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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

AN ENVIRONMENTAL STUDY OF THE UPPER DOMERIAN AND LOWER TOARCIAN IN GREAT BRITAIN

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[Plate 20]

CONTENTS

An integrated petrological and palaeoecological study has been undertaken of the *Spinatum*, *Tenuicostatum* and *Falciferum* zones of the Lias in all the major British sections. After a brief stratigraphical review the deposits are described systematically in terms of four regions, Yorkshire, the Midlands, south-west England and the Inner Hebrides. The *Spinatum* Zone consists of a series of ironstones, bioclastic limestones and fine sandstones with a rich and diverse fauna dominated by brachiopods,

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bivalves and belemnites. The *Tenuicostatum* Zone, thin or absent in most areas, tends to be finer grained and more argillaceous, with a fauna related to that of the underlying beds. The *Falciferum* Zone is characterized especially by the extremely widespread development of laminated bituminous shales with an impoverished invertebrate fauna.

A brief world stratigraphical review leads to the conclusion that there was a notable eustatic rise of sea level in the early part of the Toarcian.

The British deposits are considered to have been laid down in a very shallow shelf sea in an area of great tectonic stability and very slight relief. Within this context, the facies was controlled primarily by rates of deposition and subsidence, local topography, liability to wave action and proximity of rivers. The early Toarcian transgression, following a late Domerian regression, had the effect of inducing widespread stagnation below wave base, until the sea had deepened sufficiently in mid Toarcian times to allow freer circulation. Four different facies associations in the fauna can be distinguished and related to environmental conditions. The development of faunal provinces among the later Domerian ammonites and brachiopods and some extinction is attributed to the existence of extremely shallow seas extensively broken up by newly emergent land. The widespread phase of bottom stagnation in the *Falciferum* Zone led to extinction of most of the benthos, so that the overlying beds contain a substantially new fauna, with Middle Jurassic affinities.

I. Introduction

Of all the beds in the British Lias, those straddling the boundary of the Domerian and Toarcian are the most intriguing. A wide variety of interesting rock types, including ironstones, sandstones, limestones, marls and bituminous shales, are distributed in such a manner as to suggest a striking environmental change from the one stage to the next. The rich fauna likewise undergoes marked changes across or close to the boundary.

While a great deal of attention has been paid to these deposits in the past, the primary emphasis has almost invariably been on traditional stratigraphy and any conclusions on environments of deposition have tended to be vague and inadequately supported by facts. Now that stratigraphic correlation has achieved a degree of precision that will probably remain unsurpassed, the time is ripe for a comprehensive petrological and palaeoecological study along modern lines.

The excellent stratigraphic control afforded by the ammonites has rendered easy comparisons between widely separated sections. It soon became apparent during the research that, if one hoped to reach valid conclusions on the underlying factors controlling the spatial and temporal distribution of the sediments and fauna, an extensive area would have to be covered. Therefore consideration has been given to three successive ammonite zones across the Domerian–Toarcian boundary in all the major British sections. It has also proved vital for interpretation to treat the British area in its wider context. The more descriptive and broadly interpretative accounts are therefore interrupted by a digressive excursion into other parts of the world. The justification for this somewhat unorthodox approach should become apparent in due course.

The rocks have been examined by the usual field and microscopic methods, supplemented where desirable by chemical and X-ray diffractometer analysis. As regards the palaeontology, attention has been confined to the invertebrate macrofauna, emphasis being placed on stratonomic aspects of the commoner species. The metric system has been adhered to in measurement except in describing stratigraphic sections. Though admittedly inconsistent, this double usage has the support of convention and the advantage of familiarity and should present few difficulties to the reader.

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It is thought that an integrated study of these deposits may well hold the key to the environmental interpretation of a large part of the European Lias, and quite possibly to many other shallow-water epicontinental deposits laid down in a stable tectonic regime.

II. General stratigraphy

By his careful collecting and taxonomic work, M. K. Howarth has done a great deal in recent years to clarify and refine the ammonite zonal succession of the Upper Domerian and Lower Toarcian (see his papers listed in the references and also Dean, Donovan & Howarth 1961). The following zones and subzones are now recognized.

Lower Toarcian	*Falciferum* Zone	*Falciferum* Subzone *Exaratum* Subzone
	Tenuicostatum Zone	
Upper Domerian	*Spinatum* Zone	*Hawskerense* Subzone *Apyrenum* Subzone

The *Bifrons* Zone has sometimes been placed in the Lower Toarcian but Howarth (1964) has now recommended that it be placed in the Middle Toarcian. The Lower Toarcian is therefore restricted to two zones and the Upper Domerian to one.

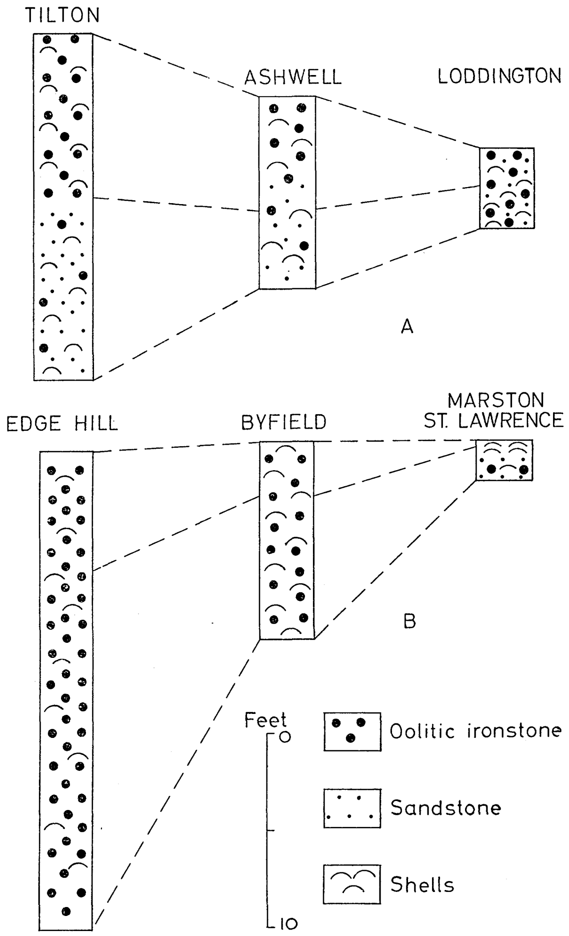

Figure 1. Proposed correlation of the Marlstone in east Leicestershire and the Banbury district, based largely on the evidence of brachiopods.

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The *Spinatum* Zone corresponds to the range of the genus *Pleuroceras*. Though *P. apyrenum* is the subzonal index of the *Apyrenum* Subzone, *P. solare* is the commonest species. The fauna of the *Hawskerense* Subzone is differentiated regionally. In Yorkshire *P. hawskerense* is abundant, while *P. spinatum* is characteristic in south-west England and the Hebrides.

The base of the Toarcian may be taken as coinciding with the first appearance of *Dactylioceras* and the disappearance of *Pleuroceras*. Only in Dorset is there an overlap of the

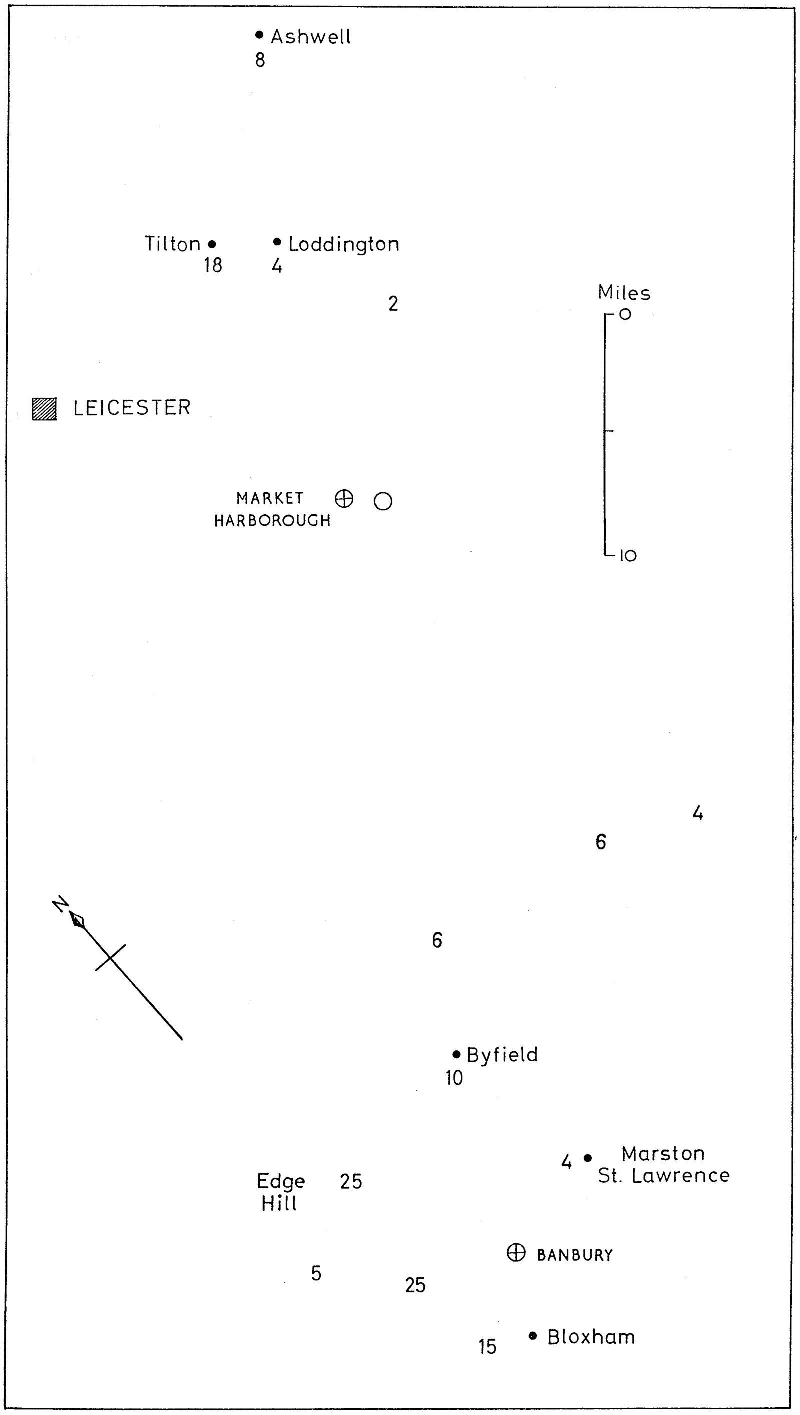

FIGURE 2. Locality and thickness map for the Marlstone Rock-bed in the east Midlands. Thickness in feet.

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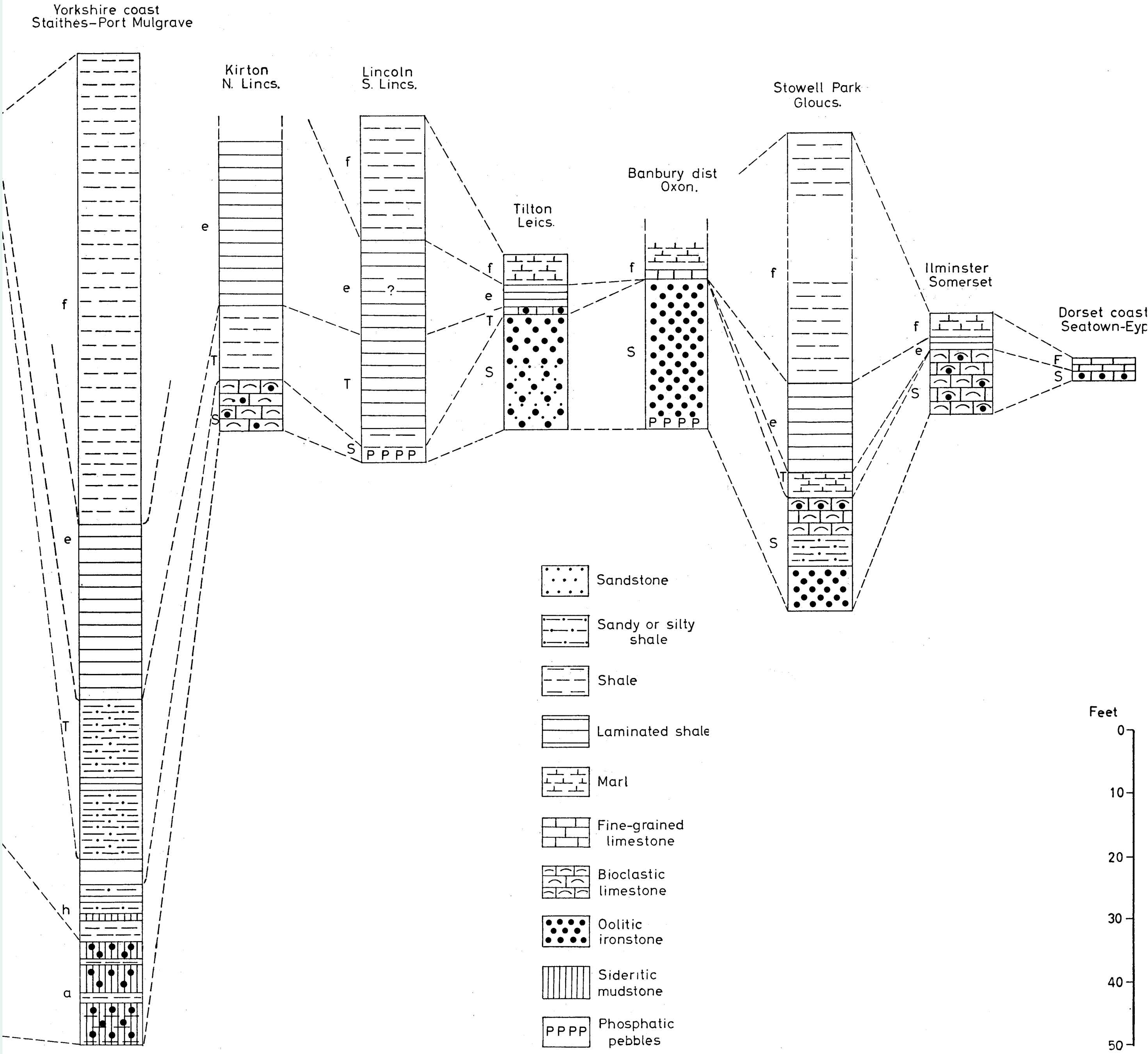

FIGURE 3. Correlation diagram for the *Spinatum*, *Tenuicostatum* and *Falciferum* zones, showing lithological variations between the main British sections. Capital and small letters signify zones and subzones respectively.

two genera. In the Midlands *Dactylioceras directum* occurs not uncommonly just below the top of the Marlstone Rock-bed, but it is convenient to begin the Toarcian with the so-called Transition Bed, which contains abundant *D. directum* and *Tiltoniceras acutum*. These species are replaced north-eastwards from Leicestershire by finely ribbed species of the subgenus *Dactylioceras* (*Orthodactylites*) and the Yorkshire ammonite fauna is virtually restricted to abundant *D.* (*O.*) *tenuicostatum* and *D.* (*O.*) *semicelatum*.

The *Exaratum* Subzone is characterized by species of *Eleganticeras* and *Harpoceras* of the

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exaratum group occurring in sequence, and by *Harpoceratoides*. The *Falciferum* Subzone is readily recognizable by the appearance of *Harpoceras* with falcate ribbing occurring with *Hildaites* and *Orthildaites*. The *Dactylioceras* species are coarsely ribbed, being closely related to the well-known *D. commune* of the Bifrons Zone.

This zonal sequence is readily applicable to all beds except the Marlstone Rock-bed of the Midlands, which is normally attributed to the *Spinatum* Zone though *Pleuroceras* is rare. Fortunately a consistent succession of brachiopods has been discovered in Leicestershire and these fossils can be employed stratigraphically (Hallam 1955). *Tetrarhynchia tetrahedra* and *Lobothyris punctata* are replaced up the succession by *Gibbirhynchia northamptonensis* and *Zeilleria subdigona*. Further stratigraphic work by the author, as yet unpublished, has led to the conclusion that throughout the Midlands condensation is the only factor that need be invoked for the lateral thinning of the Marlstone (figures 1 and 2), though locally there was a small amount of pre-Toarcian erosion. This is supported by the fact that there is generally an inverse relationship between the abundance of shells, per unit volume of rock, and the thickness of the bed.

A correlation chart for the major British sections is presented in figure 3 and facies maps for each zone given in figures 4, 5 and 6. These representations are inevitably somewhat generalized and recourse should be made to §III for local detail. All the sections of figure 3 have been studied personally, except for the Stowell Park borehole (Green & Melville 1956) and those at Lincoln (Trueman 1918; Howarth 1958) and Kirton (Howarth & Rawson 1965).

The British Upper Domerian and Lower Toarcian outcrops fall conveniently into four regions. One of these, the Inner Hebrides, is clearly distinct from the others geographically. The three English regions are separated by the Mendip and Market Weighton swells (formerly called axes) over which the sediments, especially those of the Domerian, thin considerably. Each region, Yorkshire, the Midlands (in an extended sense, ranging from Lincolnshire to Gloucestershire) and the south-west (Somerset and Dorset), has its own distinctive lithological and faunal characteristics, though inevitably there is overlap. The Gloucestershire *Spinatum* Zone, for instance, is faunally intermediate between south-west England and the East Midlands.

Table 1 gives a list of the commoner or more interesting species of macro-invertebrates occurring in the Upper Domerian and Lower Toarcian of the four regions, with an indication of relative abundance. This is based partly on personal collecting and examination of museum material and partly on published data. For a more comprehensive list of ammonites and *Spinatum* Zone brachiopods the reader should consult the works of Howarth cited in the references and Ager (1956).

III. *SPINATUM* ZONE

(1) *Yorkshire*

(*a*) *Petrology*

The well-known Cleveland Ironstone attains its maximum development in the North Cleveland Hills around Eaton and Upleatham, the Main Seam alone exceeding 10 ft. in places. South-eastwards from this region the general succession thickens while the ironstone

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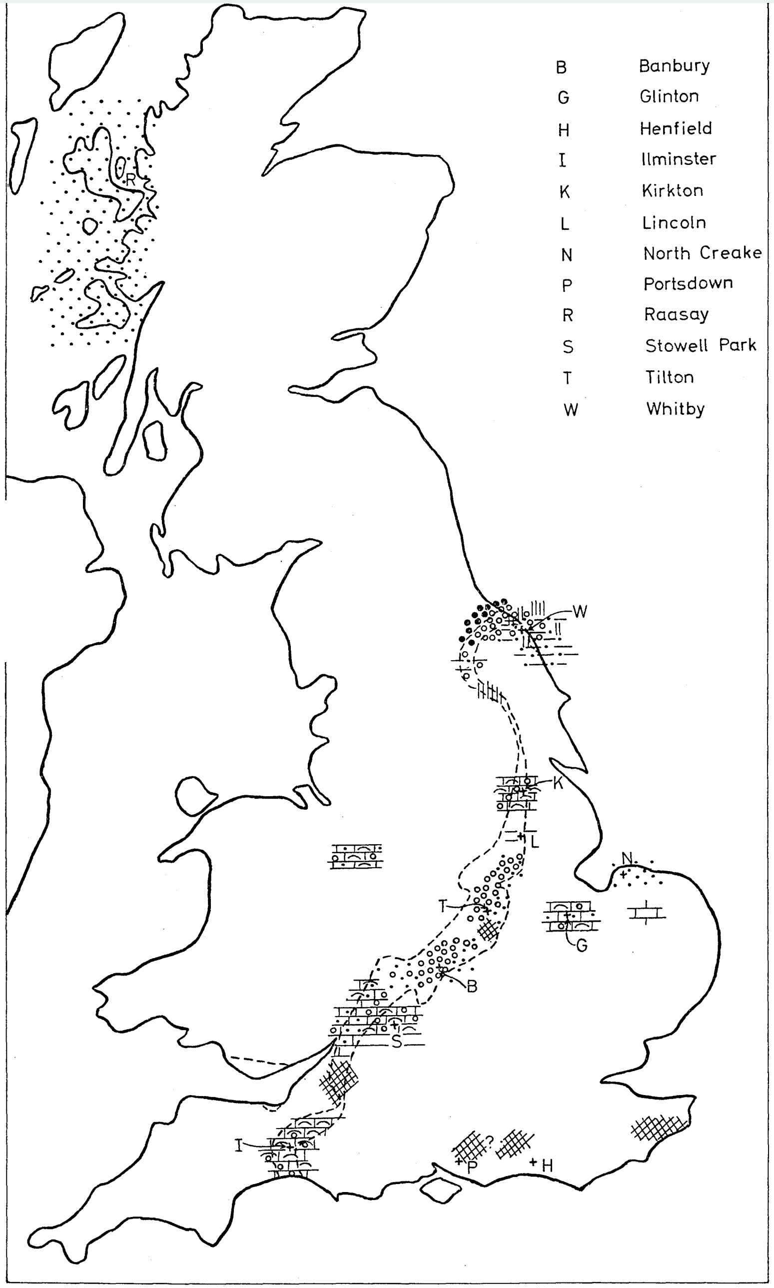

FIGURE 4. Lithofacies map for the *Spinatum* Zone. Ornamentation as in figure 3. Cross-hatching signifies absence of strata.

FIGURE 5. Lithofacies map for the *Tenuicostatum* Zone. Ornamentation as in figures 3 and 4.

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TABLE 1. FAUNAL LIST

C = common. **O** = occurs.

	Yorkshire			Midlands			S.W. England			Hebrides		
Brachiopods	*Spin.*	*Ten.*	*Fal.*	*Spin.*	*Ten.*	*Fal.*	*Spin.*	*Ten.*	*Fal.*	*Spin.*	*Ten.*	*Fal.*
Aulacothyris resupinata (J. Sow.)	.	.	.	O	.	.	C	.	.	.	.	.
Cirpa sp.nov. (= *R. egretta* Dav. non Deslongchamps)	.	.	.	.	.	.	C	.	.	.	.	.
Discinisca cf. *laevis* (J. Sow.)	.	.	O	.	.	O	.	.	O	.	.	.
Gibbirhynchia gibbosa S. Buckman	.	.	.	O	.	.	C	.	.	.	.	.
G. micra Ager	.	.	.	C	.	.	C	.	.	O	.	.
G. northamptonensis (Dav.)	.	.	.	C	.	.	O	.	.	.	.	.
G. tiltonensis Ager	.	.	.	O	C	O	.	O	.	.	.	.
Grandirhynchia grandis S. Buckman	.	.	.	O	.	.	.	.	.	O	.	.
Homoeorhynchia acuta (J. Sow.)	.	.	.	O	.	.	C	.	.	C	.	.
H. capitulata (Tate)	C	.	.	.	.	.	.	.	.	O	.	.
Lobothyris punctata (J. Sow.)	O	.	.	C	.	.	C	.	?	O	.	.
Lobothyris sp.	.	.	.	.	.	O	.	.	O	.	.	.
Nannirhynchia? *pygmaea* (Dav.)	.	.	.	.	O	.	.	.	C	.	.	.
Prionorhynchia serrata (J. de C. Sow.)	.	.	.	.	.	.	C	O	.	.	.	.
Quadratirhynchia quadrata S. Buckman	.	.	.	O	.	.	C	.	.	.	.	.
Rhynchonelloidea lineata (Young and Bird)	C	.	.	O	.	.	.	.	.	.	.	.
Spiriferina walcotti J. Sow.	O	.	.	O	.	.	C	O	?	O	.	.
Stolmorhynchia bouchardi (Dav.)	.	.	.	.	.	.	.	O	C	.	.	.
'*Terebratula*' *globulina* Dav.	.	.	.	.	.	.	.	.	O	.	.	.
Tetrarhynchia tetrahedra (J. Sow.)	C	.	.	C	.	.	O	.	.	C	.	.
Zeilleria quadrifida (Lam.)	.	.	.	O	.	.	C	.	.	.	.	.
Z. subdigona (Oppel)	C	.	.	C	C	.	.	.	.	C	.	.
Bivalves												
Arcomya vetusa (Phillips)	O	.	.	.	O	.	.	.	.	.	.	.
Astarte obsoleta Dunker	C	O	.	O	.	.	.	.	.	.	.	.
Astarte sp.	.	.	O	.	.	O	.	.	O	.	.	C
Bositra radiata Goldf.	.	.	C	.	.	O	.	.	O	.	.	.
Camptonectes cf. *lohbergensis* (Emerson)	C	.	.	O	.	.	O	.	.	.	.	.
Cardinia concinna (J. Sow.)	.	.	.	O	.	.	O	.	.	.	.	.
Chlamys sp.	.	.	O	.	.	.	.	.	.	.	.	.
Chlamys textoria (Schloth.)	O	.	.	.	.	.	O	.	.	.	.	.
Entolium lunare (Roemer)	C	.	.	C	O	.	C	.	.	C	.	.
Gervillea spp.	.	.	.	.	.	.	.	.	O	.	.	.
Goniomya hybrida (Münster)	O	.	.	O	.	.	.	.	.	O	.	.
Grammatodon insons Melville	O	.	.	O	O	.	.	.	.	.	.	.
G. intermedius (Simps.)	C	.	.	O	.	.	O	.	.	.	.	.
Gresslya intermedia (Simps.)	C	O	.	.	.	.	.	.	.	O	.	.
Gryphaea gigantea (J. Sow.)	.	.	.	C	.	.	C	.	.	C	.	.
Hippopodium ponderosum J. Sow.	O	.	.	.	.	.	O	.	.	.	.	.
Inoceramus dubius (J. de C. Sow.)	.	.	C	.	.	C	.	.	C	.	.	O
Lima (*Antiquilima*) *succincta* Schloth.	O	.	.	O	.	.	.	.	.	O	.	.
Lima cf. *gigantea* (J. Sow.)	O	.	.	O	.	.	O	.	.	O	.	.
Liostrea submargaritacea (Brauns)	C	.	.	.	.	.	.	.	.	.	.	.
Mactromya cardioides (Phillips)	C	.	.	.	.	.	O	.	.	.	.	.
Meleagrinella cf. *papyria* (Quenstedt)	O	.	.	.	.	.	.	.	.	.	.	.
Meleagrinella substriata (Münster)	O	.	C	.	.	O	.	.	.	O	.	.
Modiolus cf. *scalprum* J. Sow.	C	C	.	O	.	.	O	.	.	.	.	.
Myoconcha decorata (Münster)	O	.	.	O	.	.	O	.	.	.	.	.
Nucula sp.	.	.	.	.	.	O	.	.	O	.	.	.
Oxytoma inaequivalve (J. Sow.)	C	O	?	O	.	.	O	.	?	O	.	.
O. (*Palmoxytoma*) *cygnipes* (J. Sow.)	C	.	.	O	.	.	O	.	.	C	.	.
Palaeoneilo galatea (d'Orb.)	C	O	.	.	.	.	.	.	.	.	.	.
Parallelodon buckmani (Rich.)	.	.	.	.	O	.	.	.	.	.	.	.
Pholadomya ambigua (J. Sow.)	C	.	.	O	.	.	O	.	.	C	.	.
Pleuromya costata (Young and Bird)	C	O	.	O	.	.	C	.	.	C	.	.
Plicatula spinosa (J. Sow.)	C	C	.	C	O	.	C	.	.	C	.	.
Protocardia truncata (J. de C. Sow.)	C	O	.	O	.	.	O	.	.	O	.	.
Pseudolimea pectinoides (J. Sow.)	C	C	.	C	O	.	.	.	.	C	.	.
Pseudopecten aequivalvis (J. Sow.)	C	O	.	C	C	.	C	.	.	C	.	.
Pseudotrapezium sp.	C	.	.	.	.	.	O	.	.	.	.	.
Rollieria bronni (Cox)	C	.	.	.	.	.	.	.	.	.	.	.

