

REGIONAL ENVIRONMENTAL CHANGES ACROSS A LOWER JURASSIC STAGE-BOUNDARY IN BRITAIN

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ABSTRACT. In much of Northern Europe and in particular Britain, the end of the Sinemurian stage was marked by substantial environmental changes which caused numerous faunal changes. Lands bordering the Sinemurian sea (East Greenland, Southern Scandinavia, the London Platform) were transgressed as the Pliensbachian commenced. In persistently marine areas the sediments became finer grained and less kaolinitic, representing deeper-water environments than those of the Sinemurian. Sedimentary cycles, reflected by the faunas and trace-fossils, resulted from small-scale changes of water-depth. Deeper-water environments represented by shales were characterized by low-diversity faunas of thin-shelled pectinids and protobranchs. Shallower-water bioturbated sandstones were typified by higher diversities with pholadomyoids, venerids, mytiloids, thick-shelled pectinids, and complex crustacean burrows. The substrates of marly sediments were too soft and unstable to allow the development of a diverse benthos, and argillaceous calcilitites were only slightly more stable. Condensed sequences occurred on swells and were either chamositic with shallow-water faunas and structures; or calcareous (calcarenes and micrites) with abundant shallow-water faunas, glauconite and phosphate. The latter formed away from the terrigenous iron sources.

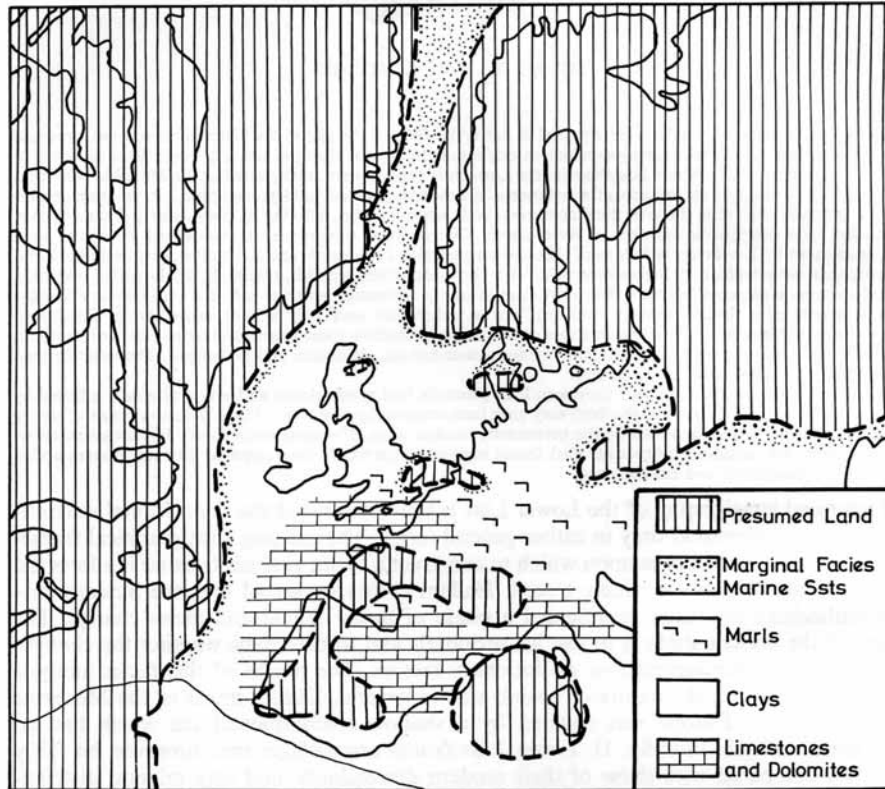
The epeiric sea of the Northern European Lias generally had gentle slopes and was profoundly affected by small-scale changes of water-depth which may have been eustatically controlled. There is little evidence of strong salinity controls to the fauna within the persistently marine areas. The presence of tidally influenced marginal sequences testify against salinity-controlled faunal regimes which would have required minimal current action for their development and maintenance.

THE zonal stratigraphy of the Lower Lias is well known but the depositional environments are understood only in rather general terms. The existing stratigraphical framework forms a sound base upon which to construct a facies analysis because it allows the short time zones to be widely traced. Hallam (1961) suggested that the Sinemurian-Pliensbachian boundary represented a phase of major faunal and facies change. The aim of the present study is to test his proposals and to determine whether the changes were due to environmental or evolutionary factors. The results of this facies analysis also shed light on the nature of epeiric seas in general. During much of the Mesozoic Era, Northern Europe was covered by a shallow epicontinental sea which has no modern analogue (text-fig. 1). Lower Lias faunal assemblages can, however, be fairly closely compared with those of their modern descendants, and clay mineral distributions, sedimentary structures, and geochemical variations can all be compared with information from modern seas. The less tangible concepts such as eustasy (Hallam 1969a), tidality (Klein 1970; Sellwood *in press*) and salinity (Hallam 1969b) remain more open questions.

Stratigraphy. The Raricostatium and Jamesoni Zones fall below and above the boundary separating the Sinemurian and Pliensbachian Stages (Table 1). In northern Britain the commencement of the Pliensbachian is generally marked by a loss of quartz sand, and in southern Britain by an increase in the carbonate content of the sediment. Hallam (1961) noted that whilst some invertebrate genera persisted beyond the Sinemurian, many more appear at about the base of the Pliensbachian; particularly brachiopods and belemnites.

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Table 1 gives the zonal scheme for the Lower Lias with the subzonal stratigraphy and ranges of the main ammonite genera. This zonal sequence (Dean *et al.* 1961) is applicable to most of the sections studied (text-fig. 2), but the lack of continuous and unmetamorphosed exposure on Mull; and of ammonites in the Golspie and Lossiemouth



TEXT-FIG. 1. Lithofacies reconstruction of the European region in Jamesoni Zone times. Carbonates extended south to North Africa.

sections makes the application of their zonal scheme difficult in these areas. Correlation of the major British sections is given in text-fig. 3, while text-figs. 4 and 5 give the major lithofacies distributions during Raricostatum/Jamesoni times. Work in Britain was supplemented by visits to Scandinavia and Spain, thus permitting some of the broad interpretations presented below.

Palaeoecological principles. The more important factors which control the distributions of marine faunal assemblages are temperature, salinity, water and substrate chemistry,

biological competition, and nutrient supply (Ellison 1955 gives an expanded list). Many of these factors are depth related. The proportion of suspended material in sea-water is broadly related to depth and environmental energy as well as to the availability of the material and its size; the distributions of suspension-feeding animals are coincident with this (Jørgensen 1966). Thus with large quantities of suspended material and rela-

TABLE 1. Ranges of the characteristic ammonite genera (modified from Dean *et al.* 1961)

SINEMURIAN				PLIENSACHIAN				STAGE
RARICOSTATUM ZONE				JAMESONI ZONE				ZONE
DENSINODULUM	RARICOSTATUM	NACDONNELLI	APLANATUM	TAYLORI	POLYMORPHUS	BREVISPINNA	JAMESONI	SUBZONE
CRUCIOBICERAS	ECHIOCERAS	LEPTECHIOCERAS		APODEROCERAS			UPTONIA (jamesoni)	CHARACTERISTIC AMMONITE GENERA (RANGES) (Typical species in parenthesis)
HENIMICROCERAS		EODEROCERAS			POLYMORPHITES (polymorphus)	(trivialis)		
		NEOMICROCERAS		PHRICODOCERAS	PLATYPLEUROCERAS (caprarium)	(brevispina)		
			EPIDEROCERAS					
PALTECHIOCERAS					RUSTOCERAS			

tively low sedimentation rates in fairly high energy environments, suspension-feeders are dominant (Driscoll 1969), whereas detritus feeders dominate areas of high turbidity and more rapid sedimentation. Sanders (1958) found that suspension-feeders dominated the modern marine sands of Buzzards Bay, whilst the clay content (which is itself controlled by depth and geographical factors) controlled the distribution of deposit-feeders. Seilacher (1967) has clearly argued a case for regarding feeding-mode as an important clue in interpreting depositional environments and suggests a direct bathymetric relationship between the predominance of either suspension- or deposit-feeders.

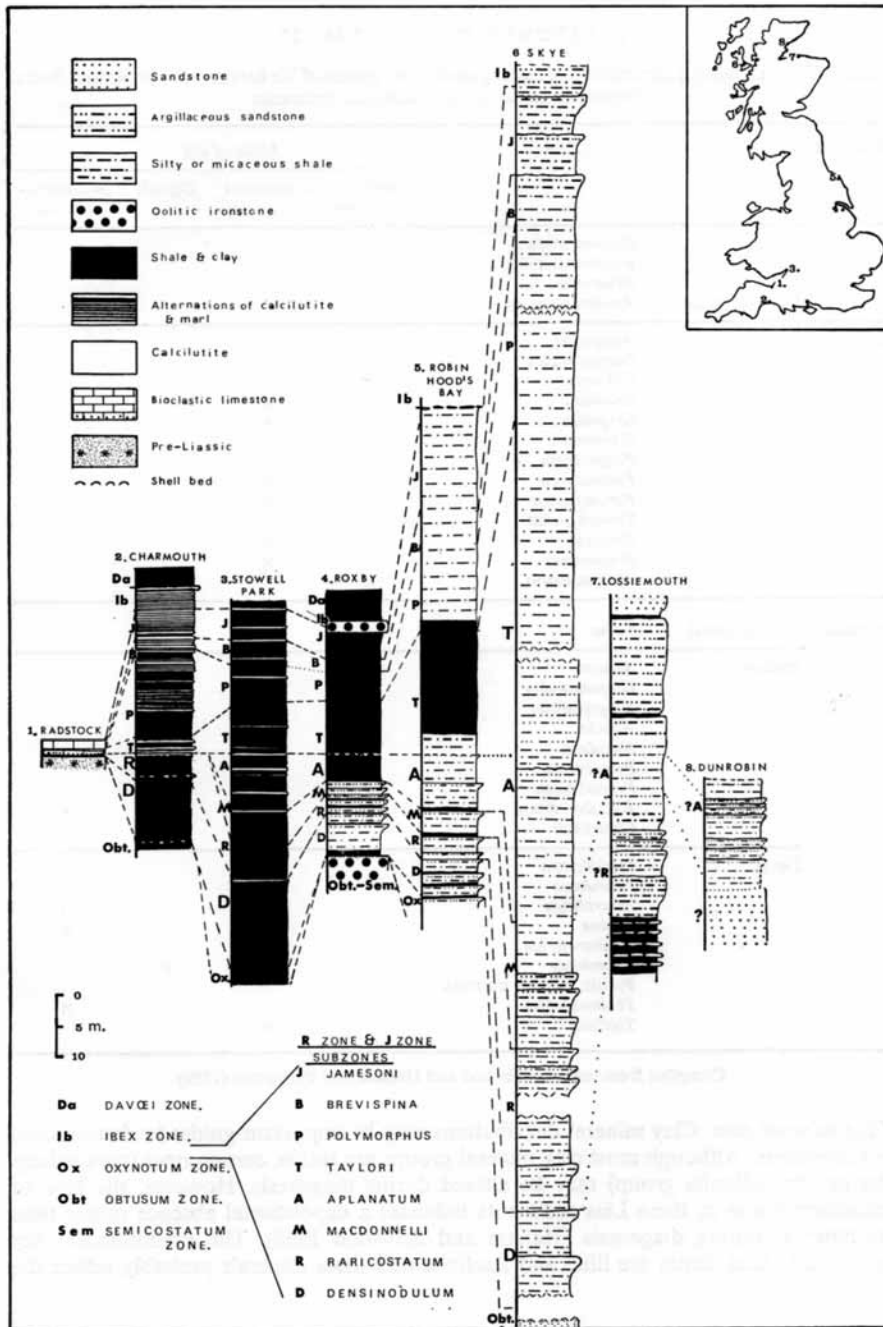
The Lias fauna consists mainly of bivalves whose modes of life are readily interpretable, both from their attitudes within the sediment and in the light of much modern work on living communities (Allen 1953, 1958; Driscoll 1969; Kauffman 1967, 1969a; Parker 1956, 1964; Saleuddin 1965; Stanley 1968; Yonge 1923, 1939, 1953a, 1953b,

1957, 1960; and many others). Table 2 summarizes the modes of life of the faunal and trace-faunal elements and the general lithofacies relationships of the more important ones are given in text-figs. 6, 7. In general, shales are typified by thin-shelled pectinids and protobranchs. This fauna is similar to that of modern outer-shelf muds; the pectinids were well adapted to a life in mud (because of their valve-clapping and swimming



TEXT-FIG. 2. Lias outcrops in Britain and locality map of major sections mentioned in text.

habits) while protobranch bivalves like *Nuculana* and *Nucula* were deposit-feeders and lived at shallow depths within the substrates. Rarer lucinoid bivalves also occur like *Lucina* and *Mactromya* and by comparison with modern Lucinoids, it seems that these were not strictly siphonate, but constructed mucus-lined tubes and were really suspension/deposit-feeders. At present, lucinoids burrow deeply in muddy substrates where adverse Eh or high turbidity prevents colonization by truly infaunal suspension-feeding bivalves (Allen 1958). The shales also contain a high proportion of bivalve juveniles indicating a high juvenile mortality. The bioturbated sandstones contain radically different body- and trace-faunas from those of the shales (Sellwood 1970, and text-figs. 6, 7). These are typified by suspension-feeders which indicate increased energy and probably lower turbidity conditions.



