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The stratigraphy of the Kimmeridge Clay Formation (Jurassic) at Westbury, Wiltshire, U.K.

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ABSTRACT

The former Blue Circle Cement quarry at Westbury, Wiltshire exposed extensive sections in the lower part of the Kimmeridge Clay Formation, and a continuously cored borehole proved the lowest part of the formation and the underlying succession down to the top of the Oxford Clay Formation. The succession exposed in the quarry between 1979 and 2001 ranged from the Cymodoce to Eudoxus zones, and that in the borehole from the Baylei to Mutabilis zones. Taken together, the quarry and borehole proved the most complete section through the Kimmeridge Clay in a region where much of the formation has never been exposed. The lithological and palaeontological successions proved at Westbury are closely similar to those proved in continuously cored boreholes throughout the English outcrop and subcrop of the formation and can be matched in detail with that exposed in the type area on the Dorset coast. When the quarry was in work the sections yielded a profuse ammonite fauna that enabled the Cymodoce-Mutabilis and Mutabilis-Eudoxus zonal boundaries to be studied in detail. They also yielded a diverse bivalve and vertebrate fauna.

Keywords: Jurassic; Kimmeridge Clay Formation; Kimmeridgian; Westbury; stratigraphy;

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1. Introduction

In May 1979, the Institute of Geological Sciences (IGS now the British Geological Survey (BGS) was asked by Blue Circle Group to survey their quarry in the Kimmeridge Clay Formation (KCF) at Westbury Cement Works, Wiltshire [ST 885 529] (Fig. 1) and to log a continuously cored borehole through the lower part of the formation at the same site in order to determine the 3D distribution of organic-rich mudstones (oil shales of authors) that were detrimental to cement-making. The present author, who had recently completed a nationwide study of organic-rich mudstones in the Kimmeridge Clay as a possible source of synthetically generated hydrocarbons for the Department of Energy (Gallois, 1979a), made a geological map of the quarry and recorded the succession proved in the quarry and the borehole. Blue Circle Cement and the IGS agreed at that time that the geological map and stratigraphical report (Gallois, 1979b) would remain commercial-in-confidence for an estimated 2-3 years, after which time the borehole cores would be transferred to the IGS core store and the report would be placed on open file. The report and map remained commercial in confidence until 1982 when it was copied to a research team led by Prof. Tove Birkelund to assist them in a biostratigraphical study of the succession (Birkelund et al., 1983; Nøhr-Hansen, H., 1986).

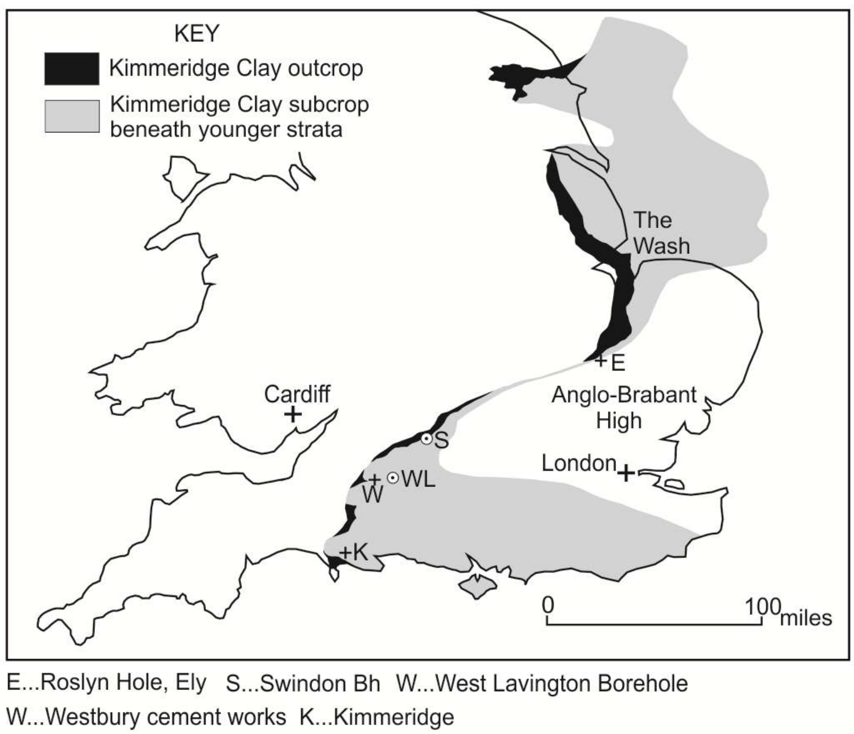

Fig. 1. Geological sketch map of the outcrop and subcrop of the Kimmeridge Clay Formation showing the position of localities referred to in the text.

