Pinhay Bay to Fault Corner, and East Cliff, Dorset

[SY 317 907]–[SY 453 907] and [SY 463 902]–[SY 475 896]

Introduction

The importance of the Lower Jurassic succession exposed at the Pinhay Bay to Fault Corner GCR site, which incorporates the Seatown to Watton Cliff GCR site, and farther east at the East Cliff GCR site, cannot be overstated. This locality provides the most continuous section of this stratigraphical interval exposed anywhere in Britain, exposing a diverse range of facies, and is among the most intensively studied Jurassic areas in Britain. The succession at Pinhay Bay to Fault Corner is more frequently cited as a comparative succession for Lower Jurassic sequences elsewhere than any other site in Britain and, probably, the world. The diverse fossil fauna from this locality is uniquely well-documented and includes a greater number of type specimens than any other Lower Jurassic site in Britain. The sites form part of the Dorset and east Devon Coast, England's only natural World Heritage Site. They are of immense importance for understanding early Jurassic stratigraphy, palaeontology and sedimentology.

The earliest reference to the Lias of Dorset was by Woodward (1728) who commented on 'incredible numbers of these shells thus flattened and extremely tender in shivery stone about Pyrton Passage, Lime and Watchet'. Maton (1797) gave a general description of the Dorset Lias, referring to the presence of septarian nodules and also to the abundance of pyrite and organic matter in the shales. Other early accounts included those of De Luc (1805) and Townsend (1813); more detailed descriptions were published by De la Beche (1822, 1826) and Conybeare and Phillips (1822). De la Beche (1826) noted the main lithological and palaeontological features and was the first to illustrate the cliffs and their contained successions in the schematic form that has become characteristic of publications dealing with this stretch of coast. Many subsequent publications have referred to the Dorset Lias in some context. Notable among these are the works of Day (1863), Wright (1878–1886), Woodward (1893), Woodward *et al.* (1911), Wilson *et al.* (1958) and the seminal series of papers by Lang (1914 to 1936). The application of new technology has seen the publication of useful alternative stratigraphies based on, for instance, spectral gamma-ray analysis (Parkinson, 1996; Bessa and Hesselbo, 1997) which has proven a useful aid to correlation with successions elsewhere as well as a tool for palaeoecological interpretations.

There have been many useful summary accounts of the succession, notable among which are those by Wilson *et al.* (1958), Macfadyen (1970), House (1989), Callomon and Cope (1995), and Hesselbo and Jenkyns (1995), although Arkell's (1933) description seems somewhat confused in parts.

The succession in this locality is of immense palaeontological significance on account of its extensive exposures, the often fossiliferous nature of the succession, and the exceptional preservation at some horizons. Material from here has formed the basis of many monographic studies and continues to do so. It is the type locality for at least 14 species of fossil reptile (Benton and Spencer, 1995), many species of fish (Dineley and Metcalf 1999), and an even greater diversity of invertebrates of all types. It also played an important part in the early development of the science of palaeontology and the theory of evolution, particularly through the collecting of Mary Anning.

Description

The western boundary of this locality lies just west of a fault that downthrows the lower part of the Blue Lias Formation to the west against the Triassic Langport Member (formerly White Lias) of the Lilstock Formation (Figure 2.4). The Langport Member, described by Hallam (1957), consists largely of matrix-supported intraclastic conglomerates, with individual beds showing internal deformation due to slumping. It is succeeded by the lowest, late Triassic part of the Blue Lias Formation, which is exposed only at the western end of the GCR site and has been described recently by Wignall (2001). The Blue Lias Formation, as recognized here, is about 26 m thick at Lyme Regis. The formation is wholly exposed in the cliffs and foreshore between Pinhay Bay and Monmouth Beach, Lyme Regis, in an easterly dipping section that brings successively higher beds to beach level (Figure 2.4). The upper half of the formation is exposed in Church Cliffs (Figure 2.5), to the east of the town, before descending eastwards below beach level under the western flank of Black Ven. It was divided by Lang (1924) into 143 beds; beds 1 to 53 for the succession exposed in the Church Cliffs and Chippel Bay anticlines (Lang, 1914), and H1 to H91 for lower parts of the succession exposed only farther west. Although Lang (1924) took Table Ledge (Bed 53) as the top of the formation, on lithofacies grounds it is more appropriately placed above Bed 49 (Hesselbo and Jenkyns, 1995) (Figure 2.6).

The Blue Lias Formation comprises frequent alternations, mostly on a scale of a few decimetres or less, of tabular or nodular micritic limestones interbedded with darker, organic-rich, laminated shales, and light and dark marls (Figure 2.5). Symmetrical cycles, displaying a sequence of limestone–marl–mudstone–marl–limestone, are well developed at some levels. The limestones are of two types; most are tabular to highly nodular with numerous fossils and burrow mottling but no trace of lamination. Much rarer are tabular limestones with planar surfaces, lamination and a virtual absence of benthos. These laminated limestones are restricted, within the Blue Lias Formation, to two groups within the Johnstoni Subzone (Lang beds H30, H32, H34 and H36, and H46, H48, H50 and H52). The marls show various degrees of burrowing and evidence of benthos while the laminated shales contain neither benthos nor burrows (Moghadam and Paul, 2000). The limestones and marls typically are sharply demarcated from each other. Any laminations within the marls envelope, rather than are cut by, irregularities in the surface of the limestones. Thin (< 2 cm) fibrous calcite, or 'beef', seams may be present at marl–shale junctions. Some of the limestones form distinctive marker bands and many of these were named by quarrymen who worked the limestones for building stone and cement manufacture. Intruder (Bed H30) is a homogeneous, fine-grained limestone with a strikingly sharp base, and is the most distinctive of the lower beds exposed to the west of Lyme Regis. It is unusual in having centimetre-wide vertical fissures part-filled with bioclastic limestone, a feature otherwise seen only in Under Copper (Bed 11), and in containing limestone intraclasts. Mongrel (Bed 23) is conspicuous by its highly undulose upper surface, while Top Tape (Bed 29) has its upper surface crowded with large specimens of the ammonite *Metophioceras conybeari.* Grey Ledge (Bed 49) is also distinctive. Its upper surface is characterized by an erosion surface with truncated ammonites, shell and belemnite accumulations, together with glauconite, phosphate and limestone intraclasts.

On a larger scale, division into limestone-dominated and shale-dominated intervals is less strongly developed than at some other sites, such as the Blue Anchor–Lilstock Coast or the Lavernock to St Mary's Well Bay GCR sites, although mudstone-dominated intervals are evident in the Liasicus and mid-Bucklandi zones. This can be seen clearly in Church Cliffs, where the lower 5 m is characterized by crowded limestones with Top Tape (Bed 29) at the top, and is overlain by some 9 m of more widely spaced limestones.

The Blue Lias Formation contains a rich and diverse fauna. Benthic taxa are well represented, particularly in some of the limestones and the paler mudstones but not in the organic-rich paper shales. Benthos includes various species of bivalve, including *Plagiostoma* and *Gryphaea arcuata,* the crinoid *Isocrinus psilonoti,* echinoids including *Miocidaris lobatum* and *Diademopsis,* the brachiopods *Calcirhynchia calcaria* and *Spiriferina* and, at some horizons, gastropods, bryozoa and, rarely, isastraeid corals. The microfauna includes foraminifera and ostracods (Lord and Boomer, 1990), ophiuroid and holothurian debris (Gilliland, 1992), and both marine and non-marine palynomorphs (Cole and Harding, 1998; Waterhouse, 1999). Copestake (pers. comm. in Parkinson, 1996) noted a significant incursion of benthic foraminifera near the top of the Blue Lias Formation. Among the non-benthic fauna ammonites are the most conspicuous element, and many, particularly the schlotheimiids and coroniceratids, attain a large size. They are sufficiently common and well preserved to have allowed a detailed biostratigraphical subdivision to be developed with the identification of several ammonite-correlated horizons in the Hettangian and Sinemurian stages (Page, 1992, 1994a, 2002). Other non-benthic invertebrate macrofossils are much rarer. They include the belemnite *Nannobelus* and the pseudoplanktonic crinoid *Pentacrinites doreckae,* which has been found in an exquisite state of preservation comparable with examples of the better-known *P. fossilis* from higher in the succession. Vertebrate remains, other than occasional disarticulated teeth and bones, are rare but the Blue Lias Formation and overlying Shales-with-Beef Member along this stretch of coast has furnished many type specimens of fish and marine reptile (Benton and Spencer, 1995; Dineley and Metcalf 1999). Many specimens were obtained by early collectors such as Mary Alining, but articulated skeletons are still being found.

The Blue Lias Formation is succeeded by a substantial thickness of mudstone-dominated strata, the Charmouth Mudstone Formation, which has as its type section the cliffs and foreshore of Black Ven and Stonebarrow (Figure 2.4). It has been subdivided into several members following the work of Lang (1936; Lang *et al.,* 1923,1928; Lang and Spath, 1926). The lowest of these is the Shales-with-Beef Member (Lang *et al.,* 1923), incorporating about 30 m of strata from the top of Grey Ledge (Bed 49) to the base of the Birchi Tabular (Bed 76a) spanning the Scipionianum Subzone to about the middle of the Birchi Subzone (Figure 2.6). Above Grey Ledge (Bed 49) there is a marked increase in the proportion of mudstone. The Birchi Tabular (Bed 76a) is a lenticular, and usually beef-enveloped, limestone that forms a conspicuous marker band across The Spittles and Black Ven, before finally descending below beach level at the mouth of the River Char. The Shales-with-Beef Member is well exposed in the cliffs and terraces of The Spittles and Black Ven, and also as a series of ledges on the foreshore below, where they were mapped out by Lang (Lang *et al.,* 1923, fig. 1). The succession is dominated by dark mudstones, many of them organic-rich and finely laminated. Such paper shales are prominent in the lower part of the member, which includes the Fish Bed Shales (Bed 50), Fish Bed (Bed 51) and Saurian Beds (Bed 52), and particularly in the middle part of the member (beds 74 and 75). The mudstones contain numerous thin beds (mostly < 10 cm) of fibrous calcite, or 'beef', which were discussed in detail by Richardson (in Lang *et al.,* 1923). Typically they form double or multiple seams, separated by day partings, which often show cone-in-cone structure. They are always developed along bedding planes except where they envelope nodules and fossils; seams often thin or even pinch out altogether beneath large nodules. Most of the reefs on the foreshore outcrop are formed by thick 'beef' seams. Richardson (in Lang *et al.,* 1923) recorded small biconvex discs of barite in the paper shales of Bed 71e.

The Shales-with-Beef Member contains a few limestone beds, most of which are nodular and/or laterally impersistent. Several contain well-preserved ammonites from which they take their names, as in the Brooki Bed (Bed 74d), the Black Arnioceras (or Hartmanni) Bed (Bed 74f) and the Birchi Nodular (Bed 75a) (Figure 2.7). The last has been the subject of research into the growth of carbonate nodules and fibrous calcite veins within mudstones (Raiswell, 1971; Marshall, 1982). Preservation of ammonites and other invertebrate fossils in the mudstones is almost invariably poor. The loWer part of the Shales-with-Beef Member contains a moderately diverse benthic fauna similar to that in the mudstones of the Blue Lias Formation. Lang *et al.* (1923) recorded a number of bivalve taxa, including *Plagiostoma, Gryphaea, Liostrea, Chlamys, Avicula* and *Gervillia,* from numerous levels between Table Ledge (Bed 52) and Little Ledge (Bed 74). Brachiopods are present at several horizons and include clusters of *Piarorhynchia juvensis* in Table Ledge (Bed 53) and *Spiriferina* in the Pararnioceras alcinoe Bed (Bed 70c). Fragmentary remains of the crinoid *Isocrinus tuberculatus* are not uncommon at some horizons. In the lower part of the Shales-with-Beef Member the organic-rich mudstones of beds 50 to 52 are reputed to have been the source of many of the superbly preserved fossil fish and marine reptiles obtained from the Dorset Lias over the past two centuries, though precise horizons for most of these are lacking (Benton and Spencer, 1995; Dineley and Metcalf 1999). Little Ledge (Bed 74) marks an abrupt change to the organic-rich paper shales that dominate the upper part of the Shales-with-Beef Member. These have yielded virtually no benthic fauna, containing only nektonic, planktonic or pseudoplanktonic taxa, including ammonites, the bivalve *Avicula* and, rarely, the crinoid *Pentacrinites fossilis.*

The base of the Black Ven Marl Member (Lang and Spath, 1926) is taken at the base of the Birchi Tabular (Bed 76a) and the top is defined by the hiatus above the Coinstone (Bed 89) on Stonebarrow, although a comparable development of hiatus concretions has not been observed on Black Ven (Hesselbo and Palmer, 1992). The full thickness of the member is exposed on Black Ven and all except the lowest part on Stonebarrow. It comprises about 27 m of mostly dark-grey mudstones, with subordinate beds of nodular and tabular limestone (Figure 2.8). A 6.5 m-thick development of organic-rich paper shales in the upper part of the member corresponds to a peak in authigenic uranium concentration documented by Bessa and Hesselbo (1997). Within the mudstones there are several good marker horizons. The lowest of these, about 7 m above the Birchi Tabular (Bed 76a), is the 0.3 m-thick Lower Cement Bed (Bed 80), which is particularly conspicuous at the western end of Stonebarrow. The only other continuous limestone bands are the rather irregular Pavior (Bed 82), about 5 m above the Lower Cement Bed, and the 0.25 m-thick Limestone with Brachiopods (Bed 87), some 11 m above this. Other marker horizons include the Flatstones (Bed 83), a band of lenticular, laminated limestone nodules famed for their superbly preserved ammonites (*Asteroceras, Promicroceras, Xipheroceras*)*;* the Topstones (Mudstone of Lang and Spath, 1926; Bed 85), which has yielded an important vertebrate fauna including the giant ichthyosaur *Leptopterygius* (now *Leptonectes*) *solei,* now held in Bristol City Museum (McGowan, 1993), and several specimens of the dinosaur *Scelidosaurus harrisoni;* and the Stellare Nodules (Bed 88f), spheroidal septaria famed for the large *Asteroceras stellare* they sometimes contain. The so-called 'Pentacrinite Bed' (Bed 84b) is not a single horizon but actually encompasses more than 2 m of organic-rich mudstones through which groups of the crinoid *Pentacrinites fossilis,* often associated with driftwood and exquisitely preserved (Figure 2.9), are scattered (Simms, 1986, 1999). Lang and Spath (1926) commented on the difficulties of correlating several of the nodular limestone beds between

Black Ven and Stonebarrow. Several distinct bands of laminated limestone nodules, known locally as the 'Yellowstones', 'bloodstones', 'Lower Flatstones', 'Goldstones' and 'Flatstones', are present on Black Ven but not all have been recognized on Stonebarrow. Hesselbo and Jenkyns (1995) noted that the succession was slightly expanded on Black Ven in comparison with that on Stonebarrow, with the first *Asteroceras* appearing at a slightly higher level above the Pavior (Bed 82) on Black Ven. On Stonebarrow they noted a distinctive burrowed surface with a concentration of belemnites a short distance above the Pavior (Bed 82).