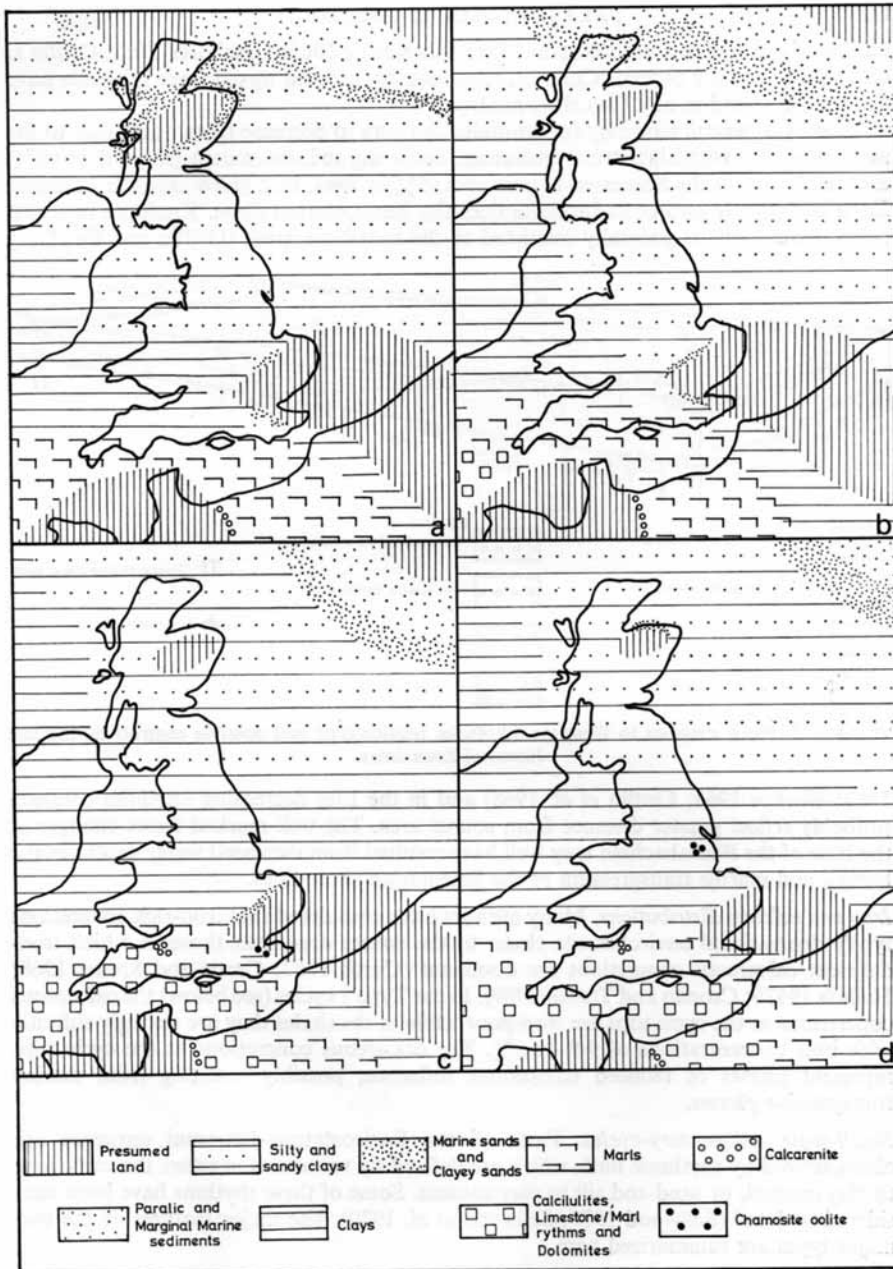
TEXT-FIG. 3. Stratigraphic summary of major sections mentioned in text.

TABLE 2. Table showing interpretation of feeding modes and modes of life for the more important faunal elements in *Raricostatum-Jamesoni* sediments

Mode of Life	Fauna	Mode of life			
		Carnivore-scavenger	Suspension	Deposit	Suspension-deposit
Nekton	Echioceratidae	×			
	Polymorphitidae	×			
	Belemnites	×			
Nekto-Benthos	<i>Apoderoceras</i> sp.	×			
Epifauna	<i>Antiquilima</i>		×		
	<i>Camptonectes</i>		×		
	<i>Chlamys</i>		×		
	<i>Entolium</i>		×		
	<i>Gryphaea</i>		×		
	<i>Oxytoma</i>		×		
	<i>Plagiostoma</i>		×		
	<i>Pseudolimea</i>		×		
	<i>Pseudopecten</i>		×		
	<i>Tetrarhynchia</i>		×		
	<i>Zeilleria</i>		×		
	<i>Pentacrinus</i>		×		
	<i>Pleurotomaria</i>	×			
Infaunal	Semi-Infaunal	<i>Pinna</i>		×	
	Shallow	<i>Astarte</i>		×	
		<i>Grammatodon</i>		×	
		<i>Hippopodium</i>		×	
		<i>Nucula</i>			×
		<i>Nuculana</i>			×
		<i>Protocardia</i>	×		
		<i>Procerithium</i>		×	
		<i>Rhizocorallium</i>			×
		<i>Chondrites</i>		×	
	Deep	<i>Pholadomya</i>	×		
		<i>Pleuromya</i>	×		
		<i>Mactromya</i>			×
		<i>Lucina</i>			×
		<i>Diplocraterion</i>	×		
		<i>Chondrites</i>		×	
		Pyritic, tubular burrows		×	
		<i>Thalassinoides</i>			×
		<i>Tigillites</i>	×		

Compiled from references in text and Hudson and Palframan (1969)

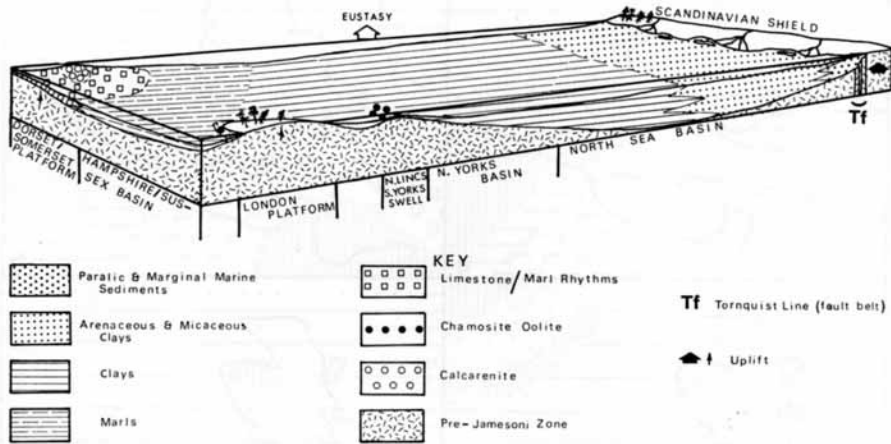
Clay mineral data. Clay mineral distributions may be important guides to depositional environments. Although most clay mineral groups are stable, certain ones (particularly the montmorillonite group) may be altered during diagenesis. However, the lack of montmorillonite in these Lias sediments indicates a depositional absence rather than its removal during diagenesis (Hallam and Sellwood 1968). The predominant clay minerals in Lias shales are illite and kaolinite and these minerals probably reflect the



TEXT-FIG. 4. Changing lithofacies distributions through the Raricostatum and Jamesoni Zones: (a) lower Raricostatum, (b) upper Raricostatum, (c) lower Jamesoni, (d) upper Jamesoni.

nature of the source areas (Weaver 1958; MacKenzie 1965; Gluskoter 1967; Griffin *et al.* 1968, and many others). Chlorite, montmorillonite, and mixed layer minerals have not been detected in any Lias clays analysed.

There is a general tendency for kaolinite contents to decrease from north-east to the south and west with highest concentrations occurring at Lossiemouth (more than 60%) and the lowest in the Somerset-Dorset area (5% or less). In a given area the Jamesoni Zone is generally poorer in kaolinite than the Raricostatum Zone. Kaolinite in recent Marine sediments is generally restricted to the nearshore areas (Griffin and Goldberg

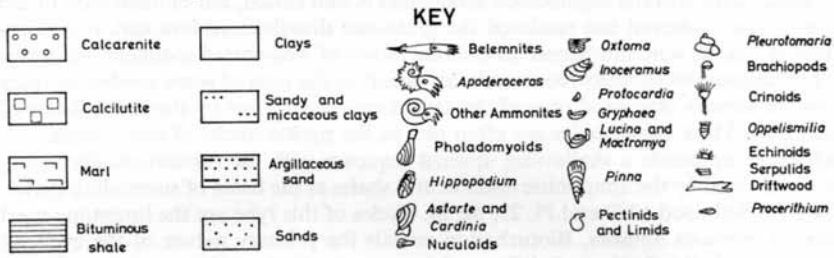
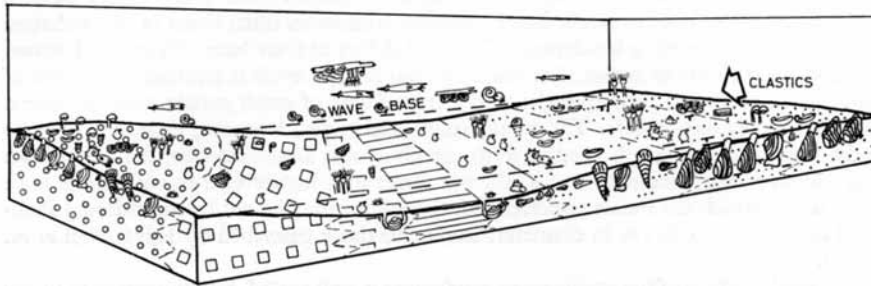


TEXT-FIG. 5. Block diagram to illustrate lithofacies relationships and possible controls during late Jamesoni Zone times.

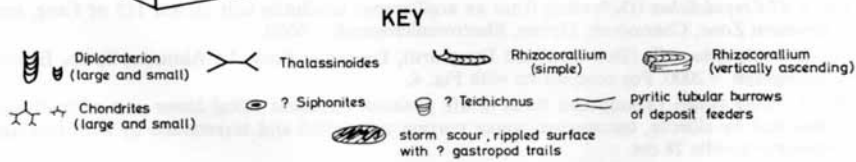
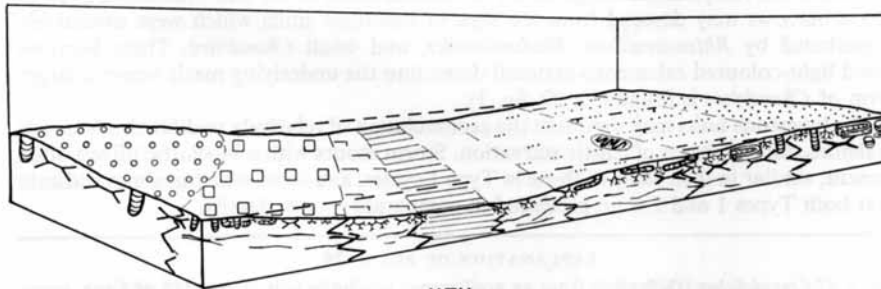
1963; Biscaye 1964; Griffin *et al.* 1968) and in the Lias decreasing kaolinite contents probably reflect greater distance from source area. The well-marked facies changes at the base of the Pliensbachian may well have resulted from increased water depths in the basins, and marine transgression of the Sinemurian shore-lines.

