BRITISH LOWER JURASSIC SEQUENCE STRATIGRAPHY

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2 authors:


Stephen Peter Hesselbo
University of Exeter


Hugh C. Jenkyns
University of Oxford

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STEPHEN P. HESSELBO AND HUGH C. JENKYNS
Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, U.K.

ABSTRACT: Biostratigraphically well-calibrated exposures of Lower Jurassic rocks in the Wessex, Bristol Channel, Cleveland and Hebrides basins have been remeasured and interpreted in the context of sequence stratigraphy. The aim has been to see whether the stratigraphy and facies are compatible with the hypothesis that relative sea-level changes were synchronous across all these basins. The Lower Jurassic Series can be subdivided into four large-scale (so-called 2nd-order) lithologic cycles, with durations of approximately 3–10 my, that appear to be synchronously developed in all onshore British basins; the cyclic changes in facies become more extreme as the cycles young. Candidate maximum flooding surfaces in the large-scale cycles, identified on the basis of distal starvation, or facies successions indicative of maximal accommodation space in proximal areas, occur in the lower *semicostatum* zone (Lower Sinemurian), *obtusum–oxynotum* zones (upper Sinemurian), lower *jamesoni* zone (lower Pliensbachian) and *falciferum–bifrons* zones (lower Toarcian). Candidate sequence boundaries in the large-scale cycles, defined on the basis of major unconformities or facies successions indicative of minimal accommodation space in proximal areas, are recognized in the upper *turneri* zone (mid-Sinemurian), mid-*raricostatum* zone (upper Sinemurian), basal *margaritatus* zone (mid-Pliensbachian) and *levesquei* zone (upper Toarcian).

In general, at the large scale, the Lower Jurassic Series of the Dorset area of the Wessex Basin shows the most distal pattern of sediment accumulation, in which condensed sections (limestone or mudrock) correspond to relative sea-level rise or highstand and expanded sections (mudrock or sandstone) correspond to relative sea-level fall or lowstand. In contrast, the Lower Jurassic Series of the Skye, Pabay and Raasay areas of the Hebrides Basin exemplify the proximal pattern of sedimentation in which expanded sections (sandstone and mudstone) correspond to relative sea-level rise or highstand, and condensed sections (sandstone) correspond to relative sea-level fall or lowstand. The Yorkshire coast successions of the Cleveland Basin exemplify an intermediate setting. Significant divergence from this pattern is evident in the Toarcian (and through the Middle Jurassic) deposits over which interval the style of accumulation in the Hebrides is intermediate between that of the Wessex Basin and that of the Cleveland Basin. This indicates a reduction of clastic supply or increase in creation of proximal accommodation space in the Hebrides area relative to Yorkshire that began in the early Toarcian.

Lithologic cyclicity at the scale of ammonite zones and subzones (so-called 3rd-order) is recognized in a variety of facies; durations are inferred to be approximately 0.5 to 3 my. In a manner that contrasts with the large-scale cycles, the medium-scale cycles become more weakly expressed upwards through Lower Jurassic successions. The link between medium-scale sedimentary cycles and relative sea-level change is more interpretative than is the case for the large-scale cycles. There are few surfaces that have a definitive expression in all basins considered here; those that do are: candidate maximum flooding surfaces in the *lyra* and *taylori* subzones, and at the *stokesi–subnodosus* subzonal boundary (all major); and candidate sequence boundaries in the mid-*jamesoni* zone (moderate), and at the base of the *stokesi* subzone (major). Similarly, there are few surfaces that appear strongly localized, the best examples being candidate sequence boundaries in the *subnodosus* and *gibbosus* subzones, which are developed mainly in the south and north respectively. In hemipelagic-dominated, distal facies, there is evidence to suggest that stratigraphic condensation is a consequence of relative sea-level *fall* rather than rise; relative sea-level rises in these settings appear to have generated erosion surfaces. A new relative sea-level curve is presented with medium- and large-scale cycles shown that are compatible with all the successions considered in this study.

INTRODUCTION

This study utilizes exposures of the marine Lower Jurassic successions of the British Isles to examine the proposition that synchronous depositional sequences, of distinct orders of frequency and magnitude, can be recognized in different basins across the U.K. We intend this work to form a frame of reference against which sequence stratigraphic interpretations from other parts of the world may be compared. Not only can the British successions be correlated with those in other basins in north-west Europe at the level of an ammonite subzone (Dean et al., 1961; Cope et al., 1980; Cox, 1990), but they may also be compared on a global basis using Sr-isotope stratigraphy with almost equal precision (Jones et al., 1994). It is a central aim of this study, therefore, to root a Lower Jurassic sequence stratigraphic scheme in a careful assessment and documentation of the onshore U.K. exposures.

The development of lithologic cycles within the British Jurassic System, and their relationships to sea-level change has been a subject of much discussion (see Arkell, 1933; Duff et al., 1967; Einsele et al., 1991 for general reviews; see Hallam, 1961, 1964, 1981, 1988; Haq et al., 1988, for the interpretation of lithologic cycles). The successions exposed on the coasts of Dorset and Yorkshire played an important role in the calibration of the cycle chart of Haq et al. (1988). Differences between the Hallam (1988) and Haq et al. (1988) curves stem largely from the fact that the same surfaces in the Dorset and Yorkshire sections were given different interpretations regarding relative sea-level change, and because Hallam (1988) did not consider global sea-level change to have been established unless indicative phenomena could be traced widely across the world. A further difference between these curves arises because Hallam (1988) did not explicitly recognize an intricate hierarchy in the cyclicity.

Different levels in the hierarchy of sedimentary cyclicity (Haq et al., 1988; Vail et al., 1991) have been assigned to orders, defined on the basis of their perceived durations; those of concern to us here are: (1) large-scale cycles, with durations approximating to stages and thought to represent some 10 my (so-called 2nd-order, or transgressive-regressive facies cycles) and (2) medium-scale cycles, approximating to ammonite zones or subzones and representing approximately 0.5 to 3 my (so-called 3rd-order or sequence cycles). In the present study, we discuss separately the large-scale and medium-scale cycles. Lithologic cycles also occur at a smaller scales (so-called 4th order, etc.), but their occurrence is sporadic in the British Lower Jurassic successions, and regional correlation is not possible with the biostratigraphic resolution presently attainable; hence their origin is not discussed. It should not, of course, be assumed that every lithologic cycle at the same scale was produced by the same mechanism.

Recent years have seen the development of sophisticated models describing the architecture of depositional sequences in response to relative sea-level change (Posamentier et al., 1988;

Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, SEPM Special Publication No. 60

Posamentier and Vail, 1988; Sarg, 1988; Galloway, 1989; Van Wagoner et al., 1990; Vail et al., 1991; Tucker, 1991; Posamentier et al., 1993). However, doubt still exists as to whether the sequence stratigraphy of any basin is primarily a response to eustatic or regional sea-level fluctuation, or even whether the genesis of a given depositional sequence was necessarily governed by sea-level change at all (Galloway, 1989; Miall, 1991; Schlager, 1992). Central issues in this debate are both the areal extent and the pervasiveness of sedimentary cycles and associated bounding surfaces at several hierarchical levels: these are issues that can only be addressed with confidence in cases where first-class chronostratigraphic data exist and exposure or borehole control is very good.

One approach to the application of sequence stratigraphic concepts to outcrop exposures is the identification of 'key surfaces' in a given sedimentary cycle: (1) sequence boundaries, (2) transgressive surfaces and (3) maximum flooding surfaces (van Wagoner et al., 1988). The sedimentary expression of these will differ at different positions on a proximal to distal transect, but the following criteria are common. (1) A sequence boundary is an erosional unconformity or an abrupt basinward shift in facies inferred to be the correlative conformity. (2) A transgressive surface is an abrupt juxtaposition of deep-water facies over shallow. (3) A maximum flooding surface is indicated by stratigraphic condensation. Additionally, the arrangement of small-scale sedimentary cycles within larger ones has also been used to infer relative sea-level changes (van Wagoner et al., 1988; Mitchum and van Wagoner, 1991); most commonly this involves the relationships of '4th-order' within '3rd-order' depositional sequences. A further approach may be to identify the positions within lithologic cycles of particular facies, thought theoretically to be related to states of relative sea-level change (cf. Hallam, 1978).

BRITISH LOWER JURASSIC SUCCESSIONS

All major British Lower Jurassic sections have been remeasured (Figs. 1–9), including, from south to north, the coastal exposures of Dorset (Wessex Basin), Somerset and Glamorgan (Bristol Channel Basin), Yorkshire (Cleveland Basin) and western Scotland (Hebrides Basin). In areas where lithostratigraphic and biostratigraphic controls were relatively poor, further collections of ammonites were made in the course of the present study, and emphasis was placed on obtaining as detailed and complete a lithologic succession as possible; this has applied particularly to the Sinemurian strata of Robin Hood's Bay, Yorkshire (Hesselbo and Jenkyns, 1995; Fig. 3) and most of the Lower Jurassic strata of western Scotland (Hesselbo et al., 1998; Figs. 5–7).

The Lower Jurassic sedimentary rocks considered here were deposited in epicontinental extensional basins with broadly similar tectonic histories and patterns of sediment accumulation (Whittaker, 1985; Chadwick, 1986; Lake and Kamer, 1987; Penn et al., 1987; Milsom and Rawson, 1989; Ziegler, 1990; Jenkyns and Senior, 1991; Bradshaw et al., 1992; Morton, 1992; Hesselbo and Jenkyns, 1995). The strata were probably all laid down in fully marine environments, are predominantly siliciclastic and are typically, though not exclusively, fine-grained. In all the British onshore basins, the Lower Jurassic rocks are the first major marine accumulations following a period of continental sedimentation during the Triassic, and they preceded widespread deposition of Middle Jurassic restricted, coastal or non-marine sediments (Hallam, 1975, 1992; Ziegler, 1990; Bradshaw et al., 1992; Underhill and Partington, 1993, 1994).

The summary stratigraphic sections for each basin shown in Figures 3–8 are distillations from more detailed sections measured at the principal localities. Each stratigraphic section was compiled in an attempt to represent one structural location. However, in some cases, a composite section has been compiled through necessity. Where major synsedimentary faults have been traversed in the composites, they are indicated in the figures. Straightforward sections in simple structural settings were most difficult to obtain for the Hebrides Basin (Hesselbo et al., 1998). Therefore, several columns appear in Figures 5–6, possibly representing slightly different locations in a series of half grabens. Also, in western Scotland there are two distinct areas of outcrop that need to be distinguished when discussing the Hettangian–lower Pliensbachian strata, a northern area from the Isle of Skye to Applecross in Torridon, and a southern area, particularly Mull and the adjacent mainland of Morvern (Fig. 1).

In general, we first discuss the stratigraphy of the basins for which the clearest interpretations can be made, and then move to progressively more ambiguous sections. A summary of the large-scale transgressive and regressive trends in the Wessex, Cleveland and Hebrides basins is shown in Figure 10.

LARGE-SCALE CYCLES

Distribution of Large-Scale Sedimentary Cycles in British Onshore Basins

Yorkshire (Cleveland Basin).—

Large-scale cycles are strongly expressed as 100-m-scale sandstone and mudrock alternations (Fig. 3). The generally silty- and very-fine sandstone formations were deposited in shallow-marine, wave-dominated settings and, in contrast, the mudrocks were laid down in lower energy, deeper water environments (Hemingway, 1951; Sellwood, 1972; Hallam, 1978; Greensmith et al., 1980; Rawson et al., 1982; Howard, 1985; Pye and Krinsley, 1986; van Buchem and McCave, 1989; van Buchem et al., 1992; Hesselbo and Jenkyns, 1995). The lithological cyclicity is paralleled by a cyclicity in the thickness of accumulated sediment. In these stage-scale cycles, as expressed by *zonal* thickness, sandstones are relatively condensed whereas mudstones are relatively expanded (Fig. 3). On the basis of gross grain-size variations, the most distal facies are recognized in the Lower Sinemurian, lower Pliensbachian and lower to mid-Toarcian substages, whereas the most proximal facies occur in the Upper Sinemurian, upper Pliensbachian and uppermost upper Toarcian substages. A lithologic cyclicity, intermediate between the large-scale and the medium-scale discussed below, is observed in upper Sinemurian strata, evident through a general fining into the basal *oxynotum* zone. This cycle assumes much greater importance in the Hebrides Basin.

Strong arguments can be advanced in support of the proposition that the large-scale cyclicity observed in the Yorkshire succession is a result of large-magnitude relative sea-level rises and falls. Firstly, the muddy Upper Sinemurian sandstones had

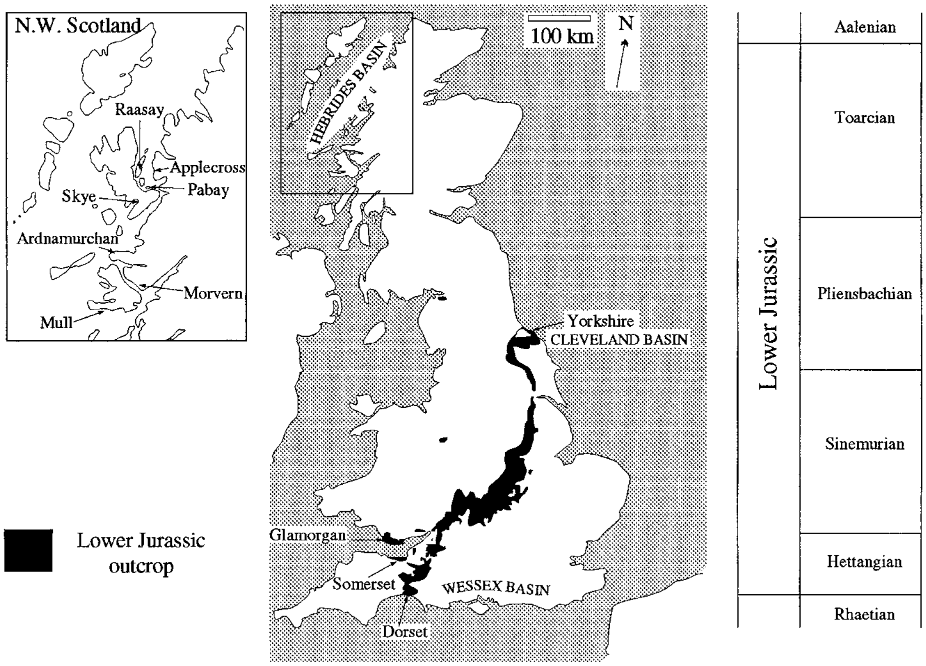

FIG. 1.—Location map and stratigraphic orientation for the Lower Jurassic strata of the British area.

