

# Integrated stratigraphy of the Kimmeridge Clay Formation (Upper Jurassic) based on exposures and boreholes in south Dorset, UK

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**Abstract** – For the purposes of a high-resolution multi-disciplinary study of the Upper Jurassic Kimmeridge Clay Formation, two boreholes were drilled at Swanworth Quarry and one at Metherhills, south Dorset, UK. Together, the cores represent the first complete section through the entire formation close to the type section. We present graphic logs that record the stratigraphy of the cores, and outline the complementary geophysical and analytical data sets (gamma ray, magnetic susceptibility, total organic carbon, carbonate,  $\delta^{13}\text{C}_{\text{org}}$ ). Of particular note are the new borehole data from the lowermost part of the formation which does not crop out in the type area. Detailed logs are available for download from the Kimmeridge Drilling Project web-site at <http://kimmeridge.earth.ox.ac.uk/>. Of further interest is a mid-*eudoxus* Zone positive shift in the  $\delta^{13}\text{C}_{\text{org}}$  record, a feature that is also registered in Tethyan carbonate successions, suggesting that it is a regional event and may therefore be useful for correlation. The lithostratigraphy of the cores has been precisely correlated with the nearby cliff section, which has also been examined and re-described. Magnetic-susceptibility and spectral gamma-ray measurements were made at a regular spacing through the succession, and facilitate core-to-exposure correlation. The strata of the exposure and core have been subdivided into four main mudrock lithological types: (a) medium-dark–dark–grey marl; (b) medium-dark–dark grey–greenish black shale; (c) dark-grey–olive-black laminated shale; (d) greyish-black–brownish-black mudstone. The sections also contain subordinate amounts of siltstone, limestone and dolostone. Comparison of the type section with the cores reveals slight lithological variation and notable thickness differences between the coeval strata. The proximity of the boreholes and different parts of the type section to the Purbeck–Isle of Wight Disturbance is proposed as a likely control on the thickness changes.

## 1. Introduction

The main purpose of this paper is to describe the lithological succession found in recently drilled boreholes in Dorset, and to compare these boreholes with the nearby type section of the Kimmeridge Clay Formation exposed between Hobarrow Bay [SY 896 790] and Chapman's Pool [SY 955 771], Dorset, UK. Based on a detailed comparison of the boreholes with the type section, we present a precise correlation of the uppermost *Aulacostephanus eudoxus* and *Aulacostephanus autissiodorensis* zones of the Lower Kimmeridge Clay, and the *Pectinatites elegans* to *Virgatopavlovia fittoni* zones of the Upper Kimmeridge Clay. The holes were drilled as part of the

Natural Environment Research Council's Rapid Global Geological Events (RGGE) special topic 'Anatomy of a Source Rock', and the project involves primarily seven research groups who are investigating various aspects of the Kimmeridge Clay, such as inorganic and organic geochemistry, micropalaeontology, and orbital cyclicity of the mudrock rhythms. The goal of the project is to understand the principal controls on this key episode of petroleum source-rock formation. The Kimmeridge Clay has long been recognized as the major source rock for North Sea oil, although at its type locality in Dorset the succession is immature, having suffered only modest burial (e.g. Farrimond *et al.* 1984; Scotchman, 1987; Ebukanson & Kinghorn, 1986; Sælen *et al.* 2000.). The boreholes are situated on the flat-lying limb of the Purbeck monocline, close to coastal exposures, at Swanworth Quarry [SY 9675

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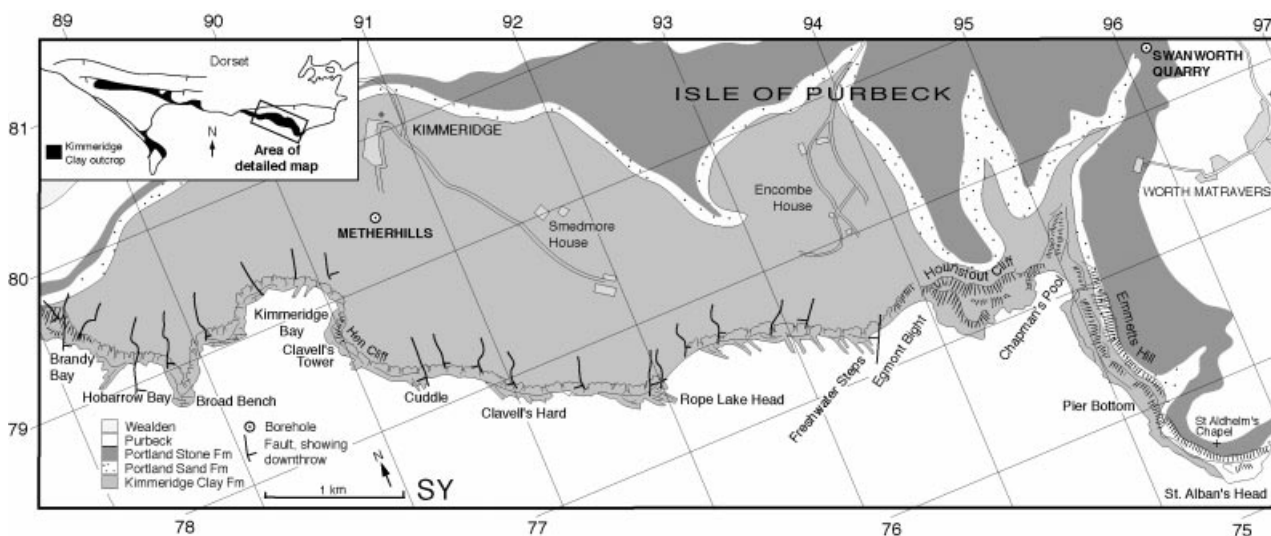


Figure 1. Map showing the outcrop of the Kimmeridge Clay Formation in south Dorset, UK, and localities mentioned in the text. Constructed using Ordnance Survey Landranger Maps, sheet numbers 194 and 195, and British Geological Survey Sheets 341, 342 and 343. Numbers around the edge of the map box refer to National Grid 10 km squares on the stated Ordnance Survey sheets.

7823] and at Metherrhills [SY 9112 7911], these sites chosen to make best use of the comprehensive palaeontological, sedimentological and geochemical work already carried out on the type section (e.g. Cope, 1967, 1978; Gallois & Cox, 1976; Cox & Gallois, 1979, 1981; Wignall, 1990; A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992; Tyson, 1996 and references therein). Together, the cores represent a complete section through the Kimmeridge Clay Formation and allow a variety of analytical methods to be applied at high resolution to the full thickness of the formation.

Two parallel boreholes were drilled in Swanworth Quarry (Fig. 1), in order to recover as complete a section of the formation as possible. The site and double-coring strategy were chosen so as to diminish the influence of the steeply dipping faults and fractures that are apparent in the cliff section. The first hole, Swanworth Quarry 1, terminated around the level of the Metherrhills Stone Band (Gallois, 1998) in the *Aulacostephanus mutabilis* Zone. Swanworth Quarry 2 penetrated down to the Hobarrow Bay Stone Band in the *eudoxus* Zone before drilling was halted because of fracturing that endangered the hole's stability. Therefore, to sample the lower part of the formation, a third hole was drilled at Metherrhills (Fig. 1), the fully cored interval extending from above the Maple Ledge Stone Band (*elegans* Zone) down to the Corallian Group (*Ringsteadia pseudocordata* Zone). See Gallois (1998) for further details of the drill sites and their specifications.

Before a comparison between the cores and the type section is given, the first part of this paper describes how the cores have been recorded, and what has been done to ensure their precise correlation. This work forms the essential framework for the numerous RGGE Kimmeridge Clay sample collections and

analyses. The sections detail the lithological succession comprising the Kimmeridge Clay and are organized in a chronological manner. An overview is given of the Lower Kimmeridge Clay that the cores have fully revealed for the first time, and the less easily accessible, uppermost part of the formation is discussed. The type section is also described based on fieldwork carried out between 1996 and 1999, which builds upon the lithological succession summarized by Cox & Gallois (1981) and Coe (A. L. Coe, unpub. D. Phil. thesis, Univ. Oxford, 1992). The lithological discussions that make up this paper correspond to detailed graphic logs for the type section and the Swanworth Quarry and Metherrhills cores. These logs are reproduced herein in summary form (Figs 2, 3 and 4); the interested reader may obtain detailed, large-scale (1 cm : 1 m) graphic logs either from the British Library Document Supply Centre as Supplementary Publication no. SUP 90490 (51 pages; details of how to obtain a copy are given in the Acknowledgements) or by downloading them from the Kimmeridge Drilling Project web-site at <http://kimmeridge.earth.ox.ac.uk/>. Figure 5 shows a short section of one of these more detailed logs, to give a sample of the information they contain. The Swanworth Quarry and Metherrhills cores discussed in this paper are housed at the British Geological Survey (BGS) in Keyworth, Nottinghamshire, UK.

## 2. Regional setting of the Wessex Basin

The Wessex Basin is a Mesozoic extensional basin formed during post-Carboniferous subsidence of the northwest European continental area (Whittaker, 1985; Karner, Lake & Dewey, 1987; Ziegler, 1990; Bradshaw *et al.* 1992; Underhill & Stoneley, 1998;

Hesselbo, 2000). During Kimmeridgian times, the basin occupied a mid-latitude position at approximately 32° N (Ziegler, 1990; Smith, Smith & Funnell, 1994). Sediment accumulation in the basin took place from Permian to Late Cretaceous times (e.g. Whittaker, 1985; Sellwood, Scott & Lunn, 1986; Penn *et al.* 1987; Selley & Stoneley, 1987), and was terminated by inversion of the region during the Late Cretaceous to Palaeogene, culminating synchronously with the Helvetic phase of Alpine deformation in the Oligocene–Miocene (Lake & Karner, 1987). The basin includes much of southern England and extends southwards under the English Channel. To the west are the Bristol Channel and Western Approaches Basins, and to the southeast the Paris Basin. The Wessex Basin is delimited by structures that are thought to have been inherited from thrust and transfer faults in the Hercynian basement (Chadwick, Kenolty & Whittaker, 1983; Lake & Karner, 1987). To the north and east lies the London–Brabant Massif, to the northwest the Mendips High and Welsh Massif, to the west the Cornubian Massif, and to the south the Armorican Massif (Bradshaw *et al.* 1992). The area with the highest elevation is interpreted to have been the Brabant Massif, the eastern part of the London–Brabant Massif, but this was probably no higher than a few hundred metres (Vercoutere & Van den Haute, 1993).

During Mesozoic time, deposition was principally influenced by E–W-trending, deep-seated normal faults, which defined the northern edges of a number of sub-basins, typically developed as half-graben that stepped-down progressively towards the south in the Jurassic (Penn *et al.* 1987; Jenkyns & Senior, 1991). A more widely spaced set of faults trend N–S to NW–SE, and probably had sinistral strike-slip and minor dip-slip components during Jurassic time (Lake & Karner, 1987). The succession that we are concerned with here was deposited on the downthrown side of the roughly E–W-trending Purbeck–Isle of Wight Disturbance, a major fault system which partially delimits the northern margins of the Central Channel Sub-basin. Variation in structural styles along the length of the *en-échélon* fault-bounded segments that collectively form the northern margin of the basin are probably related in part to the presence of Triassic-age salt horizons of varying thickness (Harvey & Stewart, 1998).

The area is thought to have been covered by epicontinental shelf seas linked by networks of long and narrow seaways during late Jurassic time, with islands of various sizes dotted across the region (Ziegler, 1990; Smith, Smith & Funnell, 1994). A major N–S-trending seaway developed during the Kimmeridgian along the Laurentian continental margin, linking the Boreal and Tethyan oceans. The Boreal character of the ammonite fauna suggests a surface current flowing from the Boreal Ocean southwards over warm saline

bottom waters generated in Tethys (e.g. Kutzbach & Gallimore, 1989; Miller, 1990; Ross, Moore & Hayashida, 1992). In general terms, a temperature-stratified water system with oxygen-depleted stagnant bottom water is inferred for the Kimmeridge Clay (e.g. Tyson, Wilson & Downie, 1979; Myers & Wignall, 1987; Tyson, 1989; Wignall & Hallam, 1991). Furthermore, biomarker evidence and the small, regular size of pyrite framboids in the Kimmeridge Clay imply free H<sub>2</sub>S in the water column (euxinic conditions), which commonly reached into the photic zone (Wignall & Myers, 1988; Wignall & Newton, 1998; Van Kaam-Peters *et al.* 1998; Sælen *et al.* 2000; Raiswell, Newton & Wignall, 2001).

In a general sense, alternating humid and dry climate intervals can be recognized in the North Sea region during latest Jurassic times. Clay mineralogy, sedimentary (distributions of coals, evaporites), floral and tree-ring evidence point towards humidity during the Oxfordian–early Tithonian, aridity during the mid- to late Tithonian, and humidity from earliest Cretaceous times onwards (e.g. Parrish, Ziegler & Scotese, 1982; Francis, 1984; Pelzer & Wilde, 1987; Hallam, Grose & Ruffell, 1991; Abbink *et al.* 1998). The climate of the arid interval is thought to have been Mediterranean in character, with warm dry summers and cool wet winters (Francis, 1984), described as the winter-wet biome in phytogeographic terms (Rees, Ziegler & Valdes, 2000).

### 3. The Kimmeridge Clay Formation and its geological setting

At the type section along the Dorset coast, as well as in other parts of England, the formation essentially consists of mudrocks that can be simply categorized as medium-dark-grey, dark-grey-black laminated, and greyish-brownish-black. Intercalated are medium-grey to creamy-white coccolith limestones, and minor grey and pale-yellow limestones and dolostones. The top part of the formation in the Kimmeridge and Weymouth areas comprises siltstones and silty mudstones. Rhythmic alternations of these mudrocks occur on a small-scale (0.5–1.5 m thick) and a large-scale (tens of metres) throughout the succession (Tyson, Wilson & Downie, 1979; Aigner, 1980; Cox & Gallois, 1981; Wignall, 1989), and have been linked to Milankovitch cyclicity (Dunn, 1974; Hallam & Bradshaw, 1979; House, 1985; Melnyk, Smith & Amiri-Garroussi, 1994; Weedon *et al.* 1999). Analysis of palynofacies cycles within the *autissiodorensis–elegans* zone part of the Kimmeridge Clay in Dorset and the Boulonnais, northern France, suggests that orbital-precession controlled variations in runoff of terrestrial organic debris into the basin, whilst orbital-obliquity with an eccentricity-cycle overprint influenced marine organic preservation through bottom-water oxygenation, because of its effect on wind and circulation



(Waterhouse, 1995, 1999). Weedon *et al.* (1999) used magnetic-susceptibility measurements from the exposure and Swanworth Quarry 1 to demonstrate that the lithological cyclicity is likely dominated by orbital-obliquity forcing in the *autissiodorensis* and *elegans* zones.

One of the primary tools for the correlation of the type section with the cores is the recognition and linkage of stone bands and other marker beds. The laterally persistent stone bands provide useful datum levels for sample collecting, and those of primary origin (the coccolithic limestones) assist in correlating the Kimmeridge Clay between localities in the Wessex Basin and further afield (Gallois & Cox, 1974). The dolostones are less laterally continuous due to their diagenetic origin (Irwin, Curtis & Coleman, 1977; Irwin, 1981; Feistner, 1989; Scotchman, 1989). The stone bands are carbonate-rich and commonly pale in colour, resistant to weathering and, in cliff exposures, weather proud from most of the more friable mud-rich lithologies. Many of the stone bands are named (Cox & Gallois, 1981 and references therein).