Iron and calcium distributions. Many authors have considered that iron-rich concretions typify depositional environments closer to the source area than those in which iron-deficient calcareous concretions are dominant (Curtis 1967; Curtis and Spears 1968; Hallam 1967*b*; Cronan and Tooms 1969). In the Type 1 cycles (see below) the calcareous concretions at the cycle tops are iron-poor while in the shales they are strongly sideritic with iron concentrations of 9.8–12.6%. The calcareous concretions at the cycle tops represent phases of reduced terrigenous influence, possibly resulting from marine transgressive phases.

Small-scale sedimentary-cycles. Parts of the Raricostatum-Jamesoni sequence are characterized by rhythmic units which are defined by variations in either the carbonate to clay content, or sand and silt to clay content. Some of these rhythms have been considered in detail (Sellwood 1970; Sellwood *et al.* 1970). The major features of the two major types are summarized here.



TEXT-FIG. 6. Lithofacies/faunal relationships for the major faunal elements.



TEXT-FIG. 7. Lithofacies/trace faunal relationships. Key to lithofacies as in text-fig. 6.

Type 1 (of Sellwood 1970). Each cycle coarsens upward from shales at the base to a bioturbated argillaceous sandstone. Lenticular sandstones often occur in basin-shaped scours, sometimes with a lag-deposit of crinoid-debris at their base. These filled-scours are attributed to storm action. The shale interval in each cycle is typified by a fauna of thin-shelled pectinids, protobranchs, and a trace-fauna of small pyritic tubes produced by infaunal deposit-feeders. The bioturbated sandstones, however, contain a diverse body- and trace-fauna (polyadomyoids, brachiopods, *Diplocraterion*, *Rhizocorallium* and *Thalassinoides*) indicative of shallower water and higher energy conditions than those under which the shales accumulated. Cycle-tops may be cut by meandering shell-filled runnels up to 50 cm in diameter, similar to those described by Häntzschel *et al.* (1968).

The sand fraction of the argillaceous sandstones is well sorted, but bioturbation of the sands with finer material has rendered the grain-size distributions bimodal. It is probable that the sands were introduced as discrete pulses of well-sorted sediment. Accumulations of ammonites (in calcareous nodules) occur on the tops of some sandstone units and the hummocky burrowed tops of the sandstones are draped by the basal shales of the next unit. These basal shales are often rich in the pyritic nuclei of ammonites.

Each cycle represents a shallowing upward sequence with the subsequent deepening phase represented by the ammonitic nodules and shales at the bases of succeeding cycles.

Type 2 (of Sellwood 1970 and Pl. 22, fig. 3). Cycles of this type are the limestone-marl rhythms of previous authors. Bioturbation reveals the primary nature of the cyclicity and the vertical distribution of different ichnogenera displays the asymmetry in the cycles. The tops of limestone units define the tops of individual cycles.

The coccolith *Crepidolithus?* (Deflandre) (Pl. 28, fig. 1) is commonly present in the limestones. These organisms may have been the primary contributors of fine-grained carbonate but recrystallization generally obliterates much of the fine structure. *Diplocraterion* burrows may descend from the tops of limestone units which were extensively bioturbated by *Rhizocorallium*, *Thalassinoides*, and small *Chondrites*. These burrows piped light-coloured calcareous material down into the underlying marls where a larger form of *Chondrites* is found (Pl. 29, fig. 3).

The limestone units may represent the accumulation of relatively undiluted calcareous skeletons during phases of clastic starvation. Storm scours with a bioclastic fill are often present, similar in their scale to those in *Type 1* cycles, and these structures may indicate that both *Types 1* and *2* were produced in comparable water depths.

EXPLANATION OF PLATE 28

Fig. 1. (?)*Crepidolithus* (Deflandre) from an argillaceous calcilutite unit in Bed 115 of Lang, upper Jamesoni Zone, Charmouth, Dorset. Electronmicrograph $\times 5000$.

Fig. 2. *Schizosphaerella* (Deflandre and Dangeard), Levesquei Zone, La Almunia, Spain, Electronmicrograph $\times 2000$. For comparison with Fig. 4.

Fig. 3. *Pinna folium* (Young and Bird) in life position. Sediment filling lower part of body-cavity cemented by siderite, uncemented upper portion compacted and surrounded by shell fragments. Hammer handle 28 cm.

Fig. 4. *Schizosphaerella* (Deflandre and Dangeard), basal Jamesoni Zone, Charmouth, Dorset. Electronmicrograph $\times 1600$.

Fig. 5. Wavy- and flaser-bedded sands and clays, marginal facies, and possibly tidal-flat sediments. (?)Sinemurian, Bornholm, Denmark. Clinometer 12 cm in diameter.

YORKSHIRE AND LINCOLNSHIRE

The sections at Robin Hood's Bay (text-fig. 8; National Grid Reference NZ 950055) and Roxby (text-fig. 9; SE 910170) are generally similar.

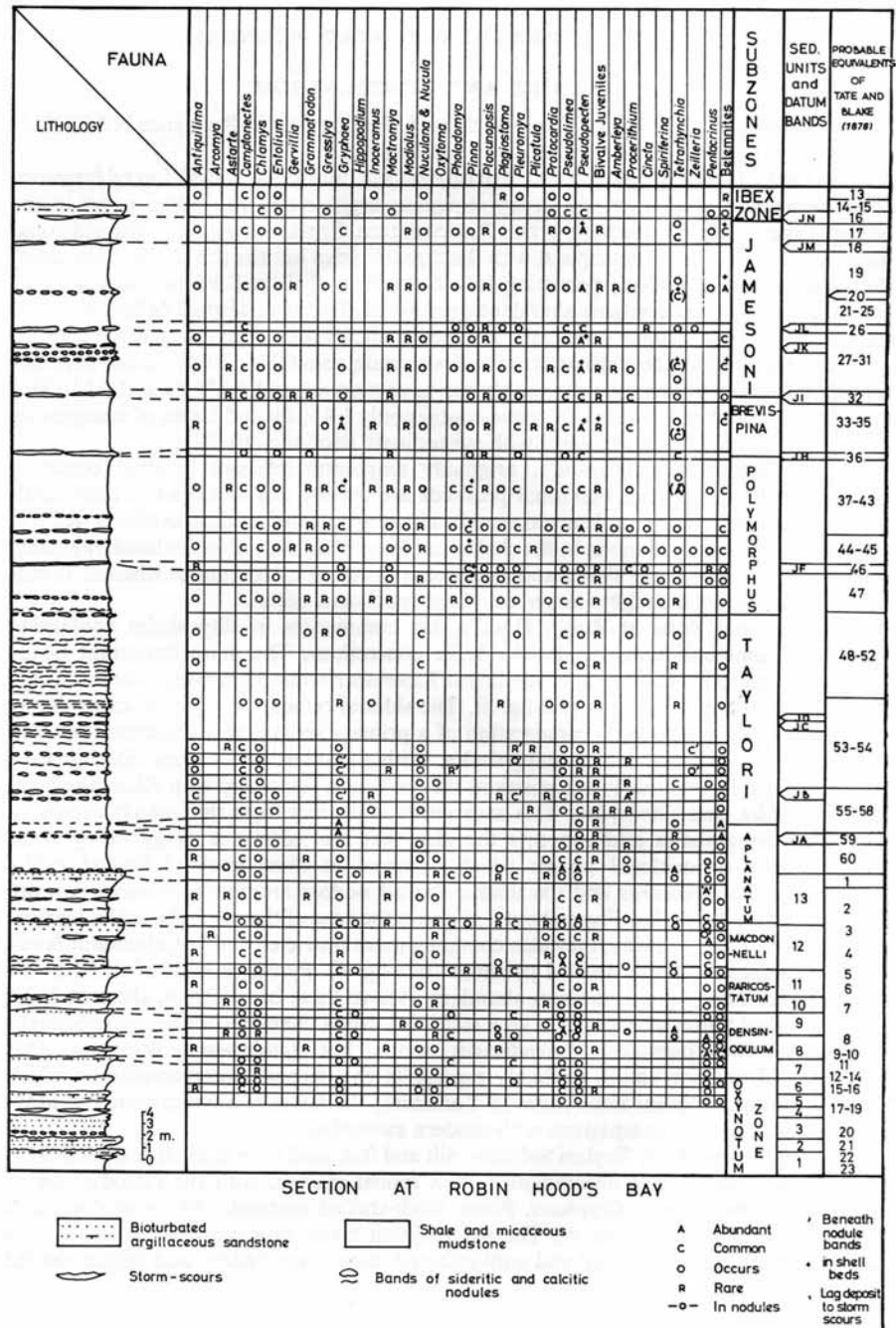
Robin Hood's Bay (text-figs. 2, 3, 8). 21 m of *Raricostatum* Zone and 49.5 m of *Jamesoni* Zone occur in a predominantly shaley sequence; argillaceous sandstones occur in the seven Type 1 cycles composing the *Raricostatum* Zone. In general, the subzonal boundaries in this zone correspond with the tops of cycles but the top of the *Aplanatum* Sub Zone is an exception; persisting to a 6-cm-thick shell bed 3.7 m above unit 13 (text-fig. 8). This bed contains abundant overturned *Gryphaea*, aligned belemnites, and rarer ichthyosaur and bone fragments. This bed probably represents a winnowed deposit.

Siderite nodules in the *Raricostatum* shales contain about 9.8–12.6% Fe and approximately 1.2% Mn whereas the shales themselves contain around 3.5% Fe and 0.1% Mn. Calcareous nodules at the tops of cycles contain only 1.4% Fe and traces of manganese. Illite is the dominant clay mineral with subordinate kaolinite (10–30%).

In the argillaceous sandstones, originally aragonitic infaunal bivalves occur as moulds (in life-positions). Epifaunal pectinids are usually disarticulated in both sandstones and shales, and protobranchs may be either articulated or disarticulated. Rarely, *Pentacrinus* is preserved intact in the shales, but more often only disarticulated fragments occur. Ammonites in the shales and sandstones occur as pyritic nuclei whereas in calcareous and sideritic nodules larger calcitized specimens occur.

The *Jamesoni* Zone at Robin Hood's Bay commences in silty shales containing numerous semicontinuous bands of siderite concretions. The more important bands may be traced to the south side of the Bay at Ravenscar, some 3 km away, where they are useful datum bands (JA–JO in text-fig. 8). The siderite cement in these bands probably reflects a selective secondary cementation of a primary sedimentary difference between the nodule bands and the intervening shales. Within and just below some sideritic beds, *Gryphaea* and *Pleuromya* (in life-position) may be found associated with *Rhizocorallium*, *Thalassinoides*, and *Chondrites*. This association is distinct from that which occurs in the intervening shales and supports the idea that the siderite is exaggerating some non- or slow-depositional phases which occurred at these levels (Sellwood 1971). Belemnites, *Phricodoceras* and the thicker-shelled nodose ammonite *Apoderoceras* are present in the silty shales. From about 3 m above the base of the zone, the shales become more uniform and less silty, they also contain a more restricted and less abundant fauna of protobranchs and thin-shelled pectinids (text-fig. 8). Pyritic moulds of the deposit-feeder *Procerithium* are sometimes abundant. Above these basal shales, the remainder of the *Taylori* Subzone contains a very restricted fauna characterized by protobranchs and thin shelled pectinids. *Phricodoceras* occurs, but *Apoderoceras* does not. This sequence of uniform shales probably represents the deepest water conditions which existed during *Jamesoni* Zone times in Yorkshire; the fauna is a typical outer muddy-shelf assemblage (by comparison with modern examples).