2. Stratigraphy

One of the results of the Department of Energy survey, which included continuously cored boreholes along the Kimmeridge Clay outcrop from Yorkshire to Dorset, was that stratal units (currently numbered KC 1 to KC 63) based on a combination of lithological, palaeontological and geophysical features that had been shown to be applicable in The Wash area of south Lincolnshire and west Norfolk (Gallois and Cox, 1974; 1976), could be extended and applied to the whole of the English outcrop and subcrop including the KCF type section exposed on the Dorset coast (Cox and Gallois, 1981; Gallois, 2000). Comparison of the standard sequence with the Westbury succession showed that the quarry exposed KC 15 to KC 30; the borehole penetrated KC 1 to KC 19 and the underlying Corallian Group (Wright, this volume).

In 1979, the quarry (the old quarry of Fig. 2) comprised three faces separated by a gently sloping scraped area which together exposed a continuous succession through part of the Lower Kimmeridge Clay (KC 15 to KC 30). The lowest part of the quarry, which at that time was partially flooded, could not be safely accessed. It contained intermittent exposures in the more durable beds in KC 15 to KC 17, notably a calcareous siltstone in KC 17 and a line of cementstone doggers in KC 18. The fauna of the lowest part of the quarry was recorded by Prof. John Callomon in 1976 at a time when the water level was unusually low, and the remainder of this previously inaccessible part of the quarry was measured and collected in detail by Birkelund et al. (1983). The 1979 lower face exposed pale grey calcareous mudstones (*c*. 50% $CaCO_3$) in the middle to upper parts of KC 18 overlain by the medium and dark grey mudstones of KC 19 to KC 23. The lower face was capped by a cemented silty mudstone (KC 24) which could be traced across the intervening area to the top of the middle face, and from there eastwards to the edge of the quarry, a total of *c*. 500m of outcrop. Between the middle face and the south face, a gently sloping scraped area exposed KC 25 to KC 30. A prominent line of fossiliferous calcareous doggers could be traced across the full width of the quarry floor within the pale grey calcareous mudstones of KC 30.

In 1994, an additional excavation became available for examination (the new quarry of Fig. 2). This proved a similar succession to that in the old quarry with part of KC 16 and KC 17 to KC 29 well exposed; part of KC 30 was poorly exposed in the south-east corner. As in the old quarry, the thick calcareous mudstone KC 18, the calcareous siltstone KC 24 and three lines of cementstone doggers (in KC 18, KC 24 and KC 30) formed prominent marker beds. On the east side of the quarry the KC 24 separated low angle (c. 5º) slopes in the upper part of the excavation from steeper (up to 35º) slopes in the lower part. Much of the north face was graded at a continuous 35º which allowed more accurate thicknesses to be measured for KC 17 to KC 29 than in the old quarry.

The composite Kimmeridge Clay succession proved in the quarries and in Borehole 79/1 is summarised below and graphically in Fig. 3, together with that recorded by Birkelund et al. (1983). The thicknesses for KC 5 to KC 17 are based on the Westbury 79/1 Borehole, and those for KC 18 to KC 29 on measurements made in the north face of the new quarry. The latter differ in minor detail at some levels from those made by the present author (Gallois, 1979b) and Birkelund et al. (1983) in the old quarry due to the difficulty of making accurate measurements of bed thicknesses on low-angle scraped surfaces, but when allowance is made for the differences in thickness, the successions recorded by all the authors and their stratigraphical interpretations are closely similar, with one exception (see 2.4 below).