The Swanworth Quarry 1 and Metherhills 1 cores reveal five stone bands in the Lower Kimmeridge Clay (*mutabilis* and *eudoxus* zones) that have not been recorded at the type section. They are named the Metherhills and Swanworth A to D stone bands (Fig. 4). These stone bands are also recorded by the geophysical well-log signatures of deep hydrocarbon-exploration boreholes in the Isle of Portland (Gallois, 2000). Across the Weald Basin, wireline logs indicate that in this more northeasterly area the bands are relatively weakly developed (Taylor *et al.* 2001). Other marker intervals useful for precisely linking different exposures and boreholes are layers with a high organic-matter content, such as the Blackstone, and the packages of organic-rich sediments present in the *eudoxus* and *Pectinatites pectinatus* zones. The Hobarrow Bay Fluidized Bed is present in the boreholes and at the type section. Locally, faunal content can be used to recognize particular layers: the Nannocardioceras and Supracorallina Beds are examples. Nineteen prominent beds, ranging stratigraphically between the Nannocardioceras Cementstone and Blake's (1875) Bed 2, are correlatable and well developed in both the exposure and boreholes. The framework created by correlating stone bands and marker beds was supplemented at a higher resolution using lithological detail and geophysical log signatures (e.g. magnetic susceptibility as used by Weedon *et al.* 1999).

### 3.a. Stratigraphic nomenclature

Kimmeridge Clay sections from further afield in England have previously been correlated with the type section in Dorset using a combination of lithological and macrofaunal characteristics, supported by the presence of the more laterally continuous marker

bands such as the coccolithic limestones and packages of organic-rich mudrocks. Forty-nine stratigraphic units based on lithology and macrofaunal content were originally defined, using successions from boreholes in eastern England. These range from the base of the formation (*Pictonia baylei* Zone) upwards to part way through the *pectinatus* Zone, and were termed 'beds' (Gallois & Cox, 1976; Gallois, 1978; Cox & Gallois *in Gallois*, 1979; Cox & Gallois, 1981; Gallois, 1994). These units have since been correlated to Dorset (Cox & Gallois, 1981), recognized in geophysical logs (Penn, Cox & Gallois, 1986), and subsequently amended and extended at outcrop. Wignall (1990) added units 51–55, and Coe (A. L. Coe, unpub. D. Phil. thesis, Univ. Oxford, 1992) 56–62. The divisions were subsequently used by Ahmadi & Coe (1998), and have been applied during this study. It should be noted that the units that were termed 'beds' by Cox & Gallois (1981) were re-named 'bed groups' by Coe (A. L. Coe, unpub. D. Phil. thesis, Univ. Oxford, 1992), because the units commonly contain a number of beds made up of lithologically distinct layers, separated from other layers above and below by well-defined surfaces (cf. Salvador, 1994). The individual beds making up the bed groups are numbered from the base up: for example, 42/12 refers to Bed Group 42, Bed 12 (the Blackstone). Gallois (2000) revised the boundaries of some of the original units defined by Gallois & Cox (1976), Gallois (1978), Cox & Gallois *in Gallois* (1979), Cox & Gallois (1981), and Gallois (1994). The work of Gallois & Etches (2001) builds upon Gallois (2000), focusing on the uppermost beds of the Kimmeridge Clay, combining field observations with data from Swanworth Quarry 1 in order to subdivide the strata into lithostratigraphic units. Gallois (2000) also continues to use the term 'bed' for what might be considered a succession of beds, and believes these units to be chronostratigraphic. However, no reference sections are defined and the possible correlations across southern England are not proven to be unique; thus we consider that there is insufficient evidence to justify the assumption that each of the units was deposited during the same interval of geological time. The three coccolith limestone beds (46/1, 47/11, 49/8) might be considered exceptions, but there is still no independent way of demonstrating that they are coeval across the region.

Throughout the paragraphs below we refer to the bed group numbering scheme of Coe (A. L. Coe, unpub. D. Phil. thesis, Univ. Oxford, 1992), because the bed groups are all easily recognizable on the basis of lithological criteria (such as prominent marker beds and changes in grain size) in Dorset. Over the course of this study the stratigraphic position of some of the individual bed boundaries have been amended, but not the bed group boundaries. In order to make the graphic logs summarized in Figures 2, 3 and 4 as useful as possible, we have also added the bed nomencla-

ture of Blake (1875, pp. 198–9), Arkell (1947, pp. 71–3), and Gallois (1998, 2000). Full details of the lithostratigraphic schemes employed for successive parts of the formation are described below and outlined in the figure captions. It should also be noted that herein we consider the ammonite zones referred to in this paper as biozones, not chronozones (cf. Salvador, 1994); the uncertainty, in terms of stratigraphic position, associated with each of the ammonite zone boundaries is shown where possible for the type section in Figure 2 and Swanworth Quarry 1 in Figure 3.

Originally, the Kimmeridge Clay in England was taken to correspond to the Kimmeridgian (*baylei–fittoni* zones), but since the Kimmeridgian was used in a different manner in France (equivalent only to the lower part of the (British usage) Kimmeridgian), the International Stratigraphic Subcommittee recommended that (British usage) Kimmeridgian be no longer employed. Instead, it is agreed that the Kimmeridgian and Tithonian should be employed as the last two Primary Standard Stages of the Jurassic. At the type section, the base of Blake's Bed 42 is thought to be close to the base of the Tithonian, as recognized in central European sections (Cope, 1993). It should be noted, however, that stratotypes for the base of the Kimmeridgian and Tithonian have yet to be defined, and therefore their precise stratigraphic position remains uncertain. Cope (1993) has proposed the re-introduction of a secondary stage name, the Bolonian (Blake, 1881), for the interval between the top of the Kimmeridgian and base of the Portlandian. However, a stage of such local significance has little geological utility and we do not use it in the present work. Blake's Bed 42 itself comprises the lowest bed of the *elegans* Zone (and Bed Group 36), and defines a major faunal turnover from an aulacostephanid-dominated ammonite fauna to a pectinatitid-dominated fauna (Cope, 1967).

#### 4. Description and measurement of the cores and exposure

##### 4.a. Methodology

Graphic logs have been constructed for the Swanworth Quarry 1 core, from the Hobarrow Bay Stone Band to the top of the Kimmeridge Clay Formation, and for the Metherhills 1 core, from the base of the formation to the Hobarrow Bay Stone Band. The two logs overlap by several metres and form a composite section through the entire formation. The stratigraphic level at which the Swanworth Quarry 1 and Metherhills 1 cores are tied is that of the *Nannocardioceras*-rich bands, and this correlation is supported by a discrete horizon (some 3 cm thick) of mini-sedimentary fissures found in both cores, namely the Hobarrow Bay Fluidized Bed (Gallois, 1998). This correlation is also supported by the overlap of matching magnetic-

susceptibility profiles measured from the Swanworth Quarry 1 and Metherhills cores. The graphic logs recorded for Swanworth Quarry 1 and Metherhills 1 cores (Figs 2, 3 and 4, and 1:100 graphic logs on the web-site) supplement the 1:500 plots produced by Gallois (1998), based upon drill-site logging and the downhole geophysical data sets.

Visual description was carried out on a detailed centimetre scale and a variety of features were recorded, including grain size, lithology, sedimentary structures, nature of bed boundaries, faunal content, degree of fissility or cementation, presence of macroscopic pyrite, amount of coring disturbance, and colour (relative to the Munsell Color Chart). The organic content of each bed was evaluated by running a knife blade across the core's surface and checking for a brown streak; less organic-rich deposits leave a pale-grey streak when scratched. This crude test was later substantiated using total organic carbon (TOC; whole rock wt% total organic carbon) results. Using these criteria, four basic mudrock lithological types were distinguished, based principally on grain size, colour and texture, as shown in Figures 2, 3 and 4: (a) medium-dark-dark-grey marl; (b) medium-dark-dark-grey-greenish-black shale; (c) dark-grey-greenish-black-olive-black laminated shale; and (d) greyish-black-brownish-black mudstone.

Further additions to the graphic logs were made using the magnetic-susceptibility data measured from the cores. Magnetic-susceptibility values are known to relate broadly to lithology, depending upon the type and proportion of magnetizable material: generally the ferroan dolostones induce very high readings (e.g. the Washing Ledge Stone Bed), the coccolithic limestones give low readings (e.g. the White Stone Band), and mudstones and shales furnish rather more variable values depending on sediment type and stratigraphic position (Weedon *et al.* 1999). This approach proved especially useful for the more fragmentary parts of the core, which were difficult to describe by visual inspection alone. The relationship between lithology and magnetic susceptibility outlined above was also observed at the type section, where magnetic-susceptibility measurements were made every 10 cm using a Bartington Instruments MS2 meter and F-probe (Weedon *et al.* 1999).

As a further check of the logging results, the spectral gamma-ray data measured downhole were compared with the graphic logs measured from the cores: typically, organic-poor limestones and dolostones give low gamma-ray values, whereas organic-rich shales yield high values. Again, variations in the downhole total and spectral gamma-ray results could be compared to those measured on the exposure, where a record was made every 30 cm using a portable gamma-ray spectrometer (Exploranium GR320). The gamma-ray data collected downhole are measured in eU, whereas those collected from the exposure are set

against gAPI. The 30 cm sample spacing, and the time taken to measure the gamma-ray response at each sample point (200 seconds), was a reasonable compromise between statistical reliability and the time taken to complete fieldwork. The portable gamma-ray spectrometer was set up to measure both total gamma-ray and individual U, Th and K emission values. The spectrometer uses a thallium-doped sodium iodide detector and carries out automatic gain stabilization every 60 seconds, allowing instrument drift due to changes in temperature and humidity to be reduced. The instrument was calibrated using local background readings taken offshore from Swanage, Dorset. All measurements were taken with the detector held perpendicular to bedding, creating a moving-average signal rather than absolute values for each bed (see Ahmadi & Coe, 1998, for discussion). Measurements were always taken at least 50 cm above the beach level and wet areas of cliff were avoided. Furthermore, cliff sections flat in the vertical plane over at least 1 m were chosen whenever possible, avoiding irregularities such as overhangs and recesses, to ensure that the same volume of rock was measured at each reading; such variations in rock volume are the most significant source of error in the collection of spectral gamma-ray data (Parkinson, 1996).

The TOC and carbonate data measured from continuous, uncontaminated, vertically orientated central slices of the Swanworth Quarry 1 and Metherhills 1 cores constitute another important data set. These slices were divided into intervals of 10 cm, and the whole of each interval was homogenized to form a composite sample. Only every other sample was analysed, however, ultimately giving a spacing of 20 cm between the centre of each of the sampled intervals. The composite samples weighed approximately 250 g, and were air-dried and jaw-crushed to produce particles of <5 mm diameter. Some 35–40 g of each homogenized sample was then powdered in a five-pot tungsten carbide TEMA mill. About 2 g of this was reserved for the carbon analysis, and the remainder was used for bulk and trace-element geochemistry at the Postgraduate Research Institute for Sedimentology, Reading University. The rest of the crushed sample was sub-sampled for clay-mineral, micropalaeontological, stable-isotope, pyrolysis and thermal-maturity analysis. The residue is lodged at the Department of Earth Sciences, University of Oxford.

Analysis of TOC and carbonate contents in the Kimmeridge Clay is problematic because the host lithology varies from essentially pure limestone to organic-rich shales. It is from these lithologies that the organic carbon and mineral carbonate have to be separately determined and then recalculated to TOC and calcite. The method selected to separate the two carbon types was decarbonation. One analysis was determined from untreated sample to give total carbon, with a separate analysis of decarbonated sample. The

powdered sample was decarbonated in a glass vial with ~10–15 ml of firstly diluted, and then secondly concentrated (32–36%), Analar HCl. The samples were then repeatedly washed using MilliQ deionized water before being dried and stored in a desiccator. The carbon content in the samples for the TOC and calcite profiles was measured using a Carlo-Erba EA-1108 elemental analyser configured for C and N analysis. Between 2–3 mg of sample was placed in a tin capsule, loaded into the machine using the autosampler, and then flash-combusted in a helium stream into which it was introduced with an injection of ultra-pure oxygen. The resulting gas mixture was passed through an oxidation column (Chromium sesquioxide, Cr<sub>2</sub>O<sub>3</sub>), followed by a reduction column (Cu), to reduce the various NO<sub>x</sub> species to N<sub>2</sub>. Next, the gas stream was passed through a gc column to separate the CO<sub>2</sub> and N<sub>2</sub> before measurement using a hot-wire detector retained at a constant temperature. This gives a rapid (3 minute) analysis of carbon content, which is essential for the determination of the TOC and mineral-carbonate content in such large data sets. The elemental analyser was usually calibrated with acetanilide (C<sub>8</sub>H<sub>9</sub>NO). Following calibration, the machine was checked against the standard as an unknown. If these standard results varied by more than 0.3% of the value, the machine was re-calibrated. Between every 10 samples a check was made using a standard as an unknown. The results derived from the total carbon and acidified carbon analyses for each sample were then re-proportioned to give a TOC and mineral-carbonate (as calcite) content. The recalculation was necessary because the 'acidified' samples had calcium carbonate removed prior to analysis. Note that all these analyses represent composited 10 cm samples and as such will not show the extreme values quoted by other Kimmeridge Clay studies.

Bulk organic carbon-isotope data were also measured from the composite samples, at the Universities of Oxford and Newcastle. In Oxford, the powdered samples were decarbonated with 3M HCl overnight, and repeatedly washed to remove all traces of acid. Next, the decarbonated samples were weighed out for isotopic analysis. Depending on total organic carbon content, 5–25 mg of each sample were sealed in a tin-foil cup. A Europa Scientific Limited CN Biological sample converter connected to a 20–20 stable-isotope gas-ratio mass spectrometer, at the Archaeology Research Laboratory, measured the carbon- and nitrogen-isotope ratio of each sample and an internal nylon standard ( $\delta^{13}\text{C}_{\text{nylon}} = -26.2 \pm 0.2\text{‰}$  and  $\delta^{15}\text{N}_{\text{nylon}} = -2.0 \pm 0.4\text{‰}$ ). At Newcastle, 1–4 mg (depending on TOC content) of decarbonated sample were measured into tin cups and then analysed for  $\delta^{13}\text{C}$  by the Bio-medical Mass Spectrometry Unit using continuous flow isotope-ratio mass spectrometry (ANCA SL 20/20). All Newcastle samples were analysed in duplicate (a random sub-set in triplicate) and referenced using an



internal flour standard calibrated to PDB via NBS22. The experimental precision for the samples measured in Newcastle was 0.05‰ for  $\delta^{13}\text{C}$ , based on the standard deviation of replicates of the internal standard.

#### 4.b. Common depth scale

Accurate exchange and comparison of the different data sets collected from the core, exposure, and downhole required a means to relate the assortment of data to a single common depth scale. Initially, there were several depth frameworks for the cores based on downhole wireline log interpretations, the 'driller's depths', and 'box and section numbers', and it was within these schemes that many of the first sample collections were made. During each run to retrieve core lengths a variable amount of core slippage and breakage occurred, affecting the 'driller's depth' scale. These are the depths that are marked on the wooden blocks separating the lengths of core in each box. Once in the laboratory, analytical data (such as magnetic susceptibility) were collected at 5 cm intervals using a Bartington Instruments loop sensor. Other analytical data sets were also collected against this 'laboratory depth scale', such as the composite samples used for elemental, carbonate and TOC data. The large-scale graphic logs of the cores are also drawn against this 'laboratory depth scale', an example of which is shown in Figure 5. Because of the friable nature of the lithology, and cutting of the core for sampling, some break-up and an effective 'expansion' of the core has occurred, so the laboratory depth is not an accurate reflection of the true thickness. Therefore, the depth scale against which geophysical data were measured downhole is our best approximation to 'true' depth; this is referred to as 'downhole' depth. In Figures 3 and 4, the details of large-scale graphic logs of the cores have been summarized against 'true' (downhole) depth.

