The stratigraphy of the Kimmeridge Clay Formation (Upper Jurassic) in the RGGE Project boreholes at Swanworth Quarry and Metherhills, south Dorset.

Ramues Gallois

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Three continuously cored boreholes were drilled in the Kimmeridge Clay Formation in south Dorset to provide unweathered samples for a multidisciplinary study of late Jurassic rhythmic sedimentation and its possible causes. Taken together, the borehole cores provide the first complete sequence through the Kimmeridge Clay and the Kimmeridgian Stage in their type area. The cores have been correlated in detail with the succession exposed in the nearby Kimmeridge cliffs and other sections in south Dorset, as well as with those proved in borehole sections elsewhere in southern and eastern England. The cores have enabled the current chronostratigraphical classification of the Kimmeridge Clay to be extended to the top of the formation, covering strata that are poorly exposed at outcrop. Four types of small-scale rhythm are present within the formation, each of which can be related to the sequence stratigraphy. Only one of these is organic rich and of importance as an oil-source rock.
Corresponding author: R. W. Gallois (email: gallois@geologist.co.uk)

1. INTRODUCTION

Rapid Global Geological Events (RGGE) Project

In 1995 the Natural Environment Research Council (NERC) initiated the Rapid Global Geological Events (RGGE) special research topic to examine rhythmicity and its possible causes in the Kimmeridge Clay. The formation was chosen for the study because it consists of an almost unbroken sequence of relatively uniform, highly fossiliferous marine-shelf mudstones that have suffered little tectonic deformation. The mudstones contain rhythmic variations in clay mineralogy, and faunal and organic contents that reflect climatic and sea-level changes, some of which have been interpreted as Milankovitch precession/obliquity rhythms (House, 1995). In order to obtain enough material for the multidisciplinary study, it was proposed that two continuously cored boreholes, about 20m apart, should be drilled through the full thickness of the formation at a single site close to the type section at Kimmeridge, Dorset.

The drilling site originally chosen, in the floor of Swanworth Quarry [SY 9675 7823] near Worth Matravers (Figure 1), enabled drilling to begin at a known stratigraphical horizon (the top of the Portland Sand), and it could be seen from the adjacent quarry faces to be in an unfaulted area. Examination of the geophysical logs from boreholes through all or part of the Kimmeridge Clay in this area, together with seismic-reflection profiles provided by British Petroleum Ltd., had suggested that the full thickness of the formation here was between 535 and 585m. To this was added 40m for the overlying Portland Sand and 15m to allow for an over-run of the geophysical tools at the bottom of the borehole, to give an estimated total required depth of 590 to 640m if the full formational thickness was to be recovered.

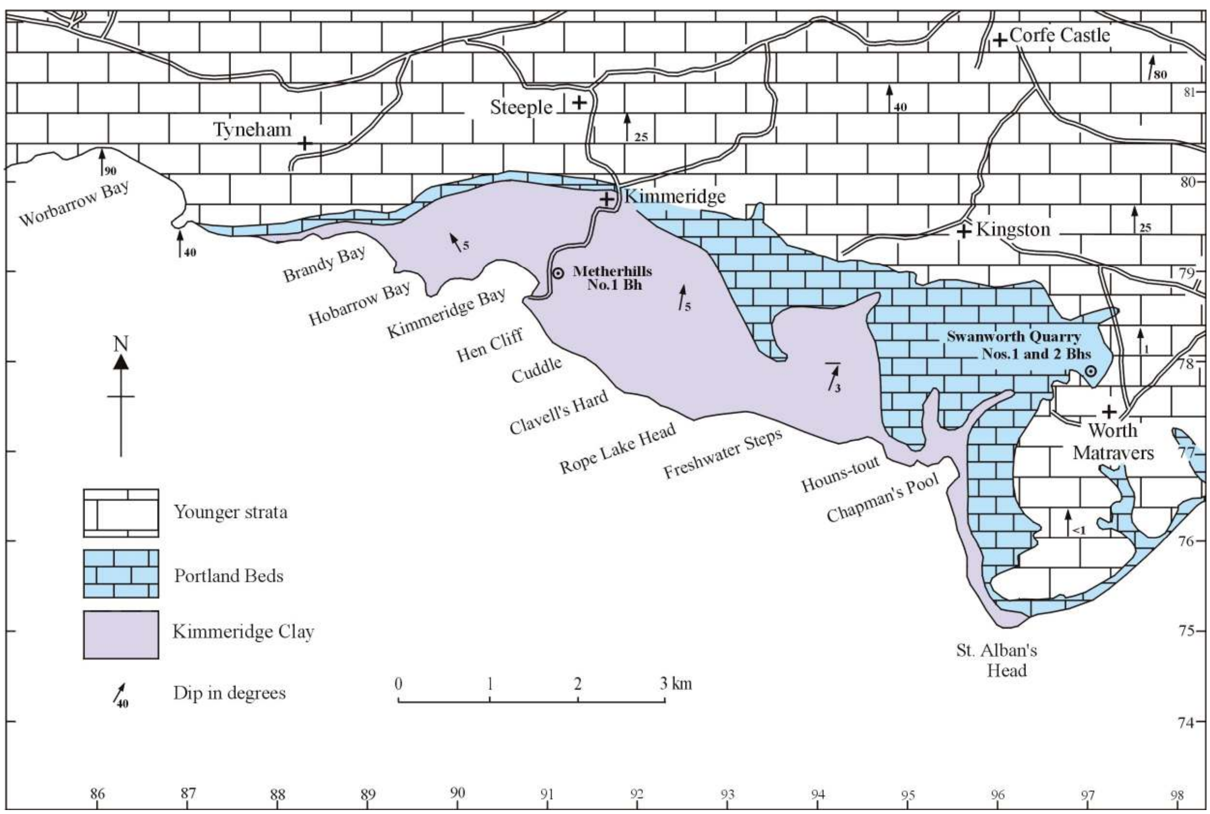


Figure 1. Sketch map of the solid geology of the Kimmeridge-Worth Matravers area showing the positions of the Swanworth Quarry and Metherhills boreholes.

The first borehole at Swanworth Quarry was terminated at a depth of 505.21m within the lower part of the Lower Kimmeridge Clay, at an estimated 90m above the base of the formation, when its stability was threatened by heavily fractured horizons. A second continuously cored borehole at Swanworth Quarry, 18m from No.1, was terminated at a depth of 388.30m, a few metres below the Hobarrow Bay Stone Band marker bed. A third borehole was, therefore, drilled through the lower part of the formation at Metherhills [SY 9112 7911], Kimmeridge Bay on what was anticipated to be the same Kimmeridge Clay isopachyte as Swanworth Quarry. A reconnaissance field survey and comparison of the geophysical logs from the Swanworth Quarry No. 1 Borehole with an incomplete resistivity log from the Kimmeridge No. 5 hydrocarbon-exploration borehole [SY 9042 7935] (British Petroleum, 1961), suggested that the Yellow Ledge Stone Band was close to ground level at the Metherhills site (Figure 2). The Metherhills No. 1 Borehole was rock-bitted to 90m depth, to a level a little above the estimated position of the Hobarrow Bay Stone Band, and continuously cored from there downwards to provide a small overlap with the Swanworth Quarry No. 2 cores. Coring was continued to a sufficient distance into the Corallian Group, to a depth of 319m, to allow the geophysical tools to record the base of the Kimmeridge Clay. Taken together, the Metherhills No.1 and Swanworth Quarry No. 2 boreholes provide a continuous core through the full thickness of the Kimmeridge Clay. The Swanworth Quarry No. 1 core duplicates all except the lowest 90m of the formation (Figure 3). Core recovery in all three boreholes was a nominal 100%.

