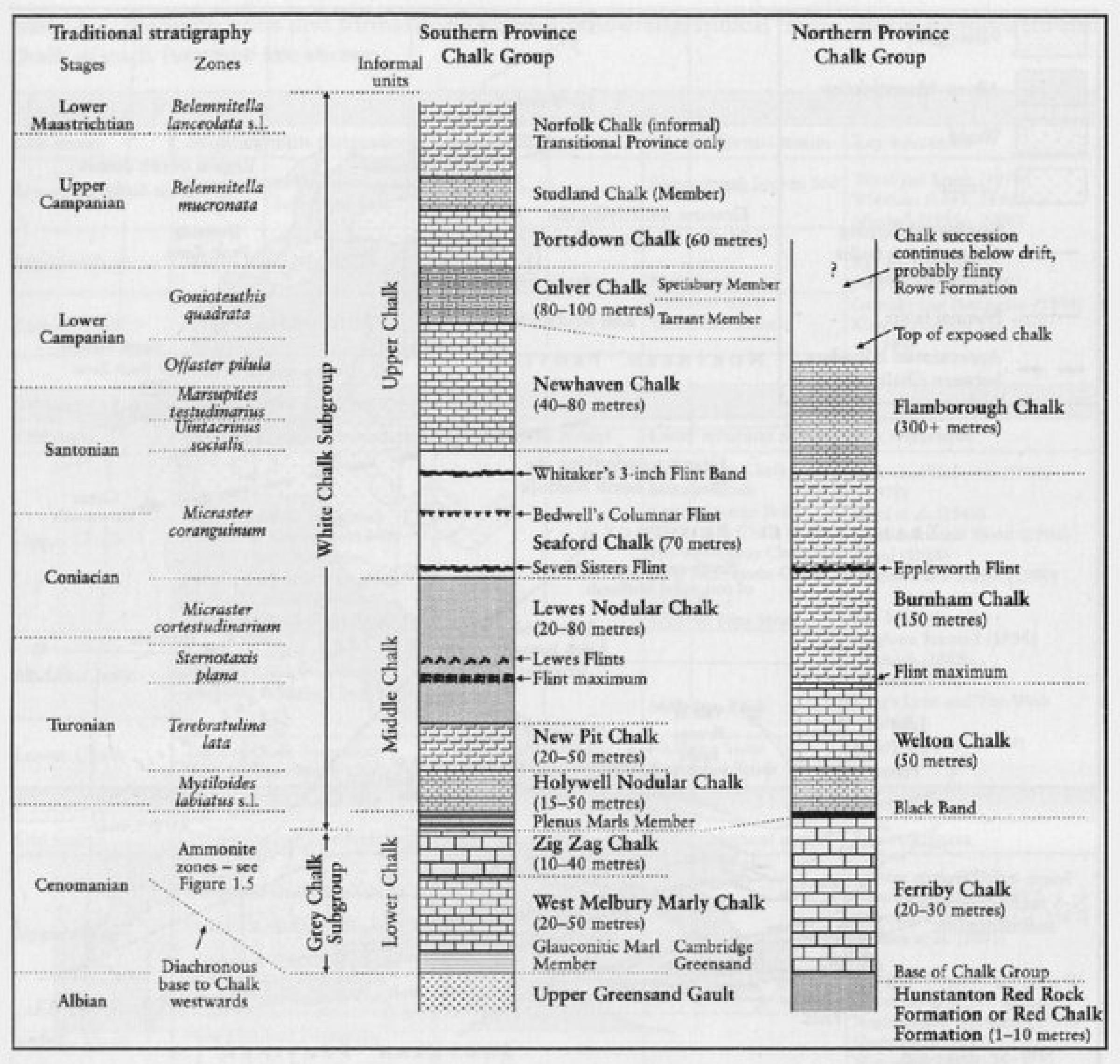
Old units	Mapping units (formations)	Local formal names	Local informal names	Key references
Upper Chalk	Portsdown Chalk Formation Culver Chalk Formation Newhaven Chalk Formation Seaford Chalk Formation Lewes Nodular Chalk Fmn	Studland Chalk Member Spetisbury Chalk Member Tarrant Chalk Member Chalk Rock (Member in parts of Wiltshire/ Berkshire)	Dover Chalk Rock (North Downs)	Bristow *et al.* (1997) Mortimore (1986a, 1997) Mortimore and Pomerol (1987) Rawson *et al.* (2001) **Key BGS Memoirs** Lewes (1987) Brighton and Worthing (1988) Shaftesbury (1995) Wincanton (1999)
Middle Chalk	New Pit Chalk Formation Holywell Nodular Chalk Fmn	Plenus Marls Member	Melbourn Rock	
Lower Chalk	Zig Zag Chalk Formation West Melbury Marly Chalk Formation Beer Head Formation (Devon)	Glauconitic Marl Member	White Bed/ Falling Sands Member Jukes-Browne Bed 7	