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TABLE 1 (*cont.*)

	Yorkshire			Midlands			S.W. England			Hebrides		
ivalves (*cont.*)	*Spin.*	*Ten.*	*Fal.*	*Spin.*	*Ten.*	*Fal.*	*Spin.*	*Ten.*	*Fal.*	*Spin.*	*Ten.*	*Fal.*
Tutcheria cingulata (Goldf.)	O	.	.	.	.	.	O	.	.	.	.	.
Variamussum pumilum (Lam.)	.	.	O	.	.	.	.	.	.	.	.	.
Velata velata (Münster)	O	.	.	O	.	O	O	.	.	.	.	.
ephalopods												
Amauroceras ferrugineum (Simps.)	C	.	.	.	.	.	.	.	.	O	.	.
Cenoceras cf. *striatus* (J. Sow.)	.	.	.	O	.	.	O	.	.	O	.	.
Dactylioceras directum S. Buckman	.	.	.	O	C	.	O	O	.	.	?	.
D. gracile (Simps.)	.	.	C	.	.	C	.	.	C	.	.	C
D. semicelatum (Simps.)	.	C	.	.	?	.	.	.	.	.	.	.
D. tenuicostatum (Young and Bird)	.	C	.	.	O	.	.	.	.	.	.	.
Dactyloteuthis vulgaris (Young and Bird)	.	.	C	.	.	?	.	.	?	.	.	O
Eleganticeras elegantulum (Young and Bird)	.	.	C	.	.	C	.	.	?	.	.	?
Geoteuthis sp.	.	.	O	.	.	O	.	.	O	.	.	.
Harpoceras aff. *falciferum* (J. Sow.)	.	.	C	.	.	C	.	.	C	.	.	C
H. elegans (J. Sow.)	.	.	C	.	.	?	.	.	?	.	.	?
H. exaratum (Young and Bird)	.	.	C	.	.	C	.	.	C	.	.	C
Harpoceratoides alternatus (Simps.)	.	.	C	.	.	C	.	.	C	.	.	?
Hastites clavatus (Blainv.)	O	.	.	O	.	.	.	.	.	.	.	.
Hildaites aff. *levisoni* (Simps.)	.	.	O	.	.	C	.	.	O	.	.	.
Nodicoeloceras crassoides (Simps.)	.	.	C	.	C	C	.	C	C	.	.	O
Paltarpites paltus S. Buckman	.	.	.	.	.	.	O	.	.	.	.	.
Passaloteuthis paxillosus (Schloth.)	C	C	C	C	C	O	C	?	O	C	O	?
Pleuroceras apyrenum (S. Buckman)	C	.	.	.	.	.	O	.	.	.	.	.
P. hawskerense (Young and Bird)	C	.	.	O	.	.	O	.	.	.	.	.
P. paucicostata Howarth	C	.	.	.	.	.	.	.	.	.	.	.
P. spinatum (Brug.)	.	.	.	O	.	.	C	.	.	O	.	.
P. solare (Phillips)	O	.	.	O	.	.	C	.	.	C	.	.
P. salebrosum (Hyatt)	.	.	.	O	.	.	C	.	.	C	.	.
Phylloceras heterophyllum (J. Sow.)	.	.	O	.	.	O	.	.	.	.	.	.
Teudopsis sp.	.	.	O	.	.	O	.	.	O	.	.	.
Tiltoniceras acutum (Tate)	.	.	.	.	C	.	.	?	.	.	.	.
astropods												
Actaeonina ilminsterensis Moore	O	O	.	O	O	.	O	.	.	O	.	.
Amberleya aff. *guadryana* (d'Orb)	O	O	.	O	C	.	C	O	.	.	.	.
Ataphrus cf. *bullatus* (Moore)	O	.	.	O	O	.	O	.	.	.	.	.
Coelodiscus minutus (Schubler)	.	.	C	.	O	C	.	.	C	.	.	?
Dimorphotectus lineatus (Moore)	.	.	.	O	C	.	C	?	.	O	.	.
Lewisiella? *aciculus* Stoliczka	C	O	.	O	O	.	C	C	.	.	.	.
Pleurotomaria aff. *anglica* (J. Sow.)	O	.	.	O	O	.	C	C	.	.	.	.
Procerithium liassicum (Tate and Moore)	O	O	.	O	C	.	O	O	.	.	.	.
Ptychomphalus expansus (J. Sow.)	C	.	.	O	C	.	C	?	.	O	.	.
Talantodiscus mirabilis (Desl.)	.	.	.	.	.	O	O	.	.	.	.	.
Zygopleura (*Katosira*) *blainvillei* (Münster)	O	O	.	.	O	.	?	.	.	O	.	.
chinoderms												
Echinoid radioles	O	.	.	O	O	O	O	.	O	.	.	.
Isocrinus spp.	C	O	O	C	O	.	C	.	O	O	.	.
rustacea												
Proeryon sp.	.	.	.	.	.	O	.	.	.	.	.	.
Pseudoglyphaea sp.	.	.	.	.	.	O	.	.	.	.	.	.
nnelids												
Serpula (*Pentaserpula*) *quinquesulcata* Münster	O	.	.	C	O	.	C	.	O	O	.	.
ryozoa												
Berenicea sp.	.	.	.	.	.	.	O	.	.	.	.	.
Multisparsa sp.	.	.	.	.	.	.	O	.	.	.	.	.
Stomatopora sp.	.	.	.	O	.	.	O	.	.	.	.	.

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bands thin, being replaced by clays (Fox-Strangways & Barrow 1915; Hemingway 1934, and figure 7). While inland sections are now poorly exposed, since iron ore mining has virtually ceased, there are excellent coastal exposures between Staithes and Kettleness, several miles north-west of Whitby, and at Hawsker Bottoms, between Whitby and Robin Hood's Bay, to the south-east. Attention has therefore been confined to these exposures.

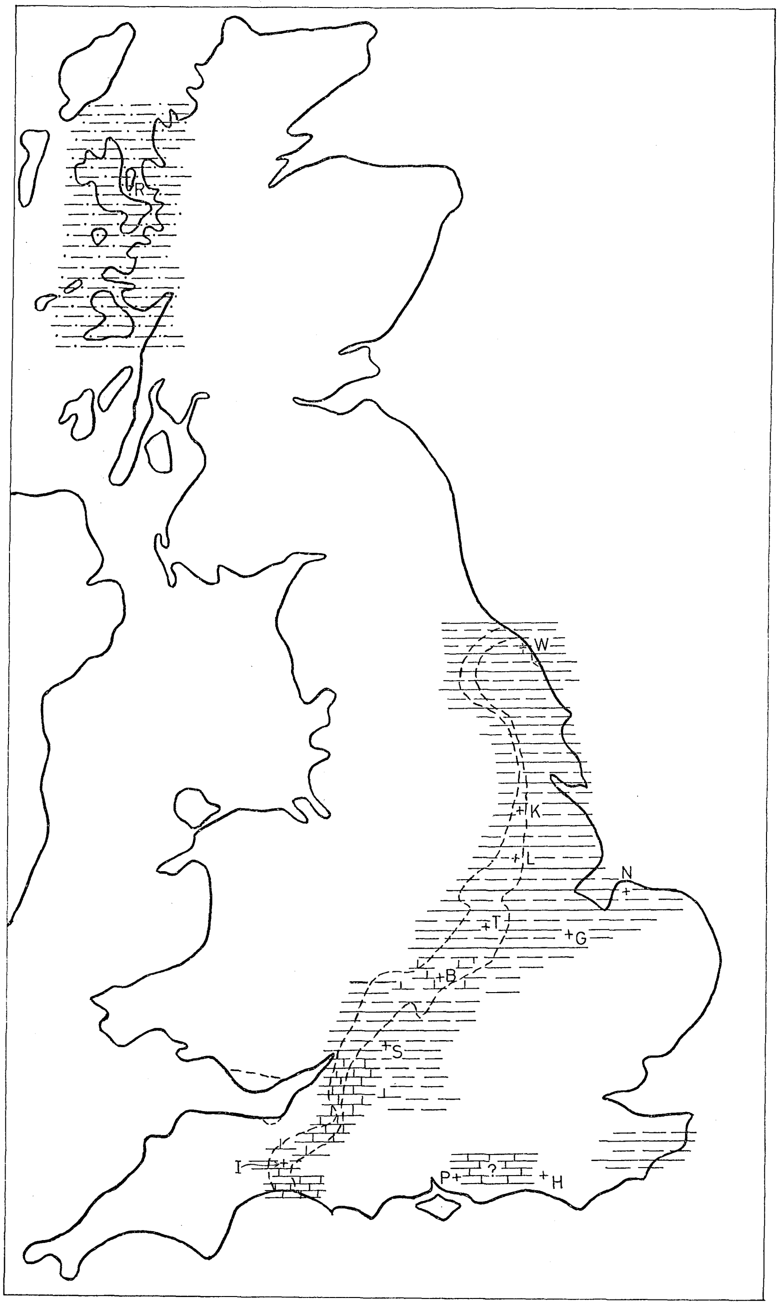

Figure 6. Lithofacies map for the *Falciferum* Zone. Ornamentation as in figures 3, 4 and 5.

The stratigraphy has been described in detail by Howarth (1955) and his bed numeration has been adopted here. As shown in figure 7, some 25 ft. of variably oolitic, sideritic ironstones and associated silty/sandy clays at Old Nab and Brackenberry Wyke, near Staithes, pass south-eastwards to about 40 ft. of silty/sandy clays with thin bands of siderite

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mudstone at Hawsker Bottoms. Bed 58, Old Nab (which correlates with the lithologically similar bed 43 at Hawsker) is a bituminous laminated silty shale (plate 20, figure 21). This makes a better base for the Toarcian than bed 61, adopted by Howarth, since it directly succeeds the last appearance of *Pleuroceras* and is highly distinctive and persistent.

The petrography of the Main Seam in the old ironstone field of the North Cleveland Hills has been described by Dunham (Whitehead, Anderson, Wilson & Wray 1952; Dunham 1960) and is summarized in table 2, together with other beds on the coast. This table is based on the author's own observations (see also figures 18 to 20, plate 20).

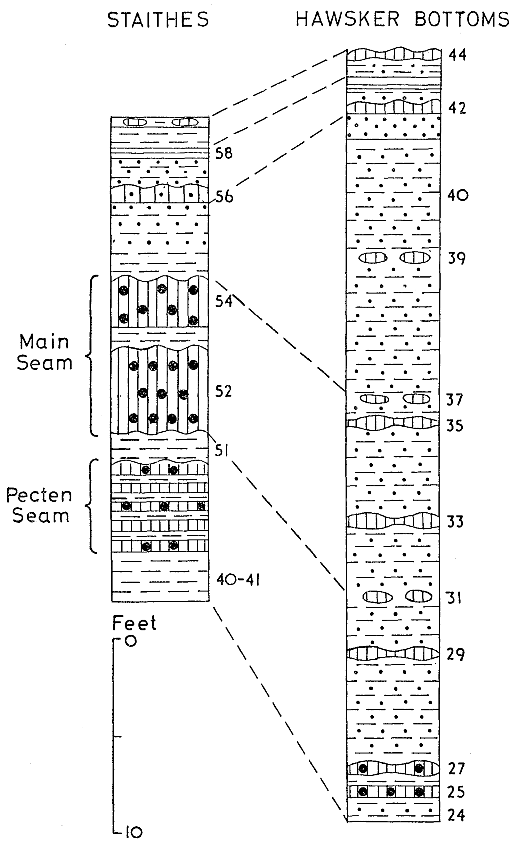

FIGURE 7. Lithofacies variations in the *Spinatum* Zone of the Yorkshire coast. Correlation based mainly on Howarth (1955).

The results of chemical analyses of typical samples of the different lithologies are given in table 3. The highest iron contents occur, not surprisingly, in the Main Seam near Staithes. Chemically the Top and Bottom Block (beds 54 and 52 respectively) are closely similar. Partial analyses of beds 42 and 44 of the Pecten Seam at Old Nab gave Fe_2O_3 contents of 38·8 and 42·3 % respectively, which indicates close similarity with the Main Seam.

The siderite mudstones of the Hawsker Bottoms section (beds 37 and 42) are somewhat poorer in iron but richer in silica and, in one case, alumina. The clays associated with the exploitable ironstones tend to have reduced iron at the expense of increased silica and alumina, but are ferruginous rather than calcareous, with siderite crystals scattered throughout. Beds 43 and 47 of the Pecten Seam at Old Nab gave Fe_2O_3 contents of 34 %. Bed 53 between the Top and Bottom Blocks of the Main Seam is somewhat abnormal in

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its low iron and high silica content, suggesting a deposit rich in detrital quartz. Bed 56 of the same section is essentially a ferruginous siltstone, but the nodular carbonate bed 60 is calcareous, with 32·1 % of CaO and only 4·7 % of Fe_2O_3. It is noteworthy that this change of lithology corresponds almost exactly with the base of the Toarcian.

TABLE 2. PETROGRAPHY OF U. DOMERIAN ROCKS, YORKSHIRE AND MIDLANDS

	U. Domerian, Old Nab etc.		U. Domerian	Marlstone
constituents	ironstones	clays	Hawsker Bottoms	ironstone
chamosite ooliths	c–u[1], 0·80	$H_{41,51,53}$[1, 2]	$H_{26,27,44}$[1, 2]	a[3], 0·35
siderite	a, 0·03	a	a	a, 0·10
calcite	c	c[4]	c[4]	a[5]
illite	c	a	a	r
kaolinite	c	c	c	r
detrital quartz	u, 0·15	a–c, 0·15[6]	c, a (H_{41})	r[7]
detrital feldspar	r	r	.	r
framboidal pyrite	c–u, 0·25	c	c–u	r
collophane	r	.	.	r
glauconite	.	.	.	u
opal	u	u	u	.
faecal? pellets	r, 0·25 × 0·10	.	.	.

a = abundant, c = common, u = uncommon, r = rare.
H numbers refer to Howarth (1955).
Other numbers give maximum size in mm.

1. Replaced diagenetically by calcite, kaolinite, opal.
2. Mainly spastoliths.
3. Include subordinate broken and compound varieties and superficial ooliths.
4. As shells and diagenetic replacement.
5. As shells and interstitial cement.
6. Abundant in *Hawskerense* Subzone.
7. Abundant in lower half of Marlstone in Leics.

In the south-western corner of the Cleveland Hills, in the neighbourhood of Osmotherly, the ironstones and shales have been supposed to pass into sandstones (Arkell 1933, p. 160) but recent stratigraphical work suggests that the *Spinatum* Zone is in fact partly or wholly represented by a thin layer of siderite mudstone (T. M. Chowns, personal communication). The whole Domerian appears to be highly condensed in the region of the Market Weighton Swell and stratigraphical details are obscure.

(*b*) *Fauna*

The faunal list of table 1 inevitably gives only a very generalized picture. The excellence of the coastal exposures of the *Spinatum* Zone, with extensive foreshore reefs, has allowed more detailed biostratonomic study than elsewhere. The account in this section is largely descriptive. It is convenient to divide the fossils into *endobionts*, organisms which lived more or less permanently within the sediment, *epibionts*, living on the sediment surface, and *nekton*, swimming in the waters above (cf. Hallam 1960, 1963*a*).

(i) *Composition and distribution*

The most striking feature of the fauna is the richness and diversity of the molluscs, notably the bivalves, ammonites and belemnites. The latter two groups tend to be distributed fairly evenly throughout the rocks, though sometimes concentrated in certain bands, as noted for the ammonites by Howarth (1955). Common epibiont bivalves such as

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Entolium, *Oxytoma*, *Plicatula* and *Pseudopecten* and deep-burrowing endobionts such as *Gresslya*, *Pleuromya* and *Pholadomya* are more or less uniformly distributed laterally. The Top Block of the Main Seam (bed 54) contains distinctive clusters, several centimetres in diameter, of the shells of small bivalves such as *Nuculana*, *Pseudotrapezium*, *Protocardia* and *Tutcheria* which, by analogy with their modern relatives, were shallow-burrowing endobionts. These occur with subordinate *Pseudolimea*, *Entolium*, gastropods (e.g. *Ptychomphalus*) and belemnites suggesting random assemblages of shells that have been drifted together. This is explicable on the grounds that the original sediment surface was hummocky as a result of the activity of burrowing organisms, as on many parts of the sea bed today (e.g. Emery 1953). The shells would then tend to accumulate in the depressions. Similar shell clusters have been seen in the siderite mudstones of Hawsker Bottoms.

TABLE 3. CHEMICAL ANALYSIS OF IRONSTONES AND ASSOCIATED ROCKS

	shale 51	sideritic mudstone 52	shale 53	sideritic mudstone 54	silty shale 55	sideritic siltstone 56	sideritic mudstone 37	chamosite oolite M	limestone T
SiO_2	29·40	10·30	44·90	10·60	55·20	29·50	18·00	11·90	9·40
TiO_2	0·92	0·39	0·93	0·37	0·93	0·57	0·39	0·46	0·25
Al_2O_3	18·20	8·00	17·60	7·10	9·90	9·40	4·70	7·50	4·50
Fe_2O_3	29·10	41·10	16·80	39·50	16·50	22·90	34·50	37·80	9·80
MnO	0·15	0·52	0·10	0·46	0·05	0·22	0·50	0·28	0·20
MgO	3·20	3·79	2·30	3·76	1·83	3·50	3·60	2·70	1·40
CaO	0·84	7·40	1·20	8·90	1·54	8·90	11·70	15·00	39·40
Na_2O	0·54	0·36	0·94	0·32	0·72	0·47	0·52	0·06	0·09
K_2O	1·60	0·42	2·05	0·46	1·88	1·13	0·51	0·05	0·33
P_2O_5	0·18	1·16	0·23	1·87	0·26	0·12	1·57	0·40	1·47
H_2O-	2·11	0·86	1·11	0·85	1·58	0·76	1·49	0·61	0·75
H_2O+	9·80	5·70	6·10	5·20	6·50	4·20	4·70	nd	nd
CO_2	5·79	23·40	3·60	24·30	1·66	20·70	20·50	23·10	31·30
C	0·84	0·83	0·52	0·96	0·88	0·46	0·35	nd	nd
S	0·63	0·11	1·10	0·13	1·25	0·95	0·28	0·08	0·35

Bed numbers refer to *Spinatum* Zone succession at Old Nab, Yorkshire. M stands for Marlstone and T for Transition Bed at Tilton, Leicestershire. Fe_2O_3 is total Fe expressed as Fe_2O_3, S stands for total S expressed as S. No totals can be given because of the presence of ferrous iron and sulphur.

Brachiopods are also common, though subordinate in importance to the molluscs. They are best seen in bed 46 near Staithes and bed 42 at Hawsker Bottoms, where *Tetrarhynchia* is abundant, occurring characteristically as single-species clusters or 'nests', comparable with the better-known ones in the Marlstone Rock-bed of the Midlands. Ager (1956) has recognized a distinctive Yorkshire brachiopod province, characterized by the abundance of *Rhynchonelloidea lineata* and *Zeilleria subdigona* and the presence of *Homoeorhynchia capitulata*.

Nektonic elements include belemnites and ammonites. The latter, like the brachiopods, are regionally distinctive, and characterized by slender-whorled species, unlike in south-west England (Howarth 1958).

Body fossils of other groups are much less common, but trace fossils are important at a number of horizons. The most conspicuous of these is *Rhizocorallium*, described in more detail elsewhere (Hallam 1963*a*) and recently figured by Farrow (1966). This consists of plugged U-tubes, on average about 1·5 cm in diameter, oriented more or less parallel to the bedding. They possess a surface sculpture of discontinuous longitudinal grooves and bifurcating thread-like ridges, which have been compared with the scratch-markings

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produced by certain burrowing crabs. *Rhizocorallium* is common throughout the Cleveland Ironstone. *Chondrites* is common in the Main Seam, in association with some obscure vertical burrows, and in the sandstone bed 41 at Hawsker Bottoms, where it is associated with *Thalassinoides*, another trace fossil attributable probably to burrowing crustaceans. Fossils frequently attain large sizes for the species, most notably in the case of *Pseudopecten aequivalvis*, which commonly reaches 12 cm in diameter, and there is no suggestion of stunting.

The fauna of the ironstones and the clays is apparently similar, except that brachiopods are somewhat commoner in the oolitic ironstone than in the clays. The density of fossils differs appreciably, however, being sparser in the clays. In this connexion it is noteworthy that Tate & Blake (1876) found that, in the Cleveland Ironstone of the main ore field, fossils were most abundant in the oolitic rock. In detail, an intimate coincidence of lithology and shell beds within the ironstone group is lacking. The shelliest part of the Pecten Seam, for instance, ranges through the clay beds 43 and 45 and the ironstone bed 44. The laminated shale bed 58 (and its equivalent at Hawsker Bottoms in bed 43) is, however, distinctive in being poorly fossiliferous except for belemnites. A diagrammatic representation of the general biostratonomic features of the Main and Pecten Seams, as studied at Old Nab, Brackenberry Wyke and Kettleness, is given in figure 8.