The relationship between the downhole and laboratory depth scales is not linear and depends on the degree of fragmentation at particular intervals of the core. The simplest and most effective way to correlate the different depth scales was thus to tie the mid-point of each stone band. This was done by precisely correlating (1) the geophysical data (primarily formation micro-scanner and spectral gamma-ray data) measured downhole, with (2) the laboratory depth and magnetic-susceptibility values collected by the loop sensor. With a downhole depth and corresponding laboratory depth for each stone band in the succession, depths in between were interpolated at 5 cm intervals. For example, if we take The Flats Stone Band in Swanworth Quarry 1, there is a difference of 8.21 m between downhole and laboratory depths (Table 1). Our depth comparisons agree well with those select stone bands measured by Gallois (1998). The same interpolation process was carried out for both the Swanworth Quarry 1 and Metherhills cores,

and together they form a common depth scale for the entire Kimmeridge Clay. This high-resolution correlation, and the ability to translate core-related data measured in the laboratory onto a common ('true') depth scale, permits a more accurate comparison between the cores and type section. Translation of all the core data to the downhole depth scale (Fig. 3) allows direct comparison with the exposure (Fig. 2).

### 5. The main lithological types of the Kimmeridge Clay Formation

Four main components make up the Kimmeridge Clay lithofacies at outcrop: (1) clay minerals (20–65%), in the form of illite and kaolinite, with minor amounts of smectite and chlorite; (2) quartz silt or fine-grained sand (12–40%); (3) carbonate minerals; and (4) kerogen. Minor sediment constituents include macro- and microfauna (the former locally phosphatized), and plant debris. The kerogen is dominated by marine amorphous organic matter, which in the richest shales is so abundant that it becomes a major rock-forming constituent (Tyson, 1989). Terrestrial phytoclasts, spores and pollen, and dinoflagellate cysts occur in much smaller amounts (Tyson, 1989; Waterhouse, 1995). Differing quantities of these components characterize the lithological types listed below, which were defined at type section and subsequently applied to the cores.

#### 5.a. Medium-dark–dark-grey marl

Mainly found within the Upper Kimmeridge Clay, this lithology dominates the *huddlestoni* to *rotunda* zones. Fresh, dry specimens are typically a medium-dark grey (Munsell Color N4), although below the Cattle Ledge Stone Band in the type section (about the 39 m level in Fig. 2) this lithology is a bluish grey colour (5B 5/1). Deposits of this type show no internal structure and, where exposed, weathered surfaces have a conchoidal fracture. The fracture pattern of this lithology tends to lead to break up of the cores. Bed thickness is commonly 3–4 m but may reach up to 19 m (Bed Group 44). Magnetic-susceptibility and gamma-ray values for this lithology are variable and partly depend on the degree of cementation. In Swanworth Quarry 1, the lower part of Bed Group 44 (essentially between just above the Short Joint Coal and Basalt Stone Band) shows a range of magnetic-susceptibility values between 2 and  $25 \times 10^{-5}$  SI, with an average of  $\sim 17 \times 10^{-5}$  SI, whereas gamma-ray readings range from 80 to 115 gAPI, and have an average of  $\sim 100$  gAPI. TOC contents range between 1 and 3 wt%. The same stratigraphic level of the type section yields magnetic-susceptibility readings that range from 5 to  $12 \times 10^{-5}$  SI, with an average of  $7 \times 10^{-5}$  SI, and total gamma-ray results that vary between 18 and 26 eU, with an average of 22 eU.

Exposure between Kimmeridge Bay and Chapman's Pool

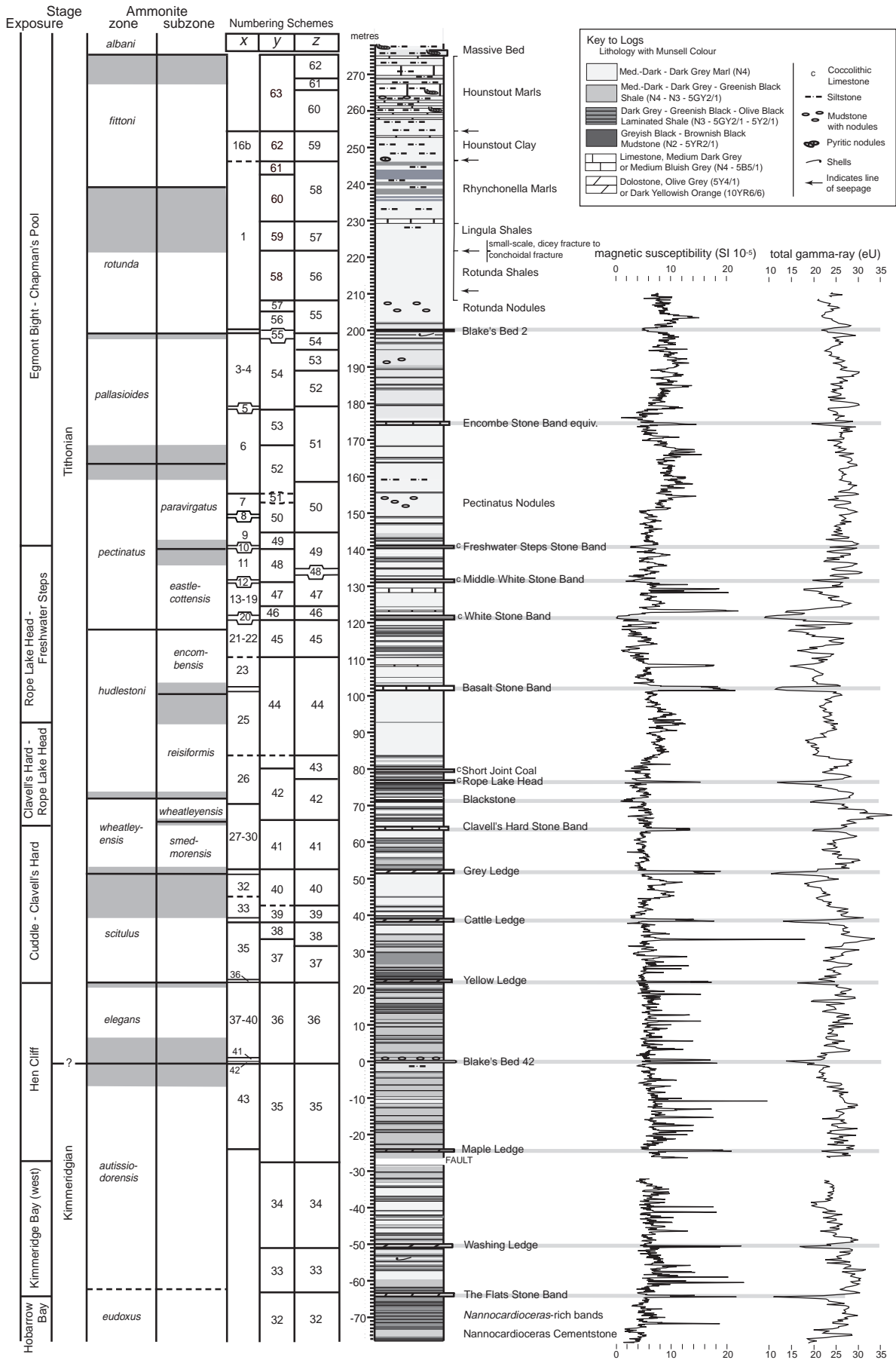


Figure 2. For legend see facing page.



### 5.b. Medium-dark–dark-grey–greenish-black shale

Semi-laminated, with weak to well-developed fissility. Fresh, dry specimens are medium-dark grey to greenish black (N4–N3–5GY2/1). Bed thickness is typically 0.3–2 m, although the greenish-black shales are more commonly 0.5–2 m thick. The TOC content is typically 6 wt%. Beds composed of this lithology are more abundant in the Lower Kimmeridge Clay than in the Upper Kimmeridge Clay. This lithology has been grouped with the type below for the purpose of the type-section and core summary logs (Figs 2, 3 and 4), but for the detailed graphic logs it is separate.

### 5.c. Dark grey–greenish-black–olive-black laminated shale

This lithological type shows a well-developed fissility and lamination, and may be described as ‘paper shale’, which where exposed generally weathers proud of the cliff face. Typically, beds of this type are 0.1–1 m thick. Fresh, dry specimens are dark grey to greenish black (N3–5GY2/1). Small, disseminated pyrite nodules (2–5 mm) are commonly associated with this lithology. The upper *eudoxus* Zone and lower to mid-*autissiodorensis* Zone consist of laminated shales of this type. The laminated shales that form the *Nannocardioceras*-rich bands in the type section produce magnetic-susceptibility values of  $2\text{--}9 \times 10^{-5}$  SI (average of  $5 \times 10^{-5}$  SI) and total gamma-ray readings of 20–30 gAPI (average 25 gAPI). The same section of the Swanworth Quarry 1 core yields an average of 8 wt% TOC, ranging from 3–26 wt%.

### 5.d. Greyish-black–brownish–black mudstones

Where exposed, beds composed of this lithology weather proud from the cliff face and show smooth surfaces; lamination is detectable with a hand lens. Fresh, dry specimens are greyish black to brownish black (N2–5YR2/1) and leave a brown streak when scratched. This lithological type corresponds to the ‘oil shales’ of Cox & Gallois (1981). Small (<1 cm),

disseminated pyrite nodules are commonly associated with this lithology together with larger nodules up to 20 cm across. Our data indicate that TOC content is typically 8–15 wt%, but may reach >35 wt% (the Blackstone in Swanworth Quarry 1). Uranium content, determined from the spectral gamma-ray, attains its highest concentrations in this lithology. The most uranium-rich horizons are an organic-rich bed just above the Cattle Ledge Stone Band (~8 ppm), the beds about the level of the Freshwater Steps Stone Band (5–6 ppm), and a black mudstone unit above the Encombe Stone Band, near the base of Bed Group 52 (5–6.5 ppm).

### 5.e. Silty mudstone, siltstone and fine-grained sandstone

Discrete levels of the Kimmeridge Clay Formation consist of these lithologies, principally within the uppermost (*fittoni* Zone) and lowermost (horizons within the *cymodoce*, *mutabilis* and basal *eudoxus* zones) parts of the succession. The colour ranges from light-medium grey to buff. Geophysical-log data measured against the top of Swanworth Quarry 1 (see Fig. 3) show magnetic-susceptibility and spectral gamma-ray values decreasing gradually as the strata become progressively more silty. The magnetic-susceptibility data drop from around  $20 \times 10^{-5}$  SI to  $0 \times 10^{-5}$  SI, whereas the spectral gamma-ray readings, although somewhat variable, essentially range between 65 and 85 gAPI. The TOC content is generally <2 wt%.

### 5.f. Coccolith limestone

The coccolith limestones comprise white limestones that are relatively low density, cream to pale brown in colour, and almost entirely composed of coccoliths, millimetrically interlaminated with greyish-black to brownish-black mudstone. Confined to the *hudlestoni* and *pectinatus* zones, the best-developed coccolith limestones are the White Stone Band, Middle White Stone Band and Freshwater Steps Stone Band. Coccolith limestones produce both magnetic-susceptibility and

Figure 2. Summary graphic log of the type section of the Upper Kimmeridge Clay exposed along the sea-cliff and foreshore near Kimmeridge. Ammonite zonation follows Cope (1967, 1978) and Cope *et al.* (1980). The grey shaded bands straddling the zonal boundaries correspond to the degree of uncertainty due to lack of zonal index species; there is not enough information available to show the degree of uncertainty at the *eudoxus*–*autissiodorensis* zonal boundary. The stratigraphic position of the Kimmeridgian–Tithonian boundary is uncertain. A large-scale version of this summary log is available as a PDF file at <http://kimmeridge.earth.ox.ac.uk/>. Stone bands and marker beds are labelled and the numbering schemes are shown in three separate columns: column ‘x’ after Blake (1875, pp. 198–9; 1880 for the Hounstout Clay) and Arkell (1947, pp. 71–3); column ‘y’ indicates ‘bed’ numbers after Gallois (1998, 2000) and Gallois & Etches (2001); column ‘z’ shows bed group numbers from this study, which builds upon works by Cox & Gallois (1981), Wignall (1990) and Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992). Numbers of individual beds from this study are shown on the detailed logs on the web-site. Dashed bed boundaries reflect some uncertainty of their position in the section. Note that for scheme ‘y’, Gallois (2000) changed the base of unit 38 from Cox & Gallois (1981). Moreover, the base of unit 43 was not clear in Cox & Gallois (1981) and as a result the base of Gallois’ (2000) unit 43 differs from that of Wignall (1990) and Ahmadi & Coe (1998). For scheme ‘z’, Bed Groups 46 to 49 are based on Coe’s (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992) correlation with the Donington-on-Bain borehole, Lincolnshire (Gallois, 1978; Cox & Gallois, 1979), Bed Groups 51 to 55 are based on Wignall (1990), and Bed Groups 56 to 62 are based on Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992), and Ahmadi & Coe (1998). Gallois (2000) and Gallois & Etches (2001) defined units 50 to 63 for scheme ‘y’ using observations made in the field and based on the Swanworth Quarry 1 core.

Swanworth Quarry 1 borehole

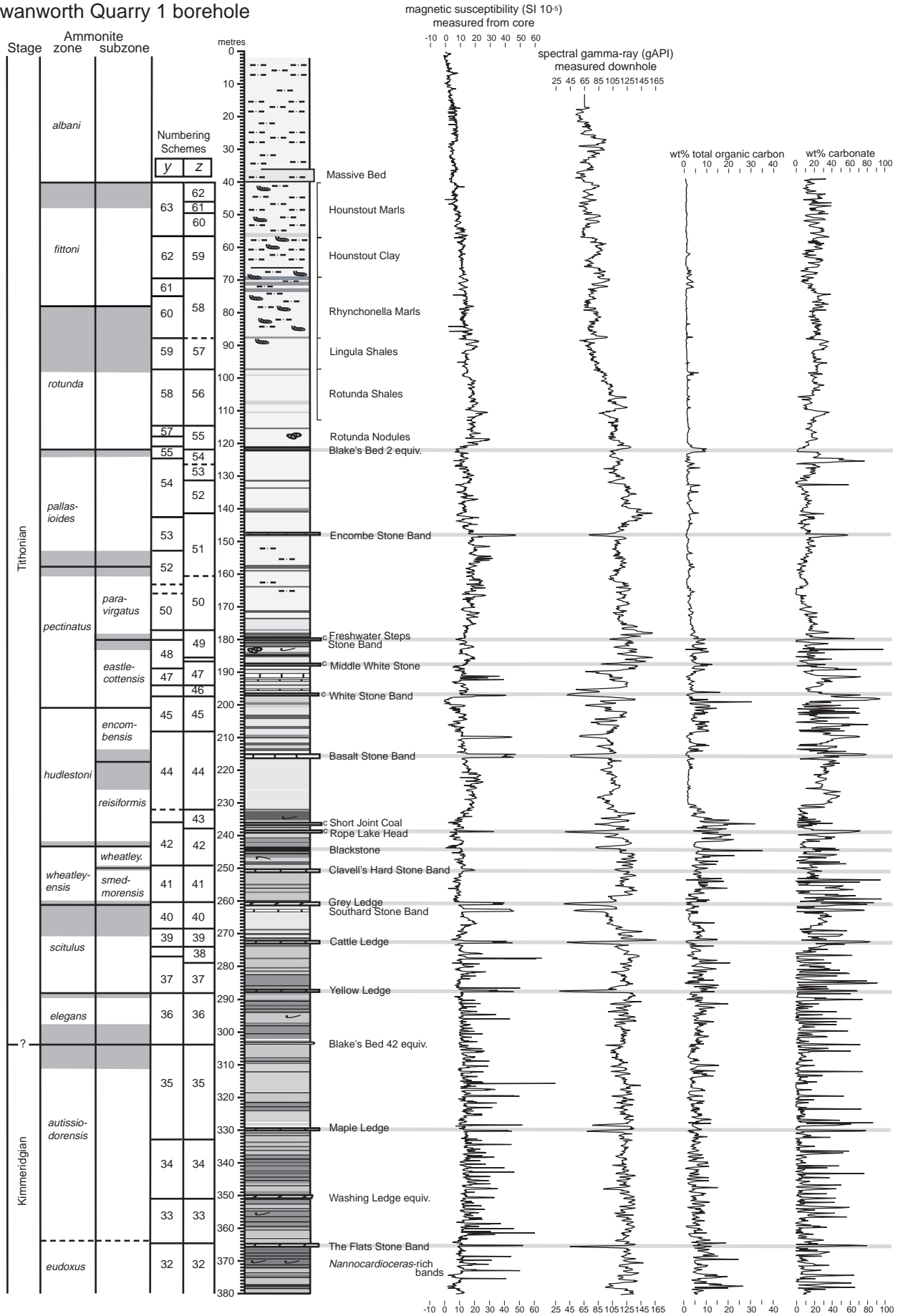


Figure 3. For legend see facing page.

gamma-ray troughs; at the exposure typical values for the White Stone Band are  $0.5 \times 10^{-5}$  SI and 9 eU respectively.

