PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

A Sedimentary and Faunal Study of the Blue Lias of Dorset and Glamorgan

A. Hallam

Phil. Trans. R. Soc. Lond. B 1960 **243**, 1-44
doi: 10.1098/rstb.1960.0003

A SEDIMENTARY AND FAUNAL STUDY OF THE BLUE LIAS OF DORSET AND GLAMORGAN

By A. HALLAM

Grant Institute of Geology, King's Buildings, Edinburgh

(*Communicated by W. D. Lang, F.R.S.—Received* 11 *June* 1959—*Revised* 2 *October* 1959)

[Plates 1 and 2]

CONTENTS

The rocks of the Blue Lias in Dorset and Glamorgan can be divided into off-shore and near-shore facies. The off-shore facies has a characteristic pattern of regular, small-scale alternations of argillaceous calcilutites, marls and sometimes bituminous shales, the main variable being $CaCO_3$ content. Two distinct types of limestone are recognized and termed laminated and normal limestone, respectively. The marls are generally comparable with the limestones in all respects except their much lower $CaCO_3$ content. The bituminous shales are rich in bituminous matter which is arranged in fine laminae parallel to the bedding. Determinations of percentages of insoluble residues reveal a consistently large difference between the limestones and marls. Fuller chemical analyses of major constituents indicate, among other things, that nearly all the carbonate is present as $CaCO_3$. The clay mineral content consists almost entirely of illite, with subsidiary kaolinite. The strontium content of the carbonate fraction of the marls appears to be markedly higher than that of the limestones. Vertical variation in Dorset, Glamorgan and Somerset is studied and compared by a graphical method based on the limestone–shale ratio.

It has been established that the Blue Lias rhythm is primary in origin, but that there has also been a limited amount of early diagenetic segregation of $CaCO_3$ to produce nodular structures. The limestone textures are accounted for by recrystallization from an original lime mud and the respective importance of several processes including drusy and grain growth and granular and rim cementation assessed. Pyrite is considered to have been formed early in diagenesis under anaerobic conditions within the sediments. Its association in some drusy cavities with calcite is explained as due to the local fall in pH of interstitial fluids.

Vol. 243. B. 698. (Price 17*s*.) [Published 14 April 1960

The difference between the normal and laminated limestones and marls is considered to be the result of aerobic and anaerobic bottom conditions, respectively. The microlaminae in the bituminous shales are interpreted as varves due to the annual fall of plankton into anaerobic bottom waters. Evidence is put forward that the Blue Lias rhythm may be the result of repeated epeirogenic oscillations.

Rocks of the near-shore facies are confined to Glamorgan. They include (besides calcilutites and subsidiary marls) skeletal limestones, oolites, conglomerates and cherty beds; locally the rocks lie unconformably on Carboniferous Limestone. Silica is found in the form of bands of nodules and silicified limestone pebbles and shells. The facies relationships of the different rock types can be satisfactorily related to the approach of an old shoreline. The silica was almost certainly derived from detrital chert weathered from the Carboniferous Limestone.

Although there is a broad similarity in the fauna between Dorset and Glamorgan, a number of important differences are recognizable. Differences between the off-shore and near-shore facies are also described; whereas the former has pelecypods and ammonites as its most conspicuous elements the latter is notable for the abundance of corals and gastropods and, locally, of ribbed pectinids. A relationship between the fauna and the sediments is recognized in three cases: (1) shell enrichment in condensed beds (with glauconite and/or collophane); (2) dwarfing and general faunal impoverishment in the laminated rocks, related to poor aeration of the sea bottom; and (3) variations in sedimentary rate and depth of sea probably account for the faunal differences between Dorset and Glamorgan in the off-shore facies. On the other hand, no relationship can be perceived in three other cases: (1) the increase in size up the succession in a number of forms, which is evolutionary; (2) the succession of different organisms due to ecological replacement and extinction; and (3) certain shell enrichments which may be due to population fluctuations.

In a summary of the Blue Lias environment deductions are made about temperature, salinity, rate of sedimentation, depth of sea and current strengths.

1. Introduction

Although the stratigraphy of the Lower Lias is known in more detail than for any other British formation, surprisingly little work has been done on the rocks themselves, while the ammonites are virtually the only fossil group to have been studied intensively in recent times. In view of their rich fauna and the comparative ease of correlating from section to section, the Lower Lias rocks provide a highly promising field for palaeoecological investigations. From a general point of view the main interest centres perhaps around sedimentary cycles, both large and small, like those described some years ago from the German Lias.

