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Faunal Provinces in Space and Time

Facies, faunas and tectonics in late Jurassic-early Cretaceous Britain

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Re-assertion of Caledonian structures late in the Jurassic (in sympathy with the Nevadan orogeny of North America) resulted in the formation of two contrasting sedimentary and faunal provinces in England, with East Anglia revealed as an extension of the Russian Platform and southern England linked to the "White Jura" province of Europe. This movement dates from the Middle Volgian and the regime thus imposed persisted into early Cretaceous times. The introduction of phosphorite as a normal feature of inhibited deposition in these regions also dates from this time and suggests that north-west Europe already lay on the eastern margin of a typical oceanic circulatory system. These events may thus be linked with the opening of the North Atlantic.

1. Introduction

Towards the end of the Jurassic period great changes in physiography resulted in the retreat of the seas from many marginal areas in the northern hemisphere and the creation of new sedimentary and faunal provinces. This is strikingly illustrated in Britain, where a barrier rose to divide the old Jurassic seaway across England into two basins of sharply contrasting facies. In the south, the Portland, Purbeck and Wealden Beds record a shrunken but rapidly subsiding area of deposition where for long periods brackish and freshwater deposits replaced marine. In eastern England, the Sandringham Sands and Spilsby Sandstone indicate a more stable, fully marine regime of shallow water and gentle subsidence.

In recent years construction of new roads, waterways and pipe-lines has brought to light unexpectedly rich faunas in the Sandringham Sands of Norfolk. These discoveries have in turn stimulated research on the strata at the Jurassic-Cretaceous boundary in East Anglia and have led to a re-appraisal of the ammonite sequence at that level and drastic re-alignment of many stratigraphical boundaries in eastern and southern England. The chief results of this work have been to assign an uppermost Jurassic (Volgian) age to the lower part of the Spilsby

Sandstone of Lincolnshire and to the basal part of the Sandringham Sands of Norfolk and to correlate these horizons with the upper part of the Portland Beds and the lower part of the Purbecks (Lulworth Beds) of southern England (Fig. 1). Clarification of the age-relationships of these deposits permits a closer correlation of events within the two basins. It now remains to be seen whether our improved chronology gives any better understanding of the processes that shaped this part of the British Isles.

2. Ammonite realms and provinces

By the end of the Jurassic ammonites in the Northern Hemisphere had become segregated into two main geographical realms: a Southern Realm centred on the circum-global "Tethys", in which the Berriasellidae predominated, and a Boreal Realm characterised by proliferation of the Dorsoplanitidae and the Craspeditidae. Within these two realms there were numerous local provinces, especially in the Boreal Realm, where the prevalence of shallow epicontinental seas and a less stable regime seems to have stimulated ammonite differentiation.

In the absence of any acceptable scheme of integration of the various provinces, it is still necessary to use a threefold scheme of nomenclature for the terminal Jurassic stage—Tithonian in the Tethyan region, Volgian and/or Portlandian for the Boreal Realm. The position is the same for the basal Cretaceous, there being no satisfactory correlation between the Tethyan Berriasian and the Boreal Ryazanian. In terms of ammonite provinces, Britain lies wholly in the Boreal Realm and here the problem centres on interrelationship and delimitation of Portlandian, Volgian and Ryazanian.

There is a long history of debate concerning the age-relationship of Volgian and Portlandian, an issue made more obscure by the varying definitions of the two stages and varying interpretations of the ammonites. In recent years the Russians have extended the Volgian down to the level of the *Gravesia* horizon of our Kimmeridge Clay (*Pectinatites elegans* Zone of Cope 1967) and introduced a tripartite division of the stage, the old Lower Volgian now becoming Middle Volgian. Continental usage fixes the base of the Portlandian at the same level. Elsewhere I have made some compromise proposals regarding delimitation of Portlandian and Volgian (Casey 1967), but in this paper the term Portlandian applies only to the Portland Beds.

Dissimilarity between the ammonite faunas of these two stages, the Volgian and the Portlandian, has been held to reflect differences of age, but in recent years the links between the two have been strengthened, particularly by the discovery of *Paracraspedites* in the Portland Stone and at the top of the Middle Volgian of the type locality (Casey 1968). Originally described from the Spilsby Sandstone and for many years used as an index to the base of the Cretaceous, *Paracraspedites* thus proves to be a key fossil for integration of the Jurassic.

Nevertheless, despite the records of Gerasimov and Mikhailov (1966), it would appear that such typical Portland genera as *Crendonites, Kerberites* and *Titanites* have yet to be found in the Volgian of the Russian Platform (Casey 1967) and that the Russian Volgian virgatitids (*Virgatites, Zaraiskites, Michalskia*) have no strictly congeneric representatives in the English Kimmeridge-Portland sequence as known at present. A prominent band of phosphorite nodules with