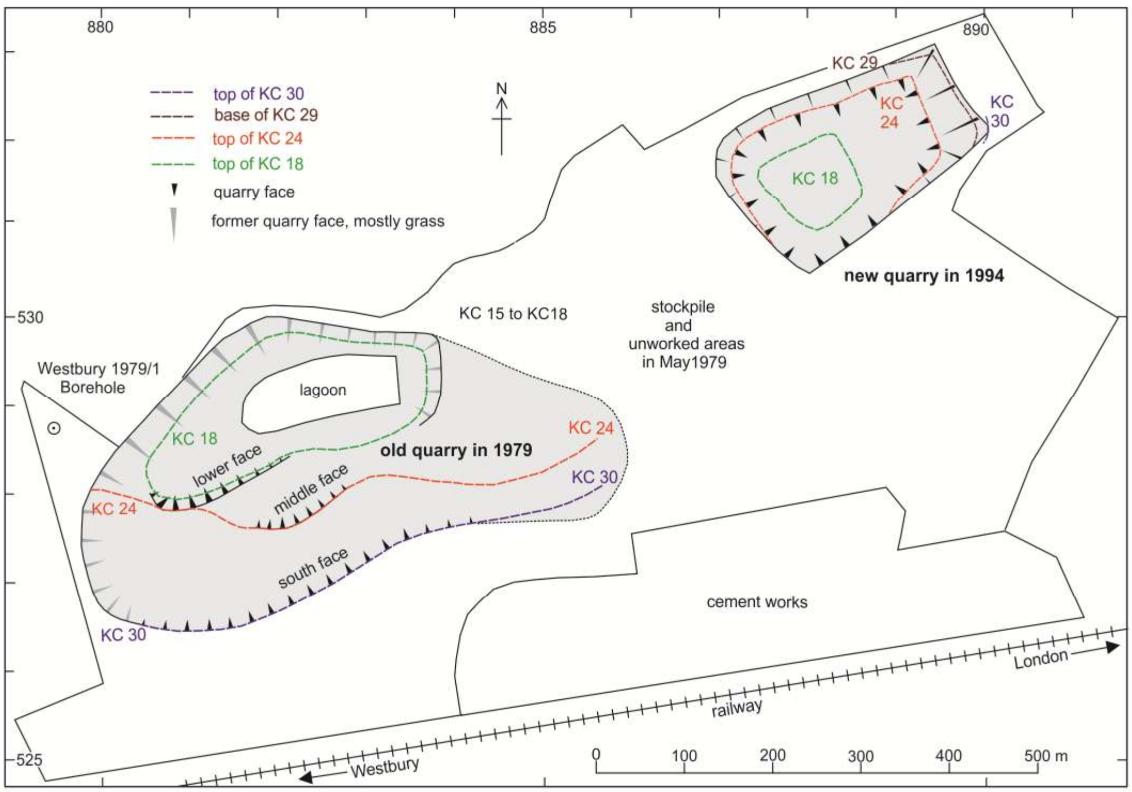

Fig 2. Geological sketch section of the old and new quarries at Blue Circle Cement works showing the outcrop of some of the key marker beds.

The abbreviated faunal details given here are based on observations made in the old quarry in 1979 and in the new quarry in 1994 to 2001. A more complete description of the biostratigraphy of the old quarry, together with a discussion of the stratigraphical significance of the ammonite succession, is given by Birkelund et al (1983). In the description of the composite succession recorded here, their bed numbers are shown in brackets e.g. KC 30 [E6].

