

The Kimmeridge Clay: the most intensively studied formation in Britain

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Introduction

The Jurassic rocks of the World Heritage coast crop out over a distance of about 60 miles between Lyme Regis and Swanage, and represent an unbroken 60 million years of Earth history. Within this succession marine mudstones, principally the Lias Group and the Oxford Clay and Kimmeridge Clay formations, represent about 60% of the time interval. Of these, the Kimmeridge Clay has been the most extensively studied with the result that much is known about its lithostratigraphy, biostratigraphy and geochemistry. Many of the lithological and faunal associations found in the Kimmeridge Clay can be closely matched with those in the Lias and Oxford Clay. All three were deposited in relatively shallow (50m to 200m deep), fully marine environments on continental shelves, and many of the conclusions reached about the depositional history of the Kimmeridge Clay can be equally well applied to the other formations.

The Kimmeridge Clay outcrop runs almost continuously from the Dorset coast to the Yorkshire coast, and the formation has an extensive subcrop beneath younger rocks in eastern England and the North Sea (Figure 1). At outcrop the mudstones weather rapidly to clay with the result that there is no natural inland exposure, and at any one time there are rarely more than five man-made sections. The only good exposures are in the cliffs at and adjacent to Kimmeridge and Ringstead bays, and these form the type sections for the Kimmeridge Clay Formation and the Kimmeridgian Stage (Arkell, 1947; Cox & Gallois, 1981).

Lithostratigraphy

At first sight, the Kimmeridge Clay looks monotonously uniform with almost no lithological variation and little colour contrast other than shades of grey. There are, however, variations in the cliff profiles in which more resistant horizons are interbedded with more friable lithologies. These correspond principally to variations in the clay, calcium carbonate and organic contents of the mudstones. When examined in detail, it can be seen that these variations are rhythmic at scales ranging from millimetres to tens of metres in thickness. A few thin muddy limestones