The highest part of the Black Ven Marl Member is perhaps the most intensely collected part of the entire Lower Jurassic succession, mostly for commercially valuable fossils such as ammonites (Figure 2.7), vertebrates and *Pentacrinites* (Figure 2.9). The organic-rich mudstone parts of the succession, and particularly the laminated, early diagenetic concretions, have yielded much scientifically important material. A rich insect fauna (Zeuner, 1962; Whalley, 1985) has been obtained, particularly from the Flatstones nodules, and includes the oldest known representative of the Lepidoptera. Soft-part preservation of both vertebrates (Martin, 1991, 1995) and invertebrates (Kear *et al.,* 1995) has also been described. Other elements of the fauna have received little attention other than by Lang and Spath (1926). In general the fauna in the organic-rich mudstones is dominated by nektonic, planktonic and pseudoplanktonic organisms, mainly ammonites, belemnites and pseudoplanktonic bivalve taxa such as *Cuneigervillia* and *Oxytoma.* Nonetheless, even here there are occasional thin discrete horizons in which benthic bivalves, notably *Plagiostoma,* occur and benthic bivalve spat (less than 2 mm) across are common throughout (Simms, 1986). The limestone bands of the Pavior (Bed 82) and the Limestone with Brachiopods (Bed 87) contain a noticeably richer benthic fauna than is typical of the mudstones, with the Pavior yielding the bivalve *Chlamys* and the brachiopod *Spiriferina,* while the Limestone with Brachiopods contains *Plagiostoma* and abundant *Cuneirhynchia oxynoti.* The Coinstone (Bed 89) on Stonebarrow is an irregular bed of bored, encrusted and partly pyritized septarian hiatus nodules that preserve evidence for a complex history of burial, exhumation and re-burial (Lang, 1945; Hallam, 1969, 1999; Hesselbo and Palmer, 1992; Coe and Hesselbo, 2000). Nodules are present at this level on Black Ven, to the west, but the hiatus itself lies more than 1 m above, at a thin horizon of bored belemnites (Lang, 1945; Hesselbo and Palmer, 1992). The diverse benthic fauna associated with the Coinstone and its enveloping marl is related to post-diagenetic exhumation of the nodules rather than being a primary feature. Hesselbo and Palmer (1992) record a range of borings (*Pypanites* and indeterminate bivalves) and encrusting taxa (*Dorsoserpula, Plicatula* and exogyrine oysters, *Nubeculinella,* bereniciform and stomatoporiform bryozoa) as well as scratch marks interpreted as those of burrowing crustaceans. Simms (1989) described the millericrinid *Shroshaecrinus obliquistratus* from holdfasts and disarticulated ossicles associated with the hiatus on Stonebarrow and Black Ven. The Stellare Nodules (Bed 880, which also are exposed at this hiatus surface on Stonebarrow, represent the *stellare* Biohorizon (Horizon 40) of Page (1992) ((Figure 1.5), Chapter 1).

The Black Ven Marl *sensu* Lang was some 44 m thick, with the lower 27 m being lithologi-cally and stratigraphically continuous with the underlying Shales-with-Beef Member but distinct from the upper 16.8 m, which lies above a hiatus at about the level of the Coinstone (Bed 89). This hiatus represents a substantial stratigraphical break, encompassing part of the Stellare Subzone, the entire Denotatus Subzone, and all of the Oxynotum Zone. The strata that succeed it are lithologically distinct from the Black Ven Marl Member beneath and comprise dark-grey, often highly pyritic, mudstones. Although pyrite also is abundant in the Shales-with-Beef and Black Ven Marl members below the Coinstone, pyritic preservation of ammonites there is relatively uncommon and, where it does occur, the pyrite usually occurs as a surface encrustation of a previously crushed ammonite. However, in the dark mudstones above the Coinstone, pyrite commonly occurs as well-preserved and uncrushed internal moulds of ammonites, bivalves and gastropods. The 16.8 m of dark mudstone above the Coinstone also lacks the large diagenetic nodules characteristic of the Black Ven Marl Member. The only prominent development of limestone is the Watch Ammonite Stone (Bed 99), a lenticular unit up to 0.3 m thick and often packed with abundant *Echioceras* grp. *aeneum* lying at various angles to the bedding. Occasional small limestone nodules may be present at other levels. Thin seams of 'beef' are present but they too are on a greatly reduced scale compared with those in the Shales-with-Beef Member. It has been proposed (Page, pers. comm.) to re-name this part of the succession, spanning the lower part of the Raricostatum Zone (Densinodulum and Raricostatum subzones) and characterized by abundant uncrushed pyritic moulds of ammonites, as the Stonebarrow Pyritic Member. On this style of fossil preservation alone it can easily be distinguished from the superficially dark mudstones below and has been recognized at outcrop throughout southern England (e.g. Hollingworth *et al.,* 1990; Simms, 2003b).

The fauna of the Stonebarrow Pyritic Member is dominated by ammonites such as *Crucilobiceras, Eoderoceras, Echioceras* and the distinctive *Oxynoticeras lymense,* whose uncrushed pyritized phragmocones are conspicuous and readily collected. A low-diversity benthic fauna of mostly thin-shelled, byssate epifaunal and free-living bivalves is present throughout much of the mudstone sequence (Sellwood, 1972). Benthic diversity is significantly higher in the Watch Ammonite Stone (Bed 99) and the bioturbated marl associated with it, and includes several genera of bivalves, gastropods and brachiopods, Including *Gryphaea mccullochi,* which otherwise is rare in the member, and 14 species of foraminifera (Barnard, 1950). Sellwood (1972) noted that the fossils are concentrated mainly in the top 0.09 m of the limestone, which has a lighter colour than the lower part, while the limestone lenticles themselves have a sharp contact with an overlying, intensely bioturbated, shell-hash rich in fragments of the crinoid *Hispidocrinus schlumbergeri.* A second small increase in benthic diversity occurs about 1.6 m below the base of Hummocky (Bed 103), where an abrupt change from laminated to more homogeneous mudstones is associated with the appearance of protobranch bivalves and an increased abundance of other species already present lower in the succession.

The abundant ammonites (Figure 2.7) found throughout the Sinemurian part of the Charmouth Mudstone Formation have allowed for a detailed biostratigraphical subdivision of this part of the succession. Page (1992) established a sequence of ammonite-correlated biohorizons for the Sinemurian Stage (Figure 1.4), (Figure 1.5), Chapter 1), with the Dorset coast as type locality for several of these. Although most of the species in Page's scheme are common and widespread elsewhere, *Oxynoticeras lymense is* known only from the basal Densinodulum Subzone (beds 90–92) of this site.

The Stonebarrow Pyritic Member is overlain by the Belemnite Marl Member, a 23 m-thick succession of blue-grey, occasionally organic-rich, mudstones alternating with pale-grey, richly calcareous mudstones. These form the uppermost Lias precipice on Black Ven and on the western flank of Stonebarrow (Figure 2.5) and (Figure 2.10), descending to form the lower part of the Westhay Cliffs before being faulted below beach level at the Ridge Fault. The upper beds are also exposed in some of the foreshore reefs below Golden Cap. The base of the Belemnite Marl Member is taken at the base of Hummocky (Bed 103), an irregular limestone band up to 0.15 m thick. Abundant echioceratid ammonites are present on its lower surface while serpulid-encrusted examples also occur sparsely throughout Bed 103 and the overlying 0.1 m-thick clay of Bed 104, the latter also yielding *Eoderoceras miles.* Hummocky contains abundant bioclastic material, including bivalves, belemnites, crinoid and echinoid debris, serpulids and fragments of reptile bone. The upper part of Hummocky and the basal few centimetres of Bed 104 contain numerous intraformational limestone clasts; these are sometimes bored, contain phosphatic specks and have a pyritic skin. Both units are intensely burrowed but these burrows are compacted only in the top centimetre or so of Hummocky. The Apoderoceras limestone (Bed 105) is a 0.3–0.4 m-thick pale limestone with abundant bioclastic debris and with *Chondrites* and *Rhizocorallium* burrows preserved in relief. Fallen blocks below Black Ven indicate that locally beds 103–105 may merge into a single complex limestone unit up to 1 m thick.

Much of the remainder of the Belemnite Marl Member, more than three quarters of which lies within the Jamesoni Zone, comprises alternating pale and dark mudstone bands, which are clearly visible in the near-vertical cliffs on Black Ven and Stonebarrow (Figure 2.10). Weakly laminated organic-rich shales form a minor component, particularly near the top. In addition to the basic stratigraphical description of Lang *et al.* (1928), detailed analyses of this part of the Charmouth Mudstone Formation have been made by Sellwood (1970, 1972) and by Weedon and Jenkyns (1990, 1999). The latter demonstrated an inverse relationship between carbonate content (higher in the pale bands) and total organic carbon content (higher in the darker bands). This correlation is also reflected in the concentrations of radioactive uranium, thorium and potassium as documented by Bessa and Hesselbo (1997). Sellwood (1970, 1972) showed that both the body-fossil and trace-fossil assemblages changed in parallel with the light-dark couplets. The pale, carbonate-rich bands proved to contain abundant fine bioclastic debris such as crinoid and echinoid fragments, foraminifera, ostracods and faecal pellets, while the more organic-rich darker units yielded a more depauperate fauna. Both the light and dark units show intense burrow mottling. Sellwood (1970) described from here his 'Type II' cycles and the trace fossils associated with them. He noted that *Diplocraterion* were present only in the tops of the pale units, piping darker sediment downwards, while *Rhizocorallium* and *Thalassinoides* were conspicuous at the lower junctions, piping paler sediment down into the darker mudstones beneath. Only very small *Chondrites* are present within the pale units. Larger *Chondrites,* where they extend down from the dark units into the paler horizons below, were found by Simpson (1957) usually to follow the dark clay fill of pre-existing *Rhizocorallium* or *Diplocraterion* burrows.

The rhythmicity conspicuous throughout much of the Belemnite Marl Member is less well-developed in the highest 4 m at the top of the member (Lang, 1917). The upper 2 m is dominated by dark, weakly laminated, organic-rich shales. At some levels, notably the thin Belemnite Bed (Bed 120c), belemnites are profuse, while pyritized ammonites are abundant in beds 120a–b. Storm scours up to 1 m wide and 0.1 m deep, and filled with debris of *Isocrinus basaltiformis,* belemnites, brachiopods and wood, are a conspicuous feature in this part of the succession. Jones *et al.* (1994) noted a sudden increase in the strontium isotope values at the level of the Belemnite Bed. The Belemnite Marl Member is capped by the Belemnite Stone (Bed 121), an irregular, pale grey-brown, richly bioclastic limestone seldom more than 0.15 m thick, which has yielded a Luridum Subzone fauna. Despite the condensed nature of the Ibex Zone here, the sequence of ammonite zonules is largely complete (Phelps, 1985).

Much of the Belemnite Marl Member contains a limited benthic assemblage. Some elements of the fauna, namely ammonites, belemnites, bivalves, gastropods and brachiopods, were described in Lang *et al.* (1928). Throughout the sequence only belemnites are common and well preserved. They are especially abundant in the Belemnite Bed (Bed 120c) and in the Belemnite Stone (Bed 121), and in the Inferior Belemnite Bed of Hesselbo and Jenkyns (1995) about 0.6 m lower in the succession. Belemnites in general are the most conspicuous fossils elsewhere in the member, which led Lang *et al.* (1928) to describe the stratigraphical succession of morphotypes (see Chapter 1). Ammonites usually are poorly preserved, either as pyritized phragmocones or mudstone impressions. There are no infaunal, semi-infaunal or protobranch bivalves, and *Gryphaea* also is absent. Only *Plagiostoma, Parainoceramus ventricosus* and thin-shelled pectinids are at all common. Barnard (1950) noted an extreme paucity of forminifera in this part of the succession. Disarticulated remains of *Isocrinus basaltiform is* are locally abundant in storm scours near the top of the Belemnite Marl Member. Brachiopods generally are rare except at two levels; in beds 111–114 and 118–119. In common with other organic-rich mudstones elsewhere in the Lias Group of Dorset, those that occur immediately below the Belemnite Stone (beds 119–120) have yielded well-preserved vertebrate remains including a new species of ichthyosaur (McGowan and Milner, 1999) and remains of *Scelidosaurus* (Ensom, 1987, 1989).

The Belemnite Stone is overlain by the Green Ammonite Mudstone Member, which comprises blue-grey mudstones (Figure 2.11). The member is well exposed beneath Golden Cap, though often badly slumped in cliff sections to the west where they form a low-angle slope above the steep cliffs of the Belemnite Marl Member. There is a marked eastward thickening of the member from about 15 m on Stonebarrow to 34 m beneath Golden Cap (Lang, 1936). Only about 5 m remains on the eastern flank of Black Ven beneath the Cretaceous overstep. Originally described by Lang (1936), the stratigraphy was significantly revised by Phelps (1985). Most of the succession falls within the Davoei Zone though the top 3 m contains *Amaltheus*and hence lies within the Stokesi Subzone at the base of the Upper Pliensbachian Substage. Limestone nodules occur scattered through the mudstone and, particularly in the lowest 6 m, may contain the so-called 'green ammonites' with their camerae filled with green calcite. More persistent irregular limestone bands occur at three levels. These are the Lower Limestone (Bed 123a of Lang, 1936; Bed 14 of Phelps, 1985), a persistent horizon of flattened blue-grey nodules; the Red Band (Lang's Bed 126; Phelps' beds 21–23), a series of three, red-weathering limestones separated by shales; and the Upper Limestone (Lang's Bed 129; Phelps' beds 32 and 34). The mudstones that dominate the member become increasingly sandy towards the top, which is taken at the base of the lowest of the Three Tiers, a 2 m-thick sandstone. The upper 2 m of the Green Ammonite Mudstone Member (Lang's beds 132b-c; Phelps' beds 40–41) is a dark, highly pyritic mudstone lithologically unlike any other mudstone in the Green Ammonite Mudstone Member or the Pliensbachian Stage of Dorset.