(ii) *Orientation and disarticulation*

The wide expanse of bedding planes allowed a large number of observations to be made on belemnite orientation. Qualitative inspection revealed no conspicuous preferred orientation over an extensive bedding surface, although locally, within the space of a few square feet, several closely spaced rostra may lie almost parallel to each other. Quantitative study

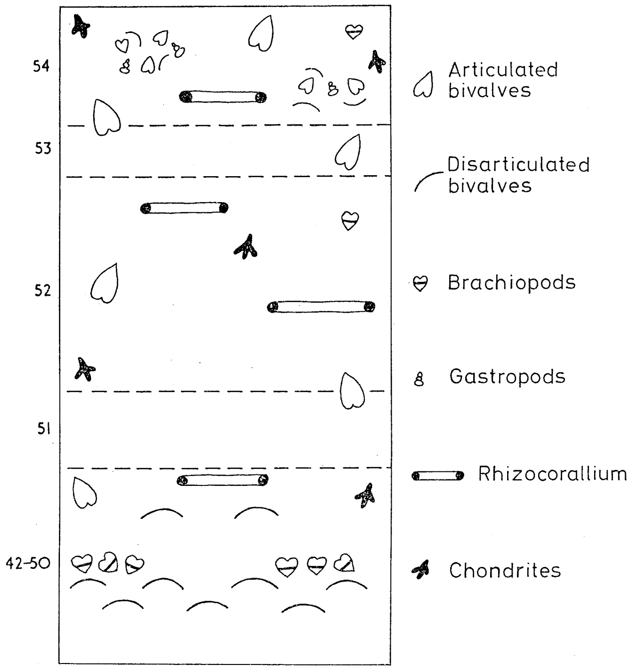

Figure 8. Diagrammatic illustration of some of the principle biostratonomic features of the Cleveland Ironstone on the Yorkshire coast. Nektonic elements of the fauna excluded for simplicity.

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was undertaken for three beds in which belemnites were especially abundant, the Pecten Seam in Brackenberry Wyke, bed 18 at Kettleness (the clay bed separating the ironstones of the Main Seam) and bed 30 at Hawsker Bottoms. The results are presented as rose diagrams in figure 9. In one instance elongate fragments of fossil driftwood, which is quite common throughout the succession, were sufficiently abundant to warrant quantitative study. It will be seen that there is no evident correlation between the rose diagram for this and for belemnites in the same bed. The results for the belemnites suggest in the case of the Cleveland Ironstone a tendency towards preferred orientations in N.E.–S.W. and N.W.–S.E. directions, though departure from randomness is not striking.

Ammonites above about 3 cm diameter lie with their maximum dimension parallel to the bedding, but those below this size are more randomly oriented. Such a relationship is known also in the Blue Lias and has been explained as a mechanical phenomenon, due to a surface layer of soft sediment a few centimetres thick (Hallam 1960).

The bivalve genera *Pholadomya*, *Pleuromya* and *Gresslya* are invariably oriented in the growth position of deep burrowers, i.e. anterior obliquely downwards. Valves of disarticulated epibiont bivalves are predominantly oriented convex upwards. Measurements of a large number of valves were made in the Pecten Seam. In the case of the commonest species, *Pseudopecten aequivalvis*, 185 valves were convex upward, 47 convex downward and 9 oblique to the bedding. Large specimens are invariably convex upwards. With the second commonest species, *Oxytoma cygnipes*, the corresponding figures are 126, 41 and 11.

Disarticulation of the epibiont bivalves is complete and that of the shallow-burrowing bivalves (e.g. *Astarte*, *Protocardia*, *Pseudotrapezium*) partial. It is absent in both the deep-burrowing bivalves and brachiopods. Isolated crinoid ossicles occur spasmodically and in one instance, in bed 30 at Hawsker Bottoms, an isolated cluster of ossicles suggested the post-mortal collapse of a crinoid and subsequent burial before scattering could take place.

(iii) *Diagenetic features and relationship with matrix*

Fossils with originally calcitic shells, including belemnites, brachiopods, oysters and pectinids, have their shell structure finely preserved, while ammonites and gastropods, with aragonitic shells, occur only as moulds, the relatively soluble aragonite having been dissolved during diagenesis. The body chamber of ammonites are filled partly with siderite mudstone and partly by sparry calcite. As myas in growth position and most of the shallow-burrowing endobiont bivalves are also preserved as moulds it is probable that their shells were aragonitic. In some instances the original shell has been replaced by secondary sparry calcite. The textural relationships of the crystals suggests they have crystallized in a cavity left by solution of the shell (cf. Bathurst 1958). One bivalve shell was seen to be replaced by sphalerite, a mineral not uncommon in the Yorkshire Domerian.

The internal moulds of fossils tend to be less oolitic than the surrounding matrix, as in similar (type A) ironstones in the Sinemurian Frodingham Ironstone (Hallam 1963*a*). There has been diagenetic segregation of siderite towards both trace and body fossils so that, for instance, myas and *Rhizocorallium* stand out prominently in relief, being richer in siderite and therefore more resistant than the surrounding rock. Siderite has also replaced calcitic shell material to a limited extent.

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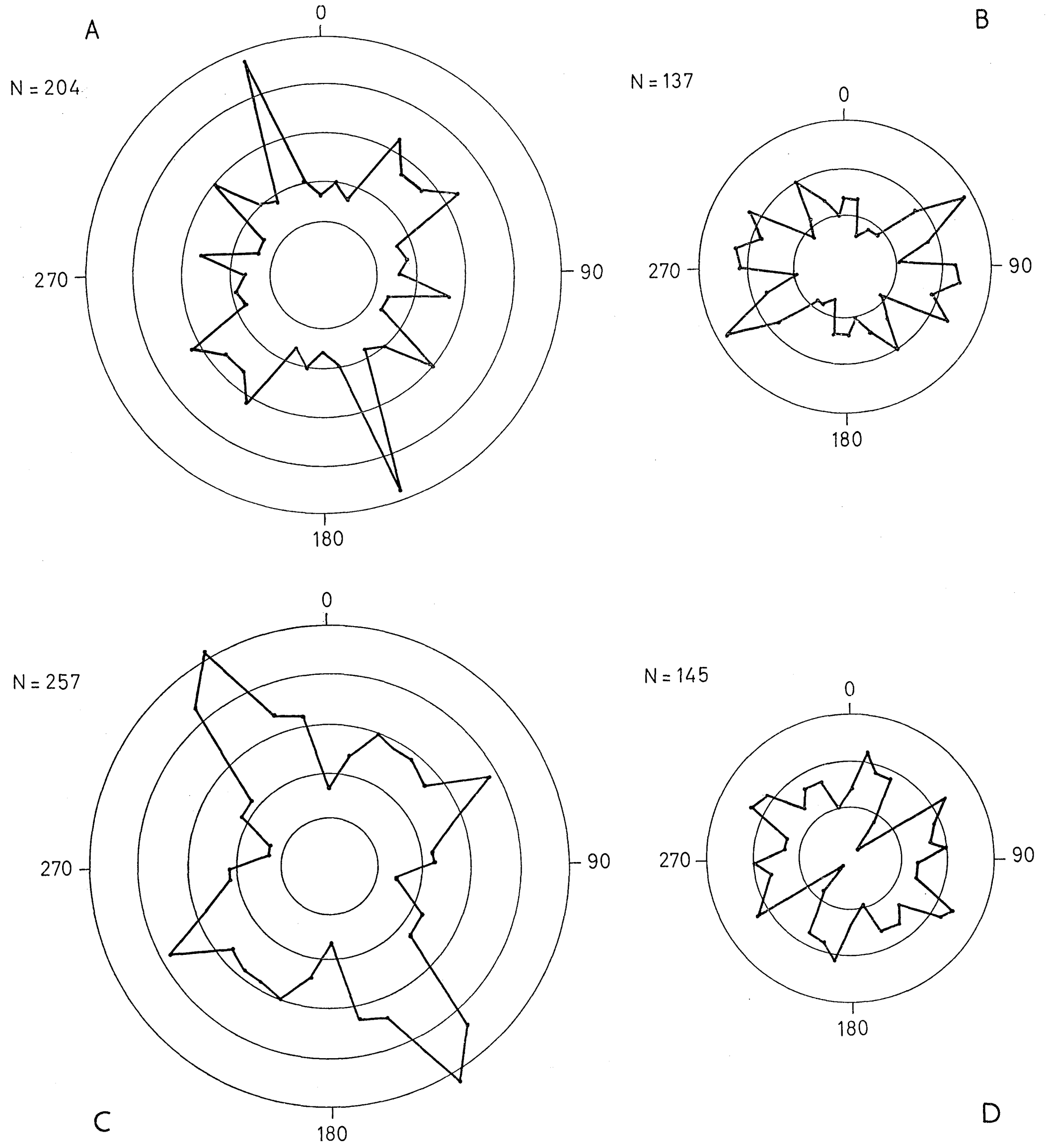

Figure 9. Orientation diagrams for belemnites (A–C) and driftwood (D) in the Cleveland Ironstone. A, Pecten Seam, Old Nab; B, bed 30, Hawsker Bottoms; C, D, bed 18, Kettleness.

(2) *The Midlands: Lincolnshire to Gloucestershire*

(*a*) *Petrology*

Deposits of the *Spinatum* Zone reappear in North Lincolnshire as the Marlstone Rock-bed, which possesses a number of characteristics throughout the Midlands rendering it distinct from the deposits in Yorkshire, notably the smaller size of ooliths and abundance of 'false ooliths', the rarity of mudstone and abundance of echinoderm and brachiopod remains.

It is best to consider first the most familiar deposits, namely the ironstones of the East Midlands, and then describe how the facies varies laterally. Full petrographic descriptions of the ironstones are given in Whitehead *et al.* (1952) and Edmonds, Poole & Wilson (1965), but the data in table 2 are based on the author's own findings (see also figures 22 to 25, plate 20).

A chemical analysis of chamosite oolite from the upper part of the Marlstone at Tilton

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is given in table 3, from which it will be seen that the resemblance to the Main Seam of the Cleveland Ironstone is very close.

In the ironstone field around Banbury the thickest succession is developed as chamosite oolite with only rare detrital quartz. As the Marlstone thins towards the east and west (figure 1) it becomes increasingly sandy. A section at Chipping Campden (SP 145389) reveals about 10 ft of sandy ferruginous bioclastic limestone (or biosparite in Folk's terminology) with abundant quartz grains ranging up to 0·16 mm. Similarly, the rich ironstone development at Tilton in Leicestershire thins rapidly within a few miles until at Loddington (figure 1) the Marlstone is represented by a few feet of sandy bioclastic limestone containing scattered flakes of chamosite.

Passing northwards into Lincolnshire, the Marlstone thickens to 8 ft at Kirton in the northern part of the county after thinning to almost nothing at Lincoln. Dr P. F. Rawson kindly sent several specimens of the Kirton Marlstone to the author for microscopic examination. It consists of a ferruginous bioclastic limestone with abundant small rhomboid crystals of siderite and less common chamosite flakes. The interstitial cement is sparry calcite. Detrital quartz of fine sand grade is present in variable quantities but the rock is not as sandy as at Loddington or Chipping Campden.

At the south-western end of the region, Marlstone is still exposed near Dursley, Gloucestershire, around Yew Tree Inn (ST 739998). It is a sandy ferruginous bioclastic limestone with scattered limonitized chamosite flakes and superficial ooliths, as at Chipping Campden.

The Stowell Park borehole, between Gloucester and Burford (SP 084118), passed through a complete Liassic succession. Some 6 ft of bioclastic and marly limestone, oolitic at the top, were attributed to the Marlstone by Green & Melville (1956). Chamosite ooliths occur together with siderite, associated with clay, siltstone and sandstone, in the beds immediately below, which were attributed to the *Margaritatus* Zone. As, however, *Amaltheus* species do not occur in the top 8 ft of these beds (Spath 1956) and as this genus occurs in the lower part of the *Spinatum* Zone, together with *Pleuroceras* (Howarth 1958), it is here considered better to equate all these beds with the Marlstone of the East Midlands (figure 3).

The Marlstone of the Prees outlier of Shropshire is a sandy limestone comparable to that occurring in the main outcrop to the south-east (Woodward 1893, p. 243).

Our knowledge of the equivalents of the Marlstone in the area east of the Midlands outcrop is limited to data from a few bore-holes. The B.P. borehole at Glinton, near Peterborough (Kent 1962) passed through 11 ft of limestones and siltstones attributed to the *Spinatum* Zone, underlain and overlain by clays. Through the kind assistance of Dr P. E. Kent the author has been able to examine these beds microscopically. The limestones are rich in shells and contain ooliths of chamosite, up to 0·5 mm diameter, which have largely been replaced by sparry calcite. The associated siltstone is sideritic and detrital quartz ranges up to 0·25 mm.

The North Creake borehole, near Hunstanton (Norfolk), revealed 4 ft of calcareous and micaceous sandstone with brachiopods and a few ferruginous ooliths, attributed to the *Spinatum* Zone. The top of the Middle Lias in the Several House borehole, about 30 miles to the south south-west, is developed as a marly limestone (Kent 1947). Thus these borehole

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data, while indicating that ferruginous deposits occur in eastern England beneath a cover of younger rocks, yield no indication of major developments of ironstone as in parts of the Midlands.

(*b*) *Fauna*

Because the exposures are poorer and because some of the most interesting features have been discussed elsewhere, the fauna of the Marlstone will be considered in less detail than that of the Cleveland Ironstone and associated beds. Compared with the latter, the Marlstone fauna differs in the rise to dominance of brachiopods and crinoids. Belemnites and epibiont bivalves, notably species of *Entolium*, *Pseudopecten*, *Plicatula* and *Pseudolimea*, are also very common, but endobiont bivalves are rare. Also unlike in Yorkshire, serpulids are common and bryozoa occur spasmodically, while the characteristic *Spinatum* Zone ammonites, *Pleuroceras* spp., are rare in the Midlands north of Kings Sutton, near Banbury (in Gloucestershire ammonites are not so rare, and of south-western affinities).

Though extremely abundant, the brachiopods are restricted in variety, being largely confined to a few species, notably *Gibbirhynchia northamptonensis*, *Tetrarhynchia tetrahedra*, *Lobothyris punctata* and *Zeilleria subdigona* (Ager's Midland Province). Gloucestershire, however, shows a transition to the south-western Province, as marked by the presence of *Quadratirhynchia quadrata* and *Homoeorhynchia acuta*.

Characteristically the brachiopods occur as closely packed clusters or 'nests' of several hundred shells. These are usually well preserved, with the shells filled by sparry calcite, and predominantly monospecific. They have generally been held to represent original colonial associations, an interpretation supported by detailed quantitative study, which reveals wide size ranges and multimodal size-frequency distributions (Hallam 1962*a*). Usually the colonies must have been rapidly extinguished by burial under shifting sediments, but on rare occasions growth was uninterrupted for the colonies to coalesce as a continuous band over many square yards, e.g. Band A near the base of the Marlstone at Tilton (Hallam 1955). At other times shell clusters were dispersed by currents into flat lenses, in which the shells are frequently broken or filled with sediment rather than calcite, e.g. Band B at Tilton.

The density of belemnites within a given volume of rock appears to be an especially good criterion of rate of sedimentation since, as also with other fossils, it varies more or less inversely with thickness of the Marlstone. In the highly condensed bed east of Banbury, at Marston St Lawrence and elsewhere, the top few centimetres consist almost entirely of belemnites.

Little can be said about the orientation of belemnites in the plane of the bedding because of the lack of suitable exposures. The epibiont bivalves are almost entirely disarticulated, the predominant orientation of the valves being convex upwards. Likewise, crinoids are entirely disarticulated into ossicles.

It is noteworthy that the commonest fossils of the Marlstone have originally calcitic shells, which are in consequence well preserved. It does not follow, however, that the rarity of *Pleuroceras* and endobiont bivalves is due to solution of their aragonitic shells and consequent loss from the record. *Dactylioceras*, for example, is quite common in mould preservation in sediment or as calcitic replacements in the top part of the Marlstone. Small

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gastropods with replacive calcitic shells are also not uncommon. Furthermore, it will be recalled that a fair proportion of the endobiont bivalve fauna in Yorkshire had calcitic replacement of their shells. We seem therefore to be dealing essentially with an original feature.

Apart from the spasmodic occurrence of *Chondrites* near Banbury, trace fossils have not been observed. This is almost certainly a function of preservation, owing to the lack of lithological alternations up the succession as in Yorkshire.

(3) *South-west England: Somerset and Dorset*

(*a*) *Petrology*

Deposits of the *Spinatum* Zone disappear in north Somerset in the neighbourhood of the Mendip Swell but return again further south near Shepton Mallet. In the Ilminster region of south Somerset they are represented once more by the Marlstone, about 8 to 12 ft thick, which thins eastward to about 1½ ft near Yeovil (Wilson, Welch, Robbie & Green 1958). It also thins southward and is represented on the Dorset coast between Seatown and Eype by the lower part of the well-known Domerian–Toarcian Junction Bed, which has received detailed stratigraphic attention from Buckman (1922) and Jackson (1926). More recently Howarth (1957) has reinvestigated the deposits of the *Spinatum* Zone, which attains a maximum thickness of only 2 ft. The *Apyrenum* Subzone (layer R) is represented by a conglomeratic oolite and the *Hawskerense* Subzone by an oolite band (layer P) underlain by a limestone with scattered ooliths (layer P_x).

Petrographically the Marlstone in Dorset and Somerset shows notable differences from that further north, suggesting a lithological change across the Mendip Swell. Thin sections have been studied of rocks from Maes Down (ST 646406), Moolham, near Ilminster (ST 364134) and the Junction Bed on the coast. The Marlstone at Maes Down (figure 25, plate 20), the upper part of the Marlstone at Moolham (beds 2 and 3 of Howarth 1958) and layer P_x of the Junction Bed, are fine-grained ferruginous limestones consisting of shells and limonitic ooliths ranging up to 0·6 mm, in a matrix of brown calcite *microspar* (in the sense of Folk 1965). The remaining rock is a ferruginous bioclastic limestone, with scattered limonitic ooliths scattered in predominantly crinoidal debris cemented by sparry calcite. The ooliths are variably translucent brown to opaque, suggesting different degrees of oxidation of chamosite. In the Junction Bed they are partly replaced by kaolinite. Detrital quartz grains, ranging up to 0·3 mm, are rare. The pebbles of layer R consist mainly of sideritic siltstone.

Data for the *Spinatum* Zone east of the main outcrop is limited to information from scattered boreholes. At Portsdown and Henfield (figure 4) the Middle Lias consists of silty and sandy limestones but the *Spinatum* Zone may be absent (Falcon & Kent 1960). It is also probably missing further east, in Kent, judging by the brachiopod fauna (Ager 1954). A full sequence may be present at Kingsclere, in northern Hampshire, but adequate stratigraphical details are not available (Lees & Taitt 1946).

(*b*) *Fauna*

A local naturalist, Charles Moore, collected a prolific fauna from the Middle and Upper Lias in Somerset around the middle of the last century. With exposures today being much

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poorer than at that time, the information recorded in his major work (1867) is still of great value.

Brachiopods are abundant, as in the Midlands, and constitute a much more varied fauna, especially in Dorset (Ager 1956). Characteristic features are the common occurrence of *Spiriferina* species, *Zeilleria quadrifida* and *Homoeorhynchia acuta*, the moderately common occurrence of *Quadratirhynchia* and *Aulacothyris* and rarity of *Tetrarhynchia*. Of especial interest is the presence of brachiopods confined to the South-West Province and occurring further south in Europe, including species of *Cirpa*, *Prionorhynchia* and *Zeilleria*.

Ammonites of the genus *Pleuroceras* are commoner than in the Midlands and are characterized by the presence of massive-whorled, tuberculate species, markedly different from those in Yorkshire (Howarth 1958). Belemnites are as numerous as elsewhere.

Moore (1867) gave a long list of bivalve species for the Marlstone of the Ilminster district, the most characteristic being large shells of *Pseudopecten aequivalvis* and *Gryphaea gigantea*. While there appear to be no regional pecularities of species as with the ammonites and brachiopods, there is a resemblance to Yorkshire rather than the Midlands in the common occurrence of a variety of endobionts. The most notable of these is *Pleuromya costata*, which can be found abundantly in the marly and fine-grained beds 2 and 3 in the Moolham section, sometimes in growth position.

Gastropods are also important in both Somerset and Dorset. While most of them belong to small-sized species, Moore recorded a giant specimen of *Pleurotomaria* some 2 ft. in diameter. Numerous gastropods occur in layers P and P_x of the Marlstone on the Dorset coast, including species with southern affinities, not found north of the the Mendips, such as *Pleurotomaria princeps* (Koch) and *Talantodiscus mirabilis* (Desl.). Moore likewise found a wide variety of small gastropods occurring in Middle Lias fissure deposits in the Carboniferous Limestone at Holwell, in the Mendips.

Another feature of interest is the occurrence of serpulids and bryozoa encrusting pebbles and an erosion surface on the top of layer R in Dorset. The under surface of this layer has a concretionary limestone adhering to it locally, with the trace fossils *Chondrites* and *Thalassinoides*. Rare corals, echinoids and sponges have been found by Moore at Ilminster.

(4) *Inner Hebrides*: *Raasay and Skye*

(*a*) *Petrology*

The best-exposed Hebridean sections of the *Spinatum* Zone, constituting the upper part of the Scalpa Sandstone, are in Raasay, and attention is here concentrated on these. Stratigraphical work by Howarth (1956) has established that the *Apyrenum* Subzone is represented by about 30 ft of alternating sandstones and sandy shales and the *Hawskerense* Subzone by about 100 ft of sandstones (figure 3).

Beds have been examined in Raasay, Trotternish and Strathaird, near Rudha na Leac (NG 600380), Holm (NG 520515) and Dun Liath (NG 543138) respectively. The lithology is very constant. The so-called massive sandstone tends to weather to a series of thin beds, in which cross bedding is rare. Large ellipsoidal calcareous doggers occur at a few horizons. As seen in thin section, the sandstone is fine-grained and somewhat argillaceous, with quartz and subordinate felspar grains ranging up to 0·25 mm and abundant flakes of pale-brown mica.

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Bed 30 of Howarth, a group of about 12 ft of alternating sandstone and micaceous shale units near the top of the *Apyrenum* Subzone, is of special interest in that petrographic examination shows it to contain scattered ooliths of chamosite, a mineral not previously recorded from the Scalpa Sandstone. The bed does not contain oolitic limestone, as Howarth stated.

Judging from the account of the Geological Survey (Lee & Bailey 1925) and from brief personal inspection, the deposits of the *Spinatum* Zone in Mull are very similar to those further north.

(*b*) *Fauna*

Howarth's bed 30, as seen in fallen blocks on the foreshore south of Rudha na Leac, is also by far the most interesting bed from the faunal point of view, and is the only one in the Scalpa Sandstone that could be described as rich in fossils.

The dominant fossils are large specimens of *Gryphaea gigantea* Sow., *Pseudopecten aequivalvis* and *Pholadomya ambigua*. Other common fossils include the bivalves *Entolium lunare*, *Oxytoma cygnipes*, *Pleuromya costata* and *Plicatula spinosa*, together with ammonites, brachiopods, belemnites and crinoid ossicles. The abnormal concentration of fossils at this horizon suggests a condensed assemblage.

The deep-burrowing myas occur almost invariably in growth position. Orientations of the large saucer-shaped left valves of *Gryphaea* shells are hard to measure accurately because they are often incompletely exposed, but it is apparent that the majority are concave upward, in contrast to *Pseudopecten*. In both cases a small minority of articulated shells were observed. The orientation of *Gryphaea* is an exception to the general rule among bivalves and is a consequence of the unusual shape of the left valve and its reaction to bottom currents (Zeuner 1933; Hallam 1963*a*). Both brachiopods (mainly *Tetrarhynchia*) and crinoid ossicles tend to occur in small lenticular clusters.

The so-called massive sandstone bed 36 is only sparsely fossiliferous. Its likely lateral equivalent on the shore near Dun Liath, Strathaird contains fairly common *Pseudopecten* and *Oxytoma* in thin bands, and more uniformly dispersed belemnites. Small clusters of brachiopods and crinoid ossicles are the only other fossils present in any abundance.

Obscure mottling due to burrowing organisms is widespread in the Scalpa Sandstone but the only well-preserved trace fossils discovered are in Howarth's bed 26 in the *Margaritatus* Zone.

The brachiopod and ammonite faunas show closer relationships to south-west England than to Yorkshire. Notable features of the brachiopod fauna are the abundance of *Tetrarhynchia tetrahedra*, *Homoeorhynchia acuta* and *Zeilleria subdigona* and the presence of *Grandirhynchia* (Ager 1956). The ammonites suggest an impoverished and somewhat dwarfed Cotswold fauna, with *Pleuroceras spinatum* (Howarth 1958).

IV. *TENUICOSTATUM* ZONE

(1) *Yorkshire*

(*a*) *Petrology*

On the Yorkshire coast the so-called Grey Shales are made up of about 30 ft of silty/sandy shales, lithologically comparable to those in the underlying *Spinatum* Zone.

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As noted earlier, the base is best taken at the laminated shale, bed 58 of Howarth in the section near Staithes, rather than bed 61.

A good section can be seen in the foreshore and cliff base between Old Nab and Port Mulgrave, south of Staithes, where, however, only the lower part of the zone is well exposed. This consists of alternations of ordinary shale containing ferruginous, red-weathering nodules, and bituminous laminated shale. Another section can be examined at Hawsker Bottoms. Here the lower half of the zone consists of shales with several bands of sideritic mudstone nodules, separated from the upper shales containing occasional scattered limestone nodules by a 6 in. band of bituminous laminated shale.