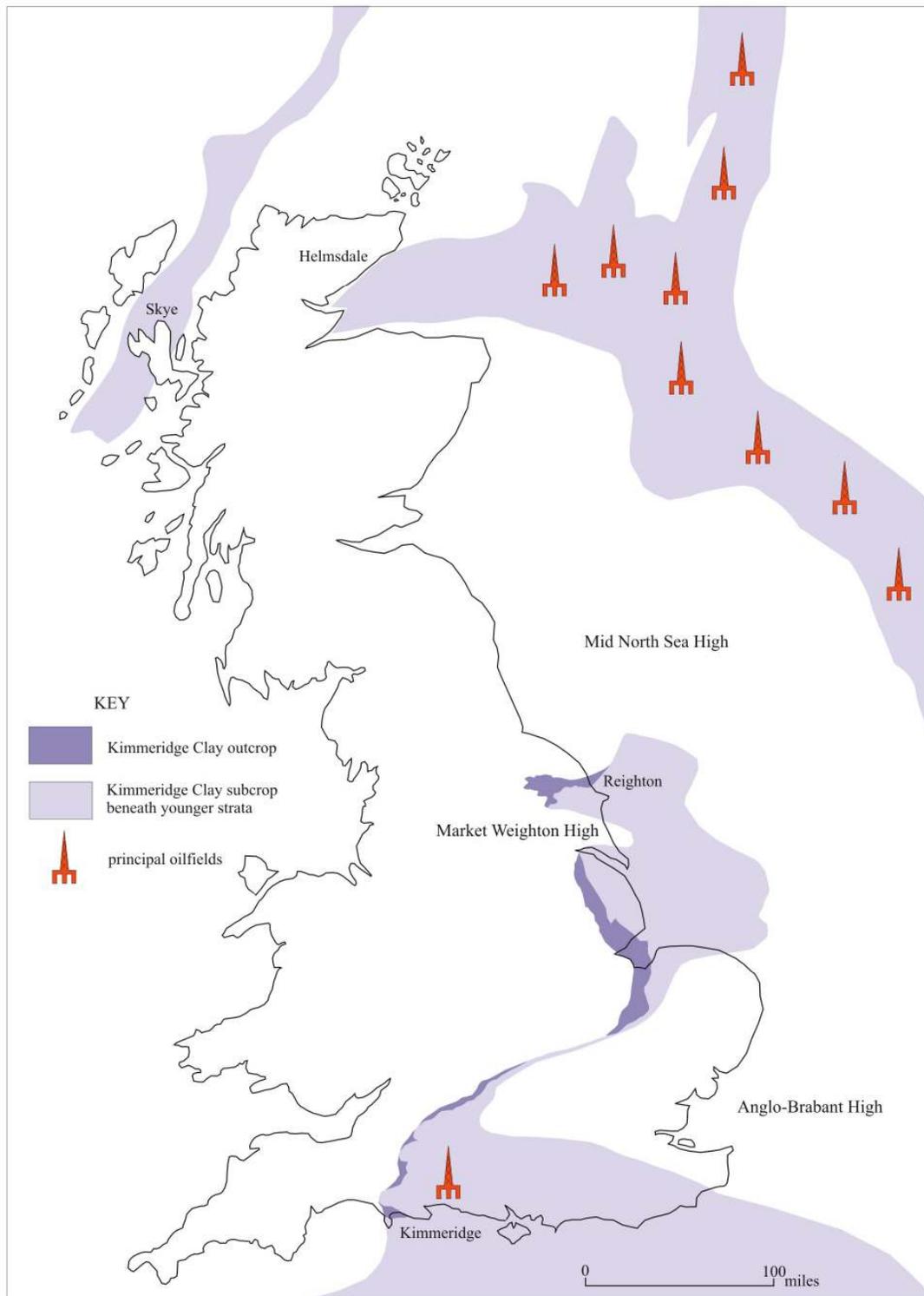


Figure 1. Geological sketch map of the outcrop and subcrop of the Kimmeridge Clay.

(cementstones), 8 or 9 horizons in the 550m-thick Dorset succession, form prominent marker beds in the cliffs.

Almost all the lithologies in the Kimmeridge Clay can be expressed in terms of their siliciclastic, calcium carbonate and organic contents (Figure 2). The organic contents are mostly kerogens, complex organic polymers with very high molecular weights that formed within the sediment by the action of chemical and bacterial degradation on recently buried decaying organic matter. Kerogens impart a brown colour to the mudstones, and when present in sufficiently high concentrations give rise to oil shales. Increases in calcium carbonate content cause the mudstones to become paler grey until they pass into chalk-like sediments.