······· Approximate boundaries of old units

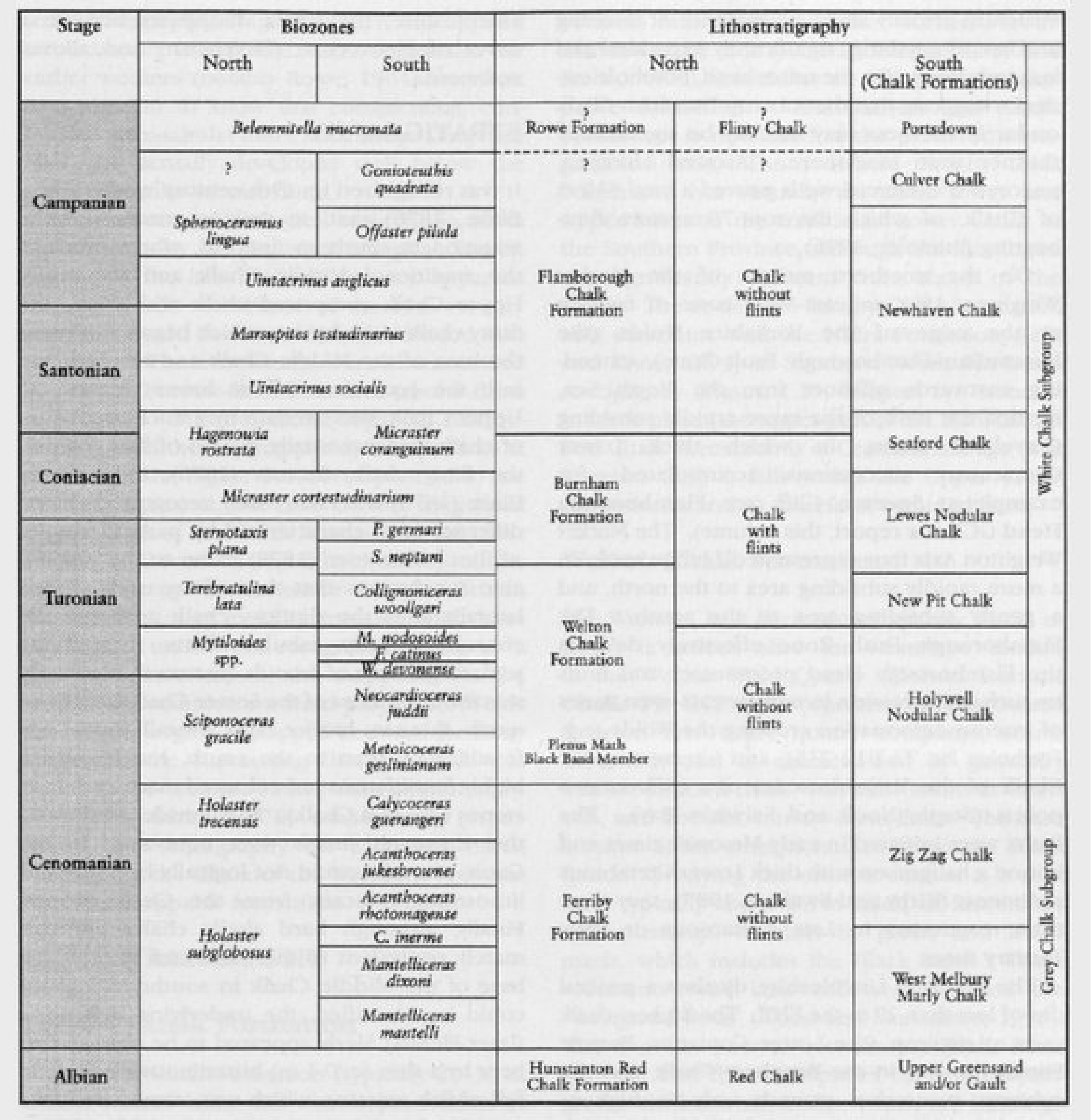
(Table 1.1) Mapping units and formal and informal lithostratigraphical terms. Key references for the Chalk of each Province are shown.



