THE STRATIGRAPHY OF THE KIMMERIDGE CLAY FORMATION (JURASSIC) OF THE ISLE OF PORTLAND, DORSET, UK

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A proposed gas-storage site at the former Upper Osprey Ministry of Defence site on the north east coast of the Isle of Portland is underlain by landslide debris and man-made deposits that wholly conceal an outcrop of Kimmeridge Clay Formation. Historical accounts of major landslides in the 17th to 19th centuries have been interpreted as evidence of deep-seated failure surfaces in the Kimmeridge Clay. A pattern of continuously cored boreholes, mostly 25 m to 100 m deep, was drilled to determine the stratigraphy and structure of the area beneath and adjacent to the proposed installations. Comparison of the succession proved in the boreholes with that exposed at the type succession of the formation in the cliffs at and adjacent to Kimmeridge Bay enabled numerous laterally persistent lithological marker beds to be identified. These were used in combination with total-gamma-ray logs to show that the successions proved in the borehole cores could be correlated with one another with a stratigraphical accuracy of ± 0.2 m or better. Taken together, the borehole and geophysical data showed that the Kimmeridge Clay dips steadily SSW at *c.* 02° beneath the site and the adjacent areas. No tectonic folding or faulting was detected, nor any significant disturbance within the rock mass that could be attributed to a deep-seated landslide. A subsequent multibeam sonar survey of Portland Bay, made for reasons unrelated to the gas-storage site, confirmed the uniform low SSW dip in the Kimmeridge Clay in the offshore area adjacent to the Upper Osprey site.

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INTRODUCTION

The site for a proposed facility to store gas in artificially created caverns in Triassic salt up to 2.5 km below the Isle of Portland is on land formerly occupied by the Ministry of Defence (MoD) under the name Upper Osprey (Figure 1) on the north east part of the Isle of Portland. The site, an area of *c.* 150 x 550 m, lies on undulating disturbed ground that slopes down from the foot of a prominent Portland Stone escarpment to the sea. It is underlain by landslide material, quarry waste and man-made deposits to depths of up to 20 m, that rest on Kimmeridge Clay Formation mudstones. Portland Borehole 1/1A, drilled in 2006 to prove the Triassic and Jurassic succession beneath the site, proved Kimmeridge Clay to a depth of 268 m underlain by 1619 m of older Jurassic rocks (Marshall *et al.*, 2007).

There are historical descriptions of up to 40 large-scale landslides on the island in the 17th to 19th centuries, some of which collectively covered the whole of the proposed gas-storage site and large parts of the adjacent areas (Damon, 1884; Hutchins, 1863). They were triggered by a combination of an accumulation of tipped stone waste and wet weather. However, there are no published quantitative data (such as measured sections) that would enable the positions of the failure surfaces to be determined. Several landslides were recorded during the MoD period of occupation (1864-1996), but these were shallow-seated and caused little damage. More recent research has suggested that some of the earlier landslides were failures in the Kimmeridge Clay Formation, and that others involved a process of ductile spreading at depth within the formation (Brunsden *et al.*, 1996).

The Kimmeridge Clay Formation is poorly exposed on the Isle of Portland where the outcrop is almost wholly overlain by drift deposits derived from the overlying Portland Beds Group. The base of the formation crops out in a low cliff at Wyke Regis [SY 671 770], about 4 km NW of the site, and the Blackstone, an organic-rich bed in the upper part of the formation, was dug for fuel in the intertidal area about 1 km NW of the Upper Osprey site prior to the construction of the Portland Harbour breakwater in 1864 (Arkell, 1947). The youngest Kimmeridgian strata recorded at outcrop on the island, NW of the site at Castletown (Salfeld, 1914) and at beach level 1 km S of the site at Grove Point (Gallois and Etches, 2001), contain ammonites indicative of the *Pavlovia* zones.

In contrast to the poor exposures on the island, the full thickness of the Kimmeridge Clay Formation is exposed in cliffs in the Osmington Mills and Kimmeridge areas (Figure 1) where the stratigraphy is well documented (Arkell, 1947; Cox and Gallois, 1981). In addition, large parts of the succession were continuously cored in boreholes drilled to explore the oil-shale potential of the formation at Encombe [SY 9446 7785] and Portesham [SY 6105 8545] (Gallois, 1979), and in research boreholes drilled for a climate-change research project at Swanworth Quarry [SY 9675 7823] and Metherhills [SY 9112 7911] 5] (Gallois, 2000).

A total of 51 continuously cored boreholes were drilled within and adjacent to the Upper Osprey site over an area of 600 x 700 m, including the adjacent offshore area, to determine the shallow and deep-seated geological structure (Figure 2). Nine were to depths of 50 to 100 m (LC Series) to determine the Kimmeridge Clay Formation succession: these were geophysically logged. The remaining 42 boreholes (FRC, LSR