#### 5.g. Dolostone

Dolostones are tabular, continuous cementstones, or lines of doggers, of diagenetic origin, composed of a mixture of dolomite, ferroan calcite and calcite. The proportion of ferroan calcite (or dolomite) to calcite varies both laterally and vertically within each dolostone, and from one dolostone to another; some beds such as the Maple Ledge Stone Band are almost entirely composed of dolomite (Feistner, 1989). Fresh, unweathered, dry specimens are olive grey (5Y4/1) whereas, in the field, weathered surfaces are a dark greenish-orange (10YR 6/6). The Yellow Ledge Stone Band is a mustard yellow in the field. Beds of this type, at the exposure and in the cores, have well-defined upper and lower surfaces, and ring when struck with a hammer. Locally, when in the form of doggers, septarian cracks filled with coarsely crystalline cement occur. Dolostones occur in the Lower Kimmeridge Clay (e.g. Washing and Maple Ledge stone bands) and in the lower part of the Upper Kimmeridge Clay (e.g. Yellow, Cattle and Grey Ledge stone bands), usually within mudstones or calcareous mudstones showing 'dicey' weathering that are interbedded with organic-rich shales. They can be recognized in geophysical-log profiles by their magnetic-susceptibility peaks (typical values are  $19 \times 10^{-5}$  SI for the Maple Ledge Stone Band at outcrop and  $45 \times 10^{-5}$  SI for the Yellow Ledge Stone Band in Swanworth Quarry 1) and gamma-ray troughs (15 eU for The Flats Stone Band at outcrop and 30 gAPI for the Yellow Ledge Stone Band in Swanworth Quarry 1).

#### 5.h. Limestone

Continuous, tabular cementstone horizons are composed of calcium carbonate. Beds of this type are typically 0.1–1.4 m thick and medium-dark grey in colour (N4). The Basalt and Encombe stone bands are good examples; several thinner limestones are interspersed between the White and Middle stone bands. Limestone

beds are confined to the Upper Kimmeridge Clay, particularly in the *hudlestoni* and *pectinatus* zones. They are commonly associated with medium-dark–dark-grey marls (see Bed Group 44 that the Basalt Stone Band lies within; Figs 2, 3). In the exposures and cores, the well-cemented limestone bands are clearly defined above and below, are light grey in colour, leave a pale-grey streak when scratched, ring when struck with a hammer, and commonly contain broken shelly debris. The limestone bands weather proud in cliff exposures. Like dolostones, the beds yield characteristic magnetic-susceptibility peaks (approximately  $20 \times 10^{-5}$  SI at the type section and  $40 \times 10^{-5}$  SI in Swanworth Quarry 1), and gamma-ray troughs (as low as about 10 eU at the type section and 40 gAPI in Swanworth Quarry 1). Peaks in carbonate content are also associated with limestone beds, between 80 and 99 wt% for the Metherhills and Swanworth A–D stone bands in the Metherhills core (Fig. 4). Limestone is also present in the form of irregular nodules with a 10–200 cm diameter, some of which have a septarian structure. Smaller nodules (10–30 cm) are confined to discrete horizons in the Upper Kimmeridge Clay (such as the Rotunda Nodules), whereas larger nodules (50–200 cm) are found widely spaced at several horizons particularly in the Upper Kimmeridge Clay. Minor amounts of disseminated glaucony, phosphate and pyrite are present in the Rotunda Nodules at the type section.

### 6. The Lower Kimmeridge Clay and the Metherhills borehole

The Metherhills 1 core provides a valuable part of the data set as it represents a complete succession through the Lower Kimmeridge Clay, including its junction with the underlying Corallian Group (Oxfordian). The Lower Kimmeridge Clay, beneath the Hobarrow Bay Stone Band, is not exposed in the cliffs near Kimmeridge. Further west, at Ringstead Bay [SY 762 815], Osmington Mills [SY 734 818], Black Head [SY 725 820] and along the Fleet [SY 665 773], there are disparate exposures of the Lower Kimmeridge Clay; the thickness of these exposures is reduced due to their location on the footwall side of the Purbeck–Isle of Wight Disturbance. The graphic log of Metherhills 1

Figure 3. Summary graphic log measured from the Swanworth Quarry 1 borehole. Numbering schemes are shown in two columns: column 'y' indicates 'beds' after Gallois (1998, 2000) and Gallois & Etches (2001), and column 'z' bed groups from this study, which builds upon works by Cox & Gallois (1981), Wignall (1990) and Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992). Ammonite zonation has been erected by lithostratigraphic correlation with the outcrop sections (Fig. 2), and the stratigraphic position of the zonal boundaries probably has a comparable attendant degree of uncertainty, as shown. Key as in Figure 2. The stratigraphic position of the Kimmeridgian–Tithonian boundary is uncertain. This record of the core is drawn at the same vertical scale as the type section in Figure 2. Here, the magnetic-susceptibility, TOC and carbonate data measured from the core in the laboratory have been transferred to the same scale as the downhole spectral gamma-ray readings. It is this downhole depth scale which is used and is the closest approximation to 'true' depth. A large-scale version of this summary log is available at <http://kimmeridge.earth.ox.ac.uk/>. Note that the magnetic-susceptibility data comprise a combination of Swanworth Quarry 1 and 2 measurements, which represent the stratigraphic succession more accurately than the Swanworth Quarry 1 data alone.

Metherhills 1 borehole

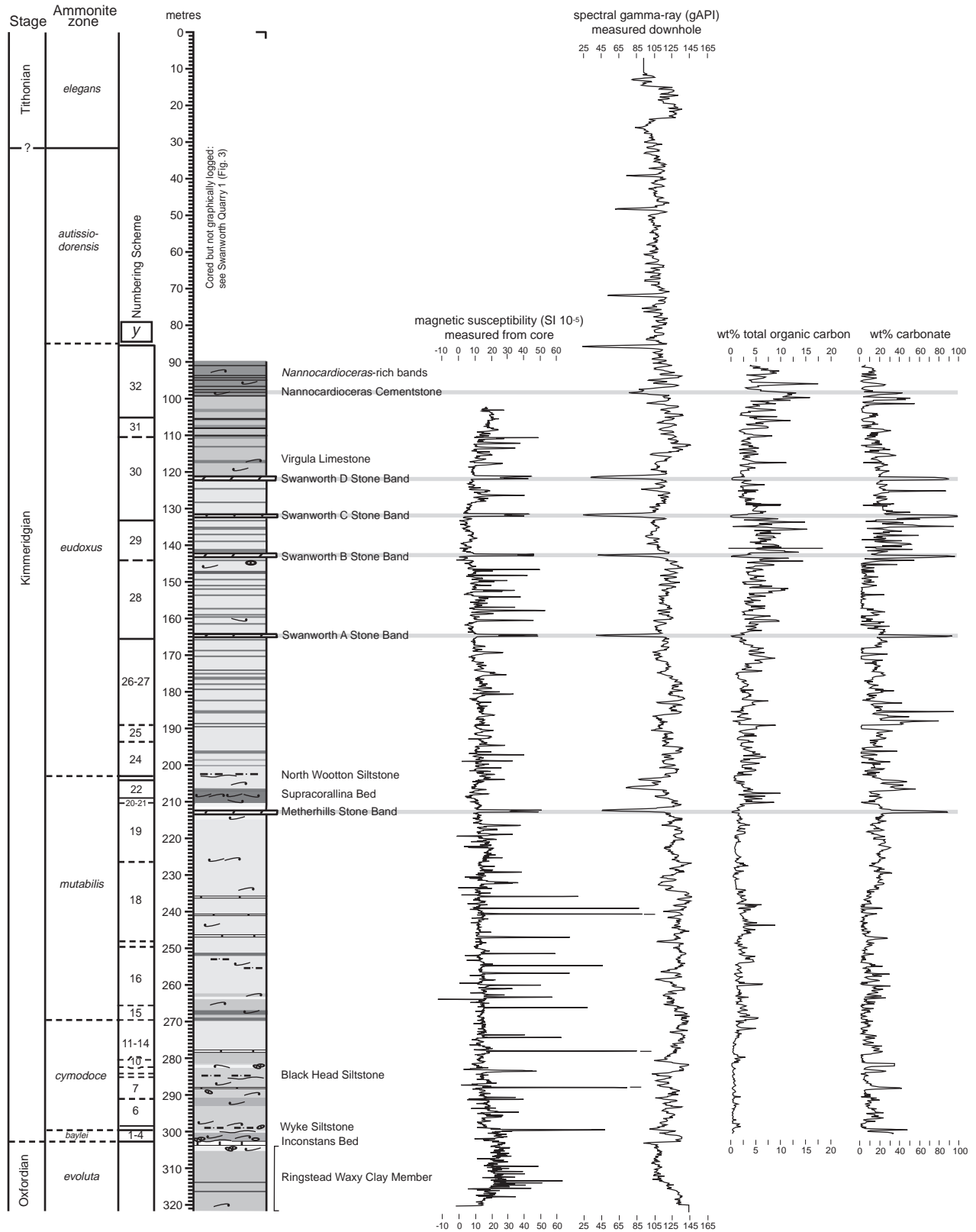


Figure 4. Summary of the Lower Kimmeridge Clay proved by the Metherhills 1 borehole. Stone bands and marker beds are labelled and 'bed' numbers are shown in the column marked 'y' (Gallois, 1998, 2000). Ammonite zonation follows the work of Cox & Gallois (1981), which is based on Salfield (1913) and Ziegler (1962). Dashed ammonite-zone and bed boundaries reflect some uncertainty of their precise position in the core. Key to figure is shown in Figure 2. A large-scale version of this summary log is available at <http://kimmeridge.earth.ox.ac.uk/>. The magnetic-susceptibility, TOC and carbonate data measured from the core in the laboratory have been transferred to the same scale as the spectral gamma-ray readings recorded downhole.



and its related analytical and downhole geophysical data sets therefore presents an extension to the Kimmeridge Bay type-section succession, supplementing the logs and descriptions produced for the more westerly exposures by Arkell (1933, p. 451), Brookfield (1978), Cox & Gallois (1981) and others. An overview of the Metherhills core is given below. The lithological descriptions are related to the bed numbers of Gallois & Cox (1976), Cox & Gallois (in Gallois, 1979), Cox & Gallois (1981) and Gallois (1998, 2000). Figure 4 presents a summary log of the lithological types comprising the core, where bed numbers are shown in column 'y', plotted against magnetic-susceptibility, total gamma-ray, carbonate and TOC data.

The basal portion of the Metherhills core comprises the Ringstead Waxy Clay Member, representing part of the Corallian Group. The unit was originally described from the Ringstead area (Arkell, 1947; Wright, 1986; Coe, 1995), where it is still well exposed today. In the core it consists of blue-grey silty clay, becoming slightly more calcareous and silty upwards, containing a scatter of small (< 1 cm diameter) pyrite nodules. The basal metre or so of the clay is sparsely shelly, including small nuculids and oysters. The Ringstead Waxy Clay has a thickness of approximately 15 m in Metherhills 1, whereas at its westerly outcrop it reaches 5 m at Sandsfoot, decreasing to 3.5 m at Ringstead (Brookfield, 1978). Over the next few metres the core does not match the lithological variability shown by the exposures. Elements of the stratigraphy described by Brookfield (1978) and Wright (1986) are not apparent, either because of the poor preservation of the core at this level, or else due to lateral changes in facies. Nevertheless, immediately below the base of the Kimmeridge Clay a sparsely shelly horizon exists which likely equates with the level of the Osmington Mills Ironstone Member, previously identified at Ringstead, Osmington Mills, Black Head, and along the Fleet. At outcrop, the unit is a very shelly mudstone with limonitic ooids, phosphate nodules and generally rare but locally abundant corals, giving rise to the local name of the Ringstead Coral Bed (Arkell, 1947; Wright, 1986; Coe, 1995). More convincing is the presence of an erosion surface at the top of this sparsely shelly horizon in the core, which has also been recorded at all exposures. The surface is sharp, partially phosphatized, iron-stained and bioturbated, piping dark grey, shelly, silty mudstone into the underlying muddy clay.

The base of the Kimmeridge Clay Formation, and the Oxfordian/Kimmeridgian boundary, is marked by the contact between the Osmington Mills Ironstone and the overlying Inconstans Bed, a heavily burrowed medium- and dark-grey mudstone containing phosphatic nodules and abundant shelly material, including the ammonite *Pictonia* and the brachiopod *Torquirhynchia inconstans* (J. Sowerby). The beds represent the *baylei* Zone, units 1 to 4 of Gallois & Cox

(1976). The more westerly exposures comprise grey, sandy, bioturbated clay, with limonitic, oolitic, clay-rich sand partitioned as lenses (Brookfield, 1978; Cox & Gallois, 1981). Above, there rest heavily bioturbated silty clays which are interbedded with thin cementstones and lenses of shelly material including the oyster *Deltoideum delta* (W. Smith). About a metre above the base of the Kimmeridge Clay at outcrop is the 'Exogyra nana Bed', which is composed of a thin, indurated marl containing numerous small oysters, *Nanogyra nana* (J. Sowerby) (Arkell, 1933, p. 451). In the core, *Nanogyra nana* have only been found in the overlying Wyke Siltstone (Bed Group 5) (Gallois, 1998). This siltstone unit lies upon a conspicuous erosion surface highlighted by angular chips of phosphatized pebbles and ammonites. Bioturbated, calcite-cemented muddy siltstones containing phosphatic nodules and copious shelly debris characterize the unit, and are overlain by finer grained, commonly medium-grey-coloured muddy clays ascribed to Bed Groups 6 and 7. At Osmington Mills, the Wyke Siltstone is about 40 cm thick and commonly bioturbated, obscuring its cross-laminated internal structure, which is visible at East Fleet [SY 662 765]. Another erosion surface associated with phosphatized material and bioturbation marks the base of the overlying Black Head Siltstone (Bed Group 8), a similarly well-cemented silty mudstone containing abundant shelly debris, including numerous ammonites typifying the *Rasenia cymodoce* Zone. Again, the overlying beds comprise medium-grey, fine-grained mudstones and clays. Both the Wyke and Black Head siltstones are present in boreholes from the area of the Wash (Gallois & Cox, 1974, 1976; Cox & Gallois, 1979).

These fining-upward cycles were first recognized in the exposures by Brookfield (1978) who, in summary, described the cycles as containing a lag deposit resting upon an erosion surface, followed by fossiliferous clayey sand and capped by grey-coloured clay. The cycles found in the core continue into the *mutabilis* Zone, on a 5–10 m scale, but include progressively more organic-rich layers upward. They have also been noted at outcrop, in the mid-*mutabilis* Zone and at the base of the *eudoxus* Zone. Numerous thin cemented bands are interspersed throughout Bed Groups 6–19, picked out as spikes in the magnetic-susceptibility profile (Fig. 4). Around the boundary of Bed Groups 16–17 the lithology is relatively silty. The well-cemented Metherhills Stone Band occurs near the top of Bed Group 19 in the core, highlighted by a prominent peak in magnetic-susceptibility values (Fig. 4). This stone band has not been recognized at outcrop. Resting upon a unit of black, shelly clays (Bed Group 20–21) is a bed measuring less than a metre in thickness, composed of medium-grey mudstone with lenses containing *Astarte supracorallina* (d'Orbigny): the Supracorallina Bed (Arkell, 1947, p. 85; Cox & Gallois, 1981) (Bed Group 22). At Osmington Mills

and Black Head, the *mutabilis* Zone is poorly exposed and composed of black clays full of iridescent shells, similar to the succession present at Ringstead (Arkell, 1947, p. 84).

