Tyneham Cap–Hounstout

[SY 888 796]–[SY 956 768]

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Introduction

This GCR site comprises the magnificent cliff and foreshore exposures of Kimmeridge Clay between Brandy Bay and Chapman's Pool on the Dorset coast (Figure 2.25) and (Figure 2.26). It includes Kimmeridge Bay, which gives its name to the Kimmeridge Clay Formation and the Kimmeridgian Stage, and is therefore a site of international renown. The cliffs at Brandy Bay and Hobarrow Bay, and eastwards to the western end of Kimmeridge Bay, fall within the Ministry of Defence's Lulworth Gunnery Range. The Kimmeridge Clay was first recognized as a discrete unit (called 'Oaktree Soil') by William Smith on his map of 1815 although subsequently he called it 'Oaktree Clay'. The first descriptive details were provided by Webster (1816), who changed the name to Kimmeridge Clay. Arkell (1947a) introduced names for nearly all the subdivisions of the formation at and adjacent to Kimmeridge Bay (e.g. Cattle Ledge Shales, Hen Cliff Shales, Maple Ledge Shales, Gaulters Gap Shales, Washing Ledge Shales), each being defined as the beds between particularly prominent limestone bands, but these names are of little value except in these coastal sections and their use has not been perpetuated. Instead, following Blake (1875), the formation is divided into Lower and Upper Kimmeridge Clay. These terms, although without formal status in modern lithostratigraphical nomenclature, remain useful for descriptive purposes. Both divisions consist of rhythmic, mudstone-dominated successions but are easily distinguished by their differing ammonite faunas. The Lower Kimmeridge Clay is characterized by genera such as *Pictonia, Rasenia* and *Aulacostephanus,* and the Upper Kimmeridge Clay mainly by species of *Pectinatites, Pavlovia* and related forms. Boreholes indicate that the total thickness of the Kimmeridge Clay Formation (and Kimmeridgian Stage) at the site is over 500 m.

Description

The general faunal and lithological characters of these Dorset coastal sections were described by Fitton (1836) and further details were added by Waagen (1865), Blake (1875), Woodward (1895) and Strahan (1898). More recent descriptions include those by Arkell (1933, 1947a), Cope (1967, 1978) and Cox and Gallois (1981). The following notes are based largely on the last-named. The Kimmeridge Clay at the GCR site comprises soft mudstones, calcareous mudstones and kerogen-rich mudstones ('bituminous' mudstones and oil shales). These occur in rhythms consisting, where complete, of brownish-grey 'bituminous' mudstone or oil shale that passes up into dark-grey mudstone and thence into pale-grey calcareous mudstone. Thin bands of cementstone (including muddy dolomitic limestones, i.e. dolostones) occur at a number of levels; the most prominent and persistent of these have been named (Figure 2.26) and (Figure 2.27). The beds are generally richly fossiliferous. As well as ammonites, the bivalve fauna is particularly abundant and diverse (Wignall, 1990a). Other invertebrates include gastropods, scaphopods, brachiopods, crustaceans, echinoids, crinoids, ophiuroids, bryozoans, serpulids and belemnites. The site has also yielded fossil fish remains (e.g. House, 1965) and is world-famous for its marine reptile fauna, which includes crocodilians, pterosaurs, plesiosaurs and ichthyosaurs (Benton and Spencer, 1995). Microfossils include foraminifera (Lloyd, 1958, 1959, 1962), ostracods (Kilenyi, 1969), coccoliths (Gallois and Medd, 1979; Young and Bown, 1991) and dinoflagellate cysts (Riding and Thomas, 1988). The strata are readily accessible for bed-by-bed collecting, mostly at, or just above, high water mark. Parts of the sequence in Brandy Bay, Hobarrow Bay and Kimmeridge Bay, and between Hen Cliff and Rope Lake Head (Figure 2.25), are exposed on the foreshore as well as in the cliff and yield better-preserved specimens, but use of geological hammers is now forbidden in Kimmeridge Bay itself

The whole of the Upper Kimmeridge Clay is available for study in a single, gently dipping section but only the upper part of the Lower Kimmeridge Clay (upper Eudoxus Zone and above) is exposed within the GCR site. However, beds equivalent to the unexposed part of the Lower Kimmeridge Clay can be seen in coastal sections further west (see site reports for East Fleet–Small Mouth, Black Head and Ringstead, this volume). The upper part of the Eudoxus Zone is dominated by numerous bands of very shelly oil shale that weather out as hard ribs of fissile shale with sulphur-yellow (?natrojarosite) coated surfaces; most of these are crowded with crushed specimens of the tiny ammonite *Amoeboceras* (*Nannocardioceras*) . These beds can be seen, repeated several times by faulting, in the cliffs and foreshore between Brandy Bay and Kimmeridge Bay. At the latter locality, the top of the Eudoxus Zone is marked by the Flats Stone Band, a thin tabular dolostone that can be readily distinguished from any other limestone in the sequence by the presence of numerous low-angle thrusts that form an intersecting pattern of sinuous ruckles on its upper surface. Below this stone band, Arkell (1947a) described abundant specimens of the ammonite *Aspidoceras,* some with aptychi in the aperture of the shell.