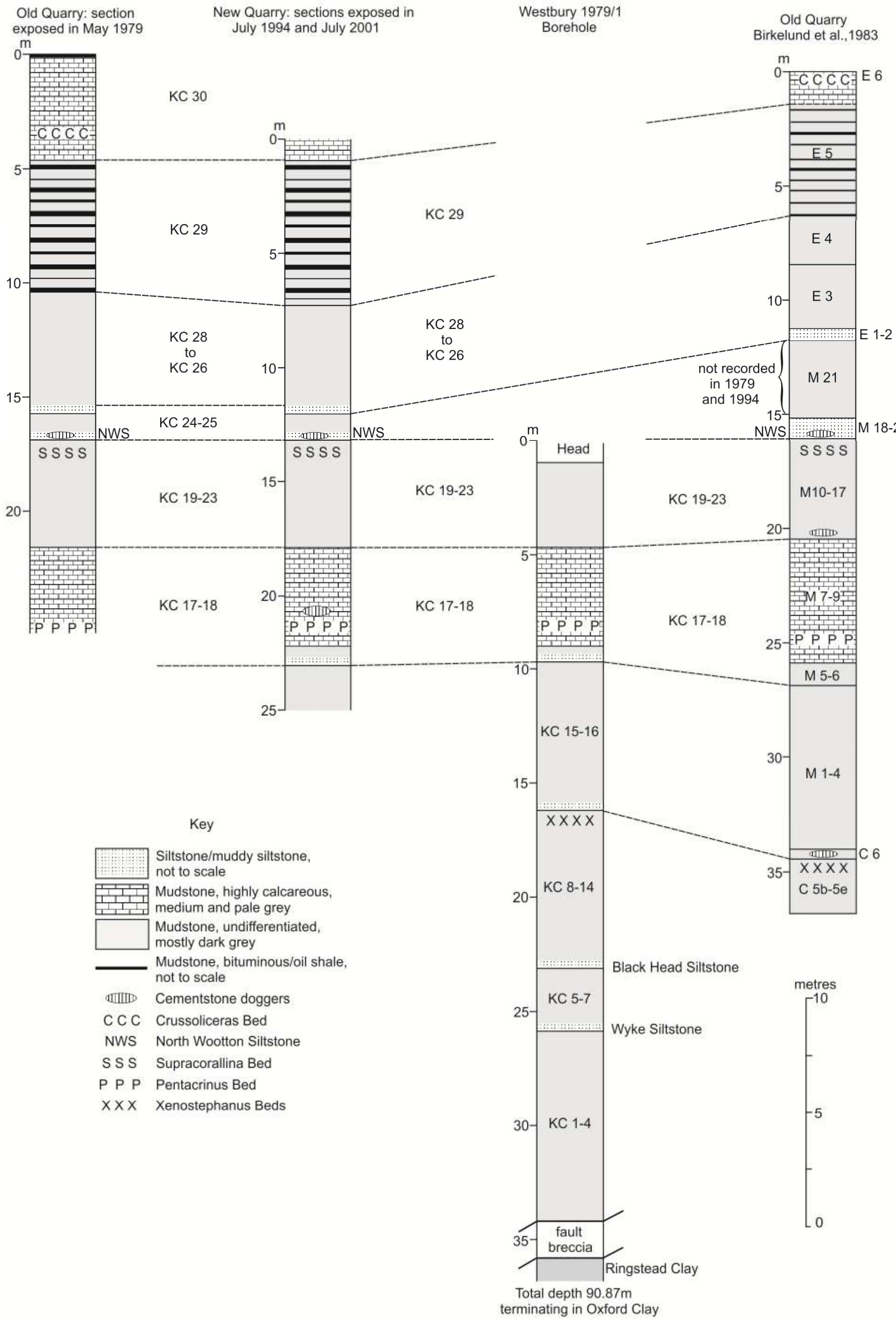

Fig.3. Correlation of the sections exposed in the old and new quarries between 1979 and 2001, and in the Westbury 1979/1 Borehole.

2.1 Zonation

Five ammonite zones based on the aulacostephanid ammonite faunas have been recognised in the lower part of the KCF following Salfeld (1913) and Ziegler (1962. In ascending order, their index species are *Pictonia baylei*, *Rasenia cymodoce*, *Aulacostephanus mutabilis*, *A. eudoxus* and *A. autissiodorensis*. Subsequent research has shown that the faunal changes that occur at the bases of the oldest four of these biozones coincide with sedimentary breaks (sequence boundaries Km 1, 2, 4 and 6 of Taylor, S.P. et al., 2001) which are laterally continuous throughout the English outcrop and subcrop of the KCF. The boundaries between these zones can therefore be regarded as synchronous within this region and for all practical purposes delineate chronozones. For continuity, the ammonite species names have been retained for these five chronozones.

2.1.1 Baylei Zone (KC 1-4)

The Corallian Group (see Wright, this volume) and the lowest part of the KCF were only recorded in the Westbury 79/1 Borehole [ST 8795 5283]. The base of the KCF is faulted against very pale grey, smooth-textured mudstones that are lithologically similar to those of the Ringstead Clay Member (formerly Ringstead Waxy Clay) exposed on the Dorset coast. The beds between the faulted junction and the base of the Wyke Siltstone (Fig. 3) comprise medium and pale grey mudstones and silty mudstones which are lithologically similar to the Baylei Zone mudstones of the Dorset coast sections and distinctively different from those of the underlying Ringstead Clay. Bivalves, gastropods and serpulids are common at several levels, but none of the recorded fauna is age diagnostic. The thickness of the sheared fault zone and the structural disturbances in the overlying 1.60 m of mudstone suggest that the fault is steeply dipping and crosses the core at an acute angle. Throughout southern England, the widespread erosion surface at the base of the Wyke Siltstone (KC 5) marks the incoming of the Horizon I Rasenia Assemblage of Birkelund et al. (1978) and the base of the Cymodoce Zone.