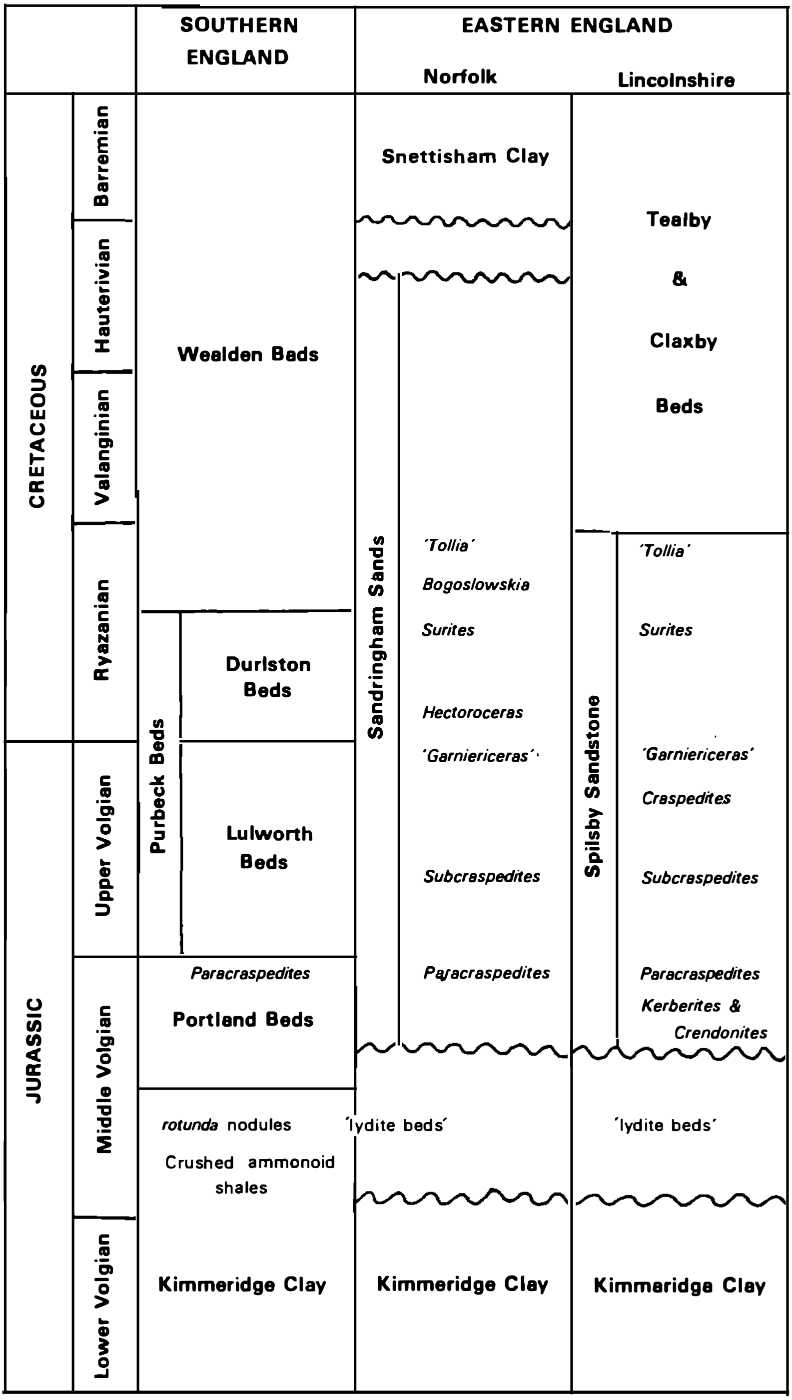


Fig. 1. Correlation chart of strata at the Jurassic-Cretaceous boundary in England. (Thicknesses not to scale).

Fig. 2. Ammonite realms in the northern hemisphere. Present-day distribution of Tithonian, Volgian and Portlandian faunas (Modified from W. J. Arkell 1956).

rolled virgatitids occurs below the *Paracraspedites* level in the stratotype Volgian, supporting the idea that the *giganteus* and *gorei* faunas of the Portlandian existed during an interval of non-deposition there and that the Volgian in its type-locality (Gorodishche, R. Volga) is not only highly condensed but incomplete. Future work must decide whether the apparent absence of Russian-type virgatitids in Britain is due to collection-failure, provincial segregation or other causes. In the meantime, it may be deemed useful to distinguish on the map those regions in which a Portland Beds fauna has been described (Fig. 2).

Despite the lack of good continuous sections at outcrop, recognition of a craspeditid sequence diagnostic of the Upper Volgian presents no problems in the Spilsby Sandstone. Data from the Fordington boreholes (described in part by Swinnerton 1935), supplemented by material from the road-cutting at Partney, near Spilsby, Lincolnshire, show that *Subcraspedites* of the groups of *S. primitivus* Swinnerton and *S. cristatus* Swinnerton, together with undescribed forms linking *Subcraspedites* with the Dorsoplanitidae, succeed *Paracraspedites* without signs of a sedimentary break. *Subcraspedites* of the group of *S. sowerbyi* Spath and rare *Craspedites plicomphalus* (J. de C. Sowerby), an ally of *C. nodiger* (Eichwald) of the Moscow synclise, follow within a few feet. At Nettleton Mine, Lincolnshire, the highest beds of the Spilsby Sandstone below the Cretaceous yield ammonites of the group of "*Garniericeras*" *tolijense* (Nikitin), indicative of the top of the Upper Volgian in the northern part of the Russian Platform.

A similar succession is found on the other side of the Wash, in the basal part of the Sandringham Sands south of Kings Lynn. Delimitation of the Volgian/Ryazanian boundary is here more difficult, since an undescribed fauna with species intermediate between "*Garniericeras*" and *Hectoroceras* lies at the junction.

Thanks largely to a series of temporary exposures at West Dereham (cut-off channel), North Runcton (North Sea gas pipe-line) and Mintlyn Wood (Kings Lynn bypass), the Ryazanian ammonite sequence of the Sandringham Sands is now well established. At West Dereham the Ryazanian commences with a unit containing several horizons of *Hectoroceras*. In Mintlyn Wood and North Runcton the *Hectoroceras* beds are succeeded by a sequence with *Surites* faunas having much in common with species found in the condensed Ryazan Beds near Moscow. These are replaced upwards in turn by species of *Bogoslowskia* and then forms provisionally referred to the genus *Tollia*. Judging by comparable occurrences in Siberia, the last group of ammonites marks the boundary with the Valanginian. *Hectoroceras* has not yet been identified in the Spilsby Sandstone; otherwise the Ryazanian sequence in Lincolnshire is substantially the same as that of Norfolk.