(Figure 1.15) Simplified structural map showing the main features affecting sedimentation of the Upper Cretaceous deposits of England.

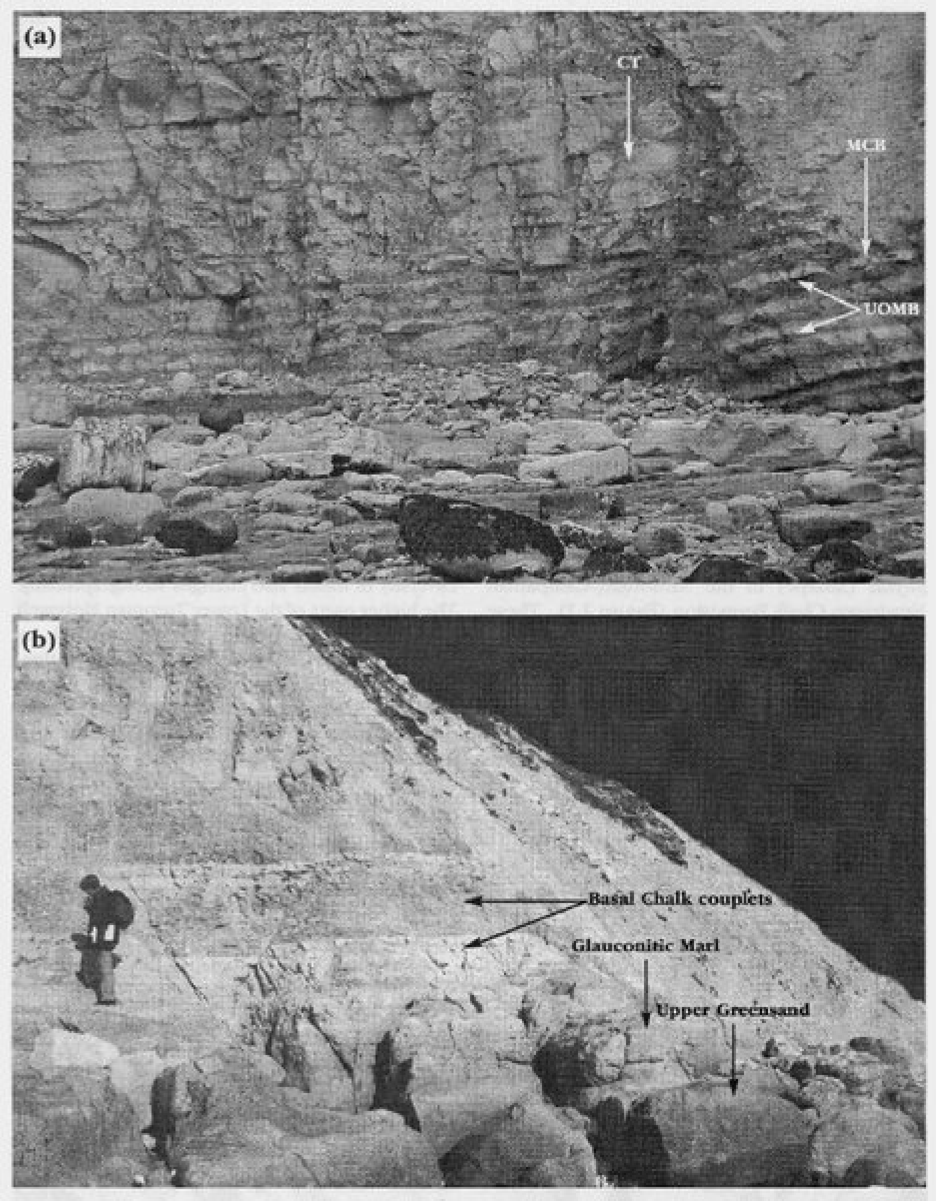


(Figure 1.16) Schematic diagram showing the comparison between the Northern Province and Southern Province chalk stratigraphies.