The whole of the overlying Autissiodorensis Zone is exposed in a gently dipping section in the cliffs at Kimmeridge Bay, as well as in Brandy Bay. The Washing Ledge and Maple Ledge stone bands provide useful lithological markers. Within the small-scale rhythms that make up the succession, brownish-grey oil shales or 'bituminous' mudstones form hard ribs in the cliffs, and pale-grey calcareous mudstones with a cuboidal or 'dicey' fracture weather back as slacks. The lower part of the zone is characterized by common *Aspidoceras* and *Aulacostephanus,* and abundant *Nannocardioceras;* the upper part by abundant large crushed *Aulacostephanus autissiodorensis* (Cotteau), large *Propectinatites?* (relatively common in the pale-grey calcareous mudstones) and *rare Gravesia.* A thin bed rich in the ammonite *Sutneria rebholzi* (Berckhemer) occurs a few metres above the Flats Stone Band, and a horizon with the ammonite *Nannocardioceras volgae* (Pavlow) occurs *c.* 4 m above the Washing Ledge Stone Band (Callomon and Cope, 1995; see (Figure 2.14)). On the top of Hen Cliff, at the eastern end of Kimmeridge Bay, Clavell Tower commemorates the Clavell family, members of which attempted to establish various industries here using the oil shales either directly as a raw material, or as a fuel. Attempts were made at starting an alum works (in 1570 and 1605), a salt works (in 1610) and a glass factory (in 1618) (Crossley, 1987; House, 1989).

Between Hen Cliff and Freshwater Steps (Figure 2.14), (Figure 2.25), (Figure 2.26) and (Figure 2.27), rhythmic alternations of kerogen-rich and calcium carbonate-rich mudstones, in which stone bands (Blake's Bed 42, Yellow Ledge, Cattle Ledge, Grey Ledge, Rope Lake Head, Basalt, White, Middle White and Freshwaters Steps) act as markers, are exposed in a continuous, gently dipping cliff section stretching for *c.* 4 km. Thick beds of very calcareous mudstone weather to form steep degraded slopes, and groups of oil-shale-rich beds form precipitous cliffs with numerous serrated and protruding ribs of oil shale (Figure 2.28). The ammonite fauna of these beds is restricted almost exclusively to species of *Pectinatites.* The same sequence is seen in Brandy Bay where dips increase westwards from 10° to 20° as the steep limb of the Purbeck Monocline is approached. A massive oil shale, known as the Blackstone, with calcareous and pyritic concretions, and pyritized plates of the pelagic crinoid *Saccocoma,* forms a marker at the Wheatleyensis–Hudlestoni zonal boundary. It is particularly tough and fallen blocks form large boulders on the foreshore. It was carved, like jet, in the Iron Age, Roman and Saxon times for ornamental purposes as well as for domestic articles such as bowls and even furniture (e.g. Calkin, 1955, 1972). There were several attempts at working it commercially in the 17th to 19th centuries but all had failed by late Victorian times. It apparently produced an unsaleable, high-sulphur-content oil, an unsaleable coke, an ammonia yield that was too small to be worth recovering and an offensive smell when distilled (Gallois, 1979a). Some of the shafts and adits of the old workings are still visible at Clavells Hard. The Blackstone ignites readily and spontaneous combustion has been reported (Cole, 1974, 1975) although House (1989) considered such claims to be spurious and the fires, which may burn or smoulder for some years, to have been manmade. Some pink colouration of the bed indicates where it has been burnt in recent years.