Compared with that of the Moscow synclise, the succession in East Anglia is notable for the apparent absence of *Kachpurites* at the base of the Upper Volgian and the replacement of *Riasanites* by *Hectoroceras* at the base of the Ryazanian. The relative abundance of *Subcraspedites* and *Craspedites* is also reversed in the two regions. In the extreme north of the U.S.S.R. *Chetaites* and *Taimyroceras* replace the more familiar Volgian craspeditids of the Moscow region and *Riasanites* again gives way to *Hectoroceras* (Saks *et al.* 1963). Each province thus has its own peculiar faunal composition caused by lateral variations in the distribution of contemporaneous genera.

3. Faunal contrast between southern and eastern England

Ammonites indicate that the basal Spilsby Sandstone is a condensed equivalent of much of the Portland Beds of the southern basin. Side by side with remanié *Pavlovia* from the underlying Kimmeridge Clay, are fragmentary *Crendonites* and *Kerberites* (in a phosphatised glauconitic matrix) comparable with species from the Portland Stone and, in the next few inches, crushed examples of *Paracraspedites* closely related, if not conspecific, with those recently found at the base of the Sandringham Sands near Kings Lynn and in the "Shrimp Bed" at the top of the

Dorset Portlands (Casey in Dodson *et al.* 1964). While there can be little doubt concerning the contemporaneity of basal Spilsby Sandstone with part of the Portland Beds, the faunas of the two regions (aside from the ammonites) offer great contrasts.

Although both Portland Beds and Spilsby Sandstone have rich assemblages of bivalves, no species common to the two formations has yet been found. In the Jurassic portion of the Spilsby Sandstone and its equivalent in Norfolk the pecten *Entolium*, the trigoniid *Myophorella* and the heterodont *Neocrassina* predominate; in the Portland Stone these are replaced by *Camptonectes, Laevitrigonia* and *Protocardia*, with local abundance of *Eomiodon* (Ragstone Beds and Upper Building Stones of the Vale of Wardour). Belemnites (*Acroteuthis*) and large brachiopods ("*Terebratula*" *rex* J. Sow. sp.) are characteristic of the basal Spilsby Sandstone and Sandringham Sands, whereas the *absence* or great rarity of belemnites and brachiopods is equally characteristic of the Portland Stone. Corals, locally well represented in the Portland Stone (*eg.* at Tisbury), have yet to be recorded from the basal Spilsby fauna.

Faunal contrast was greatly enhanced in Purbeck times, when normal marine conditions in southern England gave way to an environment of lagoons and swamps in which salinity fluctuated enormously. Here the evidence of carbon isotopes now augments the traditional methods of palaeoecology (Allen and Keith 1965). Evaporites at the base of the (Purbeck) Lulworth Beds indicate supersaline conditions and the drying up of the Portland sea; thereafter a brackish and freshwater regime intervened, with intermittent *Unio* and *Viviparus* beds and at times near-normal marine horizons with oysters and echinoids (*eg.*, in the "Cinder Beds") in a predominantly shale-carbonate environment. Conditions of variable reduced salinity persisted in southern England well into the Cretaceous within an arenaceous-argillaceous sedimentary cycle.

During Middle Volgian (Portlandian) times faunal contrast between the two basins was greater than would be expected from differences in depth of water and sedimentary facies alone. Admittedly, there was some degree of geographical isolation and faunal interchange may have been restricted to active swimmers, though provided temperature and salinity are favourable benthonic molluscs have remarkable powers of infiltration (*cf.* Kisch 1951). Clues to the palaeotemperature and palaeosalinity of the Portland Stone and Spilsby seas must therefore be sought. First thoughts are of a warm southern sea and a cold northern one. The carbonate deposition, corals and large-shelled molluscs of the Portland invite comparison with recent sub-tropical waters (as do the evaporites and the turtles and crocodiles of the Purbeck); conversely the "boreal" facies of the Spilsby belemnites may suggest the influence of cold northern currents. It is now known, however, that *Paracraspedites* of the Spilsby basin attained a diameter equal to that of the giant ammonites of the Portland Stone and that discrepancy in ammonite sizes is rather the result of selective preservation of nuclei in the Spilsby basin than of palaeoecological causes. The term "boreal" should not, of course, be given its present-day climatic connotation. Bowen's (1961) figure of 16·5°C for the temperature of the "Boreal" Valanginian-Hauterivian sea at Speeton, derived from oxygen-isotope assaying of belemnites, is higher than the summer maximum reached in Yorkshire coastal waters today (Dietrich 1962). This method of palaeotemperature determination may in future be applied to the thick-shelled molluscs of the Portland Beds and to the calcite guards of the Spilsby belemnites, but as yet there is no credible evidence to help us assess possible temperature-differentiation of faunas in the two basins.

As regards palaeosalinity, we are on firmer ground. For example, although *Eomiodon* forms part of a neritic fauna in the Portland Beds, it is not found in association with ammonites and its record throughout the Jurassic shows clearly that it favoured waters of less than normal salinity (Casey 1955). From the abundance of *Laevitrigonia* at the "Cinder Beds" level in the Vale of Wardour, the equivalent Whitchurch Sands, and horizons of a similar marine-brackish facies in Northern France (Casey and Bristow 1964), it may be inferred that this trigoniid also tolerated waters of reduced salinity.

Protocardia, the Portland counterpart of the common cockle, is well known for its occurence in estuarine and other ecological stations of variable salinity. Interdigitation of marine and brackish beds at the top of the Portland Beds at Swindon and Aylesbury has long been known from the ostracods and other fossils. Possibly belemnite guards are more certain indicators of fully marine conditions than the more buoyant and easily transportable ammonite shells. All in all, there are good reasons for believing that the Portland sea experienced episodes of freshwater dilution long before the onset of the Purbeck, and among the factors responsible for provincialism of its fauna reduced salinity evidently played an important part.