The overlying *eudoxus* Zone attains a thickness of some 117 m in the Metherhills 1 core. At the base lies the North Wootton Siltstone, a dark grey, muddy, locally very shelly siltstone showing patches of calcite cementation, overlying an erosion surface. The unit forms Bed Group 24. In exposures these cemented patches amalgamate into rare doggers (Gallois & Cox, 1976). What follows is a succession of medium-grey mudstones, which are also shelly and locally silty, interbedded with thin cemented horizons and organic-rich layers. Within these sediments are four prominent, 50–60 cm thick, well-cemented and clearly defined limestones, referred to as the Swanworth A to D stone bands. These diagenetic cementstones are not developed in exposures along the Dorset coast. Calcite veins fill fractures which cross-cut Swanworth stone bands A and B, and in Swanworth A the fractures radiate outward in a manner reminiscent of septarian nodules. Broken shelly debris is scattered throughout Swanworth D Stone Band and particularly the mudstones resting above; especially common is *Nanogyra virgula* (Defrance) suggesting that the mudstones correspond to the Virgula Bed exposed at Black Head and forming the mid- to upper part of Bed Group 30. From this level, and for the remainder of the *eudoxus* Zone, the beds become progressively more organic-carbon rich, with the level around the *Nannocardioceras* Cementstone yielding a content of >20 wt% TOC. Immediately below the cementstone there is a bed approximately 3 cm thick that appears to have been fluidized; it is a coccolith-rich mudstone run through with mini-sediment-filled fissures. The widespread occurrence of this bed (at Hobarrow Bay and possibly Ringstead Bay) led Gallois (1998) to attribute its fluidized nature to a single seismic shock. The *Nannocardioceras* Cementstone is overlain by organic-rich mudstones that are fissile and shelly, with bivalve fragments plastered along bedding planes (Gallois & Cox, 1976). Interbedded within the organic-rich mudstones are thin beds of medium-grey sparsely shelly mudstone. This short section, above the *Nannocardioceras* Cementstone and comprising the remainder of Bed Group 32, distinguishes the main *Nannocardioceras*-rich bands. In the Metherhills core, the Hobarrow Bay Stone Band is absent.

### 7. Description of the type section and the coeval beds of Swanworth Quarry 1

Between Brandy Bay [SY 889 795] and Chapman's Pool the Kimmeridge Clay forms a broad anticline with very gently dipping limbs facing east and west, positioned either side of a fold axis which cuts the coastline near to Hobarrow Bay (Fig. 1) and plunges

slightly to the east. The western limb, between Brandy Bay and Hobarrow Bay, exposes the White Stone Band to Hobarrow Bay Stone Band. The eastern limb, between Hobarrow Bay and Chapman's Pool, consists of the whole of the Kimmeridge Clay above the Hobarrow Bay Stone Band. Together, the beds exposed along this stretch of coastline comprise the type section for the Kimmeridge Clay Formation. The paragraphs below describe these beds in relation to the bed group scheme which has evolved through the work of Cox & Gallois (1981), Wignall (1990) and Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992). Figure 2 displays this bed group scheme in column 'z', and is shown against the bed numbers of Blake (1875, pp. 198–9) and Arkell (1947, pp. 71–3) in column 'x', and Gallois (1998, 2000) and Gallois & Etches (2001) in column 'y'.

During field work as part of this study, graphic logs were constructed for the uppermost *eudoxus* and *autissiodorensis* zones, and minor additions and corrections were made to the graphic log of Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992) (uppermost *autissiodorensis* to *fittoni* zones). Magnetic-susceptibility and natural gamma-radiation data were collected with direct reference to these graphic logs. The results are summarized by Figure 2 and may be compared with Figure 3, which displays a summary log of the coeval strata recovered by Swanworth Quarry 1. These figures show that the general stratigraphy present at outcrop is also evident in the core, although there are thickness differences, with the type section being generally thicker than the succession recovered from Swanworth Quarry 1 (see Section 13 and Gallois, 2000).

At the base of the type section in Hobarrow Bay is the *Nannocardioceras* Cementstone (*eudoxus* Zone; Bed Group 32). It comprises laminated, organic-rich mudstones and is partially cemented by calcite and pyrite into nodules. Throughout the cementstone are uncrushed *Amoeboceras* (*Nannocardioceras*) preserved as translucent calcite, which distinguish the bed sufficiently to allow its correlation between Hobarrow Bay and sections further west at Ringstead Bay and near to Weymouth (Arkell, 1949; Cox & Gallois, 1981). Above the cementstone there rests a succession of laminated, conspicuously organic-rich mudstones, which are intercalated between thin bands of very shelly fissile shale containing abundant crushed *Amoeboceras* (*Nannocardioceras*) that weather out as hard ribs in the cliff. These '*Nannocardioceras*-rich bands' are clearly present in Swanworth Quarry 1 core, where they comprise interlaminated mudstone beds containing varying quantities of organic carbon (from <10 to >20 wt% TOC) together with abundant bivalves and pyritic lenses and nodules. The Flats Stone Band, a dark yellow-brown dolostone with occasional thin stringers of pale-coloured, coccolith-rich material, occurs near the top of the *eudoxus* Zone

(and Bed Group 32). The tabular and laterally continuous Flats Stone Band is made distinctive by joints and low-angle thrust faults that display slickensides (Arkell, 1947, p. 74), which may have formed through chemical changes in the bed during diagenesis (Bellamy, 1977). Associated with The Flats Stone Band is a significant peak in magnetic-susceptibility values, distinct at the outcrop and in the core, with a notable dip in total gamma-ray readings.

Strata representing the *autissiodorensis* Zone first occur about 1 m above The Flats Stone Band (Cox & Gallois, 1981, p. 15). The beds between The Flats Stone Band and the Washing Ledge Stone Band, characterizing Bed Group 33, are composed of interbedded well-cemented, medium-grey mudstones showing a conchoidal fracture and more fissile mudstones and laminated shales containing small (< 1 cm diameter) pyrite nodules, shelly material, thin layers of coccolith-rich sediment, and scattered coprolites. A few metres above The Flats Stone Band a useful palaeontological marker band occurs, distinguished by abundant ammonites of *Sutneria rebholzi* (Berckhemer), strewn within a thin bed of well-cemented, organic-rich mudstone. This bed is present at the type section and across much of southern England (Cox & Gallois, 1981; Gallois, 1998). The overlying Washing Ledge Stone Band (Bed 34/1) is a distinctive dolostone at Kimmeridge Bay, including a thin mudstone unit part way through the band which is again reflected in a conspicuous double peak in magnetic-susceptibility values. In the core, however, the Washing Ledge Stone Band is relatively weakly cemented, suggesting that the stone band *sensu stricto* is either absent or more likely poorly developed in Swanworth Quarry 1.

The next parcel of strata, classified as Bed Group 34, is a series of medium-grey cemented mudstones with a conchoidal fracture, interbedded with laminated, moderately organic-rich mudstone beds, which become less common in occurrence upwards to about the level of the Maple Ledge Stone Band (Bed 35/4). In the Swanworth Quarry 1 core, the average TOC content of the strata comprising Bed Group 34 is ~5 wt%. In the core and along the exposure, several of these more cemented, organic-rich beds are coincident with high values in the magnetic-susceptibility data set. Like the *eudoxus*-Zone strata, these beds contain abundant shelly material, especially *Amoeboceras* (*Nannocardioceras*): one species of the genus, *A. volgae*, is discretely concentrated in a bed 4–5 metres above Washing Ledge, comprising the marker Volgae Bed. Just below the Maple Ledge Stone Band at the type section, it is calculated, by comparison with the Swanworth Quarry 1 core, that approximately 2–3 m of section are missing due to the presence of a normal fault. The fault also obscures the boundary between Bed Groups 34 and 35. The Swanworth Quarry 1 borehole, however, recovered this part of the succes-

sion, revealing predominantly medium-grey calcareous mudstones made distinct by their conchoidal fracture. The Maple Ledge is a thin, tabular dolostone cropping out to the eastern side of Kimmeridge Bay, comparatively mud-rich in the Swanworth Quarry 1 core. Where the stone band is exposed, petrographic examination has revealed its ferroan dolomite composition (Feistner, 1989).

The upper part of the *autissiodorensis* Zone comprises medium-dark grey mudstones, some of which are well cemented and conchoidally fractured, interbedded between distinct units of laminated, organic-rich mudstone. Sparse shelly debris, thin coccolith-rich layers, small irregularly shaped pyrite nodules (roughly 1 cm in size), rare coprolites, and networks of thin calcite veins also distinguish the beds. On the coast, near the top of Bed Group 35 (bed 49), the mudstone is slightly silty. A stone band called Blake's Bed 42 (Blake, 1875, p. 199) rests upon this succession of mudstones (exposed at Hen Cliff on the eastern side of Kimmeridge Bay). Elsewhere, Blake's Bed 42 is not as well developed (in the Swanworth Quarry boreholes) or is absent altogether (at Brandy Bay and other inland localities). The bed is stratigraphically important as its base differentiates the Lower Kimmeridge Clay from the Upper Kimmeridge Clay. The bed is succeeded by about a metre of mudstone and another, more nodular, stone band, Blake's Bed 41.

The sediments that follow, and which form the cliffs between Clavell's Tower [SY 908 788] and Cuddle [SY 912 782], are characterized by rhythmic alternations of organic-rich and organic-poor mudstones, similar to those representing the underlying *autissiodorensis* Zone. The organic-rich beds of Bed Group 36 contain a TOC content of up to 20 wt%, whereas the average TOC content for the section is only ~6 wt%. The lowermost bed of Bed Group 37 is the Yellow Ledge Stone Band (Bed 37/1), which is taken as the base of the *Pectinatites scitululus* Zone. The band pinches and swells, giving a hummocky appearance. It is composed of low-magnesian and low-ferroan calcite, and ferroan dolomite (Feistner, 1989). The Yellow Ledge Stone Band yields a clear spike in magnetic-susceptibility values and a concomitant dip in total gamma-ray counts. Between this and the Cattle Ledge Stone Band near to Clavell's Hard [SY 920 777] there occurs a further succession of cemented, medium-grey mudstones interbedded with subordinate dark-grey, laminated, organic-rich mudstone, within which Bed Group 37 passes into Bed Group 38. Shelly debris, coprolites, and pyrite nodules are common. In the core thin layers of beef calcite are prevalent.

Cattle Ledge (Bed 39/3) is a well-cemented mud-rich limestone and marks a level at which thickly bedded marl becomes predominant over dark-grey, organic-rich mudstone, weathering to form steep degraded slopes along the coastline, and characterizing Bed

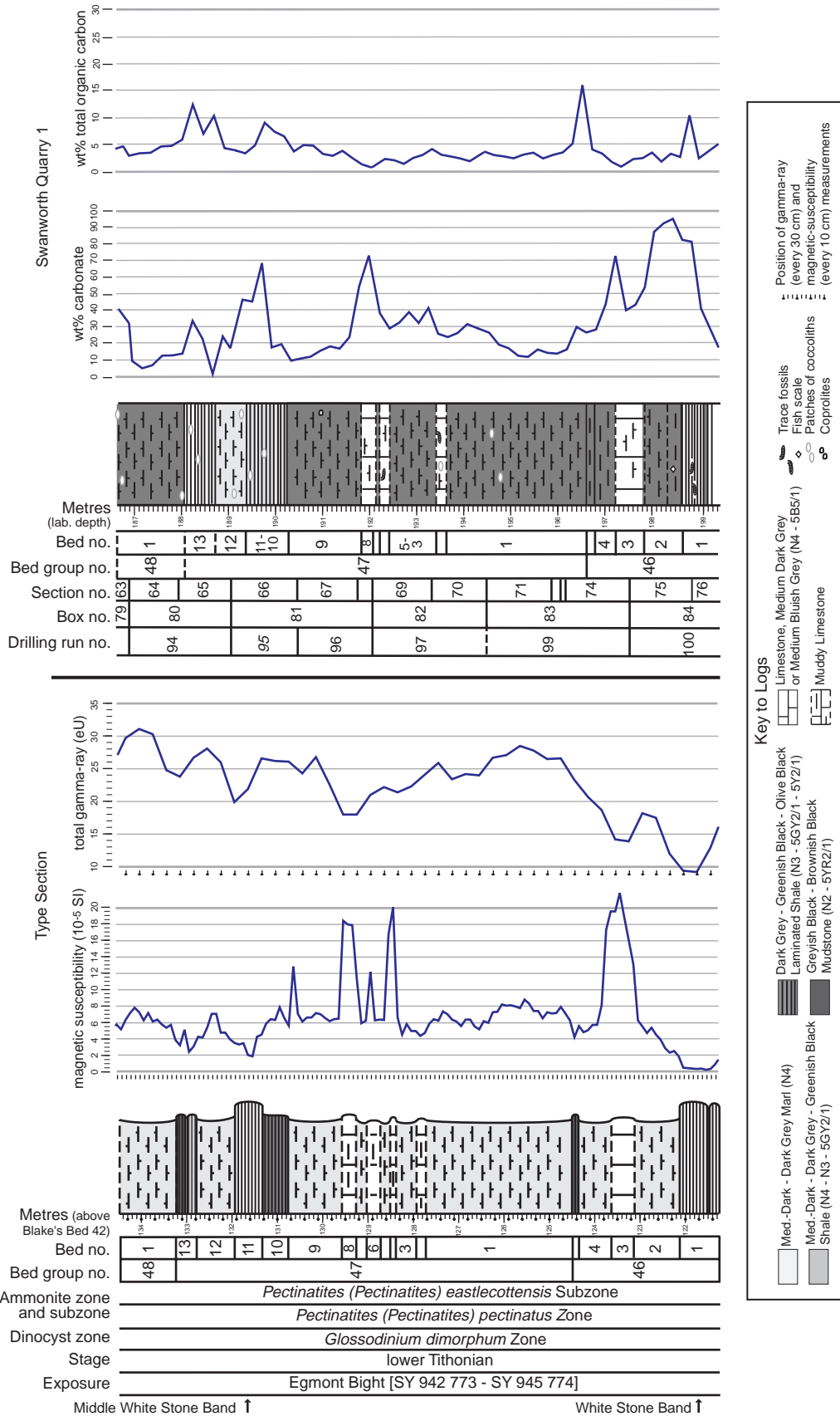


Figure 5. Example of the detailed, large-scale graphic logs available at <http://kimmeridge.earth.ox.ac.uk/>. An interval of Kimmeridge Clay is illustrated, measured at the type section and from the Swanworth Quarry 1 core. The magnetic-susceptibility (every 10 cm) and total gamma-ray (every 30 cm) data recorded at the type section are shown. Also, part of the Swanworth



Table 1. Depths at which the main stone (or marker) bands occur in the Kimmeridge Clay type-section and Swanworth Quarry 1

Stone (or marker) band	Type section (m)	Swanworth Quarry 1				
		Downhole depth (m)	Laboratory depth (m)	Depth difference (m)	Box no.	Section no.
Blake's Bed 2	199.80	122.27	123.45	1.18	52	9
Encombe	174.15	147.83	149.25	1.42	63	31
Freshwater Steps	140.70	179.70	180.65	0.95	76	58
White Stone	124.35	197.98	198.85	0.87	84	75
Basalt	101.65	215.36	218.52	3.16	92	16
Rope Lake	76.45	238.51	243.02	4.51	100	39
Blackstone	71.45	244.16	247.72	3.56	102	43
Clavell's Hard	63.55	250.51	254.52	4.01	105	49
Grey Ledge	51.75	260.60	265.32	4.72	109	58
Southard	—	262.54	267.32	4.78	110	60
Cattle Ledge	38.80	272.56	277.77	5.21	114	68
Yellow Ledge	22.05	287.24	292.67	5.43	120	81
Blake's Bed 41	0.90	303.71	309.56	5.85	127	8
Blake's Bed 42	0.00	304.05	309.91	5.86	127	9
Maple Ledge	-24.35	330.08	336.61	6.53	137	34
The Flats	-64.20	365.30	373.51	8.21	151	73

Notes: This table highlights the degree by which the core has 'expanded' since being recovered through drilling. The datum for the type section is centred on Blake's Bed 42, which crops out on the eastern side of Kimmeridge Bay. In the case of Swanworth Quarry 1, downhole (or 'true') depth is compared with laboratory depth, and the difference calculated. Box and section numbers are also shown for each stone band. The cores in storage at the British Geological Survey are therefore of 'laboratory depth length'.