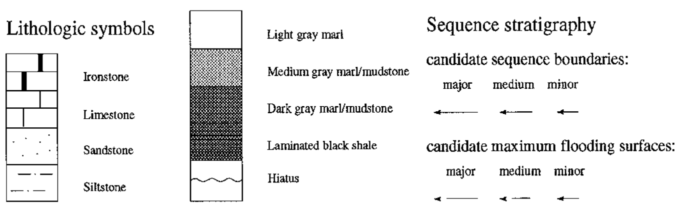

FIG. 2.—Legend for summary stratigraphic columns in Figures 3 to 8.

relatively low accumulation rates and pass upwards into lower Pliensbachian mudrocks that had relatively high accumulation rates. The same pattern is evident in upper Pliensbachian through to the lower Toarcian deposits. Therefore, in both cycles, an increase in accommodation space is required to permit shale accumulation. Our measure of accumulation rate is zonal and subzonal thickness: biostratigraphic subdivisions are taken to be of approximately constant time value, an assumption that is, of course, open to question. Any bias related to unequal duration of zones or subzones would probably increase the number of subdivisions recognized in the mudrocks, because preservation is generally better in this lithology, and a finer biostratigraphic precision would be facilitated. Correction for this potential bias would serve to amplify the apparent rate of relative sea-level rise. It is also possible that the mudrocks were deposited in *shallower* water than the sandstones, but given the very shallow aspect of most of the sandstones, the Staithes Sandstone for example (Rawson et al., 1982; Howard, 1985), such an interpretation has little merit. Furthermore, because of the significantly greater compaction that must have taken place in the mudrocks compared to the sandstones, the different relative thicknesses must originally have been considerably greater. (Differential compaction may explain partly why the upper Toarcian *levesquei* Zone, developed in sandstone, is somewhat thicker than the underlying two zones, developed in shales; this pattern may also relate to the greater ease with which coarse sediment may build into shallow water compared to fine sediment).

Secondly, unconformities on the basin margins correlate with the late Pliensbachian and late Toarcian phases of sand deposition in the basin. In the case of late Pliensbachian deposition, Howard (1985) and Copestake and Johnson (1989) have illustrated how most of the Cleveland Ironstone and the entire Staithes Sandstone are missing across the Market Weighton High to the south of the Cleveland Basin. The Toarcian/Aalenian unconformity (Black, 1934) is well displayed in the south of Robin Hood's Bay, where its relationship to the Peak Fault, a major synsedimentary structure (Milsom and Rawson, 1989), can be seen clearly. The stratigraphy on the eastern, upthrown, side of the Peak Fault is incomplete with Aalenian strata resting on mid-Toarcian. On the downthrow side, the Blea Wyke Sandstone (upper Toarcian) is preserved, but the stratigraphy is still incomplete as the uppermost *levesquei* Zone is missing (Knox, 1984). Thus, movement on the Peak Fault alone cannot explain the large-scale stratigraphic cyclicity, and sea-level fall of at least regional extent is implied.

Dorset (Wessex Basin).—

An upward change occurs from relatively slow and continuous accumulation in Hettangian and Early Sinemurian time, through to rapid but highly episodic sedimentation in the mid-Pliensbachian to Toarcian (and Middle Jurassic) time. This trend parallels the change from clays to sands as the main siliciclastic constituent (Fig. 4). Similar variations in lithology and depositional rate are superimposed at the scale of stages, with relatively continuous, gradual deposition characterizing the Hettangian to Lower Sinemurian and the lower Pliensbachian, in contrast to episodic deposition of asymmetric lithologic cycles which characterizes Upper Sinemurian, upper Pliensbachian, and upper Toarcian strata. These stage-scale cycles

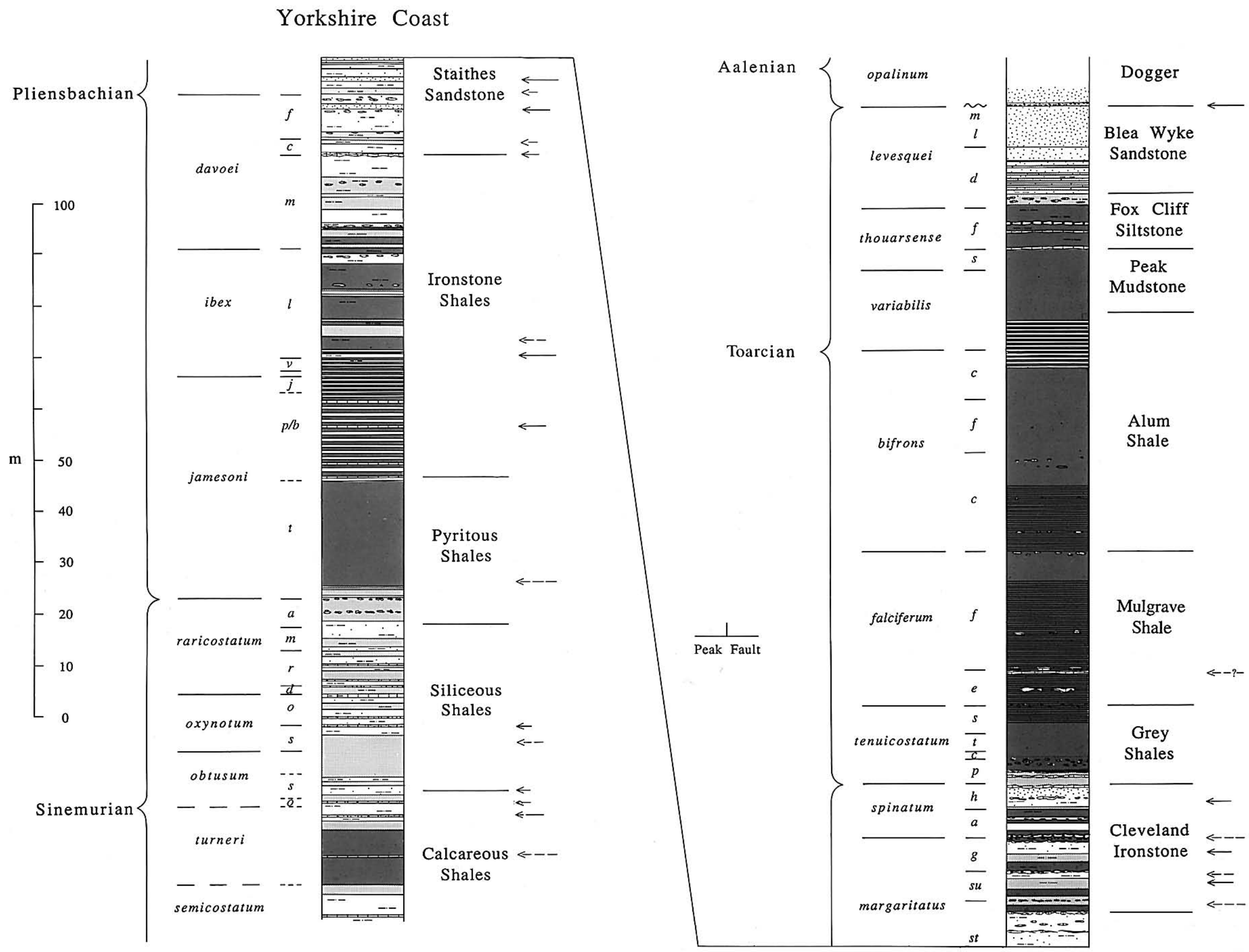

FIG. 3.—Summary sections for the Yorkshire coast Lower Jurassic (Cleveland Basin). See Figure 2 for key. All ammonite zones and subzones of the Lower Jurassic are present in the Yorkshire area except the uppermost, the *aalensis* subzone of the *levesquei* zone (Bairstow, 1969; Hemingway, 1974; Getty, 1980; Howarth, 1980a, b). Stratigraphy and sedimentology for the Robin Hood's Bay area of Yorkshire are discussed in Hesselbo and Jenkyns (1995). The Hettangian to mid-Pliensbachian strata are predominantly mudstone with subordinate sandy and Fe-rich intervals. The Redcar Mudstone (Powell, 1984), is subdivided into a number of informal units correlatable within the basin. Sandstone beds are developed in the Upper Sinemurian Siliceous Shales, whereas mudstone dominates both below, in the Lower Sinemurian Calcareous Shales, and above, in the lower Pliensbachian Pyritous Shales and Ironstone Shales. An organic-rich shale is developed in the Lower Sinemurian (*semicostatum* zone) Calcareous Shales and the lowermost Pliensbachian (*jamesoni* zone) Pyritous Shales. The ammonite zones of the Upper Sinemurian are condensed in comparison to those of lower Pliensbachian. The upper Pliensbachian is characterized by the occurrence of sandstone and ironstone: two distinct formations are recognized, the lower being almost entirely sandstone, deposited in a storm-dominated shallow-marine environment (the Staithes Sandstone) and the upper being a unit of mudstone, siltstone, sandstone and oolitic ironstone arranged in a 10-m-scale cycles (the Cleveland Ironstone) (Howard, 1985; Hesselbo and Jenkyns, 1995). Ammonite subzones of the Staithes Sandstone are similar in thickness to those of the underlying rocks, but those in the Cleveland Ironstone are somewhat condensed. The Toarcian comprises predominantly mudrock (the Whitby Mudstone; Powell, 1984; Rawson and Wright, 1995) with the uppermost part coarsening to fine sandstone (Blea Wyke Sandstone). Organic-rich facies occur mainly in the *falciferum* zone near the base of the succession, the Mulgrave Shale (formerly 'Jet Rock' sensu lato; Hallam, 1967, 1978; Morris, 1979; Myers and Wignall, 1987; Jenkyns, 1988; Rawson and Wright, 1995). The ammonite zones of the mudrocks are most expanded in the middle and condensed at the base and top.

broadly comprise the large-scale depositional sequences (Fig. 10), except in Upper Sinemurian deposits where patterns that are apparent in Yorkshire and the Hebrides are obscured in Dorset because of the incompleteness of the record.

The large-scale cycles can be interpreted in the context of relative sea-level change, although for much of the succession interpretation is somewhat difficult without also considering the other basins. The Hettangian and lowermost Sinemurian strata appear to have been deposited in relatively deep water during a relative sea-level rise with sediment starvation occurring in earliest Sinemurian time. Lower Sinemurian strata were probably then deposited during a relative sea-level highstand and, perhaps, subsequent fall, which allowed mud to prograde into the basin, filling space created during the earlier rise. Consideration of the Yorkshire and Hebrides successions suggests that the gaps in the Upper Sinemurian may have been a consequence of deposition during two episodes of relative sea-level rise, when supply to the basin was greatly reduced.

A return to relatively slow and continuous sedimentation inferred from the lower Pliensbachian strata is compatible with