4. The Middle Volgian break

A new perspective has been given to stratal relations at the Jurassic-Cretaceous boundary in Britain and a feature which now stands out conspicuously is the sedimentary break at the end of the Kimmeridge Clay. As typically developed in the southern Midlands, this break is represented by the Upper Lydite bed, which forms a persistent base to the Portland Beds from Swindon to Aylesbury and constitutes the "basal conglomerate" of the Portlands in that area. I have interpreted this bed as a local expression of a more widespread interval of inhibited deposition that widens northwards to embrace the basal beds of the Sandringham Sands and Spilsby Sandstone and eventually becomes incorporated in the much larger gap denoted by the "Coprolite bed" at the base of the Speeton Clay of Yorkshire (Casey 1963). Throughout the whole of its outcrop from Wiltshire to the Yorkshire coast this horizon is characterised by an abundance of black chert pebbles ("lydites") and rolled and phosphatized fossils derived from the underlying Kimmeridge Clay. In consequence of a re-interpretation of the zonal sequence at the top of the Kimmeridge Clay it is now possible to see the *rotunda* nodules of the Dorset coast as the southernmost end of this important marker-horizon. "Calcareous and only slightly phosphatic at Chapman's Pool, these nodules denote that the centre of the sedimentary basin experienced only a slight pause in deposition in contrast to the protracted period of phosphatization and reworking felt in more marginal areas. It is at these nodules, however, that great changes take place in the heavy residues of the clays, quartz and glauconite coming in rapidly upwards (Lloyd 1959). Already, west of Holworth House, Weymouth the condensed *rotunda* succession resembles the Upper Lydite bed at Swindon, as noted by Arkell (1947). The phosphatized *rotunda* fauna found derived in the Lower Cretaceous of the Weald points to the former wide distribution of this

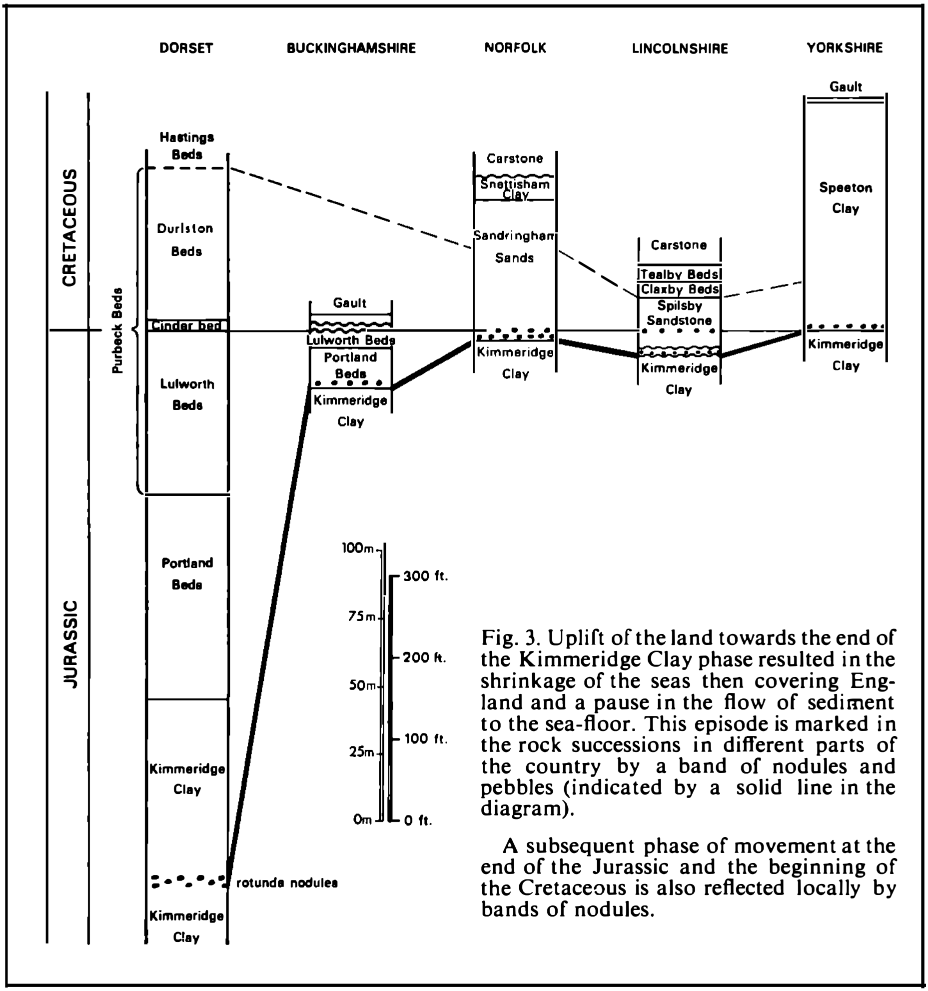


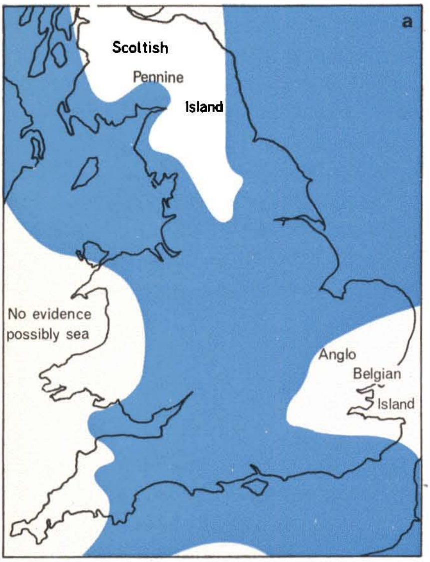
Fig. 3. Uplift of the land towards the end of the Kimmeridge Clay phase resulted in the shrinkage of the seas then covering England and a pause in the flow of sediment to the sea-floor. This episode is marked in the rock successions in different parts of the country by a band of nodules and pebbles (indicated by a solid line in the diagram).