Toward the top of the *Taylori* Subzone, silt and fine sand were again introduced. This sedimentary change was accompanied by a faunal change, with the introduction of *Pleuromya*, *Pholadomya*, *Gryphaea*, *Pinna*, thick-shelled pectinids, *Rhizocorallium*, and rarer *Diplocraterion* (text-fig. 8). The whole fauna takes on a more inner-shelf aspect and the abundance of infaunal and semi-infaunal suspension-feeders, and thicker shelled



TEXT-FIG. 8. Stratigraphic section and faunal distributions at Robin Hood's Bay, Yorkshire.

pectinids suggests a return to shallower agitated waters with high food contents (text-figs. 6, 7). *Apoderoceras* also returns with this change of facies and because this ammonite is strongly controlled by facies it may well have lived in a semi-benthonic manner as a scavenger (text-fig. 6). Certainly the shape of the animal would have prevented it from being an efficient swimmer. Storm-scours are present, as are shell bands rich in exhumed *Pinna* lying flat to the bedding. Bands of *Pinna* alternate with shales which contain *Pinna* in their life positions (Pl. 28, fig. 3). Silty shales containing a rich fauna and occasional beds of sideritic mudstone continue through the remainder of the zone. Illite is the dominant clay mineral and the remainder of the clay fraction is composed of kaolinite which constitutes from 5% to 20% usually averaging about 10%.

The top of the zone is marked by a highly bioturbated sandy clay which contains abundant *Rhizocorallium* burrows. Above this unit (JO of text-fig. 8) a number of coarsening-upward sequences containing *Chondrites* occur before the commencement of very fine grained sedimentation in Ibez Zone times (with shales containing *Inoceramus* and protobranchs).

Sedimentological and faunal data suggest that the over-all environment in Raricostatium times was shallow neritic with alternating shallowing and deepening phases reflected in the cyclicity. The Jamesoni Zone commenced with a deepening phase which continued through the Taylori Subzone producing the muds with their restricted faunas. Shallower-water conditions returned and persisted through the remainder of Jamesoni times with renewed deepening occurring in the Ibez Zone.

Roxby (text-figs. 2, 3, 9). 15.0 m of Raricostatium Zone and 19.0 m of Jamesoni Zone are exposed in a predominantly shaly and clay succession which rests upon a winnowed shell bed at the top of the Frodingham ironstone. This shell bed marks the probable omission of the upper part of the Oxynotum Zone. The Raricostatium Zone displays seven Type 1 cycles, similar to those at Robin Hood's Bay but the clays contain far less mica and silt. Illite is the dominant clay and the kaolinite content ranges from 10–15%. Subzonal boundaries occur at the tops of the cycles except for that of the Aplanatum subzone which continues to a shell-bed in the shales above the cyclic sequence (text-fig. 9). This bed contains overturned *Gryphaea*, thick-shelled *Pseudopecten*, cidarid spines, fish scales, and abundant foraminifera. The material is broken and encrusted with bryozoans and foraminifera such as *Ammovertella*. The bed represents a winnowed deposit like its counterpart at Robin Hood's Bay.

Facies in the Jamesoni Zone are similar to those at Robin Hood's Bay. *Pinna* is common in the clays, often in life-position, but more abundantly as exhumed shells. Illite is the dominant clay with kaolinite contents being usually 10–15%.

Toward the top of the zone, the facies changes suddenly to the chamosite limonite oolite known as the Pecten Bed (text-fig. 9). This bed is stratigraphically condensed and within its 1.8 m thickness is probably included the bulk of the Ibez Zone. Trough cross-bedding is present, as are storm scours, and the abundant *Pseudopecten* which occur at several horizons within the bed are thick shelled and always in their current stable positions. Thus there is evidence of at least periodic current action. Infaunal suspension-feeders like *Cardinia*, *Pholadomya*, and *Pleuromya* replace *Pinna* as the dominant faunal elements and moulds of the gastropods *Procerithium* and *Amberleya* are common in some shell beds. The whole assemblage clearly represents shallower and more turbulent

water conditions than those under which the bulk of the zone were deposited. The fauna in the chamositic Pecten Bed is not stunted and depositional conditions appear to have been normal. The problems concerning the origin of chamosite have been discussed by many authors (Hallam 1966; James 1966). In the light of recent papers by Rohrlach *et al.* (1969), and Porrenga (1965) it is probable that the chamosite formed diagenetically in faecal pellets, and in this condensed bed, where much of the sediment was reworked and digested many times by burrowers, the formation of the mineral may well have been facilitated by chemical processes within the guts of deposit-feeding organisms.

Fossil biofabrics are generally similar to those at Robin Hood's Bay, but in the shales aragonitic shells are often preserved in their original state. This may be a function of the lower sediment porosity preventing post-depositional dissolution of aragonite.

The sequence of environments represented compares with that in Yorkshire. Lower silt, mica, and kaolinite contents suggest that the area was slightly further from the sediment-source. The major difference between the two successions is the development of a chamosite oolite facies. The condensed nature of the succession and diverse shallow-water fauna support Hallam's (1966) hypothesis that these sequences formed on 'Swells'. A minor 'Swell' developed in this area during late Jamesoni times (text-fig. 5).

THE MIDLANDS AND THE LONDON PLATFORM

Cheltenham (text-fig. 2) (SO 947238). A temporary section at Folly Lane exposed between 5 m and 7 m of Densinodulum to Raricostatum Subzone clays with little mica. Many thin (15 cm) beds of bioturbated silty clay alternated with the clays which are predominantly illitic, containing less than 10% kaolinite.

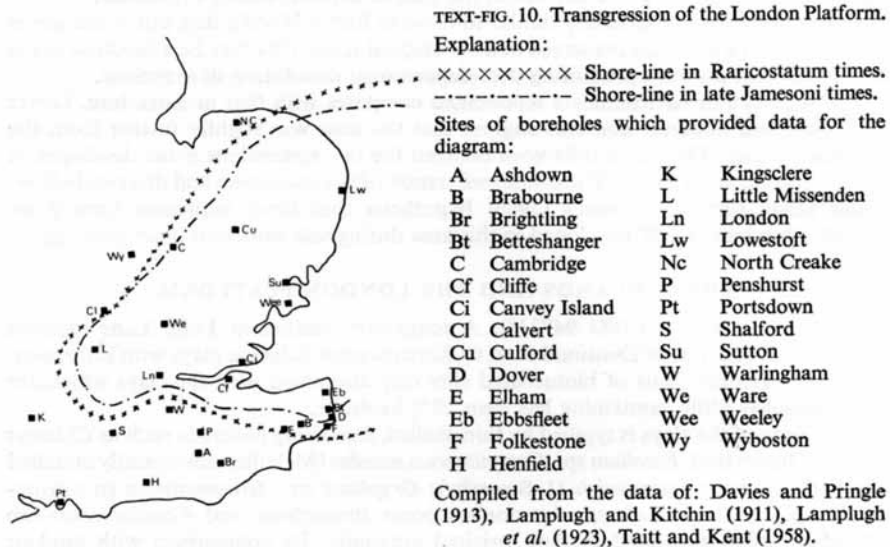
The fauna of the clays is typified by thin-shelled, free-living pectinids such as *Chlamys securis* (Dumortier), *Entolium* sp., *Camptonectes mundus* (Melville); the byssally attached pteroid *Oxytoma inaequivalvis* (J. Sowerby); *Gryphaea* sp.; *Grammatodon* sp.; *Protocardia* sp.; and *Nuculana* sp. Ammonites occur throughout and *Crucilobicerus* are abundant, often preserved in their original aragonite. By comparison with modern communities, this assemblage represents a middle to outer shelf-mud environment.

Stowell Park Borehole, Gloucestershire (SP 084118) (text-figs. 2 and 3). This hole was drilled for the Geological Survey in 1949 and as only small fragments of core are now available, the published data of Green and Melville (1956), Melville (1956), and Spath (1956) are reproduced here. In the section (text-fig. 5), subzonal boundaries have been redrawn to conform with the stratigraphy proposed by Dean *et al.* (1961).

The Raricostatum Zone consists of two main parts, the lower (Densinodulum and Raricostatum Subzones) composed essentially of dark laminated shales and mudstones, and the upper (Macdonnelli and Aplanatum Subzones) of shelly ironstone mudstones, muddy limestones, and black shales. *Lingula* occurs in the lower Raricostatum Zone, associated with a fauna containing *Nucula*, *Parallelodon*, *Grammatodon*, *Oxytoma*, *Gryphea*, *Modiolus*, *Antiquilima*, and *Mactromya*. The presence of *Lingula* and lucinoids and the absence of pholadomyoids suggests a highly turbid environment with little current action except for periodic scouring by storms.

In the upper Raricostatum Zone the fauna is more diverse with the introduction of *Tropiorhynchia*, and more infaunal suspension-feeding bivalves (e.g. *Astarte* and *Pholadomya*) indicating increased current activity and improved substrate conditions.

The Jamesoni Zone consists of mudstones with some burrowed limestones ('fucoid' beds of Green and Melville 1956) containing a diverse fauna of epifaunal suspension-feeders (mostly pectinids) but lacking a suspension-feeding infauna. These conditions persisted to the top of the Brevispina Subzone where, apart from the brachiopods *Cincta* and *Tropiorhynchia*, the fauna becomes restricted to infaunal deposit-feeders. This assemblage compares with a modern outer shelf mud environment and the 'fucoid beds' contain burrows which may represent periods of reduced sedimentation.



London Platform. Jamesoni Zone sediments overstep Raricostatum Zone sediments, and are themselves overstepped by sediments of later zones (text-fig. 10).

At Calvert (Buckinghamshire, SP 680257, text-fig. 10), a fragment of derived *Echino-ceras* was found in the 1 m thick ironshot limestone of the Jamesoni Zone (Davies and Pringle 1913). This fragment shows that Raricostatum Zone sediments were deposited

EXPLANATION OF PLATE 29

Fig. 1. Polished section through upper part of Watch Ammonite Stone. The less argillaceous portion (light coloured) contains abundant randomly disposed ammonites. Light material was piped down into the darker by *Chondrites* burrows. $\times 1$.

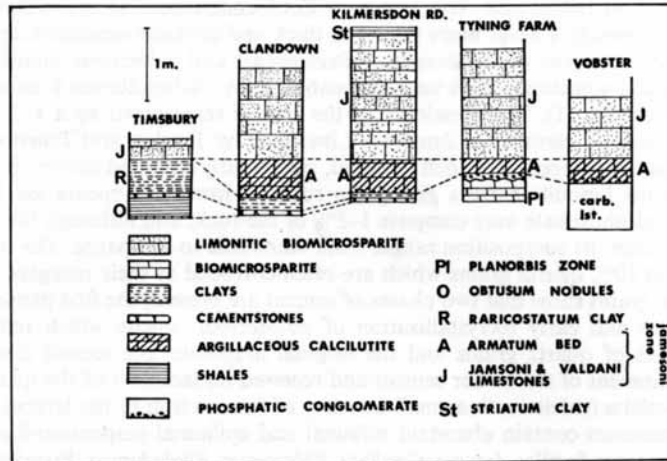
Fig. 2. Polished section through upper portion of Hummocky Limestone showing part of a *Diplocraterion* burrow (arrowed *a*) and limestone clasts (arrowed *b*). The black specks in the lower part of the picture are small *Chondrites* in section. $\times \frac{3}{4}$.

Fig. 3. Limestone/marl relationship, Belemnite Marls. *Chondrites*, *Thalassinoides*, and *Rhizocorallium* are conspicuous in section below the limestone. Burrows are filled with light coloured calcareous sediment from the bed above. Hammer handle 8 cm.