In the present work attention has been confined to the Blue Lias, comprising approximately four ammonite zones at the base, which is notable for the remarkably regular limestone-shale alternations in its normal marine development, from hereon referred to as the off-shore facies. Dorset and Glamorgan were the two areas chosen for a detailed sedimentary and faunal investigation, the former because of its accessibility and the detail in which its stratigraphy is known, and the latter because the off-shore facies passes laterally into a near-shore facies. As regards the fauna, only the invertebrates are dealt with.

2. Stratigraphy

(a) *General sub-zonal scheme*

The Blue Lias belongs to the Hettangian and lower Sinemurian stages, and corresponds almost exactly with the bottom four zones of the Lias. The ten sub-zones proposed by Spath (1942) and accepted by Arkell (1956) have proved very useful stratigraphical units over the whole country, but careful definition of the ammonite sequence is required if confusion is to be avoided. Table 1 is essentially the result of the author's own researches in Britain together with those of Donovan (1956) and Spath (1956). The ammonite nomenclature is that of Donovan (1952). Some amplifying remarks on the table are necessary. The *laqueus* sub-zone is defined here by the incoming of the first schlotheimiids (*Waehneroceras*). This is to be preferred on several grounds to the classification proposed by Donovan (1956). He took the occurrence of the psiloceratid *Psilophyllites hagenowi* to mark the top of the *planorbis* zone. But a species of *Caloceras* occurs in Somerset and Glamorgan in association with *Laqueoceras* and *Alsatites*, so that the outgoing of psiloceratids is an unsatisfactory criterion. Moreover, the incoming of the first 'wave' of schlotheimiids coincides closely with a well-marked facies change and is easily recognizable over a wide area in Europe. There is the added advantage that the *laqueus* sub-zone so defined assumes a respectable thickness in many sections and affords a fairer comparison with the other sub-zones. Within the *angulata* sub-zone there is a probable sequence *Schlotheimia extranodosa* (Waehner)-*similis* (Spath) and *pseudomoreana* (Spath)-*lymensis* (Spath) but more collecting is needed before this can be confirmed. Donovan (1956) was able to subdivide

TABLE 1

ZONES ...	*PLANORBIS*		*ANGULATA*		*BUCKLANDI*			*SEMI-COSTATUM*		
sub-zones ...	*planorbis*	*johnstoni*	*laqueus*	*angulata*	*conybeari*	*rotiforme*	*bucklandi*	*gmuendense*	*scipionanum*	*sauzeanum*
Psiloceras (*Psiloceras*) *planorbis* (J. de C. Sowerby)	—									
Psiloceras (*Caloceras*) *johnstoni* (J. de C. Sow.)		—								
Schlotheimia (*Waehneroceras*) spp.			—							
Psilophyllites hagenowi (Dunker)			—							
Psiloceras (*Laqueoceras*) aff. *laqueus* (Quenstedt)			—							
Alsatites liasicus (d'Orbigny)			—							
Schlotheimia (*Schlotheimia*) spp.				—						
Coroniceras (*Metophioceras*) spp.					—					
Coroniceras (*Primarietites*) *rotiforme* (J. de C. Sow.) and related species						—				
Arietites bucklandi (J. Sow.)							–?–			
Charmasseiceras spp.					—	—	—			
Coroniceras (*Primarietites*) *reynesi* (Spath); includes '*Paracoroniceras*'.								—		
Agassiceras scipionanum (d'Orbigny)									—	
Arnioceras aff. *semicostatum* (Young & Bird)							—	—	—	—
Pararnioceras aff. *parthenope* (Reynes)							—	—		
Euagassiceras resupinatum (Simpson) and related species								—	—	—

the *rotiforme* sub-zone in the Bristol district but it has not proved possible to apply his scheme elsewhere. *Arietites bucklandi*, from which the *bucklandi* zone and sub-zone take their names, is unfortunately known only from one horizon in Somerset. There is no doubt, however, about the usefulness of distinguishing a *bucklandi* sub-zone on other grounds. In places where the succession is thick, a definite sequence of ammonites is recognizable (Spath 1956). Similarly, in the unusually thick *gmuendense* sub-zone in the Skye area, a twofold subdivision can be made (Hallam 1959*b*). *Euagassiceras resupinatum* (= *sauzeanum* d'Orbigny) is not confined to the *sauzeanum* sub-zone. It has been found in the *gmuendense* sub-zone of Glamorgan and Yorkshire. The well-known specimens from the Arietenkalk of Württemberg, figured by Quenstedt (1883), must also come from below the *sauzeanum* sub-zone.