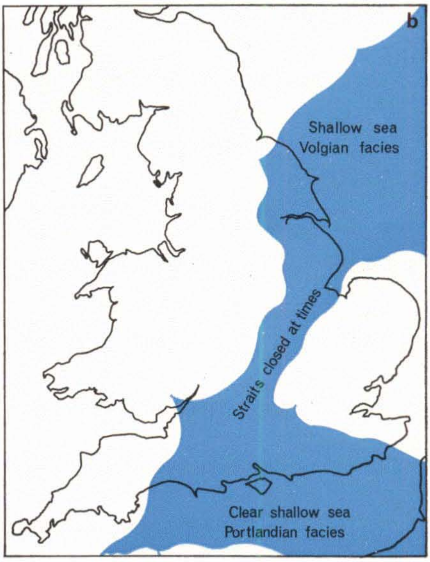
A subsequent phase of movement at the end of the Jurassic and the beginning of the Cretaceous is also reflected locally by bands of nodules.

horizon—surely one of the most important stratigraphical planes in the British Mesozoic" (Casey 1967).

Figure 3 shows the position of the *Pavlovia rotunda* nodules—"Lydite Beds" horizon (solid line) in a series of vertical sections from Dorset to Yorkshire. In terms of stage nomenclature, this regional disconformity may be dated as commencing early in the Middle Volgian on the reasonable assumption that the *Pavlovia* zones of the Kimmeridge Clay are homotaxial with the *Pavlovia pavlovi* Zone at the base of the Middle Volgian of the Russian Platform.

As regards the provenance of the chert pebbles ("lydites") which give the Lydite Bed its name, Neaverson (1925) noted how they tail out southwards from Buckinghamshire and thereby inferred a northerly source. He pointed out that their microscopic characters are similar to those of the cherts in the Carboniferous





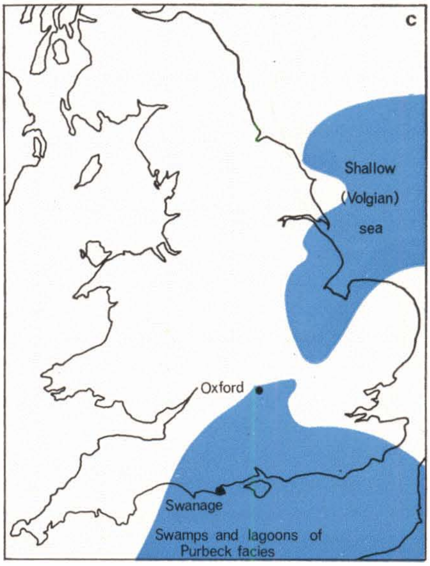


Fig. 4.

a Cartographic impression of England during the early Kimmeridgian stage of the upper Jurassic.

b Cartographic impression of England during the late Kimmeridgian and early Portlandian (Volgian) stages of the upper Jurassic.

c Cartographic impression of England during the late Volgian (early Purbeck) stage of the upper Jurassic.

Limestone of Derbyshire. A Carboniferous fauna of sponge spicules, fenestellids and foraminifera has been identified from the Lower Greensand chert pebbles in south-east England (Wells and Gossling 1947) believed to have been largely recycled from the Lydite Beds by way of the Anglo-Belgian island (Kirkaldy 1947). From the heavy mineral assemblage associated with the Buckinghamshire Lydite Bed Neaverson deduced more remote northern sources. He considered this bed to mark an important phase of uplift and rejuvenated drainage that brought sediment southwards from the Scottish Highlands as well as the north Midlands.

Evidently the Middle Volgian uplift was responsible for bringing great areas of Lower Carboniferous rocks under erosion, resulting in a tract of chert pebbles stretching from Yorkshire almost to Dorset. It is tempting to draw comparison with the Tertiary elevation of the Chalk of southern England and to visualize a newly emerged Pennine Range with white cliffs and long flinty beaches. A more significant parallel with Tertiary events is the south-easterly tilt imparted Britain by this uplift.

5. Palaeogeography and tectonics

Figure 4 is a series of cartographic impressions of Britain during the closing stages of the Jurassic. It attempts to show how the open seaway across England disappeared at the end of the Kimmeridge Clay phase, when the Middle Volgian uplift resulted in the formation of two basins of contrasting facies. Large areas of the map are speculative. It is too early to say, for example, whether the apparent absence of the Portland Sand fauna north of the Anglo-Belgian island and of the *Crendonites-Kerberites* assemblage in Norfolk indicate drastic shrinkage and isolation of the Spilsby basin during Portland times. The stratigraphical record may well be incomplete in the basal nodule beds of the Sandringham Sands and Spilsby Sandstone due to subsequent reworking of these marginal deposits. Probably there was a limited or intermittent communication between the two basins during the Portlandian (Fig. 4b), as pictured by Wills (1951).

During the early Purbeck an isthmus across Bedfordshire is believed to have barred access to the Spilsby Sea from the south (Casey and Bristow 1964) (Fig. 4c). That this barrier was again breached, albeit temporarily, at the beginning of the Cretaceous may be inferred from the increasingly marine aspect of the mollusca on the "Cinder Beds" horizon as this level is traced northwards to Stewkley, Buckinghamshire, suggesting that the sea broke into the Purbeck basin from the north (Casey 1963; Casey and Bristow 1964). Normal marine connexions were not established in this region until the Aptian.

The map illustrating the tectonic framework of northern Europe (Fig. 5) is based on the familiar one in Arthur Holmes's textbook (Holmes, 1944). North of the Baltic Sea lies a region of ancient crystalline rocks, the Baltic Shield, which forms the oldest part of the continent. Southwards and eastwards the Shield extends beneath a mantle of flat-lying sediments of Palaeozoic and later age, constituting the Russian Platform. To the north-west and to the south this stable region of Shield and Platform is bounded by the Caledonian and Hercynian orogenic belts respectively. The intersection of these two belts takes place in Britain and provides the key to understanding the palaeogeographic situation outlined above.