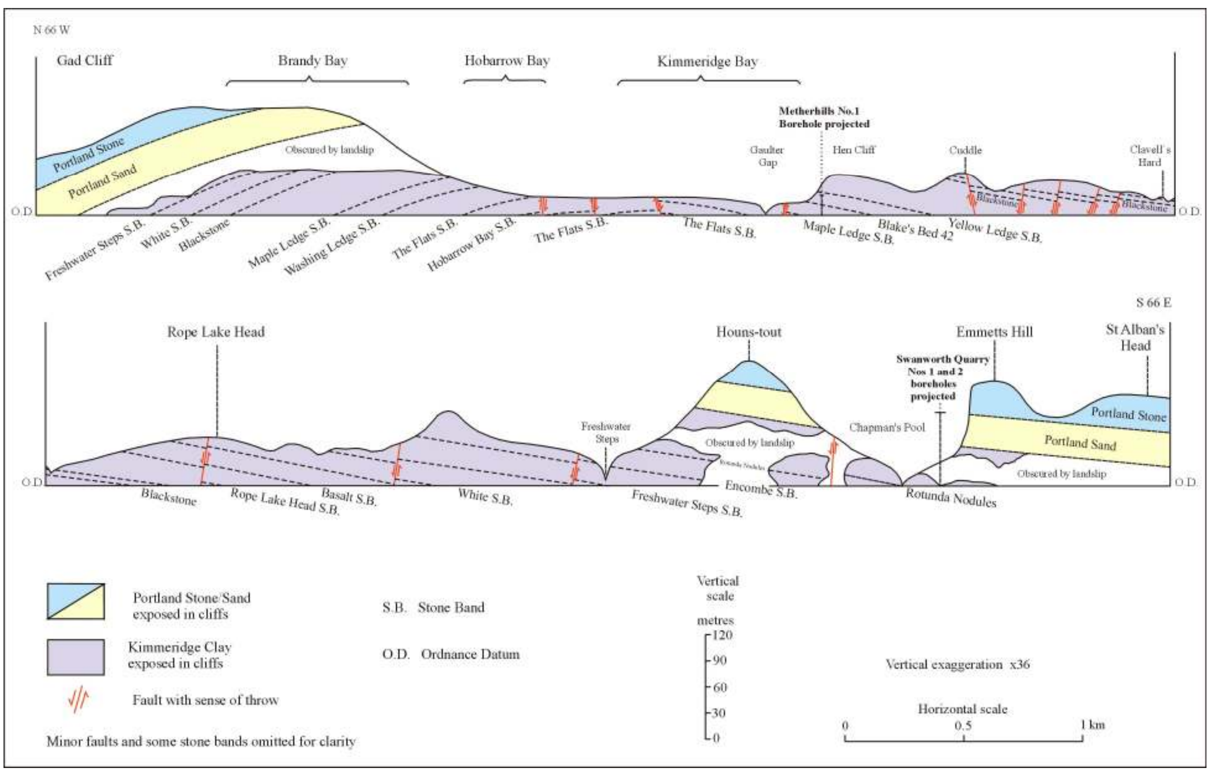


Figure 2. Geological sketch section of Kimmeridge cliffs, the positions of selected marker bands and the projected positions of the Swanworth Quarry and the Metherhills boreholes.

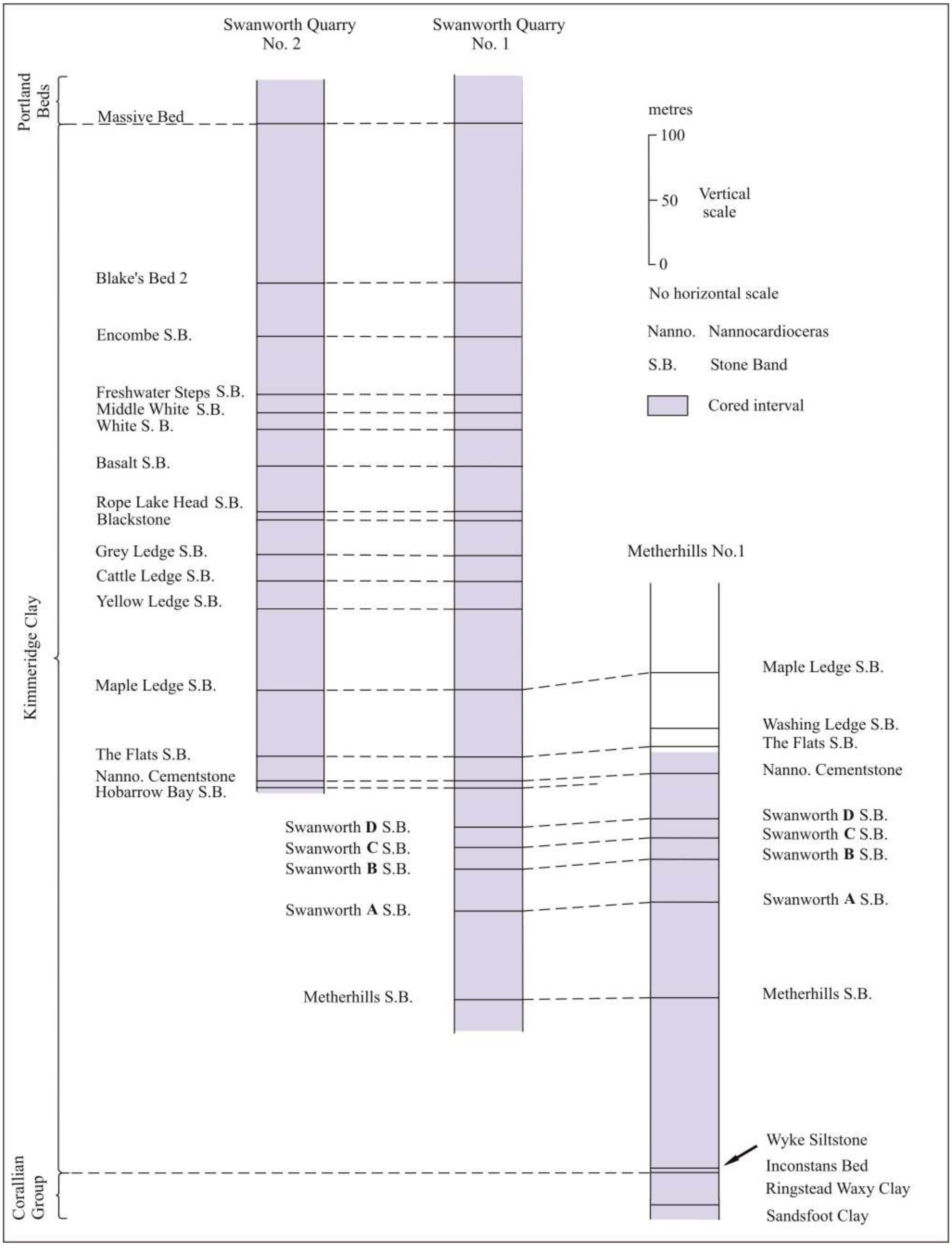


Figure 3. Cored intervals and the correlation of selected marker bands in the Swanworth Quarry and Metherhills boreholes.

Geophysical logging

In addition to the more routine resistivity, gamma-ray, bulk density and sonic logs, a selection of magnetic susceptibility, palaeomagnetism, nuclear magnetic resonance and borehole imaging logs were also run (Table 1). The unexpectedly sudden termination of the Swanworth Quarry No. 1 Borehole meant that it had to be logged at short notice and the geochemical and magnetic tools were unavailable. A minimal suite of logs was run in the Swanworth Quarry No. 2 Borehole, sufficient to provide correlation and some inter-borehole comparison of electrical and other properties. A full suite of logs was run in the Metherhills No. 1 Borehole.

Geophysical Log	Swanworth Quarry No. 1	Swanworth Quarry No. 2	Metherhills No. 1
Caliper	✓	✓	✓
Temperature	✓	✓	✓
Total Gamma Ray	✓	✓	✓
Spectral Gamma Ray	✓		✓
Resistivity, single point	✓	✓	✓
Resistivity, shallow	✓		✓
Resistivity, deep	✓		✓
Laterolog, shallow			✓
Laterolog, deep			✓
Array Sonic			✓
Lithodensity	✓		
Self Potential	✓	✓	✓
Induction	✓	✓	✓
Magnetic Resonance			✓
Magnetic Susceptibility		✓	✓
Geomagnetism			✓
Formation Microscanner	✓		
Formation Microimager			✓

Table 1. Geophysical (wireline) logs run in the RGGE boreholes.

Determining the precise depths from which rock cores have been retrieved from the ground is always difficult, for a number of reasons. Core recovery is never perfect; core slippage can lead to confusing depth measurements; and natural fractures open and the core itself expands when the lithostatic load is removed. This last can add several percent to the apparent length of the core. The net effect of these sources of depth error is impossible to quantify on site, but a close approximation to the true depths can be obtained from the geophysical logs. In the Kimmeridge Clay, thin limestone bands proved to be especially useful for this purpose because they have lithologically sharp bases and tops that give rise to gamma-ray, resistivity and density responses that are markedly different from those of the adjacent mudstones.

Formation Microscanner (FMS) and Formation Microimager (FMI) logs made by Schlumberger Ltd., which provide pictorial images of the core based on resistivity differences, proved to be particularly useful: they enabled the positions of the stone bands to be measured to within ±50mm of their true depths. Comparison of the geophysical 'true' depths with those made on the cores in the laboratory showed a non-linear expansion of over 2½ % (12.9m at 500m depth).

Details of the drilling procedures and core recoveries, and copies of the on-site geological logs and geophysical logs have been placed on open file in the British Geological Survey archive.

2. STRATIGRAPHY

Background

The Kimmeridge Clay of most of the English onshore outcrop is made up of a series of mudstone-dominated, small-scale (0.5 to 1.5m thick) to large-scale (tens of metres thick) rhythms. Many of the individual small-scale rhythms can be correlated over distances of tens of kilometres using borehole cores and wireline geophysical logs. The larger-scale rhythms can be correlated throughout much of the Kimmeridge Clay onshore outcrop and subcrop (Cox and Gallois, 1981). Coarser sediments, mostly fine-grained sands and silts, occur locally around the edges of the concealed London Platform where they replace parts of the rhythmic mudstone sequence.

The Kimmeridge Clay is wholly marine throughout Britain, and at most levels is rich in ammonites, bivalves and foraminifera. Gastropods, serpulids, crinoids, belemnites and coccoliths are abundant at some levels; vertebrate remains, mostly fish scales and vertebrae and marine reptile bones, also occur. Palynomorphs, including dinoflagellate cysts, pollen and spores which are now mostly diagenetically altered to amorphous kerogen, form up to 45 by weight of the more organic-rich horizons (oil shales). Plant debris is common at many levels.