Groups 39 and 40. Between Cattle Ledge and Grey Ledge the first notably thick bed of calcareous mudstone occurs (Bed 40/3), showing a conchoidal fracture and containing sparse, broken shelly debris. Near the top of the calcareous mudstone, 1–2 m below Grey Ledge, the Swanworth Quarry 1 core contains a sharply defined and well-cemented, highly calcareous mudstone which induces a peak in magnetic-susceptibility values. The stone band is referred to as the Southard Stone Band and is not developed at the type section. The Grey Ledge Stone Band (Bed 40/4) is a well-indurated cementstone composed of ferroan dolomite and calcite (Feistner, 1989), marking the boundary between Bed Groups 40 and 41.

In contrast to the underlying succession, Bed Group 41 is primarily composed of organic-rich shale (up to 19 wt% TOC in the Swanworth Quarry 1 core), with marl a subordinate constituent until it becomes predominant 2–3 m below, and above, the next stone band, Clavell's Hard, distinguished by a greater degree of cementation, a pronounced magnetic-susceptibility peak, and a total gamma-ray trough. Clavell's Hard Stone Band (Bed 41/22) is well developed at the type section, where it was identified and named by Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992), and it is clearly present in the core. The shales of Bed Group 41 have a low species diversity (Wignall, 1990) and are for the most part devoid of shells, but small patches of

coccolithic material are scattered throughout certain intervals. Small (centimetre-size) chips of phosphate occur. Above Clavell's Hard Stone Band, the abundance of organic-rich mudstone beds increases once again, culminating in the Blackstone (Bed 42/12), a very dark brown, highly organic-rich, laminated, weakly fissile mudstone containing pyritic nodules and shelly material. The Blackstone is heterogeneous, containing organic-poor layers (< 10% TOC) intercalated between more numerous organic-rich beds (40–60% TOC; Huc *et al.* 1992; Herbin *et al.* 1995). Analysis of the Blackstone in Swanworth Quarry 1 gave a value of 35 wt% TOC. This comparatively low value probably relates to our mode of sampling, as 10 cm composites were analysed for TOC content. The Blackstone forms the most prominent bed in a package of organic-rich shales that straddle the *Pectinatites wheatleyensis*–*Pectinatites huddlestoni* zonal boundary (Bed Group 42). Immediately below the Blackstone lies a bed rich in pyritized specimens of the planktonic crinoid *Saccocoma*, and above rest a series of olive-grey, organic-rich, coccolithic mudstones, weakly laminated in part. Almost at the top of Bed Group 42 lies the Rope Lake Head Stone Band (Bed 42/24), a well-cemented, laminated, coccolithic limestone showing evidence of burrowing in its upper surface. Above this cementstone occurs another thin carbonate band sandwiched between two oil shales (Bed 43/2), termed

Quarry 1 total organic carbon and carbonate data set is displayed. The graphic log of the core is shown against the laboratory depth scale, which is effectively a slightly expanded version of the 'true', downhole scale. The laboratory depth scale was implemented because of the core's 'expansion' during transportation; the cores in storage at the BGS are effectively of this expanded, 'lab depth' length. Note that the summary logs in Figures 2, 3 and 4 have been redrawn against 'true' depth scale, allowing direct comparison with the type section. Dinocyst stratigraphy after Riding & Thomas (1988), ammonite zones and subzones after Cope (1967, 1978) and Cope *et al.* (1980). Bed group numbers after Cox & Gallois (1981), Wignall (1990), and Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992).

the Little Stone Band by Coe (A. L. Coe, unpub. D. Phil. thesis, Univ. Oxford, 1992), but herein referred to as the Short Joint Coal (Strahan, 1920).

The mid- to upper part of the *hudlestoni* Zone, represented by Bed Group 44, comprises thick beds of very calcareous, sparsely fossiliferous mudstone, including the Basalt Stone Band which induces a characteristic peak in magnetic susceptibility and trough in gamma-ray values. The Basalt Stone is a well-cemented, dark-grey limestone with a pronounced conchoidal fracture (Bed 44/2). A further, unnamed, cementstone lies almost at the top of Bed Group 44. The strata up to the White Stone Band, which are exposed between Rope Lake Head and Freshwater Steps, are similar to the calcareous mudstones below, but include more laminated, organic-rich layers (Bed Group 45). Pyrite nodules and phosphate chips are scattered throughout the section, and coccoliths that are concentrated in discrete laminae become increasingly prevalent upwards into the base of the White Stone Band, one of the most prominent and easily recognizable beds in the Kimmeridge Clay (Bed 46/1). The boundary between the *hudlestoni* and *pectinatus* zones is placed some 2.7 m below the White Stone Band according to Cope (1978). The stone band is a finely laminated limestone abounding in coccoliths and coccospheres of the species *Watznaueria fossacincta* (Young & Bown, 1991).

The White Stone is overlain by < 2 m of calcareous mudstone and another cemented horizon; together these units form Bed Group 46. A further unit (Bed Group 47) of thickly bedded calcareous mudstones follows, intercalated with three thin, sharply defined cementstones that are picked out as spikes on the magnetic-susceptibility profile, and succeeded by the Middle White Stone Band (Bed 47/11), a coccolith-rich limestone which overlies a laminated organic-rich bed (Bed 47/10). Bed Groups 48 and 49 are made up of calcareous mudstones with interbedded organic-rich laminated mudstones containing irregular masses of pyrite and numerous phosphatic nodules. Upward, the amount of coccolithic material once again increases, topped by the Freshwater Steps Stone Band (Bed 49/8), a unit of interlaminated olive-grey, organic-rich, and medium-grey, coccolith-rich, mudstone. The overlying part of the *pectinatus* Zone exposed in Egmont Bight is dominated by thick beds of calcareous mudstone, including fewer and thinner organic-rich mudstone units upwards, occasional silty partings, and some quite sizeable septarian limestone nodules, such as the Pectinatus Nodules within Bed Group 50.

Uniform, thickly bedded, calcareous mudstones dominate the *Pavlovia pallasoides* Zone, including subordinate organic-rich mudstones and septarian limestone nodules, some of which are formed around large ammonites. In the cliffs at Egmont Bight a weakly cemented, medium-grey mudstone exists

which is picked out more clearly by geophysical-log data collected from the boreholes, warranting the unit's definition as the Encombe Stone Band (Bed 51/9). In the Swanworth Quarry 1 core the bed is an indurated well-cemented limestone that has a magnetic-susceptibility peak more pronounced than that induced by the same beds at outcrop. Above, the strata represented by Bed Groups 54–56 include more organic-rich mudstones, perhaps the most notable of which is Blake's Bed 2 (Bed 55/1), a greyish-brown, finely laminated, organic-rich mudstone. In the upper part of Bed Group 54, just below Blake's Bed 2, ammonites are particularly common and some of the body chambers are phosphatized (see Gallois & Etches, 2001, for further details). These ammonite fragments mark the first appearance of *Pavlovia rotunda* (J. Sowerby) (Cope, 1978; Cox & Gallois 1981). Standing proud from cliffs of medium-dark grey marls on the eastern side of Chapman's Pool, about 5 m above Blake's Bed 2, are two lines of calcareous septarian concretions that are 5–15 cm in diameter. They are composed of fine-grained microsparite, and commonly contain uncrushed, well-preserved, strongly ribbed ammonites of the *Pavlovia rotunda* Zone and are termed the Rotunda Nodules (Arkell, 1933, p. 446; Cox & Gallois, 1981).

## 8. Overview of the uppermost Kimmeridge Clay and its subdivision

The purpose of this section is to describe the uppermost Kimmeridge Clay, commenting upon the subdivision of the strata into bed groups. Beds belonging to the *rotunda* and *fittoni* zones are exposed in steep and partially landslipped cliffs above Chapman's Pool and beneath Hounstout (Fig. 1). The broad characteristics of these beds were summarized by Buckman (1909–30) and Arkell (1933, 1947 and references therein); Cope (1978) subsequently re-measured the section and described the associated ammonites. Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992) subdivided this existing stratigraphy and produced the first detailed graphic log of the succession; this was checked during fieldwork for this study, and minor amendments were made. Since the advent of the Kimmeridge Drilling project, Gallois (1998, 2000) and Gallois & Etches (2001) have re-measured the type section and compared it with the Swanworth Quarry cores, resulting in a log with a total thickness some 15% greater than the equivalent graphic logs produced by Arkell (1933, 1947), Cope (1978), Coe (A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992), and this study. In the paragraphs below, we describe the strata at outcrop and in the cores with reference to the bed group scheme shown in column 'z' of Figure 3.

In the Swanworth Quarry core, the Rotunda Nodules are rather poorly represented and the bed comprises a pyrite-rich band, some 3 m above Blake's

Bed 2. The succession above shows a progressive increase in silt content, reflected by a pronounced decrease in gamma-ray values through Bed Group 56. These so-called Rotunda Shales (Cope, 1978; Cope *et al.* 1980) form a 13.3 m thick succession of medium-dark grey calcareous slightly silty shales containing a sparse fauna of ammonites, belemnites and bivalves. Some 4.6 m above the base of the unit is the lowest prominent and continuous line of seepage (indicated by an arrow in Fig. 2) at Chapman's Pool. Resting upon the Rotunda Shales is a series of dark, silty clays and mudstones. Although these have been grouped by Cope (1978) and Cope *et al.* (1980) into the *Lingula* and *Rhynchonella* beds, we prefer that these beds are separated into the *Lingula* Shales and *Rhynchonella* Marls as they were in the older literature (Buckman, 1926; Arkell, 1933), because they are distinct recognizable units. The contact between the *Lingula* Shales and the underlying Rotunda Shales can be distinguished by another continuous line of seepage at Chapman's Pool and a prominent change in fracture pattern, from medium-dark grey mudstones showing a conchoidal fracture below, to lighter grey mudstones that fracture into very small pieces (<1 cm) above (Fig. 2).

At Chapman's Pool, the base of the *Lingula* Shales (Bed Group 57) is marked by a 60 cm thick bed of fissile mudstone (Bed 57/1; described as the 'Cidarid Siltstone' by Gallois, 2000), the unit as a whole achieves a total thickness of 8.6 m. Today, it is rather difficult to decipher exactly how the *Lingula* and *Rhynchonella* beds were originally divided at Pier Bottom, south of Chapman's Pool, especially given how badly degraded the cliff-section has become. So, the basal bed of the overlying *Rhynchonella* Marls (Bed Group 58) is taken as a prominent calcitic cementstone (Bed 58/1), overlain by a thin bed of shale. The *Rhynchonella* Marls have a total thickness of 16.2 m at the most easily accessible exposure on the western side of Hounstout and consist of silty, fossiliferous, calcareous mudstone exhibiting alternating faint light and dark bands possibly relating to calcium carbonate and/or organic-carbon content. In the Swanworth Quarry 1 core, the boundary between Bed Groups 57 and 58 is tentatively taken at the level of a thin, organic-rich mudstone that is bioturbated (*Planolites*, *Chondrites* and *Teichichnus*) but apparently barren of shelly remains (Fig. 3).

The overlying Hounstout Clay, which is well exposed and accessible on the western side of Hounstout, is 7.85 m thick and clearly defined top and bottom by lines of seepage (Blake, 1880; Cope, 1978; A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992). The unit is made up of bioturbated silty clays containing occasional bivalves and ammonites, with a slightly coarser-grained cemented horizon near the top (Bed 59/2). Scattered pyrite nodules, 1 cm in diameter, occur within the lowermost metre. In the Swanworth

Quarry 1 core, the unit displays well-preserved burrow traces in the more silty layers, but is apparently devoid of body fossils. Above the highest line of seepage, visible on the western side of Hounstout, lie the overlying Hounstout Marls. These comprise calcareous silty clays, containing some very fine-grained sand; interbedded with coarser grained, better-sorted units that are commonly fairly well cemented. The unit consists of some 18.6 m of section at the exposure (Bed Groups 60–62). The equivalent beds in the core reveal exceptionally heavy and diverse bioturbation (which appears to be dominated by *Teichichnus*), where the burrows are picked out by medium-grey siltstone, set against a background of bluish-grey to medium-grey and brownish-grey siltstone and silty mudstone. Resting upon the Kimmeridge Clay Formation, and marking the base of the Portland Beds, lies the Massive Bed, a 2 m thick fine-grained, calcareous sandstone.

## 9. Lateral variation of the stone bands

Stone bands (or cementstones) interspersed within the diverse mudrock facies which make up the Kimmeridge Clay are variable in terms of their composition, mode of formation and lateral continuity. Their character essentially depends on a combination of primary lithological content and secondary diagenetic features. Both of these varied significantly in time and space during deposition and burial of the Kimmeridge Clay. Essentially, the stone bands can be divided into two types: (1) coccolith limestones of primary origin, and (2) calcareous cementstones and dolostones composed of primary and/or diagenetic forms of low-magnesian and ferroan calcite, and diagenetic ferroan dolomite.

The development of the diagenetic calcareous cementstones and dolostones is understood to have been influenced by sedimentation rate, burial rate, and the degree of organic-matter preservation during burial (Scotchman, 1991). Early diagenetic carbonates in the Kimmeridge Clay are largely concentrated in bands of concretions, or as cementstones with intervening mudstones showing later cementation (Scotchman, 1989). The development of the nodules is thought to be related primarily to lulls in sedimentation rate (Scotchman, 1989). In a spatial sense, differences in sedimentation rate across submerged fault blocks could explain why many of the calcareous cementstones are laterally discontinuous, and appear to be better developed at some localities (that is, on less subsident tilted blocks) than in others (that is, on more subsident tilted blocks). Furthermore, changes in sedimentation rate with time could also explain why the stone bands are confined to specific parts of the succession. For example, Scotchman (1991) suggests that the Rotunda Nodules (Bed 55/7) are related to a depositional hiatus. During times of, or in



areas typified by, higher sedimentation rates and organic-matter preservation ( $> 5\text{--}6$  wt% TOC), pyrite and ferroan calcite concretions formed at the base of the sulphate-reduction zone (e.g. portions of Bed Group 32, such as the *Nannocardioceras*-rich bands) (Scotchman, 1991). Even higher sedimentation rates and organic-matter enrichment led to the development of complex and concretionary dolomites and ferroan dolomites within the methanogenesis and decarboxylation zones (Irwin, Curtis & Coleman, 1977; Irwin, 1981; Scotchman, 1991). Such conditions would have been especially common across the relatively deep shelf (Scotchman, 1991). These dolomites and ferroan dolomites include the Maple Ledge and Yellow Ledge stone bands (Feistner, 1989), and occur within the medium-dark-dark-grey marls of the Kimmeridge Clay.