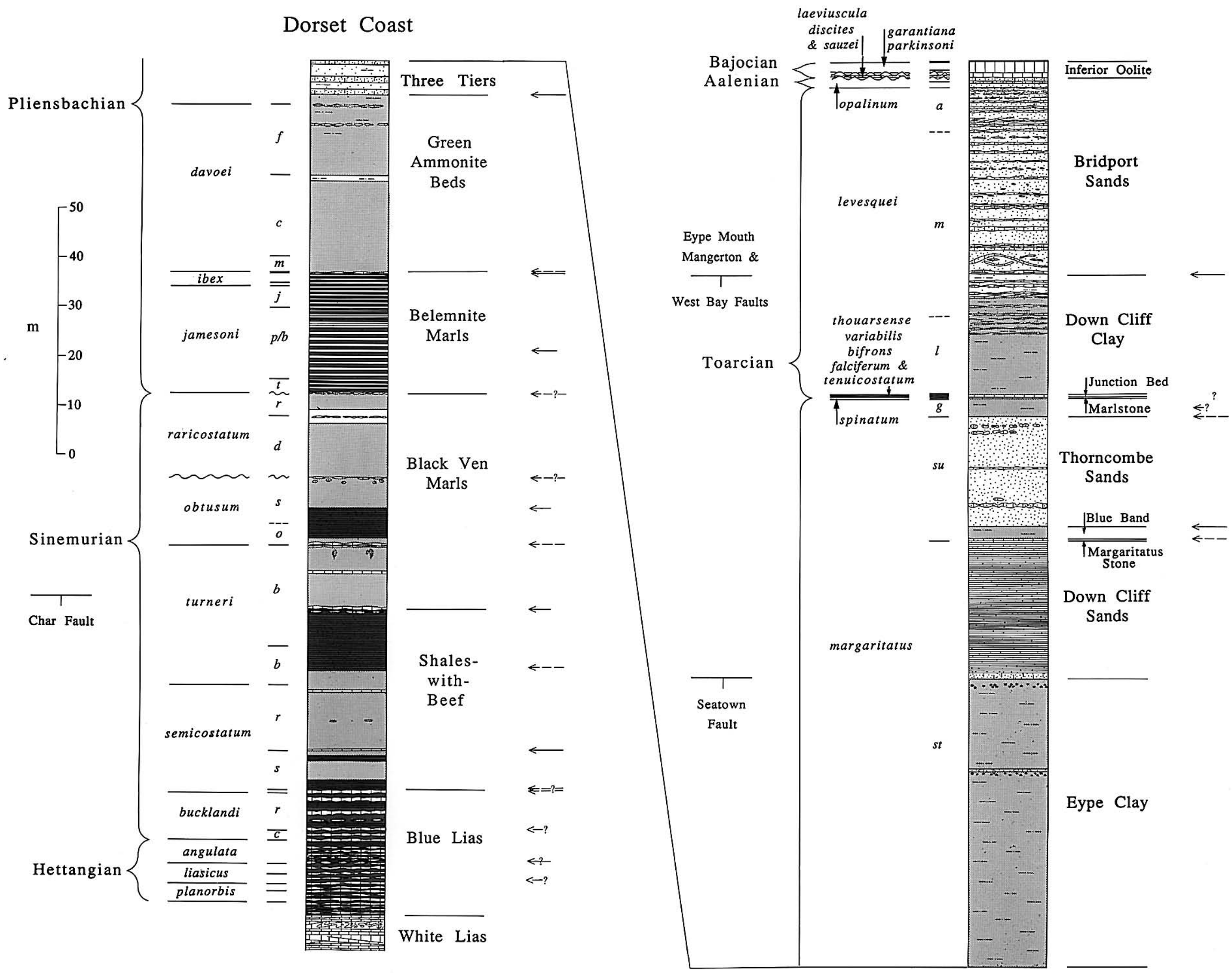

FIG. 4.—Summary sections for the Lower Jurassic Series of the Dorset coast (Wessex Basin). See Figure 2 for key. The Hettangian to mid-Pliensbachian of the Dorset area is predominantly mudrock, deposited in fully marine environments (Lang, 1924, 1936; Lang and Spath, 1926; Lang et al., 1923, 1928, Hesselbo and Jenkyns, 1995). The mudrock of the Hettangian and Lower Sinemurian section (the Blue Lias) is interbedded with limestone (Hallam, 1960, 1964; Weedon, 1985). Higher parts of the succession, the mid-Sinemurian to lower Pliensbachian (comprising the Shales-with-'Beef', Black Ven Marls and Belemnite Marls) also contain discrete and commonly thick intervals with significant volumes of carbonate, albeit more dispersed than in the Hettangian. The Belemnite Marls show a marked interbedding of organic-rich mudstone and carbonate-rich mudstone which is attributed to climatic control (i.e., Milankovitch cycles; Weedon and Jenkyns, 1990). Thick intervals of organic-rich, laminated black shales occur in the succession, particularly in the Lower to lower Upper Sinemurian (*semicostatum*, *turneri* and *obtusum* zones). Also important are biostratigraphic gaps in the Upper Sinemurian, upper *obtusum* to *oxynotum* and *raricostatum* zones (the Coinstone and the Hummocky respectively; Lang, 1945; Hallam, 1969; Sellwood, 1972; Hesselbo and Palmer, 1992). Lang has documented the ammonite zones and subzones, tied to a detailed lithostratigraphic succession (Palmer, 1972b; Getty, 1980; Howarth, 1980a). Overall, there is an increase in thickness of zones from the Hettangian to mid-Sinemurian (*planorbis* to *turneri* zones), above which level the pattern is complicated by missing zones and subzones in the Upper Sinemurian, and condensation in the lower Pliensbachian. (Some authors continue to recognize the *bucklandi* subzone at the top of the *bucklandi* zone (e.g. Page, 1992), whereas other authors subsume this within the *rotiforme* Subzone (Ivimey-Cook and Donovan, 1983); in this study we follow Ivimey-Cook and Donovan (1983), but indicate in the stratigraphic columns in parentheses the limits of the *bucklandi* subzone as previously recognized.) In the mid-Pliensbachian (Green Ammonite Beds) the carbonate content decreases and the silt content increases; the zonal thicknesses also increase upwards. The upper Pliensbachian is characterized by siltstone and sandstone (Howarth, 1957, 1980a) which passes upwards into the Junction Bed. Maximum sandstone thickness occurs at the top of the upper Pliensbachian section, though not at the end of the time interval that it represents. The two ammonite zones of the upper Pliensbachian are vastly different in thickness with the lower, *margaritatus* zone, being very expanded, and the upper, *spinatum* zone, being very condensed (in the Junction Bed *sensu lato*). Stratigraphic gaps occur in the succession, but are relatively small. The bulk of the upper Pliensbachian succession undoubtedly represents a shallowing of the depositional environment, with the shallowest water deposition occurring probably in the upper *subnodosus* subzone of the *margaritatus* zone. The basal unit of the Junction Bed (*sensu lato*), the Marlstone, belongs partly to the lowermost Toarcian and is an argillaceous, crinoidal and Fe-oolitic grainstone (Howarth, 1980c). The bulk of the Toarcian is represented by the very condensed limestone forming the Junction Bed *sensu stricto* which, although containing many gaps locally, is stratigraphically complete at a zonal level (Jackson, 1922, 1926; Howarth, 1980b, c, 1992; Jenkyns and Senior, 1991). Above the Junction Bed, the Toarcian strata comprise a thick coarsening upward succession of silt to fine sand (Down Cliff Clay to Bridport Sands).

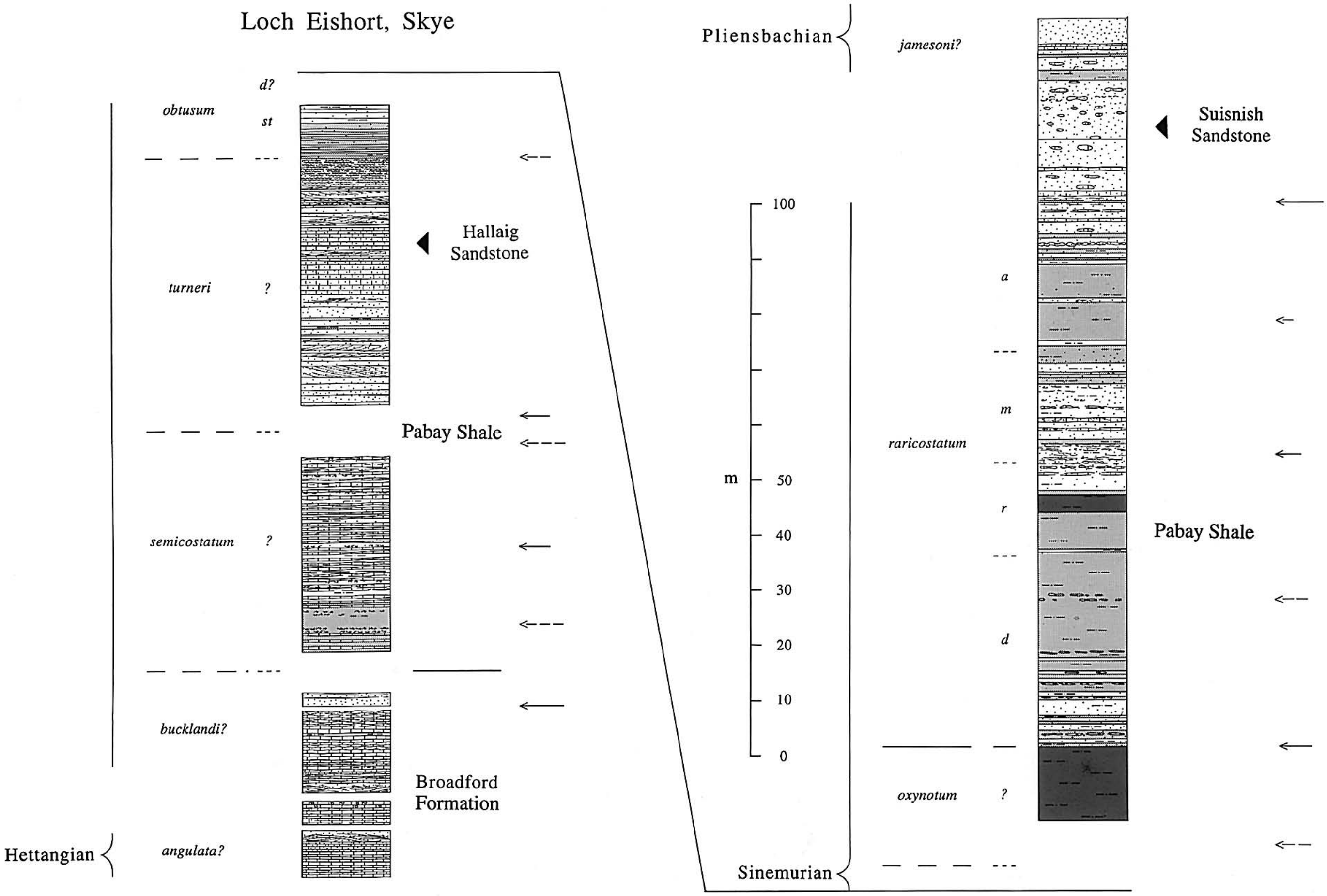

FIG. 5.—Summary section for the Hettangian–Sinemurian strata of Skye (northern Hebrides Basin). See Figure 2 for key. The succession comprises alternating sandstone and sandy mudstone, with minor pure mudstone, limestone and ironstone (Judd, 1878; Lee, 1920; Lee and Bailey, 1925; Richey and Thomas, 1930; Hudson, 1983; Hallam, 1992; Morton, 1990a, b; Hesselbo et al., 1998) and is relatively complete. Biostratigraphic assignments in are based on Hallam (1959) and Oates (1976, 1978). Lithostratigraphy is as revised in Hesselbo et al. (1998). The Hettangian to mid-Pliensbachian is a heterogeneous succession of limestone, sandstone and mudstone with a general pattern of expansion of the ammonite zones from the Hettangian into the lower Pliensbachian and condensation into the top of the lower Pliensbachian, complicated by condensation in the mid-Sinemurian (*obtusum* and *oxynotum* zones). The Broadford Fm, of Hettangian and earliest Sinemurian age, comprises interbedded carbonate and siliciclastic rocks deposited in environments as shallow as beach (Searl, 1989, 1992). Ammonites are rare but demonstrate termination of shallow-water deposition at the end of the *bucklandi* zone. The lower Pabay Shale (Lower to mid-Sinemurian) comprises sandy mudstone and sandstone. The *semicostatum* and *turneri* zones are relatively expanded and sandstone of the *turneri* zone exhibits meter-scale, roughly tabular, cross-bedding. Condensation of the mid-Sinemurian strata coincides with the development of less turbulent-water environments, culminating in the deposition of dark micaceous shales in the *oxynotum* zone. The upper Pabay Shale (Upper Sinemurian and lower Pliensbachian) is predominantly sandy mudstone. The more sandy units within the Pabay Shale are defined as members (Hesselbo et al., 1998).

deposition in deeper water, which probably began in Sinemurian time because the erosion surface that characterizes the Sinemurian–Pliensbachian boundary (the Hummocky) is less marked than the erosion surface within the Upper Sinemurian (the Coinstone). Milankovitch cycles, present in the Hettangian (Blue Lias) and in the lower Pliensbachian (Belemnite Marls) deposits (Weedon, 1985; Weedon & Jenkyns, 1990), may also indicate deposition in deeper water, more hemipelagic environments, less prone to disruption by near-shore or near-surface processes.

Upper Pliensbachian strata can be interpreted simply as a consequence of progradation of sediments into deeper water during a late Pliensbachian relative sea-level highstand and, possibly, fall; the expansion of the upper Pliensbachian strata with respect to the underlying strata is interpreted here as a consequence of increasing grain-size (silts to fine sands) and supply rate, which permitted the sediment pile to build into shallower, more turbulent water.

Bathymetric interpretation of the Junction Bed (Fig. 4) has always been a matter of some discussion. For this bed, and the lithologically similar Middle Jurassic Inferior Oolite, Sellwood and Jenkyns (1975) favored deposition in water that was too shallow to allow significant accumulation of clay, but they were frank about a lack of diagnostic paleobathymetric criteria. However, limestones such as the Junction Bed clearly characterized areas of reduced subsidence within the Wessex Basin. Other areas within the basin with higher rates of subsidence (e.g., the Winterborne Kingston Trough; Rhys *et al.*, 1982), accumulated a less condensed, muddier lower to mid-Toarcian succession. On the basis of correlation with widespread transgressive facies