The Middle Volgian uplift responsible for delimiting the two basins of Late

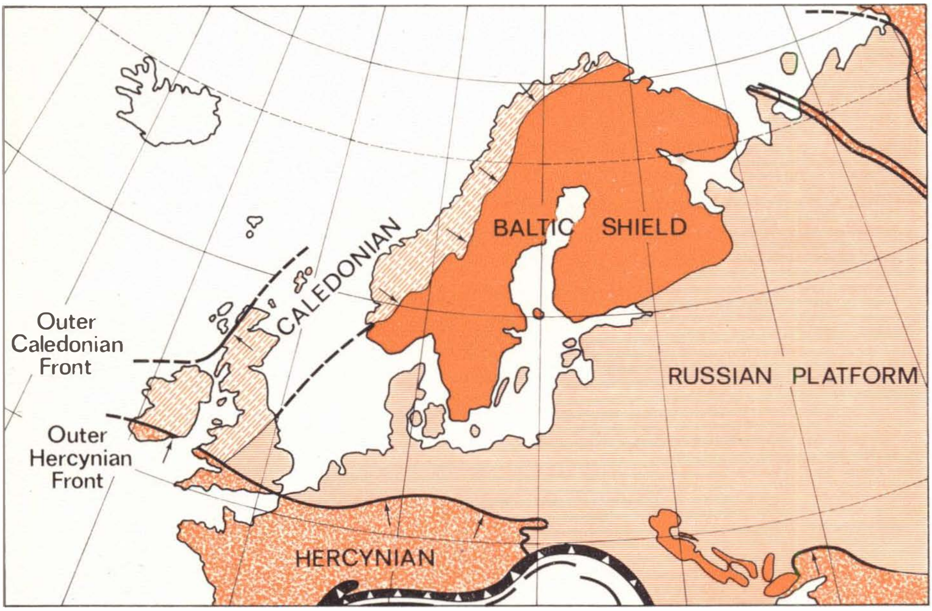


Fig. 5. Tectonic framework of northern Europe showing that the East Anglian (Spilsby) basin of deposition and the southern (Portland-Purbeck) basin are linked with the deep-seated geological structures.

Jurassic-Early Cretaceous deposition in England can be seen as essentially a movement within the Caledonian belt. If we imagine the south-eastern front of this belt asserting itself over the length of England and cutting across the outer Hercynian front in the west country we have the palaeogeographic setting for the Portland and Spilsby basins.

Not only is the Spilsby basin tectonically part of the Russian Platform, but its affinities are clearly shown in the nature of its shelf-like deposits and its faunas, which are virtually products of the same shallow sea. The clastic sediments of the Spilsby Sandstone and equivalent parts of the Sandringham Sands, rich in phosphorite nodules and glauconite, are mirrored in the condensed Volgian and Ryazanian deposits of the Moscow synclise. Their molluscan faunas can be matched nowhere else but on the Russian Platform.

Turning southwards to the Portland-Purbeck area of deposition, there can be little doubt that, though part of the Boreal ammonite realm, the affinities of this region lie with the Hercynian troughs to the south of the Russian Platform. In Late Jurassic times these troughs were the site of active subsidence and of predominantly calcareous deposition, leading to formation of the familiar "White Jura". The Portland Beds and lower half of the Purbecks (Lulworth Beds) could thus be interpreted as a western outpost of the "White Jura" province.

Subsequent movements of adjustment along the Hercynian front, such as the Osterwald phase of Saxonian folding, may have contributed to the emergence of the Bedford isthmus in Late Volgian times and to sea-floor elevation and reworking of Upper Volgian deposits in Norfolk. Although subordinate in importance to the Middle Volgian movement, this final phase of Jurassic uplift in England should be credited with providing us with a unique glimpse of the terrestrial fauna of the time, as revealed in the ancient soil of the Purbeck "Mammal Bed". Recent work on the North Sea basin raises the possibility that some of these subsidiary Upper Volgian movements were halokinetic in origin (Kent 1967).

To the structural geologist one of the benefits provided by the Middle Volgian uplift was to bring out a difference in tectonic province between eastern and southern England which in earlier Jurassic times had been concealed or poorly expressed, giving reality to Stille's "Palaeo-Europe" and "Meso-Europe". It was perhaps the nearest approach to "mountain-building" in the whole of the so-called Cimmerian orogeny and was coincident in time (though hardly of the same order of magnitude) with the Nevadan orogeny of North America. It is interesting to see that this fundamental movement in the Mesozoic structures of the British Isles lies within the late Precambrian mobile belt extending from the Arctic geosyncline to the Pacific and along which the North Atlantic Ocean formed (Sutton 1968). A possible clue to the date of opening of the North Atlantic may be gained from consideration of certain sedimentary features of the Middle Volgian break in the British Isles.

6. Phosphatization and the North Atlantic

Anyone who has gained his experience of neritic clay deposits from the English Gault will be surprised by the absence of phosphatic nodules in the Oxford Clay. This example highlights a significant difference between the Cretaceous and the main mass of the Jurassic in Britain. In the Lower Cretaceous and the base of the Upper Cretaceous beds of nodular phosphorite, frequently accompanied by glauconite, are the normal expression of inhibited deposition. Higher in the Cretaceous the Chalk hardgrounds maintain the link between interrupted sedimentation and phosphatization (Bromley 1967). Although the British Jurassic carries abundant signs of local pauses in sedimentation under bathymetric conditions similar to those which obtained in the shallow-water episodes of the Cretaceous, it is not until the Middle Volgian break that phosphatization on a large scale made its appearance in the British Mesozoic. In this respect the British sequence is typical for north-west Europe, where pre-Volgian phosphatization is insignificant compared with the extensive spreads of phosphorite characteristic of off-shore deposition in the Cretaceous.