Besides ammonites, a number of other macrofossils may be used for stratigraphical purposes and are reliable for north-west Europe at least. The incoming of *Gryphaea arcuata* Lamarck coincides almost exactly with the Hettangian–Sinemurian boundary. The replacement of *Chlamys subulata* (Münster) by the closely comparable *Chlamys? calva* (Goldfuss) takes place at about the same horizon. *Placunopsis striatula* (Terquem) is usually common in shaly beds of the *rotiforme* and lower *bucklandi* sub-zones. *Piarorhynchia juvenis* (Quenstedt) replaces *Calcirhynchia calcaria* Buckman, and *Oxytoma inaequivalve* enters the succession near the base of the *bucklandi* sub-zone. *Spiriferina walcotti* (J. Sowerby) and *Nannobelus brevis* (Blainville; = *Bel. acutus* auct.) come in at the base of the *semicostatum* zone. In addition, certain faunal associations may characterize horizons over large areas in Britain.

(*b*) *Dorset and Glamorgan*

The classic locality of the Dorset coast around Lyme Regis has attracted the attention of fossil collectors for well over a century and is the source of many fine specimens of vertebrates. An excellent basis for modern work is provided by the highly detailed maps and section of Lang (1914, 1924). This section is, generally speaking, so accurate that revisions are unwarranted, but the zonal scheme is obsolete and must be modified in the light of further discoveries (see table 2). The base of H 30 is taken in the present work as the *planorbis-johnstoni* boundary. The boundaries of the *gmuendense* sub-zone are now taken above beds 45 and 49, the natural top of the Blue Lias. This is based upon correlation with the Somerset succession. The *scipionanum* sub-zone appears to be missing. There should be no difficulty in locating individual beds if Lang's instructions are followed. The best sections are to the west of Lyme Regis.

The Glamorgan coastal sections cover a much larger area and the beds are thicker and less fossiliferous than in Dorset, so it is not surprising that they are known in less detail. Nevertheless, a good deal of work has been done, notably by Trueman (1920, 1922, 1930), to elucidate the stratigraphy. Though the broad picture established by Trueman remains unchanged, the results given in table 2 include a number of modifications to his scheme.

Rocks of the off-shore facies can be examined on the coast between Penarth and Southerndown (figure 1). Westwards, at Southerndown, and northwards towards Cowbridge and Bridgend, they pass partly into near-shore facies. There is no need to repeat Trueman's sections, which are fairly adequate, but some explanatory remarks are required on correlations and the choice of sub-zonal boundaries. The *planorbis* zone is well exposed between Lavernock Point (190680) and St Mary's Well Bay (177677) and in the Bull Cliff west of Barry (090667). The most useful horizon for correlating is the shale with abundant *Psiloceras planorbis* about 10 m above the base of the Lias (= bed 30 of Trueman 1920). In the west the *planorbis* zone is represented by the Sutton Stone. Although the *angulata* zone is thick and widespread, good, accessible sections are uncommon. The *laqueus* sub-zone can only be examined at Lavernock and Penarth in the east, and in the reefs south-east of Dunraven Castle (891725). The base is taken above the highest shelly limestones of the *planorbis* zone at Lavernock (*ca.* bed 53 of Trueman). This is marked by a passage into shaly beds and coincides almost exactly with the incoming of *Waehneroceras*. The *angulata* sub-zone may be studied just north of Nash Point (915684) and on the west side of Stout Bay (977670). Fixing the boundary of the two sub-zones is a matter of

Table 2

		Dorset		Glamorgan	
zones	sub-zones	feet	metres	feet	metres
semicostatum	*gmuendense*	4½	1·35	—	—
	bucklandi	13	3·90	9	2·70
bucklandi	*rotiforme*	10¼	3·08	13	3·90
	conybeari	9¼	2·78	78	23·40
angulata	*angulata*	15⅓	4·60	*ca.* 60	18·00
	laqueus	12½	3·75	*ca.* 60?	18·00?
planorbis	*johnstoni*	8½	2·55	22	6·60
	planorbis	12	3·60	22	6·60