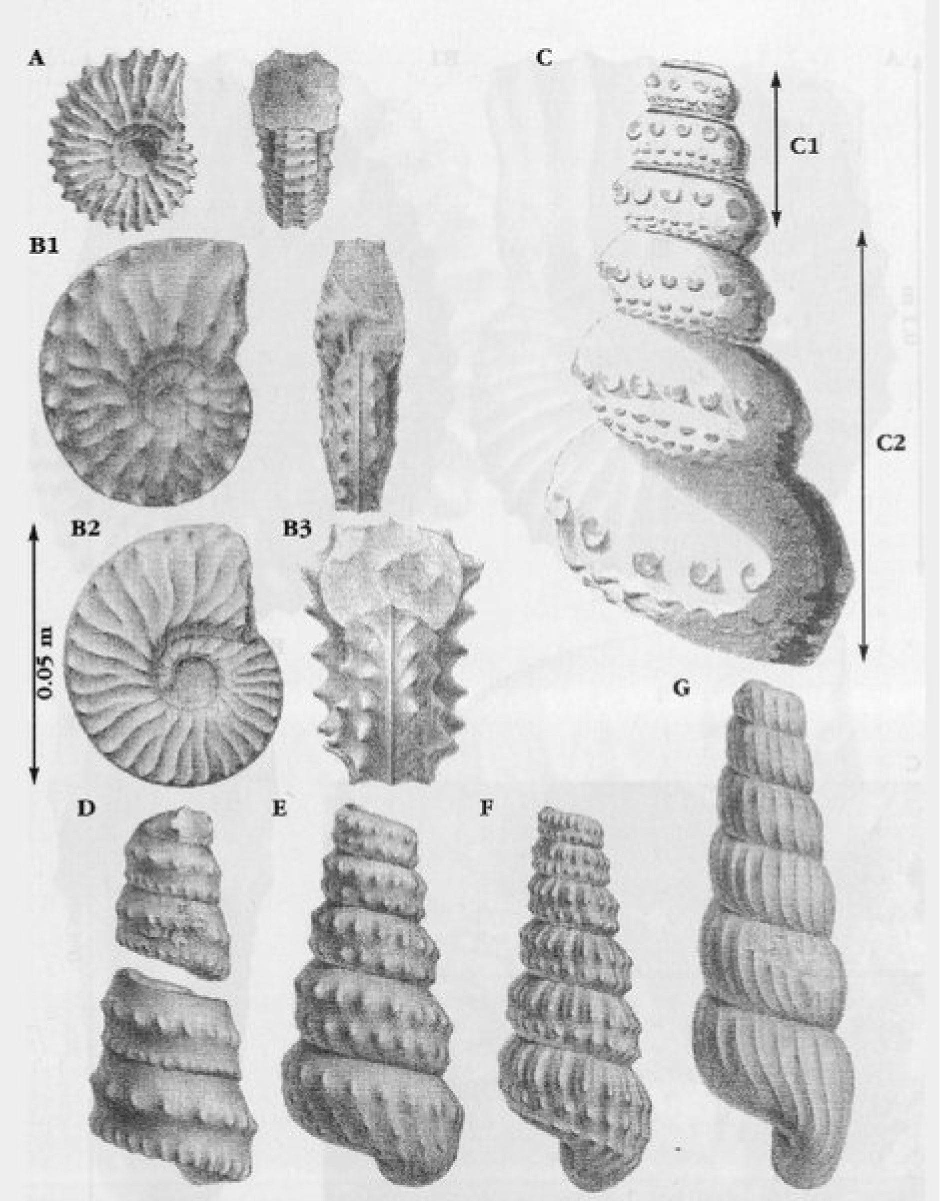


Stage	Biozones		Lithostratigraphy			
	North	South	North		South (Chalk Formations)	
Campanian	*Belemnitella mucronata*		? Rowe Formation	? Flinty Chalk	Portsdown	White Chalk Subgroup
	?	*Gonioteuthis quadrata*	? Flamborough Chalk Formation	? Chalk without flints	Culver Chalk	
	Sphenoceramus lingua	*Offaster pilula*			Newhaven Chalk	
	Uintacrinus anglicus					
Santonian	*Marsupites testudinarius*					
	Uintacrinus socialis					
Coniacian	*Hagenowia rostrata*	*Micraster coranguinum*	Burnham Chalk Formation	Chalk with flints	Seaford Chalk	
	Micraster cortestudinarium				Lewes Nodular Chalk	
Turonian	*Sternotaxis plana*	*P. germari*				
		S. neptuni				
	Terebratulina lata	*Collignoniceras woollgari*	Welton Chalk Formation		New Pit Chalk	
	Mytiloides spp.	*M. nodosoides*		Chalk without flints	Holywell Nodular Chalk	
		F. catinus				
		W. devonense				
Cenomanian	*Sciponoceras gracile*	*Neocardioceras juddii*				Grey Chalk Subgroup
		Metoicoceras geslinianum	Plenus Marls Black Band Member			
	Holaster trecensis	*Calycoceras guerangeri*	Ferriby Chalk Formation	Chalk without flints	Zig Zag Chalk	
	Holaster subglobosus	*Acanthoceras jukesbrownei*				
		Acanthoceras rhotomagense				
		C. inerme			West Melbury Marly Chalk	
		Mantelliceras dixoni				
		Mantelliceras mantelli				
Albian			Hunstanton Red Chalk Formation	Red Chalk	Upper Greensand and/or Gault	