The ammonites in the Kimmeridge Clay are mostly crushed, but otherwise well preserved. They are present in large numbers at most stratigraphical levels, are sufficiently common in borehole cores to be stratigraphically useful, and they occur in assemblages of rapidly evolving forms. The zonal scheme is based on species of the perisphinctaceans *Pictonia*, *Rasenia*, *Aulacostephanus*, *Pectinatites*, *Pavlovia* and *Virgatopavlovia* (Arkell, 1933; Ziegler, 1962; Cope, 1967; 1978). Other ammonites are common at some horizons in the *Rasenia* and *Aulacostephanus* zones: these include *Amoeboceras* (*Amoebites*), *Amoeboceras*

(*Nannocardioceras*), *Aspidoceras* and its aptychal plate *Laevaptychus*, *Crussoliceras* and *Sutneria.* Rare *Gravesia* occur in the middle part of the formation (Cox and Gallois, 1981). In the present account, the names of the ammonite-based zones follow the current majority practice for the Jurassic in which the zones are regarded as chronostratigraphical and referred to by their species name with an initial capital and in Roman script, e.g. Pectinatus Zone. Thin beds containing flood occurrences of coccoliths, the crinoid *Saccocoma*, rhynchonellid brachiopods, belemnites and certain species of ammonite and bivalve, provide additional marker horizons that are probably isochronous.

Detailed classification of the Kimmeridge Clay

The Kimmeridge Clay has been extensively studied using continuously cored boreholes in eastern England and has been divided into 49 stratigraphical units (referred to as Beds KC 1 to KC 49) on the basis of a combination of lithological and macrofaunal characters (Gallois and Cox, 1976; Cox and Gallois, 1979). Updated descriptions are given in Gallois (1994). The scheme has been applied to exposures and cored boreholes throughout the Kimmeridge Clay onshore outcrop and subcrop, including the Dorset type section, and has been correlated with geophysical logs (Penn, Cox and Gallois, 1986). The units are considered to be chronostratigraphical.

The original classification ended at Bed KC 49, a little above the base of the Pectinatus Zone because, in eastern England, younger parts of the Kimmeridge Clay are mostly cut out by erosion at the base of the latest Jurassic or early Cretaceous. Stratigraphically higher beds occur locally, as at Hartwell, Bucks (Neaverson, 1924) and Swindon, Wilts (Chatwin and Pringle, 1922), but these sequences contain major sedimentary breaks, and much of them in sandy facies. The published descriptions of the highest beds in Dorset are incomplete and contain little lithological detail. New measurements made by Mr S. Etches and the author suggest that at least 10m of strata have not previously been recorded.

Classification of the highest Kimmeridge Clay (White Stone Band and above) in Dorset

The youngest part of the Kimmeridge Clay in Dorset, up to the junction with the Portland Group, is exposed in mudstone facies in cliffs and steep slopes between Freshwater Steps and Chapman's Pool (Figure 2). The highest beds (Rotunda and Fittoni zones) crop out in deeply weathered and partially landslipped exposures above Chapman`s Pool and beneath Houns-tout. The revised field measurements (see above) were confirmed by the Swanworth Quarry

No.1 Borehole in which thicknesses for the youngest part of the Kimmeridge Clay proved to be within a few percent of that measured in the cliffs.

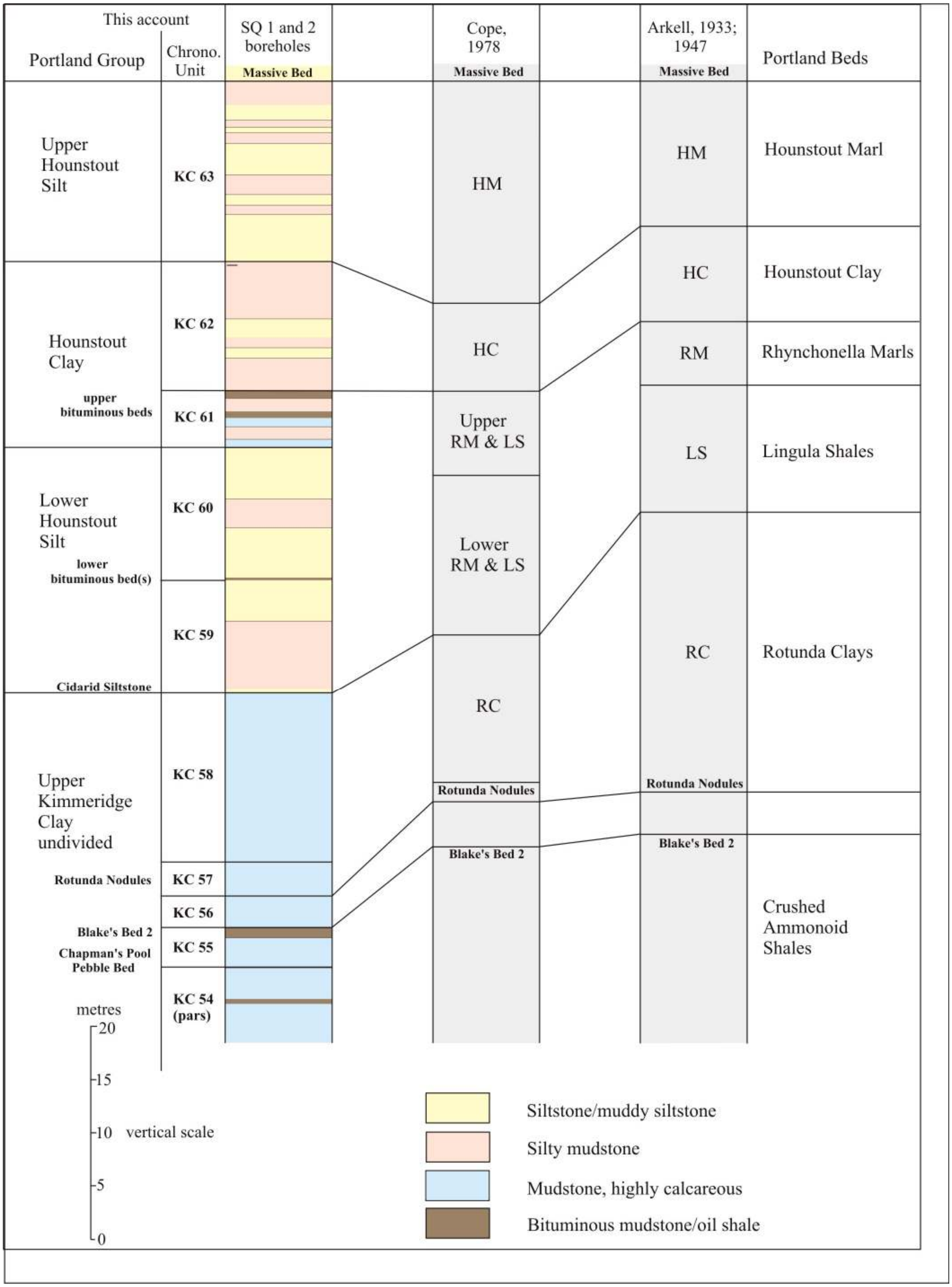


Figure 4. Subdivisions of the Kimmeridge Clay above Blake's (1875) Bed 2 at Chapman's Pool and in Houns-tout Cliff, and in the Swanworth Quarry boreholes.

Few marker bands can be correlated between the outcrop and the borehole cores because of the deeply weathered nature of the outcrop, but the broader lithological changes can be closely matched.

The opportunity is taken here to present a lithological description of the highest Kimmeridge Clay strata and to extend the detailed classification of Gallois and Cox (1976) and Cox and Gallois (1979) from the base of the White Stone Band to the top of the formation. It includes minor revisions of Beds KC 46 to KC 49 (as given by Cox and Gallois, 1979) because the original scheme, based largely on sections in eastern England, proved to be too detailed to be recognisable throughout southern England. The currently used terms, Lingula Shales (Buckman, 1926), Rhynchonella Marls (Buckman, 1926) and Hounstout Marl (Arkell, 1933), have been replaced by **Lower** and **Upper Hounstout Silt** and a modified **Hounstout Clay** (Arkell, 1933) that better describe the broad lithological characters of the sequence (Gallois, 1998) (Figure 4). There has been little published on the fauna of this part of the Kimmeridge Clay, largely because of the poorly accessible and deeply weathered nature of much of the section. The description of the ammonite stratigraphy by Cope (1978) remains the most recent and is used in the bed descriptions below.

The bed descriptions and their true (geophysical) depths and thicknesses in the Swanworth Quarry No. 1 Borehole are as follows:

Portland Sand: base taken at base of the Massive Bed (2m-thick bed of fine-grained, calcareous sandstone) as recommended by Arkell (1947, p. 91) and followed by most subsequent workers.