Recent phosphate deposits are found in warm climates and chiefly in areas of oceanic upwelling caused by divergence (Kazakov 1937; Sheldon 1964). Due to the oceanic circulation system phosphate deposition occurs mainly along the west coast of continents or in large mediterranean seas along the equatorial side of the basin. Lesser concentrations form in areas of dynamic upwelling along the eastern coasts of continents (McKelvey 1967).

Figure 6 reproduces McKelvey's analysis of an idealized oceanic circulation system. The main elements of this system consist of a large circulating gyral in each hemisphere. Water cooled in polar latitudes moves towards the equator along the east side of the ocean and water warmed in equatorial latitudes moves

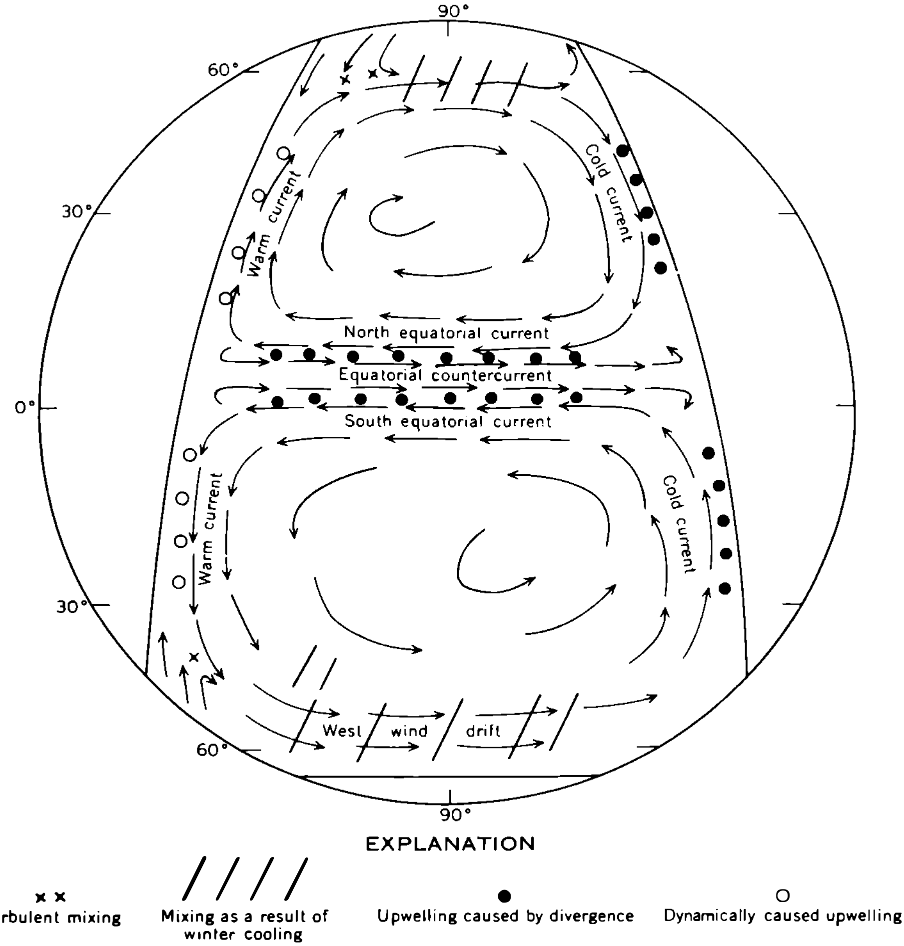


Fig. 6. Surface circulation in an idealized ocean, showing areas of ascending nutrient-rich water (McKelvey 1967).

polewards along the west side. Aided by the seaward movement of coastal surface waters resulting from the combined effects of the trade winds and Coriolis force, cold phosphate- and nutrient-rich water wells up along the western margins of the continents. The rise in temperature and pH of the upwelling water saturates it with respect to calcium phosphate, which then tends to be precipitated onto the sea-floor by organic or inorganic agencies. A similar process takes place where two currents diverge, as along the equatorial belt and in certain other situations (McKelvey 1967).

Sheldon (1964) has shown that modern phosphate deposition occurs between the 40th parallels, whereas ancient phosphorite has a much wider distribution, some occurring in positions where the phosphate-producing process could not operate today. However, the apparent anomaly can be explained by relocating their positions with reference to their palaeolatitudes as determined from magnetic studies. There is then a fairly close correspondence between the latitudes of young phosphorite and the palaeolatitudes of ancient phosphorite.

The relatively sudden introduction of phosphatization into the Mesozoic sedimentary pattern towards the end of the Jurassic in north-west Europe could thus be explained by (1) a northward shift of the climatic belts relative to the continents, or (2) a change in the oceanic circulation system.

What little is known of Mesozoic palaeoclimatology does not lend support to the idea of a strong shift of the climatic belts during the Jurassic. The coral reefs and giant saurians of the Oxfordian suggest waters at least as warm as those of the Portlandian. Bowen (1961), working on palaeotemperature analysis of belemnites, considers that the positions of the Jurassic and Cretaceous equators were much the same, probably extending through southern Europe. It seems more likely, therefore, that a change in the oceanic current system is indicated.

The Upper Jurassic-Lower Cretaceous phosphorite in Britain and the adjoining parts of the continent is commonly nodular, contains phosphatized shells and other organic remains and occurs in an arenaceous or argillaceous matrix seldom more than a few feet thick. It is typical of phosphate deposition on the platforms or stable areas adjacent to regions of cold-water upwelling associated with divergence (McKelvey 1967 pp. 10-11).