Ammonites are abundant in the Green Ammonite Mudstone Member and include species of *Aegoceras, Oistoceras, Liparoceras* and *Tragophylloceras.* Several species of *Prodactylioceras,* a relatively rare genus in the British Lias, occur in the middle part of the member. *Lytoceras* is very rare in the Green Ammonite Mudstone Member although it occurs commonly in the Belemnite Stone below and in the Three Tiers above. Phelps (1985) defined a series of fine-resolution ammonite zonules within the Ibex and Davoei zones based largely on the Dorset coast succession. He showed that all three subzones and the full sequence of zonules of the Davoei Zone are present in the GCR sections. The Maculatum Subzone at the base is much thinner than the Capricomus and Figulinum subzones. He also identified here a local *Cymbites* horizon between his Figulinum and Bifurcus zonules, the latter equivalent to the Occidentale and Monestieri zonules of (Figure 1.6) (Chapter 1) indicating that the Davoei Zone and basal Margaritatus Zone succession is unusually complete on the Dorset coast. Belemnites also are common; stout species of *Pseudohastites* are particularly conspicuous, and slender hastitids are present throughout.

A diverse benthic fauna was recorded from the Green Ammonite Mudstone Member by Lang (1936), with several new species of bivalve, gastropod and brachiopod described by Cox (1936) and Muir-Wood (1936). Small gastropods are particularly abundant in the lowest few metres, together with the epibenthic bivalve *Parainoceramus ventricosus,* the echinoid *Eodiadema minuta* and the crinoids *Isocrinus basaltiformis* and *Balanocrinus subteroides.* Higher in the succession shallow-burrowing nuculid bivalves are the only common macro-benthos. Macfadyen (1941) recorded a total of 55 species of foraminifera, together with sparse ostracods, in the Green Ammonite Mudstone Member.

The Charmouth Mudstone Formation is succeeded by the Dyrham Formation, which equates approximately with the lower part of the Upper Pliensbachian Substage (Figure 2.2). Its outcrop on the coast extends from the western flank of Stonebarrow, where only a few metres are preserved beneath the Cretaceous overstep, eastwards for about 5 km, beneath Golden Cap and Thorncombe Beacon (Figure 2.12), to where it is faulted out against the Bathonian strata of West Cliff. The base of the Dyrham Formation is marked by an abrupt lithological change from the mudstones of the Green Ammonite Mudstone Member to the sandstones that comprise the Three Tiers at the base of the Eype Clay Member. The Dyrham Formation of Dorset attains a thickness of about 123 m of which all but about 0.5 m can be assigned to the Margaritatus Zone. This is the maximum thickness of the zone anywhere in Britain. The succession was described in detail by Howarth (1957) and by Hesselbo and Jenkyns (1995).

Three well-cemented, fine-grained, muddy sandstones, each 0.5–1 m thick, form conspicuous marker bands in the lowest part of the Dyrham Formation. They form prominent ledges in the cliffs and have long been known as the "Three Tiers'. Each has a gradational boundary with the intervening, less cemented, silty and sandy mudstones and, although often well-bioturbated with conspicuous *Thalassinoides* (Sellwood *et al.,* 1970), show planar and ripple bedding. Above the Upper Tier lies about 60 m of grey, micaceous, silty mudstone, the Eype Clay Member, in which there are a few thin sandstone beds (Figure 2.12). Body fossils, other than crushed *Amaltheus* and *Tragophylloceras loscombi,* are scarce except at two levels. The lower of these is the Eype Nodule Bed, some 38 m above the Upper Tier, which contains bivalves, brachiopods, crinoids and crustacea along with a diverse ammonite fauna (Howarth, 1957), some of which show evidence of predation (Ensom, 1985a). Beneath Golden Cap the Eype Nodule Bed is overlain by a bed of blue-grey calcareous sandstone up to almost 1 m thick which, in places, incorporates some of the nodules into its base. The fauna of this sandstone includes bivalves, brachiopods, gastropods, ammonites and a mondivaltiid coral. Eastwards from there the sandstone pinches out and the nodules show the development of pyritic rims and clear evidence of reworking by burrowing organisms. Near Eype Mouth the nodules were exhumed and colonized by a diverse range of encrusting organisms before being re-buried (Ensom, 1985b; Hesselbo and Jenkyns, 1995).

Near the top of the Eype Clay Member is Day's Shell Bed, an indurated shelly and crinoidal mudstone less than 0.3 m thick with occasional small calcareous nodules. It has yielded an abundant and diverse benthic fauna together with ammonites and belemnites, described by Palmer (1966), many of which are immature individuals.

About 1 m above Day's Shell Bed a conspicuous fine-grained sandstone, the Starfish Bed, marks the base of the Down Cliff Sand Member. The Starfish Bed is a composite unit about 1 m thick that comprises several distinct beds, each of which has a sharp base succeeded by planar-laminated sands. The sands are locally rippled or show hummocky cross-stratification, and become increasingly bioturbated upwards. The ophiuroids, from which the Starfish Bed gets its name, are confined to the sole of the lowermost of these units (Goldring and Stephenson, 1972). Most are immature individuals of *Palaeocoma milleri,* with a second species referred to by Hess (1960) as *Ophioderma tenuibrachiata.* Scattered remains of the crinoid *Balanocrinus gracilis* also occur together with rare examples of the asteroid *Tropidaster pectinatus.* Ensom (1988) recorded siltstone dykes in fallen blocks of the Starfish Bed near Eype Mouth, though not on Thorncombe Beacon farther to the west. The Down Cliff Sand Member consists mainly of grey-brown sandy mudstones, becoming more sandy towards the top. It contains many indurated lenticles (Howarth, 1957), some of which contain abundant superbly preserved examples of *Balanocrinus gracilis* and *Palaeocoma milleri* (Simms, 1989), together with rarer examples of the ophiuroid *Hemieuryale lunaris* and the asteroids *Tropidaster pectinatus, Archastropecten* and *Solaster* (C. Moore, pers. comm.). Sellwood *et al.* (1970) noted abundant trace fossils and the presence, locally, of load structures on the sole of some beds. Wilson *et al.*(1958) cited a thickness of about 30 m for the Down Cliff Sand Member below Thorncombe Beacon, thinning eastwards to about 22 m near Eype Mouth. The Margaritatus Stone, a 0.3 m-thick bluish fossiliferous sandy limestone, is the only conspicuous marker band within the member and defines its top, although Wilson *et al.* (1958) noted several other minor marker horizons within the member. The ammonite fauna shows this bed to correspond to the base of the Subnodosus Subzone. Sellwood *et al.* (1970) described the Margaritatus Stone as a complex conglomeratic bed with angular sandstone blocks up to 0.6 m long as well as rolled and bored bioclasts and lithoclasts.

The Margaritatus Stone is succeeded by the Thorncombe Sand Member. This is mostly more yellow-weathering and homogeneous than the Down Cliff Sand Member, and contains conspicuous cemented 'doggers', up to 2 m thick and 3 m across at several levels, together with a 0.3 m-thick sandy limestone about midway up the succession. The sands frequently exhibit bioturbated units interbedded with hummocky cross-stratification (Sellwood *et al.,* 1970). The basal 2 m of the member is a blue-grey mudstone, termed the 'Blue Band' or 'Margaritatus Clay'. The top 2.3 m of the member also is of grey mudstone. This is overlain by the Thorncombiensis Bed, a 0.36 m-thick bipartite unit of highly bioclastic limestone and calcareous mudstone that yields an ammonite assemblage indicative of the Gibbosus Subzone. Fossils, notably amaltheid ammonites (Howarth, 1957), rhynchonellid brachiopods (Ager, 1956–1967) and crinoids (Simms, 1989), are locally abundant. Lord (1974) recorded some 40 species of ostracod from from the clays and silts of the Margaritatus Zone, with species of *Ogmoconcha* particularly abundant.

The base of the Beacon Limestone Formation (= Junction Bed *sensu lato* of earlier authors) rests on an erosion surface at the top of the Thorncombe Sand Member. At West Cliff the Thorncombiensis Bed and overlying clays are absent and the Beacon Limestone Formation contains large blocks of Thorncombiensis Bed at its base (Howarth, 1957). The Beacon Limestone Formation is exposed only in the cliffs between Seatown and West Cliff and is rarely accessible in *situ;* its type locality is on Thorncombe Beacon [SY 4354 9148]. Detailed accounts of the Beacon Limestone Formation were published by Jackson (1922, 1926), Jenkyns and Senior (1991) and Howarth (1992), with descriptions of some inland sections by Walker (1892). The formation reaches a maximum thickness of 3.65 m adjacent to the Eypemouth Fault but thins rapidly westwards and typically is less than 1 m thick. It contains a diverse ammonite fauna, mainly of amaltheids and hildoceratids, which establishes the presence of the full sequence of seven successive ammonite zones, and many of the subzones, from the Spinatum Zone to the Dispansum Zone; on the Yorkshire coast this interval is represented by almost 130 m of strata. At the base of the Beacon Limestone Formation is the Marlstone Rock Member, a brown or pink, conglomeratic limestone with abundant berthierine and goethite ooliths, and containing a diverse fauna including ammonites (Howarth, 1957, 1980), brachiopods (Ager, 1956–1967, 1990), bivalves and other invertebrates (Jackson, 1926). There is a conspicuous planar hardground surface between the Marlstone Rock Member and the overlying Eype Mouth Limestone Member (= Junction Bed *sensu stricto* of earlier authors). The basal bed of the Eype Mouth Limestone Member comprises pink to buff stromatolitic calcilutites, containing ammonites indicative of the Serpentinum Zone, overlain by pale conglomeratic limestones containing ammonites indicative of the Bifrons to Dispansum zones. Planar erosional hiatuses occur at several levels and are often conspicuously marked by planed-off ammonites and other fossils. Pebble beds and worn and broken ammonites also occur at some levels. The Eype Mouth Limestone Member is traversed by numerous fissures, mostly sub-parallel to bedding but with some at an angle to it (Jenkyns and Senior, 1991). These are filled with pale calcilutites, sometimes cross-bedded, which contain ammonites younger than the enclosing sediments. Both the matrix sediments and fissure fills have yielded a moderately diverse benthic fauna alongside the rich ammonite assemblages. Certain elements of the fauna within this member here are unique to the British Lias. These include several species of ammonite (Howarth, 1992) and brachiopod (Ager, 1956–1967) of Tethyan affinities, and the crinoid *Plicatocrinus inornatus,* which occurs as profuse disarticulated ossicles in vertical fissures close to the Eypemouth Fault (Simms, 1989).

The Eype Mouth Limestone Member is overlain by the Down Cliff Clay Member of the Bridport Sand Formation (Figure 2.11). The latter member comprises silty clays that pass up into sandy siltstones with cemented horizons. The Down Cliff Clay Member reaches a maximum thickness of 21 m in the Bridport area, but thins rapidly away from there and is less than 11 m thick at East Cliff it is succeeded by the main part of the Bridport Sand Formation, magnificently exposed in the sheer cliffs between West Bay and Burton Bradstock, the type section of the formation being at East Cliff (Figure 2.13) and Burton Cliff (the latter is a Middle Jurassic GCR site, see Cox and Sumbler, 2002). Its thickness is fairly constant, at a little over 40 m, between West Bay and Burton Bradstock. Farther west, on Thorncombe Beacon, less than half of the formation, extending up to about Bed 10 of Hesselbo and Jenkyns (1995), is preserved beneath the Cretaceous overstep yet there is a 140% expansion in thickness relative to the same succession to the east.

There is a progressive increase in grain size from the silty clays of the Down Cliff Clay Member, through siltstones to fine sand about the middle of the Bridport Sand Formation and then a decrease again towards the top (Hesselbo and Jenkyns, 1995). This grain-size pattern is roughly coincident with an increase, and then decrease, in bed spacing upwards through the succession. Calcite-cemented bands and 'doggers' are a conspicuous feature of weathered exposures of the Bridport Sand Formation (Figure 2.13). Sellwood *et al.* (1970) noted that detrital mica grains are crumpled in the softer bands but remain undistorted in the cemented units, indicating pre-compactional cementation. Intense bioturbation has destroyed most non-biogenic sedimentary structures, although small-scale scours occur sporadically in the lower part of the formation (Davies, 1967, 1969; Hounslow, 1987). Near the base of the Bridport Sand Formation both on East Cliff and on Thorncombe Beacon there is a series of conspicuous undulating cemented bands, with a wavelength of about 20 m and amplitude of about 3 m, that have been described by Hesselbo and Jenkyns (1995) and Pickering (1995). The top of the Bridport Sand Formation is marked by a hardground that is locally overlain by a thin iron-stained clay seam, immediately beneath the Scissum Bed at the base of the Inferior Oolite Group.

Identifiable fossil material is generally sparse in the Bridport Sand Formation except in the uppermost beds, which are packed with ammonites and other fossils. Buckman (1910) and Jackson (1926) recorded impressions of the ammonite *Dumortieria in* the Down Cliff Clay Member, but generally only the more robust calcitic fossil material such as belemnites (Doyle, 1990–1992) and crinoids (Simms, 1989) have survived. There has been little work on the microfauna, though Lord (1974) recovered ten species of ostracod from the lower part of the Down Cliff Clay Member.

Interpretation

The Lias Group on the Dorset coast has been the subject of intense collecting and research for at least two centuries. An outline of the ammonite sequence was already well-established by the time Lang and his co-authors (1914 to 1936) described the stratigraphy in this area. Subsequent stratigraphical work has served to refine the earlier stratigraphical schemes and define the position of the biostratigraphical and lithostratigraphical boundaries.

The base of the Lias Group and of the Blue Lias Formation was placed by Lang (1924) at the base of a conspicuous paper shale (Bed H1), which rests on an erosion surface at the top of the limestones of the Langport Member (formerly White Lias) of the Penarth Group (Wignall, 2001). This boundary was formerly taken to mark the base of the Jurassic System, but this is now defined by the first appearance of the ammonite *Psiloceras,* which at Pinhay Bay occurs in Lang's Bed H25 (Cope *et al.,* 1980a).

The junction of the Blue Lias Formation and the overlying Charmouth Mudstone Formation was originally placed by Lang (1924; Lang *et al.,* 1923) at Table Ledge (Bed 53). However, this boundary is well above the onset of mudstone-dominated deposition and accordingly it is now placed at an erosion surface at the top of Grey Ledge (Bed 49), which marks the upper limit of closely spaced limestones in the type section. The junction between the Shales-with-Beef and the Black Ven Marl members is taken at the base of the Birchi Tabular (Bed 76a) at an upward change from predominantly organic-rich to carbonate-rich mudstones. A significant boundary, and hiatus representing at least three ammonite subzones, lies within the Black Ven Marls of Lang and Spath (1926) at about the level of the Coinstone (Bed 89). Although the dark-grey mudstones above the hiatus resemble those below, they lack the large diagenetic limestone nodules and are much richer in pyritized ammonites. This same facies can be recognized elsewhere in the Wessex Basin and in the Severn Basin, and at its maximum development spans the Oxynotum and Raricostatum zones. Accordingly Page (pers. comm.) has proposed that the Black Ven Marl Member be emended to include only the lower part of the succession beneath the Coinstone, with the pyritic ammonite-rich mudstones above being re-named as the 'Stonebarrow Pyritic Member'.