Upper Kimmeridge Clay
Upper Hounstout Silt:
KC 63 Siltstone, muddy and silty and very silty mudstones, thickly interbedded; medium grey and brownish grey becoming paler with increasing silt content; highly bioturbated at many levels with *Teichichnus, Rhizocorallium, Arenicolites* and other burrows picked out by pale silt content; poorly preserved bivalves and ammonites including *Virgatopavlovia hounstoutensis* Cope, *V.* sp. nov. aff. *fittoni* Cope and *Pavlovia* spp. indet.; base taken at downward change to finer-grained lithologies: 40.05 to 56.87 (16.82m)

Hounstout Clay:
KC 62 Mudstone, silty and very silty with several thick interbeds of silty mudstone; medium grey, paler where more silty; highly bioturbated as bed above with burrows exceptionally well preserved in more silt-rich horizons; fauna as bed above including *Virgatopavlovia hounstoutensis, V.* sp. nov. aff. *fittoni* and *Pavlovia* spp.; base taken at top of bituminous mudstone: 56.87 to 69.58 (12.71m)

KC 61 Mudstone, silty and very silty, highly calcareous in part and with thin interbeds of fissile slightly bituminous and bituminous mudstone in upper part; base taken at downward change to more silty lithologies; no fauna recorded: 69.58 to 74.87 (5.29m)

Lower Hounstout Silt:
KC 60 Siltstone, muddy and silty and very silty mudstones, thinly and thickly interbedded, commonly in units 0.10 to 0.40m thick; base taken at top of thin bituminous bed; no fauna recorded: 74.87 to 87.50 (12.63m)

KC 59 Siltstone, muddy and silty mudstone; rhythmically interbedded as KC 60; one (locally two) thin (0.05 to 0.15m), laminated brownish grey bituminous mudstone beds with common pyritized oysters and other bivalves at top of unit; thin siltstone at base rests with marked lithological contrast on underlying mudstones; basal siltstone contains rich and diverse fauna including oysters, *Entolium, Pachyteuthis*, rhynchonellids and cidarid spines; 87.50 to c.98.0 (c10.5m)

Upper Kimmeridge Clay (undivided):
KC 58 Mudstone, medium and pale grey, highly calcareous, becoming progressively more silty in highest part; interbeds of very pale grey mudstone with subconchoidal weathering at several levels; two or more thin (0.1 to 0.2m) beds of dark grey, fissile shelly mudstone with abundant crushed bivalves; small oysters, *`Astarte', Protocardia, Thracia* scattered throughout and common at some levels; *Pavlovia rotunda* (Sowerby), *P. concinna* (Neaverson), *P.* aff *concinna*: base taken at top of line of burrowfill nodules: c.98.0 to 113.83 (c15.8m)

KC 57 Mudstone, medium and pale grey, highly calcareous with subconchoidal weathering in part; line of large (up to 0.1 x 0.2m) dense calcareous burrowfill nodules at top enclosing bivalves and rare *Pavlovia*; line of similar, but smaller nodules at base commonly containing well preserved *Pavlovia*, including *P. concinna*, *P. rotunda* and *P. rotunda gibbosa* (Buckman): 113.83 to 117.12m (3.29m)

KC 56 Mudstone, medium and pale grey, as bed above; *Pavlovia concinna, P. rotunda*, and *P.* sp. B of Cope 1978; base taken at top of oil shale: 117.12 to 120.33 (3.21m)

KC 55 Mudstone, thinly interbedded, dark and medium grey with thick oil shales (Blake's Bed 2) in highest part with *Pavlovia concinna, P.* sp. nov. aff. *varicostata* Ilovaisky, *P. rotunda* and *P.* sp. B of Cope 1978; erosion surface at base overlain by gritty, shell-rich pebble bed (Chapman's Pool Pebble Bed, see below) with crushed and partially phosphatized *Pavlovia*, abundant *Pachyteuthis*, whole and fragmentary oysters and other bivalves, and phosphatic-pebble casts of bivalves and 'pavlovid' body-chambers: 120.33 to 123.95 (3.62m)

KC 54 Mudstone, mostly medium and pale grey with widely spaced thin (<0.3m) interbeds of brownish grey bituminous mudstone; *Pavlovia composita* Cope, *P. composita waddingtoni* Cope, *P. pallasiodes* (Neaverson), *P. superba* Cope, *P.* aff. *strajevsky* Ilovaisky, *P.* sp. B? of Cope 1978, *Pectinatites (P.) circumligatus* Cope; thin bituminous bed at base: 123.95 to 142.95m (19.0m)

KC 53 Mudstone, medium and pale grey, highly calcareous with subconchoidal weathering at several levels; very pale, weakly cemented band in middle part of bed passes locally into cementstone (Encombe Stone Band, see below) in much of south Dorset; *Pavlovia composita, P.* sp. A of Cope 1978, *Pectinatites (Pectinatites) devillei* (de Loriol), *P. (P.)* cf. *devillei*; base taken at top of thin bituminous bed: 142.95 to 152.88 (9.93m)

KC 52 Mudstone, medium and pale grey with some thin dark grey interbeds and several thin, brownish grey bituminous mudstones; *Pavlovia* spp. fragments in upper part; *Pectinatites (P.) dorsetensis* Cope, *P. (P.) strahani* Cope and *P. (P.) tricostulatus* (Buckman) in lower part; base taken at thin bituminous mudstone: 152.88 to 163.04 (10.16m)

KC 51 Mudstone, medium and pale grey, highly calcareous with up to three horizons with small (mostly 0.1 to 0.2m), dense calcareous concretions; *Pectinatites* sp. indet.:163.04 to 166.00 (2.96m)

KC 50 Mudstone, medium and pale grey with two or more thin, dark grey, fissile pyrite-rich beds; base taken at top of underlying laminated mudstones; *Pectinatites (P.) cornutifer* (Buckman), *P. (P.) paravirgatus* (Buckman), *P. (P.) pectinatus* (Phillips), *P. (P.) naso* (Buckman) and *P. (P.) rarescens* (Buckman): 166.00 to 175.70 (9.70m)

KC 49 Mudstone, finely laminated pale and dark grey, brownish grey bituminous and off-white coccolith-rich; finely laminated coccolith-rich limestone (Freshwater Steps Stone Band) at base. *Pectinatites (Pectinatites) cornutifer*, *P. (P.) naso* and *P. (P.) paravirgatus*: 175.70 to 178.50 (2.80m)

KC 48 Mudstone, predominantly medium and pale grey thinly interbedded with dark grey fissile mudstone, brownish grey bituminous mudstone and greyish brown oil shale; pale coccolith-rich laminae in several oil shales; finely interlaminated coccolith-rich mudstone and oil shale at base passing laterally into coccolith-rich limestone (Middle White Stone Band): 178.50 to 187.55 (9.05m)

KC 47 Mudstone, predominantly dark and medium grey with several thin interbeds of pale grey mudstone and, in upper part, oil shale; generally sparsely shelly with *Isocyprina miniscula* (Blake), *Protocardia morinica* (de Loriol), *Pseudorhytidopilus latissima* (J Sowerby) and *Lingula ovalis* J Sowerby common at some levels; *Camptonectes* cf. *morini* (de Loriol), G*rammatodon*, *Modiolus autissiodorensis* (Cotteau), *Pleuromya, Oxytoma* and small oysters also present; fragments of finely ribbed perisphinctacean ammonites including *Pectinatites (P.) eastlecottensis* (Salfeld); base taken at base of coccolith-rich band: 187.55 to 194.18 (6.63m)

KC 46 Mudstone, dark and medium grey, thinly interbedded with fissile, shelly oil shales which include several thin bands of pale brownish grey, coccolith-rich limestone; fauna as KC 47 but with fish debris and faecal pellets common in oil shales; *Pectinatites (P.) eastlecottensis* common throughout; rarer *P. (P.) cornutifer* (Buckman) and *P. (P.) pectinatus* (Phillips); base taken at base of White Stone Band where present, or at base of shelly oil shale which marks lower limit of *P. (P.) eastlecottensis*: 194.18 to 196.75 (2.57m)

Beds KC 46 to 58 are wholly exposed in the cliffs between Freshwater Steps [SY 944 773] and Chapman's Pool [SY 955 771], and KC 59 to 63 in the lower and middle cliffs below Houns-tout [SY 951 772]. Beds KC 46 to 59 crop out, mostly in deeply weathered sections, below Gad Cliff [SY 880 794], and parts of KC 60 to 63 are present in small exposures separated by landslip in the same area. Beds KC 46 to 55 are patchily exposed on the higher slopes [SY 762 815] at Ringstead Bay; part of KC 63 and possibly KC 62 crop out below Dungy Head [SY 817 798]; and KC 55 to 58 form a low degraded cliff [SY 706 722] below Grove Point on the Isle of Portland.