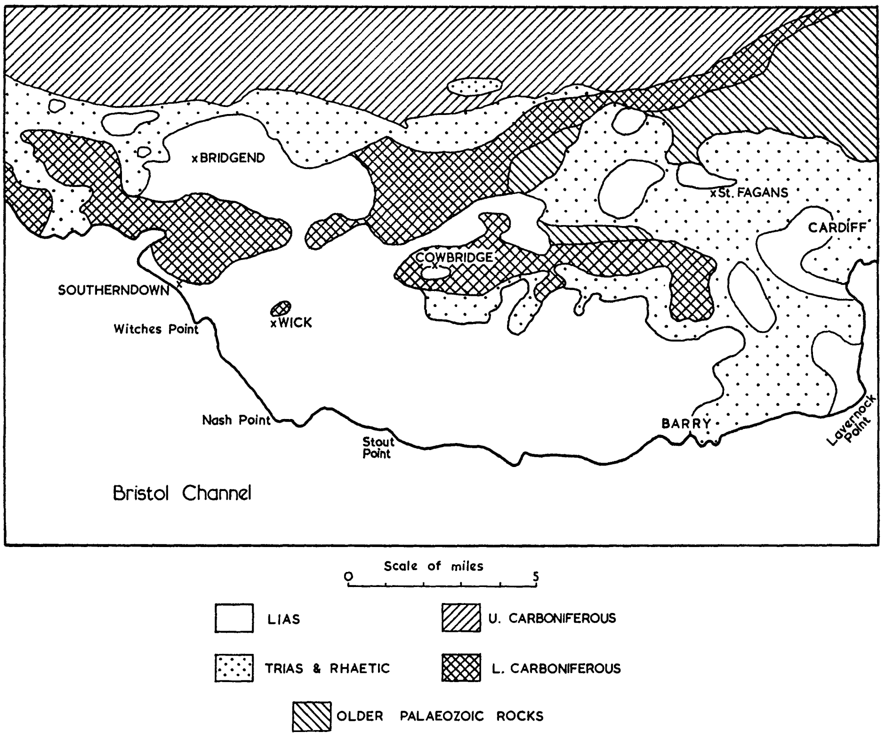


Figure 1. Sketch geological map of part of Glamorgan.

some difficulty. In the Penarth–Lavernock region it is taken at the base of Trueman's bed 75, which contains the first *Schlotheimia* s.s. Near Dunraven, *Schlotheimia extranodosa* has been found above beds containing *Psiloceras laqueus* and *Alsatites liasicus*, but the succession is not easy to work out because of faulting. The top of the *angulata* zone is taken at the incoming of the first band of *Gryphaea arcuata*. This is a prominent horizon which can be found in all sections. In the west, at Sea Mouth (884732), it occurs only a few feet above the top of the Southerndown Beds (near-shore facies). At Nash Point the first gryphaeas come in just above the base of Trueman's (1930) section. One or two metres below, Trueman discovered a specimen of *Schlotheimia*. The basal *Gryphaea* band reaches the cliff bottom further east, in the middle of Stout Bay. The top of the *conybeari* sub-zone is taken above a bed containing large specimens of *Metophioceras*, which were identified by Trueman as *Coroniceras* cf. *rotiforme*. The bed is well seen south-east of Nash Point (bed 48 of Trueman) and on the foreshore immediately west of Dunraven Castle (886728). Within the *conybeari* sub-zone there are bands rich in *Montlivaltia* and *Calcirhynchia*, which make very useful marker-horizons for detailed correlation between Stout Bay and Southerndown. The *rotiforme* and *bucklandi* sub-zones are seen only in the west, at Gwter Fawr and Sea Mouth. Trueman's bed 35 at Gwter Fawr contains *Coroniceras rotiforme* and marks the top of the sub-zone. A little higher is a prominent massive limestone, with marl partings, about 2 m thick (Trueman's bed 58). This is the most conspicuous bed in the whole succession. It can be traced with ease westwards to Sea Mouth, where it descends to the foot of the cliff. Here it was referred to by Trueman (1922, p. 262). At Gwter Fawr, a huge arietitid related to *Arietites bucklandi* was discovered in this bed. As *gmuendense* sub-zone ammonites have been collected from immediately above, it is clear that the top of the thick limestone coincides with the top of the *bucklandi* zone. Although about 25 m of limestones and shales are visible above this horizon in these western cliffs, only the basal part is accessible, so that it cannot be ascertained whether any beds higher than the *semicostatum* zone are present.

3. The rocks of the off-shore facies

(*a*) *Petrology*

In both Dorset and Glamorgan the Blue Lias consists of more or less uniformly alternating limestones, marls and shales (figure 8, plate 1). In Dorset the great majority of the limestones range between 0·05 and 0·30 m in thickness; in Glamorgan they range from 0·04 to 0·38 m, though if marl partings are excluded they measure up to 1 m. The shale groups (shales and marls together) vary between wider limits, from mere partings to 1·80 m in both areas. In Dorset there is frequently a development of the symmetrical cycle, limestone–marl–bituminous shale–marl–limestone, but more commonly, and in Glamorgan almost invariably, bituminous shale is not present. The bituminous shales rarely exceed 10 cm in thickness.