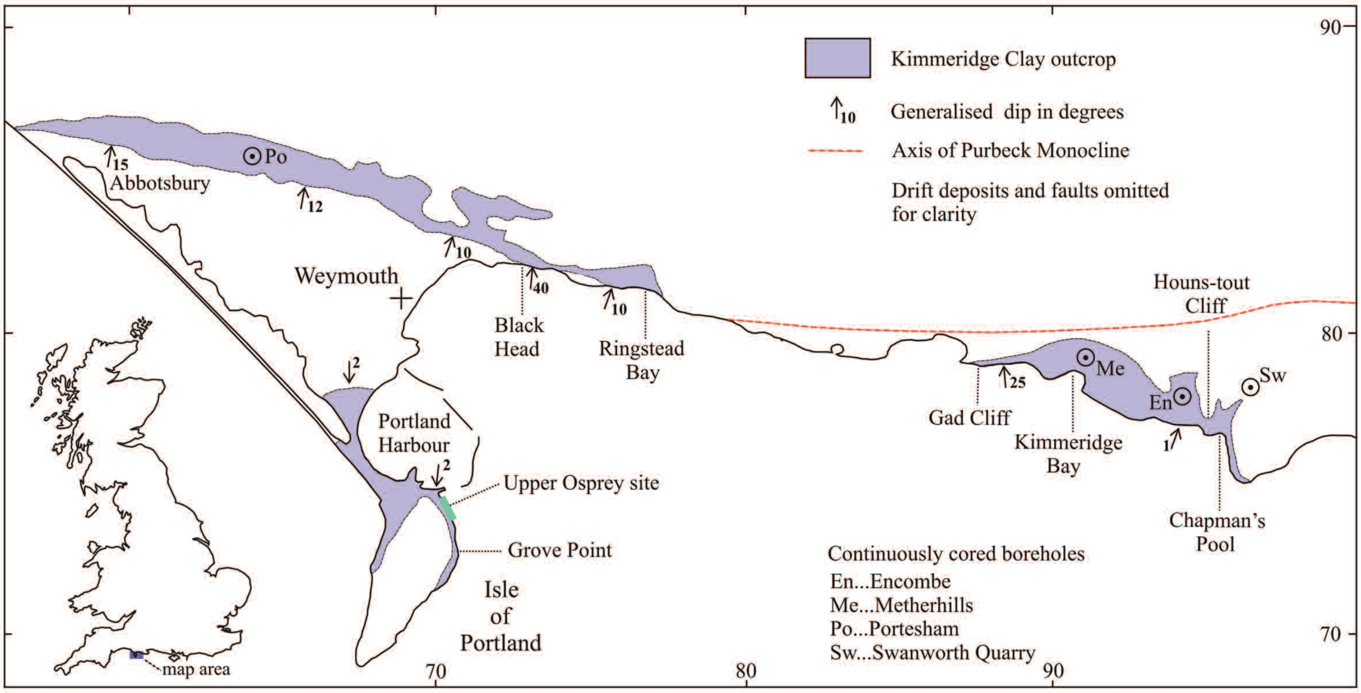

Figure 1. *Geological sketch map of the Kimmeridge Clay Formation outcrop in south Dorset showing the position of the Upper Osprey site and localities referred to in the text.*

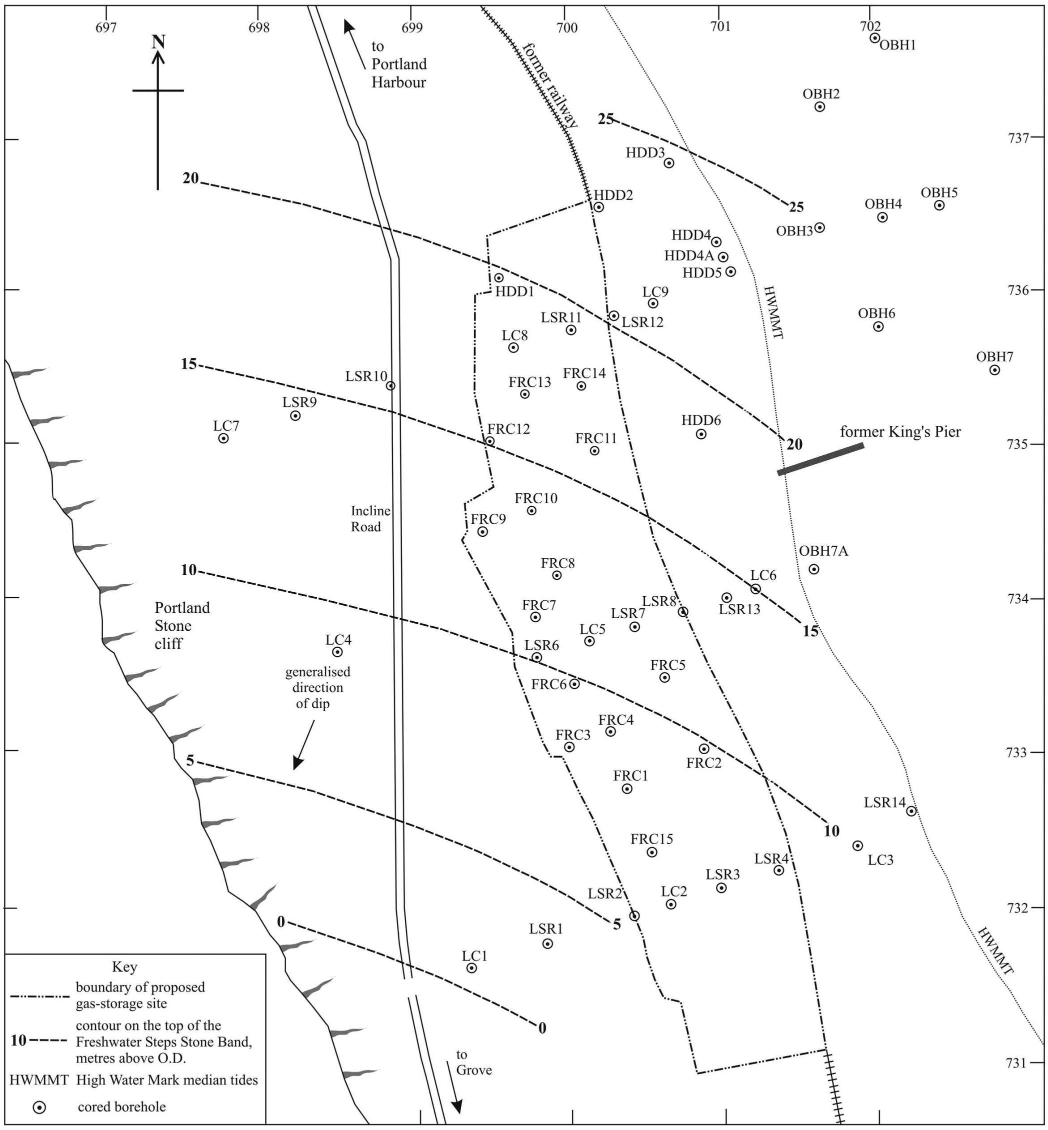

Figure 2. *Sketch map showing the locations of the proposed gas-storage facility at the Upper Osprey site, the positions of the site-investigation boreholes, and the geological structure (see text for details).*

and OBH series) were drilled to depths of 5 to 26 m to determine the geological succession and structure that would underlie the gas- and brine-pipeline routes, and the gas-injection and processing plants. The present account describes the geological succession proved in the Kimmeridge Clay Formation beneath the site, and its correlation with the type succession on the Dorset coast.