The **Encombe Stone Band** (in KC 53) was proved in the Swanworth Quarry boreholes, in the BGS Encombe Borehole [SY 9446 7785], and in the geophysical-log signatures in hydrocarbon-exploration boreholes in the area, but is present only as a weakly cemented, very pale mudstone in the cliffs at Egmont Bight. The **Chapman`s Pool Pebble Bed** (in KC 55) is exposed at Chapman's Pool where it comprises a gritty, shelly, silt-rich mudstone up to a few centimetres thick with abundant belemnites and oysters, and phosphatised bivalves and body chambers of 'pavlovid' ammonites resting on a bioturbated surface. It marks an important sedimentary break and faunal change at the base of the Rotunda Zone. Its correlatives at Gad Cliff, Ringstead Bay and on the Isle of Portland also contain abundant belemnites, phosphatised ammonite and bivalve fragments, and phosphatic and other pebbles. Casey (1971) suggested that the Rotunda Nodules, about 7m above the pebble bed, marked a sedimentary break that could be correlated with the NW-Europe-wide "mid Volgian [erosional] event". The erosion surface at the base of the pebble bed is the more likely correlative of that event. Elsewhere in southern England, phosphatic debris from the pebble bed is incorporated into the Upper Lydite Bed at the base of the Portland Sand.

Classification of the Kimmeridge Clay below the White Stone Band in Dorset.

The detailed classification into beds KC 1 to 45 has previously been applied to the type section at and adjacent to Kimmeridge Bay (Cox and Gallois, 1981), and linked to the sequence of lithological marker bands (mainly named stone bands) which have been used as stratigraphical markers there since the time of Arkell (1933). This part of the classification has been applied to the sequences in the RGGE boreholes without modification.

With the exception of the Dorset coastal sections, the base of KC 36 has been taken consistently throughout the onshore Kimmeridge Clay at the base of an oil shale immediately above the highest recorded *Aulacostephanus*; this boundary has also marked the base of the

Elegans Zone and the Upper Kimmeridge Clay. On the Dorset coast, notably on the east side of Kimmeridge Bay, the base of the Upper Kimmeridge Clay and (by default) the base of KC 36, has traditionally been taken at the base of Blake's (1875) Bed 42, an impersistently cemented bituminous mudstone about 8m above the highest recorded *Aulacostephanus.* Blake's Bed 42 is only seen in Hen Cliff [SY 909 785], on the east side of Kimmeridge Bay (Figure 2). It was tentatively correlated with a cemented oil shale 2km to the west in the cliffs at Brandy Bay [SY 888 796] (Cox and Gallois, 1981), but is absent in the Swanworth Quarry boreholes, and in all the inland boreholes recorded to date.

The sudden disappearance of *Aulacostephanus* seems to provide a reliable biostratigraphical marker event throughout Britain. For consistency, the KC 35/KC 36 boundary at Kimmeridge Bay should be taken at the base of the first oil shale above the highest recorded *Aulacostephanus*. This interval is important for international correlation as it includes the correlative of the base of the Tithonian Stage which is the internationally agreed standard terminal stage of the Jurassic System.

Almost all of the named lithological marker bands of the coastal sections and most of the faunal marker bands recorded from inland sections were readily identifiable in the RGGE borehole cores. New names have been introduced for previously unrecorded marker bands that have been shown to be laterally persistent. Some of these have been proved in boreholes beyond the Isle of Purbeck, but others are as yet only known locally. The beds to which new names have been given are described below in ascending stratigraphical order.

The base of the Eudoxus Zone throughout the onshore outcrop and subcrop of the Kimmeridge Clay is marked by an erosion surface that is overlain by a shelly and gritty siltstone (KC 24), here named the **North Wootton Siltstone,** which marks the last, and probably the most extensive of a series of early Kimmeridgian transgressions. The type section is the continuously cored interval between 87.30 and 88.55m in the North Wootton Borehole, Norfolk [TF 6439 2457] (Gallois, 1979). At some localities, particularly those close to the edge of the concealed London Platform, a second transgressive pulse gives rise to a lithologically similar bed (KC 25) a little higher in the succession.

A thin (up to 30mm thick), lithologically distinctive bed of fluidised shelly mudstone which cuts a laminated coccolith-rich bed (probably marker band EU 1 of Gallois and Medd, 1979), is present in KC 32 in all three RGGE boreholes. It had only previously been recorded in situ at Hobarrow Bay and as loose blocks of uncertain stratigraphical provenance at Ringstead Bay. The Hobarrow Bay and borehole occurrences are all at the same stratigraphical level, close below the Nannocardioceras Cementstone: the bed seems to mark an isochronous event, probably a seismic shock. It is referred to here as the **Hobarrow Bay Fluidised Bed**.

New names have been given to five stone bands which were recorded in the Metherhills No.1 and Swanworth Quarry No.1 boreholes, and in the geophysical-log signatures of several deep hydrocarbon-exploration boreholes in the region. None of them has been identified at outcrop in south Dorset. These are the **Metherhills** (in KC 19), **Swanworth A** (in KC 28), **Swanworth B** (in KC 29) and **Swanworth C** and **D** (in KC 30) stone bands.

An additional stone band recorded close below the Grey Ledge Stone Band in the Swanworth Quarry No. 1 and No. 2 boreholes, but absent at outcrop in Kimmeridge cliffs, has been named the **Southard Stone Band** after the Southard Quarry Borehole [SZ 0234 7775] (drilled by British Petroleum in 1989) where it has a strong geophysical signature. The limited borehole data suggest that it is restricted to the eastern part of the Isle of Purbeck. A seventh stone band, high in KC 44 between the Basalt Stone Band and the White Stone Band, was proved in the Swanworth Quarry and several nearby boreholes, but is absent in Kimmeridge cliffs.

Sequence stratigraphy

Despite its apparent lithological uniformity at some levels, the Kimmeridge Clay is rhythmic throughout. The thin silty horizons at the bases of Beds KC 1, 5, 8,12,15,17 and 24 (at the bases of the Type A rhythms of Cox and Gallois, 1981) are rich in phosphatic pebbles and broken shell debris, and rest on erosion surfaces (Figure 5). They can be interpreted as the bases of Transgressive Systems Tracts that formed during an early Kimmeridgian transgressive phase that resulted from a prolonged period of pulsed rises in sea-level. Most are accompanied by an influx of new fauna. In marginal areas, for example around the edges of the concealed London Platform and adjacent to penecontemporaneously active fault lines such as the Wight-Purbeck structure, the erosion at the bases of these siltstones becomes more marked. In the basinal areas they are represented by expanded sequences in which the erosion surfaces are difficult to identify, and which may locally pas into correlative conformities. The faunal ranges of some species, which are discrete in the marginal areas, become extended and overlapping within the basins.

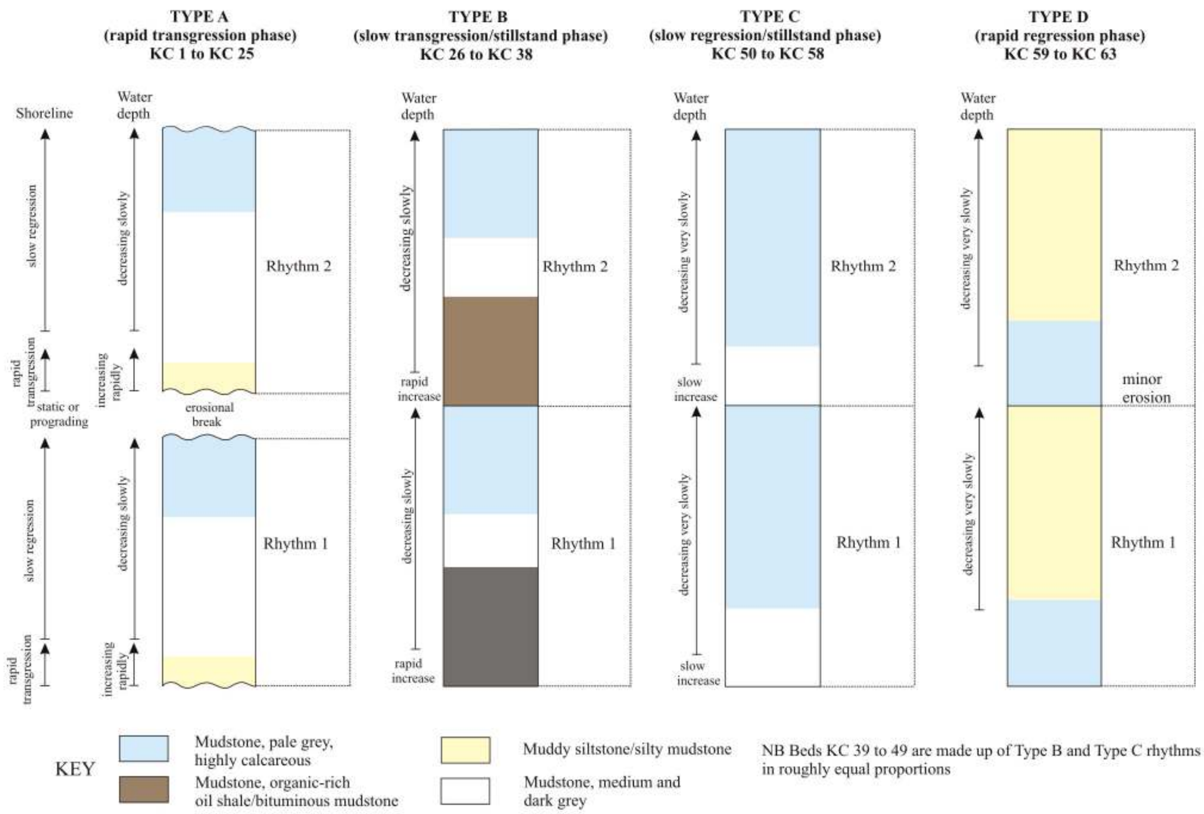


Figure 5. Principal types of small-scale Kimmeridge Clay rhythm and their presumed paleogeographical interpretations.