The *limestones* are light grey-blue in colour in the unweathered state, and vary in composition from about 75 to 95% $CaCO_3$, but the majority range between 82 and 87%. Though they are sharply demarcated from the marls, there is a slight tendency for them to become more argillaceous near the margins. They contain a large variety of shelly fossils including pelecypods, ammonites, gastropods, brachiopods, echinoderms, foraminifera and ostracods. Elongate fragments of woody lignite up to 2 m in length and orientated parallel to the bedding are fairly common. The limestone surfaces vary from planar to highly irregular (figure 8, plate 1). The irregularities, as seen on foreshore reefs, take the form of evenly distributed hummocks. Good examples in the Dorset section are Lang's beds H 54, H 66, 1 and 23. Beds are sometimes observed to thicken around large fossils such as ammonites or *Nautilus*. Occasionally it can be observed that thickening in a pair of closely adjacent limestones is complementary, i.e. where one thickens the other thins. Some limestones pass laterally into layers of lenticular nodules, separated by hard, calcareous marl, which may be regular or irregular in shape according to the character of the equivalent limestone beds. The location of the nodules does not seem to be related intimately to the presence of fossils. Nodules or swellings on limestone surfaces do not usually transgress the enveloping shale or marl but, instead, bedding planes of the latter wrap round the limestone.

In thin section the limestones are seen to be composed essentially of a fine, homogeneous mosaic of interlocking calcite crystals. Accurate estimation of size-variations of the crystals is not an easy matter, but a fair idea can be obtained if all the visible crystals in a small sector of each slide are measured, using a $\frac{1}{12}$ in. oil immersion objective, and the mean determined. In practice one has to deal usually with the edge of the slide, near to where it thins off to zero, because only here can the error due to the superimposition of several crystals be eliminated. A large number of limestone slides has been examined in this way. The means for limestones containing over 80 % $CaCO_3$ vary between the narrow limits of 5 and 12 μ. The crystals in the more argillaceous limestones are distinctly larger. This is well illustrated in the case of Lang's bed H 30. This is a pure, porcellanous limestone, containing 96 % of soluble carbonate, and has a mosaic mean of 8 μ. It is immediately underlain by a limestone similar in all respects except its soluble carbonate content, which is only 76 %. This has a mosaic mean of 12 μ. Bed 53, with only 75 % carbonate, has an even higher mean of 17 μ. The relationship between chemical composition and the calcite mosaic is not an intimate one; it is complicated by the isolated occurrence of crystals ranging up to 20 μ or more. Locally, also, there are small patches of larger crystals (20 to 50 μ) which may or may not have sharp boundaries. Small veins, both irregular and roughly radial from a centre (septarian structure), traverse the rocks. These are composed of a coarse mosaic of calcite crystals ranging up to 100 μ and above. The crystals tend to coarsen with their distance from the margins and generally meet along planes rather than along irregular edges. Angular quartz grains of silt grade are evenly distributed throughout the rocks, and vary from rare to uncommon. The maximum dimensions of the grains were measured for many limestones, and found to average 26 μ and to range between 1 and 170 μ.

Two fundamentally different types of limestone can be distinguished. The first type always has planar surfaces and shows faint or strong traces of lamination. Except for a few thin bands in the *semicostatum* zone of Dorset (e.g. 51) laminated limestones are found only in the *johnstoni* sub-zone (the planar limestones of the *planorbis* sub-zone do not exhibit fine lamination on the whole). The Dorset examples include H 30 to 36 and H 46 to 52. Fossils are absent except ostracods, a few ammonites and rare, spasmodically distributed, fragments. The most striking characteristic observed in thin section is the abundance of shreds of carbonaceous matter orientated parallel to the bedding (figure 17, plate 2). This is reddish to dark brown in colour and shows no visible structure. The shreds vary usually between 5 and 15 μ in thickness. It is the alternation of the carbonaceous shreds and calcite which gives rise to the lamination. Accurate measurement of the thickness of the laminae is usually not possible since recrystallization of the calcite has disrupted the carbonaceous matter. The most reliable determination, shown on a thin seam of limestone near the top of H 1, gave a mean laminal thickness of 0·23 mm. Other measurements are of this order. Quartz grains are rare and occupy much less than 1 % of the rock, as measured in thin section. Pyrite is widely disseminated as tiny cubic or subspherical granules, mostly less than 10 μ.