The top of each specimen is to the left.

there, but later reworked. The Jamesoni Zone rests upon an erosion surface cutting reddened and weathered Tremadocian rocks. Thus, temporary transgression occurred in the Raricostatum Zone, followed by an extensive transgression in Jamesoni to Davoei Zone times. On the margins of the London Platform (text-fig. 10), if Raricostatum and Jamesoni sediments are preserved at all, they tend to be condensed and are often ironshot.

Beneath Kent, the Jamesoni zone rests upon Palaeozoic basement in bore-holes at Dover, Folkestone, Brabourne, and Elham; and Raricostatum Zone sediments are



TEXT-FIG. 11. Stratigraphic sections in the Radstock Area. Modified from Tutchter and Trueman (1925).

overstepped (text-fig. 10) (Lamplugh *et al.* 1923). In the Dover bore-hole plant debris was found in the basal ironshot sands (Lamplugh and Kitchin 1911). In a number of other boreholes such as Kingsclere, North Creak, Shalford, Warlingham, and Penshurst (text-fig. 10) the facies in the Jamesoni Zone change to sediments with a deeper water aspect and a finer grain size. These facies changes, and the overstep by the zone on to older rocks, suggest that partial transgression of the Platform occurred during the zone. There are enough facies changes in the neighbourhood of the London Platform to show that the absence of both Raricostatum and Jamesoni strata over most of the region is due to the area having been a source of sediment at the time and not simply to their removal during later phases of erosion.

Wales. The Raricostatum and Jamesoni Zones are not represented in the main Lias outcrop of Glamorgan, but the recent Institute of Geological Sciences bore-hole at Mochras (text-fig. 2) passed through a 'great thickness of silty-clay sediments representing these zones' (Dr. A. W. Woodland *pers. comm.*). There is little coarse material to suggest a local source-area and Wales was probably totally submerged in this part of the Lias.

SOUTH WEST ENGLAND: SOMERSET AND DORSET

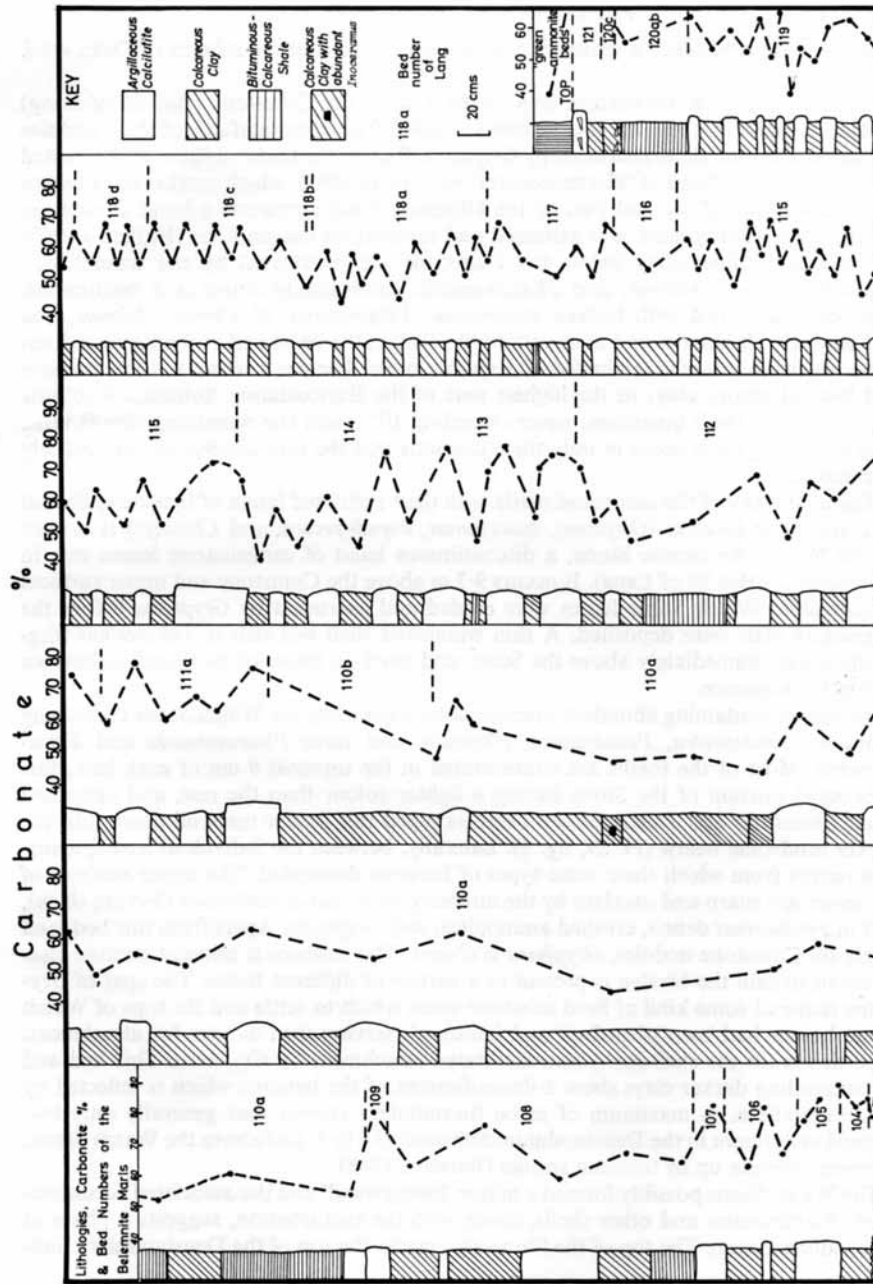
Somerset (The Mendip Region). The Lias is very condensed in this area with the succession from upper Rhaetic to Jamesoni Zone being less than 5 m thick.

Three quarries near Radstock still expose the Raricostatium and Jamesoni Zones (Kilmarston Road ST 687545 and 689541; and Vobster ST 705498) (text-figs. 2 and 11). Many quarries were available to Tutcher and Trueman (1925) but most of these have been filled subsequently. The Raricostatium Zone is represented by a few centimetres of brown clays containing derived (phosphatized) and *in situ* *Echioceras*, *Leptechioceras*, *Procerithium*, and belemnites. The Jamesoni Zone commences as the rather variable Armatum Bed which is never more than 1 m thick and contains abundant derived and phosphatized specimens of *Echioceras*, *Paltechioceras* and calcareous mudstone fragments. This bed sometimes rests unconformably upon Carboniferous Limestone (e.g. at Vobster, text-fig. 11). The remainder of the zone is represented by a 1–1.5 m-thick bioclastic limestone, termed the Jamesoni Limestone by Tutcher and Trueman (1925). This limestone is composed of shell material, particularly echinoid debris. It also contains numerous limonite oolites giving the rock its ironshot appearance. Pellets of glauconite and phosphate may compose 1–2% of the rock, and although the Jamesoni Limestone is thin, its composition ranges from biomicrite to biosparite. The biosparites contain up to 10% quartz grains which are often corroded at their margins. Reaction rims to these grains show that two phases of cement are present, the first phase involved the formation and early recrystallization of non-ferroan calcite which replaced the outer portions of quartz grains and the original aragonite, the second involved the partial replacement of the earlier cement and renewed replacement of the quartz grains by ferroan-calcite (calcite with a small quantity of ferrous iron in the lattice).

These limestones contain abundant infaunal and epifaunal suspension-feeders both as fossils and trace-fossils; *Astarte*, *Cardinia*, *Pleuromya*, *Pholadomya*, *Pseudolimea*, and *Gryphaea* are abundant at certain levels along with *Thalassinoides* and *Diplocraterion* burrows. The bed is condensed stratigraphically and the majority of the shells have been winnowed from their life-positions, but sufficient remain to show that the fauna is representative of the area and not derived from elsewhere. The fauna also indicates soft-sediment conditions beneath agitated and probably shallow water. According to Tutcher and Trueman, northward from Radstock, the limestone facies passes into clays but no exposures exist now.

The Radstock–Mendip area acted as a swell, starved of clastics, upon which bioclastic material slowly accumulated. Raricostatium Zone sediments were probably more thickly developed there originally, but the bulk of this material was removed before Jamesoni times. This was probably during the same phase of erosion which produced the winnowed shell beds at the top of the Raricostatium Zone in Yorkshire and Lincolnshire and also the major non-sequence below the Jamesoni Zone on the Dorset coast.

Dorset. Between Charmouth (SY 368930) and Seatown (SY 420917) 13.5 m of Raricostatium Zone and 23.7 m of Jamesoni Zone are exposed (text-figs. 2, 3, 12). The Raricostatium Zone composes the uppermost part of the Black Ven Marls, whilst the Jamesoni and Ibex Zones together form the Belemnite Marls. Much of the detailed stratigraphic work was done by Lang (in Lang *et al.* 1926, 1928) and although this zonal



TEXT-FIG. 12. Stratigraphic sequence in the Belemnite Marls with insoluble residue data for each bed.

scheme is now obsolete his sequence can be easily fitted into the scheme of Dean *et al.* (1961).

The base of the Raricostatum zone is marked by the Coinstone (Bed 89 of Lang) which is a discontinuous line of calcareous nodules. The upper surfaces of these nodules are bored and sometimes encrusted by *Gryphaea*. Rarely, the undersurfaces are encrusted by serpulids. This band of 'Hiatus concretions' (Voigt 1968), which marks the omission of the Oxynotum Zone and part of the Obtusum Zone represents a band of septaria which, when already hard, was exhumed and exposed on the sea floor (Hallam 1969c).

The marls immediately below the Coinstone are penetrated by the trace fossils *Chondrites*, *Rhizocorallium*, and *Thalassinoides*: immediately above is a continuous, 2-cm-thick shell bed with broken *Inoceramus*, *Plagiostoma*, *Oxytoma*, *Chlamys*, and protobranchs, fish scales and abundant pyrite. This is the basal bed of the Raricostatum Zone which continues in laminated bituminous marls. There is a return to more massive and less calcareous clays in the highest part of the Raricostatum Subzone. Kaolinite occurs in only small quantities, never exceeding 10%, and the remaining clay is illite. Iron and manganese occur in only trace amounts and the rare concretions are entirely calcareous.

The monotony of the laminated marls with their restricted fauna of byssate epifaunal and free-living bivalves (*Oxytoma*, *Inoceramus*, *Pseudopecten*, and *Chlamys*) is broken by the Watch Ammonite Stone, a discontinuous band of cementstone lenses rich in echioceratids (Bed 99 of Lang). It occurs 9.3 m above the Coinstone and upper surfaces of individual Watch Stone lenses were eroded and encrusted by *Gryphaea* before the succeeding beds were deposited. A thin winnowed shell bed rich in *Pentacrinus* fragments occurs immediately above the Stone and marks a phase of increased turbulence within the sequence.

As well as containing abundant uncrushed echioceratids, the Watch Stone commonly contains *Pseudopecten*, *Pseudolimea*, *Plicatula*, and rarer *Pleurotomaria* and *Tetrarhynchia*. Most of the fossils are concentrated in the topmost 9 cm of each lens, this uppermost portion of the Stone having a lighter colour than the rest, and abundant small *Chondrites* and *Thalassinoides* burrows piped this lighter material down into the darker mudstone below (Pl. 29, fig. 1). Laterally, between the individual lenses, a surface occurs from which these same types of burrows descended. The upper surfaces of the lenses are sharp and overlain by the intensely bioturbated shell-hash (3–5 cm thick), rich in *Pentacrinus* debris, crushed ammonites, and *Gryphaea*. Apart from this bed, and rarely on Coinstone nodules, *Gryphaea* is absent. This absence is unusual because elsewhere in Britain the bivalve is present in a variety of different facies. The spat of *Gryphaea* required some kind of hard substrate upon which to settle and the tops of Watch Stone Lenses had been planed-off and hardened, serving then as sites for attachment. Shell debris (in the shell-hash) also facilitated attachment by *Gryphaea*. This bed and the succeeding darker clays show a diversification of the benthos which is reflected by the foraminifera. A maximum of seven foraminifera species (but generally only two species) are present in the Densinodulum Subzone; the beds just above the Watch Stone, however, contain up to fourteen species (Barnard 1948).