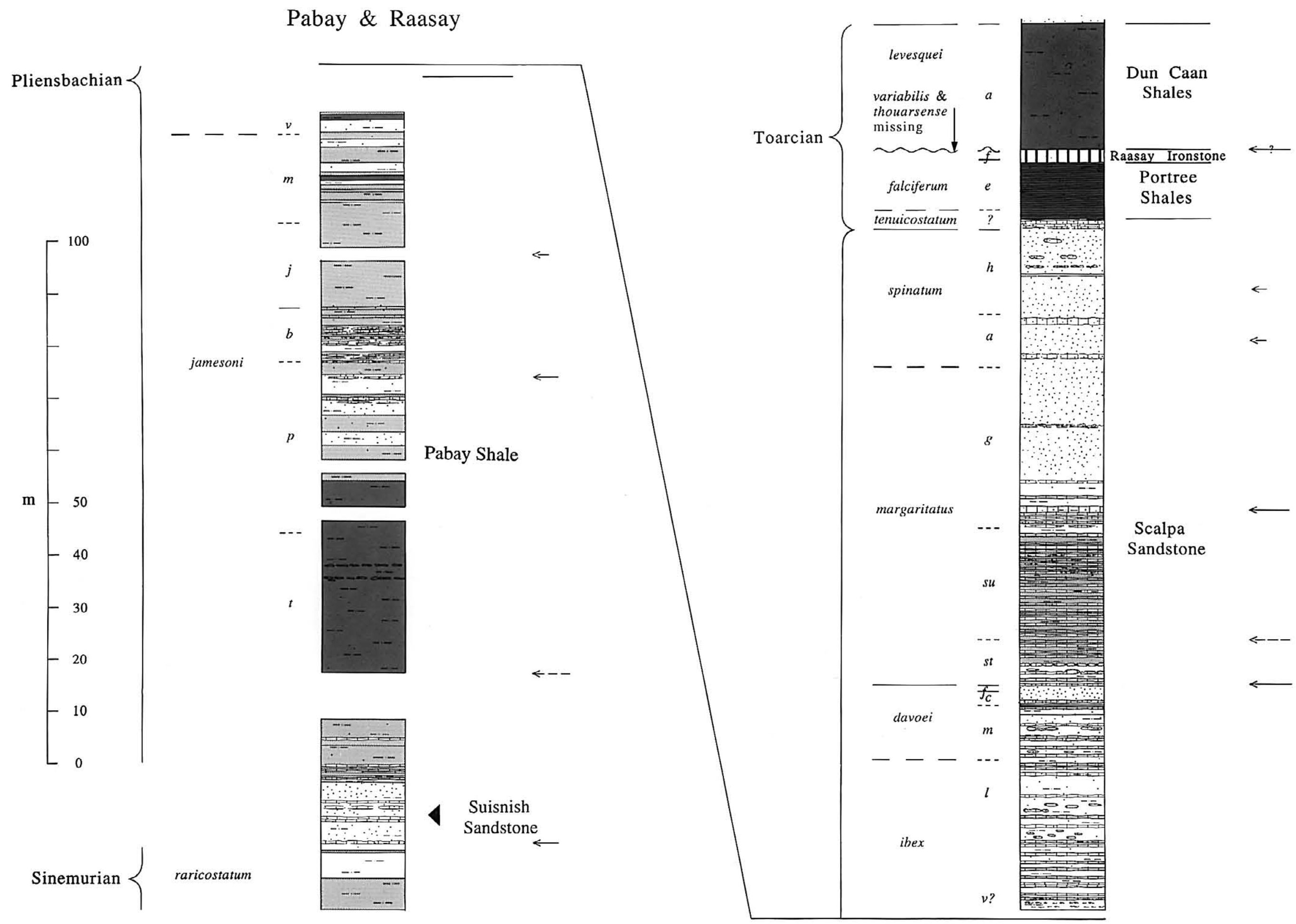

FIG. 6.—Summary section for the Pliensbachian–Toarcian of Pabay and Raasay (northern Hebrides Basin). See Figure 2 for key. In the Pabay Shale, a thick homogeneous sandstone member (Suisnish Sandstone) is developed locally at the Sinemurian/Pliensbachian boundary, overlain by dark mudstone with siderite concretions which is an identical facies to the age-equivalent strata in Yorkshire (i.e., the Pyritous Shales). The upper Pliensbachian succession, the Scalpa Sandstone, comprises a very-fine-grained bioturbated sandstone or siltstone. The sandstones locally extend down into the lower Pliensbachian and up into the Toarcian. The Scalpa Sandstone section shown is as seen on Raasay, using the stratigraphy of Howarth (1956), Phelps (1985) and Hesselbo et al. (1998): sedimentology of the upper part of the Scalpa Sandstone has been discussed by Hallam (1967). The Toarcian strata contrast greatly with those underlying, in that they are relatively condensed. Condensation and missing section are particularly marked in the mid-Toarcian Raasay Ironstone which lies between two mudrock units, the organic-rich Portree Shales below, and the Dun Caan Shales above. The Portree Shales are of *falciferum*-zone age, and there is close correlation with the Mulgrave Shale (= 'Jet Rock') of Yorkshire in terms of age and lithology. These units are representative of widespread carbon-rich *falciferum*-zone-age shales that occur throughout Europe and elsewhere (Jenkyns, 1988). Ammonites within the Raasay Ironstone of Raasay indicate the *falciferum* zone (Howarth, 1992), but on Ardnamurchan (Richey and Thomas, 1930; Dean et al., 1961; Howarth, 1992) indicate additionally the *thouarsense* zone (?*striatulum* subzone): the whole is clearly condensed and incomplete. A further stratigraphic break above the ironstone is indicated by the ammonites in the Dun Caan Shales which are upper *levesquei* zone (*aalensis* subzone); although mostly developed as shale, the Skye sections, particularly those exposed in the Strathaird area, are very sandy.

elsewhere, Hallam (1975, p. 165) considered the Junction Bed to have formed at a time of rising sea-level: its condensed nature being partly a function of sediment starvation (cf. Talbot, 1973), and a conclusion with which we concur. The early Toarcian relative sea-level rise probably began in the late Pliensbachian time, judging from the lack of documented latest Pliensbachian (*spinatum* Zone) sand in the Wessex Basin.

Although the influx of silt and sand from the north in late Toarcian time has previously been interpreted as due to deepening (i.e. to the creation of accommodation space; Sellwood and Jenkyns, 1975), it now seems much more likely that it resulted from a late Toarcian relative sea-level highstand and fall that caused renewed (and latterly rapid) progradation of sands from north to south. It was pointed out by Hallam (1978) that this juxtaposition of fine-grained facies over condensed limestone in the Toarcian (and the Bajocian-Bathonian) strata was local to the Dorset and Normandy areas, and he thus argued for local tectonic override of a eustatic regressive trend. However, if the Junction Bed is viewed as a phenomenon indicative of starvation in distal areas, albeit best developed on intra-basinal highs, the late Toarcian silt to sand (Down Cliff Clay and Bridport Sands) succession is not anomalous within the wider context. Relative sea level may have begun to rise again in the latest Toarcian because a lower Aalenian expanded equivalent

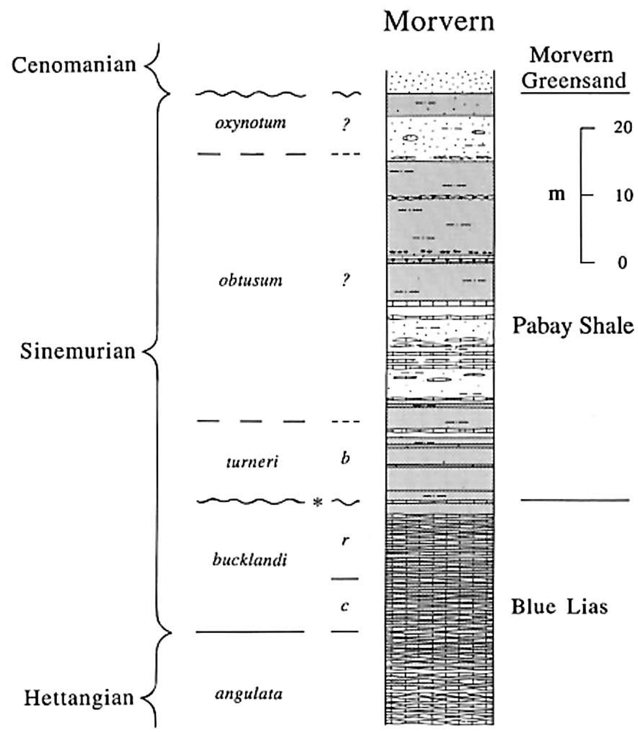

FIG. 7.—Summary section for the Lias of Morvern (southern Hebrides Basin). See Figure 2 for key. The shallow-water Broadford Fm of the northern Hebrides area is not well developed in this part of the basin. Here mudstone/limestone interbeds (Blue Lias) are instead predominant in the Hettangian and Lower Sinemurian (Oates, 1978; Hesselbo et al., 1998). These are overlain, by a coarsening-up succession of sandy mudstone and muddy sandstone of mid-Sinemurian age assigned to the Pabay Shale. The ammonite succession is relatively complete, except at the junction between the Blue Lias and the Pabay Shale where the only subzonal representative of the *semicostatum* zone is the *lyra* subzone, occurring locally in a thin pryritized crinoidal limestone at the level marked by an asterisk.

of the Bridport Sands has not yet been reported in the English Channel area, where one might expect to find accumulated sediment had it been forced into a more distal setting through lack of accommodation space.

Western Scotland (Hebrides Basin).—

Broadly, the large-scale lithologic cycles recognized in the Lias of the Hebrides (Figs. 5, 6) are similar to those of Yorkshire and Dorset (Figs. 3, 4). The overall trend from Hettangian into lowermost Sinemurian strata is one of deepening with shallow-water, marginal facies (Broadford Fm), passing upwards into quiet-water, open-marine facies (Pabay Shale Fm). It is also clear that the middle Lower Sinemurian rocks are relatively regressive, comprising in part coarse siliciclastic sediment deposited in shallow, highly energetic marine or paralic environments (the Hallaig Sandstone Member of Hesselbo et al., 1998; Fig. 10). Unfortunately, in what are probably the most proximal areas, Raasay and Skye, the mid-Sinemurian stratigraphic relationships are uncertain and, beyond the indication that sandstone of the *turneri* zone is replaced upwards by sandy mudstone of the *obtusum* zone and shale of the *oxynotum* zone, we can determine little about the completeness of that transition. Nevertheless, in the Skye area, the evidence does seem to point

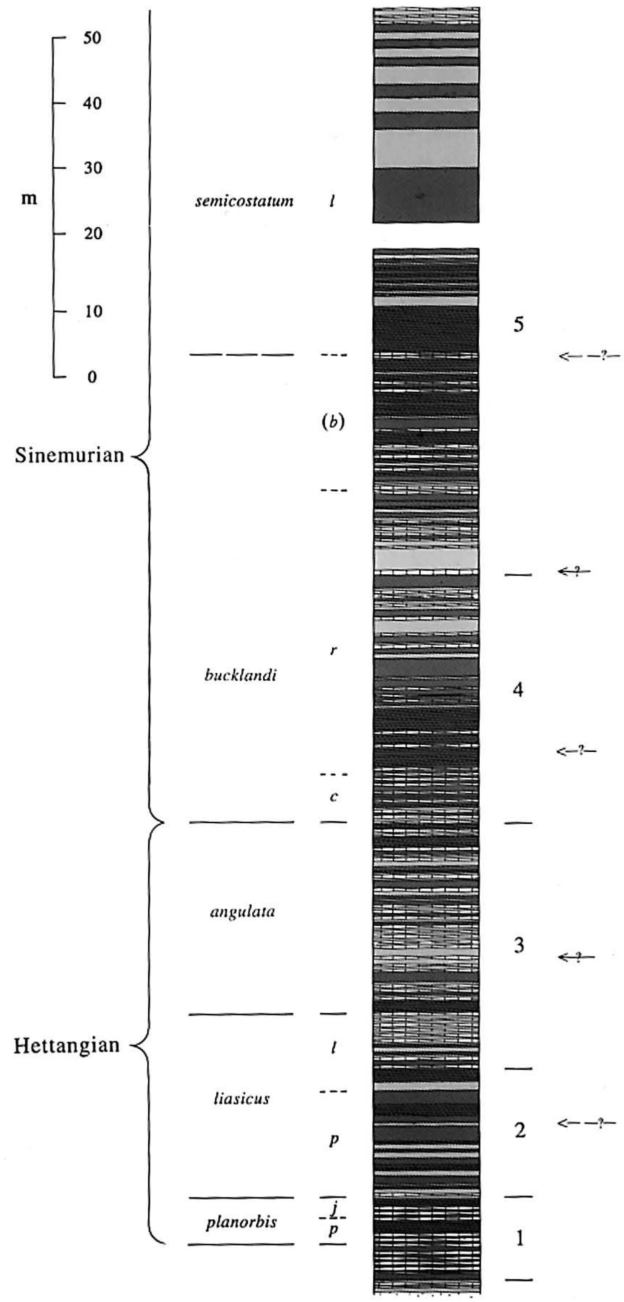

FIG. 8.—Summary section for the Lias of the north Somerset coast (Bristol Channel Basin). Locations of measured sections for individual segments indicated. See Figure 2 for key. Although the Somerset section is one of the most expanded Hettangian onshore successions in the British area, exposure does not permit examination of strata younger than the *semicostatum* zone. The Lower Jurassic rocks overlie uppermost Triassic strata of the Penarth Group which were deposited in marine, or marginal marine environments subject to subaerial exposure and desiccation. By convention, Cope et al. (1980) take the first appearance of the ammonite *Psiloceras planorbis* as defining the base of the Jurassic System. The summary section is a composite based on our own work, and integrates data published previously (Palmer, 1972a; Whittaker and Green, 1983; Page, 1992). At the top of the section we observe that the succession comprises interbedded light and dark marls decreasing in thickness upwards. The sedimentary facies are closely comparable with those of the Blue Lias and Shales-with-'Beef' of Dorset with which they correlate. The successions do, however, differ in that the *lyra* subzone of the *semicostatum* zone is not condensed in Somerset, where it may be as much as 90 m thick (Page 1992).