The second type has surfaces varying from planar to highly irregular and is much the more common. Fossils are often abundant, and traces of organisms always present. Carbonaceous matter is present only in the form of tiny equidimensional fragments, and is always subordinate. No traces of lamination are ever found. Quartz grains are uncommon (< 1 %), though often more abundant than in the laminated limestones. Pyrite is a dominant component. It occurs as isolated granules, but more characteristically is found as clumps or clots which might reach up to several centimetres in diameter. It is markedly associated with shells; it frequently infills small ammonites, ostracods, foraminifera, and echinoderm pores, and partly envelops larger fossils or replaces part of the calcite (figure 20, plate 2). Pyrite is also found in some drusy cavities (e.g. veins and recrystalized shells), associated with calcite, with which it appears to have crystallized interstitially (figure 19, plate 2). In weathered rocks it is altered to red-brown Fe_2O_3, as seen in thin section. Shell fragments, especially of pelecypods and echinoderms, are numerous. The echinoderm fragments are present as single plates. The rest have for the most part been replaced by a coarse calcite mosaic, but fragments of brachiopods and the pelecypods *Lima gigantea* and *Pinna hartmanni* are usually preserved intact. Glauconite, occurring as discrete granules or as infillings of foraminifera and ostracods, is rather

---

DESCRIPTION OF PLATE 1

FIGURE 8. Blue Lias Beds at Seven Rock Point, west of Lyme Regis. The hammer rests on the limestone bed 19. The *angulata–bucklandi* zone boundary is taken above bed 15*c*, the third limestone from the base.

FIGURE 9. Concretionary structure developed along the line of a minor fault (roughly parallel to the hammer shaft) near base of Blue Lias, Pinhay Bay, Devon.

FIGURE 10. Transverse section of ?*Bidiastopora* sp. from the *bucklandi* zone, Glamorgan. (Magn. × 20.)

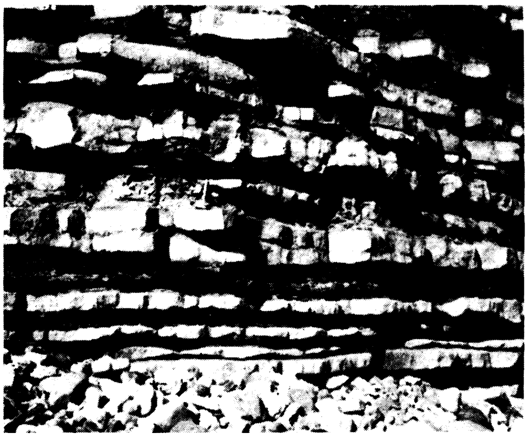
FIGURE 11. Concretionary structure near base of Blue Lias, Pinhay Bay, Devon.

FIGURE 12. Witches Point from the south, showing Sutton Stone resting uncomformably on Carboniferous Limestone.

FIGURE 13. Upper surface of bed 29 on foreshore west of Lyme Regis, crowded with ammonites.

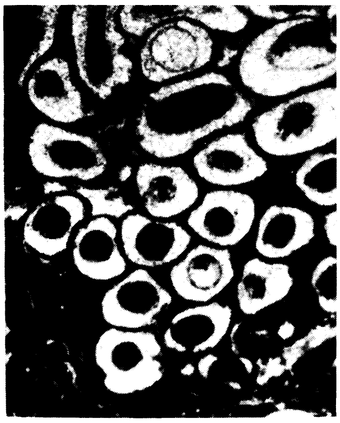
FIGURE 14. Vertical section of bed 49, Dorset. The dark grey rock at the base is argillaceous limestone which has been penetrated by *Chondrites* burrows infilled by material from the more calcareous rock above. This has in turn been penetrated by vertical tubes of *Rhizocorallium*. Subsequently, erosion has produced a minor unconformity, truncating *Rhizocorallium* and overlain by shelly marl passing locally into argillaceous limestone. (Magn. × 1·3.)