The Watch Stone possibly formed a minor 'hardground' and the associated accumulations of ammonites and other shells, along with the bioturbation, suggests a phase of slow sedimentation. The top of the Stone also marks the top of the Densinodulum Sub-

zone and it is probable that the slow or non-sedimentation phase exaggerated the change from the one subzone to the next. The Stone represents an extreme example of a Type 2 cycle (Sellwood 1970). Above, the facies returns to laminated marl and still the fauna continues to have a relatively low diversity, consisting of occasional ammonites, *Antiquilima*, *Inoceramus*, and bivalve juveniles. The sharp lithological change which occurs about 1.6 m below the Hummocky Limestone, from laminated to homogeneous marls, is accompanied by a slight diversification in the fauna. Protobranch bivalves and rare *Grammatodon* occur, while *Pseudolimea*, *Plagiostoma*, and other pectinids become more common. The Raricostatum Zone ends just above an irregular limestone bed containing the coccolith *Crepidolithus* (?) (Pl. 28, fig. 1), the bed was termed the Hummocky Limestone (Bed 103 of Lang 1928). Echioceratids are abundant on the undersurface of the bed, where *Chondrites*, *Thalassinoides*, and *Rhizocorallium* burrows also occur. Apart from the Watch Stone, the 'Hummocky' is the only other hardened bed within the zone; these are the only beds which contain more than 80% CaCO₃. The top of the Hummocky is penetrated by abundant small *Chondrites* burrows (0.1 to 1.0 mm in diameter) and rarer small *Diplocraterion* tubes (0.7 cm in diameter and 4.0 cm in length), which are filled with marl from the overlying bed (Pl. 29, fig. 2). *Rhizocorallium* burrows also penetrate the topmost 1 cm of the bed, and their sediment-fillings, along with those of the *Diplocraterion*, have been reworked by larger *Chondrites* (which are otherwise absent). The small *Chondrites* and *Diplocraterion* which penetrate the lowest 9 cm of the limestone are totally uncompacted, whereas in the topmost 1 cm of this 10 cm thick bed the burrows are compacted by more than 50%. The absence of *Rhizocorallium* and large *Chondrites* from the uncompacted and hardened portion of the bed may indicate that some hardening of the unit occurred at an early stage at a shallow depth below the sea bed.

Intraformational clasts of limestone up to 1.0 cm in diameter are present towards the top of the Hummocky Limestone (Pl. 29, fig. 2) and these clasts contain dark specks of phosphate. Irregularly shaped clasts like these persist for 2–3 cm up into the overlying marls. Two cm above the top of Hummocky, a discontinuous band of nodular limestone 1 cm thick occurs and above, the rhythmic Belemnite Marls commence. This band of nodular limestone marks the omission of the top two subzones of the Raricostatum Zone and this erosive episode is indicated by the reworked clasts of limestone.

Apart from a few calcilutite/marl rhythms at the base of the Taylori Subzone, this subzone is predominantly composed of marls and bituminous shales. As explained earlier (Sellwood 1970; and Sellwood *et al.* 1970), there is good evidence to suggest that the light to dark rhythms in the Belemnite Marls have a primary origin. It is likely that the development here of more uniform marls and shales in the Taylori Subzone parallels the development of uniform shales during the same subzone in Yorkshire.

Light to dark alternations (Pl. 29, fig. 3) can still be recognized even when the difference in carbonate content between adjacent beds is only 5% and a similar record was reported by Kennedy (1967) from sedimentary rhythms in the Lower Chalk. The carbonate component in the argillaceous calcilutites (light beds) consists of echinoid spines, crinoidal fragments, foraminifera, and ostracod shells in the microscopic fraction, and these components often represent micro-lag deposits at the bases of burrow-fills and in storm-scours. The storm-scours are similar to those described earlier, but are filled with bioclastic material, particularly belemnites and crinoid debris.

The presence of scour structures of similar scale to those from the more clastic sequences suggests that the calcareous sediments accumulated under water that might have been no deeper than in northern Britain. The differences in sediment type are attributed to the greater distance of Dorset from the sediment source area. The fine-grained 'lutite' matrix composing some 60% or more of the rock consists of microcrystalline calcite growing on clay flakes (Pl. 28, figs. 1, 4). But a contribution is also made by numerous coccoliths and ?*Schizosphaerella* (Pl. 28, figs. 2, 4). The latter may be the outer cell-wall layers of calciodinellid dinoflagellates similar and possibly ancestral to those described by Wall and Dale (1968). The clay mineral and iron composition is not detectably different in the calcilutites and marls and only trace quantities of both kaolinite and iron are present in the sequence.

The Belemnite Marls contain a poor benthonic assemblage; belemnites are the most common fossils, and ammonites are usually poorly preserved. Bivalves are limited to *Inoceramus*, *Plagiostoma*, and thin-shelled pectinids. Protobranchs do not occur, nor do infaunal and semi-infaunal bivalves like *Pholadomya* and *Pinna* which are so characteristic of the other areas. Even *Gryphaea* is absent.

It is obvious from the poor state of preservation of the ammonites that some aragonitic shell material has been lost during diagenesis. Ammonites are mostly preserved as moulds, but not even the moulds of aragonitic burrowing bivalves occur, and certainly the absence of such bivalves as *Gryphaea*, with strong calcitic shells, cannot be explained simply in terms of their diagenetic loss. Barnard (1948) also noted the extreme paucity of foraminifera compared with equivalent beds in Germany. Brachiopods are only abundant at two horizons in the Jamesoni Zone, firstly at the top of the Polymorphus Subzone and secondly toward the top of the zone in beds 118-119 of Lang (in Lang *et al.* 1928). Brachiopods occur sporadically throughout the Belemnite Marls and are mostly represented by *Cincta* and *Piarorhynchia*. Crinoid debris is sometimes common in the storm-scours and it is probable that eddying occurred around small assemblages of crinoids causing their collapse and disintegration (Sellwood 1970). Echinoids are represented by cidarid and diademid spines, particularly in the calcilutite units. The burrows of suspension-feeders like *Diplocraterion*, *Rhizocorallium*, and *Thalassinoides* are present. *Chondrites* is prominent but the burrow walls of these systems are not as distinct as they are in other areas, suggesting that the sediments were poorly consolidated (Rhoads 1967, 1970). Sediment instability may have been one of the reasons for the restricted benthos, with the sediments having an oozy consistency similar to that envisaged by Kauffman (1967) for some Cretaceous chalks dominated by *Inoceramus*.

Inoceramus ventricosus (J. de C. Sowerby) from the Belemnite Marls is a relatively large flattened form and by comparison with some Cretaceous *Inoceramus* described by Kauffman (1967) may have been adapted to a life on a soft substrate. The smaller *I. dubius* usually occurs as disarticulated valves and this species may well have been pseudoplanktonic, attached to floating material like the *Inoceramus* figured by Hauff (1953) from the Posidonienschiefer.

In summary, the high energy and shallow-water conditions represented by the Coinstone were succeeded by a phase of deepening. Through much of the Raricostatum Zone, the lime-mud and low clay content produced unstable substrates and it was only during times of substrate stabilization in phases of winnowing and shallowing when a more normal benthos became established (Watch Stone). Toward the top of the zone

shallowing occurred allowing winnowing and substrate stabilization with a higher diversity benthos. This phase of shallowing culminated in scouring to produce intraclasts of limestone within the 'Hummocky' and an extensive non-sequence above it. Deepening occurred in basal Jamesoni times succeeded by the alternating deeper- to shallower-water limestone/marl rhythms of the remaining Belemnite Marls whose impoverished benthos primarily reflects unstable soft substrate conditions.

THE INNER HEBRIDES

In Scotland, sediments ranging from the *Raricostatum* to *Ibex* Zones are included in the Pabba Shales (Judd 1878). The sequence is never continuously exposed and text-fig. 3 is based on a tentative correlation from Loch Slapin, Skye (text-fig. 13, NG 588175), to Pabba (text-fig. 14, NG 673264). The thickness of the *Raricostatum* Zone (82.6 m) and Jamesoni Zone (111 m) in the Hebridean Area is only exceeded by their thickness at Mochras, Wales. The Hebridean-Irish Sea region may have been one basin with rather more rapid sedimentation and subsidence than other areas.

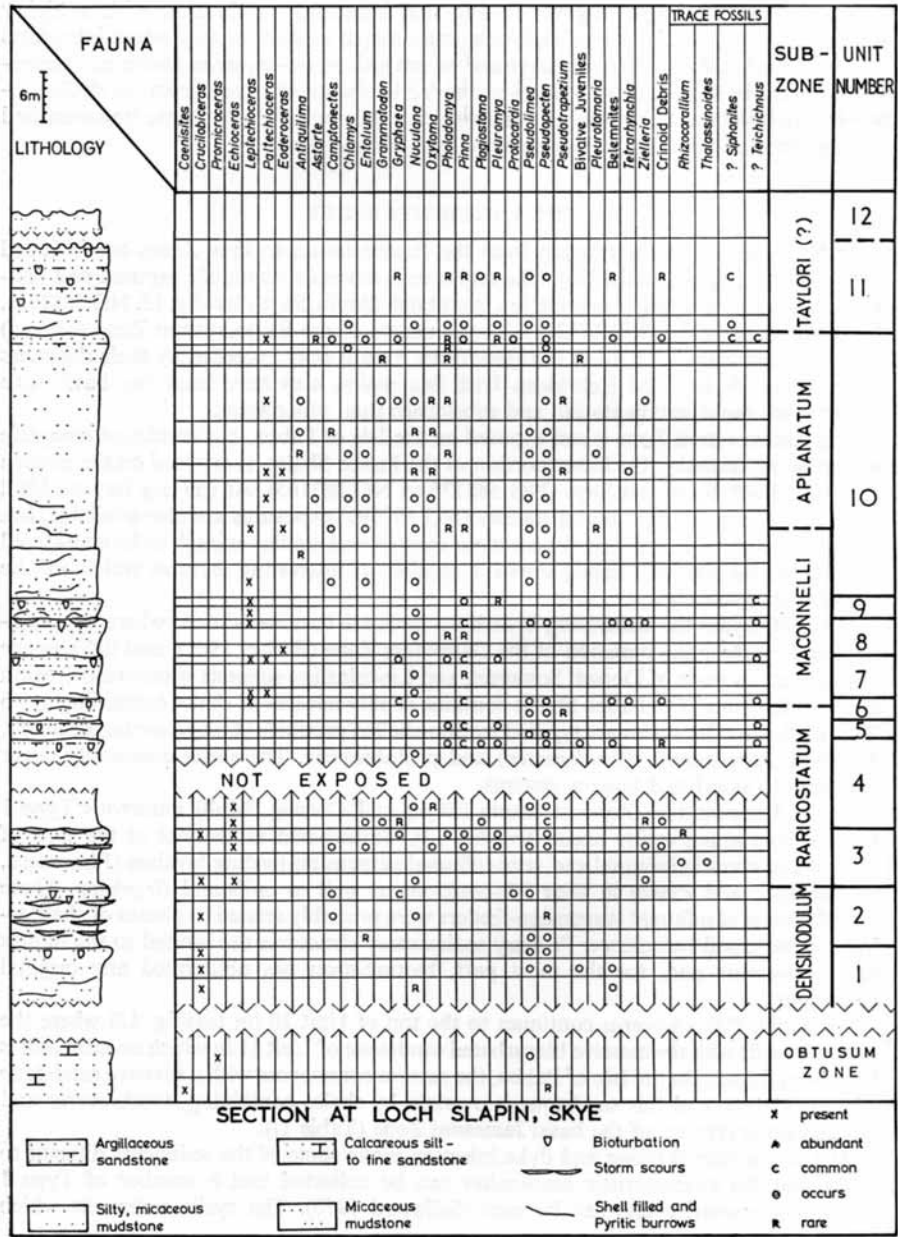
The *Raricostatum* Zone is not exposed on the Isle of Pabba, but an almost complete sequence, representing the lower portion of the Pabba Shales, is exposed on the eastern shores of Loch Slapin on Skye (NG 588175 to NG 587165). At Carsaig Bay on Mull (NM 535215) and at Hallaig on Raasay (NG 592391) exposures are also available, but the sections on Skye and Raasay are close enough and similar enough to be considered together whilst that at Carsaig shows a number of interesting features which will be mentioned separately.