Geological succession

The palaeontology and sedimentology of the bulk of the Kimmeridge Clay Formation proved at outcrop and in boreholes in England are indicative of deposition in fully marine environments on a continental shelf in relatively shallow water (mostly 50 m to 150 m deep) below storm-wave base. Sea-bed conditions varied from oxygenated, when shelly calcareous mudstones were deposited, to dysaerobic when organic-rich sediments (bituminous mudstones and oil shales) were deposited (Raiswell *et al.*, 2001). At outcrop the mudstones that comprise >95% of the succession weather rapidly to clay with the result that there are few natural inland exposures. However, the importance of the formation as a natural oil-source rock and the possible use of the oil shales as a fuel, has resulted in numerous academic and commercial research projects. The full thickness of the formation has been proved in numerous hydrocarbon-exploration boreholes (for which there are suites of geophysical logs) in England, and in a smaller number of continuously cored boreholes drilled for research purposes.

The components of the mudstones can be divided into three genetic groups, clastic (clay minerals, quartz and re-worked biogenic material), biogenic (calcareous and phosphatised fossils, principally ammonites, bivalves and foraminifera) and chemogenic (diagenetically formed calcium and magnesium carbonate concretions and cements, pyrite and phosphate). Using the parameters of colour, texture, grain size and shell content, a wide range of lithologies can be recognised at outcrop and in borehole cores in the formation. These have been used in combination with the biostratigraphy and the geophysical-log signatures to divide the formation into 63 chronostratigraphical units that can be recognised throughout the English onshore outcrop and subcrop (Taylor *et al.*, 2001). Many of the smaller fossils, mostly bivalves (Figures 3d and 3e), are well preserved and indicate that much of the sedimentation occurred below storm-wave base.

Ammonites are common throughout much of the Kimmeridge Clay Formation where they form the basis of the zonal scheme. The diameters of mature specimens of those