The position of the Sinemurian–Pliensbachian boundary has been the subject of some debate. Lang *et al.* (1928) placed the boundary below the upper part of Hummocky (Bed 103b) but, based on later discoveries, Cope *et al.* (1980a) placed it at the base of the Apoderoceras Limestone (Bed 105), as did Page (1992). However, Hesselbo and Jenkyns (1995) maintained that Hummocky and the clays above Hummocky (beds 103 and 104) accumulated during extensive reworking of Raricostatum Zone sediments in earliest Pliensbachian times and hence the boundary should be drawn at the base of

Hummocky (below Bed 103a). The boundary between the Belemnite Marl and Green Ammonite Mudstone members is clearly defined, both lithostratigraphically and biostratigraphically, by the top of the Belemnite Stone, which is coincident with the Ibex–Davoei zonal boundary.

The junction between the Charmouth Mudstone Formation, and hence also the Green Ammonite Mudstone Member, and the succeeding Dyrham Formation is placed immediately below the lowest of the Three Tiers at the base of the Eype Clay Member, one of three members within the formation. This is not quite coincident with the base of the Upper Pliensbachian Substage, which is marked by the first appearance of amaltheid ammonites about 3 m below the top of the Charmouth Mudstone Formation. The base of the Down Cliff Sand Member is drawn at the base of the Starfish Bed, with the base of the Thorncombe Sand Member placed at the top of the Margaritatus Stone. An erosion-surface contact with the highly condensed Marlstone Rock Member marks the junction of the Dyrham Formation with the Beacon Limestone Formation. The Marlstone Rock Member has yielded ammonites indicating both subzones of the Spinatum Zone and all but the Clevelandicum Subzone of the Tenuicostatum Zone (Howarth, 1980). The vertical extent of pale, fine-grained limestones of the overlying Eype Mouth Limestone Member clearly define its boundaries. The member is highly condensed and incorporates representatives of nearly all of the Toarcian zones and subzones. Howarth (1980) noted that there was no evidence for the presence of the lower part of the Exaratum Subzone. However, the presence of ammonites in the neptunian fissures caused considerable difficulties of interpretation for some of the earlier accounts (Buckman, 1922; Jackson, 1922, 1926) and was not satisfactorily resolved until the work of Jenkyns and Senior (1977, 1991). The base of the overlying Bridport Sand Formation is clearly drawn above the topmost limestone bed of the Beacon Limestone Formation and, although more than ten times as thick as the latter formation, It represents only the uppermost two ammonite zones of the Toarcian Stage. A distinct hiatus marks the boundary with the succeeding Middle Jurassic succession.

There has been considerable discussion concerning the primary or secondary (diagenetic) nature of some of the conspicuously rhythmic sequences developed in the Lias Group of Dorset. Richardson (in Lang *et al.,* 1923) proposed a secondary origin for both the Blue Lias Formation limestones and the limestone nodules higher in the succession. Hallam (1957) and Simpson (1957) described evidence, particularly from trace fossils, for an essentially primary origin for the limestones although subsequently Hallam (1960a, 1964a) conceded that many of the limestones in the Blue Lias Formation were accentuated to some degree by diagenetic segregation. More recently Hallam (1986) proposed that many may have formed solely through rhythmic unmixing of calcium carbonate during diagenesis. Bottrell and Raiswell (1989) concluded from a study of pyrite abundance and sulphur-isotope composition that the limestone–mudstone rhythms reflected primary differences in the carbonate content of the sediment, which subsequently exerted a direct effect on the diagenetic accentuation of the carbonate-rich units. They noted that diagenetic cementation would be enhanced by a hiatus in sedimentation. Moghadam and Paul (2000) concluded that the limestone units were entirely diagenetic, but that the rhythmicity evident in the Blue Lias Formation reflected primary differences in the sediment rather than the effects of diagenetic unmixing. Hesselbo and Jenkyns (1995) have suggested that a few of the limestones, notably beds H4 and H30, may have been deposited from submarine mudflows, analogous to those seen in the Langport Member (formerly White Lias) at the western end of the GCR site (Hallam, 1969b), or from low-density turbidity currents.

Hallam (1960a, 1964a) suggested that the rhythmicity in the Blue Lias Formation might reflect epeirogenic oscillations in sea level. Others have suggested climatic control related to Milankovitch orbital cycles (House, 1985; Weedon, 1986, 1987; Smith, 1989; Weedon *et al.,* 1999). Waterhouse (1999) described paly-nofacies cycles in the Blue Lias Formation that appear independent of lithology and which may also be linked to Milankovitch cycles. Cole and Harding (1998) found a close correspondence between palynofacies cycles and transgressive–regressive sequence boundaries in the Charmouth Mudstone Formation. Bessa and Hesselbo (1997) noted cyclicity in their gamma-ray log for the Belemnite Marl Member reflecting variable calcium carbonate contents through the succession. Supposed Milankovitch cyclicity has also been described from beds 110 to 117 (Polymorphus to Jamesoni subzones) in the Belemnite Marl Member (Weedon and Jenkyns, 1990, 1999). Bioturbation and changes in the body-fossil and trace-fossil assemblages in parallel with the light-dark couplets indicate a primary origin for these cycles, which they considered had experienced less diagenetic modification than the Blue Lias Formation. Weedon and Jenkyns (1990, 1999) identified at least two scales of cycle that they they interpreted as a 20 ka precession cycle and more irregular, larger amplitude, climatic variations. Van Buchem and McCave (1989) documented a strikingly similar succession of light-dark sediment couplets in the Banded Shales, also spanning the Polymorphus to Jamesoni subzones, of the Redcar Mudstone Formation at Robin Hood's Bay. They too suggested a periodicity of 20 ka for each couplet. House (1986) has identified analogous rhythms elsewhere in the Lias succession, specifically in the Shales-with-Beef Member and Bridport Sand Formation. In both cases there is evidence for at least some diagenetic accentuation of the cyclicity. Hesselbo and Jenkyns (1995) also identified small-scale, coarsening-upward cycles in the Bridport Sand Formation. Diagenetically cemented bands within this formation also display a conspicuous rhythmicity but Davies (1967) suggested that the cementation reflected primary differences in the detrital carbonate content of the sediments.

Evidence for a diagenetic origin is clearer for many of the limestones in the Shales-with-Beef and Black Ven Marl members, most of which are discontinuous and nodular. Many are laminated or have a septarian structure, and the frequent presence of beautifully preserved uncrushed ammonites indicates nodule formation at shallow burial depth before compaction. Raiswell (1971) considered that the Birchi Nodules (Bed 75) (Figure 2.7) may have developed during a pause in deposition, with porosity estimates, strontium isotopes and mineralogy indicating growth in a geochemical system partially open to the sea. Hesselbo and Palmer (1992) have described the sequence of events in diagenetic nodule formation. In the Lias within the GCR section this reached its acme in the Coinstone (Bed 89) and associated nodule horizons that experienced burial, exhumation and re-burial over the duration of at least three ammonite subzones. Their observations indicate that initial fracturing during septaria formation occurred not in a hard, brittle material, such as the nodules present today, but in a more plastic medium perhaps analogous to cheese.

The development of early diagenetic limestone nodules in the Shales-with-Beef and Black Ven Marl members contrasts with their scarcity in the Stonebarrow Pyritic Member. Conversely, although pyrite is common in all three members it is only in the Stonebarrow Pyritic Member that it commonly occurs as uncrushed pyritic moulds of ammonites and other fossils, indicating early diagenetic formation. In the Shales-with-Beef and Black Ven Marl members it more typically occurs as nodules and encrustations of already crushed ammonites, indicating formation later in diagenesis. Both pyrite and early diagenetic carbonate nodules form in the sulphate reduction zone but differences in the development of these in the mudstones above and below the Coinstone hiatus may reflect differences in sedimentation rates and probably in benthic oxygen levels. Precipitation of pyrite is inhibited by rapid burial of organic-rich sediment, since this allows insufficient time for the necessary downward diffusion of sulphate (Curtis, 1995). Downward diffusion rates of sulphate will also be slowed significantly by the exclusion of burrowing benthos, which is a consequence of benthic anoxia, since burrows provide potential diffusion routes for sulphate ions. Consequently, pyritization of fossil material in the Shales-with-Beef and Black Ven Marl members tends to occur at a relatively late stage, after the fossils have been crushed by sediment compaction. However, benthic anoxia does seem to favour the precipitation of very early diagenetic calcite concretions in which the ammonites are uncrushed; these are a conspicuous feature of many organic-rich mudstone units at this site, particularly in the Shales-with-Beef and Black Ven Marl members, but are also a significant component of organic-rich successions at other GCR sites, notably those in the Toarcian succession on the Yorkshire coast. There are at least two horizons in the Dorset Lias, the Coinstone (Bed 89) of the Black Ven Marl Member and the Eype Nodule Bed of the Eype Clay Member, where early diagenetic calcite concretions locally have a pyrite skin. In both instances this is associated with a history of burial, exhumation and re-burial, thereby allowing two distinct periods of sulphate reduction to occur at these horizons. Observations made by Hesselbo and Palmer (1992) indicate that this pyritization did not occur during the exhumation phase but was associated with, or shortly preceded, re-burial by the mudstones of the Stonebarrow Pyritic Member. These examples may be analogous to some of the pyrite-skinned carbonate nodules noted in the Jet Rock of the Mulgrave Shale Member on the Yorkshire coast (Hallam, 1962a; Coleman and Raiswell, 1981), such as at the Staithes to Port Mu'grave GCR site.

The development of discontinous layers and lenses, or seams, of fibrous calcite, or 'beef', within parts of the Dorset Lias, notably in the Shales-with-Beef Member, has long elicited debate. Richardson (in Lang *et al.,* 1923) recognized that the 'beef' seams post-dated the carbonate nodules and concluded that the 'beef' was deposited by downwardly percolating carbonate solutions into cracks that had opened as a result of the desiccation and contraction of the shales. It is now thought that 'beef' seams form as a result of rapid over-pressuring of organic-rich shales at burial depths of several tens to hundreds of metres, within the methanogenic zone (Marshall, 1982; Stoneley, 1983). On the Dorset coast, about 100 m above the Shales-with-Beef Member lies the base of the Dyrham Formation, of which the lowest 93 m (the Eype Clay and Down Cliff Sand members) was deposited during just one ammonite subzone (Stokesi Subzone) (Figure 2.11). This rapid influx of sediment may have caused the hydrostatic over-pressuring of the organic-rich shales of the Shales-with-Beef and Black Ven Marl members while their high organic content ensured that sufficient carbon survived oxidation in the sulphate-reducing zone to generate carbonate for 'beef' formation during methano-genesis. The absence or poor development of 'beef' in organic-rich successions elsewhere in the British Lias may reflect the unusually high sedimentation rate during the Stokesi Subzone in Dorset, while its poor development in the Blue Lias Formation and other parts of the Charmouth Mudstone Formation reflects generally lower organic-carbon contents.

The Dorset Lias has been important for understanding the varied nature of stratigraphical hiatuses, the processes by which they are formed, and the various techniques by which they can be detected. That associated with the Coinstone (Bed 89) is among the best documented of these. Hesselbo and Palmer (1992) attribute the exhumation of the carbonate nodules in large part to bio-erosion but could not decide whether this event reflected lower sea level or reduced sediment supply. Hallam (1969, 1999) favoured the former and cited the absence of any associated condensed facies as evidence against sediment starvation. Further examples include the hiatus at the top of the Watch Ammonite Stone (Bed 99), the top of Hummocky (Bed 103) (Sellwood, 1972) and, in the Upper Pliensbachian, the Eype Nodule Bed (Ensom, 1985b), the Margaritatus Stone (Sellwood *et al.,* 1970) and others noted by Wilson *et al.* (1958). The Beacon Limestone Formation, encompassing the top of the Pliensbachian Stage and much of the Toarcian Stage, is highly condensed and contains spectacular hiatuses with ammonites and other fossils abruptly truncated along some surfaces (Jackson, 1922, 1926; Jenkyns and Senior, 1977, 1991). Many hiatuses elsewhere in the Lias are less obvious, with no evidence of a major biostratigraphical break or lithological change. They may be indicated by concentrations of obdurate fossils, such as belemnites, or by reworked lithoclasts, or an intensely burrowed horizon. Examples include the erosion hiatus surfaces at Grey Ledge (Bed 49), in the mudstones of Bed 83 (Hesselbo and Jenkyns, 1995), and at the top of the Belemnite Bed (Bed 120c). Jones *et al.* (1994) also found evidence in the strontium isotope record for a hiatus at this last horizon. More tenuously, Smith (1989) suggested, on the basis of correlation of presumed Milankovitch cycles, that there was a hiatus within the Angulata Zone of the Blue Lias Formation on the Dorset coast that is not present in equivalent strata in the Somerset coast section.

The Dorset Lias has contributed a great deal to our understanding of the effects of syn-sedimentary fault movement and its manifestation in the geological record. One example is the westward thinning of the Belemnite Marl Member and the Green Ammonite Mudstone Member away from the Eypemouth Fault. The Bridport Sand Formation has been cited as an exception to this westward thinning, showing a distinct thickening westwards from East Cliff to Thorncombe Beacon (Hesselbo and Jenkyns, 1995). However, this supposed exception does not take into account the fact that different stretches of the coastline are being compared. The sections through the Belemnite Marl and Green Ammonite Mudstone members referred to all lie to the west of the Eypemouth Fault, known to have been active during Early Jurassic times (Jenkyns and Senior, 1977, 1991), whereas the Bridport Sand Formation exposures are located both to east and west of the fault. Hence the apparent westward thickening of the latter formation may reflect thickness differences across the fault rather than being analogous with the eastward thickening of the Belemnite Marl and Green Ammonite Mudstone members. More direct evidence of syn-sedimentary movement comes from the correlation of individual marker bands across specific faults. Various authors (Lang, 1945; Hallam, 1969; Hesselbo and Palmer, 1992) noted that whereas there was a hiatus directly above the Coinstone (Bed 89) on Stonebarrow, the same hiatus occurred more than 1 m above the level of the Coinstone on Black Ven. Similarly, the difficulties of tracing several of the nodule bands in the Obtusum Zone from Black Ven to Stonebarrow, a problem noted by Lang and Spath (1926), may be attributable to erosive removal of the Woodstone (Bed 83f) and Lower Flatstones (Bed 83d) horizons on Stonebarrow. This is suggested by a hiatus surface above the Pavior (Bed 82) at the latter site (Hesselbo and Jenkyns, 1995). Both the Coinstone and Pavior hiatuses may indicate syn-sedimentary movement on the nearby Char Fault.