From Freshwater Steps to Chapman's Pool, the coastal exposures of Kimmeridge Clay comprise uniform, very calcareous mudstones in which a few lines of limestone doggers and some thin, weakly developed oil shales form markers. Without resistant stone bands or oil shales, the beds form steep degraded slopes which, in places, have been overridden by slipped masses of the topmost Kimmeridge Clay and succeeding Portland Group; a complete succession is nonetheless present. A weakly cemented, very pale mudstone, seen *c.* 30 m above the Freshwater Steps Stone Band in Egmont Bight, has been named the Encombe Stone Band by Gallois (2000); it is a well-defined stone band in boreholes in the area. At Chapman's Pool, thin oil shale and 'bituminous' mudstone seams are again present and form prominent hard ribs in the cliff and ledges on the foreshore. The section, up to the base of the Portland Group, was summarized by Arkell (1933, 1947a) and later described by Cope (1978), but the exposures, which are deeply weathered, partially landslipped and poorly accessible, have recently been reassessed by Gallois (2000) with the help of data from nearby cored boreholes. Two lines of small calcareous concretions (the Rotunda Nodules), 3 and 6 m above the highest oil shale (Blake's Bed 2), provide a useful marker. They contain uncrushed and partially crushed 'payloviid' ammonites including *Pavlovia rotunda* (J. Sowerby) which gives its name to the Rotunda Zone. A few metres below Blake's Bed 2, Gallois (2000) identified a gritty, silt-rich mudstone, up to a few centimetres thick, with abundant belemnites and oysters as well as phosphatized bivalves and 'pavloviid' ammonite body chambers. This bed, which he named the Chapman's Pool Pebble Bed, rests on a bioturbated surface and marks an important sedimentary break and faunal change at the base of the Rotunda Zone. Another new marker horizon recognized by Gallois (2000 and pers. comm.) in the cliffs here is the Cidarid Siltstone. It occurs about 15 m above the Rotunda Nodules and contains a rich and diverse fauna including oysters, the pectinid bivalve *Entolium,* belemnites (*Hibolithes*) and cidarid spines. The overlying beds, up to the base of the Portland Group, have traditionally been divided, in ascending sequence, into the Lingula Shales, Rhynchonella Marls, Hounstout Clay and Hounstout Marl — terms that originate with Buckman (1925–1927) or Arkell (1933). However, Gallois (2000) used instead the terms 'Lower Hounstout Silt', 'Hounstout Clay' and 'Upper Hounstout Silt', as shown in (Figure 2.27), because they reflected better the broad lithological characters (mainly siltstone, muddy siltstone or silty mudstone) of the succession. The main marker in this interval is a cluster of three thin 'bituminous' mudstones at the base of the Hounstout Clay.

Interpretation

In recent years, much interest has been shown in the exposures of Kimmeridge Clay that constitute this GCR site and they have been intensively investigated by academics and petroleum geologists because the formation is a principal source rock in the North Sea Basin where it occurs at depth. This has led to an extensive literature, particularly in the fields of sedimentology, geochemistry, palaeoecology and sequence stratigraphy (Cosgrove, 1970; Gallois, 1979a; Irwin, 1979, 1980, 1981; Tyson *et al.,* 1979; Aigner, 1980; Farrimond *et al.,* 1984; House, 1985; Williams, 1986; Myers and Wignall, 1987; Scotchman, 1987a, b, 1989, 1991a, b; Astin and Scotchman, 1988; Oschmann, 1988; Wignall and Myers, 1988; Wignall, 1989, 1990a, 1991, 1994; Coe *et al.,* 1990; Wignall and Ruffell, 1990; Herbin *et al.,* 1993; MacQuaker and Gawthorpe, 1993, 1994; Herbin *et al.,* 1995).

The lower boundary of the formation is not exposed within the site although it was cored in the nearby Metherhills No.1 Borehole (Gallois, 2000). The upper boundary, with the overlying Portland Group, is seen in the cliff face (Hounstout) above Chapman's Pool. Arkell (1933) summarized the reasons given by previous authors, from Fitton (1836) to Cox (1929), for their individual choices of this boundary, which Arkell (1933, 1947a) placed at the base of a prominent bed of sandstone known as the 'Massive Bed'. Most subsequent authors have followed this despite Townson's (1975) detailed sedimentological work, which suggested that a more appropriate place for the lithostratigraphical boundary was lower down at the base of the Rhynchonella Marls. He considered this position to represent a downward mappable change from silts to shale. It is only on the Dorset coast that the positioning of this boundary is controversial; elsewhere, the highest beds of the Kimmeridge Clay have been removed and the base of the Portland Group rests on an erosion surface. According to Gallois (2000 and pers. comm.), the thickness of 66 m given by Cope (1978) for the beds between the Rotunda Nodules and the base of the Massive Bed is underestimated by up to 12 m.