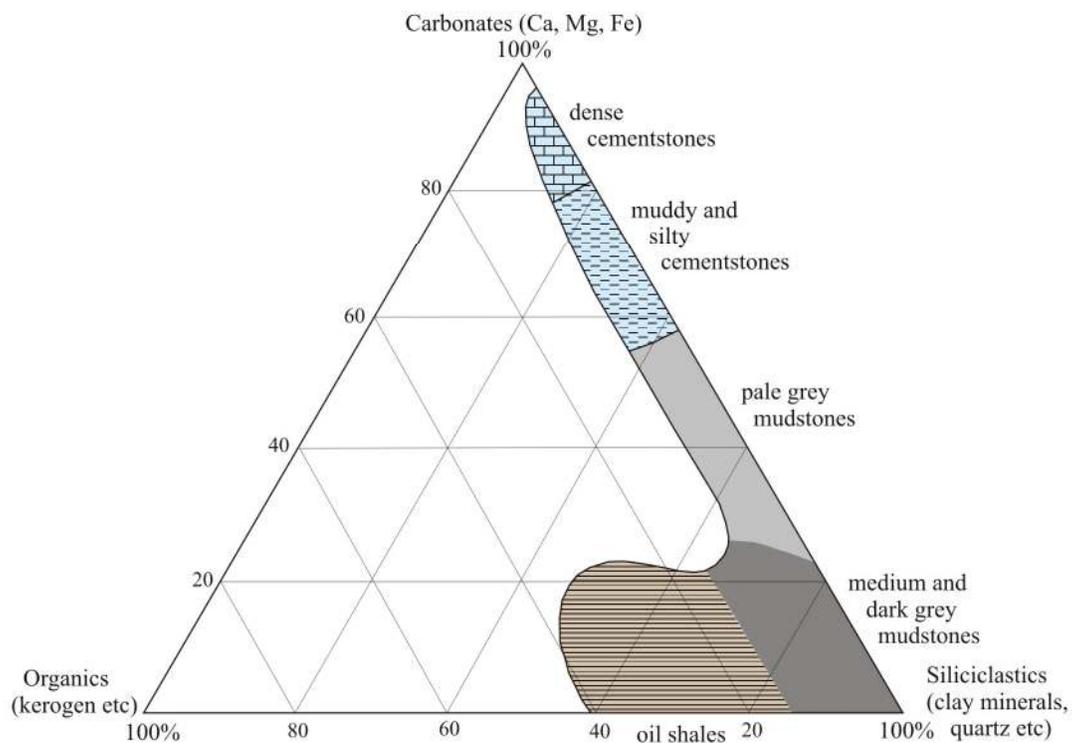


Figure 2. Diagrammatic representation of the bulk chemistry of the more common Kimmeridge Clay lithologies.

These components can be divided into three genetic groups, clastic, biogenic and chemogenic. The clastic components consist of clay minerals, detrital quartz and re-worked biogenic and chemogenic materials such as shell and plant debris, and phosphatic pebbles. The biogenic components consist of calcareous fossils, principally ammonites, bivalves and foraminifera with lesser numbers of gastropods, brachiopods, serpulids, crinoids, ostracods and coccoliths; phosphatised fossils, mostly vertebrate debris such as fish scales, vertebrae and faecal pellets; and kerogens

derived from dinoflagellates, acritarchs and plant debris including pollens. The chemogenic components consist principally of diagenetically formed calcium and magnesium carbonate concretions and cements, pyrite and phosphate.

Using the parameters of colour, texture, grain size and shell content, a wide range of lithologies can be readily recognised in borehole cores and hand specimens. These can be closely correlated with the mineralogy and chemistry of the mudstones. The lithological logs can be calibrated against geophysical logs made in cored boreholes, and then used to make correlations over long distances in uncored boreholes in areas where the formation is not exposed (Penn *et al.*, 1986). In the more extreme examples, individual beds less than 0.3m-thick have been traced over distances of more than 200km. At such horizons, the depositional environments must have been closely similar over areas in excess of 15,000 square miles.

Biostratigraphy and Chronostratigraphy

The Kimmeridge Clay is richly fossiliferous, despite the statement in *British Mesozoic Fossils* (Anon, 1983, p. 5) that it is not particularly attractive to the collector, and has yielded as great a range of fossils as almost any other Mesozoic formation in Europe. In addition to the profuse invertebrate fauna described above, the exposures in Kimmeridge Bay have yielded a variety of marine reptiles and fish (Figure 3), and several exotic finds (Etches & Clarke, 1999).



Figure 3. Almost complete specimen of a ray (Rhinobatidae): Etches collection.

One of these last is a dragonfly wing (Figure 4) that was preserved at least 100 miles from the nearest land. As elsewhere along the World Heritage coast, geology is deeply indebted to the small number of highly skilled 'amateur' collectors, starting with Mary Anning and her contemporaries, who have provide almost all the material on display in museums.



Figure 4. Dragonfly wing, the first recorded insect remains from the Kimmeridge Clay: Etches collection.

The vertebrate and exotic fossils are of enormous interest when it comes to the reconstruction of Kimmeridgian depositional environments. They help us to understand who lived where within the water column and sea-bed sediment, how they lived, and who probably ate whom. However, they provide little stratigraphical information. For that we have the ammonites, the stratigraphically most important fossils in the Jurassic, where they are used to make regional correlations that are an order of magnitude more accurate than that possible using any other fossil group.