8

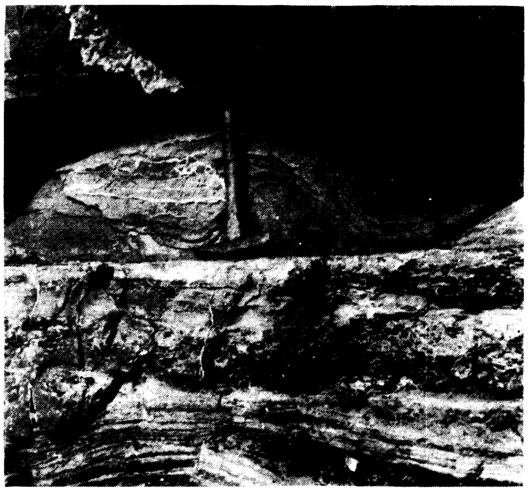


9

10



11



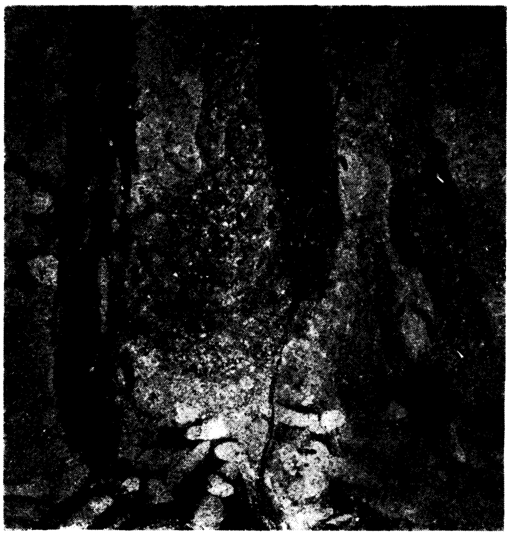
12

13

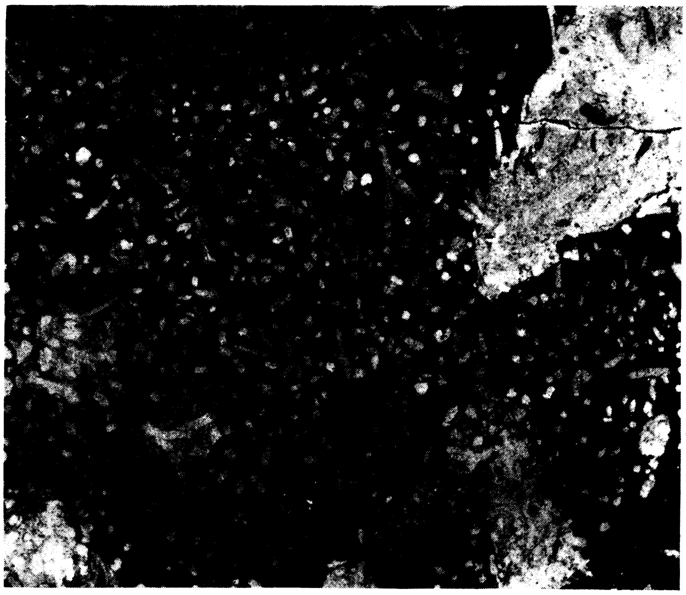
14

(*Facing p.* 8)

15



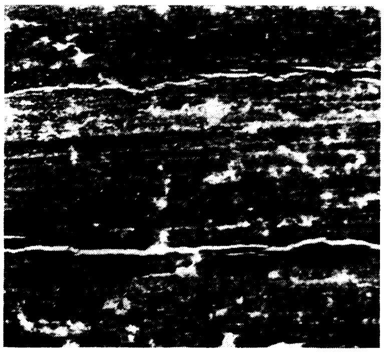
16



17

19

18



20

22

21

23

24

uncommon in Dorset and rare in Glamorgan. It is, however, common at certain horizons, e.g. 29 and 49 in Dorset and the top of the *rotiforme* sub-zone in Glamorgan (Trueman 1930, bed 55). Collophane is found in association with a trace-fossil, and also as infillings of shells in 49 (Dorset) and as small nodules in the immediately overlying shales. Barite crystals are rare and have only been found in association with lignite.

A dark mottling is observed in these normal-type limestones, frequently in Dorset, but rather uncommonly in Glamorgan (figure 7, and figure 15, plate 2). This is due to the activity of trace-fossils, which will be considered later. Isolated pockets of small shells and shell fragments are common and may be related to *Kulindrichnus*. Within these shelly pockets the calcite has crystallized as a coarse granular cement, and echinoderm plates may have syntaxial rims.

The natural top of the Blue Lias in Dorset is a highly interesting limestone bed called 'Grey Ledge' (49), which coincides with a notable change of facies towards a decreasing limestone–shale ratio. This may be studied best on the reefs east of Lyme Regis (see map in Lang 1914) and as loose blocks on the foreshore in Chippel Bay. It possesses a number of unusual features. The rich glauconite–collophane content has already been mentioned. Fossils and lignite are abundant. There is pronounced mottling due to trace-fossil activity, especially vertical 'U' structures. Locally the upper surface is irregularly truncated, and unconformably overlain, by shales. The basal few centimetres of the shale are often welded on to the limestone (figure 14, plate 1). It is crowded with pyritic ammonites and belemnites in several thin layers. Small limestone and phosphatic pebbles and the occasional *Acrodus* tooth may be found in the part immediately overlying the limestone. This fossiliferous layer was erroneously placed at the base of 48, the Grey Ledge Shales, in Lang (1924).

Description of plate 2

Figure 15. Vertical section of limestone showing *Rhizocorallium* both transgressing and being transgressed by other trace-fossils. (Magn. × 1·3.)

Figure 16. Horizontal section of limestone showing *Chondrites* and *Rhizocorallium*. (Magn. × 1·3.)

Figure 17. Vertical section of laminated limestone, Dorset. (Magn. × 60.)

Figure 18. Vertical section of bituminous shale, Dorset. (Magn. × 27.)