In the Hebrides the underlying Broadford Beds are terminated everywhere by a non-sequence marking the omission of the *Oxynotum* Zone (Richey 1961), and the absence of this Zone in parts of Dorset, Somerset, and Lincolnshire suggests widespread erosion at about this time. The Pabba Shales continue in silty micaceous shales containing up to 20% kaolinite. The shales are typified by thin-shelled pectinids (*Camptonectes*, *Chlamys*, *Entolium*, *Pseudolimea*, *Pseudopecten*) and protobranchs. The shells commonly occur as fillings to sideritized burrow systems.

In the *Raricostatum* Zone at Slapin (Skye) and Carsaig (Mull) numerous Type 1 upward coarsening cycles occur (text-fig. 13). Bioturbated sandstones at the tops of these cycles contain infaunal and semi-infaunal suspension-feeding bivalves (*Pleuromya*, *Pholadomya*, and *Pinna*) in their life-positions as well as epifaunal *Gryphaea*. These introductions of infaunal suspension-feeders were probably related to phases of shallowing and increased turbulence. Primary sedimentary structures are limited to the fillings of storm-scours and, for the most part, bioturbation has obliterated any original lamination.

At Slapin, *Paltechioceras* continues to the top of Unit 10 (in text-fig. 13) where the sequence ends with the massive bioturbated sandstone of Unit 11 in which no ammonites have been found. On the Isle of Pabba, the section commences with a massive sandstone of Unit 11 type and this sandstone is overlain by shales containing *Apoderoceras* and *Phricodoceras* (typical of the basal Jamesoni Zone (Table 1)).

At Carsaig Bay, faulting and dyke injection make some of the sediments difficult to study, but the characteristic ammonites can be collected and a number of Type 1 coarsening-upward cycles can be seen (Sellwood 1970). The cyclic sediments which



TEXT-FIG. 13. Stratigraphic section and faunal distributions at Loch Slapin, Skye.

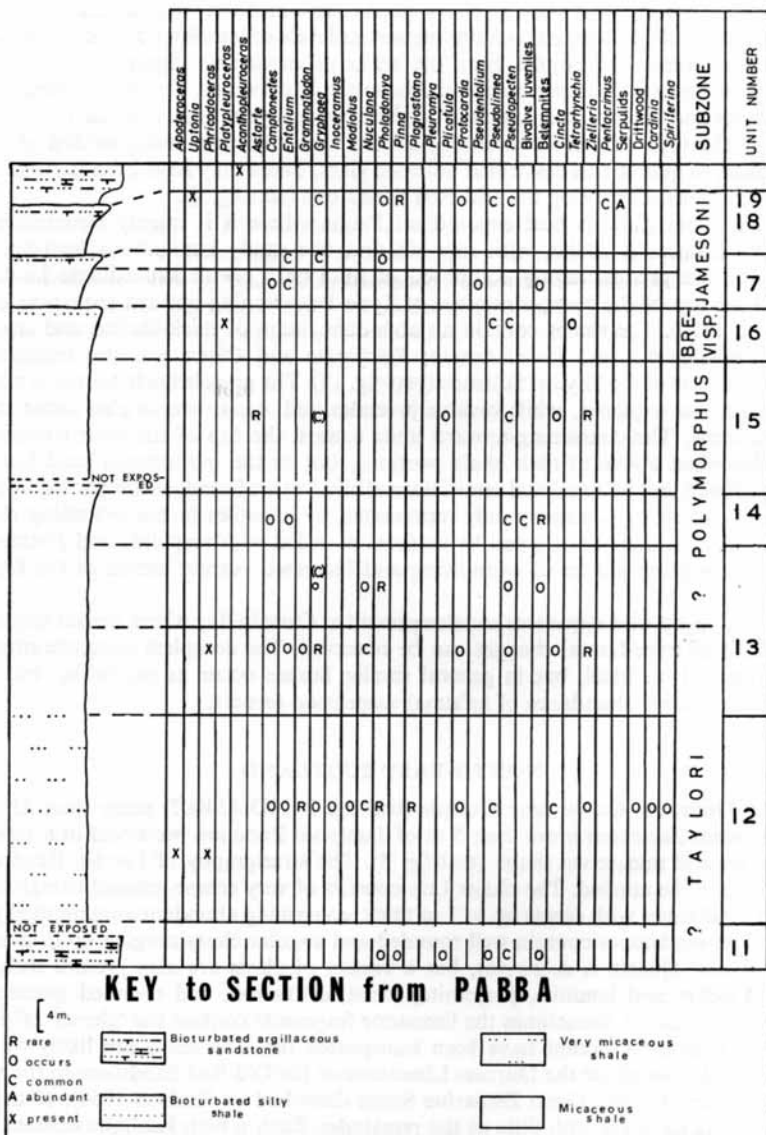
contain *Paltechioceras* rest upon a yellow-green coarse-medium grained sandstone which is devoid of fossils, but which contains numerous levels of interference and symmetrical ripples. Sometimes the ripples bear the trails of organisms (?gastropods) and the openings of vertical (?escape) burrows. Above the basal sands, the beds become more argillaceous and bioturbated, and take on their typical cyclic nature. Some of the sandstones at the tops of these coarsening-upward cycles contain well-rounded granule-grade clasts of quartz and devitrified volcanic glass. These may have been derived from a local source area exposing the Old Red Sandstone (text-fig. 4).

The Jamesoni Zone is best exposed on Pabba where it is mostly represented by extremely micaceous shales, with rare silt and fine sandy laminations (text-fig. 14). The shales are predominantly composed of illite (90%) with subordinate kaolinite. Toward the top of the zone, a number of Type 1 coarsening-upward sequences occur (Sellwood 1970). The shales contain an abundant fauna of thick-shelled and strongly ribbed *Pseudopecten* and *Pseudolimaea*; *Spiriferina* and *Cincta* are also common at certain horizons in the Taylori Subzone (text-fig. 14). The protobranch *Nucula* is present throughout the sequence, while bivalve juveniles and *Apoderoceras* also occur in the basal subzone. The coarsening-upward units toward the top of the zone contain the fauna described above in their shale portions, but in the bioturbated sandstones at the top of each unit infaunal and semi-infaunal bivalves are found, accompanied by adult *Gryphaea*. *Gryphaea* is usually only represented by juveniles in the preceding shales. Some sandstone units are capped by surfaces crowded with serpulids and *Pentacrinus* debris representing phases of winnowing and increased current action at the tops of the units.

Coarsening-upward sequences are also present at Carsaig Bay where similar sequences of faunal and trace-faunal changes can be observed. The complete sequence may not be represented on Mull, but in general similar faunas occur as on Pabba, but with probably a greater abundance of infaunal suspension-feeders.

NORTH-EAST SCOTLAND

Below Dunrobin Castle near Golspie (text-fig. 2, ND 854007) more than 23 m of Raricostatum Zone and more than 5 m of Jamesoni Zone are preserved in a series of sandstones and micaceous shales (text-fig. 3). The stratigraphy of Lee (in Read *et al.* 1925) can still be applied. The oldest Lias consists of very coarse-grained trough cross-bedded sandstones with cosets up to 1 m thick, containing abundant comminuted plant debris. The sandstones contain well rounded and angular clasts ranging up to granule-grade in size. Quartz is dominant, but a variety of clasts are also present including silicified oolite and laminite, psammite, schist, driftwood, and rounded granules of microsparitic calcite. Sometimes the limestone fragments contain the 'ghosts' of pellets and such fragments cannot have been transported far. The clasts are likely to have been derived from either the Durness Limestone or the Old Red Sandstone to the north and north-west (cf. the Great Estuarine Series described by Hudson 1964). 40 to 50% of the clay is kaolinite with illite as the remainder. Such a high kaolinite content indicates deposition near to the source area. Fossils and burrows are absent from the unit and exposures are poor but the trough cross bedding indicates that the currents which deposited the sandstone moved in a southerly or south-easterly direction. Upward



TEXT-FIG. 14. Stratigraphic section and faunal distributions on the Isle of Pabba.

through the unit (Bed 1 of Lee) there is a general decrease in grain-size, and fine-grained plant debris forms carbonaceous drapes on the toesets of cross-bedded units. These sands may have been deposited under a strong fluvial influence.

Above the sandstone, the marine sequence of Raricostatum Zone sediments commences (text-fig. 3). A number of Type 1 coarsening-upward cycles are present and the silty clay portions of each cycle contain abundant muscovite. Some of the sandstones contain rounded, granule-grade quartz clasts (Bed 16 of Lee) and the majority of the sediments have been strongly bioturbated. Kaolinite to illite ratios are lower than in the basal sandstone with illite resuming its dominance of the clay fraction (kaolinite 20–30%).

Rhizocorallium, *Thalassinoides*, and *Tigillites* (probably the burrows of suspension-feeders) are present in the sandy tops of coarsening-upward units, but in general, the fauna of these beds is poor; rare *Astarte*, *Myochoncha*, *Modiolus*, and *Gryphaea* occur but are not abundant. *Mactromya* and other lucinoids are also present in the shales. Two shale beds (Beds 8 and 9 of Lee) are, however, highly fossiliferous. Bed 8 contains abundant disarticulated *Pseudolimea* (with their original colour-banding still preserved) and abundant juvenile *Gryphaea*. Specimens of the latter are usually disarticulated, but the bed preserves both right and left valves which are often preserved in their life-orientations. *Paltechioceras* occurs in this and the succeeding bed (Bed 9 of Lee) which also contains abundant bivalves; juvenile *Gryphaea* are particularly common, accompanied by *Astarte*, *Cardinia*, *Pleuromya*, *Mytilus*, and *Nuculana*. *Pseudolimaea* and *Chlamys* are present as disarticulated valves, and fish-scales are sometimes abundant. The whole assemblage is reasonably diverse and comparable to a modern muddy marine shelf assemblage. The *Gryphaea* represent a life-assemblage but their smallness may indicate adverse conditions (e.g. turbidity). The size-sorted nature of the uncemented shells suggests that some degree of winnowing has affected the bed, and *Thalassinoides* burrows present in Beds 8 and 9 are often filled with the minute disarticulated valves of bivalve-juveniles representing the smaller shells which are absent from the rest of the bed. These open burrows were probably filled as a result of weak current action. The shell-beds occur at the base of a coarsening-upward unit and three more cycles follow before the Raricostatum Zone ends at the top of Lee's Bed 16. The ammonites collected by Lee from Beds 7 to 15 indicate the Aplanatum Subzone (Donovan in Berridge and Ivimey-Cook 1967).

The Jamesoni Zone continues in fossiliferous shales (Beds 17–21) with much less mica than those in the preceding zone. They contain no obvious structures and are dominantly illitic (80%).

Both the exposure and the fossil preservation are poor, but the moulds of small, thick-shelled *Pseudopecten*, *Pseudolimea*, and thinner-shelled *Cardinia* are common; accompanied by *Gryphaea*, *Chlamys*, *Inoceramus*, *Astarte*, *Grammatodon*, and *Protocardia*. Protobranchs are also common, but the absence of the larger infaunal suspension-feeders probably indicates a low environmental energy.

Thus fluvial sandstones derived from the north-west were replaced during Raricostatum times by a shallow-marine cyclic sequence showing alternating deeper- and shallower-water phases. The poor fauna in most of the Raricostatum succession was probably due to relatively high sedimentation rates and lower than normal salinities. Phases of reduced sedimentation rates, higher salinities, and substrate stabilization

(possibly during transgressive periods) were marked by diversification in the faunas (Beds 8 and 9 of Lee). In Jamesoni times, a deepening occurred which resulted from a transgressive phase. This lessened the influx of kaolinite, mica, and coarser clastic materials and produced the deeper-water aspect of the Jamesoni sediments.