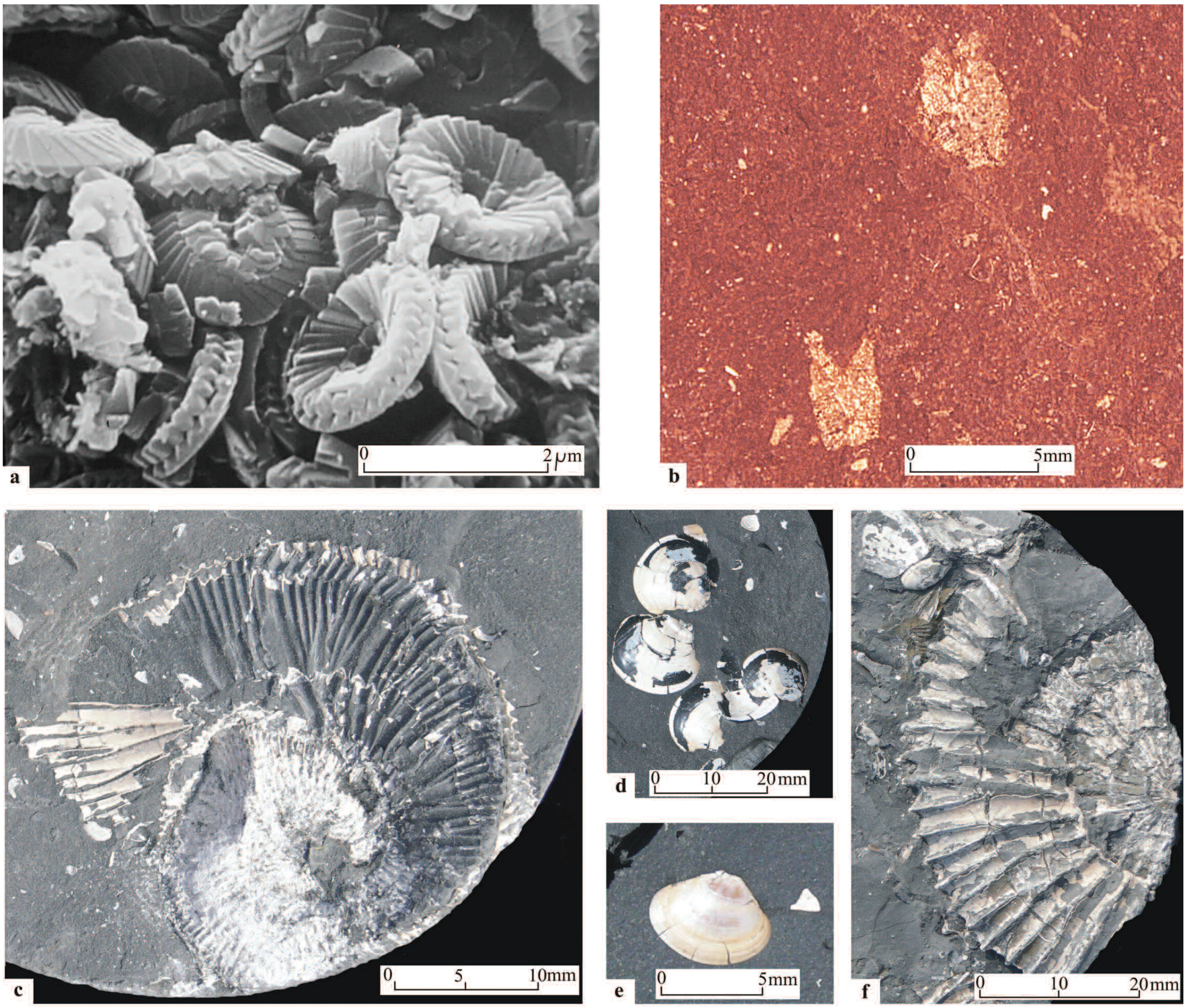

Figure 3. ***(a)*** *Electron micrograph of disaggregated plates of the coccolith* Watzsnaueria fossacincta *(Black), White Stone Band, Kimmeridge Cliffs.* ***(b)*** *Calyx plates of the microcrinoid* Saccocoma tenella *(Goldfuss), Blackstone, Kimmeridge Cliffs.* ***(c)*** Pectinatities (Virgatosphinctoides) *sp. Borehole LC 7, 26.25 m depth.* ***(d)*** *Paired valves of* Protocardia morinica *(de Loriol), Borehole LC 7, 36.50 m depth.* ***(e)*** Tellina *with traces of colour banding, Borehole LC 7, 54.50 m depth.* ***(f)*** Pavlovia *sp., Borehole LC 7, 12 90 m depth.*

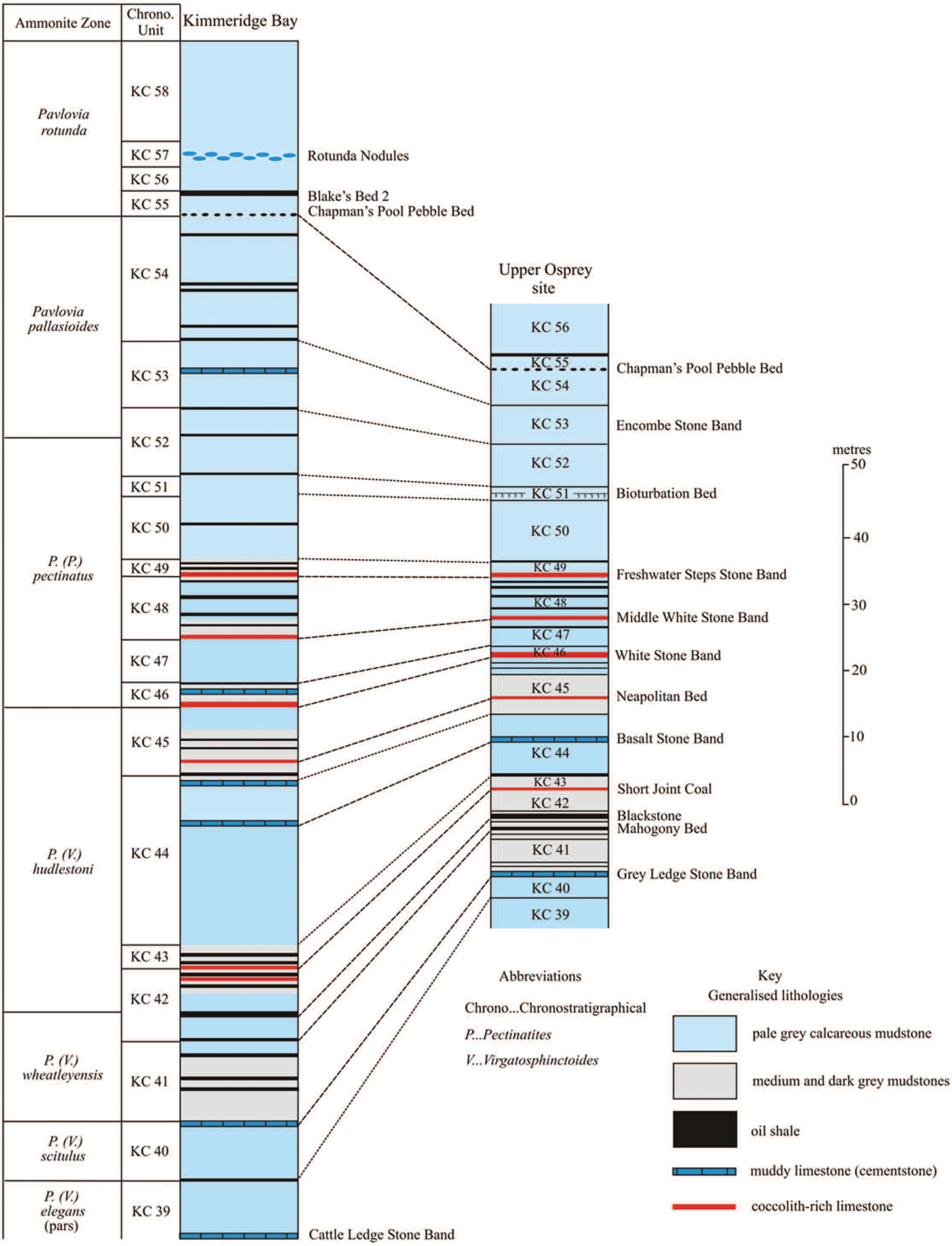

Figure 4. *Summary of the Kimmeridge Clay succession (chronostratigraphical units KC 39 to KC 56) exposed in the cliffs between Kimmeridge Bay and Chapman's Pool showing the principal named marker beds and the correlation with the succession recorded at the Upper Osprey site.*

present in the strata recorded beneath the Upper Osprey site, species of *Pectinatities* and *Pavlovia* (Figure 3c and 3f), are mostly as large as, or larger than the 80 to 100 mm diameter of the borehole cores. Too few ammonites were sufficiently complete or well preserved in the borehole cores to be specifically identifiable and useful for correlation between the boreholes (Figures 3c and 3f). However, several of the named lithological marker beds that are prominent in Kimmeridge Cliffs, beds of argillaceous limestone, coccolith-rich limestone and oil shale, were present in the borehole cores (Figure 4). Taken together, the lithological variations proved in the borehole cores gave rise to characteristic geophysical-log signatures that confirmed and enhanced the correlations made between the lithological marker beds.