The Eypemouth Fault at the eastern end of the GCR site has provided some of the most convincing evidence for syn-sedimentary faulting Genkyns and Senior, 1977, 1991). As the fault is approached from the west the Eype Mouth Limestone Member thickens dramatically, from less than 0.5 m to as much as 3.5 m over a distance of less than 0.5 kin, and is cut by many sediment-filled 'neptunian' sills and dykes. These formed as a result of tectonic stresses associated with fault movements and allowed ammonites and other fossils to become intercalated, out of sequence, into older parts of the succession. Ensom's (1988) observations of siltstone dykes cutting the Starfish Bed near Eype Mouth, and their absence from this same unit farther west, provides further evidence of syn-sedimentary movement on this fault and the extent of its influence on surrounding sediments.

The relationship between syn-sedimentary movement on faults and the development of erosional hiatuses is exemplified by the diachronous nature of the hiatus surface associated with the Eype Nodule Bed. As the Eypemouth Fault is approached from the west the sequence shows an initial incorporation of nodules into the base of the overlying sandstone, then the pinching out of the sandstone and development of pyritic rims on the nodules, and finally evidence of exhumation and encrustation of nodules adjacent to the fault.

There have been few broad-based palaeoenvironmental interpretations of the Lias of Dorset, largely because the mudstone-dominated nature of much of the succession has deterred investigations of this type. Hesselbo and Jenkyns (1998) provide the only general account, describing the succession in terms of sequence stratigraphy and relative sea level. They have interpreted the organic-rich mudstones, such as those of the Shales-with-Beef and Black Ven Marl members, as deposited during periods of sea-level rise or highstand, and the erosional hiatuses associated with the Coinstone and the Hummocky horizons to represent sediment starvation during deepening events. In the Belemnite Marl Member, they attributed the condensed nature of the Belemnite Bed to shallowing, and condensation in the Belemnite Stone to deepening. They concluded that the facies developed at any particular level reflect the interplay of a variety of factors.

Some of the sandier units in the Lias have been specifically discussed and some general observations and interpretations can be made for other parts of the succession or extrapolated from contiguous strata. Goldring and Stephenson (1972) concluded that the exceptional preservation of the ophiuroids in the Starfish Bed at the base of the Down Cliff Sand Member was due to burial by a sudden influx of sand that was thick enough to prevent subsequent disruption of the remains by bioturbation. The load structures reported by Sellwood *et al.* (1970) from other levels in the Down Cliff Sand Member also suggest rapid sedimentation. A similar mechanism can be invoked for the occurrence of most intact echinoderms throughout the Lias Group of Dorset, including other occurrences of intact crinoids, ophiuroids and asteroids from the Eype Clay Member and intact examples of the echinoid *Miocidaris lobatum* and the ophiuroid *Palaeocoma escberi* from the Blue Lias Formation. In other parts of the sucession the presence of intact multi-element skeletons, such as echinoderms and vertebrates, is due largely to preservation in anoxic or dysaerobic benthic environments. The organic-rich parts of the Shales-with-Beef and Black Ven Marl members are developed in such facies and have proven an important source of well-preserved marine reptiles and fish. Simms (1986) demonstrated that the extraordinary preservation of the crinoid *Pentacrinites fossilis* in the Black Ven Marl Member was also due to benthic anoxia, though current winnowing of the upper surfaces of these specimens demonstrated that conditions were not entirely stagnant and that sedimentation rates were low. Although very low levels of bioturbation sometimes are present in these organic-rich mudstones, benthic bivalve larvae did not generally survive spatfall except during brief periods of more oxygenated conditions that allowed the development of thin shell pavements. In contrast, the pseudoplanktonic *Pentacrinites* was brought in on floating driftwood, which then sank to the anoxic sea floor. Simms (1999) has suggested that a current gyre may have developed across this area for a relatively brief period during the Obtusum Zone, trapping many crinoid-laden floating logs that eventually sank to form a relatively high concentration of specimens through some 2 m of the Black Ven Marl Member.

Dysaerobic benthic conditions appear to have been fairly prevalent in the basal part of the Blue Lias Formation on the Dorset coast, and in other areas such as the north Somerset coast. The fauna has a relatively low diversity dominated by the bivalve *Liostrea bisingeri* and the slender-spirted echinoids *Diademopsis* and *Eodiadema,* presumably tolerant of low oxygen levels. The echinoids typically are disarticulated but intact material occurs in some laminated shales, suggesting that benthic oxygen levels periodically dropped still further.

Despite the overwhelming dominance of marine organisms in the Lias at this GCR site, fossil evidence for a nearby landmass is also present. Fossil driftwood occurs sporadically thoughout the Lias Group, but it is particularly abundant in the upper part of the Shales- with-Beef and Black Ven Marl members, where trunks up to nearly 4 m long have been recorded (Macfadyen, 1970). This part of the succession has also yielded a rich fauna of insects, which are otherwise virtually unrepresented in the Dorset Lias, and several specimens of the ornithischian dinosaur *Scelidosaurus.* Whalley (1985) postulated that the preservation of the insects indicated a landmass less than 80 km away, perhaps an extension of the Cornubian Massif to the west ((Figure 1.10); Chapter 1), which may have persisted for a few hundred thousand years.

The Bridport Sand Formation has been the subject of several palaeoenvironmental analyses. More than a century ago (Buckman, 1889) showed that the Toarcian sands of south-west England were diachronous and younged to the south. Davies (1969) proposed that the sands represented a large migrating sand-bar while others have suggested deposition in a lower or middle shoreface environment above storm wave-base (Colter and Harvard, 1981; Hounslow, 1987; Bryant *et al.,* 1988). More recently, Pickering (1995) proposed that broadly undulating cemented bands near the base of the Bridport Sand Formation formed as near-symmetrical scours beneath standing waves in shallow water, while Hesselbo and Jenkyns (1995) suggested that they are predominantly aggradational and formed as ridges at the toe of an advancing sand slope. The well-cemented layers have been interpreted as tempestites and have a significantly lower clay content than the uncemented layers. This suggests that their higher permeability allowed earlier cementation of these horizons (Bryant *et al.,* 1988).

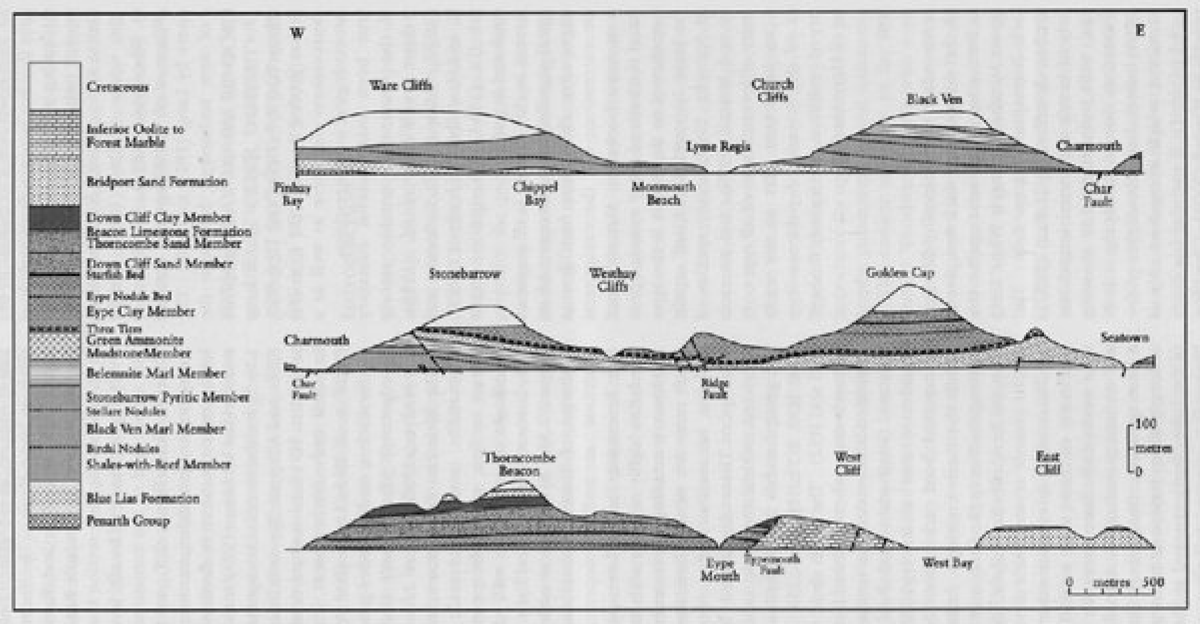
The Lias succession in Dorset has long served as a standard against which other Lower Jurassic successions in Britain and farther afield have been compared. The most recent lithostratigraphical comparison was by Hesselbo and Jenkyns (1995), between the Dorset succession and that exposed on the Yorkshire coast. Although some eustatic signals are evident in both basins, they noted a relationship between several of the facies units in the two areas in which a coarser-grained unit in one basin would be represented by a finer-grained one in the other basin and vice versa. Assuming the same sea-level histories for both areas they explained these differences in terms of proximal and distal settings and the role of local tectonics in creating accommodation space for sediment.

Faunal differences between the Dorset Lias and correlative strata in other basins have formed the basis of several palaeobiogeographical studies and established the existence of distinct provinces for several groups of fossils, notably ammonites (Howarth, 1958) and brachiopods (Ager, 1956a).

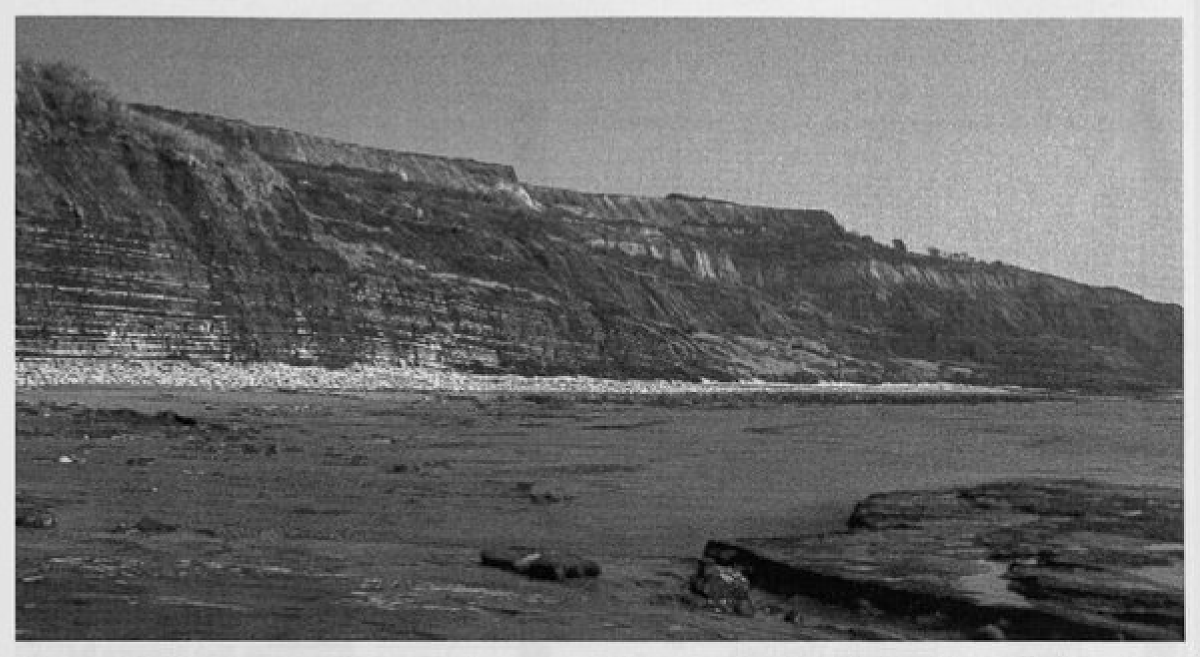
Conclusions

The Dorset coastline between Pinhay Bay and Fault Corner, and the separate GCR site of East Cliff provides unparalleled and readily accessible exposures through the entire Lower Jurassic succession. The site has been investigated and collected from for more than 200 years and has played an important role in the development of geology as a science and in the sub-disciplines of palaeontology and stratigraphy. As such it has been of fundamental importance in establishing a biostratigraphy for the marine Lower Jurassic Series and has also furnished an impressive diversity of type specimens of both vertebrate and invertebrate fossils. It continues to be of outstanding importance as a source of fossil material. It incorporates lithostratigraphical type sections and has contributed significantly to an understanding of the relative roles of climate, sea-level change, syn-sedimentary faulting and diagenesis on preserved sedimentary sequences. The organic-rich horizons within the succession are oil-source rocks for the richest onshore oilfield in Britain, at Wytch Farm, and hence have been much studied.