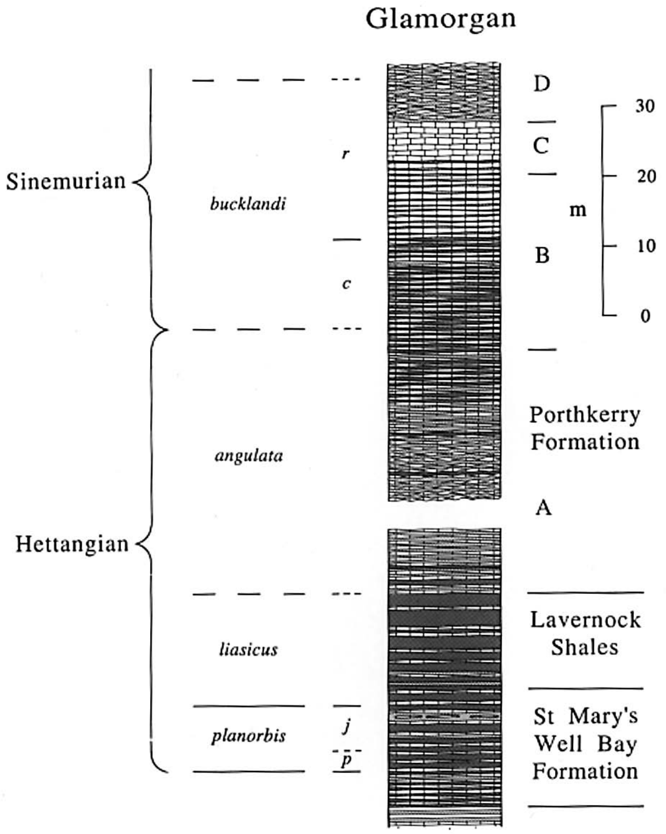

FIG. 9.—Summary section for the Lias of the Glamorgan coast (Bristol Channel Basin). See Figure 2 for key. The Lias is exposed only up to the lowermost Sinemurian and comprises rhythmically interbedded limestone and mudrock typical of the Hettangian and Lower Sinemurian (referred to as the 'offshore' facies) and conglomeratic and oolitic limestone (known collectively as 'marginal' facies). Detailed stratigraphic work has been carried out by Trueman (1920, 1922, 1930), Hallam (1960), Wobber (1965, 1966, 1968), Waters and Lawrence (1987), Wilson et al. (1990) and Hodges (1986, 1994). The summary section in the present study is a composite from two localities representing only 'offshore' facies, St Mary's Well Bay to Lavernock Point and Nash Point. It is likely that the Hettangian section at Nash Point, concealed below surface, is considerably thinner than that at Lavenock. The 'offshore' facies are very similar to those of the same age in Somerset and Dorset, except that millimeter-laminated organic-rich shales are only well developed in the uppermost Rhaetian (Pre-Planorbis Beds) and the lowermost Hettangian (*planorbis* zone). The most pronounced contrast between the Glamorgan succession and that of Somerset or Dorset is in the lowermost Sinemurian (mid-*bucklandi* zone) which comprises thick-bedded limestone in South Wales. The limestone is commonly packstone and contains coarse skeletal debris including crinoids and vertebrate material at the bases of fining-upwards units (Wilson et al., 1990). Cross-stratification is locally evident in the limestone despite the abundant bioturbation.

to a progressive and sustained deepening from the uppermost *turneri* zone to the *oxynotum* zone. In the more distal regions (e.g., Morvern, Figure 6) the *turneri*-zone to *obtusum*-zone succession coarsens steadily upwards and a subtle fining is evident between the *obtusum* and the *oxynotum* zones, but the existence of an *oxynotum*-zone deepening in the southern area of the Hebrides Basin, particularly on Mull, is far from proven (see e.g., Hesselbo et al., 1998). In contrast to Morton (1989, 1990b), we find no evidence to suggest that the limited *semicostatum*-zone non-sequence between the Blue Lias and Pabba Shale in Morvern is part of a diachronous unconformity, supposedly continuous with an erosion surface at the base of the *obtusum* zone in Skye.

The uppermost Sinemurian succession (*raricostatum* zone) in the proximal areas is, like the mid-Sinemurian, also sandy (the Suisnish Sandstone Member of Hesselbo et al., 1998; Fig. 10), although neither the sediment grade nor the sedimentary structures achieve the dimensions observed in the *turneri* zone (Hallaig Sandstone), suggesting that the former were deposited in a greater depth of water. It is also notable that the *raricostatum* zone is relatively expanded (Fig. 6), which we attribute to the infilling of accommodation space created from the *obtusum* to the *oxynotum* zones and an increasing rate of creation of accommodation space in the time equivalent to the uppermost *raricostatum* zone.

The lower Pliensbachian (*jamesoni* zone) section of Pabay is markedly expanded; indeed, extrapolating from the increased thicknesses of *raricostatum*-zone sandstone on Skye compared to Pabay (Figs. 5, 6), it is likely that in any single vertical succession the strata are more expanded than the underlying *raricostatum* zone (no such section has been discovered at outcrop). The Pliensbachian section of the Pabay Shale is also less sandy than the Sinemurian portion. We take the earliest Pliensbachian to be the time of maximum rate of creation of accommodation space in the large-scale cycle. The mid- to upper Pliensbachian section shows a return to deposition of shallow-marine sandstone. Sedimentary thicknesses are most reduced in the mid-Pliensbachian, around the *davoei-margaritatus* zonal boundary, which we interpret as representing the level of minimum accommodation space in the large-scale cycle. The expanded upper Pliensbachian section is interpreted as reflecting renewed relative sea-level rise. The lower Toarcian is a deepening succession characterized by the occurrence of organic-rich mudrocks overlying the condensed top of the Scalpa Sandstone.

The mid-Toarcian Raasay Ironstone is somewhat problematic. It may owe its origin to starvation during relative sea-level rise (as we have argued for the partly age-equivalent Junction Bed of Dorset), but the top surface may also have been winnowed during relative sea-level fall in latest Toarcian time prior to the resumed abundant supply of siliciclastic sediment. The uppermost Toarcian section clearly represents an overall shallowing phase into the Middle Jurassic sandstone above.

Somerset and South Wales (Bristol Channel Basin).—

Although the facies in Somerset (Fig. 8) are very similar to those in Dorset, the notable expansion of the *lyra* subzone suggests that sediment supply was sufficiently great to fill all available accommodation space and, hence, that relative sea level showed a progressive and accelerating rise through Hettangian and earliest Sinemurian time.

In the Glamorgan area of South Wales (Fig. 9), the progressive onlap and upward expansion of ammonite-zone thicknesses are compatible with deepening through Hettangian and earliest Sinemurian time. However, an alternative explanation for the onlap, that it is generated by increasing sediment supply driven by relative sea-level fall in the source area, cannot be ruled out on the basis of data presently available. It is relevant to this debate that the 'marginal' facies of South Wales have for the most part been interpreted as littoral with the outcrop

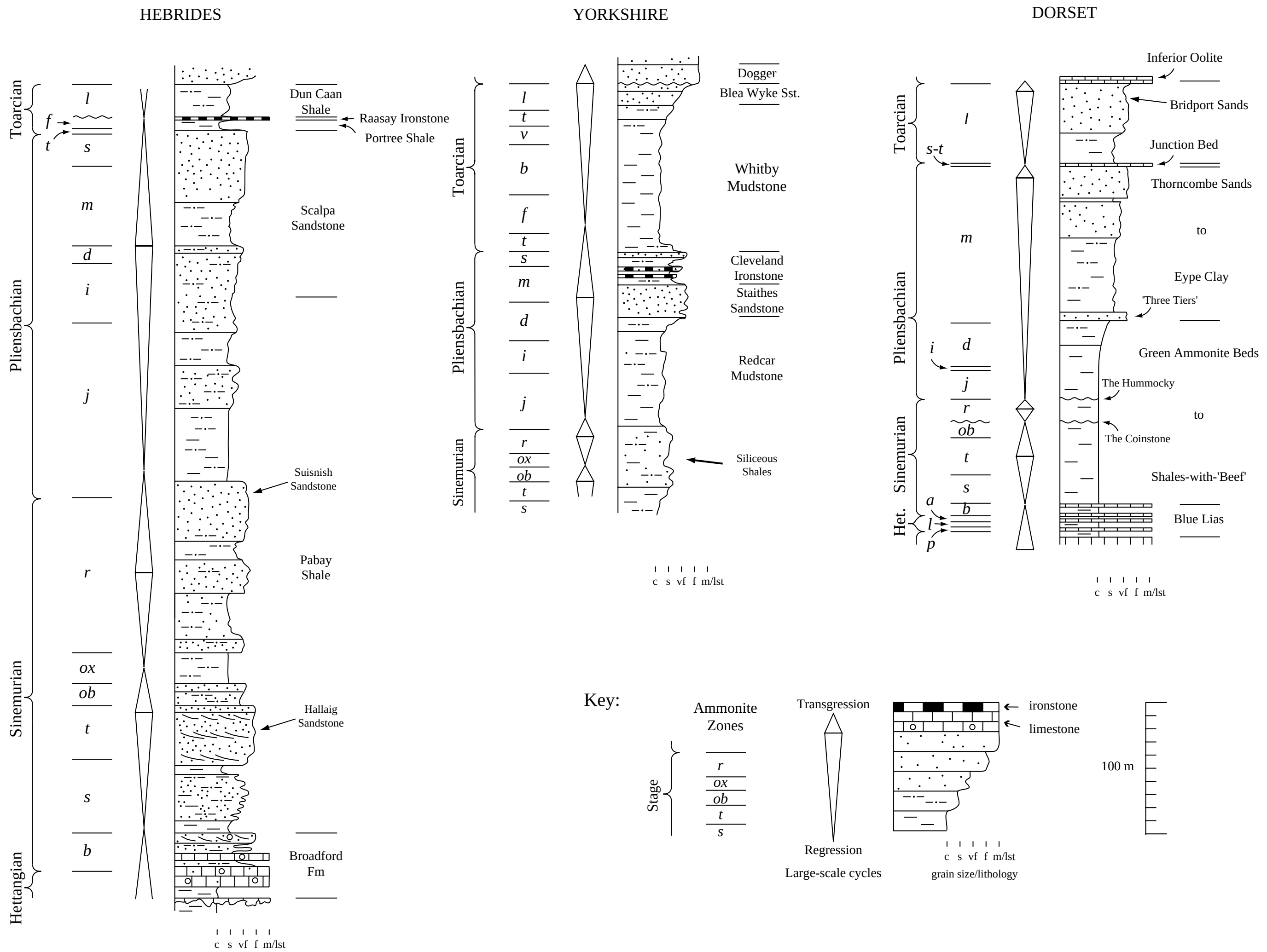

FIG. 10.—Lower Jurassic successions of the Hebrides, Cleveland and Wessex basins, showing large-scale transgressions and regressions generated by relative sea-level change.

relations thought to indicate progressive inundation of the Carboniferous basement, during Early Jurassic transgression (e.g., Trueman 1922), but interpretation of these deposits is somewhat controversial (Ager, 1986; Hodges, 1986; Fletcher et al., 1986; Fletcher, 1988; Wilson et al., 1990). Fletcher (1988) has detailed the nature of the unconformity surface around Ogmore and the relationships of the basal conglomerates and breccias to that surface. The surface morphology resembles modern tropical shorelines, and the orientations of bored pebbles, cobbles and boulders in the rocks immediately overlying the unconformity, led Fletcher (1988) to suggest a model of tidal-nip formation and subsequent cliff collapse. However, beds higher in the succession at Ogmore, are, as Ager (1986) pointed out, matrix-supported conglomerates and may indeed be the products of debris flow. Wobber (1965) suggested a number of depositional processes, ranging from cliff-collapse and wave-action on a beach to density currents, slumps and slides in deeper water. The strong evidence for mass-flow depositional processes lends more weight to the deeper-water hypothesis. Thus the onlap observed may not be limited by shallow-water reworking.

Comparison of Large-Scale Sedimentary Cycles in the British Area

Relative Sea-Level Change and Stratigraphic Response.—

We have argued for the existence and ages of the large-scale cycles independently for each basin, but we also believe that the large-scale (2nd-order) relative sea-level cycles, which were the driving mechanism behind the formation of the lithologic cycles, were largely synchronous in all British basins (Fig. 10). Four large-scale lithologic cycles are recognized, with durations of approximately 3–10 my. Maximum flooding surfaces, identified on the basis of distal starvation, or facies successions indicative of maximal accommodation space in proximal areas occur in the *lyra* subzone of the *semicostatum* zone (Lower Sinemurian), at the *obtusum–oxynotum* zonal boundary (Upper Sinemurian), in the *taylori* subzone of the *jamesoni* zone (lower Pliensbachian), and within the *falciferum* zone (lower Toarcian). Sequence boundaries, defined on the basis of major unconformities or facies successions indicative of minimal accommodation space in proximal areas, are recognized in the *birchi* subzone of the *turneri* zone (mid-Sinemurian), the mid-*raricostatum* zone (Upper Sinemurian), the *stokesi* subzone of the *margaritatus* zone (mid-Pliensbachian), and the mid-*levesquei* zone (upper Toarcian).

There is a striking reciprocal relationship in stratigraphic thickness observed in a comparison of the Pliensbachian and Toarcian between Yorkshire and Dorset: thick sections in Yorkshire correspond to condensed sections in Dorset and *vice versa* (Hesselbo and Jenkyns, 1995; cf. Wilson, 1967). This relationship is also evident in a comparison of the Lower Jurassic Series of all the British onshore basins (Fig. 10).

We suggest that those parts of basins that were underfilled with respect to creation of marine accommodation space accumulated sediments preferentially when relative sea-level was falling (i.e., when sediment was forced basinward by lack of proximal accommodation space). Within the Dorset area of the Wessex Basin, thicknesses of strata related to long-term relative sea-level falls are significantly greater than those deposited during long-term relative sea-level rise (Fig. 10).

In contrast, areas of basins receiving large quantities of sediment in comparison with available accommodation space will only be able to accumulate large amounts of sediment during relative sea-level rise, so long as sediment is able to bypass the basin when it cannot accumulate in the local marine environment. This case is exemplified by the Hebrides Basin in the Skye–Raasay area, where thicknesses deposited during 2nd-order sea-level cycles, synchronous with Dorset, show proportionally much greater net accumulation during rises than is the case in Dorset (Fig. 10), particularly for the uppermost Sinemurian–lowermost Pliensbachian and uppermost Pliensbachian sections. In the Hebrides Basin, the Toarcian section is relatively condensed, and the pattern of accumulation is in many respects intermediate between that seen in the Wessex Basin and that seen in the Cleveland Basin, suggesting a relative reduction in the supply of siliciclastic sediment to the Hebrides Basin at this time or an increase in rate of creation of accommodation space closer to sediment source.

The Cleveland Basin (Yorkshire) represents the case in which approximately equal thicknesses of strata accumulated during Early Jurassic long-term rises and the falls (Fig 10). From early Toarcian and through Middle Jurassic time, the situation changed such that the Cleveland Basin was the most proximal of the three main basins considered here, since most of the Middle Jurassic Series is predominantly non-marine and the succession appears to be punctuated by an unconformity spanning most of the Bathonian stage (Hogg, 1993). Within any one basin, some areas would have been oversupplied with sediment and some undersupplied, and a good example of this is shown by a comparison of northern with southern successions in the Hebrides Basin (e.g., Skye *versus* Morvern, Figs. 5, 7).