In contrast to the lithostratigraphical boundary, there has been no dissent from the choice of the Massive Bed as the Kimmeridgian–Portlandian stage boundary assuming the traditional British usage of those terms (see Chapter 1). The coastal sections here have played an important part in the development of the ammonite-based standard zonation for the Kimmeridgian Stage. The zonally diagnostic ammonite genera here are *Aulacostephanus* for the Eudoxus and Autissiodorensis zones (Ziegler, 1962), and *Pectinatites, Pavlovia* and *Virgatopavlovia* for the higher zones (Cope, 1967, 1978). The stage is divided into Lower and Upper. The boundary between these two substages has traditionally been taken at the base of the stone band known as Blake's Bed 42, which crops out in Hen Cliff, and which forms one of the famous 'Kimmeridge Ledges' on the adjoining foreshore, just east of Kimmeridge Bay. However, for consistency with other English sections, Gallois (2000) suggested that the substage boundary should instead be taken at the base of the first oil shale above the highest recorded *Aulacostephanus,* which is *c.* 7 m below Blake's Bed 42. This part of the section is particularly important because it correlates with the basal beds of the Tithonian Stage; in recent years, the latter has been ratified by the International Subcommission on Jurassic Stratigraphy (ISJS) as the primary terminal Jurassic stage for international usage. The ammonite provincialism in the Late Jurassic and the different stage nomenclatures to which it has given rise do not need to concern us here, but the section at Hen Cliff is nonetheless of international importance because, although the term Tithonian' is not applied to the British succession, the locality is a potential auxiliary boundary stratotype or reference section for the base of that stage. The occurrence of the ammonite genus *Gravesia* is of particular importance in this respect because its geographical distribution is relatively widespread thus enabling international correlation. It ranges from 3 m below the Maple Ledge Stone Band up to 1.8 m above the Yellow Ledge Stone Band (Cox and Gallois, 1981; Callomon and Cope, 1995) (Figure 2.14).

The palaeoecology of the Kimmeridge Clay exposed at this site was investigated by Wignall (1990a) on the basis of the benthic macrofauna amongst which bivalves are predominant. He concluded that the thick sequences of rhythmic organic-rich shales and mudstones of the upper Eudoxus Zone–middle Wheatleyensis Zone were deposited in an offshore basinal area where low-diversity populations of opportunists, such as the bivalves *Corbulomima* and *Protocardia,* colonized during brief oxygenation events. The sediments were generally fairly soft and excluded most epifaunal forms. According to Wignall (1989), who logged all the sedimentary features in the Kimmeridge section, the principal mechanism for supplying oxygen to the sea-bed environment was storms. Organic-rich and oxygen-restricted bottom waters characterized the depositional environment of the overlying sediments up to the upper part of the Pectinatus Zone. Relative to other areas of southern and eastern England, the mudstones at these latter levels on the Dorset coast, which contain the ubiquitous bivalve *Protocardia* and the patellid gastropod *Pseudorbytidopilus,* were deposited in a deeper-water, more offshore environment. Epifaunal forms are more common, suggesting that substrates were firmer and, by implication, sedimentation rates were slower than previously. Within the sediments of the Hudlestoni Zone, Wignall and Ruffell (1990) combined palaeoecological investigations and biofacies analysis with clay mineralogy and geochemistry to suggest evidence of a sudden palaeoclimatic change from humid to semi-arid. From the upper part of the Pectinatus Zone to the top of the Kimmeridgian, organic-rich shale deposition became progressively more restricted to the centres of the offshore basins such that on the Kimmeridge coast the facies persists into the basal part of the Rotunda Zone. The benthic faunas of the latest Kimmeridgian become much more diverse and indicate better-oxygenated shallower marine conditions. Wignall (1989) also concluded that the proportion of organic-rich shales was the most reliable indicator of palaeobathymetry, with the main areas of organic-rich shale deposition occupying the deepest water sites.

The dolomitic limestones (dolostones), which form prominent ribs and ledges (some of the so-called 'Kimmeridge Ledges') in the cliffs and foreshore in and adjacent to Kimmeridge Bay, usually weather to a greyish-yellow or even orange surface colour owing to the presence of the mineral ankerite ($Ca(Mg,Fe)(CO_3)_2$). They formed by diagenetic replacement of a pre-existing lithology (mudstones or shales) in the methanogenic zone (*c.* 10 m to *c.* 1000 m burial depth), probably at several hundred metres burial depth (Irwin *et al.,* 1977). They are confined to basinal depositional settings where methanogenic processes prevailed. Dolostone formation requires substantial quantities of metabolizable organic matter to survive to relatively great burial depth; this can be accomplished by rapid burial of organic matter through the near-surface sulphate reduction zone (Wignall and Ruffell, 1990). By contrast, calcareous nodules or limestone doggers, which occur in the highest beds of the Kimmeridge Clay, require prolonged residence time in the sulphate reduction zone (up to 10 m burial depth), and are common over high/swell depositional settings. Thus, dolostones and limestone nodules do not co-occur in the Kimmeridge Clay.

The Rope Lake Head, White, Middle White and Freshwater Steps stone bands and the Short Joint Coal, a thin limestone close above the Rope Lake Head Stone Band, are examples of the coccolith-rich bands first identified by Downie (1957) (Gallois and Medd, 1979). Gallois and Cox (1974) suggested that the White Stone Band, which is a particularly well developed and widespread example, formed from an algal bloom. Of the 11 bands identified by Gallois and Medd (1979), all but one are inter-laminated with oil shales, and the beds themselves, particularly the White and the Freshwater Steps stone bands, show distinct lamination. Gallois (1976) suggested that the interlamination may have resulted from alternating coccolith and dinoflagellate blooms.