2.1.2 Cymodoce Zone (KC 5-14)

The Cymodoce Zone in the borehole is represented by 9.45 m of predominantly medium and dark grey mudstones between the erosion surface at the base of the Wyke Siltstone and that at the base of the unnamed siltstone (KC 15) which is taken to mark the base of the Mutabilis

Zone (see 2.1.3). The lithological and palaeontological successions are similar to those proved elsewhere in England including that at the Dorset type section. In the lower part of the succession, the Black Head Siltstone and the highly bioturbated surface at its base forms a prominent lithological marker bed. Serpulid-encrusted oysters including *Deltoideum delta* (Smith) are common at several levels. The highest part of the zone was exposed in the lowest part of the old pit at times when the water level in the lagoon was low (Birkelund et al., 1983). These authors recorded *c*. 2.4 m of fossiliferous mudstones (their Beds C5b to C5e) with a diverse bivalve fauna and abundant *Rasenia* including *R. evoluta* Spath and *R. involuta* Spath. In the highest part of the zone they recorded coarsely ribbed *Rasenia* at a similar level to those in the borehole that had been identified by the present author as *Xenostephanus*[1] and correlated with the *Xenostephanus* marker bed of Gallois and Cox (1976). Birkelund et al. (1983) drew attention to the difficulty of differentiating in crushed specimens between coarsely ribbed *Xenostephanus*-like *R. evoluta* (e.g. their Fig. 5 A-C) and true *Xenostephanus* with its characteristically deep ventral groove. In addition to the records of this genus in borehole cores, Cox and Gallois (1981) and Van der Vyver (1986) confirmed the presence of *Xenostephanus* in the highest part of KC 14 at Black Head, Dorset where it is possible to examine specimens at various angles to the bedding, including those in which the venter is uncrushed.

2.1.3 Mutabilis Zone (KC15-23)

The base of the Mutabilis Zone was taken by Ziegler (1962) at the upward change from species of *Rasenia* (in which ribs cross the venter unbroken) to species of *Aulacostephanus* (in which there is a smooth ventral band or a weakening of the ribs across the venter), but noted that, in practice, the dividing line between the genera is arbitrary. For example, some authors have interpreted *Aulacostephanus* as a genus in which the majority of individuals in the population have a smooth ventral band throughout life, others as a genus in which the ribbing is interrupted only on the later whorls. Birkelund et al. (1978) included their Horizon IV Rasenia Assemblage characterised by *Rasenioides askeptus* Ziegler and *R. lepidulus* (Oppel) in the Cymodoce Zone, but later Birkelund et al. (1983) placed it in the Mutabilis Zone (Bed M1 at Westbury) with the recommendation that

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[1] *Xenostephanus* was later renamed *Zenostephanus* as the name was discovered to be pre-occupied (Callomon et al., 2009).

the base of the Mutabilis Zone should be drawn in Britain at the level where fine-ribbed raseniids suddenly become dominant over coarse-ribbed *Rasenia*. Gallois and Cox (1976) used the first occurrence of specimens with a smooth ventral band at any growth stage as the most practical method of positioning the base of the Mutabilis Zone. Throughout the outcrop and subcrop of the KCF this occurs close above a widespread erosion surface at the base of KC 15 (sequence boundary Km 4 of Taylor et al., 2001). A similar erosion surface and ammonite succession is present at the same stratigraphical level at the base of the Argiles de Croquet supérieure on the Normandy coast (Gallois, 2005).

The oldest part of the Mutabilis Zone is represented at Westbury and throughout the KCF outcrop and subcrop by a lithologically distinctive, smooth-textured, dark grey mudstone (KC 16 [M1]) with abundant crushed iridescent finely ribbed ammonites variously identified as *Rasenioides lepidulus*, *Aulacostephanus eulepidus* (Schneid), *A. linealis* (Quenstedt), and *A. mutabilis* (J. de C. Sowerby). *Orthaspidoceras* is present throughout the zone and abundant at one level (KC 17) at Westbury and at the same stratigraphical level at Black Head, Dorset (S. Etches pers. comm.) Birkelund et al. (1983) noted an unusual occurrence of *Deltoideum delta*, which had previously been thought to be restricted to the Upper Oxfordian and the Cymodoce Zone, at one level in the upper Mutabilis Zone (KC 18 [M12]) in the old quarry. The same bed was present in the new quarry, but has not been recorded in beds younger than the Cymodoce Zone at any other locality. In the higher part of the Mutabilis Zone, the bivalve *Nicaniella extensa* (Phillips), formerly *Astarte supracorallina* d'Orbigny, is common but is especially abundant over a narrow stratigraphical range (KC 22) where it forms a faunal marker bed, the Supracorallina Bed of Arkell (1947).