Taking this model for development of the British Lower Jurassic stratigraphy further, we can attempt to explain the thickness differences and timing of sandstone formations within each large-scale cycle with the caveat that if we divide the relative sea-level cycles into early and late rise and early and late fall we are approaching a level of analysis close to that of the medium-scale cycles discussed below. In underfilled settings the late stage of relative sea-level fall appears to have resulted in an expanded succession as sediment was forced basinwards into water depths that placed no restrictions on vertical accumulation; a good example is the mid-Pliensbachian of Dorset. In the same setting the early and late rise in sea level is characterized by fining and/or condensation as exemplified also by the Dorset section in the late Pliensbachian/earliest Toarcian (the Junction Bed *sensu lato*). It should be noted, however, that the depth of water which limits accumulation may be greater for clay than for sand. Hence, even though in the Dorset area the Wessex Basin was generally underfilled for sand in Early Jurassic time, it appears not to have been underfilled for clay, which was unable to accumulate substantially through the mid-Sinemurian.

In contrasting the Dorset succession with that of the Hebrides once again, a good case can be made that the mid-Pliensbachian relative sea-level fall created condensed sand and granule facies across much of the Hebrides Basin, as the water became too shallow for significant accumulation to occur and considerable reworking and winnowing took place. During the subsequent early rise, further accommodation space was created which was completely filled with sediment. In the early Toarcian late stage of rise and highstand, only clay was available to accumulate. Similarly, the uppermost Sinemurian sandstones in the Skye area, which occupy the same early rise position in the preceding large-scale cycle as the upper Pliensbachian sandstones, are similar in facies, stratigraphically expanded and overlain rather abruptly by deeper water clays (Fig. 6).

In summary, the Wessex Basin occupied a distal position for much of the Early Jurassic Epoch and large amounts of sediment accumulated at times when accommodation space was not available in more proximal settings such as the Cleveland or the Hebrides basins. Most differences in the sedimentary fills of these basins can be adequately explained by their positions on proximal to distal gradients and, in contrast to Hallam (1984), we see no reason to postulate independent and contrasting patterns of uplift and subsidence.

Where our analysis contrasts with recent studies on neighboring basins, mainly in the North Sea, discrepancies appear either to be a consequence of different interpretations of the same successions, or else they cannot be be assessed because insufficient evidence has been presented to justify the previous interpretations.

In a study of the Lower Jurassic North Viking Graben, Parkinson and Hines (1995) subdivide the succession into four 'genetic stratigraphic sequences' bounded by maximum flooding surfaces of late Sinemurian, late Pliensbachian and early Toarcian age. The Lower Jurassic successions of the North Sea are not well calibrated biostratigraphically, and Parkinson and Hines (1995) placed interpretations on the hiatus-levels in Dorset, different from those made herein, which were used as 'keys' to understanding the North Sea stratigraphy. Parkinson and Hines (1995) considered that the Coinstone erosion surface (Fig. 10) formed as a consequence of lack of accommodation space, whereas the Hummocky erosion surface (Fig. 10) formed due to sediment starvation. As discussed in the next section, we interpret both surfaces as having formed by transgression-related sediment starvation, immediately following a prolonged period of regression.

Underhill and Partington (1993) reviewed the Jurassic North Sea and adjacent areas and stage-scale cycles are clearly indicated in the figures of Partington et al. (1993) and Underhill and Partington (1994). These exhibit a striking similarity to the cycles described herein. Within the limitations of the offshore biostratigraphic resolution, these cycles, which are labelled as '3rd-order', appear to be synchronous from the base of the Sinemurian up to the mid-Pliensbachian with those described in the present study. However, the upper Pliensbachian has been subdivided into several '3rd-order' sequences that bear little relationship to the large-scale cycles described in the present study, and are not easily reconciled with the medium-scale cycles described in the following section. In the absence of a detailed account of their interpretations, it is difficult to identify the reasons for this contrast, which is most marked at the base of the *margaritatus* zone, interpreted as a time of maximum flooding.

The 'genetic stratigraphic sequences' of Stephen et al. (1993), described for the Moray Firth Basin, offshore eastern Scotland, do appear to coincide with the large-scale cycles described herein; the setting was considerably more proximal in Early Jurassic time than was the case for any of the basins described in the present study, and only the Upper Sinemurian to upper Pliensbachian lithologic cycle is clearly recognizable. A maximum flooding surface is described from the late *raricostatum*–lower *jamesoni* zones. The very marked early Toarcian deepening, so well manifested elsewhere, is not reported; this part of the Moray Firth succession is poorly dated, and it is probable that the succession does not extend up to the *falciferum* zone and is instead truncated beneath the Bathonian strata. The 'genetic stratigraphic sequences' of Morton (1989, 1990b) are approximately of the same scale as the cycles discussed in this study, although for the Lower Jurassic strata his interpretation of the Hebridean sections differs considerably from ours, particularly in the Sinemurian interval.

MEDIUM-SCALE CYCLES

In the following sections, we identify, on a stage-by-stage basis, candidate sequence boundaries and maximum flooding surfaces within lithologic cycles at a medium scale, and assess to what extent these can be said to be synchronous across the U.K. area. The most parsimonious interpretation is illustrated in Figures 3–9 and Figure 11. We also discuss the occurrence of constituent sedimentary cycles at smaller scales in the relatively few instances in which they have been observed.

Hettangian Interval

The Hettangian rocks of southern Britain are characterized by a simple and widespread stratigraphic motif, well exemplified by the section at St Audrie's Bay on the North Somerset coast (Figs. 1, 8). The successions comprise interbedded limestone and mudrock that is locally organic-rich (the Blue Lias; see e.g., Fig. 4). Limestone is most abundant in the basal (*planorbis*) and top (*angulata*) zones, with the thickest and least calcareous mudstones occurring in the middle (*liasicus*) zone. This pattern is well developed over the whole southern British area, and has been noted or described by Donovan et al. (1979), Hallam (1981), Brandon et al. (1990), and many other workers. In Glamorgan, where the typical 'offshore' interbedded limestone-marl facies can be traced into 'marginal' facies, the evidence has been interpreted as indicating *liasicus*-zone deepening. There, south of the Dunraven Fault, the 'marginal' facies which possibly belongs to the *planorbis* zone (Tawney 1866; Hodges 1986) is overlain by shale of mid-*liasicus* zone age (Hodges, 1986; Wilson *et al.,* 1990). *Angulata*-zone 'offshore' facies are not observed overlying *liasicus*-zone 'marginal' facies, although it might be argued that there is no exposure where this transition would be expected. Hence a candidate maximum flooding surface is recognized in the mid-*liasicus* zone.

An alternative explanation for the stratigraphic relationships in the mid-Hettangian must also be considered; the relatively condensed and carbonate-rich interval of the Pre-Planorbis Beds and the *planorbis* zone are sediment starved and correspond approximately to maximum flooding, whereas the *liasicus*-zone shales are the result of an increase in supply of argillaceous sediment to the basin. In this case, onlap across the London Platform (Donovan *et al.,* 1979; Horton *et al.,* 1987) may be the distal expression of progradation, rather than a reflection of increase in relative sea level.

The mudstone of the *angulata* zone is highly calcareous and it has been suggested that it represents a shallower water facies than the underlying *liasicus* zone. Some support for this interpretation comes from the exploratory work of Smith (1989) who suggested that, on the basis of correlation of Milankovitch-scale cycles between Somerset and Dorset, a hiatus is present in the Dorset section in the middle of the *angulata* zone. Further evidence cited in support of a regression at that time, or at least a stillstand, is the cessation of onlap across the London Platform (Donovan *et al.,* 1979). However, a contrasting interpretation, that the *angulata* zone represents a time of maximum flooding, is equally tenable because all of these phenomena can be accounted for by postulating siliciclastic sediment starvation. The evidence in support of an *angulata*-zone relative sea-level fall or stillstand in the U.K. area is weak.

In summary, two competing hypotheses for medium-scale relative sea-level cycles through the Hettangian interval may be entertained, based on the U.K. sections. The evidence for either position is at present inconclusive. We prefer an interpretation of mid-*liasicus* transgression and mid-*angulata* regression.

Lower Sinemurian Interval

In Dorset and in Somerset (Figs. 4, 8), the lower *rotiforme* subzone of the *bucklandi* zone is, like the *liasicus* zone, characterized by the occurrence of a relatively argillaceous and, apparently, expanded succession. The mid-*rotiforme* subzone is dominated by calcareous mudstone and limestone, whereas the upper *rotiforme* subzone shows a return to argillaceous deposition. In Glamorgan, a closely similar pattern is observed (Fig. 9) except that the lower *rotiforme* subzone is not markedly argillaceous, but the mid-*rotiforme* subzone is developed as a limestone. Inland in south Wales, in the St Fagan's borehole (Waters and Lawrence, 1987), a sequence of oolitic and peloidal limestone occurs between the *angulata* and *semicostatum* zones and displays a thickening-up bedding pattern; this is correlated with the limestone on the coast. The sequence in the borehole is capped by a hardground, overlain by limestone–marl facies of the uppermost *bucklandi* or *semicostatum* zones. Although it may be argued that the sequence represents redeposition during relative sea-level rise (i.e., highstand shedding in the sense of Schlager, 1992) an interpretation as shoaling has been preferred by previous authors (Waters and Lawrence, 1987; Wilson et al., 1990). The evidence appears ambiguous, but as in the

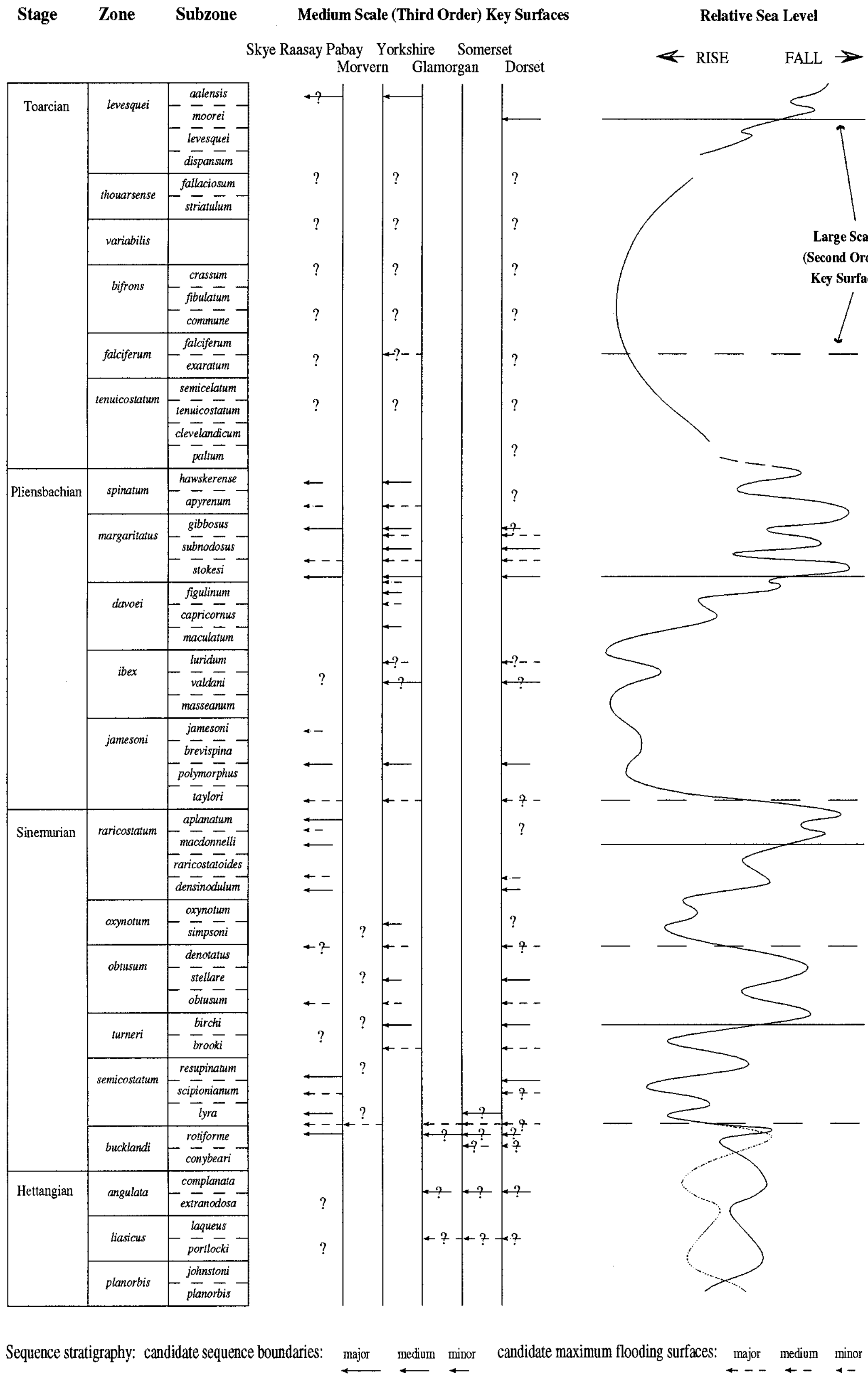

FIG. 11.—Summary of sequence stratigraphic interpretations for the Lower Jurassic of the British area and proposed relative sea-level curve compatible with the sections discussed. An alternative curve for the Hettangian-earliest Sinemurian time is shown by the gray stroke.

case of the Hettangian, we prefer to interpret the more argillaceous intervals as representing maximum flooding.

It is now well established that the *semicostatum* zone, in particular the *scipionianum* subzone, was a time of major deepening on the basis of diverse facies changes in many parts of the world including the British area (Hallam 1981). In Dorset, the top few decimeters of the Blue Lias comprise condensed limestone and organic-rich mudstone of the *lyra* subzone. These are overlain by the Shales-with-'Beef' which comprises organic-rich mudstone of the *scipionianum* subzone and calcareous mudstone of the *resupinatum* subzone (Fig. 4). The boundary between the *lyra* subzone and the *scipionianum* subzone is a hiatal surface showing evidence of erosion (Hallam, 1960; Hesselbo and Jenkyns, 1995) and is the oldest of several such surfaces in the Hettangian–Pliensbachian mudrocks. Considered in isolation, condensation of the *lyra* subzone may be ascribed to either shallowing or sediment starvation.