Most of the ammonites in the Kimmeridge Clay are crushed, but their distinctive ornamentation is commonly preserved and they occur in sufficiently large numbers throughout the formation to form the basis for a detailed zonation (Callomon and Cope, 1995). In the early Kimmeridgian, Britain lay in the southern part of a cool Boreal Sea with a warmer Tethyan Ocean several hundred miles to the south. The

ammonite assemblages reflect this with dominantly Boreal species, but also a few wide-ranging forms that can be traced into the Tethyan Province. Earth movements in the later Kimmeridgian produced new land areas and caused what had been an extensive continental shelf to break up into separate marine basins. These became progressively more isolated from one another with time, and each developed its own, separately evolving fauna. As a result, even within the Boreal Province there are different zonal schemes for northern Boreal, sub-Boreal, and Franco-German areas, and long-distance correlations become progressively more difficult to make with time.

Fortunately, the Kimmeridge Clay contains additional faunal elements that form stratigraphically specific marker beds at several levels. These include the small bivalve *Nicaniella* (formerly *Astarte*) which has a long stratigraphical range but which occurs by the billion in one bed about 1m thick (the Supracorallina Bed of Arkell, 1933) that can be traced throughout the outcrop from the Dorset to Yorkshire coasts. This 'flood occurrence' can be matched by that of the tiny free-swimming crinoid *Saccocoma* whose pyritised remains are restricted to four horizons, each only a few millimetres or centimetres thick, that can also be traced throughout the outcrop.

When the lithostratigraphy of the Kimmeridge Clay is combined with the biostratigraphy and the geophysical-log signatures it enables the formation to be divided into 63 chronostratigraphical units (Figure 5) that can be recognised throughout the onshore outcrop and subcrop (Gallois, 2000). Current estimates based on radiometric dating suggest that the Kimmeridge Clay was deposited over a period of about 7 million years, which suggests that the average time span represented by the chronostratigraphical units is a little more 100,000 years. This is about five times more accurate than the ammonite zonation. The availability of a chronostratigraphy has made it possible to develop a sequence stratigraphy (Taylor *et al.*, 2000) that should enable international correlations to be made that are complementary to but independent of the biostratigraphical correlations

Kimmeridge Clay as an oil source rock

Although the KC is worthy of study because it has much to tell us about Earth history in this part of the Jurassic, most of the research into its stratigraphy, sedimentology and geochemistry has been prompted by its economic importance. In the northern North Sea, the primary energy resource is oil derived mostly from the geothermal breakdown of the kerogens in the deeply buried Kimmeridge Clay.