Coccolith limestones are regionally extensive, consistent with their reputed origin through a succession of algal (coccolithophoroid) blooms (Gallois & Cox, 1974; Gallois, 1976; Gallois & Medd, 1979; Oschmann, 1991; S. Pearson, unpub. Ph.D. thesis, Univ. Southampton, 2000). For example, the Rope Lake Head and White Stone bands are both well developed in Dorset and as far north as Yorkshire, where they have been recovered from boreholes (Herbin *et al.* 1995). Of the coccolith limestones, the White Stone Band is the best developed and most laterally continuous. Banding within the unit, composed of organic-rich mudstone finely intercalated with the coccolith laminae, may relate to the seasonal nature of the blooms. In part due to the intermittent incorporation of organic-rich mudstone, we found that the TOC content of the stone band as a whole is enhanced (Fig. 3). Composite samples collected across the White Stone Band in the core yield TOC values of up to 15 wt%, while a complementary high-resolution study of the same interval by Pearson (S. Pearson, unpub. Ph.D. thesis, Univ. Southampton, 2000) proves that some layers contain TOC contents of up to 50 wt%. Similarly, high-resolution analysis of the White Stone Band at outcrop has returned TOC values as high as 57.2 wt% (Farrimond *et al.* 1994). Low siliciclastic input and bottom-water dysoxia most probably helped the rapid accumulation and subsequent preservation of the coccolith laminae (Gallois, 1976; Tyson, Wilson & Downie, 1979; Oschmann, 1988). The relatively high uranium content of the coccolith limestones supports the possibility of there being dysoxic bottom waters, as uranium is absorbed onto organic matter on stagnant seafloors (Bjørlykke, Dypvik & Finstad, 1975; Myers & Wignall, 1987). In Swanworth Quarry 1, uranium content of the White and Middle White Stone bands ranges between  $\sim 2\text{--}4$  ppm, and the section around the Freshwater Steps Stone Band measures about 4 ppm. Lower uranium contents of the less organic-rich mudstones indicate that oxygen levels were probably increased during their deposition.

## 10. Character and lateral extent of organic-rich mudstone intervals

Greyish-black–brownish-black mudstones characterize organic-rich intervals within the Kimmeridge Clay at the type section and in the Swanworth Quarry and Metherhills cores, matched by broad gamma-ray peaks and increased TOC content. The intervals are commonly millimetre-laminated, caused by variations in carbonate content relative to clay mineralogy and organic matter. The constituent faunal assemblages are relatively impoverished compared with other sections of the Kimmeridge Clay, although bivalves are commonly present (Wignall, 1990; Oschmann, 1991). Overall, spectral gamma-ray values for these intervals are the same or slightly higher than the mean of 110 gAPI for the formation as a whole (Fig. 3). The same is true for uranium content: organic-rich bands yield values higher than the background average of 2.4 ppm for Swanworth Quarry 1.

The Swanworth Quarry 1 and Metherhills cores record a broadly organic-rich interval spanning the *eudoxus* to *pectinatus* zones, with an average of 7–8 wt% TOC. Total organic carbon values from the *wheatleyensis* Zone reach 35 wt% (the Blackstone). In the overlying *pallasoides*–*fittoni* zones, values decline to an average of 1 wt%, reflecting a fall in sea level. Imprinted upon this long-term trend are smaller scale fluctuations in organic-carbon content. These fluctuations comprise intercalated cycles of mudstones that are enriched, and depleted, in TOC. On a broad level, our data show the presence of five main organic-rich intervals (TOC values commonly  $> 15$  wt%) in the Kimmeridge Clay in the type area. These horizons can be traced from Dorset to Yorkshire and into the North Sea (Gallois, 1979; Cox and Gallois, 1981; Herbin & Geysant, 1993; Herbin *et al.* 1993, 1995). Tyson (1996) linked these organic-rich intervals to maximum marine-flooding surfaces. Throughout the southern and eastern England outcrop and subcrop the organic-rich bands are persistent, except in the Devizes–Aylesbury area where the two highest bands are replaced by sands (Gallois, 1978). The bands occur within (1) the middle part of the *eudoxus* Zone, (2) the upper part of the *eudoxus* Zone, (3) the *elegans* and *scitulus* zones, (4) the upper part of the *wheatleyensis* Zone and lower part of the *hudlestoni* Zone, and (5) the upper part of the *hudlestoni* Zone and the lower part of the *pectinatus* Zone (Gallois, 1978). Correlation between the Kimmeridge Clay of Dorset and Yorkshire is also possible based on more minor variations in TOC (Herbin *et al.* 1995).

The middle part of the *eudoxus* Zone exposes an organic-rich band that is represented by Bed Groups 28–30 in the Metherhills core (Fig. 4). A broad increase in TOC contents (between 5 and 6 wt% TOC) tracks the progressive predominance of organic-rich mudstones across this interval. Total gamma-ray values peak during the initial stages of the TOC increase,



at about the level of the Swanworth B Stone Band. Interbedded between the organic-rich mudstones are relatively carbon-depleted sediments. These beds account for the high carbonate contents that are also associated with this interval (Fig. 4). The presence of the organic-rich interval within the upper *eudoxus* Zone is marked by brownish-black mudstones which yield increased total gamma-ray values paired with enhanced TOC contents (approx. 8 wt%). The *Nannocardioceras*-rich bands (Bed Group 32) exemplify this organic-rich band. At the top of the *elegans* Zone, a further organic-rich band is characterized by TOC values that record an average of ~7 wt%, paired with an increase in gamma-ray values (Bed Group 36; Figs 2, 3). The band is composed of medium- to dark-grey, to brownish-black, partly laminated shales, which occur between Blake's Bed 42 and the Yellow Ledge Stone Band (Figs 2, 3). Up to the level of the Grey Ledge Stone Band, the overlying medium- to dark-grey marl becomes somewhat depleted in organic-matter content. The marls are replaced by organic-rich mudstones that dominate the section across the *wheatleyensis*–*hudlestoni* zonal boundary (Bed Group 42). These organic-rich beds are well developed in Dorset, as recorded by the lithological section, gamma-ray and TOC profiles (Figs 2, 3). The average TOC content is particularly high (~10 wt%), and reaches a maximum of 35 wt% in the Blackstone. There is an accompanying increase in uranium content across this organic-rich interval, suggesting bottom-water dysoxia (Miller, 1990). The uppermost organic-rich band falls within the upper *hudlestoni*–lower *pectinatus* zones, and coincides with a series of coccolith limestones (Bed Groups 45–49) (Figs 2, 3). Further organic-rich beds occur within the uppermost part of the Kimmeridge Clay, but they are comparatively thin and depleted in carbon content. Blake's Bed 2, at the base of the *rotunda* Zone, is an example of such a unit (Bed 55/1). The bed is < 1 m and yields a narrow high amplitude peak in TOC content (9–10 wt%). Over the silty succession comprising the *rotunda* and *fittoni* zones, TOC contents yield an average of 1 wt% (Fig. 3). However, the general decline does show some variation, with thin, more organic-rich bands contained within the *Lingula* Shales, *Rhynchonella* Marls and Hounstout Clay (Fig. 3).

Superimposed upon the five, main organic-rich intervals (middle and upper *eudoxus* Zone, *elegans*–*scitulus* Zone, *wheatleyensis*–*hudlestoni* Zone, and *pectinatus* Zone), and also in other parts of the Kimmeridge Clay, are numerous thin (< 1 m) organic-rich horizons, some of which are parts of sedimentary cycles at the Milankovitch scale. The horizons correspond to high total gamma-ray values. The composition and character of such beds bears resemblance to the Blackstone: as well as being thin and highly organic-rich, they are distinct from mudstone beds above and below. In the lower part of the formation,

TOC values above 15 wt% constitute such organic-rich horizons (see Bed Groups 29 and 32 of the *eudoxus* zone; Fig. 4). In the beds above, where the succession is generally more organic-rich, there are TOC spikes with over 20 wt% (*autissiodorensis*–*pectinatus* zones). Note the TOC peaks at the level of the Yellow Ledge and White Stone bands (Fig. 3). The section that includes the Blackstone appears to contain a particularly high abundance of TOC spikes (Fig. 3). Where TOC values exceed 20 wt%, the hydrogen index is generally > 700 mgHC/gTOC (Huc *et al.* 1992).

The most readily recognizable of the organic-rich beds is the Blackstone. Within the bed, intervals of maximum organic-carbon enrichment have yielded TOC values as varied as 35% (Oschmann, 1988; this study), 50% and greater (R. V. Tyson, unpub. Ph.D. thesis, Open Univ., 1985; Myers & Wignall, 1987; A. L. Coe, unpub. D.Phil. thesis, Univ. Oxford, 1992; Sælen *et al.* 2000), 57% (Tyson, 1989), and 63% (Van Kaam-Peters *et al.* 1998). Relative carbon enrichment at the top of the *wheatleyensis* Zone can also be recognized in boreholes in Yorkshire, in the area of the Wash, and in the North Sea (Gallois & Cox, 1974; Gallois, 1978; Herbin *et al.* 1993, 1995). Correlation of this interval with the Boulonnais in France is uncertain. Better developed in the Boulonnais is a series of organic-rich mudstones that compose the Argiles de Châtillon, within the *autissiodorensis*–*elegans* zones (Herbin *et al.* 1993, 1995; Tribovillard *et al.* 2001). This succession is the likely stratigraphic equivalent of the two levels of organic enrichment in Dorset, that within the upper *eudoxus*–*autissiodorensis* zones and that within the *elegans* Zone (Herbin *et al.* 1995). Organic-rich deposits of the upper *eudoxus*–basal *autissiodorensis* Zone are also present in southern England and north of the London Platform (Gallois & Cox, 1974; Gallois, 1978; Wignall & Hallam, 1991).

## 11. Isotope stratigraphy

A  $\delta^{13}\text{C}_{\text{org}}$  record through the Kimmeridge Clay of the Swanworth Quarry 1 and Metherhills boreholes is given in Figure 6. In the *cymodoce* to mid-*eudoxus* zone interval there is a progressive decline from approximately –26‰ to –28‰, corresponding with a gradual increase in the mean TOC. This is followed by a distinct positive step up to –26‰ (followed by a peak of –22.4‰) in the mid-*eudoxus* Zone. There is also a fundamental change in the nature of the isotopic curve at this level; below  $\delta^{13}\text{C}_{\text{org}}$  values show limited (< 2‰) variation about the mean trend, whereas above (up to the *pallasioides* Zone) the curve is much more serrated with values commonly showing a 2–4‰ difference from the mean trend (mainly positive deviations). Allowing for this greater variability, between the mid-*eudoxus* and lower *scitulus* zones there is an increase in mean values from –26‰ to –24‰, followed by an overall downward drift in the baseline values to the

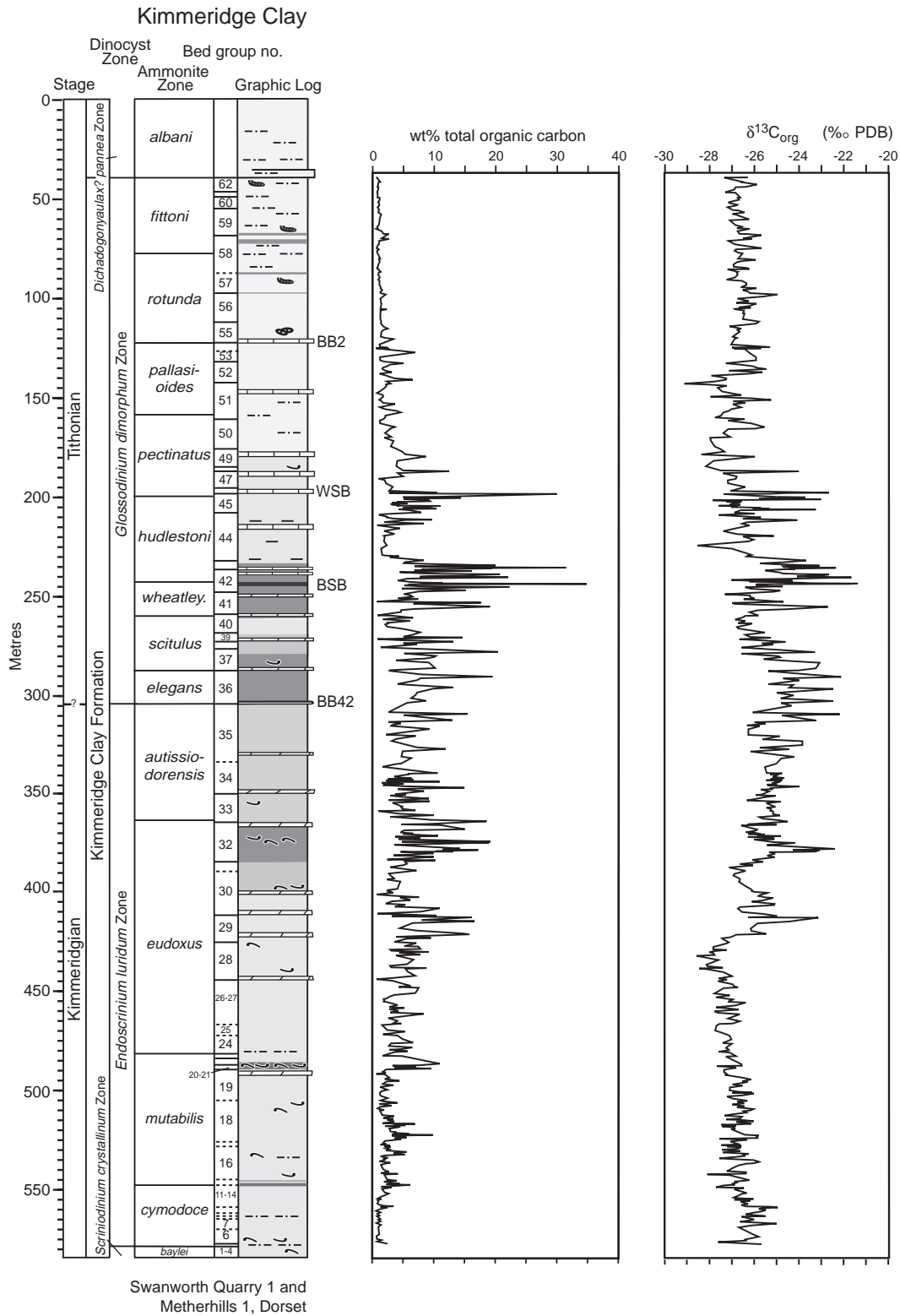


Figure 6. A composite  $\delta^{13}\text{C}_{\text{org}}$  record through the Kimmeridge Clay of the Swanworth Quarry 1 and Metherhills boreholes. The data indicate a small declining trend in  $\delta^{13}\text{C}_{\text{org}}$  values from the *cymodoce* Zone to the mid-*eudoxus* Zone where there is a positive shift. From the mid-*eudoxus* interval upwards,  $\delta^{13}\text{C}_{\text{org}}$  values are higher and more variable, as are the values of total organic carbon. In the *rotunda* and *fittoni* zones the values are lower and much less variable. Stone bands indicated: BB42, Blake's Bed 42; BSB, Blackstone Band; WSB, White Stone Band; BB2, Blake's Bed 2. The composite total organic carbon data set has been simplified from those curves shown in Figures 3 and 4, and only plots a value for every corresponding point of  $\delta^{13}\text{C}_{\text{org}}$ . Dinocyst zones after Riding & Thomas (1988), and ammonite zones after Cope (1967, 1978) and Cope *et al.* (1980). Bed group numbers from this study. All  $\delta^{13}\text{C}_{\text{org}}$  values are reported with respect to the PDB standard.

mid-*pectinatus* Zone (including a distinct negative shift to  $-27\%$  through Bed Groups 37 to 40). Within this trend there are conspicuous peaks in  $\delta^{13}\text{C}_{\text{org}}$  values that correspond to the TOC peaks centred around the Blackstone and White Stone bands. Between the mid-*pectinatus* and *pallasioides* zones there is an overall positive shift in mean values of around  $1\%$ , followed by rather stable values in the remainder of the section, where TOC values are also at their most uniform.