The *semicostatum*-zone succession in the northern Hebrides gives an unambiguous indication of deepening followed upwards by shallowing, and may aid interpretation of the southern exposures, if one assumes synchronous relative sea-level changes. In the Skye and Raasay areas, the undoubtedly shallow-marine limestone, mudstone and sandstone of the Broadford Fm pass upwards into the mudstone and sandy mudstone of the lower Pabay Shale (*sensu* Hesselbo et al., 1998). Nowhere is the transition well exposed, but this deepening occurs at about the boundary between the *rotiforme* subzone of the *bucklandi* zone and the *lyra* subzone of the *semicostatum* zone (Hallam, 1959; Oates, 1978; Searl, 1992; Hesselbo et al., 1998). The *lyra* subzone attains a substantial thickness and is more argillaceous (as opposed to sandy) in the lowermost part and in the uppermost part which extends into the *scipionianum* subzone (Figs. 5, 10). Thus, there are *two* important phases of deepening in the lower part of the *semicostatum* zone with candidate maximum flooding surfaces near the base of the *lyra* subzone and in the *scipionianum* subzone; candidate sequence boundaries occur in the mid-*lyra* subzone and near the base of the *resupinatum* subzone. The hiatal surface at the top of the Blue Lias in Dorset is thus interpreted as resulting from sediment starvation caused by relative sea-level rise, as is the similar hiatal surface separating the Blue Lias from the Pabay Shale in Morvern (Fig. 7).

Following this interval of starvation in more distal settings and relatively argillaceous deposition in more proximal settings, the sedimentation pattern for the upper *semicostatum* zone is everywhere interpretable as regressive. This is most clearly the case in the more proximal settings (e.g., on Raasay; Fig. 5) where mudstone of *scipionianum*-subzone age is overlain by fine-grained sandstone in the *resupinatum* zone. A similar transition may be seen in Cleveland on the foreshore at Redcar, Yorkshire (Tate and Blake, 1876), although there is no modern published description of either the lithologic succession or the ammonites. Certainly, the mudstone of the uppermost *semicostatum* zone of Robin Hood's Bay, Yorkshire (Calcareous Shales) is sandy relative to the mudstone yielding *Euaggasiceras scipionianum* at Redcar. This trend cannot be explained by paleogeography; in the Early Jurassic Cleveland Basin, northern localities (e.g., Redcar) were more proximal to sourcelands than were southern localities (Hesselbo and Jenkyns, 1995). In the Wessex Basin, the *resupinatum* zone (Shales-with-'Beef') is characterized by relatively carbonate-rich mudstone (Lang et al., 1923; Hesselbo and Jenkyns, 1995); this is the earliest of several intervals in which carbonate-rich facies in Dorset correspond to relatively arenaceous facies in Yorkshire.

The *turneri* zone is easiest to interpret in the Cleveland Basin. There, it is characterized by argillaceous deposition (Calcareous Shales), which begins at the base of the zone and terminates near the top through an influx of fine-grained sand (Siliceous Shales); the subzones are not well defined. One bed in the middle of this mudstone interval is unusual in containing ferruginous ooids (van Buchem and McCave 1989; Bed 13 of Hesselbo and Jenkyns, 1995). The mudstone is less silty, has fewer storm-scours than the overlying and underlying strata, and is most simply interpreted as representing deeper water. The time-equivalent stratum in Dorset is an organic-rich paper shale, in the Shales-with-'Beef', at the boundary between the *birchi* and *brooki* subzones, underlain and overlain by more marly mudstone. The cyclic facies arrangement is a repeat of that seen in the *semicostatum* zone and this is particularly strongly evident in the Dorset succession (Fig. 4). In the more distal parts of the Hebrides Basin (Morvern), the basal *turneri* zone is missing. However, sedimentation resumed with silty mudstone deposition (upper *turneri* zone, *birchi* subzone) above which a coarsening is evident.

In summary, the Lower Sinemurian strata of the U.K. area can be resolved into three deepening–shallowing cycles (Fig. 11). Two cycles are present in the *semicostatum* zone with candidate maximum flooding surfaces in the *lyra* and *scipionianum* subzones. One cycle is present in the *turneri* zone with maximum flooding probably in the mid-*brooki* subzone and a candidate sequence boundary in the mid-*birchi* subzone. In the most distal setting (i.e., Dorset), the basal cycle of the *semicostatum* zone falls within a highly condensed interval, but in the most proximal setting (i.e., Skye and Raasay), it is well expressed in open-marine mudstone–sandstone facies. By contrast, in the more proximal settings, the development of the upper, *turneri*-zone cycle is suppressed; this is compatible with its coincidence with shallowest water conditions within larger scale cycles. It should be noted that at no one locality can all four medium-scale lithologic cycles be recognized.

Upper Sinemurian Interval

Medium-scale cycles are well expressed in the Upper Sinemurian successions. In Dorset, these comprise alternations of organic-rich and calcareous mudstones (Black Ven Marls) as is the case in the Lower Sinemurian strata, except that erosion surfaces are more clearly developed (i.e., the Coinstone and the Hummocky; Fig. 10). In Yorkshire, the cycles comprise alternations of mudstone with sandy mudstone in the Siliceous Shales, and in the Hebrides, mudstone alternates with sandstone in the Pabay Shale (Figs. 5, 10).

The Yorkshire succession is apparently biostratigraphically complete. A mudstone-dominated interval occurs at the *obtusum–oxynotum* zonal boundary and in the uppermost *raricostatum* zone, continuing into Pliensbachian strata. The intervening sections contain variable quantities of sand in medium to thick, bioturbated beds. Storm scours are common (Sellwood, 1972; van Buchem and McCave, 1989). Of the sandy intervals, the uppermost *turneri* zone–lowermost *obtusum* zone, and the upper *oxynotum* zone–lower *raricostatum* zone contain the most sand. Thus, candidate sequence boundaries are identified in the upper *turneri* zone (*birchi* subzone) and mid-*oxynotum* zone (*simpsoni–oxynotum* subzonal boundary) in Yorkshire.

The Dorset Upper Sinemurian strata contain two major hiatal surfaces. The calcareous mudstone that forms the top of the *turneri* zone (*birchi* subzone) in Dorset is overlain by a thick organic-rich shale, the Obtusum Shale, belonging to the *obtusum* zone (*obtusum* and *stellare* subzones; Page, 1992). The base of the Obtusum Shale is a minor erosion surface (Hesselbo and Jenkyns, 1995) and the interval overlying the shale, belonging to the upper part of the *stellare* subzone, is a calcareous mudstone. The general pattern is thus the same as was the case for the underlying *turneri*-zone lithologic cycle, except for the occurrence of a basal hiatal surface and a reduced total thickness (Fig. 4). Paleobathymetric interpretation is obscure, but on the basis of similarity to the case of the organic-rich facies in the underlying Shales-with-'Beef', the Obtusum Shale may best be regarded as having been deposited during relative sea-level rise or a highstand. There is no strong expression of the Obtusum Shale event in the Cleveland Basin. Since this is the probable time of maximum regression in the large-scale lithologic cycle, insufficient accommodation space may have been available in Yorkshire to accumulate a mudstone facies.

In the Hebrides (Fig. 5), the *obtusum* and *oxynotum* zones are generally either poorly exposed or poorly dated, and a medium-scale signal cannot be resolved with confidence. Better data exist for the *raricostatum* zone (Oates, 1978; Getty, 1980) which comprises sandy mudstone and sandstone (Figs. 5, 10). Three sandy intervals are separated by two muddy intervals. The sandstone becomes thicker upwards at the expense of the mudstone. Based on ammonites reported from the northern Hebrides (Oates, 1978; Hesselbo et al., 1998), the mudstone intervals are at the *densinodulum–raticostatoides* subzonal boundary and in the lower *aplanatum* subzone.

In summary, although a very clear medium-scale lithological cyclicity exists for the British Upper Sinemurian units, it is difficult to make comparisons between basins in which good chronostratigraphic control is combined with unambiguous depth-related facies changes. However, based on the Yorkshire succession, candidate sequence boundaries are recognized in the *stellare* Subzone and at the *simpsoni–oxynotum* subzonal boundary. Based on Dorset, a candidate maximum-flooding surface is recognized in the *obtusum* Subzone. In the Hebrides Basin, candidate maximum flooding surfaces are recognized at the *densinodulum–raricostatoides* subzonal boundary and in the lower *aplanatum* subzone; candidate sequence boundaries are recognized in the *densinodulum* subzone, at the *raricostatoides–macdonnelli* subzonal boundary, and in the *aplanatum* subzone. It is plausible to relate the hiatuses and erosion surfaces in the Dorset succession to deepenings in the *obtusum* subzone, the *denotatus–simpsoni* subzonal boundary ('the Coinstone') and at the *aplanatum–taylori* subzonal boundary ('the Hummocky') (Figs. 4, 10).

Lower Pliensbachian Interval

Lower Pliensbachian medium-scale lithologic cycles comprise mainly silty mudstone with minor sandstone, and the successions are relatively complete down to a subzonal level. In both Yorkshire and Dorset, decimeter-scale beds are typical of the *jamesoni* and *ibex* zones (van Buchem and McCave, 1989; Weedon and Jenkyns, 1990: Hesselbo and Jenkyns, 1995), and stratigraphic variations in thicknesses of these zones give a useful indication of relative sedimentation rates. In Yorkshire, the base of the lower Pliensbachian (*taylori* subzone; *jamesoni* zone) is characterized by the occurrence of an organic-rich facies, the Pyritous Shales. Above this level in, the *jamesoni* zone, the succession gradually becomes coarser, reaching a maximum in the *valdani* subzone of the *ibex* zone where sand is fairly abundant. This upward-coarsening corresponds to a reduction in sedimentation rate as inferred from the condensed ammonite zones and subzones, thinning upsection of the decimeter-scale beds, and increasing concentration of belemnites (Hesselbo and Jenkyns, 1995). Making the assumption that coarser sediment in this setting indicates increased proximity to source, the surface of maximum condensation is more likely a surface of sediment by-pass rather than starvation. Biostratigraphic expansion and an abrupt fining characterize the upper *ibex* zone (*luridum* subzone) in Yorkshire, which is overlain by a succession that becomes progressively coarser upwards through the *davoei* zone (Hesselbo and Jenkyns, 1995).

The Lower Pliensbachian (Belemnite Marls) section of Dorset shows remarkable parallels with that of Yorkshire (Figs. 3, 4), particularly in the pattern of expansion and condensation through the *jamesoni* and lower *ibex* zones. One major difference is that in Dorset, there is no concomitant grain-size variation detectable by field observation. A second significant difference is that in the *ibex* zone of Dorset, in addition to the condensed horizon in the *valdani* subzone (the Belemnite Bed), a second condensed horizon occurs in the *luridum* subzone (the Belemnite Stone). Although the former correlates with an inferred shallowing in the Yorkshire area, the latter corresponds to an inferred deepening. Hence, condensation in the more distal Dorset area of the Wessex Basin may be related in one instance to shallowing and in the other to deepening. Condensation and erosion at the Sinemurian–Pliensbachian boundary in Dorset (the Hummocky) may also be related to deepening. The *davoei* zone in Dorset (the Green Ammonite Beds) becomes more silty upwards, although the trend is not as marked as it is in Yorkshire, as is consistent with the more distal setting of the Wessex Basin.

A reasonably well-defined succession through the *jamesoni* zone can be followed on the Isle of Pabay (Figs. 1, 6). The *taylori* subzone is a black mudstone with sideritic bands very similar to coeval facies in the Cleveland Basin. The mid-*jamesoni* zone is significantly coarser with shelly fine-grained sands occurring interbedded with mudstone. A minor fining is evident into the upper *jamesoni* zone but the *ibex* zone clearly continues the coarsening trend. Whether this reaches a maximum in the *valdani* subzone is at present unknown because the critical interval is not exposed in the Skye–Raasay–Pabay area. The significance and lateral continuity of the upper *jamesoni*-zone muddy interval is uncertain, but it is not well expressed, if at all, in the Yorkshire or Dorset successions. The uppermost *ibex*- to *davoei*-zone succession of the Hebridean area shows progressive coarsening combined with condensation (Phelps, 1985).

In summary, there is a remarkably good correlation in the stratigraphic development of the Cleveland and Wessex basins through early Pliensbachian time. Candidate maximum flooding surfaces are recognized in the *taylori* subzone of the *jamesoni* zone of all British basins, and in the *luridum* subzone of the *ibex* zone in the Cleveland and Wessex basins. Candidate sequence boundaries are identified in the *valdani* subzone of the *ibex* zone. Some evidence exists locally in the Hebrides Basin for a moderately expressed sequence boundary in the *polymorphus* subzone and a weakly expressed maximum flooding surface in the *jamesoni* subzone, both of the *jamesoni* zone.

Upper Pliensbachian Interval

The Upper Pliensbachian strata are largely arenaceous in the Wessex, Cleveland and Hebrides basins. Medium-scale lithologic cycles are well expressed in all three basins as mudstone–sandstone alternations.

In Dorset, several cycles are observed in the *margaritatus* zone (Figs. 4, 11). Sand occurs at four levels within this biozone: (a) the 'Three Tiers' unit at the base is the culmination of a coarsening-upwards trend originating in the lower *davoei* zone; (b) an unnamed, thin, discontinuous bed above the concretionary Eype Nodule Bed; (c) the Down Cliff Sands, overlying the concretionary Day's Shell Bed; and (d) the Thorncombe Sands. All, except the Thorncombe Sands, belong to the *stokesi* subzone, and the lithologic cycles that they delimit may be regarded as of higher frequency than the cycles described herein as 'medium scale'. The *gibbosus* subzone comprises a thin, silty mudstone with no name. It has been argued elsewhere (Ensom, 1984; Hesselbo and Jenkyns, 1995) that the Eype Nodule Bed and Day's Shell Bed contain hiatus concretions. Their positions at the bases of sand units (which were probably emplaced by storm processes) suggests an origin due to increased wave action on the seafloor prior to the supply of sand sufficient for deposition to occur (cf. Plint, 1988; Hadley and Elliott, 1993). In contrast, the thin, pebbly sandy limestones that cap the Down Cliff Sands and Thorncombe Sands are more likely to owe their origin to winnowing which occurred as sand supply to the basin was reduced, possibly as a result of deepening in more proximal settings. The Margaritatus Stone, which is the best developed of these possible condensed beds, caps the Down Cliff Sands. It may represent an extended period of time equivalent to the upper *stokesi* subzone and the lower *subnodosus* subzone and, as is indicated in Figure 11, is a good candidate as a maximum flooding surface. If the sequence boundary is to be placed at an abrupt juxtaposition of sandstone over mudstone, then the bases of any of the sandstones within the *stokesi* subzone may be regarded as candidate sequence boundaries, and no one surface has greater merit than another, based on currently available data. A candidate sequence boundary may also be placed at the base of the Thorncombe Sands (in the mid?-*subnodosus* subzone).