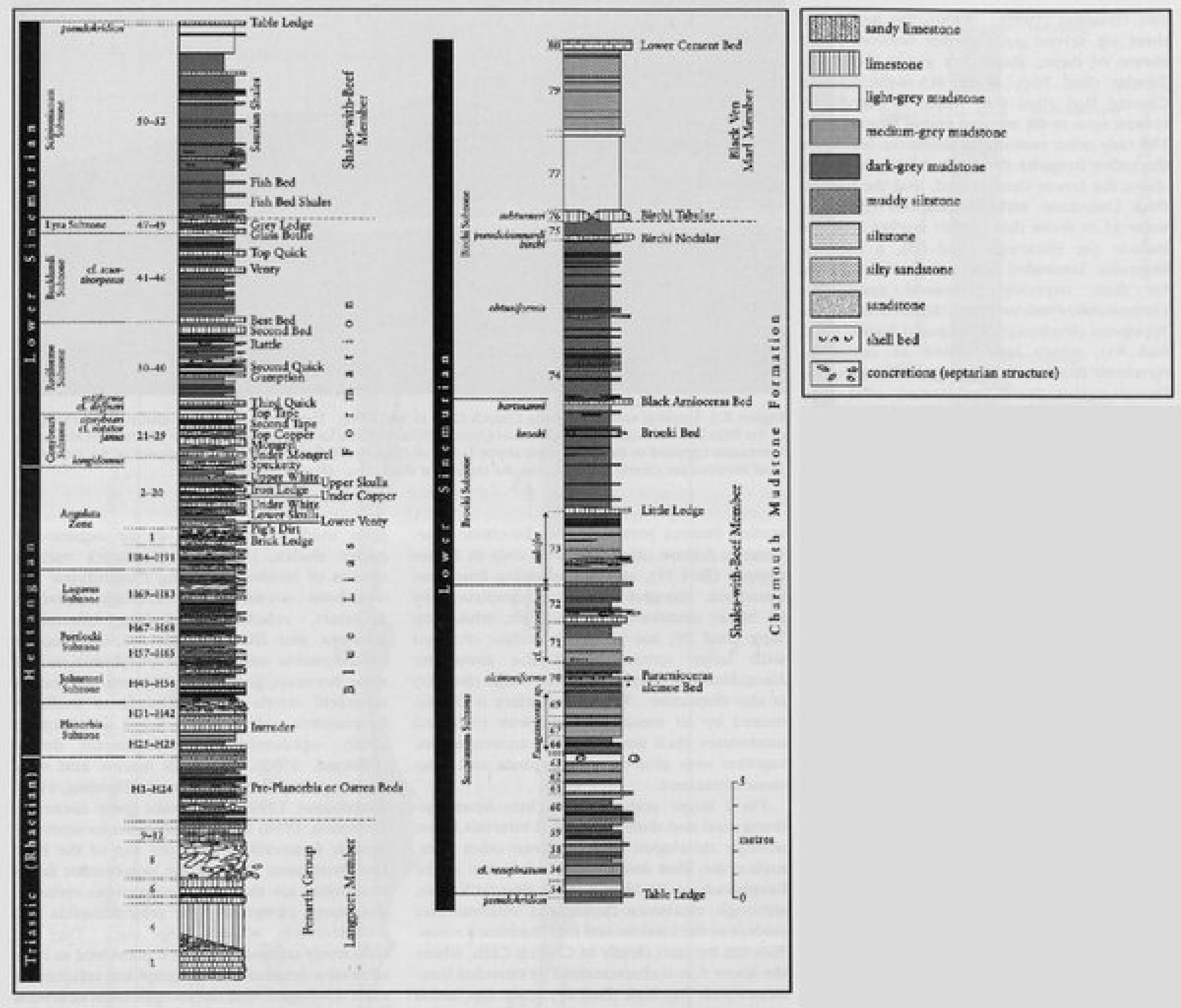
References



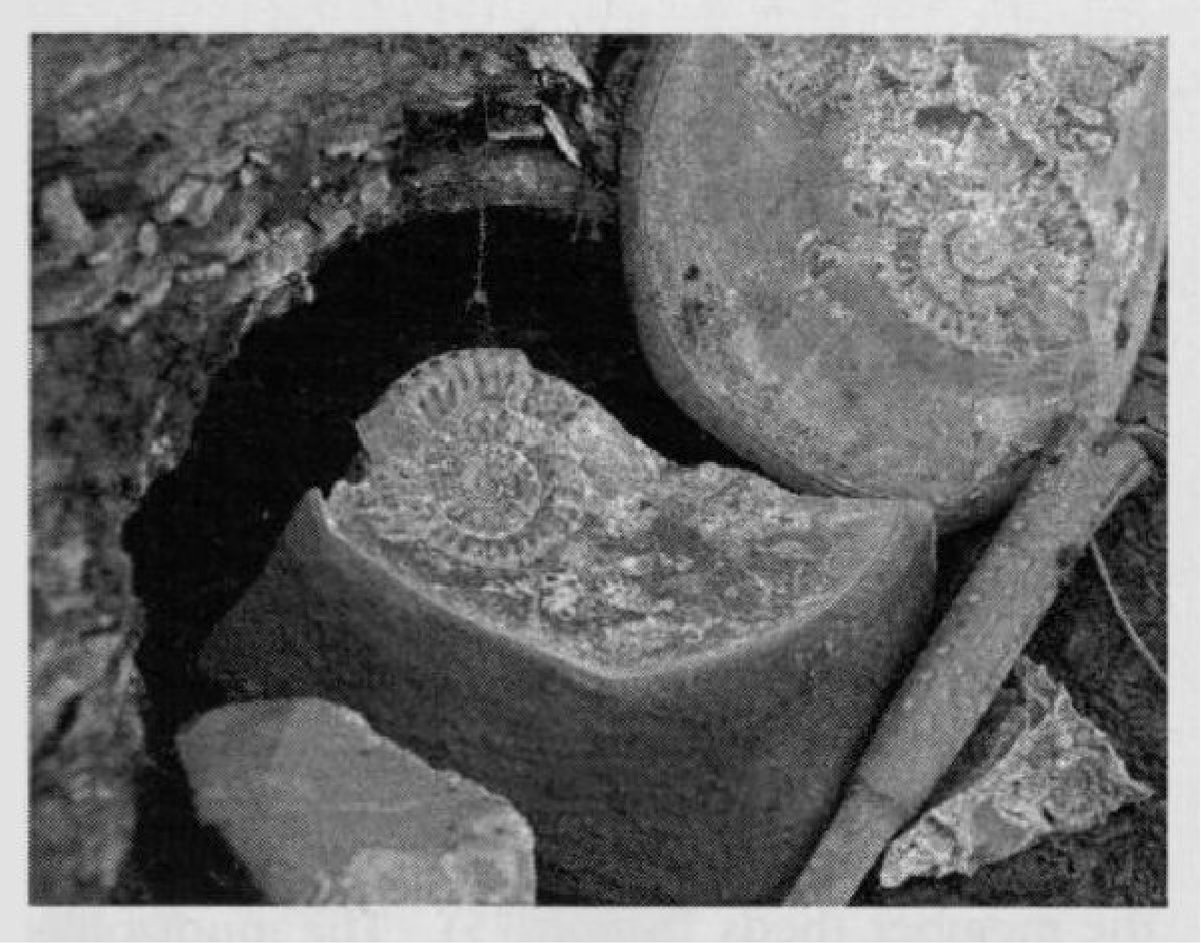
(Figure 2.4) Coastal sections of the Lower Jurassic Series between Pinhay Bay and East Cliff. Based on douse (1989) and Hesselbo and Jenkyns (1995).



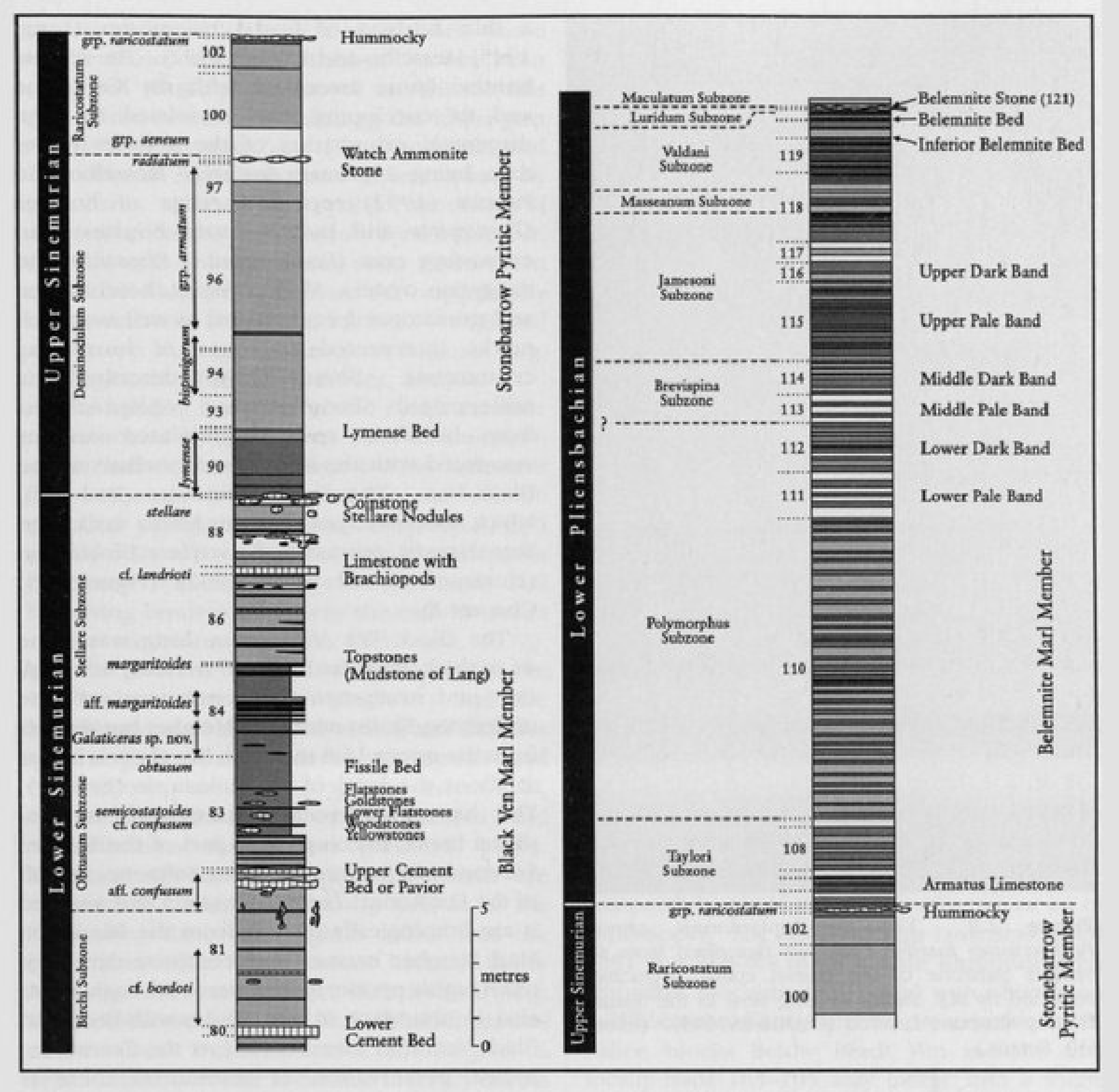
(Figure 2.5) Looking eastwards along Church Cliffs to Black Ven. The classic limestone–mudstone alternations of the Blue Lias Formation are exposed in Church Cliffs, with the various members of the Charmouth Mudstone Formation exposed in the extensively slipped cliffs of Black Ven behind. The pale mudstones of the Belemnite Marl Member are clearly visible across the middle of Black Ven. (Photo: M.J. Simms.)



(Figure 2.6) a. Section through the Penarth Group, Blue Lias Formation, Shales-with-Beef Member and basal Black Ven Marl Member west of Charmouth. After Hesselbo and Jenkyns (1995); with ammonite zones, sub-zones and biohorizons after Page (1992); and bed numbers after Lang (1924), Lang et al. (1923) and Lang and Spath (1926). b. Key to lithologies.

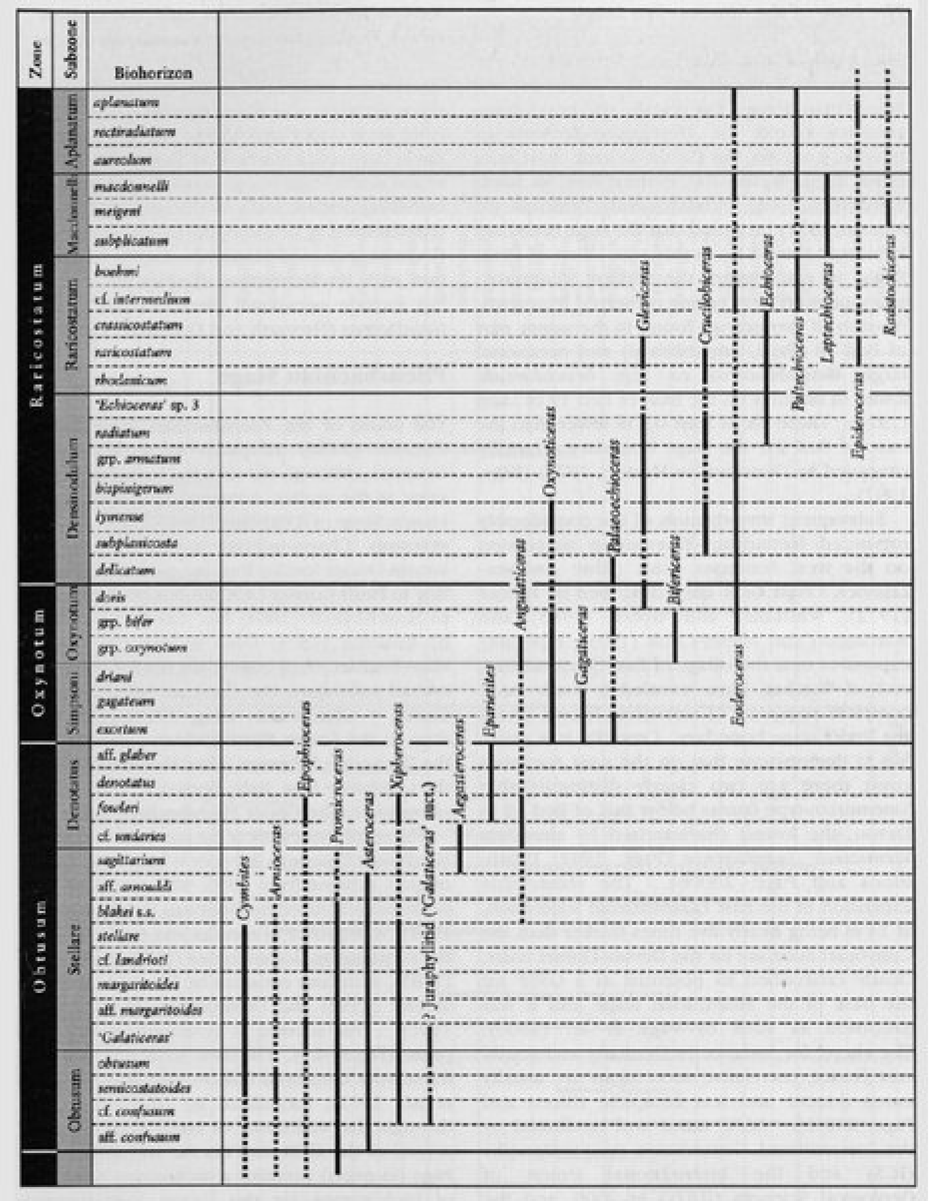


(Figure 2.7) Diagenetic concretion in the Shales-with-Beef Member containing a topotype specimen of the ammonite subzonal index fossil Microderoceras birchi (M. J. Simms collection, 1981). (Photo: M.J. Simms.)