Calcareous 'stone bands'

Tabular beds of recrystallised argillaceous micrite ('cementstones') up to 0.3 m thick with dense calcite, dolomite and ferroan dolomite cements crop out as extensive ledges in the intertidal area in Kimmeridge Bay where they are referred to as 'stone bands'. The more prominent beds have local names that were adopted by the earliest geologists (Arkell, 1947). All except two of these stone bands formed by early diagenesis in beds of calcareous mudstone. The majority of those exposed in Kimmeridge Cliffs are laterally persistent over distances of tens of kilometres. Two of them, the Grey Ledge and Basalt stone bands, were present in the Upper Osprey boreholes. Two others, the Rope Lake Head Stone Band and the Encombe Stone Band, which are laterally impersistent in the Kimmeridge area, were not recorded at the Upper Osprey site.

Coccolith-rich limestones

The Kimmeridge Clay Formation contains numerous beds that are almost wholly composed of a single species of coccolith (Figure 3a) that range from individual laminae <1 mm thick, to groups of laminae that form distinctive beds of white limestone up to 0.6 m thick. The laminae were deposited from blooms of sub-microscopic, calcareous algae that covered thousands of square kilometres (Pearson *et al.*, 2004) in which individual laminae <1 mm thick were the products of ten or more annual blooms (Lees *et al.*, 2004). Many of the thicker beds have been recognised throughout the outcrop and subcrop of the Kimmeridge Clay Formation in England (Gallois and Medd, 1979). The three most distinctive coccolith-rich beds in Kimmeridge Cliffs are, in descending stratigraphical order, the Freshwater Steps, Middle White and White Stone Bands. All three were present in all the LC Series boreholes and at least one of these beds was present in many of the other boreholes. They show little lithological variation over large areas, and their stratigraphical spacing beneath the Upper Osprey site remained constant. For example, individual laminae in the Freshwater Steps Stone Band can be correlated between boreholes throughout the site, and the pattern of sedimentation within the bed can be matched with that at outcrop at Freshwater Steps, 23 km away (Figure 5).

Oil shales

Several hundred beds of oil shale (mostly 0.02 to 0.2 m thick) are present in the Kimmeridge Clay Formation in Dorset. These also formed largely from pelagic algae (dinoflagellates) and give rise to beds that are laterally persistent over large areas. Few of these beds can be distinguished from one another, although the stratigraphical spacings between groups of oil-shale beds can be used locally for correlation purposes. The most notable exception is the 0.6 m-thick Blackstone of Kimmeridge Cliffs that has the highest recorded total-organic-carbon content (TOC > 50 wt %) of any British Mesozoic rock. In addition, it is the only bed in the Upper Kimmeridge Clay that contains abundant pyritised calyx plates of the microscopic free-swimming crinoid *Saccocoma* (Figure 3b). This has

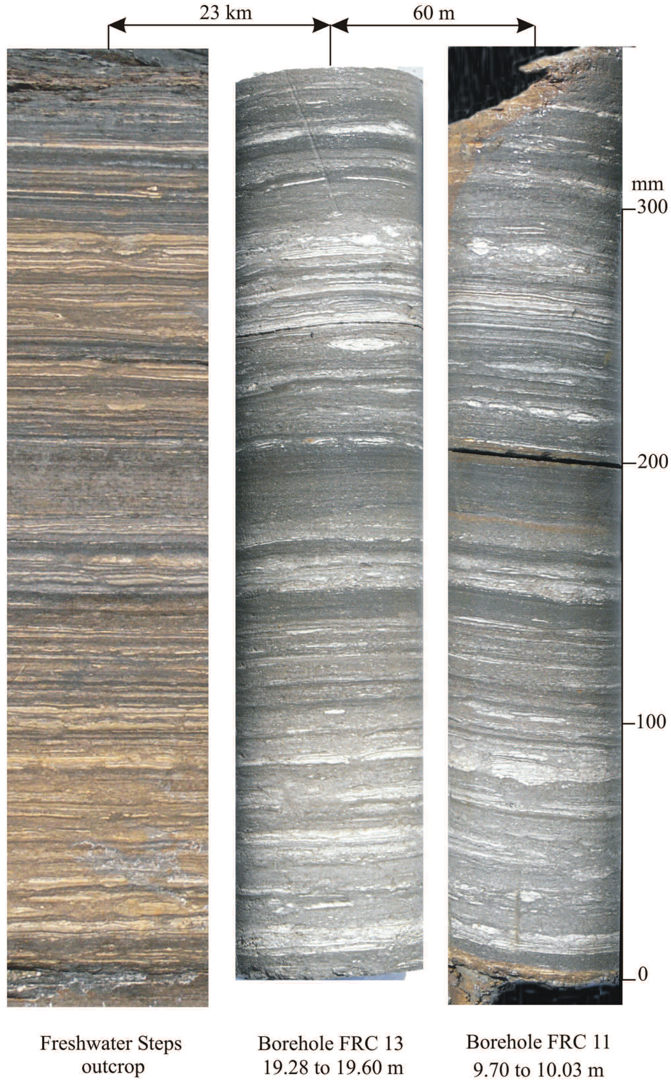

Figure 5. *Comparison of selected sections through the Freshwater Steps Stone Band; finely interlaminated coccolith-rich (white) and organic-rich (brown) laminae represent seasonal algal blooms that occurred over tens of thousands of square kilometres. Disturbances in the lamination were mostly caused by small sediment-feeding crustaceans.*

enabled the Blackstone to be recognised in borehole cores throughout the English outcrop and subcrop. The high TOCs of the richest oil shales give rise to lithologically distinctive low-density rocks with a polished mahogany-like sheen when cored. Two of these, which are prominent in Kimmeridge Cliffs but which are un-named there, were given names (Mahogany and Neapolitan bands) for convenience of reference in the site-investigation. The only marker bed recorded in the boreholes that had not previously been identified in Kimmeridge Cliffs is an erosion surface in KC 51 that is underlain by a network of burrows picked out by infillings of pale grey siltstone. The correlative of this bed in the cliffs is probably a pale grey mudstone that contains three horizons of calcareous burrowfill concretions. Comparison of the spacings between the marker beds in the cliffs and in the boreholes suggests that the erosion surface has removed less than 1 m of sediment.