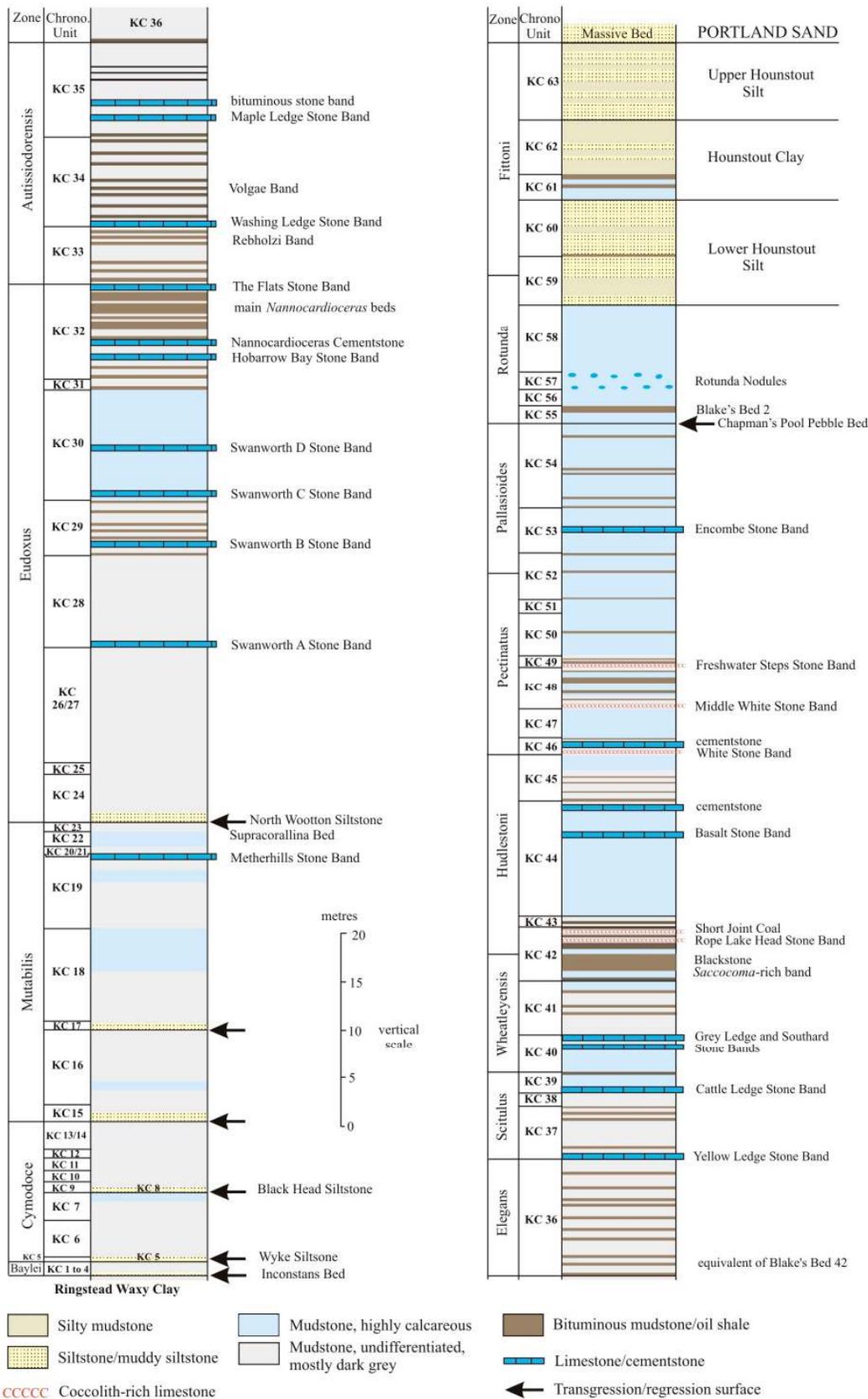


Figure 5. Summary of the Lower Kimmeridge Clay (KC 1 to KC 35) and Upper Kimmeridge Clay (KC 36 to KC 63) successions of the Dorset coast (after Gallois, 2000).

They are also the principal source of the oil in Britain's largest onshore oilfield at Wytch Farm, Dorset (Figure 1).

The most famous source rock at outcrop in the cliffs at Kimmeridge Bay is the 60cm-thick Blackstone. This has an organic carbon content of more than 50% and yields 60 gallons of oil per ton of rock when retorted. The high kerogen content imparts a translucent, dark mahogany colour to the rock, and enables it to be carved and polished. It was used in the Iron Age and by the Romans to make ornamental vases and bowls, and probably also as a fuel. From medieval times onwards this last was its principal use under the name Kimmeridge Coal. It burns with a sooty, foul smelling flame on account of its high sulphur content, and leaves behind large quantities of ash impregnated with organic carcinogens. The 17th century entrepreneur Sir William Clavel used the Blackstone as the heat source to make alum from shale and glass from sand, and to extract salt from seawater. It was also used domestically until the 1930s. Accounts of rural Dorset by Victorian gentlemen travellers describe evil smelling peasants crouching around smoky fires in their sooty hovels.

The organic content of the Kimmeridgian oil shales can be divided into two parts. Bitumens can be extracted with organic solvents and make up 5% to 8% of the total organic content. They consist of complex compounds derived from the proteins, carbohydrates and lipids ('fats') in the fossil biomass, and can provide geochemical signatures that link them to living organisms. Almost all the remainder of the organic content is in the form of kerogens, insoluble, high-molecular-weight polymers that have to be heated in the laboratory to 400-500°C before they will yield oil. In Nature, the same result can be achieved at temperatures as low as 50°C, but over a period of millions of years (Tissot & Welte, 1978).