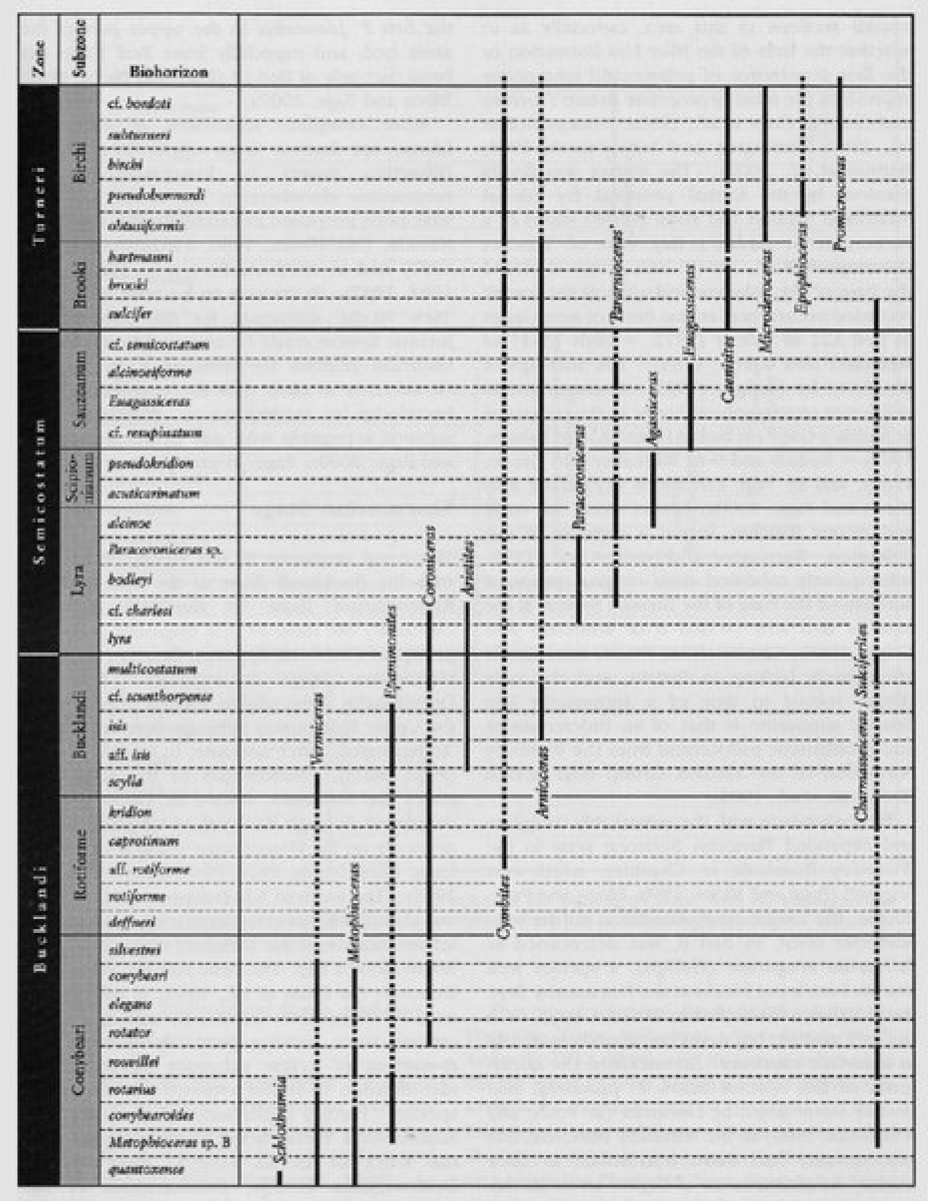


(Figure 2.8) Section through the Black Ven Marl, Stonebarrow Pyritic and Belemnite Marl members of the Charmouth Mudstone Formation on Black Ven and Stonebarrow. After Hesselbo and Jenkyns (1995); with ammonite zones, subzones and biohorizons after Page (1992); and bed numbers after Lang and Spath (1926) and Lang et al. (1928).

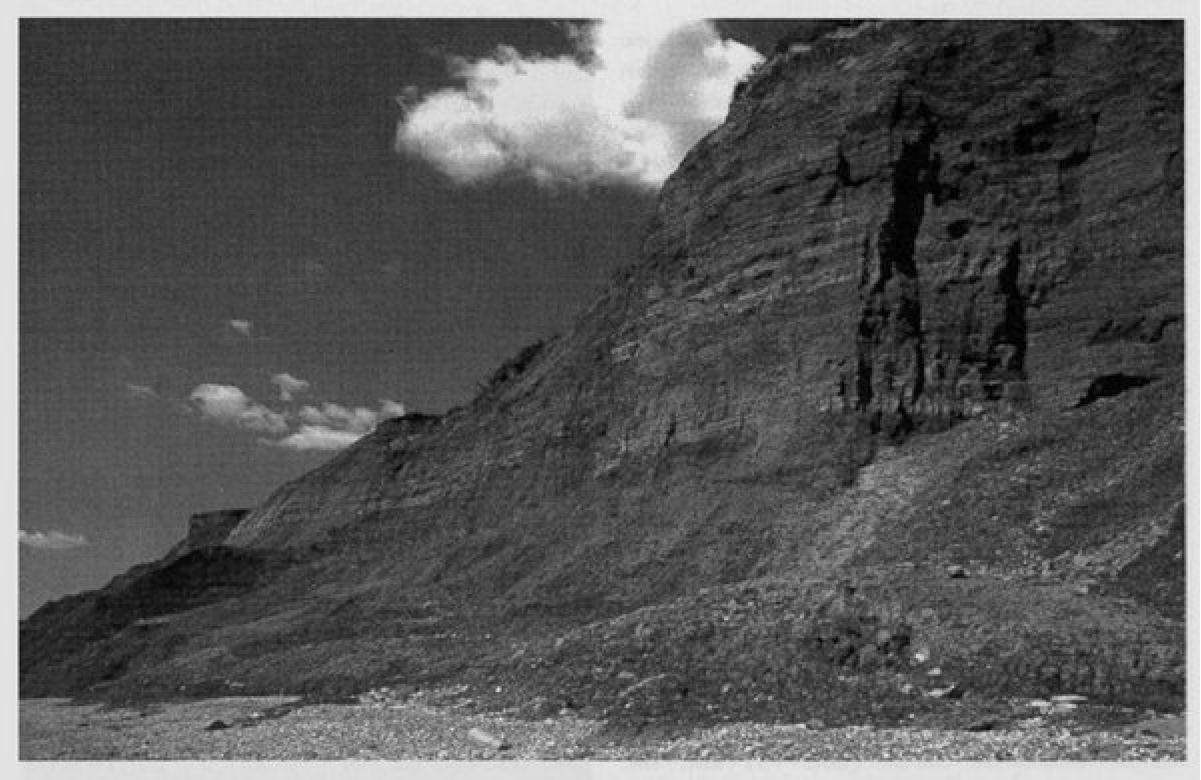
(Figure 2.9) The pseudoplanktonic crinoid *Pentacrinites fossilis*, originally described from the Stellare Subzone of the Dorset coast. Specimen collected by M.J. Simms (1982); now in the Natural History Museum, London (BMNH E69605). (Photo: M.J. Simms.)



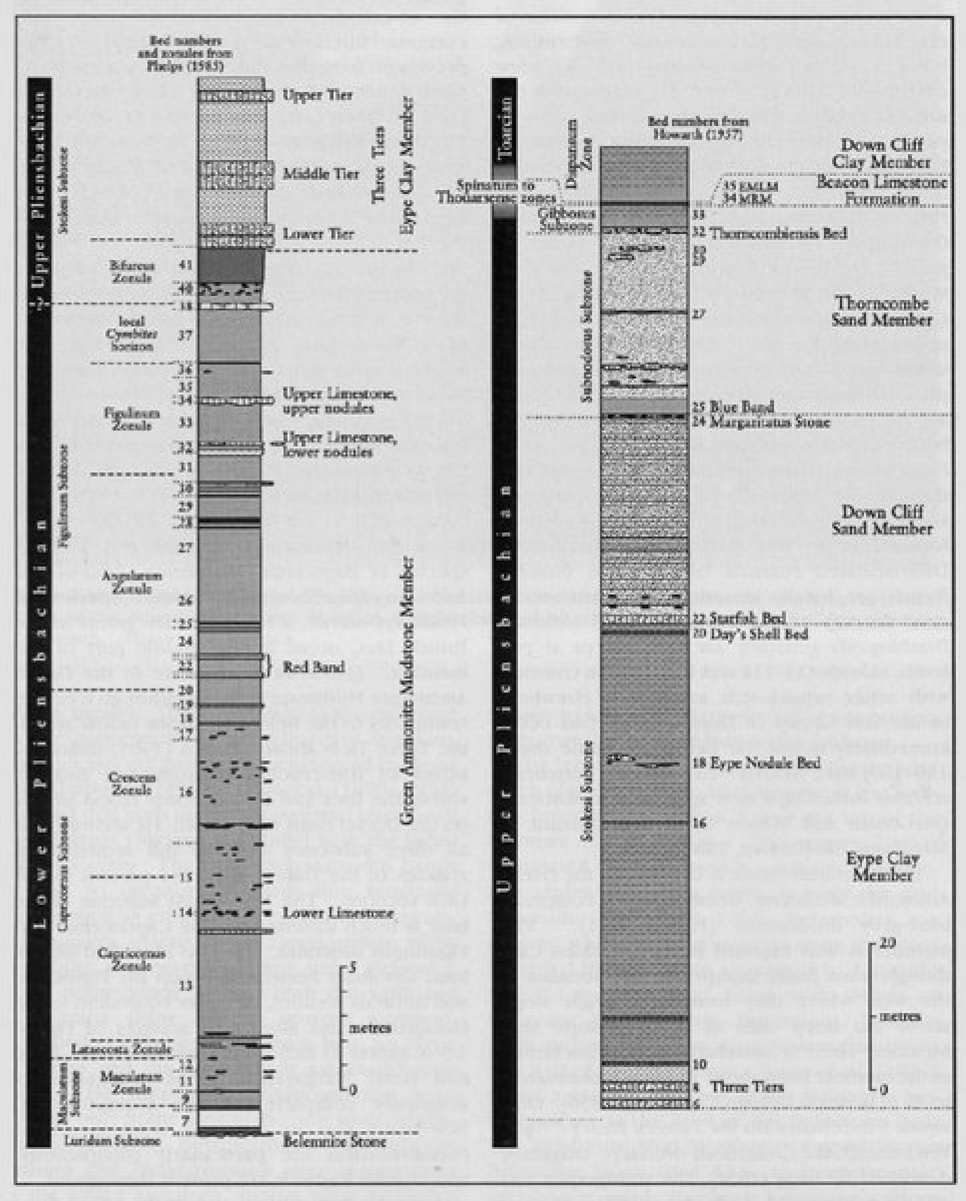
(Figure 1.5) Sequence of zones, subzones and biohorizons for the upper part of the Sinemurian Stage, with the stratigraphical ranges of ammonite genera indicated (solid line — proven; dashed line — inferred ghost range). After Page (2002) and unpublished observations.



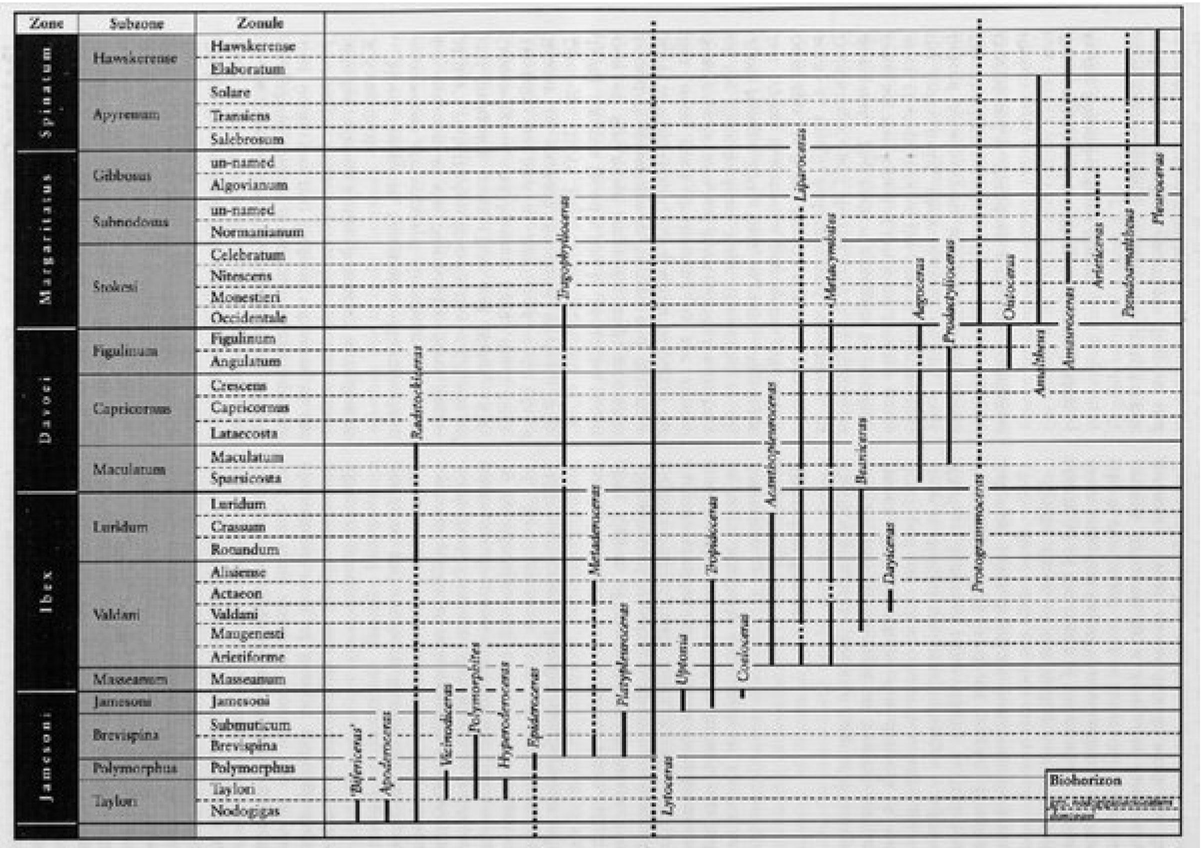
(Figure 1.4) Sequence of zones, subzones and biohorizons for the lower part of the Sinemurian Stage, with the stratigraphical ranges of ammonite genera indicated (solid line — proven; dashed line — inferred ghost range). After Page (2002) and unpublished observations.