The mid-*eudoxus* Zone shift is also registered in pelagic-hemipelagic carbonates from the Helvetic Nappes of eastern Switzerland, considered as part of the northern continental margin of Tethys (Weissert & Mohr, 1996), and is clearly a regional event of potential use for correlation. Because of the widespread nature of this event, it cannot be interpreted as related only to local palaeoceanographic conditions, such as increases in productivity in the watermasses in and around the Late Jurassic Wessex Basin. This positive shift must reflect the overall isotopic composition of dissolved inorganic carbon in European (?global) Kimmeridgian seawater. Consequently, it is most simply interpreted as the regional isotopic response to increases in organic-carbon burial in north European Kimmeridge Clay Basins, beginning in the mid-*eudoxus* Zone and clearly reflected in the organic-carbon profile (Fig. 6). Whether or not the other younger carbon-isotope excursions similarly reflect the overall isotopic composition of dissolved inorganic carbon in Kimmeridgian-Tithonian seawater or high productivity of phytoplankton and local enrichment of a near-surface watermass in  $\delta^{13}\text{C}$  (cf. Berger & Vincent, 1986), or indeed either of these palaeoceanographic effects, is not established, although the former interpretation has the virtue of simplicity. Sælen *et al.* (2000) favour productivity variations of the phytoplankton, accompanied by a change between calcareous and organic-walled species, as a first-order control on both  $\delta^{13}\text{C}_{\text{org}}$  and TOC. Possible complicating factors include changes in the levels of dissolved  $\text{CO}_2$  in the ocean and post-burial bacterial reworking of the organic matter, which may also affect  $\delta^{13}\text{C}_{\text{org}}$  values of carbon-rich deposits (e.g. Kenig *et al.* 1994). Additional factors devolve from the fact that detailed organic geochemical studies show that the  $\delta^{13}\text{C}_{\text{org}}$  record of the Kimmeridge Clay may be complicated by the change in relative abundance through the section of different compounds constituting the marine organic matter (Van Kaam-Peters *et al.* 1998; Sinninghe Damsté *et al.* 1998). Additional high-resolution carbon-isotope stratigraphy through coeval carbonate sequences will establish the regional significance or otherwise of these Kimmeridgian-Tithonian chemostratigraphic trends in  $\delta^{13}\text{C}$  values.

## 12. Cycles within the Kimmeridge Clay

Cycles are present on a number of scales within the Kimmeridge Clay. Long-term trends in the TOC data

set indicate broad organic-rich intervals spanning the *cymodoce* to *pectinatus* zones. Superimposed upon this trend are two smaller orders of cyclicity: medium-order cycles on a decimetre scale, and small-order cycles on a 0.5–2 m scale. Both sets of cycles can be easily recognized at the type section, where weathering enhances mineralogical differences between the organic-rich and organic-poor bands. The cycles are also present in the Swanworth Quarry and Metherhills cores, but over these comparatively fresh surfaces they tend to be more difficult to distinguish visually. Cyclic lithological changes in the succession comprising Swanworth Quarry 1 (Weedon *et al.* 1999) compare well with those previously identified at the type section (e.g. House, 1985; Waterhouse, 1999). The metre- and decimetre-scale cycles have been related to climatically controlled variations in sedimentary conditions in studies which have used data sets as varied as organic geochemistry (Huc *et al.* 1992), clay mineralogy (Wignall & Ruffell, 1990), macro-faunal variations (Oschmann, 1988), palaeontology and palynology (Tyson, 1989; Waterhouse, 1995, 1999).

The data collected downhole during drilling of boreholes for this project have provided further opportunity to examine the temporal resolution of the cycles. Spectral analysis of gamma-ray, TOC, carbonate, and photoelectric-factor data has revealed the predominance of the obliquity cycle during the *autisiodorensis* and *elegans* zones (Weedon *et al.* 1999, 2000), agreeing with the results of previous studies (e.g. House, 1985; Waterhouse, 1999). Within the same interval, tuning to the 38 kyr orbital-obliquity cycle elucidated intervals of small-amplitude 19 kyr precession cycles. However, there is no evidence for the 100 or 400 kyr eccentricity cycle (Weedon *et al.* 1999, 2000). Analysis of the relevant data sets proves that cycles may be present throughout the Kimmeridge Clay irrespective of whether the lithological succession records their presence; the cyclicity apparent within some of the geophysical and analytical data sets is not obvious until a spectral analysis is performed. These results support previous conclusions that the cycles represent climatically controlled variations in sedimentary conditions.

Precisely how orbital obliquity drove climatic change, which in turn influenced productivity and oxygenation, is not well understood (Gallois, 1976; Tyson, Wilson & Downie, 1979; see also discussion in Wignall & Hallam, 1991). Nevertheless, in a general sense, times of maximum orbital obliquity are correlated with periods of heightened marine productivity and/or preservation of organic matter (Waterhouse, 1999). Evidence for variations in productivity is demonstrated by elements of the organic matter. In phase with the lithological cycles are temporal variations in, for example, equidimensional sharp and lath-shaped black wood, brown wood, degraded palynomorphs, and total particle abundance (Waterhouse, 1995).

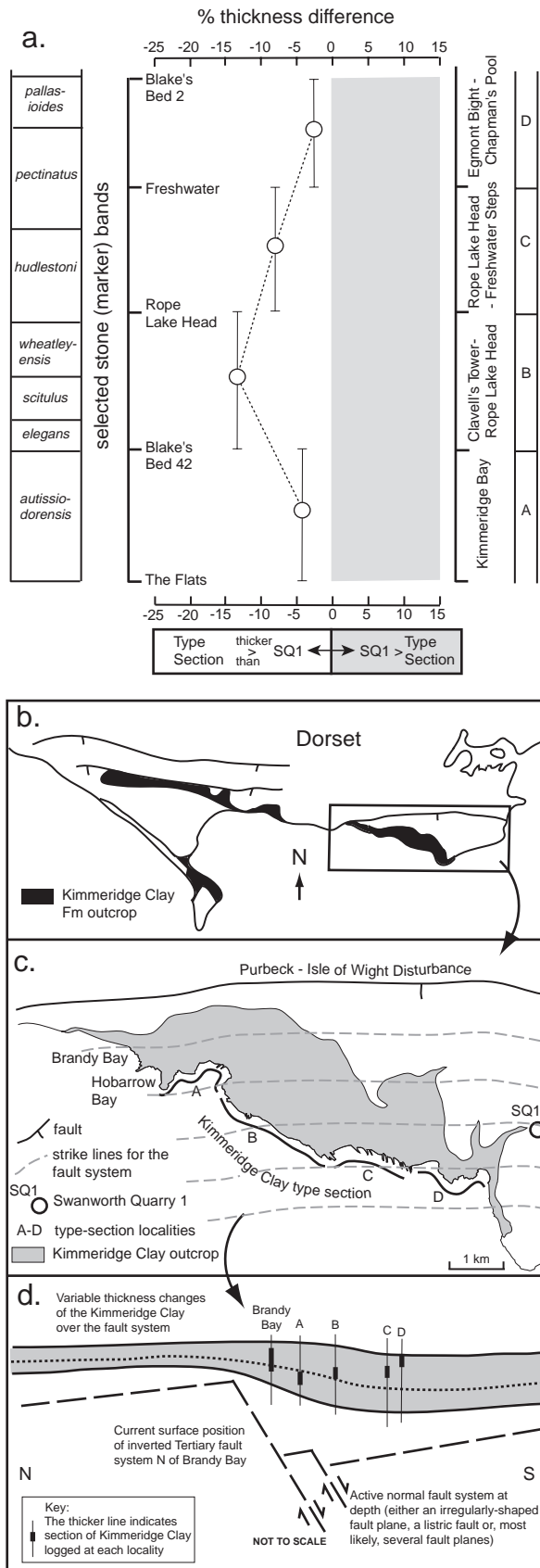


Figure 7. Thickness difference between Blake's Bed 2 and The Flats Stone Band in the Kimmeridge Clay type-section and Swanworth Quarry 1 borehole (SQ1). This interval is 264 m thick along the coastal section in comparison to 243 m downhole at SQ1. The section was divided into four equal

Chorate and proximate dinoflagellate cysts also display a mostly smooth cyclicity corresponding to the lithological cyclicity. Periods of high obliquity are understood to correspond to increased seasonality, a lower pole–equator insolation gradient, and therefore less intense atmospheric and marine currents, reducing bottom-water oxygenation and in turn enhancing the preservation of organic matter (e.g. Imbrie, 1985; Fischer, 1986; Waterhouse, 1999). Variations in preservation potential, perhaps through fluctuations in bottom-water oxygenation with time, could account for some of the organic-rich and organic-poor cycles we see today. However, variations in freshwater input, degree of storminess, and seasonal overturn, as dictated by orbital-climate controls, could have all affected productivity via nutrient supply. If we take seasonal overturning by way of example, it has the potential to enhance productivity through increased nutrient supply to the surface, triggering anoxic conditions in the deeper water layers beneath the upwelling (e.g. Gallois, 1976; Tyson, Wilson & Downie, 1979; Demaison & Moore, 1980; R. V. Tyson, unpub. Ph.D. thesis, Open. Univ., 1985; Tyson & Pearson, 1991; Sælen *et al.* 2000). Independent modelling studies (Parrish & Curtis, 1982; Scotese & Summerhayes, 1986; Miller, 1990; Ross, Moore, Hayashida, 1992;

parts using stone bands and an organic-rich bed (Blake's Bed 2) which (1) were more-or-less equally spaced stratigraphically, and (2) could be unequivocally identified in both the type section and the SQ1 data sets. Next, the amount of strata between each stone band was measured. (a) shows a comparison of the stratal thickness between the selected stone bands, for the type section and the SQ1 core. The Metherhills borehole is not included in this comparison, because the strata it comprises are not well exposed in the type area. To the right of the plot are shown the coastal localities (labelled A–D) where the type section was recorded. Zero on the x-axis represents no thickness difference between the core and type section. Comparison between the two successions shows that the type section is thicker than the core, with the greatest difference being in the interval between the Rope Lake Head Stone Band and Blake's Bed 42. (b) is a general map of the Dorset coast, showing the area under study (boxed). (c) is a detailed map of the coastal section, showing the position of the successive localities (A–D) measured to produce the graphic log in Figure 2. The location of the SQ1 borehole is also shown, together with the position of the Purbeck–Isle of Wight Disturbance, and the inferred position of strike lines pertaining to the fault. Sketch strike lines are shown for the fault system, giving an indication of how each part of the section relates to the system. Note that there must be an element of stratal thinning from west to east, as evidenced by comparison of the strata at locality B with the equivalent at SQ1. (d) shows a proposed explanation for the thickness changes in the Kimmeridge Clay Formation between the type section and the SQ1 borehole. The position of the section exposed at Brandy Bay is also shown, which is much thinner than coeval beds at the type section. The thicker parts of the vertical lines below A–D indicate approximately the part of the Kimmeridge Clay exposed at each locality.



Price, Sellwood, Valdes, 1995) have suggested the presence of seasonally persistent low pressure over the region during winter months; low pressure could have created relatively turbulent conditions, raising nutrients and causing high productivity. Summer high pressure might have led to the development of more stable watermass conditions and possibly induced thermohaline stratification, depleting surface-water nutrients and hence lowering productivity.

### 13. Discussion of thickness differences

In this section we discuss how the Kimmeridge Clay recovered by the boreholes differs in thickness from that examined at the type section and used as the standard stratigraphy. The *Nannocardioceras*-rich bands to Rotunda Nodules section exposed at the type section is compared with coeval beds established by the Swanworth Quarry boreholes.

Thickness changes between localities bearing coeval strata are commonplace in the Wessex Basin and are mostly attributed to syn-sedimentary faulting and/or erosion, particularly of uplifted footwall fault-blocks. Several episodes of extensional tectonics took place in the Wessex Basin from Permian to Cretaceous times, characterized by rapid subsidence of fault-bounded basins and frequent erosion of adjacent upfaulted blocks (Chadwick, 1986). The influence of such intra-Jurassic faulting in the basin has been documented by Chadwick (1986) and Jenkyns & Senior (1991) and constrained to two main phases, the Hettangian-Bajocian and latest Oxfordian onwards, related to early rifting phases in the Central and North Atlantic respectively. The later phase has been further substantiated by Newell (2000), who recognized successive stages of sedimentation related to the progressive breakdown of a ramp system present during activation of major normal faults in the Wessex Basin. Jenkyns & Senior (1991) collated evidence from two main sources in their study of the fault zones and their influence on sedimentation: neptunian dykes and sills, and changes in stratigraphic thickness. Strata of Kimmeridgian age show a pronounced change in thickness across the Purbeck–Isle of Wight Disturbance. In the Ringstead Bay area the formation (~180 m) is considerably reduced in thickness relative to the section at the type locality (~500 m: Arkell, 1947, pp. 71–3; Cope *et al.* 1980; Cox & Gallois, 1981; Jenkyns & Senior, 1991). The position of the Ringstead Bay section on the relatively uplifted footwall block explains the contrasting thickness of these sections.

As Figure 7a shows, the type section is generally thicker than the core, with the greatest difference (14.3%) in the middle part of the succession, between Blake's Bed 42 and the Rope Lake Head Stone Band. To the right of Figure 7a are shown the coastal localities (labelled A–D) where the type section was

recorded in the form of a graphic log. Because the beds dip south and east, the graphic log was measured in stages from the western side of Kimmeridge Bay in the north, to Egmont Bight and Chapman's Pool in the south (Fig. 7c). As Figure 7c,d shows, localities A to D present a progressively greater horizontal distance from the Purbeck–Isle of Wight Disturbance, which is situated to the north of the Kimmeridge Clay outcrop. The sketch strike lines for the major orientation of the fault system show that, in general terms, the Swanworth Quarry 1 borehole is a similar distance from the fault as coastal localities B–C. The relative position of Brandy Bay is shown on Figure 7d, which reveals a section of 162 m between the Washing Ledge and Freshwater Steps stone bands (Cox & Gallois, 1981). The equivalent section is 171 m at Swanworth Quarry and 191 m at the type section. The Brandy Bay section is interpreted to be thinner because it is relatively close to the fault. Although the equivalent section cannot be precisely measured at Ringstead Bay because the Washing Ledge Stone Band is not exposed, it is clear that the succession is much reduced in thickness and amounts to approximately 47 m of strata (Cox & Gallois, 1981).

Thickness changes apparent in the Kimmeridge Clay on the hanging wall of the Purbeck–Isle of Wight Disturbance demonstrate that the strata are not just simply thicker on the hanging wall compared to the footwall, but that there is also a systematic change in thickness across the hanging wall. Near the fault (Brandy Bay) the Kimmeridge Clay is comparatively thin, progressively thickening (interval A, Fig. 7) to reach a maximum some 3 km from the modern-day surface expression of the fault (interval B). With greater distance from the fault (intervals C and D), the strata thin again, as shown in Figure 7d. These geometries may be interpreted as due to syn-sedimentary differential compaction over the deep-seated Purbeck Fault (e.g. Harvey & Stewart, 1998) or, alternatively, related to the shape of the fault plane or the occurrence of further small-scale syn-sedimentary fault planes.

### 14. Summary

(1) Together, the cores drilled at Swanworth Quarry and Metherhills yield a complete section through the entire Kimmeridge Clay. A stratigraphic framework has been produced for the cores, which serves as a precise means for organizing the numerous geophysical and analytical data sets that have been generated by the project, and enables accurate correlation with the type section and Kimmeridge Clay exposures elsewhere.

(2) The Metherhills core recovers the lower part of the formation which is poorly exposed at outcrop in Dorset.

(3) A positive mid-*eudoxus* Zone  $\delta^{13}\text{C}_{\text{org}}$  shift is interpreted as the isotopic response to increases in

organic-carbon burial in the north European Kimmeridge Clay basin. It is a regional event of potential use for correlation.

(4) A high-resolution comparison of the type section with the equivalent Swanworth Quarry 1 beds proves that the exposure is more expanded, especially between Blake's Bed 42 and the Rope Lake Head Stone Band, probably due to its relative proximity to the syn-sedimentary Purbeck–Isle of Wight Disturbance.

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