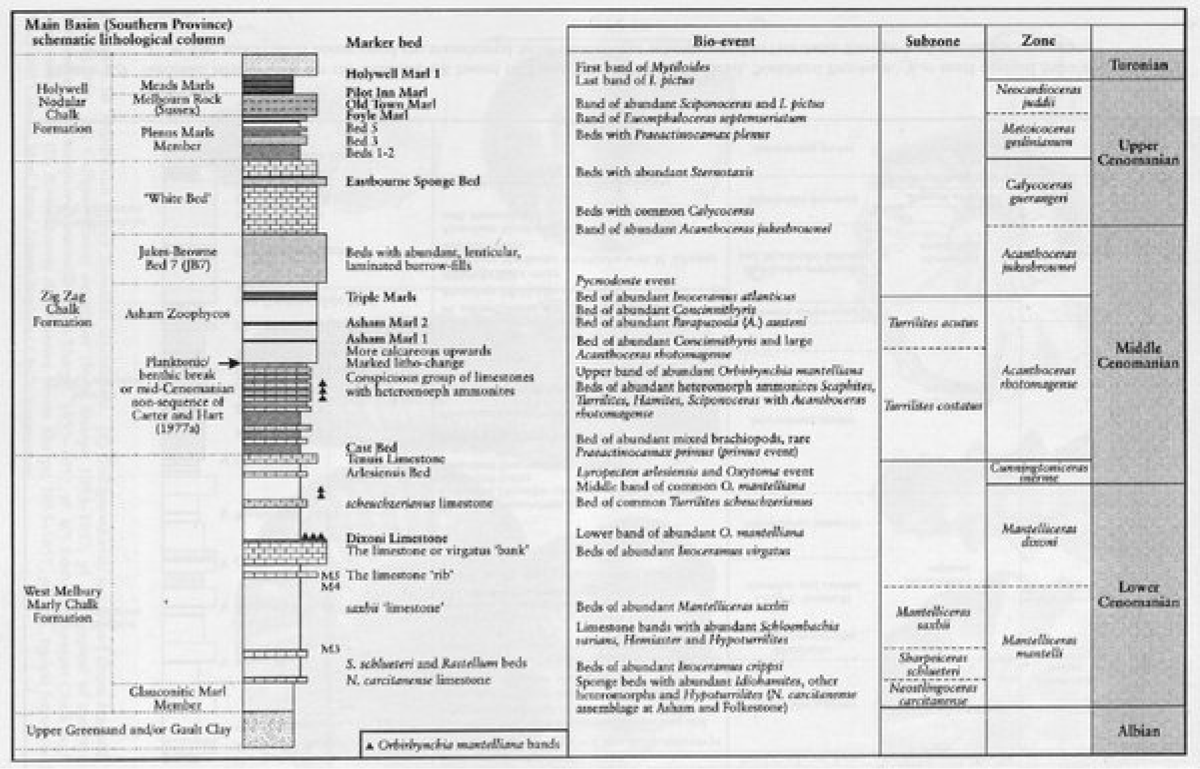
(Figure 5.3) The stratigraphy of the Northern Province Chalk (compare with (Figure 1.5), Chapter 1 and Figures 2.8, 2.9, 2.21, 2.22 and 2.27, Chapter 2).