(*b*) *Fauna*

The most striking feature of the Grey Shales fauna are the numerous specimens of *Dactylioceras tenuicostatum* and *semicelatum* that occur in about the upper two-thirds of the succession. These occur characteristically as calcite and sediment-filled moulds in small ovoidal limestone nodules, one of the few instances in the Lias in which fossils and concretions are intimately related to each other. Apart from abundant belemnites the remaining fauna is largely restricted to a few species of bivalves, notably *Pseudolimea pectinoides*, which are moderately common in the normal but rare in the laminated shales.

(2) *Midlands*

(*a*) *Petrology*

At Kirton, in north Lincolnshire, Howarth & Rawson (1965) recorded 12 ft of shale with a basal mudstone layer as belonging to the *Tenuicostatum* Zone. Further south, at Lincoln, the zone is represented, according to Trueman (1918), by some 15 ft of laminated 'paper shales', underlain by the so-called 'acutum bed', a greenish shale passing locally down into a ferruginous sandstone. In the southernmost part of Lincolnshire and in north-east Leicestershire the zone appears to be missing, but it reappears at Tilton. Here it consists of the 'Transition Bed', a richly fossiliferous limestone about 6 to 9 in. thick, locally overlain by a few inches of marl. This disappears in south-east Leicestershire, to reappear in southern Northamptonshire, in the eastern part of the Banbury ironstone field. In the west of this field, and locally in the east, it is absent through non-deposition or erosion.

The Transition Bed, as seen in thin section, contains chamosite ooliths like those in the Marlstone scattered in a matrix of chamosite mudstone and occupying from about 30 to 50% of the total area. The mudstone is somewhat patchily distributed and where the ooliths lie close together the matrix is sparry intergranular calcite. Calcitic shells and shell replacements are very common and minute siderite crystals are fairly common scattered through the rock. Detrital quartz is rare. The chemical analysis of a typical sample of rock given in table 2 shows that calcium is much higher and iron much lower than in the Marlstone. It can appropriately be described as a ferruginous limestone.

Green & Melville (1956) attribute some 3½ ft of mottled marl in the Stowell Park borehole to the *Tenuicostatum* Zone.

(*b*) *Fauna*

The paper shales at Lincoln contain the same fine-ribbed species of *Dactylioceras* as in Yorkshire but the underlying bed contains *Dactylioceras directum* and *Tiltoniceras acutum*,

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which two species occur in great abundance in the Transition Bed of the East Midlands. It is possible that this distinctive ammonite horizon is represented by the lowest few feet of the Grey Shales in Yorkshire, where, however, *Tiltoniceras* has not been found.

The Transition Bed is of great interest faunally. The great concentration of a wide variety of fossils is almost certainly the result of extremely slow deposition. Brachiopods, belemnites and ammonites are the commonest forms, followed by gastropods and epibiont bivalves. Ammonites apart, the faunal affinities are with the Domerian rather than the Toarcian.

The commonest brachiopod is *Gibbirhynchia tiltonensis* Ager, a distinctive dorsoventrally flattened species. Although Ager (1954) stated that it is confined to the Transition Bed, the author has also found it in the top part of the Marlstone at Tilton and in the *Falciferum* Zone near Banbury. Unlike other species of *Gibbirhynchia*, *G. tiltonensis* is found scattered uniformly throughout the rock. Ager (1954) thought this might reflect a distinctive life habit, but it appears more likely that it is merely a consequence of the slow deposition rate allowing ample time for post-mortal dispersal. There was probably less sediment migration than during the deposition of the Marlstone, thereby diminishing the chances of sudden burial of brachiopod colonies.

The small size of many of the Transition Bed fossils led Beeby Thompson (1889, p. 24) to suggest the possibility of stunting or dwarfing ('Fossils . . . are small . . . as though the conditions were unsuitable to their proper development'). This possibility has accordingly been investigated. Most of the collecting was done near Tilton.

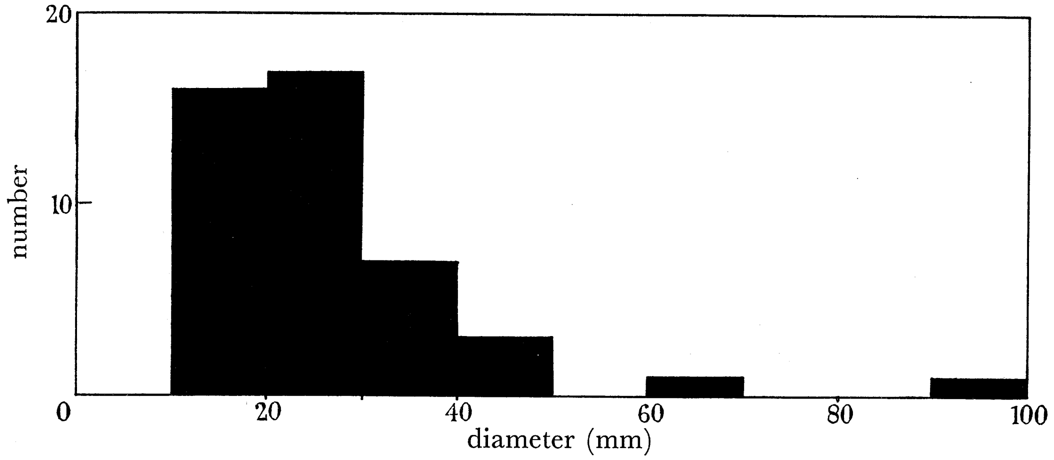

FIGURE 10. Size-frequency histogram of 46 specimens of *Tiltoniceras acutum* from the Transition Bed near Tilton, Leics.

Tiltoniceras acutum is a small ammonite occurring in large quantities. Most specimens lie on their side, with the body chambers filled by sediment and the camerae by drusy calcite. Calcite has replaced the original aragonite of the shells. The size frequency distribution of a randomly collected sample is given in figure 10. This shows a marked positive skew, with the bulk of the specimens being less than 40 mm in diameter. Two specimens attain a much greater size, one reaching nearly 100 mm.

To determine whether the smaller specimens are complete and not merely nuclei almost a third of the total were sectioned medially. All had their body chamber intact and so it is concluded that the bulk of the specimens, if not all, are complete. The small specimens

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could represent juveniles and the large ones adults, or the former could be stunted adults. The only specimen to show unequivocal septal crowding is the largest (96 mm diameter) but it is more reliable to use the technique of Vogel (1959*a*), who plotted the amount of separation of septa against whorl diameter in comparing suspected stunted ammonites with adults. This has accordingly been done with the sectioned specimens of *Tiltoniceras*

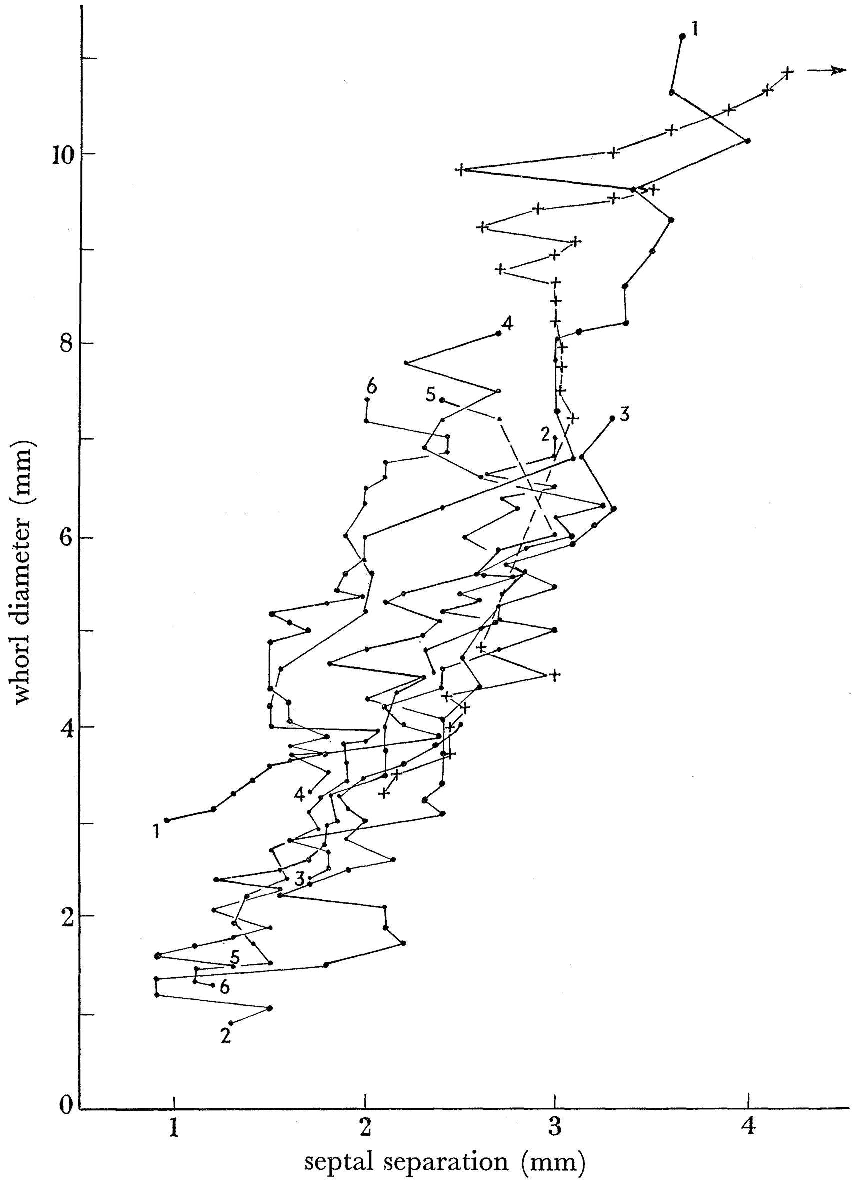

FIGURE 11. Septal separation diagram for several specimens of *Tiltoniceras acutum* from the Transition Bed. Small specimens 1 to 6 (·), large specimens (+).

(figures 11 and 12). If the eleven small specimens are stunted compared with the two large ones the septa should be appreciably more crowded together but the figures show that this is not the case. It is therefore concluded that most of the *Tiltoniceras* present in the sample are immature forms.

For other fossils, it is useful to make comparisons with the underlying Marlstone. Only two reasonably abundant species, *Passaloteuthis paxillosus* and *Zeilleria subdigona*, are common

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to both horizons. The former exhibits no apparent difference in size range. In the case of *Zeilleria*, material collected from the top 5 ft of the Marlstone and the Transition Bed has been studied. For the detection of stunting in brachiopods Vogel (1959*b*) advocated the use of strong growth lines, marking notable breaks in growth, as a criterion of the adult condition. Applying this criterion to *Zeilleria*, adult characters appear in the Marlstone specimens at a length of about 20 mm and in the Transition Bed specimens at about 16 mm. The mean size of the latter is less but the maximum size the same as the Marlstone specimens (length = 32 mm). This evidence does not warrant a firm conclusion either way, but if stunting has occurred its effects are slight.

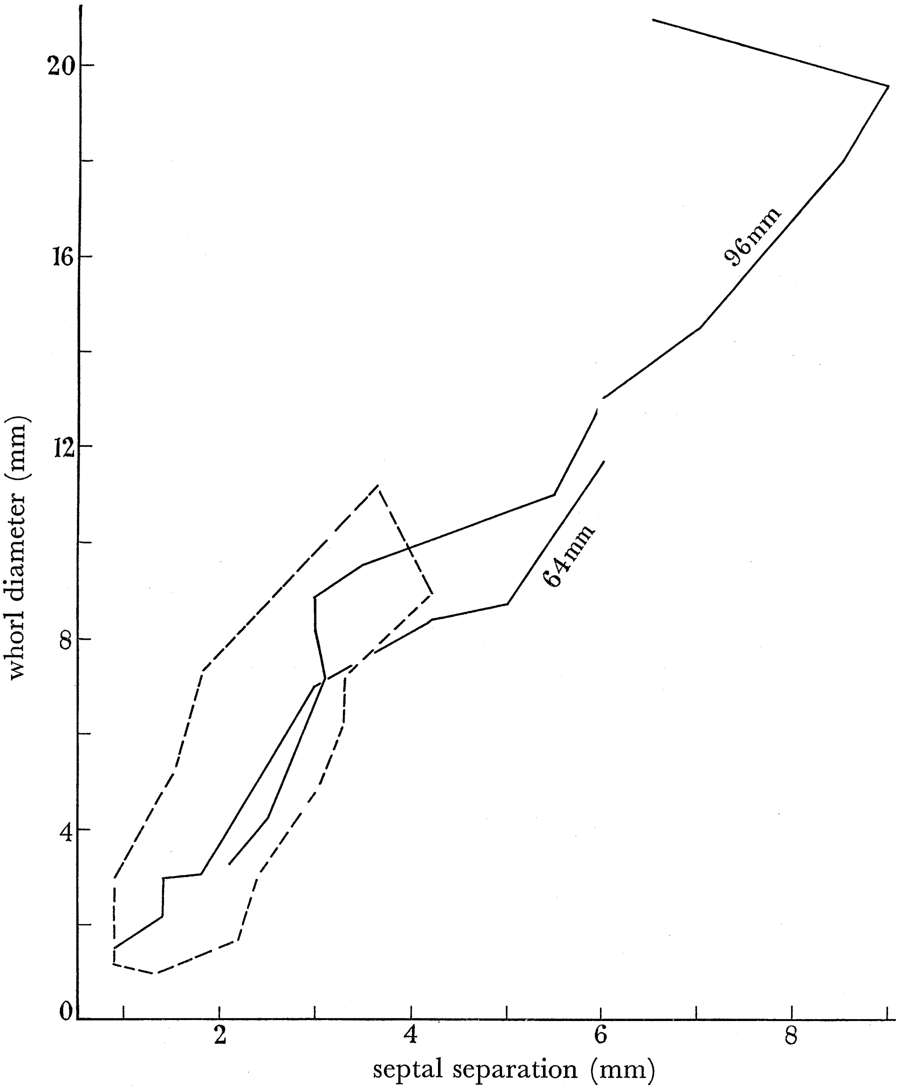

Figure 12. Simplified septal separation diagram for *Tiltoniceras*. The broken line gives the range of variation of 11 specimens of diameter less than 36 mm. The continuous lines represent 2 large specimens, of diameter 64 and 96 mm.

Amongst the other common species, *Gibbirhynchia tiltonensis* attains, according to Ager (1954), a smaller maximum size in the Transition Bed than in Dorset (length × width × thickness = 11·5 × 13·0 × 10·5 mm cf. 14·0 × 16·5 × 12·0). Stunting in this species is therefore a possibility but the evidence is hardly convincing as it stands.

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The bivalve species collected from the Transition Bed tend to be smaller than those in the Marlstone, but are too few in number for any positive conclusions to be drawn. The gastropod specimens are small, mostly of the order of a few millimetres in maximum size, but so apparently are the species. The large forms of *Pleurotomaria anglica* and *Ptychomphalus expansus* present in the Cleveland Ironstone have not, however, been recognized in the Transition Bed. For most forms at least there do not appear to be strong grounds for accepting stunting.

(3) *South-west England*

The *Tenuicostatum* Zone is missing over northern Somerset and over most of southern Somerset as well, as a result either of erosion or non-deposition, but may be present in one or two localities, such as Atherstone (Wilson *et al.* 1958). On the Dorset coast it is probably represented by a thin layer of brown oolitic limestone discovered in a fallen block below Doghouse Cliff. This bed, a few inches thick, contains abundant dactylioceratids (Jackson 1926). The basal Upper Lias shales in the Kent boreholes have yielded ammonites suggestive of the zone (Lamplugh, Kitchin & Pringle 1923) and *Tiltoniceras* is recorded by Falcon & Kent (1960) from the Brightling borehole in Sussex.

(4) *Inner Hebrides*

The top 6 ft of the Scalpa Sandstone in Raasay have yielded indeterminate dactylioceratids, which may be taken tentatively as representing the *Tenuicostatum* Zone (Lee & Buckman 1920; Howarth 1956), but it should be borne in mind that *Dactylioceras* enters the succession close to the top of the Marlstone in the Midlands. The possibility remains therefore that the lateral equivalent of the Grey Shales in Yorkshire and the Transition Bed of the Midlands is missing in Raasay and elsewhere in the Hebrides.

V. *FALCIFERUM* ZONE

(1) *Yorkshire*

(*a*) *Petrology*

The stratigraphy of the excellently exposed *Falciferum* Zone on the Yorkshire coast has recently been studied in detail by Howarth (1962). It corresponds to the Jet Rock Series, made up of the Jet Rock (*Exaratum* Subzone 28 ft thick) and the Bituminous Shales (*Falciferum* Subzone, 75 ft). The facies and thickness vary only in detail between the exposures near Port Mulgrave (NZ 798175) and the Peak (NZ 981024), respectively north-west and south-east of Whitby.

The Jet Rock is of considerable interest petrologically. It consists of brown-black finely laminated bituminous shales with several bands of large calcareous and pyritic concretions. The shales, normally with less than 5% $CaCO_3$, have illite and subordinate kaolinite as the clay minerals, as determined by X-ray diffractometer analysis. The regular bituminous laminae average about 20 μm in thickness and the alternating clay laminae mostly range from 20 to 50 μm (figure 26, plate 20). The bituminous matter, reddish brown in thin section, is largely structureless but contains a variety of microplankton, especially leiosphaerids, together with pollen and spores (Wall 1965).

Detrital quartz, of silt grade, is rare (less than 2%) but scattered pyrite common,

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occurring in globular or framboidal form or as cubic crystals. Hydroxyapatite occurs quite commonly in the form of scattered fish scales. Chemical analysis of four shale samples showed organic carbon contents ranging from 3·2 to 11·8%. It is interesting to note that Bitterli (1963*a*) found a maximum of about 15% in an extensive study of Liassic bituminous shales in Western Europe. When freshly broken the shales smell strongly of mineral oil.

Howarth (1962) lists the main horizons of concretions in the best section, near Port Mulgrave. They are variably sphaeroidal, ellipsoidal or irregular in shape (e.g. 'Cannon Ball Doggers', 'Curling Stones' and 'Pseudovertebrae' respectively) and made up of a uniform mosaic of silt-grade calcite or calcite microspar, in the sense of Folk (1965). Some concretions, notably the Cannon Ball Doggers, are enveloped by thin pyritic skins. The $CaCO_3$ content ranges between about 75 and 85%, judging by analysis of five samples.

One band, the so-called Whalestones (bed 35 of Howarth), is of particular interest and has been the subject of a special study (Hallam 1962*b*). Two separate phases of segregation and interstitial crystallization of $CaCO_3$ have produced two distinct sets of calcite siltstone concretions. The earlier concretions ('Pseudovertebrae') are highly irregular in shape and are associated with small bodies of micrite, which exhibit a variety of structures including veining, colloform banding and microbreccias. A complex diagenetic history can be deduced.

Jet occurs only sporadically in the Jet Rock, mostly as small lenticles flattened parallel to the bedding (the largest piece recorded was over 6 ft long (Hemingway 1958)). It is black in colour and possesses a vitreous lustre on freshly fractured surfaces, which are often conchoidal. Microscopic examination of thin sections shows occasional tracheid cells but frequently cell structure has been obliterated. It should be pointed out that jet, or jetty lignite, is not strictly confined to bituminous shales, but may occur in normal shales with a low $CaCO_3$ content. In more calcareous rocks elsewhere in the Lias the tracheid cells of the original driftwood have been filled by diagenetic calcite, with the result that it has been preserved, without shrinkage, as recognizable branches and trunks of brown woody lignite (cf. Hallam & Payne 1958). Unlike lignite in Dorset, however, the Yorkshire jet is not appreciably enriched in germanium (K. W. Payne, personal communication).

The dark grey Bituminous Shales of the *Falciferum* Zone lack the fine laminae of the Jet Rock but detrital quartz is still rare. They are intermediate in character between the latter and the overlying smooth-textured, light grey Alum Shales of the Middle Toarcian. Compared with the Jet Rock, calcareous concretions are relatively uncommon and scattered in the Bituminous Shales, and some red-weathering concretions occur, e.g. the Ovatum Band (bed 48 of Howarth) at the top of the succession. Pyrite masses are commoner, however.

(*b*) *Fauna*

The fauna of the *Falciferum* Zone is restricted in variety and dominated by ammonites, belemnites and two species of bivalves. The distribution up the succession of the abundant ammonites, consisting largely of species of harpoceratids and dactylioceratids, is described in detail by Howarth (1962) (see also §II). Among the belemnites, *Passaloteuthis paxillosus* continues up into the Jet Rock where, however, it is accompanied by species of the Toarcian genus *Dactyloteuthis*, which make their first appearance at this level. Of especial

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interest is the occurrence in the Jet Rock of the teuthoid cephalopods *Geoteuthis* and *Teudopsis*, whose fragile skeletons are normally only found in bituminous shales. Likewise the Jet Rock and overlying shales have yielded complete, well preserved skeletons of marine vertebrates, like the lithologically comparable *Posidonienschiefer* of the same age in south-west Germany.

The two common bivalve species are *Bositra radiata* (= *Posidonia bronni* auct.) and *Inoceramus dubius*. The former occurs in great abundance in the bottom few feet of the Jet Rock (bed 32) but at the level of the Cannon Ball Doggers (bed 33) it is replaced by *Inoceramus*, which is abundant throughout the rest of the *Falciferum* Zone. A comparable change is discernible in the *Posidonienschiefer* succession in south-east Germany (Hauff 1953). The large *Bositra bronni*, i.e. var. *magna*, is confined to lower and basal middle epsilon in Quenstedt's Liassic classification. *Inoceramus dubius* enters the succession in middle epsilon and continues into higher beds.

Another common mollusc is the tiny gastropod *Coelodiscus minutus* but the only other invertebrate macrofossils discovered by the author were a few specimens of the bivalves *Astarte*, *Chlamys*, *Meleagrinella* and *Variamussum*, together with rare crinoid ossicles. Endobionts are notably absent and there could have been no soft-bodied burrowing organisms in the Jet Rock sediments since the fine lamination would have been destroyed.

Fish scales excepted, the common fossils in the Jet Rock occur characteristically crowded together in paper-thin layers in the midst of relatively barren rock, each layer tending to be dominated by a single species. Myriads of small forms of a given species occur in some layers, fewer, larger forms in others. Each species in fact exhibits a wide range in size and there is no good evidence of stunting.

Where they occur in concretions, the ammonite chambers are filled by drusy calcite and occasionally yield drops of a greenish oil when broken open. Elsewhere in the shales they are crushed flat. Pyritic replacement of ammonites and *Inoceramus* shells is widespread throughout the *Falciferum* Zone.

(2) *Midlands*

(*a*) *Petrology*

Although the beds are thinner and much more poorly exposed, so that to some extent old published records have to be used, it is apparent that lithologically both the *Exaratum* and *Falciferum* Subzones of most of the Midlands are strikingly similar to Yorkshire. Characteristically the finely laminated shales of the *Exaratum* Subzone weather to paper shales. These occur at this horizon in Lincolnshire (Howarth & Rawson 1965), Leicestershire (Judd 1875) and Northamptonshire (Thompson 1910). In the later two counties the subzone is only a few feet thick. Calcareous ellipsoidal concretions, composed of argillaceous calcite microspar, are abundant. These were called the fish and insect limestones by Judd.

The *Falciferum* Subzone over this whole area is represented by smooth-textured non-laminated shales poor in detrital quartz. Where the subzone is only a few feet thick, in Leicestershire and Northamptonshire, the rock is somewhat marly, and contains calcareous concretions and bands of fine-grained limestone, e.g. the Lower Cephalopod Bed of Thompson (1910). A feature of particular interest is the presence of a marly limestone with scattered ooliths at Grantham (Trueman 1918). An oolitic marl band has also been

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seen in the *Falciferum* Subzone by the author in a quarry near Tilton about 8 ft above the Transition Bed (SK 756056) and another is recorded by Kent (1962) from the Glinton borehole. It is possible that all three examples might belong to one widespread bed.

Laminated bituminous shales also occur near the base of the Upper Lias in East Anglia (Kent 1947) but zonal data are lacking.

In the Banbury region the *Falciferum* Zone locally rests uncomformably upon the Marlstone, for instance, at Great Purston as in the east (SP 516393), where it is represented by an oolitic limestone. Immediately to the west of Banbury the *Tenuicostatum* Zone is missing in all sections, together with the *Exaratum* Subzone. In the Neithrop cutting, for instance (SP 438419), the *Falciferum* Subzone limestone, with a basal pebble bed, rests directly on the Marlstone, suggesting a minor phase of end-Domerian or early Toarcian erosion (Edmonds *et al.* 1965, p. 59).