2.4 Eudoxus Zone (KC 24 to 31)

The base of the Eudoxus Zone is taken at a transgressive, burrowed erosion surface (Sequence Boundary Km 6 Taylor et al., 2001) at the base of KC 24 which marks an upward change from predominantly finely ribbed *Aulacostephanus* to coarsely ribbed *Aulacostephanus* of the *eudoxus* group, together with the incoming of *Aspidoceras*, its microconch *Sutneria* and aptychal plate *Laevaptychus*. It also marks an upward change in the gross lithology of the formation from predominantly calcareous mudstones to mudstones with common interbeds of bituminous mudstone (oil shales/black shales of authors), a change from Type B to Type C rhythms of Cox and Gallois (1981, Fig. 9). Throughout the outcrop and subcrop, the erosion surface is overlain by a calcareous siltstone (the North Wootton Siltstone of Gallois, 2000) with common whole and fragmentary thick-shelled bivalves and coarsely ribbed rhynchonellide brachiopods. In most areas, a second burrowed erosion surface and siltstone (KC 25) lies up to 1.5 m above this. The beds between the erosion surfaces at Westbury, Black Head, Dorset and in their correlative in the lowest part of the Argiles d'Ecqueville médian on the Normandy coast (Samson et al., 1996) contain the youngest recorded occurrences of faunal elements that are common in the underlying Mutabilis Zone, including *Orthaspidoceras*, *Aulacostephanus eulepidus* and *A. mutabilis*, and the first occurrences of *Aulacostephanus* ex. gr. *eudoxus* and *Aspidoceras*.

Both erosion surfaces and the overlying siltstone marker beds were exposed in the old and new quarries at Westbury, but there is a marked difference in the descriptions made by the present author in the old (Gallois, 1979b) and new (herein) quarries, and that made by Birkelund et al. (1983) in the old quarry. In 1979, KC 24 and KC 25 cropped out in a low-angle scraped area between the middle and south faces of the old quarry (Fig. 2) where the outcrop varied between 2 m and 10 m in width with debris from both beds spread over an even larger area. In the new quarry, they were closely spaced in the 35º slope of the north face where the vertical distance between the two erosion surfaces was calculated to be 0.86 m. In the old quarry, Birkelund et al. (1983) interpreted the correlative of KC 25 [E1] as the base of the Eudoxus Zone (Fig.3). Beneath this they recorded 3.50 m of mudstones with *A. eulepidus*, *A. mutabilis* and *Orthaspidoceras* [M20 and M21] which rested on a silty mudstone [M19] and a calcareous mudstone with cementstone doggers [M18]. These last were interpreted by the present author as KC 24 resting on the erosion surface that marks the base of the Eudoxus Zone. Both accounts recorded similar thicknesses between the cementstone doggers and the underlying Supracorallina, Pentacrinus and Xenostephanus marker beds (Fig. 3). There is no satisfactory explanation for the apparent absence of [M20] and [M21] from the exposures seen in the old quarry in 1979 and from the new quarry. The lithologies and faunas are indicative of the Mutabilis Zone, but can also occur in the lowest part of the Eudoxus Zone (KC 24). The discrepancy in the thicknesses might be explained by faulting, but there is no evidence to support or disprove this explanation. When [M20] and [M21] are omitted from the measurements, the thicknesses between the limestone doggers in KC 24 [M18] and those in the Crussoliceras Bed (KC 30 [E6]) are similar: 11.95 m in Birkelund et al. (1983) and *c*. 11.5 m in Gallois (1979a).