Geophysical logging

A suite of geophysical logs, including caliper, total gamma ray, formation density and neutron porosity, was run in the nine LC Series boreholes. The most useful of these for correlation purposes in the Kimmeridge Clay is the total-gamma-ray log. This differentiates between the very low counts of the

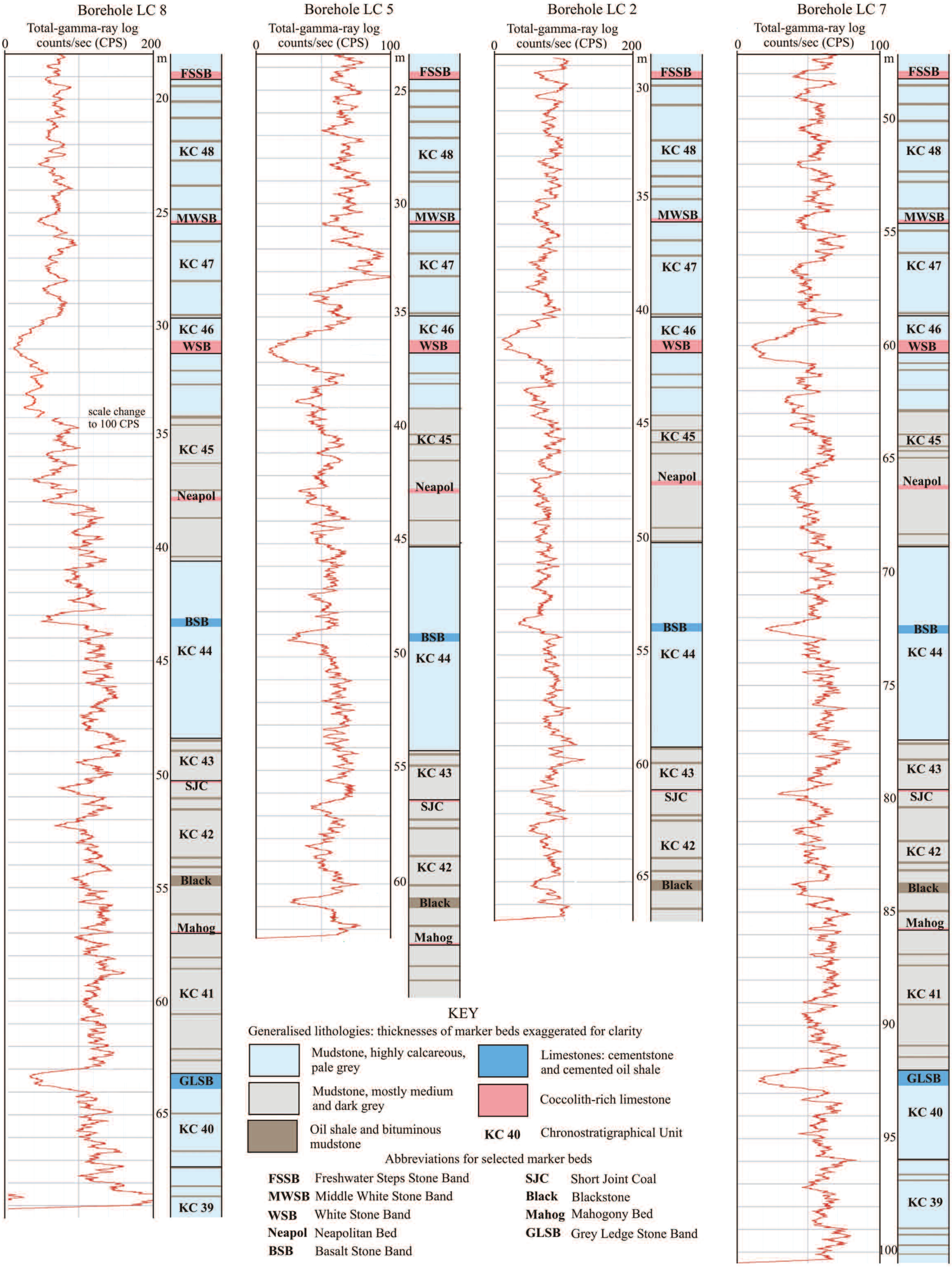

Figure 6. *Examples of correlations made on the basis of the principal marker beds proved in some of the deeper continuously cored boreholes with their total-gamma-ray logs for comparison: borehole depths in metres below ground level.*

calcareous stone bands, the low counts of the calcareous mudstones, the high counts of the clay-mineral-rich mudstones and the very high counts of the oil shales. The highest counts result from the adsorption of radioactive isotopes in the uranium-thorium decay series by the large (up to 1000 Daltons) complex molecules that make up the kerogen polymers in the oil shales.

Results

The geophysical logs of the Portland No1/1A Borehole combined with the outcrop data indicate that the total thickness of the Kimmeridge Clay Formation beneath the northern part of the Isle of Portland is *c.* 300 m. This is about half the total thickness of the formation proved close to Kimmeridge Cliffs in the Metherhills and Swanworth Quarry boreholes. The first of the LC Series boreholes to be drilled (LC 7) proved an unbroken succession of chronostratigraphical units KC 39 to KC 56 of the standard succession including the Freshwater Steps, Middle White, White, Basalt and Grey Ledge stone bands, and the Blackstone with abundant *Saccocoma*. The remaining LC series boreholes showed that these and additional marker beds were present throughout the site-investigation area and that the stratigraphical spacing between them remained constant within ± 0.2 m. The geophysical logs confirmed these correlations and the accuracy of the drillers' depths (Figure 6).