Naturally occurring organic compounds, popularly referred to as 'hydrocarbons', consist of complex mixtures of saturated (e.g. methane) and unsaturated (e.g. benzene) hydrocarbons and 'resins' (asphaltenes, organic nitrogen sulphur, oxygen (NSO) compounds). Shale oils obtained by retorting oil shales from the Kimmeridge Clay are rich in these last (Figure 6), and would have to be distilled before they had any commercial value. The high sulphur content of up to 8% would be particularly expensive to remove because it generates corrosive sulphuric acid. In contrast, 'sweet' crude oils such as that from the Brent Field in the North Sea, are rich in hydrocarbons and have only 0.5% sulphur, their refinement having been performed naturally over a period of 50 million years.

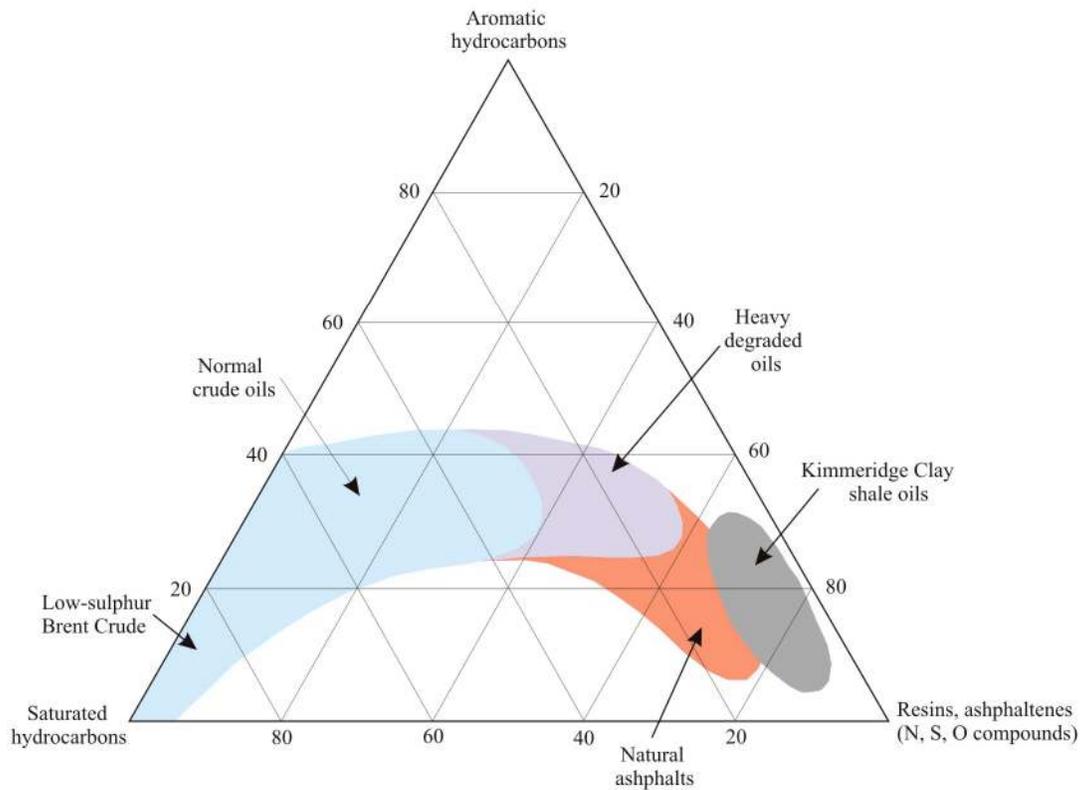


Figure 6. Relationship of Kimmeridgian shale oils to naturally occurring 'hydrocarbon' deposits.

Geochemical analyses of the bitumens, particularly that of the saturated hydrocarbon fractions, have shown that most of the organic matter preserved in the Kimmeridge Clay was derived from phytoplankton, mostly microscopic marine algae. The algae themselves are rarely preserved except where they secrete a calcareous (e.g. coccolithophores) or chitinous (e.g. *Tasmanites*) protective layer. At a few horizons pure white limestones are interlaminated with oil shales, and these provide a clue to the origin of the organic matter. Under the electron microscope the limestones can be seen to be composed entirely of coccoliths with no interstitial sediment. At the present time, coccolithophores form 'algal blooms' during short periods of the year when they occur in concentrations of billions per litre of seawater, enough to colour the sea milky white. Pictures taken of the floor of north Atlantic shortly after one of these blooms showed the sea bed to be covered with a brown, gelatinous mass, the result of cyanobacterial degradation of the rotting remains of a bloom. Such material, if protected from oxidation by a covering of sediment or a layer of anaerobic water, contains the all the ingredients to produce the organic content of the Kimmeridgian oil shales.