The organic-rich rhythms (Type B of Cox and Gallois, 1981) of the Eudoxus to Scitulus zones (Beds KC 26 to 38) were probably deposited during a predominantly still-stand phase in which there was minor transgression overall. Minor fluctuations in sea level contributed to the rhythmicity, but may not have been the principal cause of it. Carbonate-rich rhythms (Type C of Figure 5) become prominent in the upper Scitulus to middle Pectinatus zones (KC 39 to 49) and predominant in the upper Pectinatus to lower Rotunda zones (Beds KC 50 to 58). These too were probably deposited during a predominantly still-stand phase, but one in which there was overall regression. In the Dorset coastal sections, the Chapman's Pool Pebble Bed marks a sedimentary break above which organic-rich sediments are absent except for Blake's Bed 2 (in KC 55) and thin bituminous horizons in the Fittoni Zone (in KC 60 and 61).

The highest part of the Kimmeridge Clay (KC 59 to 63) is characterised by coarser sediments, silty mudstones and siltstones (Type D rhythms of Figure 5) in the basinal areas and sands in the marginal areas, which were deposited during a regressive phase. Belemnites and rhynchonellid brachiopods, which are rare in the remainder of the Kimmeridge Clay except at the bases of the transgressive KC 1, KC 24 and KC 55, are common at this level.

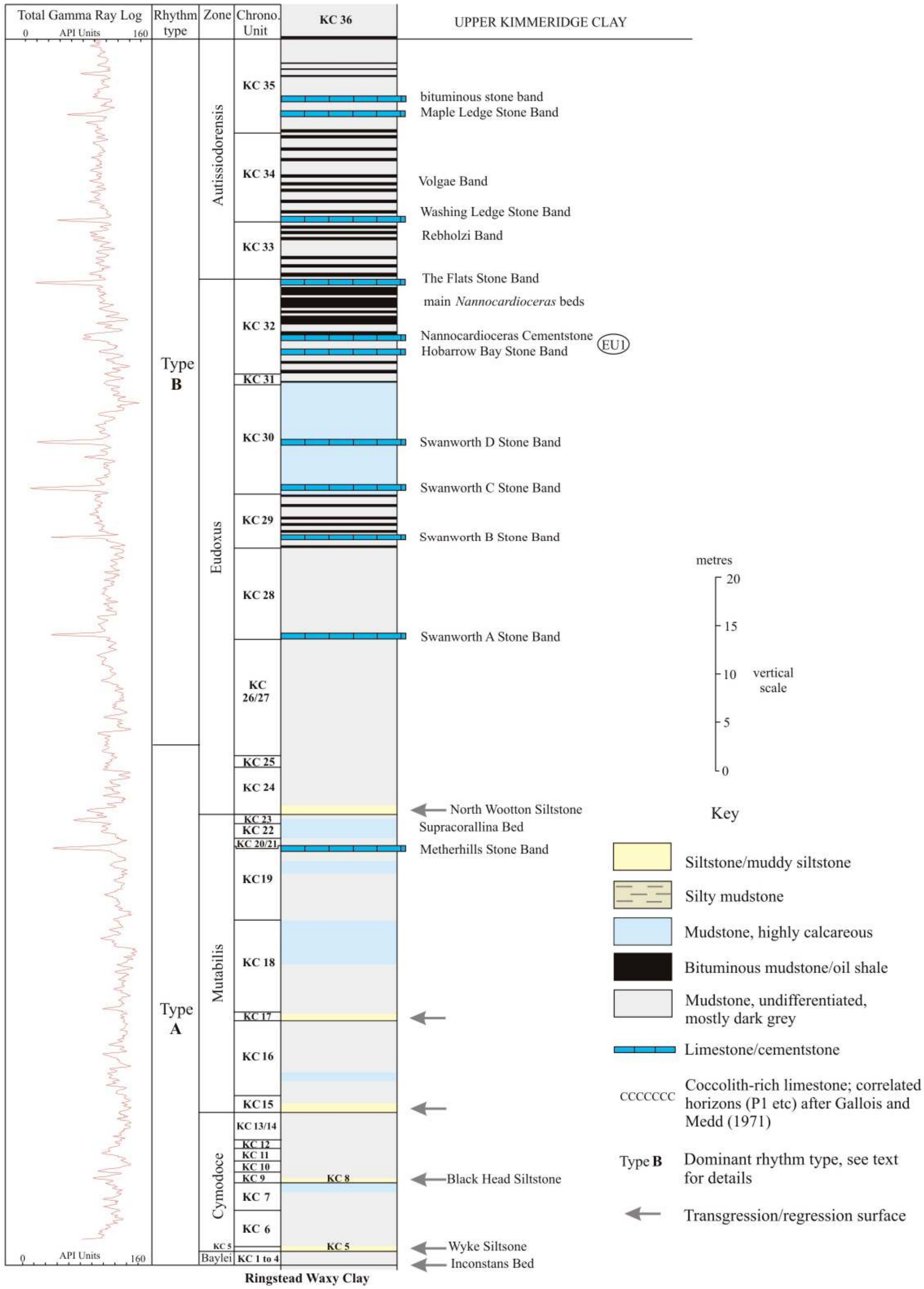
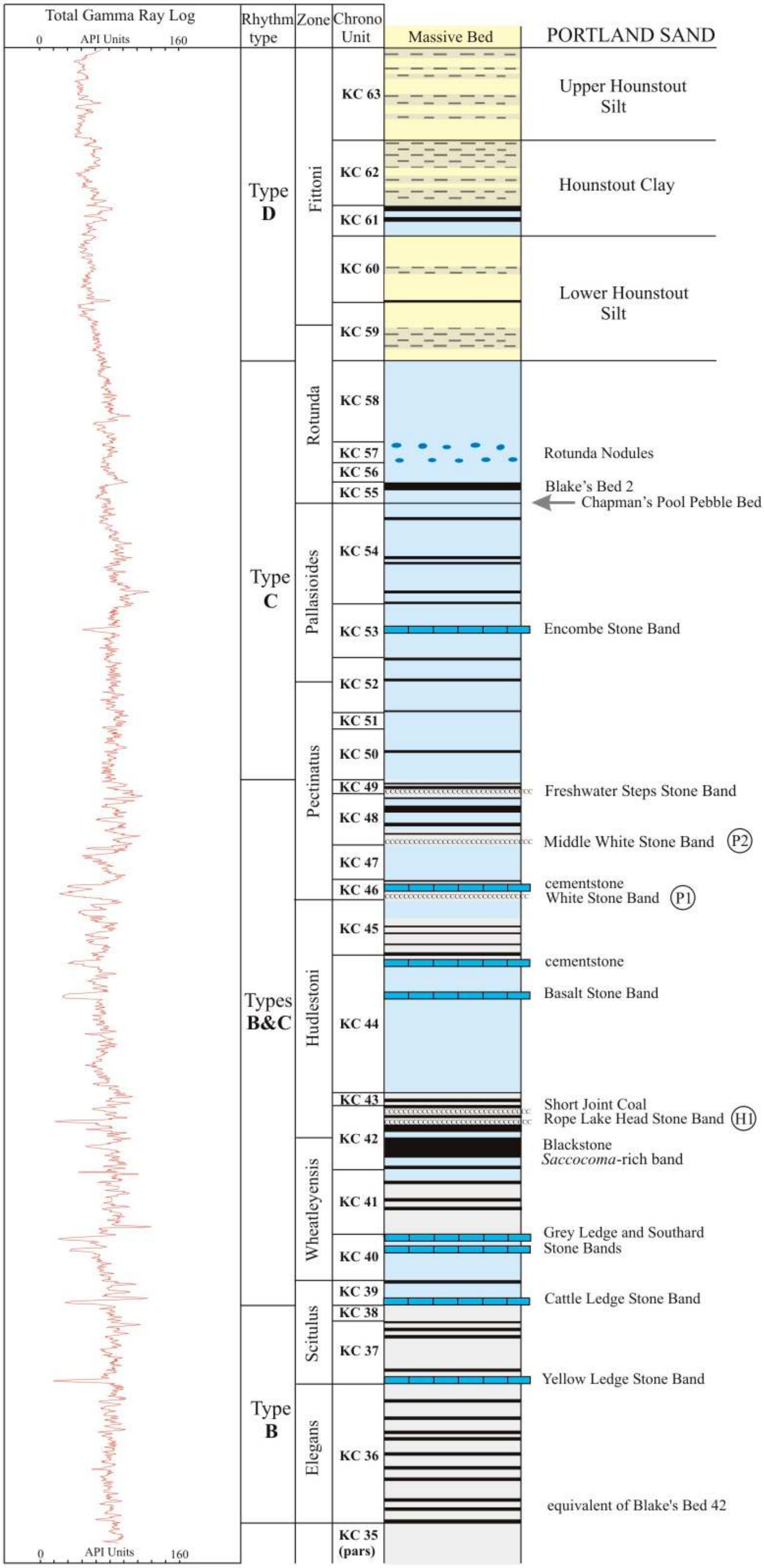


Figure 6. Summary of the Kimmeridge Clay sequence proved in the RGGE boreholes. (a) Lower Kimmeridge Clay (KC 1 to KC 35) (b) Upper Kimmeridge Clay (KC 36 to KC 63).