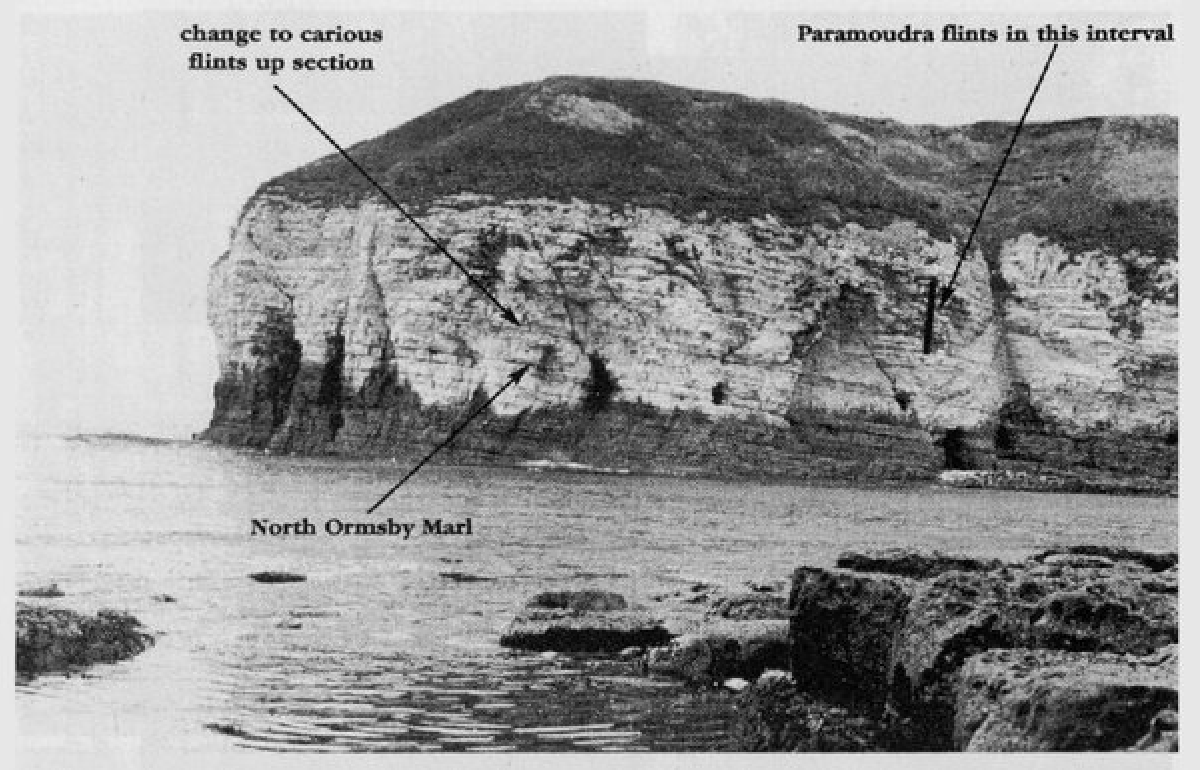
(Figure 2.2) Rhythms in the Chalk picked out by marl–limestone alternations at Beachy Head. (a) Mid-Cenomanian marl–limestone couplets and the litho-change above the mid-Cenomanian break. (b) Basal Chalk (Lower Cenomanian) couplets comprise thicker marl bands compared with the Middle Cenomanian couplets above. (CT = change in limestone-marl thickness with increase in carbonate upwards; MCB = mid-Cenomanian Break; UOMB = hard limestones with sponges and heteromorph ammonites (upper Orbirhynchia mantelliana band). (Photos: R.N. Mortimore.)