Much of the geochemical research on the Kimmeridge Clay has been driven by the desire to determine the optimal depositional environments for the preservation of high organic contents, and where they occur. In the right tectonic and stratigraphical setting, the best source rocks should give rise to the richest oil deposits. However, although the organic chemistry of the oil shales has become known in more and more detail, it has added little to the long-running debate about the relative importance of productivity and preservation. Organic-rich rocks such as those in the Kimmeridge Clay were obviously derived from marine environments that were teeming with life, but was the organic productivity of the Kimmeridgian sea markedly different from that of present-day seas?

The answer to that question lies in the ratio of the organic production to the organic preservation. Even the richest oil shales preserve only a fraction of the potentially available organic material that is generated in fertile sub-tropical seas such as that of the Kimmeridgian. The ultimate fate of the biomass is almost entirely determined by the extent to which it is degraded by oxidation prior to being trapped in the rock. It depends, therefore, on the redox potential of the water column and near-sea-bed environments, and the biochemical interactions that take place as the organic material passes through these layers. The amount of material from the same biomass source that survives in the rock (usually expressed as weight percentage Total Organic Carbon-TOC wt%) can vary by several orders of magnitude as a result of these processes. The greater the degree of oxygenation, the higher the primary organic productivity that has to be assumed to explain the TOC percentages observed in the rock.

There is much that we do not know about the food chains in the water column and the top part of the sediment into which the organic matter is incorporated, in particular the roles of viruses and bacteria. Even the most sophisticated attempts to estimate the primary productivity of the Kimmeridgian sea still have to operate within what the sedimentology tells us are the most likely boundary parameters. Namely, that in Dorset the lower water column/sea-bed conditions were in the range sub-oxic (no organic-oxygenating organisms) to dysoxic (Tyson, 2004).

Cyclostratigraphy

The most striking feature of the Kimmeridge Clay at Kimmeridge Bay is its cyclicity. Oil shales alternate with calcareous mudstones to weather out as harder and softer ribs

in couplets about one metre thick (Figure 7). These alternations have long been regarded as the product of climate changes related to Milankovitch cycles, those at Kimmeridge Bay being thought to be linked to changes in the obliquity of the Earth's axis (House, 1985). Much of the remainder of the Kimmeridge Clay does not appear to the naked eye to be cyclic. One can see small- and large-scale variations from more to less organic-rich and more to less calcareous in the cliff exposures, but these do not appear to form rhythmic patterns.



Figure 7. Alternations of organic-rich (weathered as hard ribs) and carbonate-rich mudstones at Kimmeridge Bay.

However, analyses of the distribution of TOC and properties such radioactivity that are not visible to the naked eye, have shown that the whole of the Kimmeridge Clay succession is cyclic (Weedon *et al.*, 2004) (Figure 8). The recognition that the formation contains Milankovitch-related cycles is of practical value for several reasons. First, by counting the number of cycles of known duration (precessional cycles of 19ka and 23ka; obliquity cycles of 38a etc) it is possible to obtain a more accurate estimate of the time taken to deposit the formation than that currently available from radiometric dating. This can then be used in combination with the geochemical data to estimate the average annual rate of organic productivity of the Kimmeridgian sea. Surprisingly, given the organic-rich nature of much of the

formation, it indicates an average productivity less than that of modern continental shelves (Weedon *et al.*, 2004).