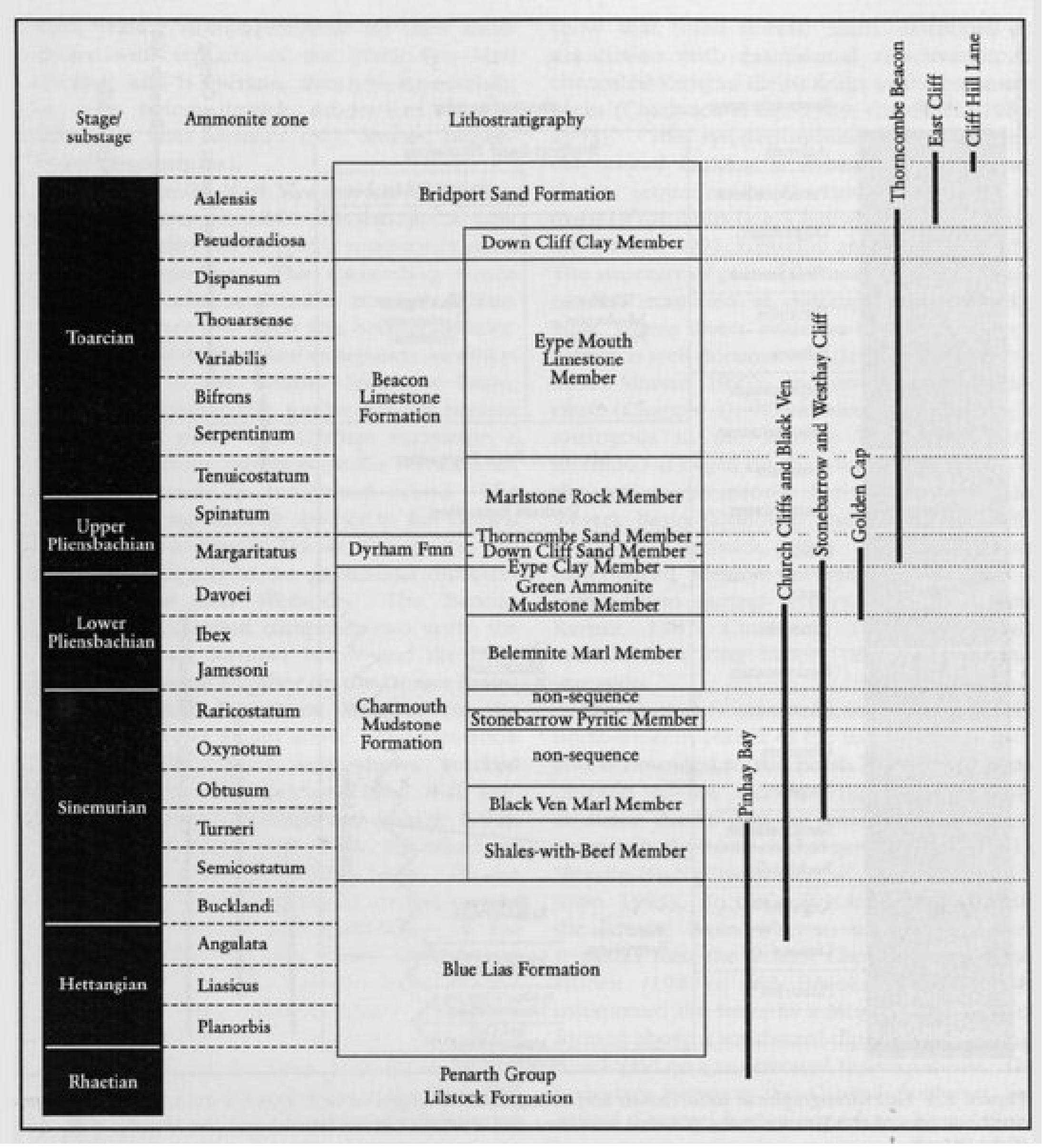
(Figure 2.10) Conspicuously striped mudstones and marls of the Belemnite Marl Member, overlying dark mudstones of the Stonebarrow Pyritic Member (largely obscured by talus) at the eastern end of Stonebarrow, Charmouth. (Photo: M.J. Simms.)



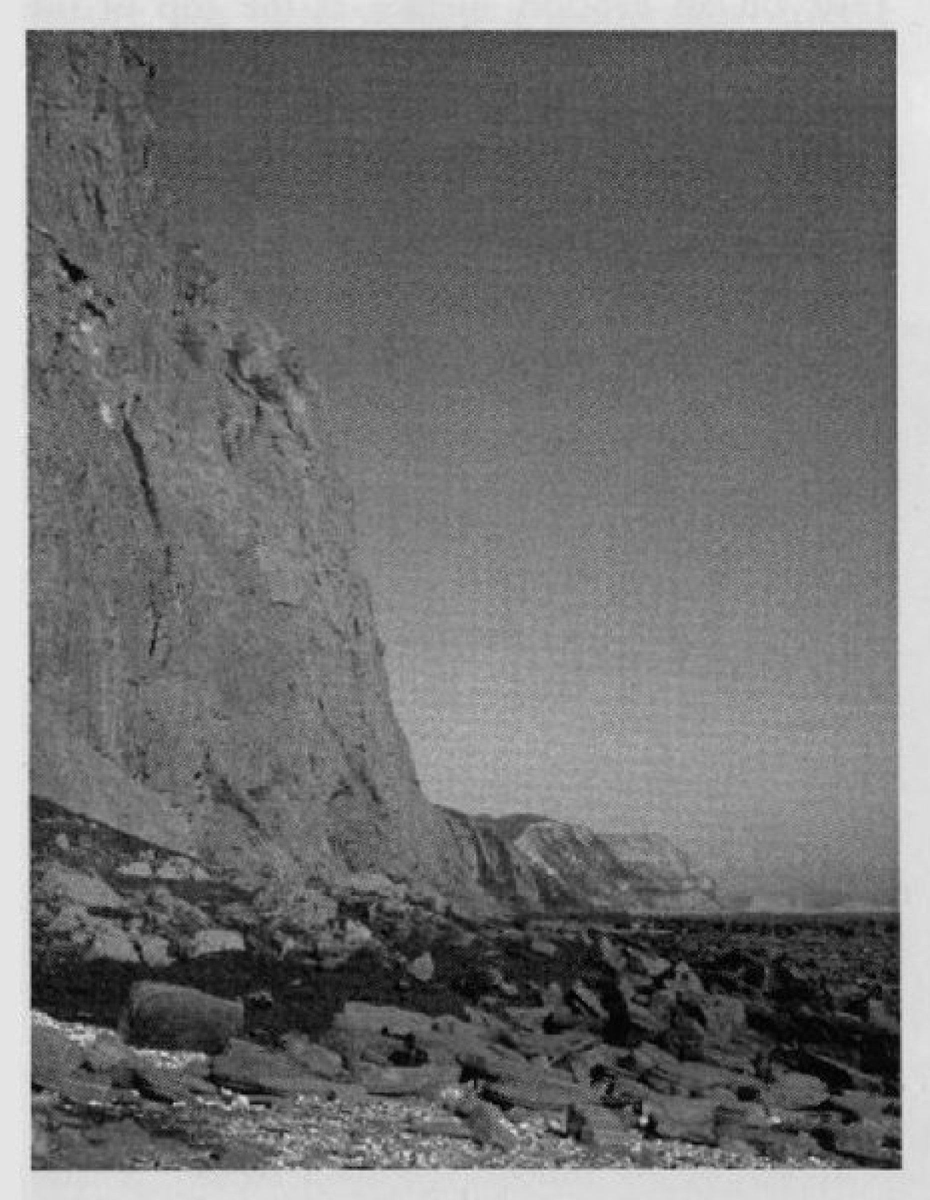
(Figure 2.11) Section from the (Lower Pliensbachian) Green Ammonite Mudstone Member to the (Toarcian) Down Cliff Clay Member of the Dorset coast. After Hesselbo and Jenkyns (1995); with ammonite zonules after Phelps (1985); and bed numbers after Lang (1936) and Howarth (1957).



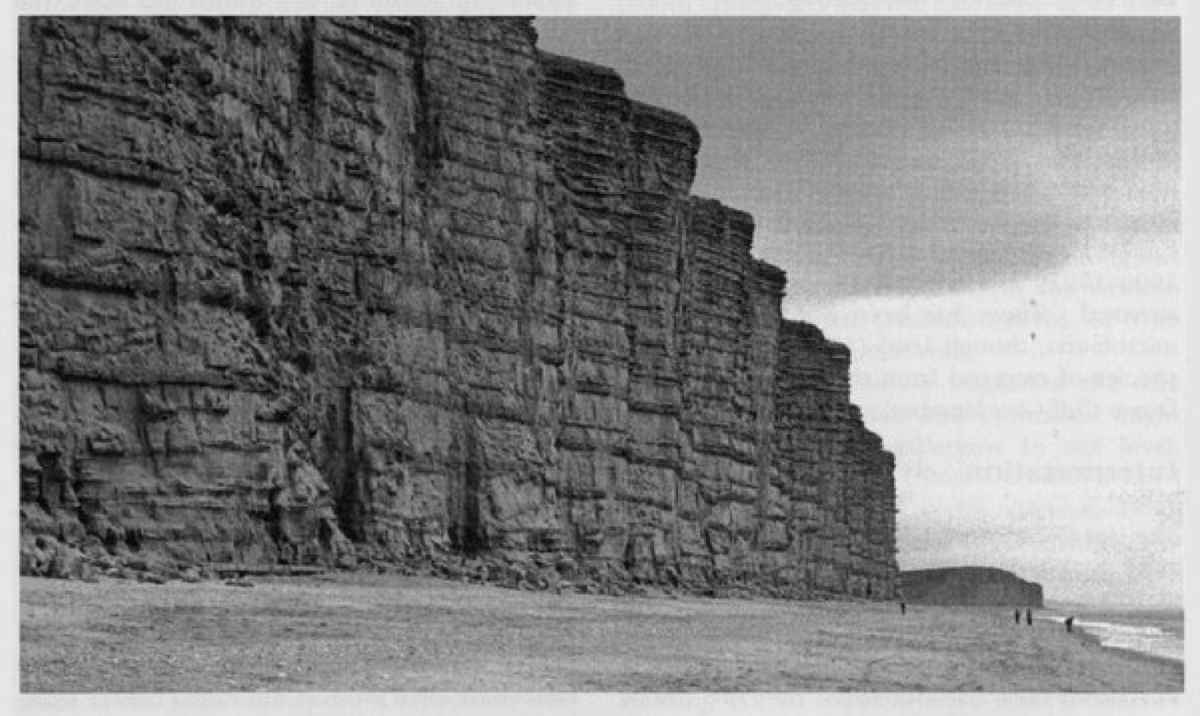
(Figure 1.6) Sequence of zones, subzones and zonules for the Pliensbachian Stage, with the stratigraphical ranges of ammonite genera indicated (solid line — proven; dashed line — inferred ghost range). After Page (2002) and unpublished observations.



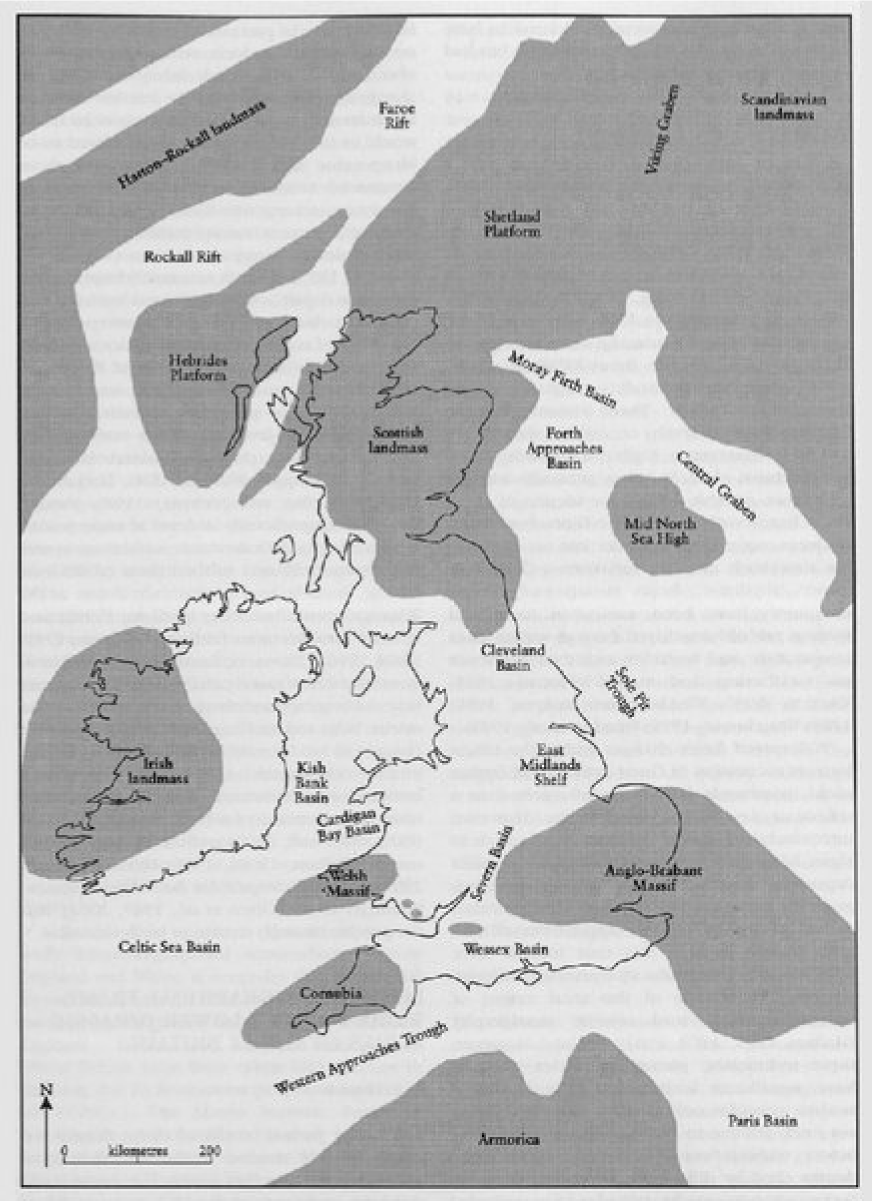
(Figure 2.2) Lithostratigraphical subdivisions and stratigraphical ranges of GCR sites for the Lias Group of the Dorset coast, in the southern part of the Wessex Basin.



(Figure 2.12) The sheer cliff face of the Eype Clay Member below Golden Cap, part of the spectacularly thick development of the Stokesi Subzone in Dorset. Thorncombe Beacon and East Cliff are visible in the distance. (Photo: M.J. Simms.)



(Figure 2.13) The Bridport Sand Formation at East Chit west of Burton Bradstock. (Photo: M.J. Simms.)



(Figure 1.10) Palaeogeographical reconstruction for the British area during the Hettangian Stage of the Lower Jurassic Series (light shading — sea; dark shading — land). After Bradshaw et al. (1992).