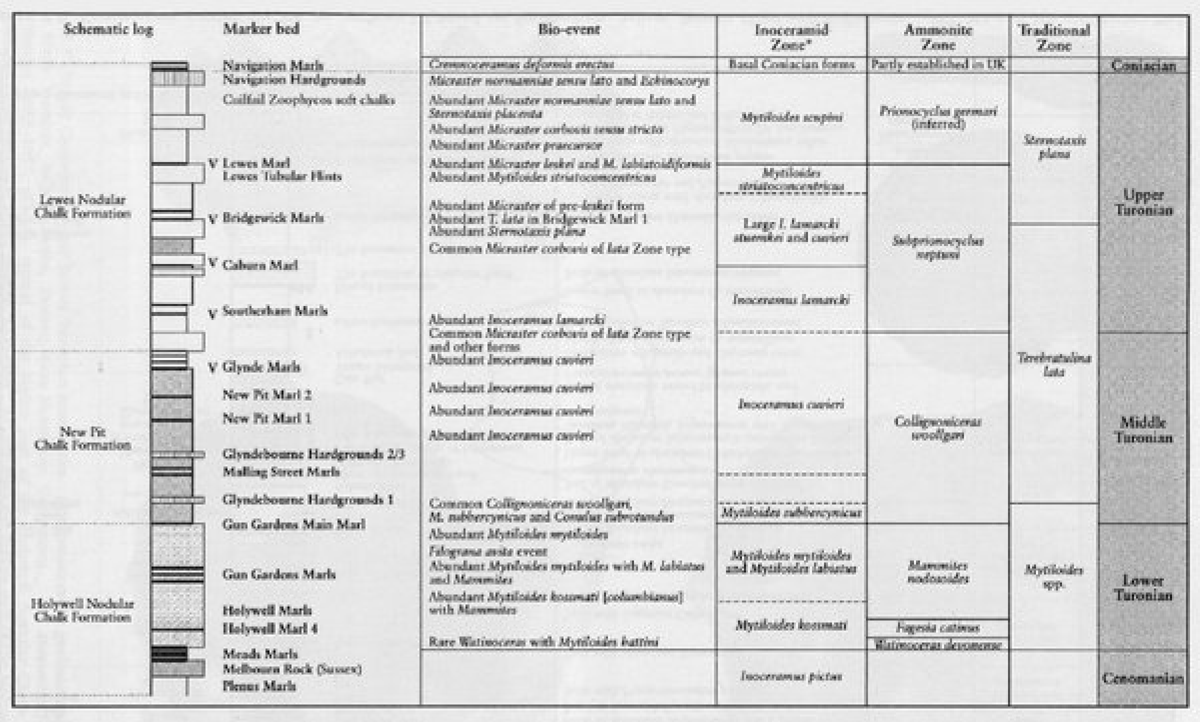
(Figure 2.4) Lower and Middle Cenomanian ammonites. (A) Mantelliceras mantelli (from Sharpe, 1853–1857). (B1–3) Schloenbachia varians (three different forms from Sharpe, 1853–1857, pl. 8). (C) A classic fake combining two fossils; (C1) Hypoturrilites gravesianus (from Mantel, 1822, pl. 26, fig. 7); (C2) Hypoturrilites tuberculatus (from Mantel, 1822, pl. 26, fig. 7). (D) Neostlingoceras carcitanense (from Sharpe, 1853–1857, pl. 26, figs 7a, 8). (E) Turrilites acutus (from Sharpe, 1853–1857, pl. 27). (F) Turrilites costatus (from Sharpe 1853–1857, pl. 27). (G) Turrilites scheuchzerianus (from Sharpe 1853–1857, p1. 26). Scale bar applies to all specimens.



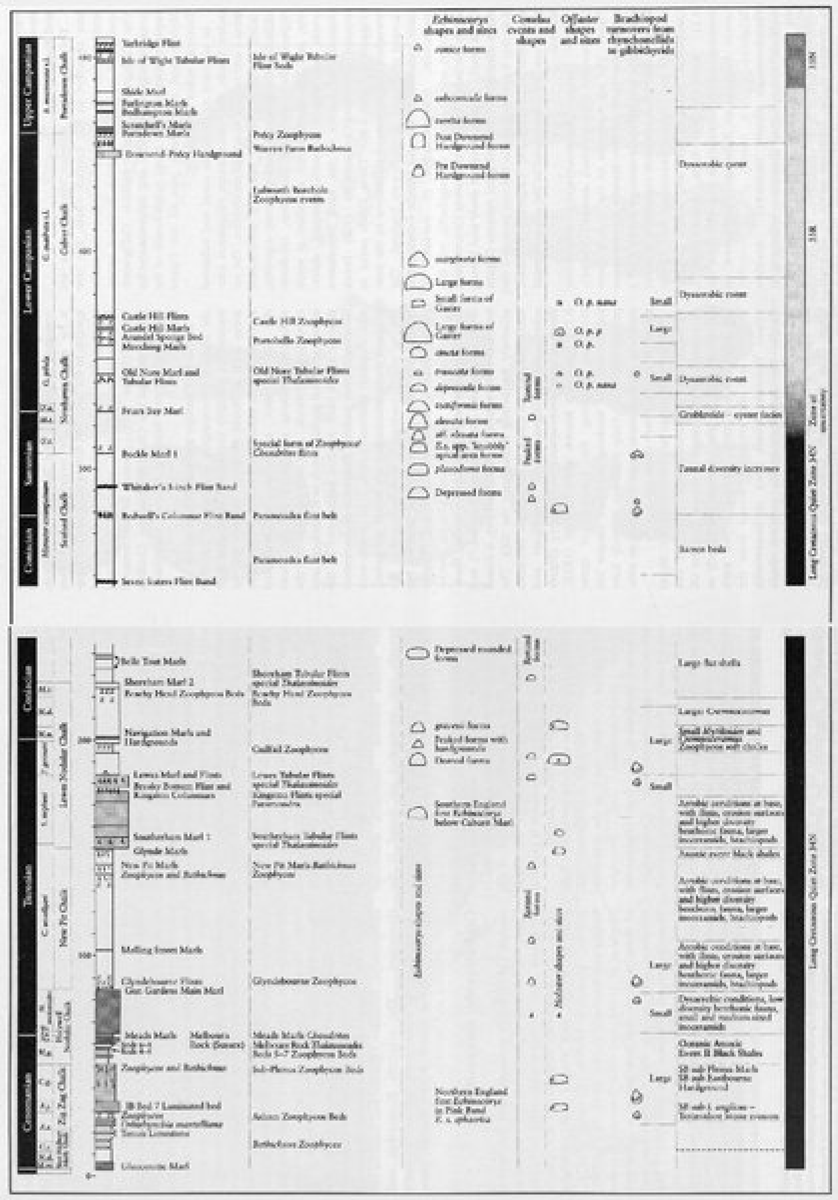
(Figure 2.8) Cenomanian stratigraphy for the onshore UK based on Southerham, Asham, Beachy Head and Folkestone. M2, M4 and M5 are Marker Beds of Gale (1995).