A 6 in. limestone band, weathering pale brown, of the same age is welded to the top of the Marlstone in a disused quarry at West Bloxham (SP 422358). This is seen in thin section to be a microspar or 'calcite siltstone' with abundant crinoid ossicles. There are numerous minute brownish opaque particles, which could represent limonitized siderite crystals. Detrital quartz is absent.

In the Chipping Campden region the basal Upper Lias clays are rather sandy, like the underlying Marlstone (Kellaway & Welch 1961) but the normal shale facies returns further south-west. 115 ft of shales were assigned to the *Falciferum* Zone in the Stowell Park borehole, of which the basal 14 ft or so, belonging to the *Exaratum* Subzone, are laminated (Green & Melville 1956). Paper shales of this age, with calcareous concretions, were formerly exposed at Alderton and Dumbleton to the north-west (Richardson 1929). The author was able to examine smooth-textural shales with calcareous concretions, belonging to the *Falciferum* Subzone, in a tip in a disused Marlstone quarry near Dursley (ST 739998). Thin section study showed that detrital quartz was rare.

(*b*) *Fauna*

The fauna of the *Falciferum* Zone in the shaly facies of the Midlands compares very closely with the corresponding beds in Yorkshire, the commonest fossils being cephalopods. In particular, conspicuous limestone moulds of large ammonites with falcate ribbing occur in great abundance in the *Falciferum* Subzone and make a striking feature of many ploughed fields where the beds outcrop. Bivalves, belonging to such genera as *Nucula*, *Astarte* and *Lima*, occur sporadically and only *Inoceramus dubius* is common. *Coelodiscus minutus* occurs in the paper shales in prolific quantities. Some bedding planes in the paper shales are covered with fish scales, together with crustacean fragments and insects, and a notable fauna was collected during the last century in the region of Dumbleton, Gloucestershire. The paper shales here also yielded teuthoids, abundant echinoid spines and minute brachiopods, similar to those in the corresponding deposits in Somerset, which will be described in the next section (Richardson 1929).

The limestone band of the *Falciferum* Subzone at West Bloxham, described above, is richly fossiliferous. The commonest fossils are *Harpoceras falciferum*, *Dactylioceras gracile* and *Passaloteuthis* sp., but unlike beds of the same age elsewhere other fossils are quite common as well, including *Gibbirhynchia tiltonensis*, *Lobothyris*? sp., *Grammatodon* sp. and *Angaria* cf.

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ornatissima. Together with the abundance of echinoderm debris and ubiquitous presence of *Chondrites* this fauna suggests conditions unusually favourable to benthonic life for this time.

The facies bears some resemblance, indeed, to the Transition Bed, and a further similarity is that the cephalopods are predominantly small. Considering, for instance, the case of *Harpoceras falciferum*, the largest specimen collected by the author had a diameter of 10 cm but the great majority were smaller than 3·5 cm. A number of these small specimens have been sectioned, and all are seen to be either incomplete nuclei, lacking body chambers, or juveniles, with no crowding of the last septa (cf. the analysis of *Tiltoniceras*). These findings may have a bearing on Howarth's recording of a species in the Banbury district, *Harpoceras exiguum*, distinguished from *H. falcifier* only by its smaller size (see Edmonds *et al*. 1965, p. 59).

The ammonite shells have been replaced by calcite, as elsewhere in Falciferum Zone limestones.

(3) *South-west England*

(*a*) *Petrology*

In north Somerset the *Falciferum* Zone forms, together with the *Bifrons* Zone, the Junction Bed, a limestone with ferruginous, oolitic and pebbly bands, ranging mostly from 5 to 10 ft in thickness. Directly south of Bath it rests non-sequentially on Lower Lias (Kellaway & Welch 1961).

In the Ilminster district to the south, Moore (1867) recorded the following beds which would now be placed in the zone.

	ft	in
3. Upper Cephalopod Beds	8	0
2. Saurian and Fish Beds	0	8
1. Leptaena Clay	1	6

We are greatly dependent on Moore's description, since exposures today are very poor. The Moolham section, referred to earlier, reveals, however, a few feet of non-laminated, smooth-textured shales directly overlying the Marlstone containing calcareous concretions and poor in detrital quartz. The abundant ammonites signify the *Falciferum* Subzone. The *Exaratum* horizon is represented by beds 1 and 2, the latter consisting of alternations of laminated marl and limestone. It is not certain whether or not the subzone is missing locally.

Eastwards towards Yeovil and southwards towards the Dorset coast the zone thins and becomes more calcareous. In the coastal cliffs and foreshore between Seatown and Watton Cliff it is represented by layers O and M of the Junction Bed (Jackson 1926), both only a few inches thick and separated by non-sequences.

The Toarcian part of the Junction Bed is a partly conglomeratic, fine-grained, grey and pink limestone, weathering yellow. It possesses a number of irregular corrosion surfaces, separating different zones or subzones, with associated red (haematitic) staining. Dendritic manganese staining is also widespread on joint planes. Two chemical analyses of typical samples have revealed an abnormally high MnO content, 0·67 and 1·10%. In thin section fairly common crinoid and other shell debris is seen to lie in a varably micritic or microsparic matrix of calcite. Small, scattered crystals of pyrite are common but detrital quartz is very rare (figure 27, plate 20).

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Further east, the Portsdown and Henfield boreholes suggest a Dorset facies for the zone (Falcon & Kent 1960). Zonal ammonites have been collected from shales in the Kent boreholes (Lamplugh *et al.* 1923). A well-developed shale sequence is probably at Kingsclere but stratigraphic details are lacking (Lees & Taitt 1946).

(*b*) *Fauna*

Both the Leptaena Clay and the Saurian and Fish Beds of the Ilminster district have features of special interest. The name Leptaena refers to a small unribbed Toarcian rhynchonellid, *Stolmorhynchia bouchardii.* Associated with this a number of minute brachiopods, occurring in abundance, has been recorded from this horizon. These include the so-called '*Rhynchonella*' *pygmaea* and '*Terebratula*' *globolina* of Davidson and also a *Spiriferina* species. None of these brachiopods is more than a few millimeters in maximum dimension, and their affinities with larger brachiopods are unknown. This could possibly be an instance of stunting, but as the author was unable to collect material *in situ* judgement is reserved.

The basal few inches of the Leptaena Clay contain abundant echinoid radioles and plates. The only other common fossil besides ammonites is *Inoceramus dubius.*

The Saurian and Fish Beds have yielded a rich fauna of ammonites, belemnites, teuthoids, crustaceans, insects, fish and ichthyosaurs, many of them in a wonderful state of preservation. The remaining fauna, thought by Moore (1867, p. 191) to be stunted because of the small size of the specimens, includes epibiont bivalves and *Discinisca* (the only brachiopod known from this horizon). Moore also recorded a piece of fossil driftwood with attached cirripedes. This fauna is typical of that which occurs in laminated beds of *Exaratum* Subzone age throughout Western Europe.

The fauna of the *Falciferum* Subzone in Somerset is dominated by small ammonites related to *Harpoceras falciferum*, together with dactylioceratids. Examination of a large sample of *Harpoceras* from West Pennard, with specimens ranging up to 40 mm in diameter, showed that many specimens were incomplete, lacking the body chamber. Of the remainder, a minority showed crowding of the last few suture lines, signifiying an adult condition. These specimens could be stunted varieties of *H. falciferum*, a species which attains 250 mm in diameter (Howarth 1962, p. 411). Alternatively they could represent a separate, small species. This is the interpretation apparently preferred by Howarth, who notes that *H. exiguum*, whose adults range up only to 55 mm diameter, is very common at some localities in Somerset. Its horizon in Yorkshire, where it is rare, is the same as *H. falciferum.*

The only abundant fossils in the Toarcian part of the Junction Bed in Dorset are ammonites (*Harpoceras* spp.) and belemnites. Some of these are oriented at a high angle to the horizontal, including one ammonite as large as 7 cm diameter (figure 13). The ammonite shells are replaced by calcite, and the interiors filled by limestone and calcite in the usual way. The upper parts of the ammonites are frequently planed away, as has been known since the work of Buckman and Jackson. This is conspicuous at the erosion horizons, but may also occur elsewhere in the rock. In this latter case the upper part of the ammonite has been lost but there is no obvious break in sedimentation (figure 13 (4)). There is in fact a distinct resemblance to the 'Subsolution' phenomena in the Ammonitico Rosso Superiore (late Jurassic) of Italy, described by Hollmann (1964).

Serpulids are not uncommon, encrusting the internal moulds of corroded ammonites

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and hence signifying that they lived during periods of negligible sedimentation. They also have been found encrusting pebbles in layer O, together with *Liostrea* and *Plicatula* (Jackson 1926).

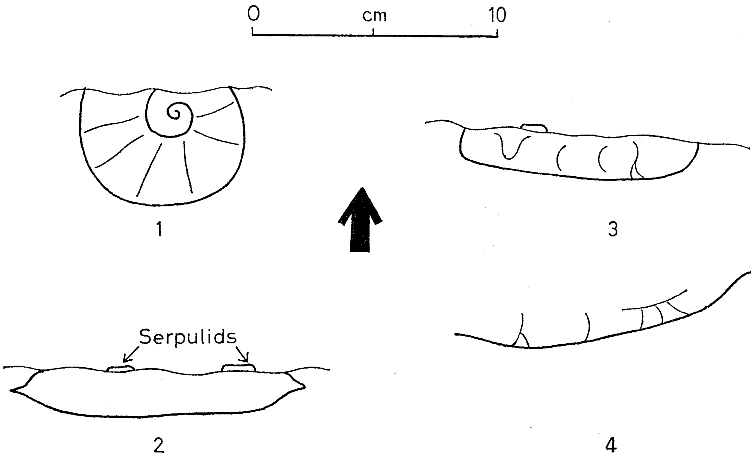

FIGURE 13. Sections of ammonites in the Toarcian Junction Bed near Seatown, Dorset, as exposed in vertical section. Arrow gives way up. Based on field sketches and photographs.

Other fossils in layer O (probably corresponding to the *Exaratum* Subzone) include *Stolmorhynchia bouchardi*, *Lobothyris* sp., crinoid ossicles and echinoid radioles.

(4) *Inner Hebrides*

The *Falciferum* Zone in Skye and Raasay corresponds to the Portree Shales. The thickness of this formation is highly variable, from only 3 to 9 ft in Raasay to nearly 80 ft in Trotternish, according to borehole data (Lee & Buckman 1920). The beds in both areas consist of uniform silty/sandy micaceous shales, with detrital quartz and subordinate felspar grains ranging up to 0·16 mm and averaging about 0·04 mm. The clay minerals consist, as in Yorkshire, of illite and subordinate kaolinite. Arkell (1933, pp. 185–6) stressed the significance of the discovery of a thin seam of jet found near Holm, in Trotternish, at the same horizon as the Jet Rock. In fact, as noted elsewhere, jet is not particularly rare in Liassic shales. In Raasay, the Portree Shales are seen to pass up gradually into the Raasay Ironstone, of the *Bifrons* Zone, chamosite ooliths entering the succession just below the ironstone proper.

The abundant fauna of harpoceratids and dactylioceratids indicates that, where the formation is strongly developed, most of it belongs to the *Falciferum* Subzone. Ammonites and belemnites apart, the only fossils occurring in any abundance are small bivalves including *Inoceramus dubius* and *Astarte* sp. Scattered fish scales are not uncommon.

VI. THE DOMERIAN–TOARCIAN TRANSITION IN OTHER PARTS OF THE WORLD

(1) *Europe and North Africa*

The stratigraphy of the classic areas in north-west Europe has been reviewed by Hallam (1961) and Hölder (1964) (see also Brand & Hoffman 1963 and Gabilly 1964). Table 4 gives a concise summary of the principal lithological features in different areas of the three zones under consideration. Generally speaking, the lithofacies of north-western France show

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TABLE 4. SUMMARIZED LITHOLOGY OF U. DOMERIAN AND L. TOARCIAN IN N.W. EUROPE

zones	N.W. France (Poitou–Normandy)	N.E. France (Lorraine, etc.)	S.W. Germany (Baden–Württemberg)	N.W. Germany (Lower Saxony)
Falciferum	laminated bituminous shales in off-shore facies, passing into marls and limestones with basal sandstone and conglomerate in transgressive marginal facies	laminated bituminous shales with calcareous concretions, passing up into non-laminated bituminous shales	laminated bituminous shales and marls, with bands of argillaceous calcilutite	laminated bituminous shales
Tenuicostatum	marls and marly limestones; missing locally	marls, locally sandy; bituminous shale in South Luxembourg. Locally absent or represented by phosphatic pebble band	thin marl sequence, not certainly belonging to zone since no ammonites found	bituminous shales in eastern or marginal facies of N. Harz foreland, mixed bituminous and normal shales and marls in western or basin facies
Spinatum	shelly, ferruginous limestone in Normandy, locally with signs of erosion at top; sandstone, conglomeratic at top in Poitou region	mixed sandstone and bioclastic ferruginous limestone, a thin bituminous shale band at top in south Luxembourg	argillaceous calcilutite with bands of marl	sandstone in eastern facies, mixed shales and sandstones with sideritic nodules in western facies

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close resemblances to those of south-west England, and north-west Germany (and, to a lesser extent, north-east France) to north-east England. The wide distribution of laminated bituminous shales in the *Falciferum* Zone (especially the *Exaratum* Subzone) is particularly worthy of note. Known in France as *schistes cartons* and in Germany as the *Posidonienschiefer*, they cover a vast area of western and central Europe, extending to southern France and the Alps. Only on the margins of sedimentary basins, in so-called transgressive facies, are they replaced by other types of rock.

The *Falciferum* Zone transgresses on to *Spinatum* Zone or older rocks locally in Normandy, Poitou and the Vendée, as in parts of south-west England and the Midlands. At Ambernac, on the borders of Limousin, the *Tenuicostatum* Zone rests upon Hettangian (Gabilly 1961). This evidence accords with that of the lithological sequence in suggesting a widespread deepening of the sea or rise of sea level from late Domerian to early Toarcian times (Hallam 1961).

In southern Europe, in the countries bordering the Mediterranean, the Domerian and Toarcian are often developed in the 'Ammonitico Rosso' facies of red marls and grey or pink limestones. The basal two Toarcian zones (or their Mediterranean equivalents) appear to be missing over a wide area, so that the Middle Toarcian (*Bifrons* Zone) rests directly on Domerian beds. This is the case for instance in north-west Spain (Hölder 1964, p. 444), in the southern Alps and northern Appenines (Donovan 1958), at Vättis in the Helvetic Zone of the Swiss Alps (Trümpy 1949) and over a wide area in the Moroccan Atlas, where Middle Toarcian of marly Ammonitico Rosso facies rests on and transgresses beyond Domerian reef limestones (du Dresnay 1962, 1964). Also, on the borders of the Palaeozoic Massif in Normandy, the *Bifrons* Zone is slightly transgressive (see Arkell 1956, fig. 5). Only in Greece has a probable equivalent of the *Falciferum* Zone been found in the Ammonitico Rosso (Hölder 1964, p. 483).

Turning to eastern Europe, the Lias passes progressively from marine to continental sandstones and shales eastwards from Germany into Poland. A major marine transgression over continental sediments in western Poland is dated, on limited fossil evidence, as Lower Toarcian (Dadlez 1964*a*, *b*). Also in the Donetz Basin, near Kharkov, beds dated as *Falciferum* Zone overstep much older rocks.

(2) *Other continents*

Evidence from other continents strongly supports the notion of a major world-wide marine transgression in the early part of the Toarcian, as suggested on the basis of a preliminary survey by Hallam (1963*b*, 1964*b*).

Domerian strata appear to be missing over a vast area in western North America, whereas Toarcian deposits are widespread. Beds of the *Falciferum* Zone overstep older rocks in Oergon and Nevada, while the *Bifrons* Zone is transgressive in British Columbia and Arctic Canada (Hallam 1965*b*), as also in east Greenland and Spitsbergen. The Lias in South America is still poorly known but preliminary study suggests a close comparison between Chile–Argentina and the western United States in that beds with Domerian ammonites are rare or absent while the Toarcian, with dactylioceratids, is widespread (G. Westermann, personal communication).

The Jurassic stratigraphy of Asiatic Russia has been reviewed recently by Krimholz

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(1959, 1964). The most striking feature of the Lias is a major Domerian marine transgression, whose effects are particularly noticeable on the eastern part of the Siberian Platform, in the basins of the Viluï and Aldan rivers. This probably corresponds in age to an important event in western Europe, where an early Domerian transgression was followed by a late Domerian regression (Hallam 1961). The transgression continued into the Toarcian, when the Liassic seas reached their maximum extent. Middle Toarcian shales are transgressive in parts of the Caucasus. In what is probably the best-developed and most ammonite-rich Liassic succession in Japan, the Toyora Group of Nagato shows conglomerates and coarse sandstones of basal Liassic age non-sequentially overlain by marine ammonitiferous shales of the Domerian (undifferentiated) and Toarcian (Takai *et al.* 1963). This suggests a close comparison with eastern Siberia.

The earliest marine Jurassic beds in Madagascar are dated as *Falciferum* Zone by Arkell (1956, p. 342) on the basis of the presence of *Bouleiceras*. This genus occurs here and in Saudia Arabia in great numbers and has an undoubted occurrence at this horizon in Portugal, where it is much less abundant. Recently, however, a few specimens have been found near the top of the Domerian in the Iberian peninsula (Geyer 1965). This appears to throw open the question of the exact age of the Madagascan transgressive deposits. From Arkell's world review (1956) it seems likely that Lower and/or Middle Toarcian deposits are also transgressive in Baluchistan, Indonesia and New Zealand, but better stratigraphic data are required.

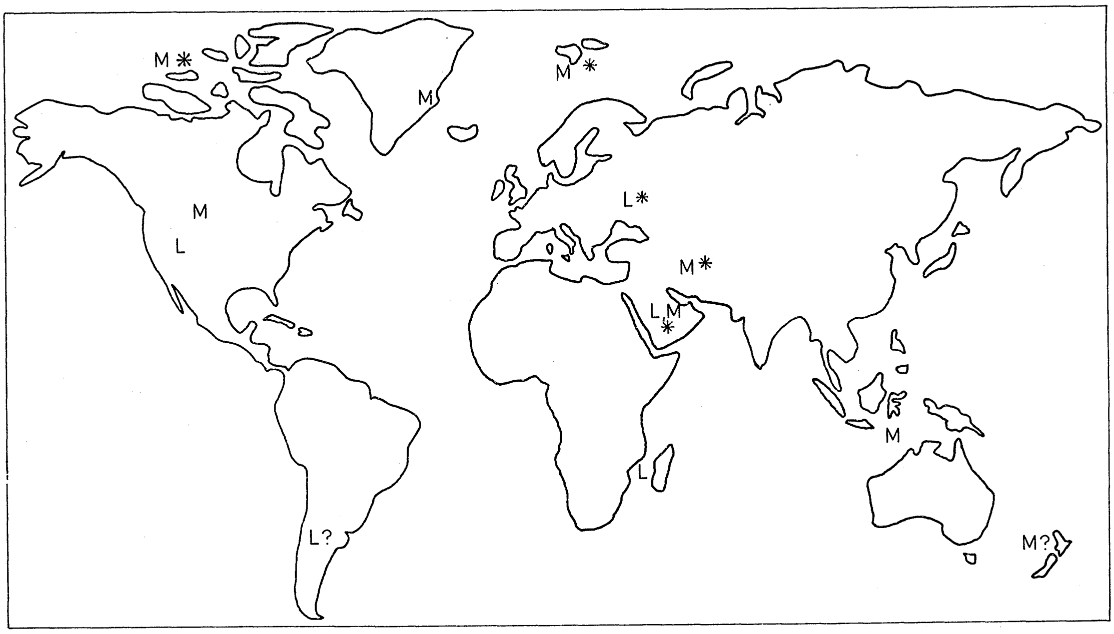

FIGURE 14. Transgressive Toarcian deposits in different parts of the world. L and M signify Lower and Middle Toarcian respectively. Asterisk signifies that these deposits are the oldest marine Lias in the area.

The wide extent of transgressive Toarcian is indicated in summary in figure 14. Whereas Lower or Middle Toarcian deposits frequently occur where the Domerian is absent, no case is known to the author where the reverse is true. Furthermore, wheras marine sedimentary sequences from the Domerian to the Toarcian in different areas often suggest a

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deepening of the sea, with, e.g. sandstones, bioclastic limestones and oolitic ironstones passing up into shales, converse types of sequence do not seem to occur. An additional point of importance is that the Middle Toarcian is often transgressive with respect to the Lower. These various facts strongly suggest that, due allowance being made for local epeirogenic warping, the transition in time from the Domerian to the Toarcian was accompanied by a eustatic rise of sea level, which continued into the Middle Toarcian. This clearly has major significance for the interpretation of the sedimentary and faunal sequences under discussion, to which we now turn.

VII. Interpretation

(1) *The sedimentary sequence in Britain*

(*a*) *The ironstones and associated rocks*

(i) *Diagenesis*

There has been fairly general agreement that the siderite in British Jurassic ironstones is mostly if not entirely diagenetic, having formed in a mildly alkaline and mildly reducing environment. Thus no primary siderite ooliths have ever been discovered despite intensive search, and the rhomboid crystals can be seen to replace chamosite, calcitic shells and even detrital quartz grains. The sideritic nodules in the Upper Domerian shales at Hawsker Bottoms in Yorkshire are obviously post-depositional and the same appears to be true of the sideritic mudstone bands forming the Pecten Seam to the north-west, because they coincide neither with shell bands nor oolitic horizons, both of which must signify changes in the original sedimentary conditions. They are therefore analogous to the secondary limestone bands in the Blue Lias (Hallam 1964*a*). In the Main Seam, there has been diagenetic concentration of siderite in the internal moulds of deep-burrowing bivalves, ammonites and the trace fossil *Rhizocorallium*.

The siderite was probably precipitated at an early stage in diagenesis, as a result of the interaction of ferrous and carbonate ions in the interstitial solutions. At a slightly later stage, presumably when the supply of ferrous iron was depleted, calcite was precipitated. Coarse cement in an ironstone from which the muddy matrix has been winnowed is invariably calcitic; in fact there is a regular association of ferruginous matter with clay. The calcitic replacements of chamosite ooliths in the Cleveland Ironstone are invariably coarsely crystalline.

The Cleveland Ironstone is distinctive in that many of the original chamosite ooliths have been replaced by kaolinite or opal. Dunham (1960) attributed this to transport of the ooliths on the sea bed to areas of low pH, since kaolinite at least requires acidic conditions for its formation. Bearing in mind the known constancy of the pH of sea water it is more plausible to propose that the replacive minerals were formed diagenetically within fine-grained sediment, in which both pH and Eh may differ appreciably from surface values. Supporting evidence for the existence of low pH during early diagenesis comes from the deep-burrowing myas, whose aragonitic shells have invariably been dissolved (cf. Hecht 1933). Kaolinite could form readily from chamosite by a leaching process, since the structure is similar. The origin of the opal is probably to be sought in the solution of diatoms (Siever 1962) or possibly the breakdown of montmorillonite.

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(ii) *Origin of the ooliths*

Generally speaking the formation of chamosite ooliths of various ages has been interpreted in two radically different ways. One group of geologists has considered that they originated in conditions of agitated water just like aragonite ooliths (e.g. Cayeux 1922; Berg 1944; Dunham 1960). Another group believes they formed by concretionary action in a gel (e.g. Pulfrey 1933; Caillère & Kraut 1954) while Taylor (1949) thought that both interpretations might be valid in specific instances.

The chamosite ooliths of the Domerian ironstones have a number of characteristics which, mineralogy apart, render them distinct from aragonite ooliths or their calcitic replacements in limestone. The nuclei are normally flakes of chamosite and detrital quartz grains or shell fragment nuclei are very rare. The ironstone matrix is frequently fine-grained, and some of the ooliths are severely distorted by compaction to spastoliths (term of Rastall & Hemingway 1939, see figure 15), indicating that they remained soft, even after burial. The ooliths of the Cleveland Ironstone, where the matrix is usually sideritic, chamositic clay, are appreciably larger than those of the Marlstone, where it is virtually absent. Chamosite, containing ferrous iron, is generally presumed to require reducing conditions for its formation, whereas the abundant benthonic fauna, much of it *in situ*, clearly signifies oxidizing conditions.