In addition to the LC Series boreholes, almost all the cores of the FRC and LSR series boreholes (drilled to 25 m depth), the HDD Series boreholes (drilled to 15 to 25 m depth) and the OBH Series boreholes (drilled to 5 to 26.5 m depth in the offshore area) proved one or more marker beds. This enabled them to be correlated with the standard succession established for the site. The distinctive Freshwater Stone Band underlies all except a small part of the proposed installations site and was recorded in the majority of the 51 boreholes. The observed and projected positions of this bed with respect to Ordnance Datum were therefore used to determine the structure beneath the site. This showed a regular dip to the SSW at *c.* 02° (Figure 2) which is in accord with what was already known about the regional structure from outcrop and seismic reflection surveys (Donovan and Stride, 1961). In 2008, after the completion of the site investigation and unrelated to it, a multibeam-sonar survey of Portland Bay commissioned for the Dorset Integrated Sea-bed Study Project (DORIS) confirmed the unbroken low SSW dip in the Kimmeridge Clay Formation in the offshore area adjacent to the Upper Osprey site (Figure 7).

Summary and conclusions

The stratigraphical succession proved in cored boreholes at the Upper Osprey site can be matched in detail with that exposed on the Dorset coast at and adjacent to Kimmeridge Bay. The succession contains a sufficiently large number of lithologically distinctive marker beds to enable correlations to be made between all the cored boreholes with an accuracy of *c.* ± 0.2 m. The borehole data indicate that the Kimmeridge Clay Formation below a depth of about 20 m beneath the site forms an intact rock mass in which a 02° SSW dip is almost normal to the topographical slope. No evidence was found of faulting, folding or large-scale movements at depth.

Comparison of the spacings of the principal marker beds proved in the boreholes with those of the type section in Kimmeridge Cliffs and the Swanworth Quarry Borehole shows linear relationships. The Kimmeridge Cliffs succession is roughly

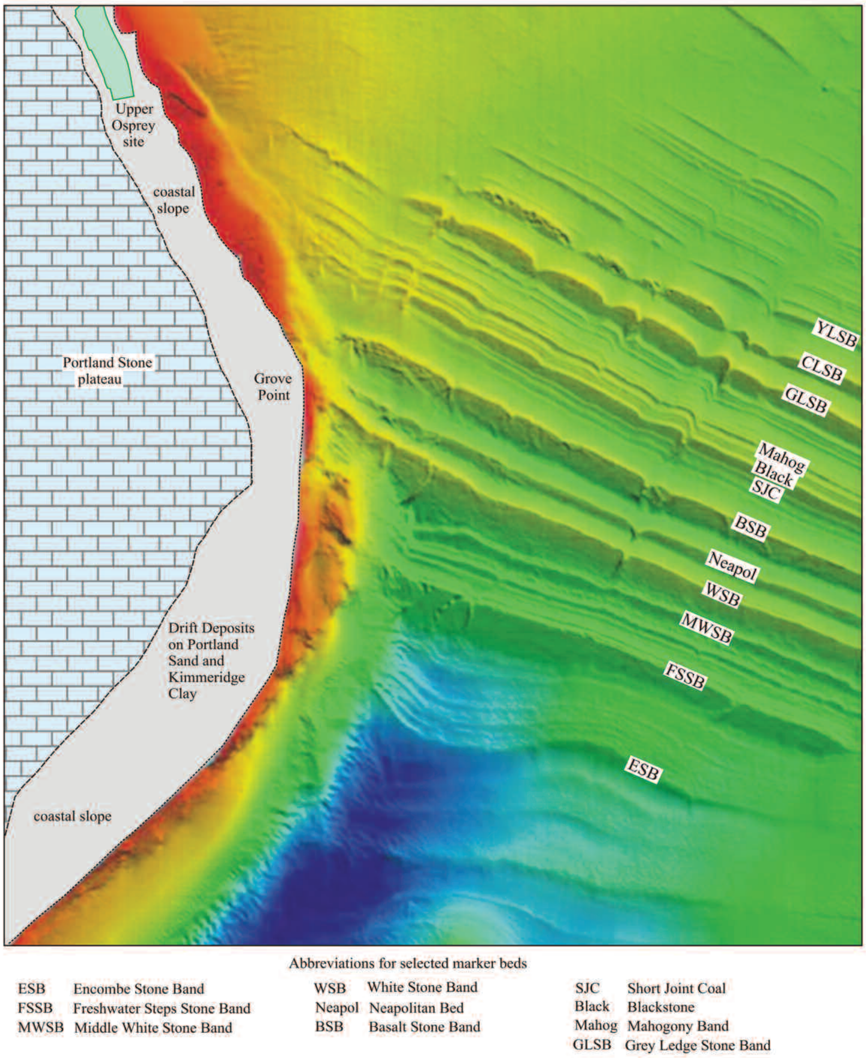

Figure 7. *Multibeam-sonar image of the sea bed adjacent to the east coast of the Isle of Portland showing a largely sand-free rock pavement in which the more resistant beds in the Kimmeridge Clay form prominent ledges. Image reproduced courtesy Channel Coast Observatory (www.channelcoast.org).*