Lossiemouth (text-figs. 2, 3). Berridge and Ivimey-Cook (1967) described 69.5 m of Lower Lias, in an I.G.S. borehole near Lossiemouth (NJ 21586986). Part of this sequence contained *Paltechioceras* (between 46–47.9 m) and is of unquestioned Raricostatum Zone age. Berridge and Ivimey-Cook suggested that the oldest sediments penetrated were lagoonal with a passage upwards into more marine beds containing *Lingula*. These pass upwards into the fully marine sediments containing the ammonites and bivalves. The sediments which occur above the highest *Paltechioceras* continue as sandstones, siltstones, and shales containing occasional *Protocardia*, *Ceratomya*, and *Pholadomya*. These sediments presumably represent part of the Jamesoni Zone and in view of their coarse-grained and highly kaolinitic nature, were probably deposited in a nearer shore situation than their equivalents at Golspie.

Berridge and Ivimey-Cook commented on the 'small scale oscillatory tendencies' shown by much of the sequence and from their figure it seems that their oscillations are coarsening-upward sequences. The highest beds are extremely rich in kaolinite (60%+) which becomes the dominant clay. The sediments become much more sandy and fossils are not present, suggesting a reversion to fresh water conditions possibly late in Raricostatum and (?) through lower Jamesoni times. Lossiemouth was marginal to the Lower Lias sea for some of the time and was periodically inundated by transgressive events.

The persistence of coarse sediments at Lossiemouth opposes the general trend of a fining in grain which occurred in the rest of Britain from the Raricostatum to the Jamesoni Zone, and this suggests that in the vicinity of Lossiemouth, and probably to the south, a positive area existed which resisted subsidence and continued to supply sandy kaolinitic material (text-fig. 4).

FACIES INTERPRETATION

In Britain, the only truly marginal facies are the basal sands at Golspie, possible lagoonal sequences in the Lossiemouth borehole, and possible littoral sediments in some of the boreholes on the margins of the London Platform. Marginal sequences outcrop in Scandinavia, Greenland, and Poland. In Sweden and on the Danish island of Bornholm, Rhaetian to Sinemurian sediments are represented by fluvial and coal-measure facies (Tröedsson 1951; Gry 1969). Accompanying these sequences are marginal marine inter-tidal and sub-tidal sequences (Sellwood *in press*) exhibiting many of the features typical of modern tidal-flat and sub-tidal deposits (Reineck 1960, 1967; Reineck and Wunderlich 1968; Reineck *et al.* 1968; Van Straaten 1954). Wavy and tidal bedding (pl. 28, fig. 5) accompany many other features considered by Klein (1970) to characterize tidal conditions. The first beds containing abundant marine faunas are of Jamesoni Zone age consisting of ferruginous sands and clays with siderite nodules. In Sweden, paralic facies of Rhaetian and Hettangian age are succeeded by a marine sequence of Jamesoni age and a similar situation also occurs in East Greenland (Rosenkrantz 1934).

In Britain the commencement of Jamesoni times is marked by renewed sedimentation

in Dorset and Somerset (regions of reduced or non-sedimentation during late Raricostatum Zone times); by the deposition of marine sediments on some parts of the London Platform; and in Yorkshire, Lincolnshire, the Inner Hebrides, and Golspie, the zone is marked by a considerable reduction in grain-size with the loss of most sand-grade material. The exception to this pattern is Lossiemouth, where coarse-grained kaolinitic sandstones may represent a part of the zone.

None of the sediments exposed in Britain take on a truly deep water facies and most of the sediments display some evidence of at least periodic disturbance by storm or wave generated currents. The lack of faunal mixing and the lack of turbidite-type sediments argues against the presence of steep gradients upon the bed of this epicontinental sea, and in most localities the faunas which occur in shell beds consist of the forms which can be found in or close to their life-positions in the surrounding sediment. This is in marked contrast to the observations of Parker (1956, 1964) who found that on modern slopes downslope movement occurred to produce considerable faunal mixing. Generally, thicker sequences tend to occur toward the margins of the basin in sandy and silty shale facies and where subsidence was greatest. Condensed deposits are of two main types: ferruginous, like the Pecten Bed (with chamosite), and calcareous as at Radstock (calcareonites with glauconite and phosphate).

Calclutite/shale rhythms are really intermediate in character between the condensed calcarenites and uncondensed shales. In Dorset, the slight positive nature of the region is revealed by a number of non-sequences (Coinstone, Watch Stone, Hummocky Limestone) and the thinness of the beds in this section compared with those in other sections (except Somerset). Both the Dorset and Somerset areas were evidently swell regions starved of clastic sediments.

The situation was analogous to that proposed by Kauffman (1969*b*) for the configuration of the Cretaceous epicontinental basin of the United States Mid West. The Lias sea of northern Europe was of course open southwards to the Tethys and possibly westwards to a proto-Atlantic trough (Smith 1971), whereas the Cretaceous basin of the United States was partially enclosed. In the Lias, the north European basin was punctuated by a number of small positive swells such as the London Platform, the Mendips-Dorset-Normandy Swell, and numerous others. Small swells of this type have not yet been recognized from the North American Cretaceous (Kauffman *pers. comm.*). Limestone/shale rhythms were developed on broad sediment-starved swells and silty and sandy clays accumulated in more rapidly subsiding nearshore belts, passing in their turn into thinner marginal and paralic sequences. Hallam (1967*a*) suggested a facies model for the Lias which has been tested in this work and the results presented here, although differing in detail, are broadly comparable and the present model (which is only applicable to the area of northern Europe) is given as text-fig. 5.

The faunal changes which occur from the Raricostatum to the Jamesoni Zone in Britain are subtle and related to the decreased grain size and changes of facies which in most places reflect a slight increase in water depth. This was accompanied by marine transgression of the Scandinavian and Greenland shorelines in Jamesoni times.

Eustasy. Hallam (1969*a*) suggested that some of the extensive marine transgressions in the Jurassic were caused by eustatic changes because of their synchronicity on a global scale. The basal Pliensbachian transgression occurred in regions bordering the North

Atlantic (Hallam 1969a) where the Jamesoni Zone marks a phase of either marine inundation or a change from shallow to deeper marine sedimentation. Smith (1971) suggests that the present phase of Atlantic ocean-floor spreading commenced in Pliensbachian times, and if this is so, oceanic ridges must have been constructed, displacing sea-water. From the studies of Fowler and Kulm (1970), Van Andel (1969), and Van Andel and Heath (1970) it is known that large-scale vertical movements on ridges can occur. Smaller-scale oscillations could also be envisaged, sufficient to produce the small-scale cycles which are so typical of Lias epeiric sea sedimentation (Sellwood 1970). Ridge construction may also coincide with subsidence on continental margins.

Tidality. On theoretical grounds, broad shallow epeiric seas should have had reduced tidal circulations (Shaw 1964). Direct evidence of tidality in shallow neritic sediments is equivocal but may be better in marginal and littoral sequences. The Lower Lias sediments from Bornholm strongly suggest a tidal origin, and facies regulation by tides (Johnson and Belderson 1969) in epicontinental seas may have been underestimated by many authors. Tidal regimes on the margins of the Lias epeiric sea indicate that tidal-current activity within the basin occurred. Tidal-current mixing of Tethyan and boreal waters would not have permitted the development of the salinity-controlled faunal realms envisaged by Hallam (1969b).

Salinity. The salinity-control of faunal realms and faunal gradients proposed by Hallam (1969b) is not supported by observations on faunal distributions within the boreal realm during Raricostatum and Jamesoni times. The Hallam hypothesis required the subtle control of faunas by minor salinity reductions over wide areas in the Boreal Realm. If minor reductions of salinity could cause such marked faunal changes in the major part of the European epicontinental basin one might expect even more drastic faunal reductions in the marginal areas where salinities should be even lower because of river influences. However, faunas at Golspie (nearer the sediment-source) are more diverse in some beds than those of the same age in Dorset, and normal, diverse, shallow-marine faunas (including ammonites) occur in the basal Pliensbachian arkoses of East Greenland (Rosenkrantz 1934).

By comparison with modern marine assemblages a temperature control to faunal realms is considered to be the most likely, but within realms, local factors such as substrate conditions, sedimentation rates and depth dependent factors caused striking faunal differences.

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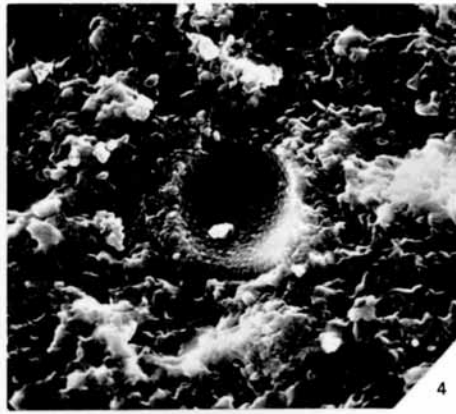
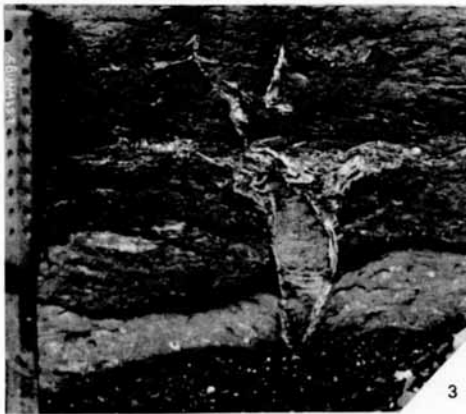
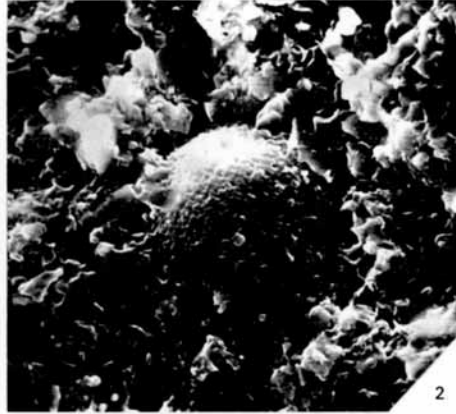
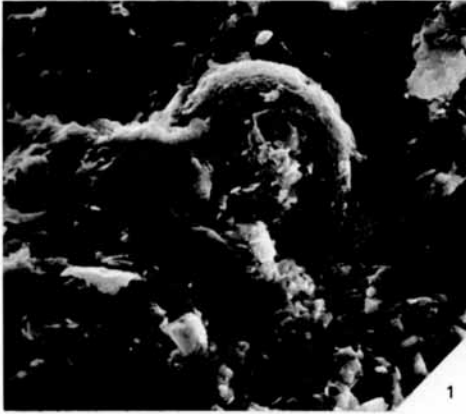
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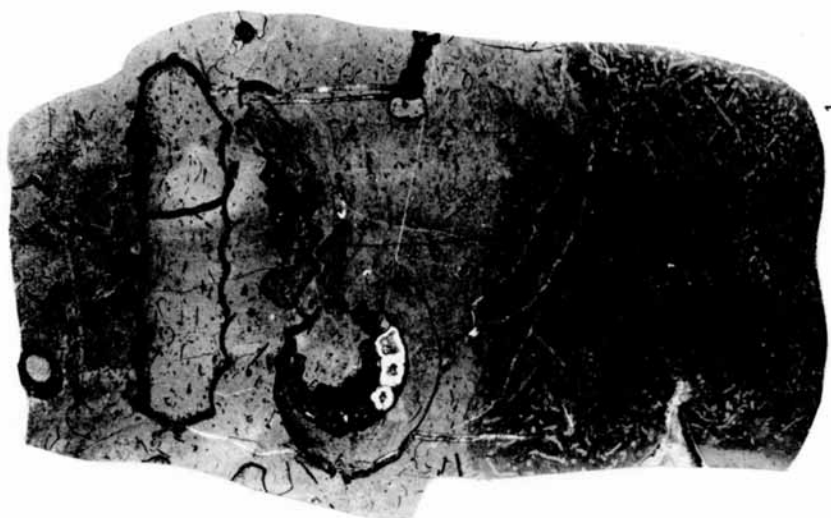
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SELLWOOD, Lower Jurassic stage boundary



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