None of these facts, however, can be held to provide conclusive support for the concretionary hypothesis. As Dunham (1960) pointed out, there is no close resemblance to concretionary pisolitic chamosite that has formed in certain bauxites, and the low upper size limit of the ooliths presents a serious difficulty. Nevertheless, they must have formed in appreciably less agitated water than aragonite ooliths, whose size is normally related to the degree of agitation, since the more turbulent the water, the larger the particles that can be held in suspension and thereby capable of uniform accretionary growth. The abundant clay-grade material in the Cleveland Ironstone signifies fairly quiet conditions but an abundance of chamosite particles available for accretionary growth of ooliths. The smaller ooliths of the Marlstone, often little more than crystal flakes with a thin covering layer, probably signify lesser availability of fine-grained chamosite in an evidently more agitated environment, from which most of the clay had been winnowed out.

It is not claimed here that the ooliths scattered thinly through mudstone, as occur in the Cleveland Ironstone on the Yorkshire coast, formed strictly *in situ*. They might have grown on small, transient banks where the water was more agitated, and periodically been carried into adjacent areas of quieter water a short distance away (cf. Purdy 1964). No large-scale one-way transport of ooliths need be envisaged, however. The precise origin of chamosite ooliths is bound to remain obscure in the absence of modern examples for comparative study. Perhaps chamosite possesses properties which enable it to form ooliths with relative facility compared with other clay minerals.

The reducing conditions apparently required for the formation of chamosite could have been achieved within fine-grained sediment. The newly formed mineral could subsequently be carried to the surface by burrowing organisms. Alternatively, it must be noted that the only chamosite so far discovered in marine sediments occurs within faecal pellets (Porrenga 1965). This suggests that organic matter has created micro-environments of negative Eh.

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In any case, it is clear that the Liassic chamosite, once formed, was stable in at least mildly oxidizing environments.

The various forms that the ooliths have adopted can be explained as the result of two different processes, progressive oxidation in a relatively agitated environment, and compaction combined with colloidal shrinkage within the sediments of a relatively quiet environment (figure 15). The first process is associated with partial conversion to limonite together with a certain amount of fracture, perhaps followed by further accretionary growth. (The conversion is probably never complete, since Cohen (1952) has found that even highly opaque 'limonite' ooliths retain an abundance of silica.) The ooliths were thereby rendered rigid and resistant to compaction, and the matrix is often sparry calcite, since mud has been winnowed out of the sediment. The well-known alternations of green and brown concentric layers in the ooliths are more likely to signify repeated burial and re-emergence due to burrowing organisms than to periodic shuttling to and fro on the sea floor between areas of different Eh, as has been suggested.

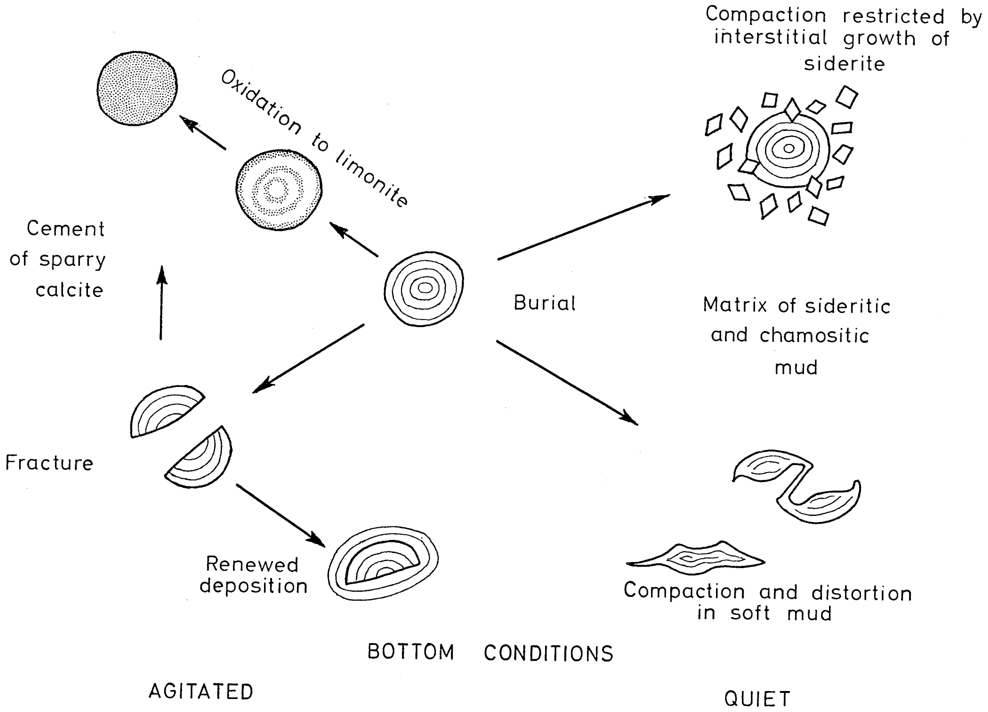

Figure 15. Interpretation of the conditions controlling the formation of different types of ferruginous oolith in the Domerian ironstones.

If the chamosite was not strengthened by partial oxidation, it was liable to compaction distortion upon burial (see Wilson (1966) for a detailed description and interpretation of such distorted ooliths). Spastoliths are therefore found in ironstones with a fine-grained matrix, in which indications of penecontemporaneous oxidation are negligible. Where siderite crystals are abundant the ooliths are undistorted, from which it may be deduced that the former pre-date compaction.

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(iii) *Environmental significance of the different facies*

The general problem of iron enrichment in marine Liassic sediments has been considered by the author in a recent article (1966). The sediments can be divided into two distinctive associations which were termed the *calcareous* and *ferruginous* facies.

The former consists of smooth-textured shales and marls with very subordinate detrital quartz of silt grade, together with subordinate layers and nodule bands of fine-grained argillaceous limestone (or microspar). Shallower-water, near-shore deposits, laid down in more agitated water, include oolitic and bioclastic limestones (oosparites and biosparites in Folk's terminology). The shales of the ferruginous facies, on the other hand, are typically rich in detrital quartz of silt to fine sand grade, together with abundant muscovite. The associated carbonate nodules are sideritic rather than calcitic, and the oolites chamositic ironstones. Whereas sandstones in the calcareous facies are characteristically well sorted, there is a distinctive type of mottled sand–clay rock occurring only in the ferruginous facies. In the article referred to above evidence is presented that the distribution of ferruginous facies is related to the proximity of major rivers. A paper has since come to light describing the first discovery of chamosite in marine deposits—in sediments of the Niger and Orinoco deltas (Porrenga 1965). This provides support for the hypothesis.

It is believed that the different facies of ironstones and associated rocks in the Domerian and Toarcian beds under discussion can be explained by reference to three main variables, degree of water agitation, rate of terrigenous sedimentation and proximity of rivers. This will be made clearer by reference to figure 16.

Facies 1 and 2 in this figure signify a relatively high rate of sedimentation in the marine deposits of river deltas. Mixed sandy and muddy beds result from burial taking place before the clay could be winnowed away by marine currents and/or wave action, together with the activity of organic burrowers. Ferric oxide brought to the sea with the clay fraction was reduced within fine-grained sediments and siderite produced interstitially by the interaction of ferrous and carbonate ions, subsequently segregating to form nodules.

Facies 3, 4 and 5 signify different types of ironstone formed in close proximity to rivers, which provided the iron partly in colloidal suspension or solution, but protected in some way from dilution by terrigenous sand and clay, probably by deposition on off-shore shoals. Deposition rates were appreciably lower than in facies 1 and 2.

Facies 6 and 7 signify deposits formed at some distance from rivers. The proportion of terrigenous clay and sand is negligible and the quantity of chamosite (or its limonitic alteration product) appreciably reduced, so that it forms only scattered flakes or ooliths of small size. The rock of facies 6 is almost wholly made up of shells. At a greater distance from river mouths, in shallow agitated water, it could be expected to grade into calcareous oolite or purer bioclastic limestones. Every gradation exists, of course, between the various facies.

Applying this interpretative model, the change from the Domerian to the Toarcian throughout Britain was from relatively agitated to relatively quiet water conditions. Such a uniformly widespread change suggests a deepening of the sea, which of course agrees with the evidence of a transgression at this time, as discussed earlier. The exceptionally widespread distribution of ferruginous deposits in the later Domerian suggests widespread

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emergence of land at no great distance, with in consequence a number of important rivers flowing into the shallow sea. At least one major river probably flowed from the Scandinavian land mass (Hallam 1966) and another (or others) drained a Scottish land mass. Others are more difficult to locate and the influence of rivers was of progressively diminishing importance towards south-west England. The early Toarcian rise of sea level resulted in a change to more calcareous facies, as river mouths were forced back.

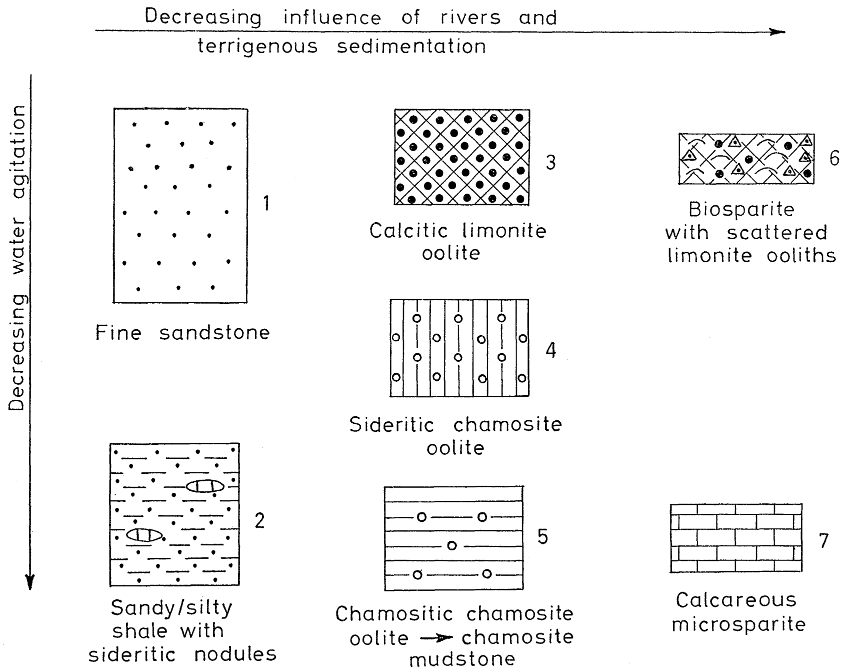

FIGURE 16. Proposed environmental conditions controlling the formation of the Domerian ironstones and associated beds.

More specifically, the occurrence of a bed with chamosite ooliths within the Scalpa Sandstone of Raasay signifies an interval of reduced terrigenous sedimentation, a conclusion suggested by the concentration of shells at this horizon. An off-shore shoal in the area of the North Cleveland Hills, where the ironstone is best developed, passed south-eastwards into an area of quieter and slightly deeper water, which acted as a 'clastic trap' for terrigenous sediment (cf. Huber & Garrels 1953). The presence of sandy beds in parts of the Marlstone in the Midlands and the south-west signifies temporary and local breakdowns in the protection against terrigenous sedimentation afforded by a marine shoal. Slightly elevated banks within the shoal, perhaps locally elevated slightly above sea level, remained areas of negligible sedimentation, marked today by highly condensed beds grading laterally into erosion surfaces.

(*b*) *The bituminous shales*

Aspects of the diagenesis of the laminated bituminous shales so widely developed in the *Exaratum* Subzone have been discussed in the section on the Jet Rock of Yorkshire. For a fuller account of such post-depositional features as concretions, pyrite crystals, jet and compaction the reader should consult the detailed work of Einsele & Mosebach (1955) on the lithologically similar *Posidonienschiefer* of Baden-Württemberg. For the present purpose

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it suffices to point out that $CaCO_3$ was originally more uniformly dispersed through the shales and probably owed its origin at least partly to precipitation by sulphate-reducing and denitrifying bacteria, as in the euxinic muds of the Black Sea (Archanguelsky 1927; Caspers 1957).

Little need be said either about the origin of the organic laminae, since this is discussed at some length elsewhere (Hallam 1960) for the very similar bituminous shales of the Blue Lias. It is concluded on the basis of modern analogies that the layers are annual, resulting from the seasonal fall of dead plankton (though part of the organic material has been derived from the land). The preservation of abundant organic matter and fine lamination and the paucity of undoubted benthos are attributed to deposition in an anaerobic or near-anaerobic environment. This interpretation will probably be regarded as unexceptionable. The really intriguing question concerns the palaeogeographic conditions responsible for widespread euxinic deposits in the early Toarcian.

Many German authors have supported Pompeckj's (1901) comparison of the *Posidonienschiefer* with the euxinic black muds in the deeper part of the Black Sea, in which the combination of a topographic still and salinity layering ensures that the deeper waters remain stagnant. Generalizing from this and less familiar recent examples, Woolnough (1937) proposed that euxinic deposits in the past formed in 'barred basins' (figure 17*a*).

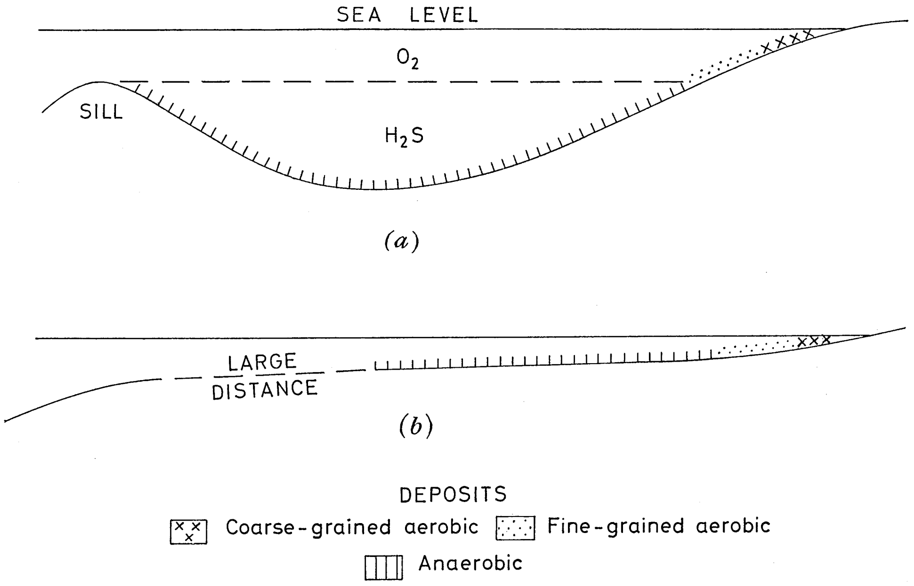

FIGURE 17. Alternative environmental models for the Toarcian bituminous shales: (*a*) barred basin, (*b*) shallow shelf sea.

Hemingway (1951) compared the Jet Rock shales to the same Black Sea deposits and Hallam (1961, 1964*b*) adopted the same model in suggesting that laminated bituminous shales in the Lias were deposited in deeper water than the other lithologies.

The strongest argument in favour of this interpretation is the similarity of modern analogues forming today in such barred basins as the Black Sea. (The organic-rich muds that accumulate in algal and grass 'meadows' in very shallow water are not comparable, since they lack fine lamination and usually contain numerous invertebrate epibionts that formerly spent their lives on the plants in aerated water (e.g. Bauer 1929).) However, there

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are a number of difficulties in this simple model and a variety of grounds exists for rejecting it.

(i) As has been pointed out, the bituminous shale facies has an astonishingly widespread extent over Western and Central Europe in the *Exaratum* Subzone. Even though no one has suggested a depth of water anything like as great as in the Black Sea, an appreciable depth within the shelf regime seems called for in the barred basin hypothesis. Thus Brockamp (1944) suggested an approximate figure of between 100 and 200 m. Bearing in mind, however, that the late Domerian ironstones and associated deposits were probably laid down in extremely shallow water this still implies a very pronounced deepening of the sea in a comparatively short geological time, which should have resulted in a far more pronounced marine transgression in Europe than the field evidence suggests. It should also be borne in mind that the first bituminous shales enter the succession in Yorkshire, Lincolnshire, the Ardennes and Lower Saxony at or near the base of the *Tenuicostatum* Zone.

(ii) Lithofacies variations between the centres and margins of sedimentary basins in Germany suggest deposition in comparatively shallow water, not far from land. Thus the *Tenuicostatum* Zone of the basin facies in Lower Saxony consists principally of normal shales or marls while in the marginal facies of the North Harz foreland it is represented by bituminous shales (table 4). Sandy layers become intercalated in the *Posidonienschiefer* near the old Bohemian and Vosges land masses (Brockamp 1944).

(iii) Wall (1965) has made a comprehensive study of microplankton, pollen and spores in British Liassic sediments. The fossils in the Lower Toarcian shales of Yorkshire and Lincolnshire, including the Jet Rock, are characterized by reduced diversity of microplankton and a great abundance of a few species of pollen. This is held by Wall to signify

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Description of plate 20

Thin sections of various Domerian and Toarcian rocks, seen in ordinary light; magnification ×20.

Figure 18. Sideritic chamosite oolite. Main Seam of Cleveland Ironstone, Upleatham, Yorks.

Figure 19. Sideritic ironstone with ooliths replaced by calcite and kaolinite. Bed 54, Old Nab, Yorks.

Figure 20. Siderite mudstone and chamosite oolite from Main Seam of Cleveland Ironstone, mixed together by burrowing organisms.

Figure 21. Silty bituminous laminated shale. Base of Toarcian (bed 58), Brackenbury Wyke, Yorks.

Figure 22. Chamositic sandstone with calcite cement. 2 ft above base of Marlstone, Tilton, Leics.

Figure 23. Sideritic chamosite oolite. 7 ft from top of Marlstone, Tilton, Leics. Arrow points to broken oolith.

Figure 24. Sideritic, calcitic chamosite oolite from Marlstone, Edge Hill, Warwicks. Arrow points to large chamosite flake.

Figure 25. Ferruginous bioclastic limestone with scattered limonite pseudo-ooliths and a pebble of siderite mudstone. Marlstone, Maes Down, Somerset.

Figure 26. Laminated bituminous shale. Jet Rock, Port Mulgrave, Yorks.

Figure 27. Calcitic microspar with echinoderm remains and pyritic aggregations. Layer O of Junction Bed, near Seatown, Dorset.

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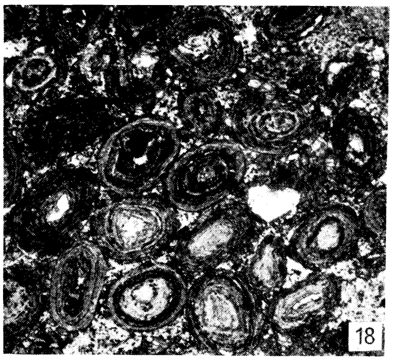

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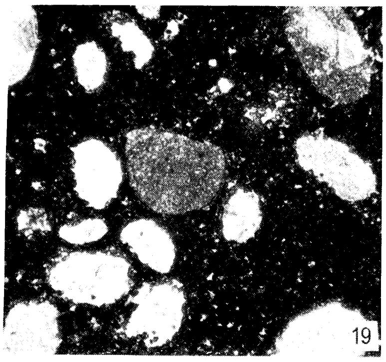

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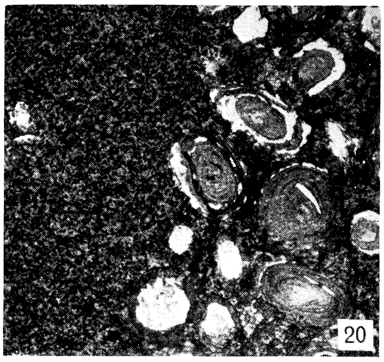

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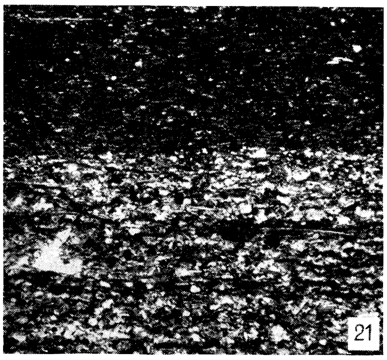

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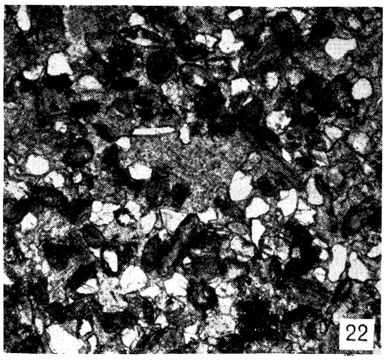

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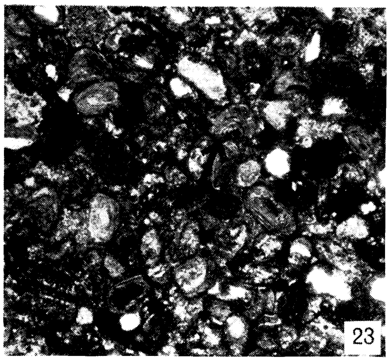

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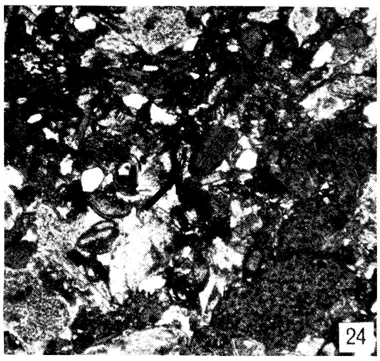

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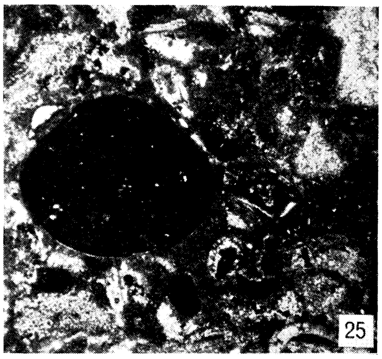

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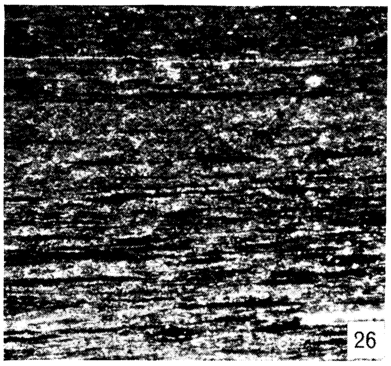

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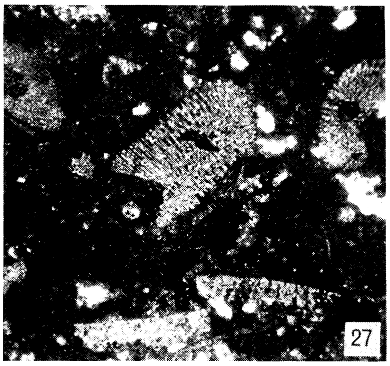

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deposition of the shales in inshore waters, quite close to land. The abundant insect remains that have been collected from various localities point more doubtfully to the same conclusion.

(iv) Though they were never well aerated, as testified by the presence of organic laminae and paucity of benthonic fossils, it is unlikely that the bottom waters were actually anaerobic all the time. This problem has been considerably illuminated by the recent discovery of laminated sediments in the Gulf of California, which are apparently being formed in poorly oxygenated waters and which can support a limited number of epibionts (sessile worm-like organisms) but not burrowing endobionts (Calvert 1964). Probably, unlike those in the Black Sea, the bituminous deposits of the Lower Toarcian ranged between what Continental geologists call *sapropel*, laid down in anaerobic water, and *gyttja*, in which the interstitial water is anaerobic but the overlying waters contain varying amounts of oxygen.

(v) The best evidence comes from the world stratigraphical review (§VI), which clearly indicates that, while the marine transgression began in the Lower Toarcian, it continued into the Middle Toarcian, which marks the maximum extent of Liassic seas. This implies that, for example, the Alum Shales of Yorkshire were deposited in deeper water than the Jet Rock, contrary to what Hemingway (1951) supposed.

It is here suggested that the only plausible model that adequately takes into account these various facts is that of an extensive shelf sea in a topographically subdued region, in which water circulation below wave base was severely impeded because of the shallowness, which was appreciably less than envisaged by Brockamp and others (figure 17*b*). If the water were very shallow even minor topographic rises would severely restrict circulation. In answer to the obvious objection that modern analogues are lacking or very limited in area, the marked differences in world Jurassic geography and that of the present should be stressed. As has frequently been pointed out, we are living in a time of marine regression, so that extensive shallow shelf seas are rare phenomena. Moreover, the existence of polar ice caps ensures a strong oceanic circulation because of the pronounced temperature differences between low and high latitudes. In the much more equable climate of the Lias oceanic circulation must have been considerably more sluggish, and wind strength (which has a bearing on the amount of wave action) correspondingly weak. Both factors could be expected to conspire against good circulation. Moreover, the abundant organic matter in the sea water would tend to decay rapidly, as in the tropics at the present day, so using up oxygen.