All recent sedimentological studies of the Kimmeridge Clay are agreed that the preservation of abundant organic matter was caused by stagnant bottom waters (Sellwood and Wilson, 1990) but various theories have been proposed to explain how these conditions, and the rhythmic variations of which they are part, came to be. Gallois (1976) suggested that land-derived nutrients stimulated blooms of phytoplankton (coccoliths and dinoflagellates) (see above), the decay of which led to temporary oxygen-deficient or hydrogen sulphide-rich zones in which organic material could accumulate and be preserved. On the other hand, Tyson *et al.* (1979) suggested that phytoplankton blooms were a symptom of widespread anaerobic bottom conditions rather than their cause, and that the lithological rhythms are best interpreted in terms of water-column stratification and occasional sea-floor anoxia. They proposed a stratified water column in which a basal hydrogen sulphide-rich zone periodically extended up through the water column. 'Bituminous' shales formed as the top of the latter zone moved from just beneath the sediment surface to just above it. Oil shales formed when the oxygen:hydrogen sulphide interface was quite high in the water column, and laminated coccolith-rich limestones formed when the oxygen:hydrogen sulphide interface reached the euphotic zone. Seasonal temperature variations or storm-induced activity resulted in the mixing of the oxygen- and hydrogen sulphide-rich layers so that the nutrients of the latter stimulated phytoplankton (coccolith) blooms and the oxygen at the hydrogen sulphide:oxygen interface killed off bacteria that thrived in the euphotic part of the hydrogen sulphide layer. Tyson *et al's* (1979) hypothesis is compatible with current interpretations of the Black Sea and Nile Cone sea-floor sediments.

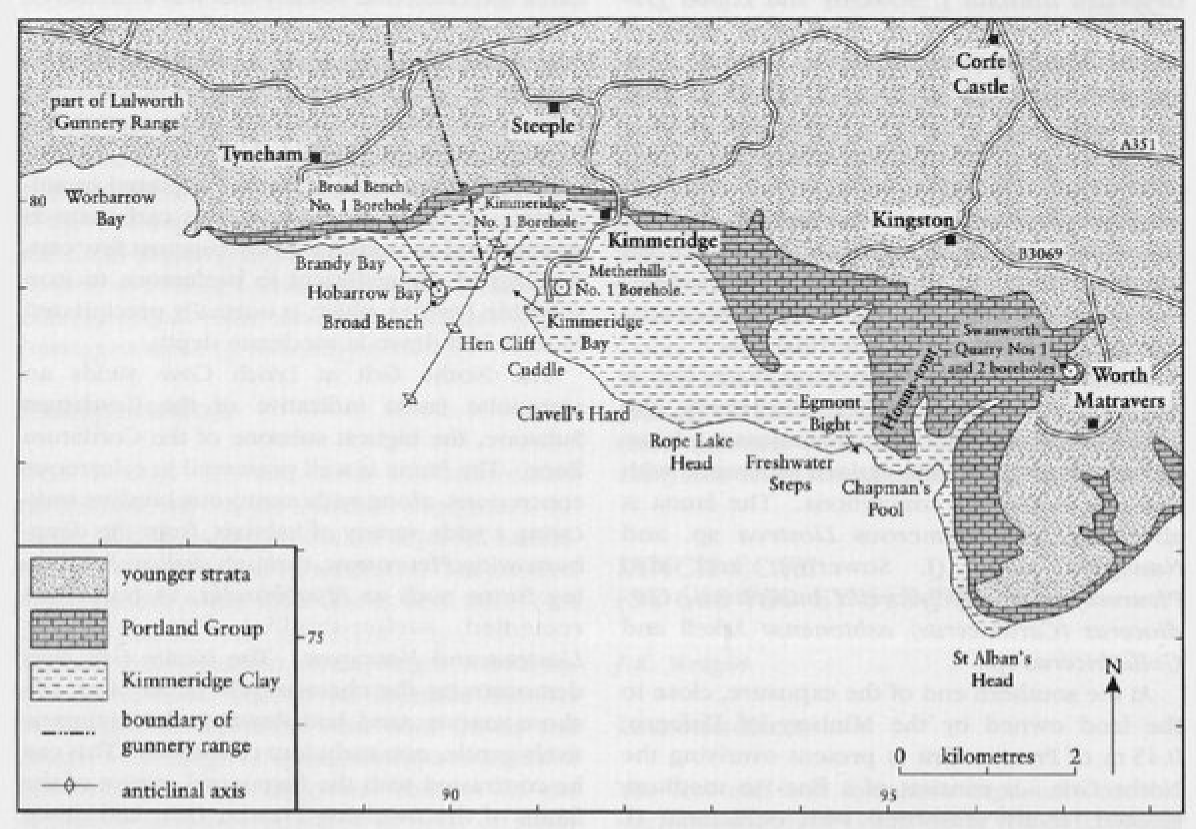
Although it is commonly accepted that stratification in the Kimmeridge Clay seas was caused by the presence of thermoclines (Tyson *et al.,* 1979; Myers and Wignall, 1987), the ultimate cause of the cyclic stratification has still not been fully resolved Mignall, 1989). The suggestion that the stratification was salinity-induced (Scotchman, 1984) has not found favour, nor has Oschmann's (1985) idea that the bottom waters in the thermally stratified water column were derived from upwelling of cold, nutrient-rich, oxygen-poor waters from the Arctic Ocean.