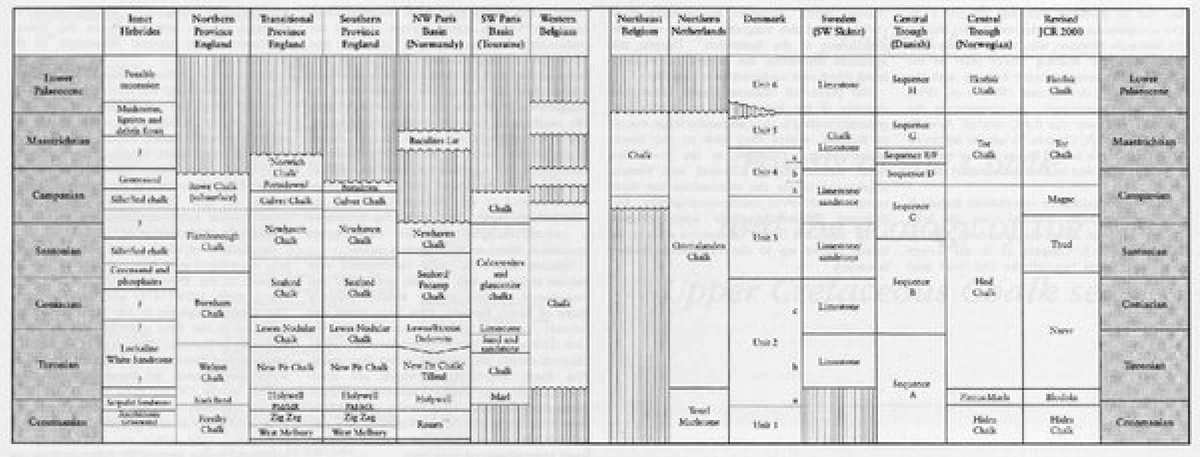
(Figure 5.25) Looking east onto the cliffs at North Landing, Flamborough Head, Yorkshire, where the Welton-Burnham Chalk boundary is well exposed. Spectacular Paramoudra flints are present in the basal unit of the Burnham Chalk Formation. (Photo: C.J. Wood.)



(Figure 2.9) Turonian stratigraphy for the onshore UK based on Lewes Pits and Beachy Head, Southern Province. V = marl derived from volcanic ash. (= The inoceramid zones used are transferred from the current scheme used in Northern Europe and are under review.)*



(Figure 2.3) Integration of trace fossil events with shape and size changes in some key benthic fossils, and the magnetostratigraphy for the Upper Cretaceous succession in southern England. See (Figure 1.5), Chapter 1, for full details of zonal fossils.



(Figure 1.17) Schematic and simplified stratigraphy of the Chalk and related carbonates in north-west Europe.