The Eudoxus Zone exposed in the quarries at Westbury is characterised by a diverse bivalve fauna in which large forms of *Nanogyra virgula* Defrance are sufficiently abundant at one level to form a marker bed that can be correlated with a similar bed in the Dorset type section and elsewhere. The ammonite assemblage is dominated by *Aulacostephanus* of the *eudoxus* group with *Aspidoceras*, *Nannocardioceras* and *Sutneria* common at some levels. Birkelund et al. (1983) recorded crushed examples of the perisphinctids *Crussoliceras* cf. *atavum* (Schneid) and *C*. cf. *sevogodense* (Contini and Hantzpergue) in the Crussoliceras Bed at Westbury. Earlier, Enay (MS, 1982) had identified the same species among specimens collected by Roberts (1892) from the correlative bed in Cambridgeshire (the Propectinatites Bed of Gallois and Cox, 1976). The only ammonite in 3D preservation recorded from this bed at Westbury has been described as the holotype of *Tolvericeras anglicum* Enay (in Enay et al., 2014, Plate XVI incorrectly cited as from Brandy Bay, Kimmeridge, Dorset).

The vertebrates collected from the Westbury quarries include important chelonian, crocodilian, ichthyosaurian and plesiosaurian remains (Grange et al., 1996). Prominent among these are a well-preserved skull, jaw and associated bones of a *Pliosaurus brachyspondylus* (Owen) (Grange, 1980; Taylor and Cruikshank, 1993) in KC 30 which may have dined on the carcass of an ornithischian dinosaur shortly before its death (Taylor, M.A. et al., 1993), and the partial skeleton of a *Pliosaurus* in KC 29 (Grange et al., 1996). Both are now on display in the Bristol City Museum and Art Gallery. Many of the other vertebrate remains are housed in the Etches Collection at Kimmeridge. The majority of the vertebrate remains were found in KC 29 in association with organic-rich mudstones that are presumed to have been deposited in anaerobic or dysaerobic environments that were conducive to their preservation. A similar situation was present in the early Jurassic elsewhere in England where an exceptionally rich and diverse vertebrate fauna is preserved in organic-rich mudstones in the Blue Lias and Charmouth Mudstone formations. There are too few specimens from Westbury to determine if there was any faunal differentiation in the vertebrates due to climatic influence. All three of the crocodile remains were found in the calcareous mudstones of KC 30, a lithology that is thought to have been deposited in a warmer, drier climate than the organic-rich mudstones, but examples of all the other groups were found in various lithologies. The only comparably rich source of vertebrate remains in the Lower Kimmeridge Clay to that recorded at Westbury is that at Roswell Pits (Roslyn Hole), Ely [TL 555 808] (Benton and Spencer, 1995) which over a period of more than 100 years exposed parts of a similar succession (Mutabilis and Eudoxus Zones) to that at Westbury (Gallois, 1988).

3. Correlation with other areas

The Kimmeridge Clay proved in the quarries and in the Westbury 79/1 Borehole can be matched in lithological and palaeontological detail with that proved throughout the KCF outcrop. In addition to the faunal marker beds, the erosion surfaces (Km1 to Km6) overlain by siltstones with shell debris are laterally persistent throughout the outcrop and subcrop. Beds with cementstone and/or septarian concretions occur at a few stratigraphically consistent levels in the KCF where they are confined to the more calcareous mudstones (> 50% $CaCO_3$) or the siltstones. All those recorded in the Westbury quarries can be correlated with concretions at or close to the same stratigraphical level elsewhere.

The septarian concretions recorded by Birkelund et al. (1983) in their Bed C6 are the correlatives of the "pumpkin-shaped septaria" in the basal part of the Mutabilis Zone on the Dorset coast (Cox and Gallois, 1981). Similarly, those in KC 18, KC 24 and KC 30 at Westbury have correlatives at closely similar stratigraphical levels at Black Head. The complete Westbury succession can be matched in detail with those recorded on the Dorset coast and in the nearest continuously cored boreholes at West Lavington [ST 9898 5633] (Gallois, 1979a) and Swindon [SU 1413 8349] (Gallois and Cox, 1994). Taken together, they show the progressive northerly overstep of the lower part of the KCF onto the Anglo-Brabant massif (Fig, 4).