Wignall (1989) reported volcanically induced changes of climate (Zimmerle, 1985) or orbitally forced climatic changes (Hallam, 1986) as the two main alternatives, and concluded that Milankovitch-type cyclicity may have been the main control (Dunn, 1974; House, 1985, 1986, 1989, 1995; Waterhouse, 1995).

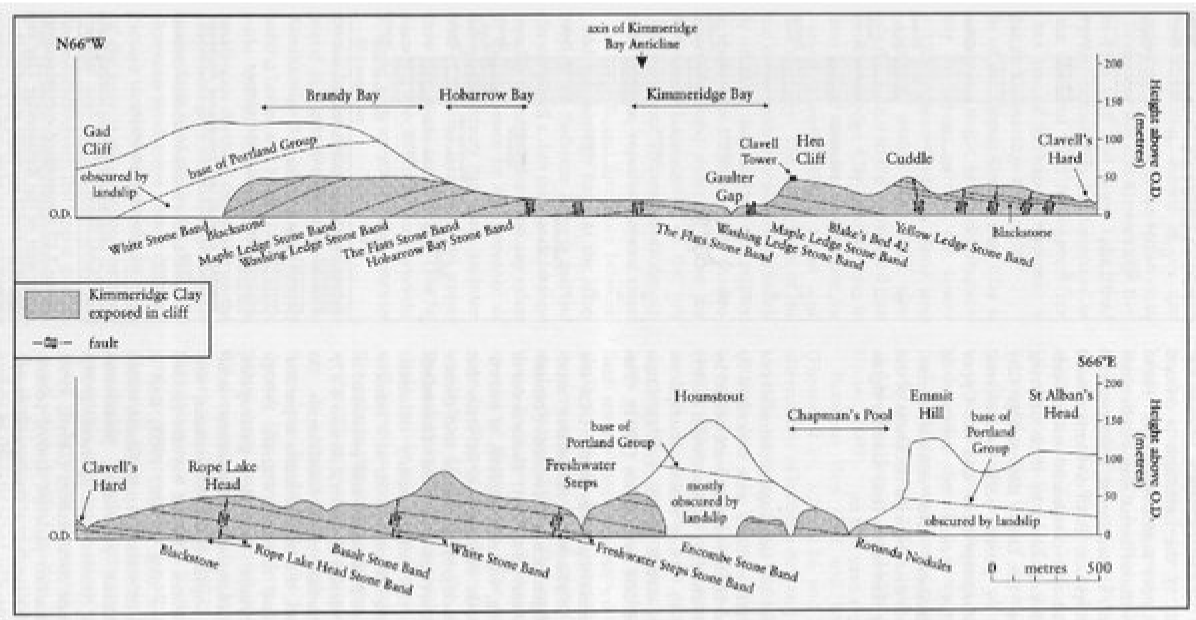
Conclusions

The cliff and foreshore exposures at and adjacent to Kimmeridge Bay in Dorset provide tectonically uncomplicated, continuous sections through the greater part of the Kimmeridge Clay Formation. They are readily accessible and consist of thick sequences of fossiliferous marine mudstones, apparently free from major non-sequences. The cliffs between Brandy Bay and Freshwater Steps are being actively eroded and fresh sections are almost always available. On the English mainland, the formation extends northwards to North Yorkshire but it is poorly exposed inland and much of our understanding of its stratigraphy has been made through study of the Dorset coastal sections (see also site reports for East Fleet–Small Mouth, Black Head and Ringstead, this volume). The locality also gives its name to the Kimmeridgian Stage, which has been an international unit of stratigraphical classification and correlation for nearly 150 years. In recent years, the exposures at this site have been intensively studied because of the occurrence of oil shales within the Kimmeridge Clay and the role of that formation, where it is buried at depth, as a principal source rock for North Sea oil. The possible causes of the well-displayed lithological rhythmicity of the succession and its relevance to the interpretation of past and possible future climates has also been investigated in recent years.