Keulegan & Krumbein (1949) have shown mathematically that, given a sufficiently low oceanward gradient of the sea bed, a condition will be attained whereby waves generated by the wind some distance offshore will dissipate their energy before reaching the shore. Not only would the formation of beaches and cliffs be prevented but extensive stretches of sediment on the shallow sea bed would be subjected to very little wave disturbance. Furthermore, it is unlikely that there would be major physical constrictions to induce strong tidal scour.

Following a rise of sea level, as from the Lower to the Middle Toarcian, circulation would be improved somewhat as the sea deepened and local 'sills' or other physical restrictions drowned. This is the only change that need be proposed to account for the

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gradual passage throughout western Europe of laminated bituminous shales in the *Falciferum* Zone to normal shales with a good benthonic fauna in the *Bifrons* Zone.

It seems pointless as yet to speculate on the depths of sea involved, beyond suggesting that they may have been less than about 20 m. This would imply that the later Domerian ironstones, etc., were deposited in extremely shallow water, and that finer material has been winnowed from the coarse-grained rocks by wave agitation. As wave disturbance diminished downwards, so finer-grained rocks could be deposited, still in aerated water. Below the limits of effective wave action the water would tend towards stagnation in the absence of strong marine currents. Dietz & Menard (1951) have observed that there is little significant wave abrasion below 10 m depth even at the present time (but allowance must be made, of course, for occasional storms).

There is good reason to believe that the palaeogeographic picture portrayed was by no means peculiar to the Toarcian. Thus Bitterli (1963 *b*) has noted that laminated bituminous shales commonly occur near the base of a marine transgressive sequence, which suggests that they may be relatively shallow-water deposits. Good examples in Britain are the Rhaetic black shales, certain beds near the base of the Lias of south-west England (Hettangian and Lower Sinemurian) and the Lower Oxford Clay in southern England.

(*c*) *The Junction Bed*

The Domerian part of the Junction Bed of Dorset is a highly condensed variant of the Marlstone in south-west England, with scattered pebbles signifying local erosion. The Toarcian part is a group of thin limestones distinguished by the presence of erosion (or corrosion) surfaces and by ferruginous and manganiferous staining. Some of the limestone is in fact pinkish because of the presence of haematite. The notable enrichment in iron and manganese supports the stratigraphical evidence in signifying negligible deposition of sediment over a long period of time, with influx of terrigenous material virtually reduced to zero.

More detailed deductions can be made by studying stratonomic features of the ammonites. The fact that ammonite shells are replaced by calcite, and the interiors filled by limestone and drusy calcite, with some of the smaller specimens oriented at high angles to the bedding, suggests a moderate rate of deposition. Otherwise the ammonites would almost invariably have lain on their side and not been partly infilled by sediment. In all probability the aragonite shells, exposed for a long period on the sea floor, would have dissolved before they could be replaced within sediment by calcite, leaving only aptychi, as in some late Mesozoic deposits in the Mediterranean.

Yet, as is well known, there are 'erosion' surfaces, with the upper parts of the ammonites frequently planed away (figure 13), and independent evidence of extreme condensation. In fact the 'erosion' surfaces are better described as corrosion surfaces, being the result of re-solution of $CaCO_3$, as discussed by Hollman (1964) for the Ammonitico Rosso Superiore of Italy. The different facts, equally valid, may be reconciled by presuming that relatively brief periods of moderate limestone sedimentation were interrupted by relatively long periods of corrosion. The presence of local pebbly layers, indicative of true erosion, could perhaps signify limited emergence above sea level for short periods.

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(2) *The faunal distribution in Britain*

(*a*) *Facies associations*

Broadly speaking, four distinct facies associations can be recognized, all of them signifying normal or substantially normal marine salinities. In the first three associations enumerated below, which lived in aerobic bottom waters, the abundance of fossils in a given volume of rock is inversely related to the rate of sedimentation. The fourth association differs from the others in the sparsity of benthos, due to anaerobic or very poorly aerated bottom water.

(i) The first association occurs in rocks containing abundant clay-grade material, such as the *Spinatum* and *Tenuicostatum* Zones of the Yorkshire coast, shaly beds (e.g. bed 30 in Raasay) of the Scalpa Sandstone and the Marlstone south of the Mendips. It is characterized by considerable diversity, including both endobionts and epibionts in abundance together with nekton.

The endobionts include deep-burrowing myas in growth position and a variety of more active shallow-burrowing bivalves, together with trace fossils signifying worms and/or crustaceans. Among the epibionts, bivalve species are slightly more dominant than brachiopods and crinoids. The fact that the myas are undisturbed in growth position while the epibiont bivalves are almost invariably disarticulated, with the valves mostly convex upwards, suggests a certain degree of agitation of the bottom water which was, however, too weak to disturb endobionts by winnowing away fine mud. Clusters of brachiopods and bivalves were presumably buried before they could be dispersed. It may reasonably be presumed that much of the broken shell material was fragmented by organic agents, in the absence of independent evidence of strong inorganic disturbance.

Among the nektonic elements, both ammonites and belemnites are abundant. The orientation data on belemnites and driftwood in the Cleveland Ironstone do not suggest the existence of powerful unidirectional currents, but the distribution in some cases departs distinctly from random.

(ii) The second association occurs in rocks from which material of clay grade has been largely or entirely winnowed out, such as the Marlstone of the Midlands and the sandier parts of the Scalpa Sandstone. Such beds signify deposition in rather more agitated water than in the previous case. Endobionts are rare, presumably because the conditions were unfavourable, with constantly shifting material of sand grade providing an unstable environment for relatively sedentary forms. The fauna is dominated by three groups of epibionts, brachiopods, bivalves and crinoids, the latter two groups always disarticulated, consisting of species which also flourished in association (i). This indicates that their mode of life was not significantly influenced by the nature of the bottom sediment.

There is a suggestion of two contrasted environments during deposition of the Marlstone. The first was one of comparative quiescence, in which colonial associations of brachiopods developed and crinoids found settlement. Locally some mud was deposited. The second was one of comparatively disturbed conditions leading to the reworking of mudstone, the redistribution of ooliths and transport and fragmentation of shells, together with the killing by suffocation of brachiopod colonies. Regions of mobile oolitic sands tend to be inimical to benthonic life since settling organisms are rapidly overwhelmed by shifting sediment.

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The rarity of *Pleuroceras* in the Marlstone cannot be attributed to preservation failure (see §III, 2*b*) and must therefore signify that the ammonites found the somewhat agitated waters unfavourable. This accords with a commonly observed restriction of many ammonoids to fine-grained rocks. In contrast, belemnites are abundant, as in other types of rock, which could signify that, like many living squids, the organisms were active swimmers not greatly affected by local bottom conditions.

(iii) The third association occurs in highly condensed strata suggestive of extremely low rates of deposition and periodic hardening of the sea bed, such as the Transition Bed in the Midlands and the Junction Bed in Dorset. It is distinguished by the relative abundance of encrusting epibionts and gastropods. The commonest encrusting forms are serpulids, followed by oysters and, less commonly, bryozoa; all these forms clearly required hard surfaces on which to grow. The gastropods, distinctly subordinate in the previous two associations, are probably abundant also because of the existence of firm surfaces on which to crawl. Snails are much more abundant and diverse today, for instance, where the sea bed is rocky, compared with muddy or sandy bottoms. This interpretation is supported by the abundant occurrence of gastropods in Liassic fissure deposits in the Carboniferous Limestone of the Mendips.

(iv) The fourth association, characterized by paucity of benthos, is found in the laminated bituminous shales of the *Exaratum* Subzone and related non-laminated shales and limestones widespread in the *Falciferum* Zone.

The benthonic fauna of these beds is confined to a few species of epibionts, the aeration being too poor to support organisms within the sediment. While a plausible case can be made for *Bositra* as a swimming organism which dropped to the bottom only after death (Jefferies & Minton 1965) there are a number of other bivalves, notably *Inoceramus dubius*, which probably lived on the sea bed. It is true that *Inoceramus* could, like crinoids, attach itself to floating driftwood, as proved by specimens discovered in the *Posidonienschiefer* (Hauff 1953), but the normal mode of occurrence in Britain is of scattered specimens not revealing any proximity to driftwood (likewise with other anisomyarians such as *Meleagrinella*). The local occurrence of, for instance, *Nucula*, *Astarte*, crabs and echinoid spines is convincing evidence of some bottom life, and there are no good grounds for considering the abundant minute *Coelodiscus* as anything but benthonic.

As discussed in §VII, 2*b*, it appears likely that there were periodic oscillations between truly anaerobic water, completely inimical to bottom life, and poorly aerated water which could support a limited, surface-dwelling fauna. The suggestion of stunting of various species in the *Falciferum* Zone of Somerset is a plausible one, since poor aeration is known to be a powerful influence in inhibiting growth (Hallam 1965*a*), but it should be recalled that there is no great probability of stunting in the Jet Rock.

(*b*) *Geographical provinces*

The work of Ager and of Howarth indicates clearly that, in contrast to the relatively homogeneous faunas of the *Margaritatus* Zone, those of the *Spinatum* Zone became differentiated geographically, allowing the recognition of several provinces. To some extent this differentiation may have been facies-controlled. Thus the change in the brachiopod fauna between Somerset and Gloucestershire correlates with a change in Marlstone lithology.

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On the other hand an important change from a 'south-western' to a 'Midlands' fauna takes place in the neighbourhood of Kings Sutton in Oxfordshire and is not obviously related to a lithological change. No geographical provinces are recognizable among the bivalves (or, for that matter, any other invertebrates), whose distribution appears to be controlled by facies. The common species of epibiont bivalves occur at all the localities studied.

It is believed that these facts can be mostly reasonably explained by the progressive regional shallowing of the shelf sea during the course of the Domerian, culminating in conditions of extremely shallow water, perhaps only a few metres depth over extensive areas. This sea was broken up by large low-lying land areas and free communication was further impeded by temporary sedimentary shoals or banks. In such a regime physical factors like temperature and salinity could be expected to vary appreciably over short periods of time, without leaving any trace in the sedimentary record. All this would have contributed towards restricting the migration and colonization of certain environmentally sensitive organisms including brachiopods and ammonites, though more robust organisms like the bivalves and belemnites were still able to migrate freely. Because of the inadequacy of outcrops and borehole data it seems unprofitable to speculate on the precise location of land and sea, especially as the geography of an area of such modest topography could be expected to be transient. The gradual reduction in faunal diversity passing from south-west England to the Midlands, and the reduced size of certain species in the latter area, is most reasonably explained as the result of a slight decrease of salinity due to dilution of the sea water by influx from an iron-bearing river or rivers.

The Lower Toarcian faunas appear to be homogeneous geographically, due allowance being made for facies variations. There are one or two doubtful exceptions among the ammonites. Thus the *Tenuicostatum* Zone fauna of the South and East Midlands differs from that of Yorkshire but this is more likely to be the result of minor stratigraphic gaps, the *acutum* horizon being missing in Yorkshire and the *tenuicostatum* horizon missing further south. In the *Falciferum* Zone, a small *Harpoceras* species, *H. exiguum*, is apparently more abundant than further north-east, unless, as is possible, it is a stunted form. The general homogeneity of the faunas is consistent with what one would expect of a transgressing sea.

(*c*) *Extinction*

The transition from the Domerian to the Toarcian was accompanied by a profound faunal change, affecting virtually every invertebrate group, with numerous species becoming extinct in western Europe (Hallam 1961).

Except in the case of the ammonites, the main change appears to coincide with the widespread occurrence of bituminous shales in the *Falciferum* Zone. That is, the *Tenuicostatum* Zone faunas are substantially similar to the Domerian, while the *Bifrons* Zone faunas have Middle Jurassic affinities. The correlation of faunal and lithological change is indeed so striking as to suggest a causal relationship, with the onset of bottom stagnation over a vast area killing off most of the benthonic fauna. In support of this interpretation is the fact that where the *Falciferum* Zone contains normal benthonic elements, as in the transgressive limestone near Banbury, presumably laid down in shallower and better-aerated water than the bituminous shales, the fauna has affinities with the older zones.

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It is also noteworthy that the common belemnite of the *Spinatum* Zone, *Passaloteuthis paxillosus*, is also found abundantly in the Jet Rock and its equivalents.

A modern example of the same sort has been described by Menzies, Imbrie & Heezen (1961). The eastern basins of the Mediterranean and Red Seas have undergone periodic bottom stagnation in the recent past, one major instance being dated at 8700 ± 1000 years B.P. Sedimentary layers rich in organic matter, fish bones and iron sulphide are depleted in benthos and correlate with phases of faunal extinction.

Toarcian hildoceratid and dactylioceratid ammonites enter the succession in force in the *Tenuicostatum* Zone and one species, *Dactylioceras directum*, even occurs at the top of the Marlstone, usually regarded as Domerian. They therefore slightly anticipate in time the main environmental change. The likeliest explanation for this is that the environmentally sensitive *Pleuroceras* species, already partly isolated from each other geographically, became extinct shortly before the sea level began to rise. The new ammonites were then able to colonize the area, filling the vacant ecological niche. It could also be argued that *Dactylioceras* itself contributed to the extinction of *Pleuroceras* by direct competition, but then one would have to explain why the ammonites chose to migrate from the Tethys in immediate anticipation, as it were, of a major environmental change. Only in Dorset do the stratigraphical distributions of the two genera overlap, but the Marlstone is here so condensed as to suggest that this apparent overlap in time is misleading. The subsequent Toarcian transgression would have facilitated the migration and adaptive radiation of ammonites.

(3) *General conclusions*

From more general Liassic studies we may assume a European environment of tectonic stability, with in consequence low rates of subsidence and sedimentation, and a warm, humid climate. The British area was intimately linked to north-west Europe as part of an extensive shallow shelf zone of very low relief, to the north of the Tethys, where the Ammonitico Rosso deposits were laid down.

Given this environmental picture, the primary factor which controlled sedimentation is seen to have been the depth of sea. The *Spinatum* Zone marks the late, regressive phase of a Domerian sedimentary cycle and the *Tenuicostatum* and *Falciferum* Zones the early, transgressive phase of a new Toarcian cycle (cf. Hallam 1961). Subordinate factors controlling the pronounced regional variations in sedimentation, notably in the *Spinatum* Zone, include the proximity to rivers bringing detritals and iron from the land, and local topography and rates of subsidence of the sea bed. The early Toarcian rise of sea level created a peculiar environment of bottom stagnation at one stage, resulting in the widespread formation of bituminous shales, before moderate marine circulation was restored in the slightly deeper sea of the Middle Toarcian.

The only reasonable explanation of eustatic sea level changes in the Lias is epeirogenic movements of the ocean floor, since polar ice caps were apparently absent (Hallam 1963*a*, *b*). Menard (1964) has estimated that sinking of the Darwin Rise in the west Pacific must have resulted in a lowering of sea level of some 100 m in the last 100 million years, a rate of change of 0·1 cm/10^3 years. On the other hand Tertiary elevation of the East Pacific and other youthful oceanic rises must have raised sea level some 300 m, a rate of 0·3 cm/10^3 years.

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Let us take, for the sake of argument, 15 m as a reasonable figure for the rise of sea level in the early Toarcian. Taking 20 million years as a round figure for the duration of the Lias gives 1 million years as the average duration of an ammonite zone. A 15 m eustatic rise during three zones is equivalent to a rate of change of 0·5 cm/10^3 years. Making due allowance for the assumptions involved in this calculation, it is interesting to find that this figure is of the same order of magnitude as those calculated by Menard.

The invertebrate fauna was profoundly influenced by the changes of sea level. The late Domerian regression apparently led to geographical differentiation and even extinction in the case of some of the more environmentally sensitive forms, while the phase of widespread stagnation in the early Toarcian resulted in extinction of most of the benthos. This is the first detailed documentation of a phenomenon regarded by Newell (1962, 1963) as of major importance in the stratigraphical record, namely the control exerted by transgressions and regressions of shelf seas on the evolution and extinction of marine invertebrates.