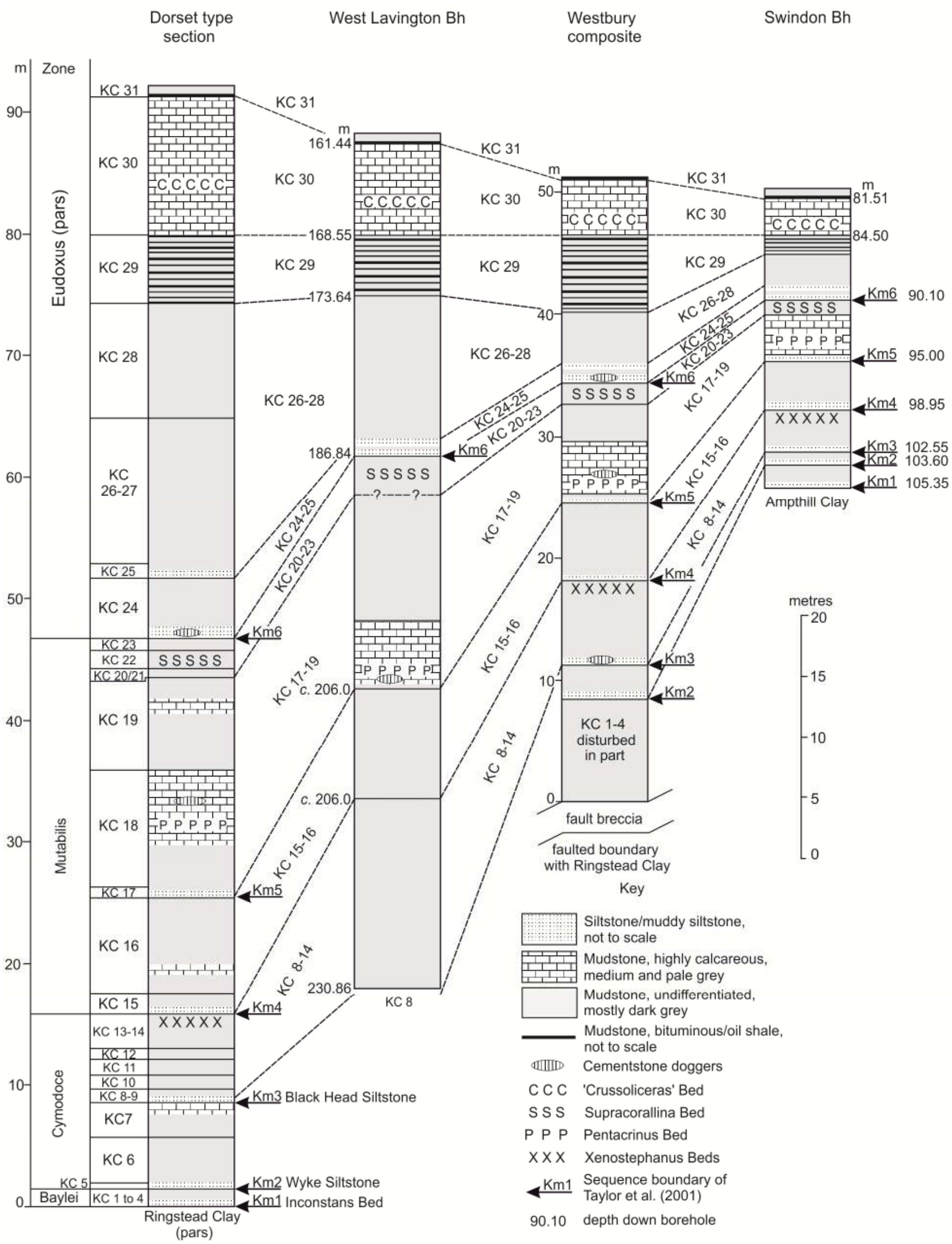

Fig. 4. Correlation of the Westbury succession with that of the Dorset type area (after Cox and Gallois, 1981) and the West Lavington (Gallois, 1979a) and Swindon (Gallois and Cox, 1994) boreholes.

4. Summary and conclusions

The quarries at Westbury Cement Works were the most extensive inland exposures in the lower part of the KCF from the 1970s to 2001. They exposed a richly fossiliferous, unbroken mudstone succession from the upper Cymodoce Zone to the middle Eudoxus Zone, parts of which were exposed as almost horizontal unweathered strata over areas of 10s to 100s m^2. As a result, parts of the succession were better preserved than the correlative beds in the type area on the Dorset coast where they crop out in the tectonically disturbed steep limb of the Purbeck Monocline. The Westbury quarries yielded stratigraphically well-documented and well-preserved diverse ammonite and bivalve faunas, and a wide range of vertebrate remains. The composite succession proved in the quarries and in the continuously cored Westbury 79/1 Borehole can be correlated in detail with the lower part (KC 1 to KC 31) of the KCF recorded at the Dorset type sections and elsewhere in England.

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