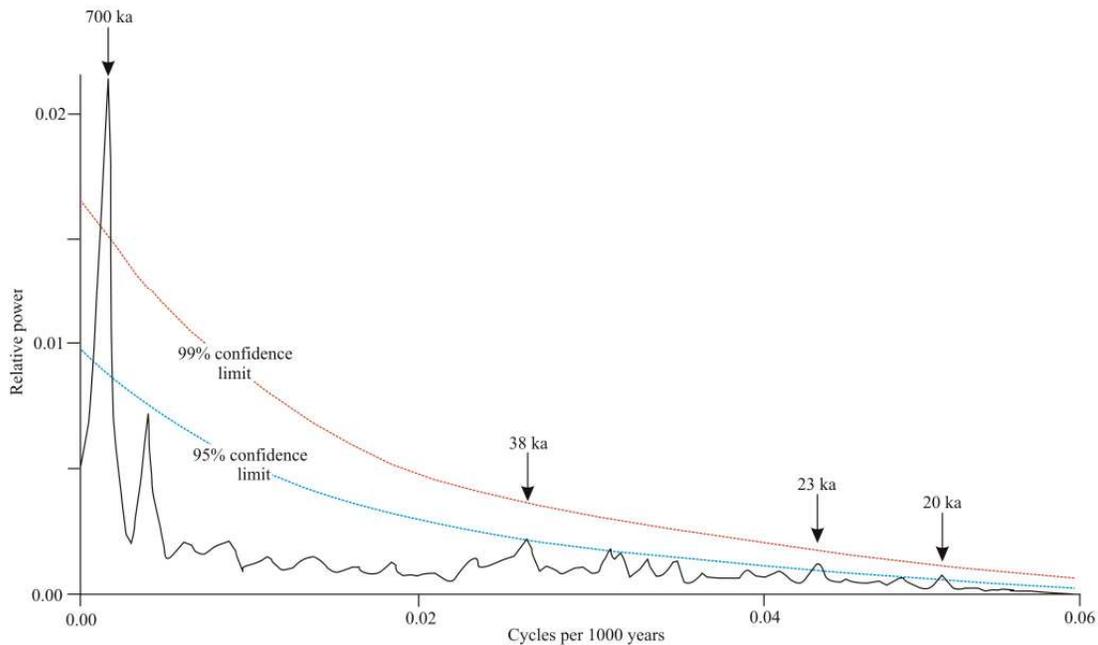


Figure 8. Statistical analysis of organic-carbon contents in Kimmeridge Clay cores from the Swanworth No. 1 Borehole, Dorset revealing Milankovitch cycles at various time scales (after Weedon *et al.*, 2004).

Second, the basis for computer modelling future climate change in Britain is based on detailed climatic records that extend back only about 150 years. Whilst they may be adequate for detecting recent changes, the only place where changes at the Milankovitch scale can be studied is in the geological column. The Kimmeridge Clay, with its unusually complete, marine sedimentary record is one of the best places in the stratigraphical column to do this.

Conclusions

Although the Kimmeridge Clay can be said to be the most intensively studied formation in Britain, there is still much that we do not know about the depositional environments and subsequent diagenesis that produced the present-day rock. As with all branches of science, the more we know the more we realise we don't know.

The chronostratigraphy and sequence-stratigraphy of the English onshore outcrop and subcrop of the formation is well established, but the correlation with European sections and with the deep-water successions of the UK continental shelf is poorly known at many stratigraphical levels. The biostratigraphy of the ammonites have been studied, but that of much of the rest of the fauna has not. In particular, the vertebrate

fauna, which in the Jurassic is matched in diversity and quality of preservation only by that from the Solenhofen Limestone, has barely been studied despite the availability of extensive collections.

Recent models of the depositional environments of the Kimmeridge Clay of the 550m-thick Dorset succession have assumed an outer-shelf water depth of 150 to 200m. Elsewhere in England, where the correlative deposits are locally less than 100m thick (Penn *et al.*, 1986), the same lithological and faunal associations and sedimentology suggest deposition in similar outer-shelf environments. In order to explain the thickness variations whilst retaining the chronostratigraphy, one has to postulate complex interactions between eustatic changes in sea-level, climate changes, sedimentation rates and tectonically-induced subsidence rates. More parameters than we can cope with at present.

In short, the Kimmeridge Clay is a very interesting and much studied formation, but one about which we still have much to learn.

References

The references listed below have been selected to illustrate particular features of the Kimmeridge Clay. A detailed, comprehensive account of the formation including an extensive list of references is given on Dr Ian West's web site at www.soton.ac.uk/~imw/kim.htm

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