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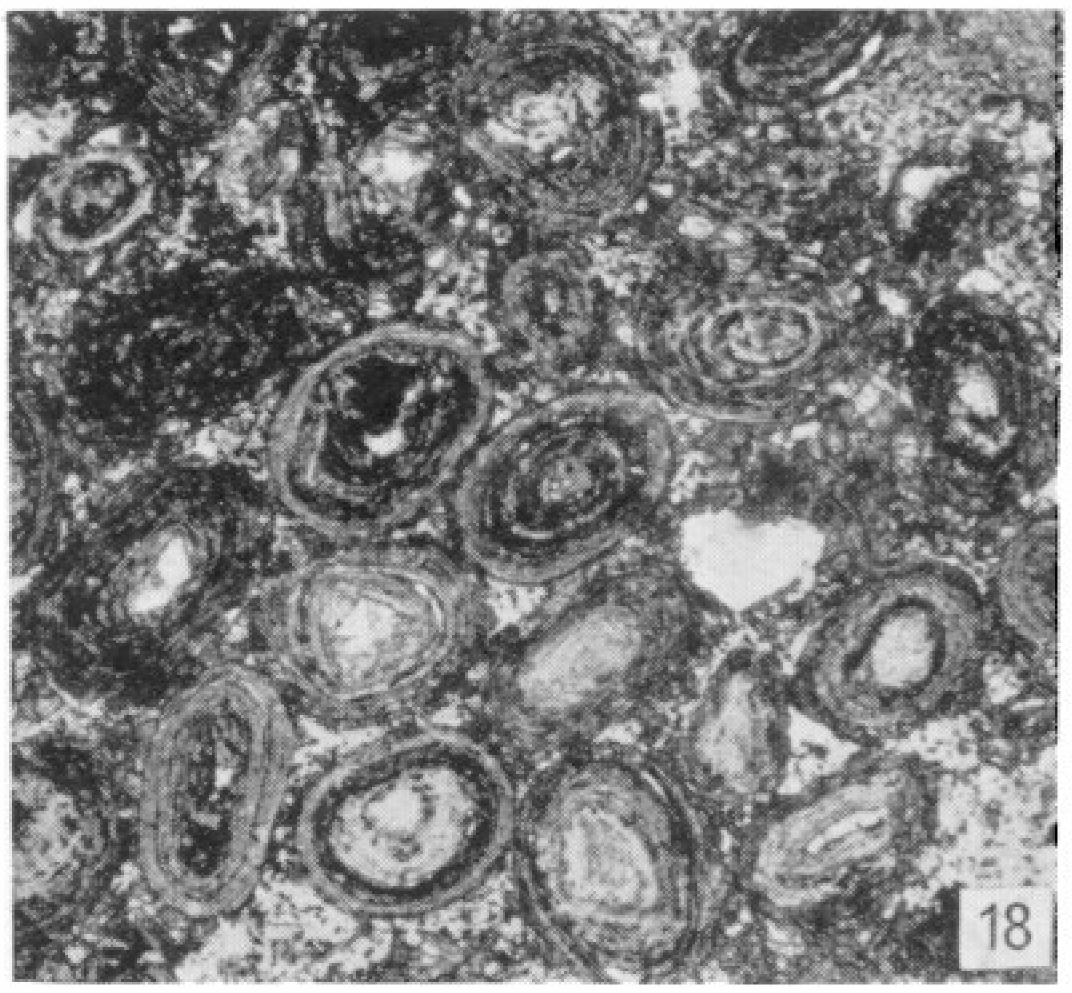
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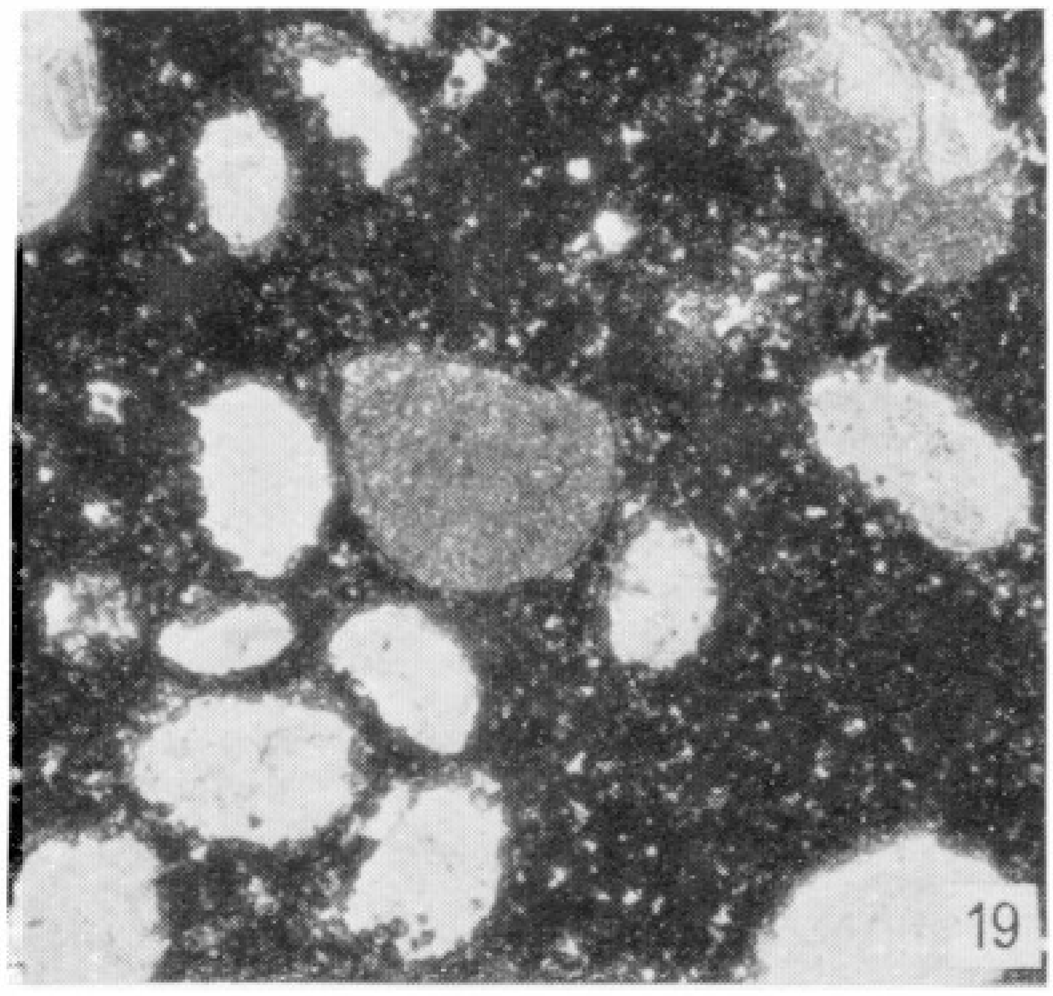
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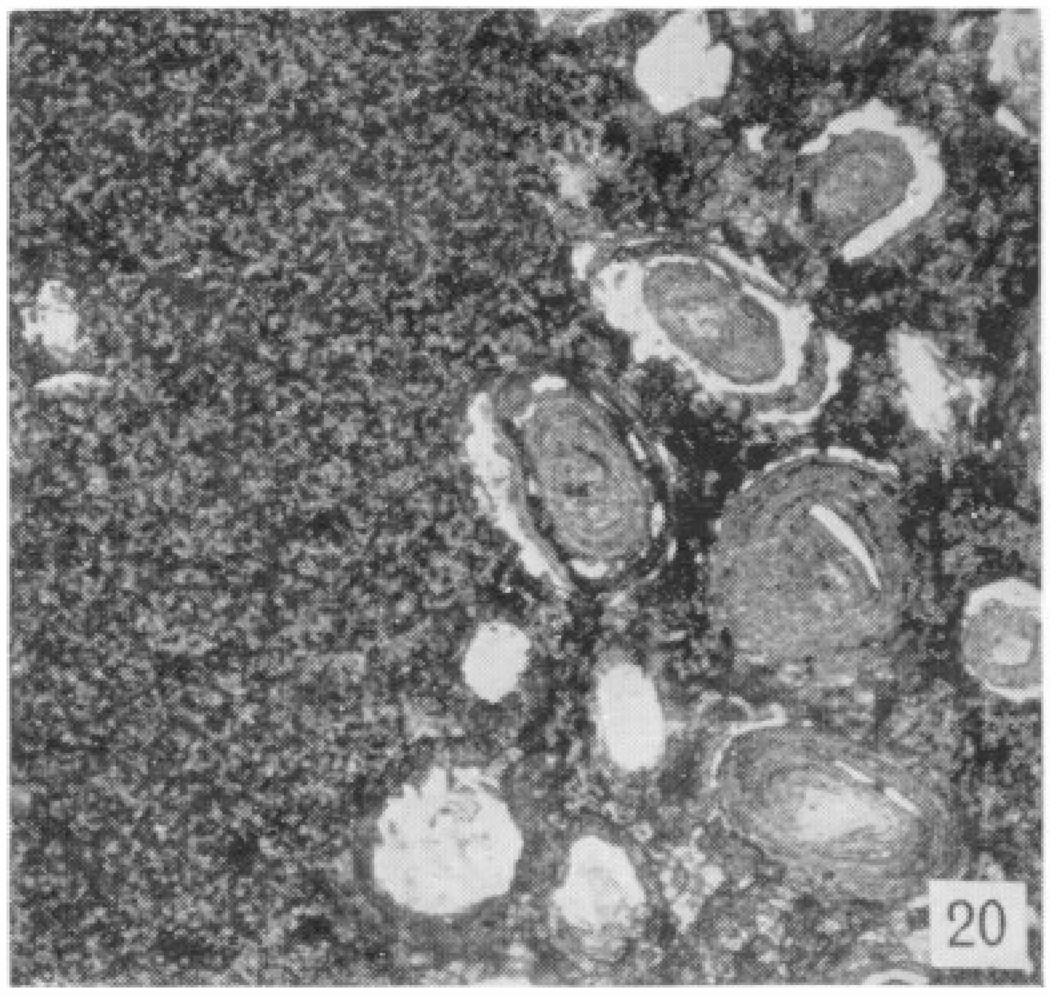
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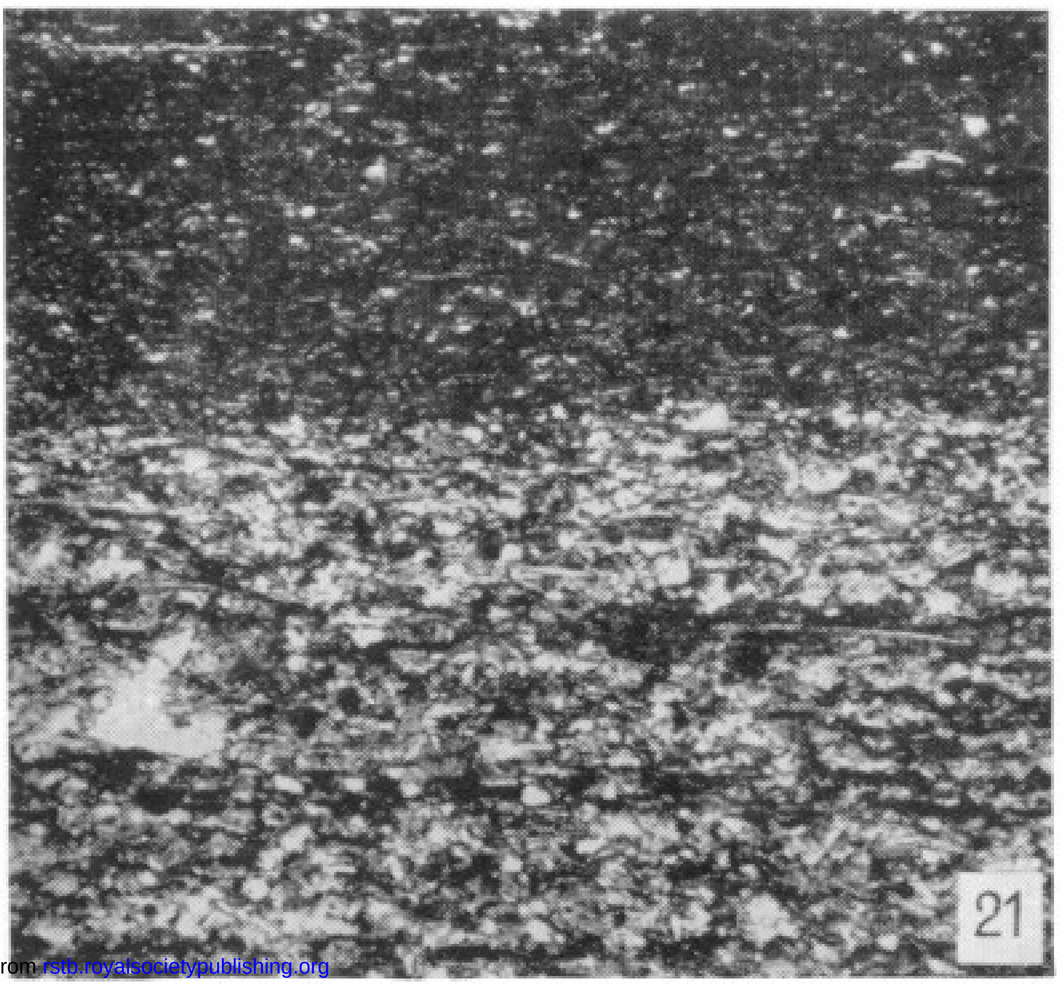
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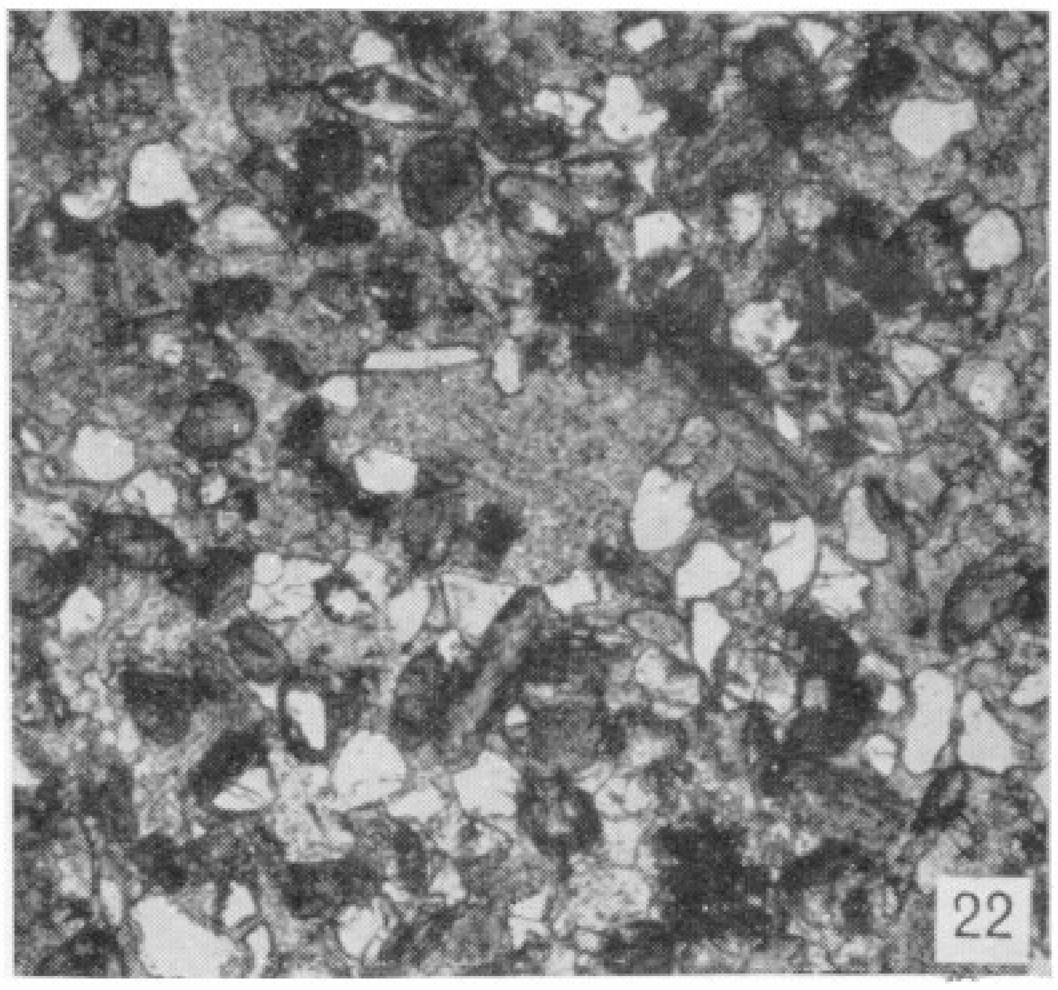
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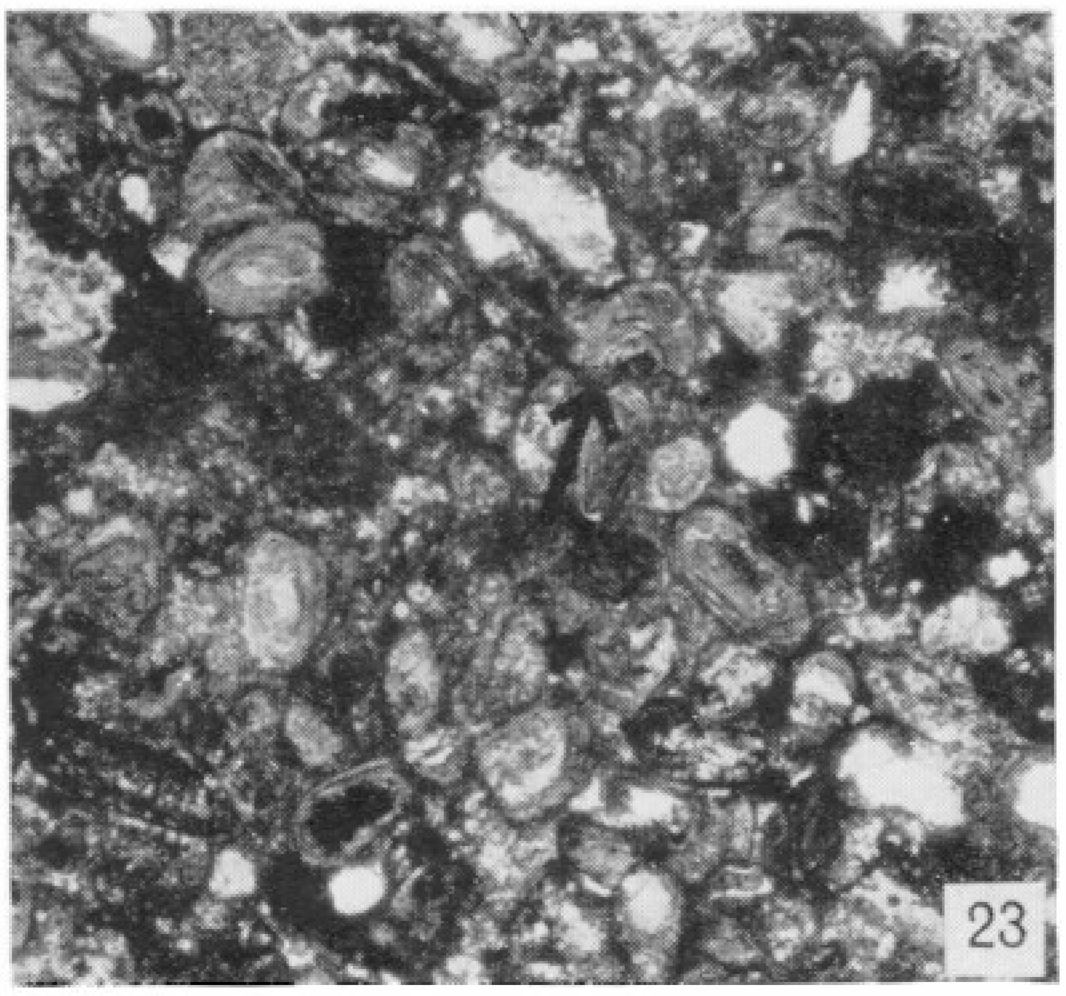
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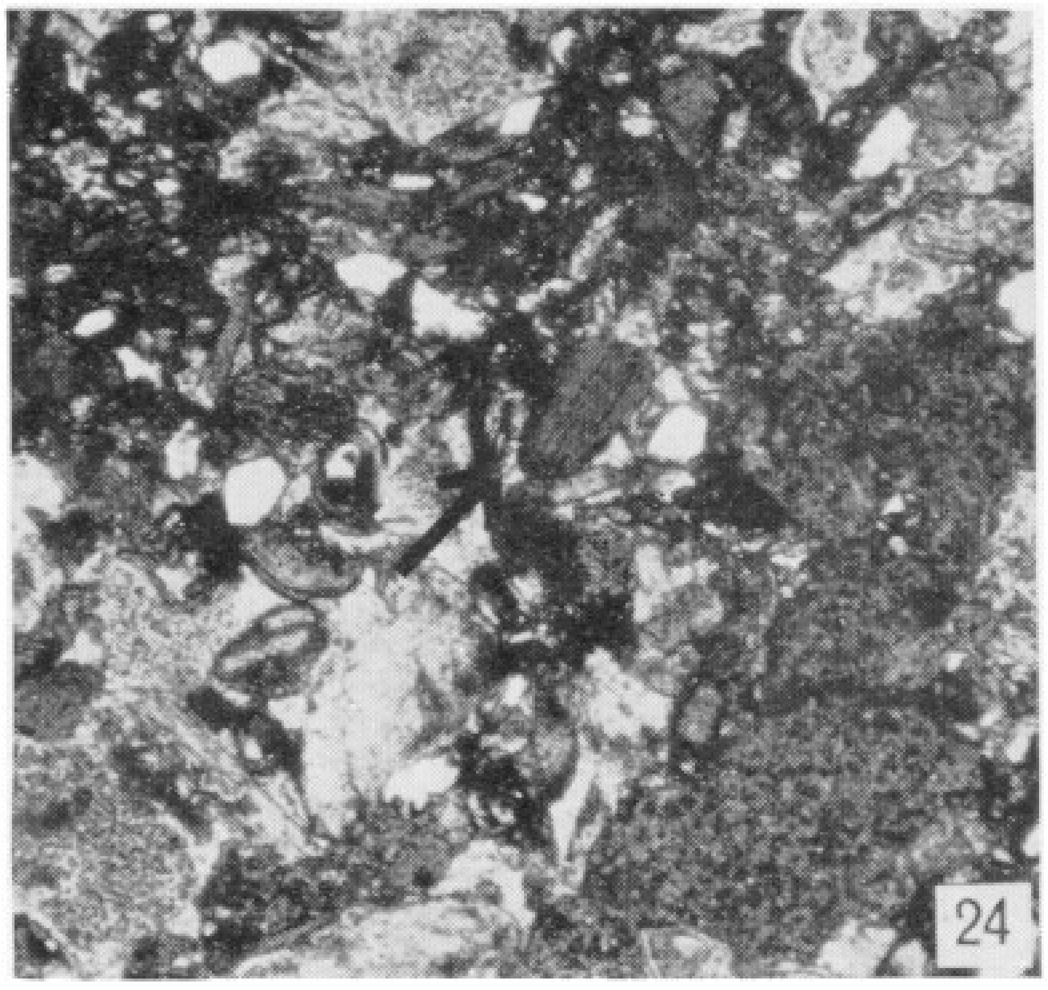
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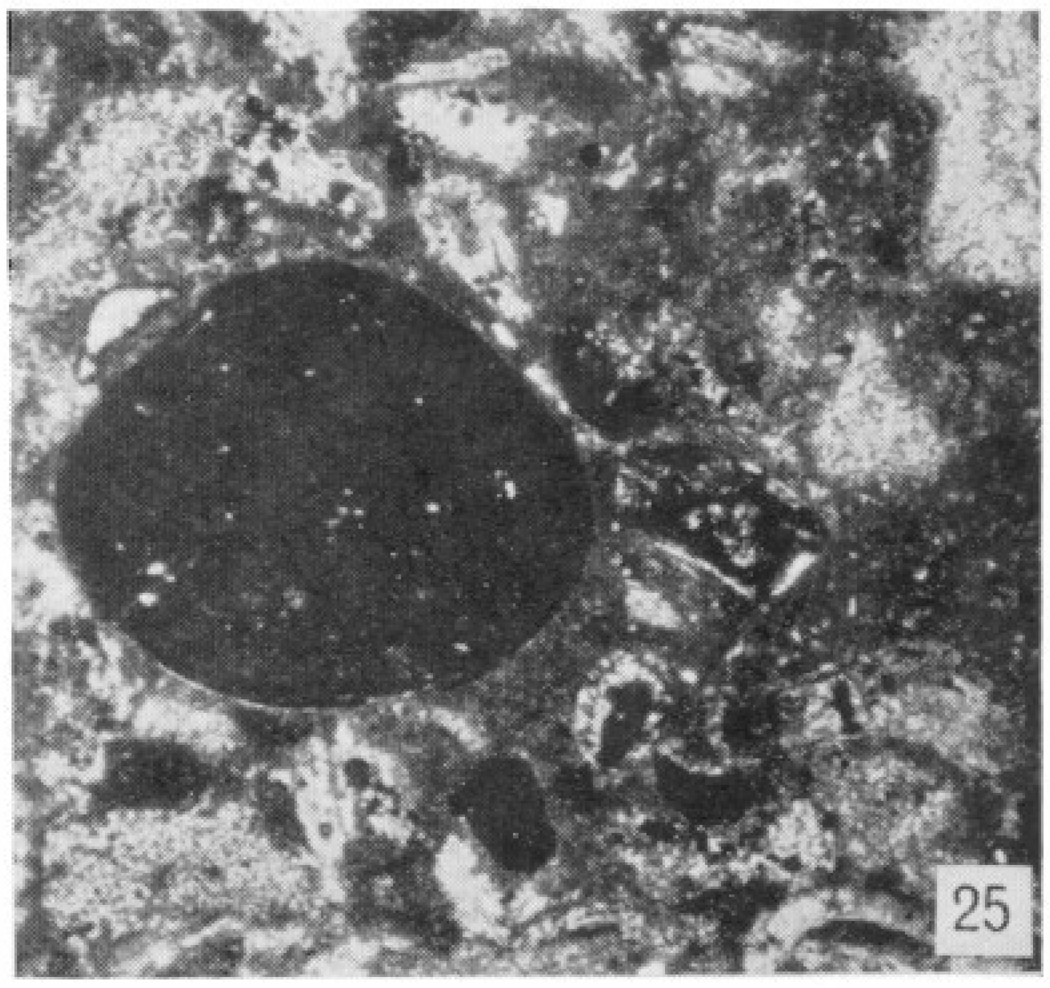
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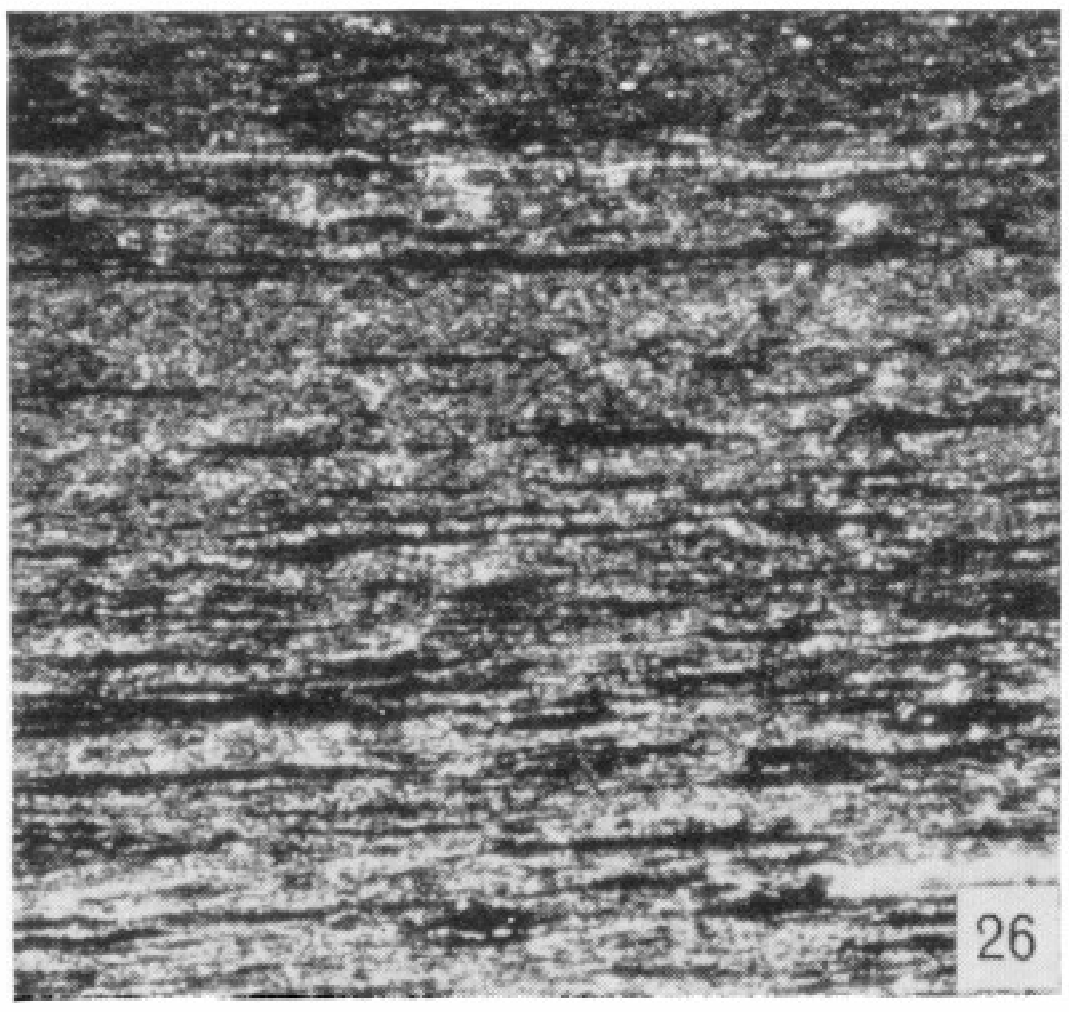
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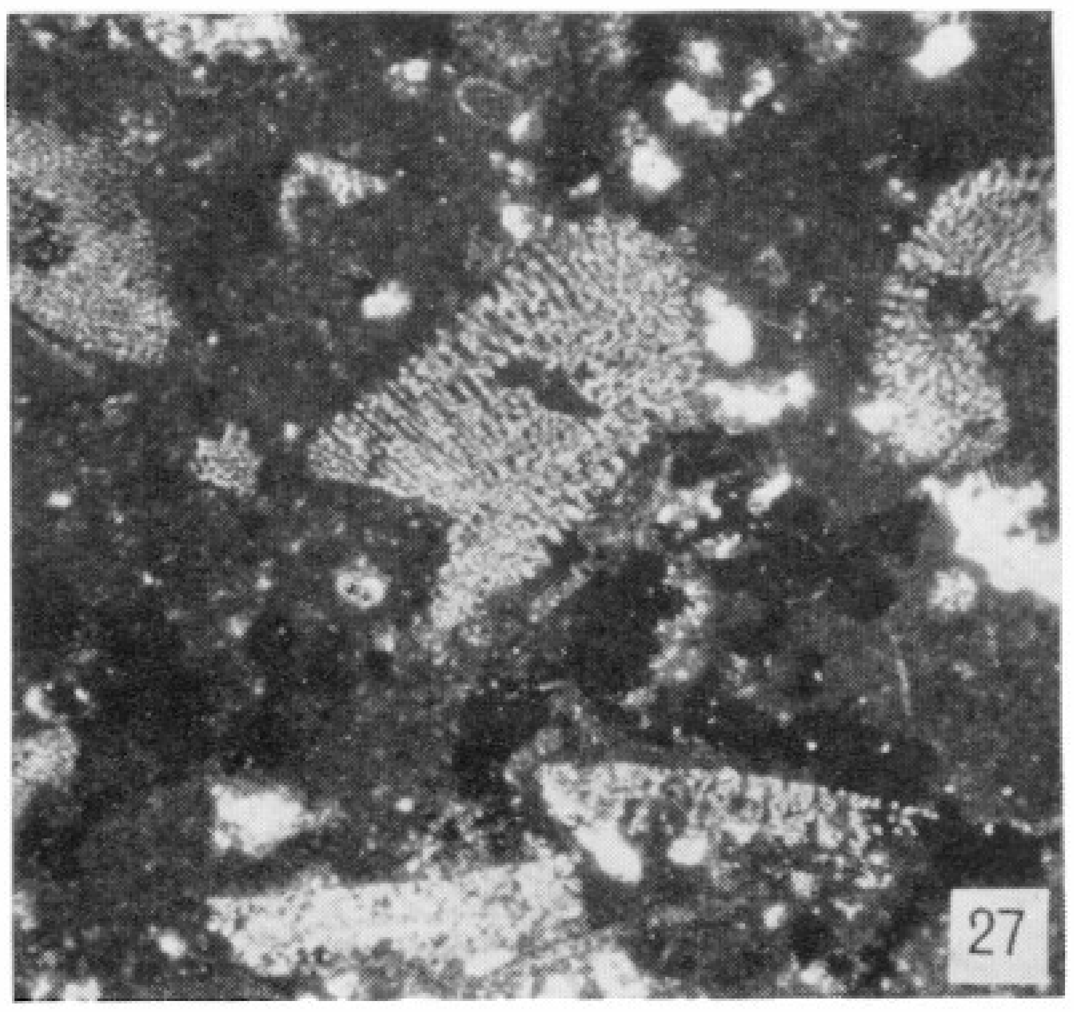
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