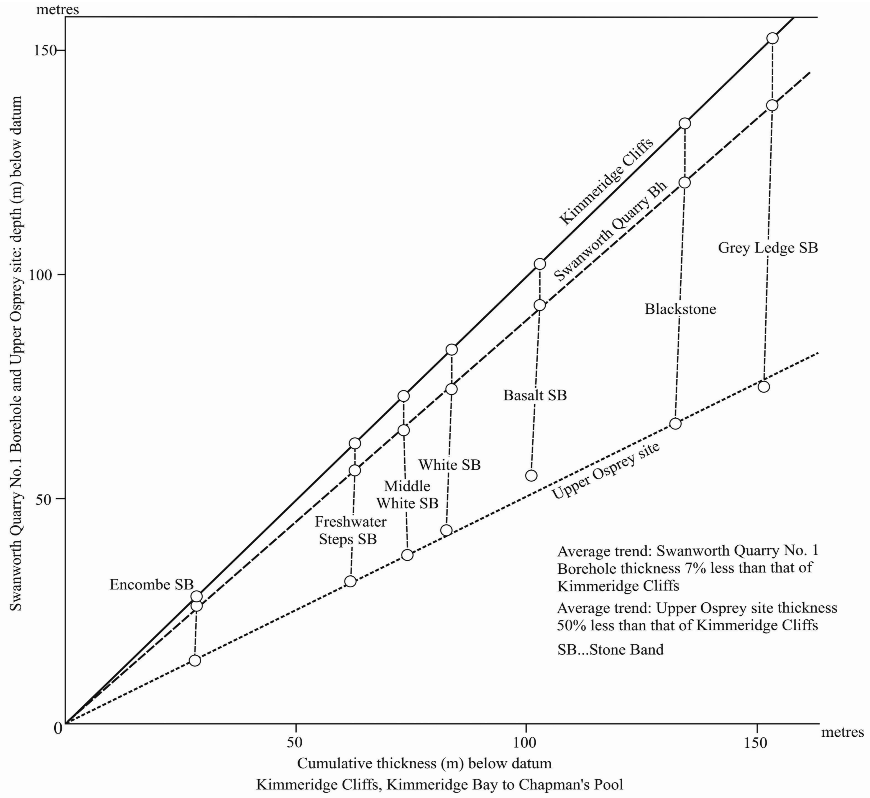

Figure 8. *Comparison of the thicknesses between selected marker beds in Kimmeridge Cliffs (after Cox and Gallois, 1981), the Swanworth Quarry No. 1 Borehole (after Gallois, 2000) and the Upper Osprey site. Chapman's Pool Pebble Bed taken as datum.*

twice as thick as that at the Upper Osprey site (Figure 8). The principal exception to this trend is the Basalt Stone Band, a diagenetic concretionary limestone that is known from boreholes elsewhere in England to occur at different stratigraphical levels within the calcareous mudstones of KC 40. This linear relationship is surprising given the marked differences in the distance of the three sites from the penecontemporaneously active major fault that underlies the Purbeck Monocline. It was known from earlier studies that the thickness of the formation decreases close to the axis of the monocline (Cox and Gallois, 1981: Gallois, 2000), but this was presumed to be a local effect. The Upper Osprey results show that the subsidence pattern in this upper part of the Kimmeridge Clay was closely similar at all three sites even though the rates of sediment accumulation were markedly different.

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REFERENCES

ARKELL, W.J. 1947. *The geology of the country around Weymouth, Swanage, Corfe and Lulworth*. Memoirs of the Geological Survey of Great Britain. HMSO, London.

BRUNSDEN, D., COOMBE, K., GOUDIE, A.S. and PARKER, A.G. 1996. The structural geomorphology of the Isle of Portland, southern England. *Proceedings of the Geologists' Association,* **107**, 209-230.

COX, B.M. and GALLOIS, R.W. 1981. The Kimmeridge Clay of the Dorset type area and its correlation with other Kimmeridgian sequences. *Report of the Institute of Geological Sciences*, No. 80/4, 1-44.

DAMON, R. 1884. *The geology of Weymouth, Portland, and Coast of Dorsetshire, from Swanage to Bridport-on-the-Sea*, 2nd edit. Edward Stanford, London.

DONOVAN , D.T. and STRIDE, A.H. 1961. An acoustic survey of the sea floor south of Dorset and its geological interpretation. *Philosophical Transactions of the Royal Society, Series B,* **244**, 299-330

GALLOIS, R.W. 1979. *Oil shale resources in Great Britain*, 2 vols. Unpublished report for Department of Energy. Institute of Geological Sciences, London.

GALLOIS, R.W. 2000. The stratigraphy of the Kimmeridge Clay Formation (Upper Jurassic) in the RGGE Project boreholes at Swanworth Quarry and Metherhills, south Dorset. *Proceedings of the Geologists' Association,* **111**, 265-280.

GALLOIS, R.W and ETCHES, S. 2001. The stratigraphy of the youngest part of the Kimmeridge Clay (late Jurassic) of the Dorset type area. *Proceedings of the Geologists' Association,* **112**, 169-182.

GALLOIS, R.W. and MEDD, A.W. 1979. Coccolith marker bands in the English Kimmeridge Clay. *Geological Magazine,* **116**, 247-260.

HUTCHINS, J. 1863. *The history and antiquities of the County of Dorset, 3rd edit.* Vol.II. Pp. 808-832. The Island and Liberty of Portland. Nichols and Sons, London.

LEES, J.A., BOWN, P.R. and YOUNG, J.R. 2004. Evidence for annual records of phytoplankton productivity in the Kimmeridge Clay Formation coccolith stone bands (Upper Jurassic, Dorset, UK). *Marine Micropaleontology,* **52**, 29-49.

MARSHALL, N., PRIVETT, K., GARLAND, R. and BROWN, M. 2007. *Supplementary geotechnical report in support of the planning application for a gas storage facility at Upper Osprey, Isle of Portland*. Unpublished report 50088-SK-00-RPT-GE-001, SRK (UK) Consulting Ltd for Portland Gas Storage Ltd.

PEARSON, S.J., MARSHALL, J.E.A. and KEMP, A.E.S. 2004. The White Stone Band of the Kimmeridge Clay Formation, an integrated high resolution approach to understanding environmental change. *Journal of the Geological Society, London,* **161**, 675-683.

RAISWELL, R., NEWTON, R.J. and WIGNALL, P.B. 2001. An indicator of water column anoxia: resolution of biofacies variations in the Kimmeridge Clay (Upper Jurassic, U.K.), *Journal of Sedimentary Research,* **71**, 286-294.

SALFELD, H. 1914. Die Gliederung des oberen Jura in nordwesteuropa. *Neues Jahrbuch fur Mineralogie, Geologie und Palaeontologie Beilage-Band,* **37**, 125-246.

TAYLOR, S.P., SELLWOOD, B.W., GALLOIS, R.W. and CHAMBERS, W.H. 2001. A sequence stratigraphy of the Kimmeridgian Stage (late Jurassic): Wessex-Weald Basin, southern England. *Journal of the Geological Society, London,* **157**, 179-192.