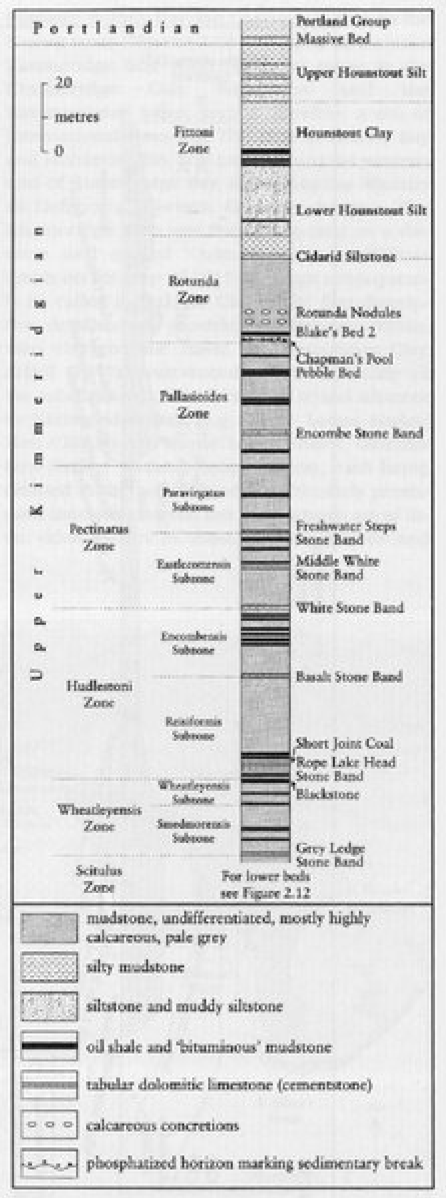
References



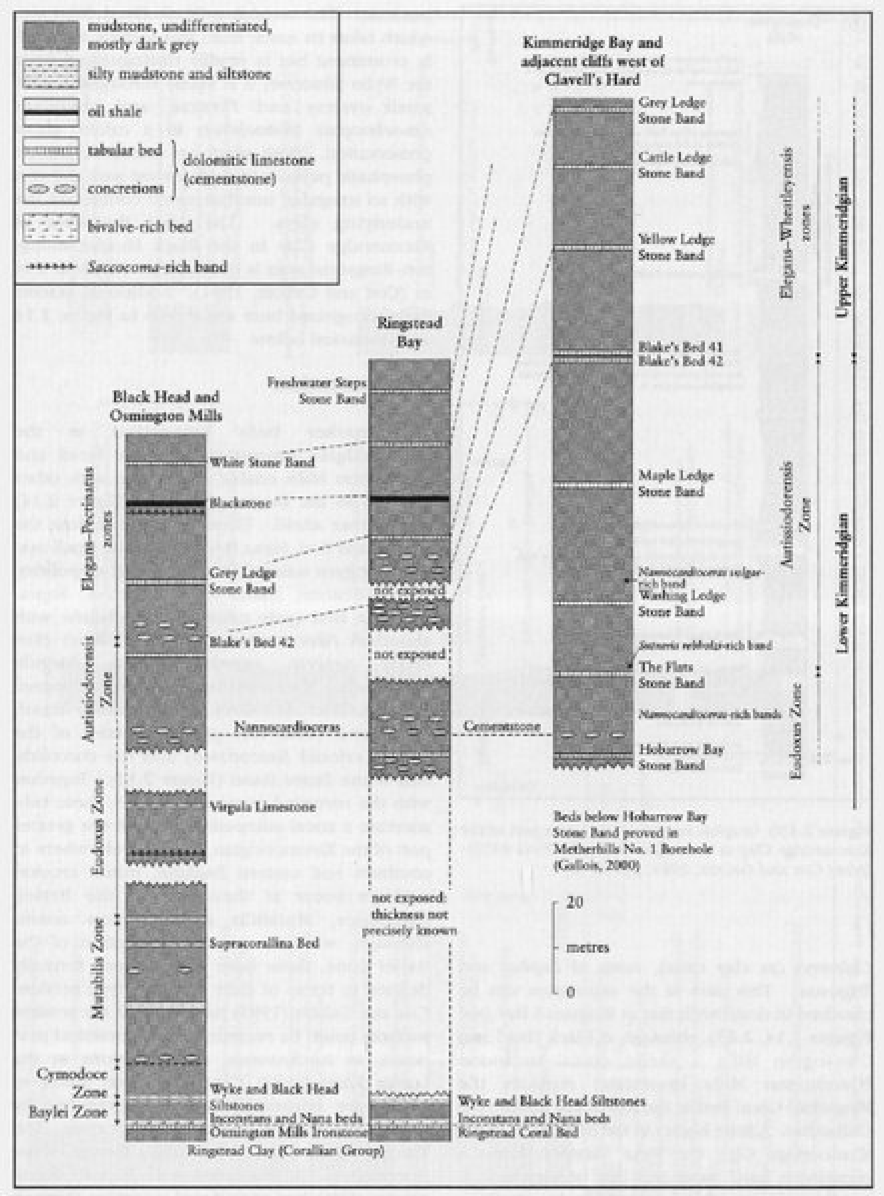
(Figure 2.25) Sketch map of the solid geology of the Kimmeridge area, (based on Cox and Gallois, 1981, fig. 7 and Gallois, 2000, fig. 1).