Recent attacks on the problems of continental displacement have tended to assign a Cretaceous date to the opening of the North Atlantic, either from the evidence of structural geology (Sutton 1968) or from sedimentology (Allen 1969). The data concerning phosphate-formation discussed above may be deemed to weight the evidence in favour of a Late Jurassic date (which would fit in with the presence of Upper Jurassic rocks on the sea-floor off the Canaries). It is suggested that by Middle Volgian times the North Atlantic rift had widened sufficiently to allow the development of a typical oceanic circulation system. The shallow epicontinental seas leading off from the European side of the early North Atlantic then came under the influence of the cold phosphate-rich waters welling up along the western side of the new continent. Whether or not the Middle Volgian uplift of Britain marked the final rupture, it was an expression of deep-seated structural changes, of which diversification of faunal provinces in England was a superficial by-product.

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References

ALLEN, P. 1969. Lower Cretaceous sourcelands and the North Atlantic. *Nature, Lond.* **222,** 657.
—— and KEITH, M. L. 1965. Carbon isotope ratios and palaeosalinities of Purbeck-Wealden Carbonates. *Nature, Lond.* **208,** (5017), 1278.
ARKELL, W. J. 1947. The geology of the country around Weymouth, Swanage, Corfe and Lulworth. *Mem. geol. Surv. U.K.*
BOWEN, R. 1961. Oxygen isotope paleotemperature measurements on Cretaceous Belemnoidea from Europe, India and Japan. *J. Paleont.* **35,** 1077.
BROMLEY, R. G. 1967. Marine phosphorites as depth indicators. *Marine geol.*, **5,** 503.
CASEY, R. 1955. The pelecypod family Corbiculidae in the Mesozoic of Europe and the Near East. *J. Washington Acad. Sci.* **45,** 366.
—— 1963. The dawn of the Cretaceous period in Britain. *South-eastern Union Sci. Soc. Bull.* **117,** 1.
—— 1967. The position of the Middle Volgian in the English Jurassic. *Proc. geol. Soc. Lond.* **1640,** 128.
—— 1968. The type-section of the Volgian stage (Upper Jurassic) at Gorodishche, near Ulyanovsk, U.S.S.R. *Proc. geol. Soc., Lond.* **1648,** 74.
—— and BRISTOW, C. R. 1964. Notes on some ferruginous strata in Buckinghamshire and Wiltshire. *Geol. Mag.* **101,** 116.
COPE, J. C. W. 1967. The Palaeontology and Stratigraphy of the lower part of the upper Kimmeridge Clay of Dorset. *Bull. Brit. Mus.* (*N.H.*), (Geol.), **15.**
DIETRICH, G. (ed.). 1962. Mean monthly temperature and salinity of the surface layer of the North Sea and adjacent waters from 1905-1954. *Conseil Permanent International pour l'Exploration de la Mer, Service Hydrographique.*
DODSON, M. H., REX, D. C., CASEY, R. and ALLEN, P. 1964. Glauconite dates from the Upper Jurassic and Lower Cretaceous. *In* The Phanerozoic Time-scale. *Q. J. geol. Soc. Lond.,* **120,** 145.
GERASIMOV, P. A. and MIKHAILOV N. P. 1966. The Volgian stage and the standard scale for the upper series of the Jurassic system. *Isv. Akad. Nauk. S.S.S.R., ser. geol.,* **No. 2,** 118. (in Russian).
HOLMES, A. 1944. *Principles of Physical Geology.* Nelson, London.
KAZAKOV, A. V. 1937. The phosphorite facies and the genesis of phosphorites in Geological investigations of agricultural ores U.S.S.R. *Sci. Inst. Fertilizers and Insectofungicides Trans.* (*U.S.S.R.*)., No. 142, 95, (special issue in English published for 17th Internat. geol. Cong.).
KENT, P. E. 1967. Outline geology of the southern North Sea basin. *Proc. Yorks. geol. Soc.* **36,** 1.
KIRKALDY, J. F. 1947. The work of the late Mr. Frank Gossling on the Stratigraphy of the Lower Greens and between Brockham (Surrey) and Westerham (Kent). *Proc. Geol. Ass.* **58,** 172.
KISCH, B. S. 1951. Mollusca of the Biarritz Aquarium Filter Basin. *Proc. malac. Soc.* **29,** 8, 44.
LLOYD, A. J. 1959. Arenaceous Foraminifera from the type Kimmeridgian (Upper Jurassic). *Palaeontology* **1,** 298.
McKELVEY, V. E. 1967. Phosphate deposits. *U.S. geol. Surv. Bull.* **1252-D.**
NEAVERSON, E. 1925. The Petrography of the Upper Kimmeridge Clay and Portland Sand in Dorset, Wiltshire, Oxfordshire and Buckinghamshire. *Proc. Geol. Assoc.* **36,** 240.
SAKS, V. N., RONKINA, Z. Z. SHULGINA, N. I. BASOV, V. A. and BONDARENKO, N. M. 1963. *Stratigraphy of the Jurassic and Cretaceous System in Northern U.S.S.R.* (in Russian). Akad. Nauk. S.S.S.R. Moscow and Leningrad.
SHELDON, R. P. 1964. Paleolatitudinal and paleogeographic distribution of phosphorites. *Prof. Pap. U.S. geol. Surv.* **501-C,** 106.
SUTTON, J. 1968. Development of the Continental framework of the Atlantic. *Proc. Geol. Ass.* **79,** 275.

SWINNERTON, H. H. 1935. The rocks below the Red Chalk of Lincolnshire and their cephalopod faunas. *Q. J. geol. Soc. Lond.* **91**, 1.

WELLS, A. K. and GOSSLING, F. 1947. Studies of pebbles from the Lower Cretaceous Rocks. *Proc. Geol. Ass.* **58**, 194.

WILLS, L. J. 1951. *A Palaeogeographical Atlas of the British Isles and adjacent parts of Europe.* Blackie and Son, London.