Total Gamma Ray Log
0 API Units 160
Rhythm type
Zone
Chrono Unit
Massive Bed
PORTLAND SAND
KC 63
Upper Hounstout Silt
KC 62
Hounstout Clay
KC 61
KC 60
Lower Hounstout Silt
KC 59
Type D
Fittoni
KC 58
Rotunda
KC 57
Rotunda Nodules
KC 56
KC 55
Blake's Bed 2
Chapman's Pool Pebble Bed
KC 54
Pallasioides
Type C
KC 53
Encombe Stone Band
KC 52
KC 51
KC 50
Pectinatus
KC 49
Freshwater Steps Stone Band
KC 48
Middle White Stone Band
P2
KC 47
KC 46
cementstone
White Stone Band
P1
KC 45
cementstone
Basalt Stone Band
Types B&C
Hudlestoni
KC 44
KC 43
Short Joint Coal
Rope Lake Head Stone Band
H1
KC 42
Blackstone
Saccocoma-rich band
Wheatleyensis
KC 41
Grey Ledge and Southard Stone Bands
KC 40
KC 39
Cattle Ledge Stone Band
KC 38
Scitulus
KC 37
Yellow Ledge Stone Band
Type B
Elegans
KC 36
equivalent of Blake's Bed 42
KC 35 (pars)
0 API Units 160

Notes on the individual RRGE boreholes

The composite lithostratigraphy, biostratigraphy and chronostratigraphy of the sequences proved in the three RGGE boreholes is summarised in Figures 6a and 6b. Detailed graphical (Wellog) plots at 1:500 scale showing the stratigraphy of each borehole together with selected geophysical logs have been placed on open file in the Association's library, in the libraries of the universities participating in the RGGE project, and the British Geological Survey library at Keyworth.

Swanworth Quarry No. 1 and No. 2 boreholes

The principal marker bands exposed in the Kimmeridge cliffs, notably the named stone bands and the more prominent oil-shale horizons, were readily identified in both Swanworth Quarry boreholes (Figure 7). Between the Hobarrow Bay Stone Band and the Massive Bed only the Washing Ledge Stone Band and Blake's Bed 42 of the cliff sections were not identified. The close similarity of the Swanworth Quarry No. 1 and No. 2 cored sequences indicates that the two missing horizons are absent through lateral variation in the Kimmeridge Clay, not because of faulting. No significant fault (throw >1m) is present in either of the Swanworth Quarry boreholes. Also present in this interval were the Nannocardioceras Cementstone, the Hobarrow Bay Fluidised Bed, the *Nannocardioceras*-rich beds, and the Rebholzi and Volgae bands based, respectively, on abundances of the ammonites *Sutneria rebholzi* (Berckhemer) and *Nannocardioceras volgae* (Pavlov) (Figure 6a).

Below the Hobarrow Bay Stone Band (Figure 7), the lowest bed exposed in Kimmeridge cliffs, the Metherhills and Swanworth A to D stone bands were proved in the Swanworth Quarry No. 1 Borehole as well as the shell-rich Supracorallina Bed (KC 22) and the North Wootton Siltstone (KC 24).

Comparison of the thicknesses between the marker bands proved in the Swanworth Quarry boreholes with those published for the nearby cliff sections shows an almost linear relationship, in which the Swanworth Quarry sequence is 7% thinner than the sequence exposed in the cliffs between Chapman's Pool and Kimmeridge Bay (Figure 8).

In the highest part of the sequence, the Chapman`s Pool Pebble Bed and the thin organic-rich horizons in KC 59 and KC 61 (Figure 4) provide useful correlative links with the outcrop at Chapman`s Pool/Houns-tout. The organic-rich horizons (the stratigraphically highest yet recorded in the Kimmeridge Clay) give rise to sharp gamma-ray spikes and low densities on the geophysical logs: this suggests that they should be easy to identify in uncored boreholes.

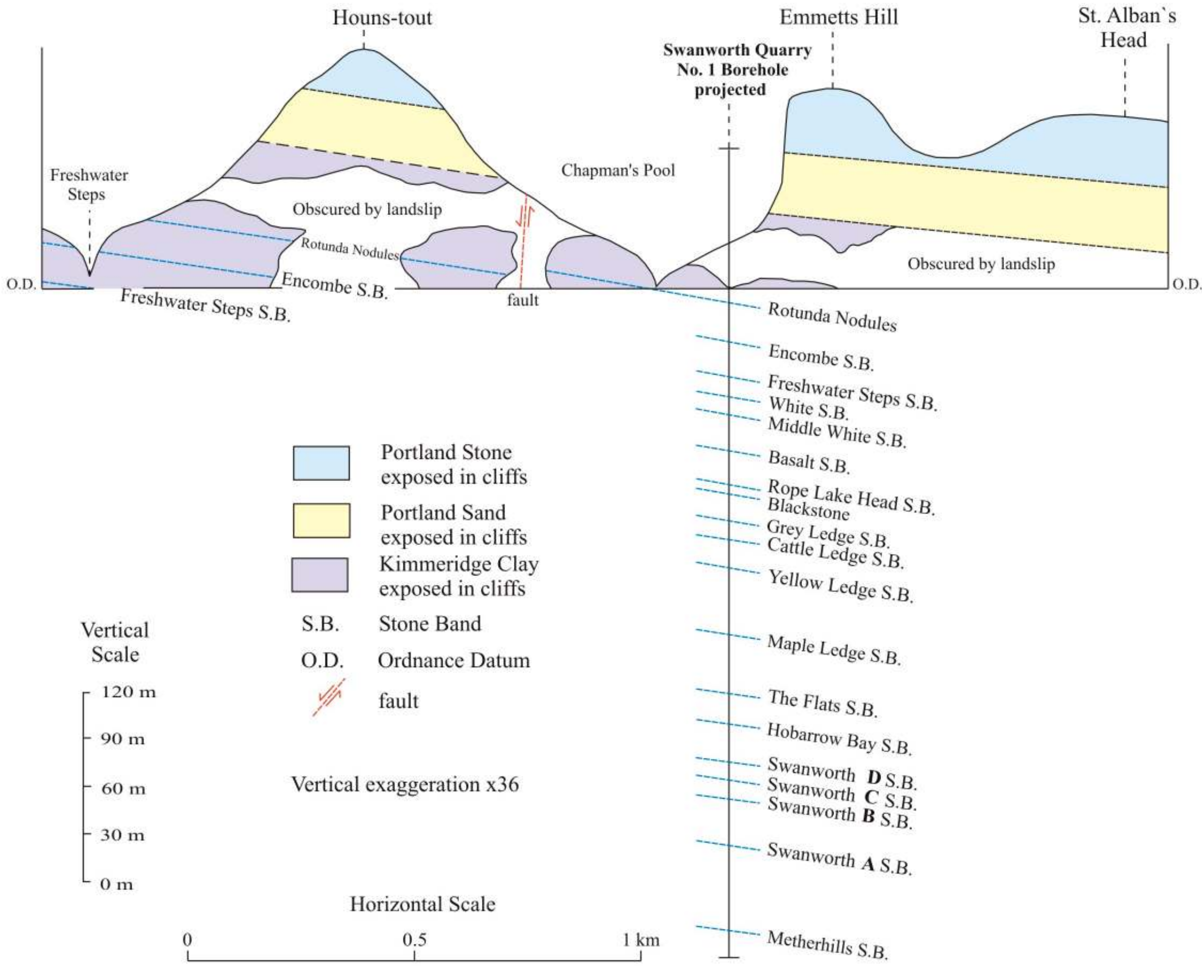


Figure 7. The positions of stone bands proved in the Swanworth Quarry No. 1 Borehole projected into Kimmeridge cliffs.

All the strata above the Rotunda Nodules crop out in sections above the zone of wave erosion and they are, in consequence, deeply weathered. In the Swanworth Quarry boreholes, the bituminous beds were highly pyritic, which in part accounts for their deeply rotted, sulphurous condition at outcrop.

The Rotunda Nodules were not recorded in the boreholes, but a pyrite-rich band about 3m above Blake's Bed 2 probably correlates with a similar bed that occurs in association with the lower of the two horizons which make up the Rotunda Nodules at outcrop. A cidarid-rich siltstone which marks the base of the Lower Hounstout Silt at outcrop (Gallois and Etches, MS) was not recorded in the Swanworth Quarry boreholes, but the rapid upward change to silty mudstones and muddy siltstones that it marks is clearly reflected in the gamma-ray, resistivity and sonic logs.