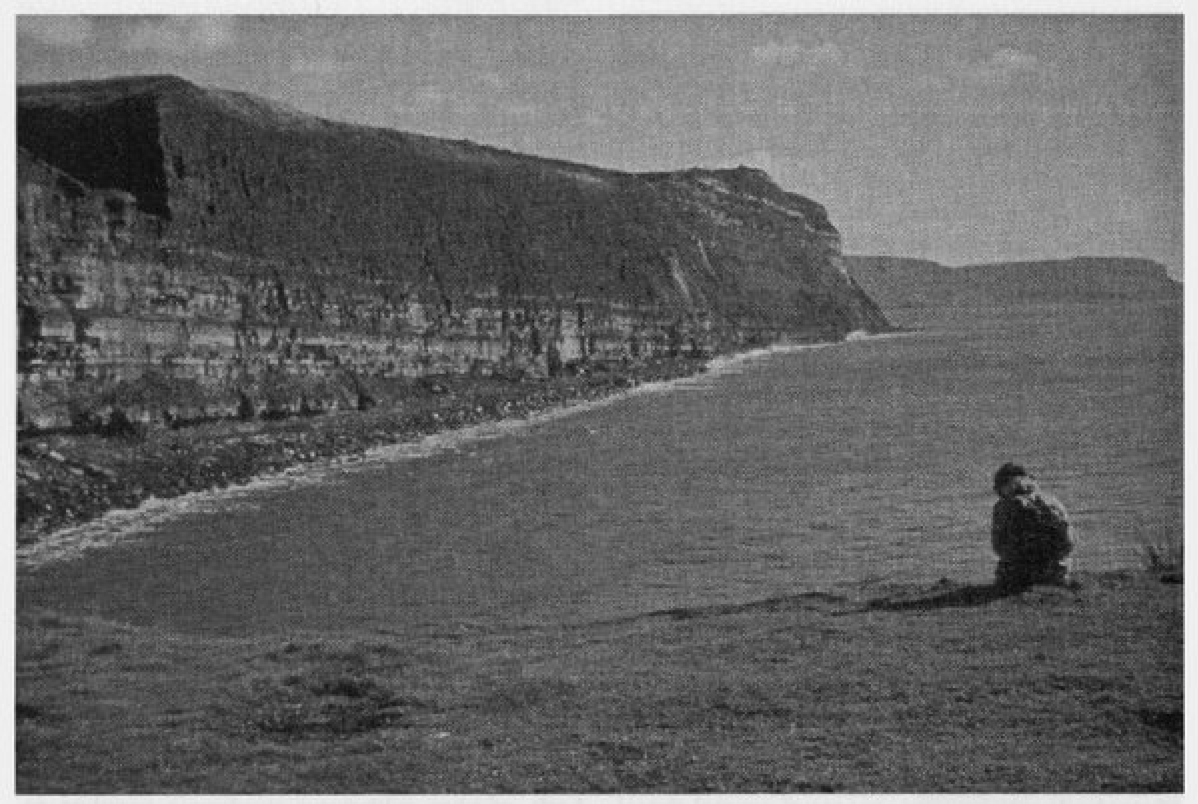
(Figure 2.26) Geological sketch sections of the Kimmeridge Clay exposed in the cliffs between Brandy Bay and Chapman's Pool (based on Cox and Gallois, 1981, fig. 8 and Gallois, 2000, fig. 2).



(Figure 2.27) Generalized vertical section through the upper part of the Kimmeridge Clay exposed in the cliffs east of Clavell's Hard (based on Cox and Gallois, 1981, fig. 13 and Gallois, 2000, figs 4 and 6).



(Figure 2.14) Correlation between the main sections of Kimmeridge Clay on the Dorset coast. Youngest zones not shown. (After Cox and Gallois, 1981, fig. 5.)



(Figure 2.28) Looking east from Clavell's Hard to Rope Lake Head and St Alban's Head (far distance). The lower part of the cliff face comprises alternating mudstones and ribs of oil shale including the Blackstone, Rope Lake Head Stone Band and Short Joint Coal. The upper part comprises a thick succession of pale calcareous mudstones including, towards the top, the Basalt Stone Band. The cliff is capped by further alternations of mudstone and oil shale including the White Stone Band. (Photo: W.A. Read.)