In Yorkshire, the Staithes Sandstone is the culmination of the coarsening trend observed from near the top of the *ibex* zone (Figs. 3, 10). More or less muddy units of sandstone occur within the formation, but the thickest and coarsest development of sand is in the lower part of the *stokesi* subzone. The succession then fines to a minimum in the Cleveland Ironstone around the *stokesi*–*subnodosus* subzonal boundary. As was the case in Dorset, a candidate maximum flooding surface can be placed at this level. The Cleveland Ironstone comprises a series of coarsening-up cycles capped by oolitic ironstones approximately equivalent to the *subnodosus* subzone, the *gibbosus* subzone and the *spinatum* zone (Fig. 3). Not all the oolitic ironstone beds sit directly on the coarsest members of each cycle. This is particularly true of the Pecten Seam at the base of the *spinatum* zone, which sits unconformably on top of silty clays of the underlying *margaritatus* zone (Chowns, 1968; Howarth, 1980a; Howard, 1985). Because there is a coarsening up to the top of the *spinatum* zone, the ironstone seams at the base of the zone may coincide with the maximum flooding surface (Fig. 3; for discussion see Macquaker and Taylor, 1996; Hesselbo, 1997).

The succession in the Hebrides Basin differs from that of Dorset and Yorkshire in that the smaller-scale lithologic cycles are not observed (Figs. 6, 10). The upper Pliensbachian section is represented by the Scalpa Sandstone. The *stokesi* subzone fines upward into the *subnodosus* subzone, which is developed entirely as a siltstone/silty limestone facies. An abrupt coarsening occurs into the base of the *gibbosus* subzone. A weakly argillaceous but very shell-rich interval also occurs in the lower *spinatum* zone (*apyrenum* subzone) on Raasay; Howarth (1956) characterized this unit at Rudha Na'Leac as an oolitic sandy limestone and Hallam (1967) has identified the ooids as chamosite (presumably berthierine). The abundant and diverse fauna of ammonites, bivalves and crinoids was taken by Hallam (1967) to indicate condensation. As was the case in both Dorset and Yorkshire, candidate maximum flooding surfaces may be placed at the *stokesi*–*subnodosus* subzonal boundary and near the base of the *apyrenum* subzone (*spinatum* zone). A notable difference between the Hebrides section and that of either Dorset or Yorkshire, is that the *stokesi* subzone is less coarse than the underlying upper subzones of the *davoei* zone. One possible explanation may be an erosional gap at the base of the *stokesi* subzone, as would befit the more proximal position of the Hebrides area at this time; indeed, at Carsaig Bay on the Island of Mull (Fig. 1), the upper subzones of the *davoei* zone are missing (Phelps, 1985).

In summary, candidate maximum flooding surfaces are recognized at the *stokesi*–*subnodosus* subzonal boundary (*margaritatus* zone), and near the base of the *apyrenum* subzone (*spinatum* zone), at all locations in this study. A candidate sequence boundary is recognized near the base of the *stokesi* subzone (*margaritatus* zone), also at all locations studied. On the basis of an abrupt increase in sand deposition, a sequence boundary may be inferred within in the *subnodosus* subzone in Dorset, although there is no clear evidence of this in the Hebrides. On the same basis, a candidate sequence boundary is recognized near the base of the *gibbosus* subzone in the Hebrides. In Yorkshire both the *subnodosus* and *gibbosus* subzones coarsen up, and it is possible to infer similarly a sequence boundary in both subzones. In Dorset, the silty mudstone comprising the *gibbosus* subzone is sandwiched between the apparently condensed horizon at the top of the Thorncombe Sands and the condensed Marlstone; thus, it *may* be interpreted as a the distal expression of a regressive package of sediment and hence compatible with the sequence stratigraphy inferred from other basins. In the case of the *gibbosus*-subzone candidate sequence boundary, its stratigraphic expression becomes stronger towards the north; this is in striking contrast to the *subnodosus*-subzone candidate sequence boundary which finds its clearest expression in the south. This is the best example of asynchronous sequence development at a medium scale; however, the sequences are not diachronous, and the evidence is not sufficient to propose different relative sea-level histories in each basin.

Toarcian Interval

There is little definite that can be determined concerning medium-scale sequences within the lower Toarcian strata. The Dorset succession is strongly condensed and incomplete, and the succession in the Hebrides suffers from poor exposure. In Yorkshire, the lower Toarcian comprises shales, some extremely organic rich, whose sequence stratigraphic significance is somewhat obscure.

A sequence-stratigraphic interpretation of the Yorkshire succession has been made by Wignall (1991) and Wignall and Maynard (1993). It has been argued that a sequence boundary occurs at the top of the *spinatum* zone on the basis of an interpretation of the Marlstone as an extensive shallow-water deposit, and because a hiatus at the base of the *tenuicostatum* zone, occurring over structural highs in southern and central England, is interpreted as being due to lack of accommodation space (Wignall 1991; Wignall and Maynard, 1993). Wignall and Maynard (1993) also argued for a sequence boundary at the base of the *falciferum* zone on the basis of a minor biostratigraphic gap (see also Wignall and Hallam (1991)). We do not regard the evidence as strong for either of these sequence boundaries in the British area. The facies succession from the *spinatum* zone to the *tenuicostatum* zone appears always to be representative of deepening (Hallam, 1967) and, as has been argued in detail for a Sinemurian example (Hesselbo and Palmer, 1992), the occurrence of biostratigraphic gaps in these open-marine, fine-grained facies cannot be ascribed safely to relative sea-level fall. Indeed, both hiatal surfaces in the lower Toarcian strata may be better interpreted as consequential upon rapid relative sea-level rise and sediment starvation. Furthermore, we have found no evidence that the top of the *exaratum* subzone in the Cleveland basin is abnormally belemnitiferous, an argument used by Wignall and Maynard (1993) to support interpretation of this level as a maximum flooding surface. Neither is there any support for condensation at this level from consideration of the subzonal thicknesses (Fig. 3).

Most of the British upper Toarcian, like the lower Toarcian, does not evince distinct medium-scale lithologic cycles. By far the most complete and best-exposed section is that in the Cleveland Basin, although the upper Toarcian section is localized to the downthrown side of the major synsedimentary Peak Fault where late Toarcian–early Aalenian erosion was less pronounced. Grain-size variations, repeating at the scale of ammonite subzones, are detectable in the *thouarsense* and *levesquei* zones (Whitby Mudstone and Blea Wyke Sandstone; Knox 1984). Each lithologic cycle brings in coarser sand, and an erosion surface occurs within the sandstone at the Toarcian–Aalenian boundary, at which level the uppermost subzone of the *levesquei* zone (*aalensis* subzone) appears to be missing (Knox, 1984). It is noteworthy that in both the Hebrides and Wessex basins the uppermost *levesquei* zone shows stratigraphic expansion compatible with a candidate sequence boundary at this level, manifested by the forcing of increased volumes of sediment into distal settings.

SUMMARY AND CONCLUSIONS

The Lower Jurassic Series can be subdivided into four large-scale (‘2nd-order’) lithologic cycles, with durations of approximately 3–10 my that appear to be synchronously developed in all onshore U.K. basins; the cyclic changes in facies become more extreme as the cycles young. Maximum flooding surfaces in the large-scale cycles, identified on the basis of distal starvation or facies successions indicative of maximal accommodation space in proximal areas, occur in the *lyra* subzone of the *semicostatum* zone (Lower Sinemurian), at the *obtusum–oxynotum* zonal boundary (Upper Sinemurian), in the *taylori* subzone of the *jamesoni* zone (lower Pliensbachian), and within the *falciferum* zone (lower Toarcian). Sequence boundaries in the large-scale cycles, defined on the basis of major unconformities or facies successions indicative of minimal accommodation space in proximal areas, are recognized in the *birchi* subzone of the *turneri* zone (mid-Sinemurian), the mid-*raricostatum* zone (Upper Sinemurian), the *stokesi* subzone of the *margaritatus* zone (mid-Pliensbachian), and the mid-*levesquei* zone (upper Toarcian).

In general the Lower Jurassic strata of the Dorset area of the Wessex Basin show the most distal pattern of sediment accumulation for large-scale sequences, in which condensed sections (limestone or mudrock) correspond to relative sea-level rise or highstand and expanded sections (mudrock or sandstone) correspond to relative sea-level fall or lowstand. In contrast, the Lower Jurassic strata of the Skye, Pabay and Raasay areas of the Hebrides Basin exemplify the proximal pattern of sedimentation in which expanded sections (sandstone and mudstone) correspond to relative sea-level rise or highstand, and condensed sections (sandstone) correspond to relative sea-level fall or lowstand. The Yorkshire coast successions of the Cleveland Basin occur in an intermediate setting. Significant divergence from this pattern is evident in Toarcian deposits (and through the Middle Jurassic) over which interval the style of accumulation in the Hebrides is intermediate between that of the Wessex Basin and that of the Cleveland Basin. This indicates a reduction of clastic supply, or an increase in creation of proximal accommodation space, in the Hebrides area relative to Yorkshire that began in early Toarcian time.

Candidate sequence boundaries and maximum flooding surfaces defining medium-scale (‘3rd-order’) sequences fall into three distinct categories: (1) those surfaces that occur unambiguously in all basins analysed in this study; (2) those surfaces that occur in more than one basin analysed in this study, but whose existence in all basins cannot be demonstrated unambiguously; (3) those surfaces that show distinct and unambiguous geographic localization. In several cases, the interpretation of the surface in terms of either rising or falling relative sea level may be in question, despite its long-range correlatibility. Additionally, it should be borne in mind that some undoubted global sea-level-related events, such as that which produced the Toarcian *exaratum*-subzone black shale (Jenkyns, 1988), are not expressed unambiguously in all basins in this study.

There are few surfaces that have a definite expression in all basins considered here. Those that do are as follows: candidate maximum-flooding surfaces in the *lyra* and *taylori* subzones, and at the *stokesi–subnodosus* subzonal boundary (all major); and candidate sequence boundaries in the mid-*jamesoni* zone (moderate), and at the base of the *stokesi* subzone (major). Similarly, there are only a few surfaces that appear strongly localized, the best examples being candidate sequence boundaries in the *subnodosus* and *gibbosus* subzones, which are developed mainly in the south and north respectively.

Unlike the large-scale lithologic cycles, the medium-scale lithologic cycles cannot be linked definitively to relative sea-level change in preference to changes in sediment supply. However, all the cycles are compatible with relative sea-level change as a driving mechanism. Where good data exist, there is clear evidence in the most distal segments of large-scale cycles for a high degree of synchroneity of medium-scale cycles, particularly in Early Sinemurian and early Pliensbachian times. Asynchronous medium-scale cycles, as recognized on the basis of sharp-based sandstone units, appear to have developed in late Pliensbachian and, possibly, Late Sinemurian times, during the longer-term relative sea-level lows inferred from the large-scale cycles.

If linked to sea level, then condensation within medium-scale cycles in distal settings may be a consequence of relative sea-level fall, as well as rise. This is most persuasively the case for the *ibex* zone, where in the Dorset succession we interpret condensation of the Belemnite Bed to be related to lack of accommodation space (i.e., winnowing), whereas the similar Belemnite Stone is more likely related to relative sea-level rise (i.e., sediment starvation). Opposing interpretations to ours were placed on these horizons by Haq et al. (1988). Erosion surfaces in distal settings correlate commonly to fining or deepening successions in more proximal settings (e.g., in the lower *semicostatum* zone) and hence appear to be the result of sediment starvation (*contra* Hallam, 1988; cf. Hesselbo and Palmer, 1992).

A relative sea-level curve can be constructed, representing large- and medium-scale cycles, that is compatible with all the successions described in this study (Fig. 11). The new curve shows broad agreement with those previously published, which were based wholly or in part on the Dorset and Yorkshire sections (Hallam, 1988; Haq *et al.*, 1988) but differs significantly in detail. The sea-level curve in this study is least certain for the Hettangian and earliest Sinemurian interval, and least detailed for the Toarcian. Large-scale relative sea-level cycles appear to have had the strongest influence on the stratigraphic architecture of the British area in the later Early Jurassic times. Medium-scale relative sea-level cycles appear to have the strongest influence on the stratigraphic architecture during the times of large-scale relative sea-level lows, probably because the apparent effects are most marked in the shallowest water facies. Hence, the structure of the relative sea-level curve is strongly influenced by the superposition of medium-scale cycles upon large-scale cycles; it is simply less elaborate when inferred from deeper water facies.

The new relative sea-level curve differs from proposed eustatic sea-level curves in a number of respects. Our curve is considerably more detailed: most of the large-scale ('2nd-order') cycles recognized in this study correspond broadly in scale and timing to '3rd-order' cycles of Haq et al. (1988) and the smallest scale of fluctuation shown by Hallam (1988). In the present study we propose about 20 medium-scale candidate sequence boundaries, in contrast to the 10 suggested by Haq et al. (1988). Principal differences in timing, apart from in the uncertain Hettangian interval, are in the Late Sinemurian where, in contrast to Hallam (1988), we recognize an important *oxynotum*-zone deepening, and in the early Pliensbachian, where in contrast to the *ibex*-zone deepening of Haq et al. (1988) we recognize deepening in the *jamesoni* zone. These differences stem largely from contrasting interpretations of the same stratigraphic horizons in distal facies.

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