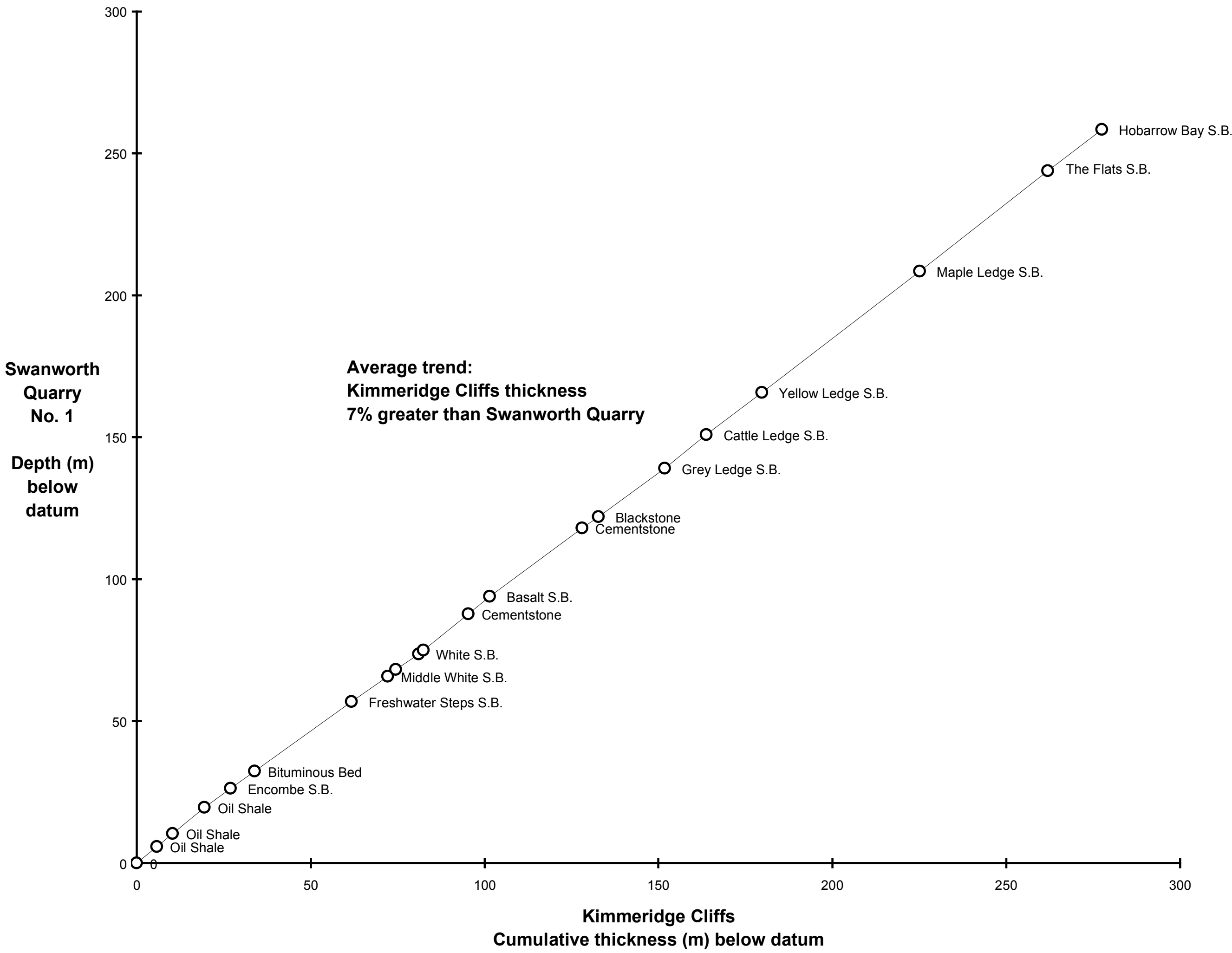


Figure 8. Comparison of thicknesses between selected marker bands in Kimmeridge cliffs with those proved in the Swanworth Quarry No. 1 Borehole. Base of Blake's Bed 2 taken as datum. Cliff thicknesses taken from Cox and Gallois (1981). S.B.......Stone Band

Metherhills No. 1 Borehole

Coring was commenced in the Metherhills No. 1 Borehole a little above the predicted position of the Hobarrow Bay Stone Band. The stone band itself was not present in the borehole, despite the fact that it was proved in both Swanworth Quarry boreholes and that its outcrop on the shore could be seen from the Metherhills site. However, its close companions, the Nannocardioceras Cementstone and the Hobarrow Bay Fluidised Bed, were present and confirmed that the absence of the stone band was due to lateral facies variation and not to faulting. The geophysical logs confirmed the presence of The Flats, Washing Ledge and Maple Ledge stone bands in the uncored part of the borehole.

The sequence proved below the presumed position of the Hobarrow Bay Stone Band in the Metherhills No. 1 Borehole is not exposed in Kimmeridge cliffs (Figure 9). Parts of it are exposed from time to time farther west at Ringstead Bay [SY 755 813], Osmington Mills [SY 734 818] and Black Head [SY 725 820], but are much affected by landslip. The base of the Kimmeridge Clay in the Metherhills No. 1 Borehole was marked by a bioturbated junction in which dark grey, shelly, gritty mudstone (KC 1) rests on and is burrowed into a partially phosphatised hardground at the top of pale grey, smooth textured (smectite-rich) mudstones of the Oxfordian Ringstead Waxy Clay. Marker bands which crop out at Ringstead Bay and Black Head, which have been recorded in boreholes throughout the onshore outcrop and which were present in the Metherhills No. 1 Borehole, include *Deltoideum delta*-rich mudstones (KC 2), the Wyke Siltstone (KC 5), the Black Head Siltstone (KC 8), the shell-rich Supracorallina Bed (KC 22), and the North Wootton Siltstone (KC 24). The five prominent stone bands (Metherhills and Swanworth A to D) were also present.

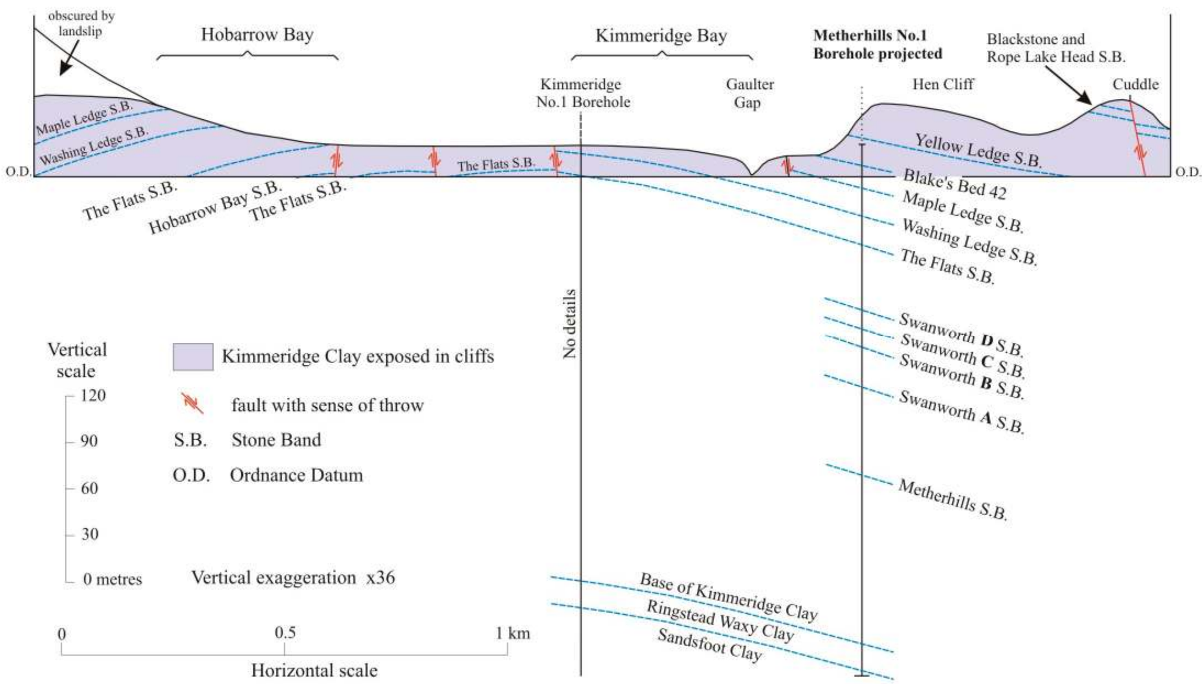


Figure 9. The positions of the principal marker bands proved in the Metherhills No. 1 Borehole projected into Kimmeridge cliffs.

3. SUMMARY

Taken together, the cores of the Swanworth No.1 and No. 2 and the Metherhills No. 1 boreholes provide the first complete section through the Kimmeridge Clay in its south Dorset type area. Previous descriptions of the stratigraphy of the formation have been based on a composite section derived from exposures at Kimmeridge Bay and Ringstead Bay, about 10km apart. The sequence proved in the boreholes has confirmed the usefulness of the current chronostratigraphical classification. This will enable the results of the current multidisciplinary studies of the sedimentology and geochemistry of the cores, and of any future stratigraphical studies, to be compared with results from sections in the Kimmeridge Clay elsewhere in Britain.

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