Figure 19. Association of calcite and pyrite in drusy cavity in calcilutite, probably the replacement of a shell. (Magn. × 7.)

Figure 20. Shell, infilled by pyrite, and calcite vein in normal calcilutite, Dorset. (Magn. × 60.)

Figure 21. Almost completely silicified pebble from limestone in Southerndown Beds. The silica is the pale-coloured material at the centre of the pebble. (Magn. × 60.)

Figure 22. Section of silicified oyster from the Southerndown Beds. The black line marks the edge of the shell, which has been largely replaced by small sphaeroids of chalcedony. The complicated fibrous structure revealed by crossed polaroids occurs in what was the interior of the shell. (Magn. × 27.)

Figure 23. Oolite from Southerndown Beds, Castle-upon-Alun. (Magn. × 60.)

Figure 24. Section of Sutton Stone showing recrystallized shell fragments rimmed by fine, opaque mosaic and enveloped by granular cement. (Magn. × 60.)

The *marls* are blue-grey in the unweathered state and are comparable with the limestones, whether laminated or of normal type, in virtually all respects save the much lower $CaCO_3$ content, which varies between 20 and 55%. They may variously be classified as conchoidal marl, which may be smooth or crumbly to the touch, and as marly shales, according to their fissility. No simple relation exists with $CaCO_3$ content. The calcite mosaic is coarser than in the limestones, with means ranging from 20 to 30 μ. Shell fragments are often bounded by prismatic crystals of calcite with optic axes normal to the surface. Such structures may also be seen in the more argillaceous limestones. The presence of clay minerals in thin section is largely obscured by the calcite. Quartz grains are commoner than in the limestones, ranging quite commonly between 1 and 5%. They are similar in range and mean to the limestones (5 to 140 μ, 26 μ). Marls underlying normal-type limestones in the Dorset rocks commonly exhibit the mottling of trace-fossils, unlike the marls directly beneath bituminous shales (figure 7).

The *bituminous shales* (= paper shales of Lang) are dark blue-grey to black in colour, and contain less than 10% $CaCO_3$. Lang (1924) gives horizons at which they occur. Good examples include parts of H 1, 53, 67 and 71. When fresh, these rocks are hardly more fissile than many marls, but they weather readily into wafery sheets which have usually been forced apart a little by the growth of minute selenite crystals. Bituminous shales differ strikingly from normal-type marls and limestones in being poor in fossils. This is without question not a phenomenon of weathering. Certain planes abound in fish scales, ammonites, or minute pelecypods, but these are rather exceptional. The most conspicuous feature in thin section is the beautiful lamination produced by uniform alternations of carbonaceous and calcitic-clay layers (figure 18, plate 2). There is surprisingly little variation from bed to bed. The carbonaceous layers vary in thickness from 9 to 17 μ and the clay-calcitic ones from 16 to 25 μ. Quartz grains are similar in abundance to the marls. Pyrite abounds as small crystals mostly under 10 μ.

At marl-bituminous shale junctions, discontinuous 'beef' seams may be present. These have a fibrous appearance due to the preferred orientation of calcite crystals normal to the bedding, and tend to exhibit cone-in-cone structure. They are never as well developed as in the overlying 'shales with beef' of the *semicostatum* and *turneri* zones, and rarely exceed 2 cm in thickness.

Fragments of jet (or jetty lignite) up to 4 cm thick are not uncommon in both the marls and shales. They are generally lenticular in cross-section. Jet is sometimes also found in association with woody lignite in the limestones.

The percentage of material insoluble in 10% HCl was determined for fifty limestones, marls and bituminous shales, especial care being taken to collect unweathered samples. The results are given in figure 2. Similar results may be obtained using 2N-acetic acid buffered at pH 23. The most striking feature is the marked difference between the limestones and marls. There is a gap between about 28 and 45% insoluble residue in which no samples fall. The limestones are clustered mainly between 10 and 20% and the marls between 60 and 70%. This need not be taken to imply that intermediates do not exist but that the limestone–marl transition, even in the case of nodules, is generally very sharp, and samples of the intermediate rock are difficult to obtain in quantity. It is most unlikely that the marls have been appreciably decalcified, for they are generally rich in shelly matter, often finely ornamented, which shows no indications whatsoever of solution. Even in the bituminous shales, which contain very little $CaCO_3$, pelecypod shells in the fresh rock appear to be largely unaltered, although the aragonite of ammonite shells has been dissolved away, for they are normally preserved only as impressions or pyritic replacements.

Table 3 gives the results of partial chemical analyses of several limestones and marls of the off-shore facies, together with three specimens from the near-shore facies of Glamorgan. The samples were dried at 105 °C.

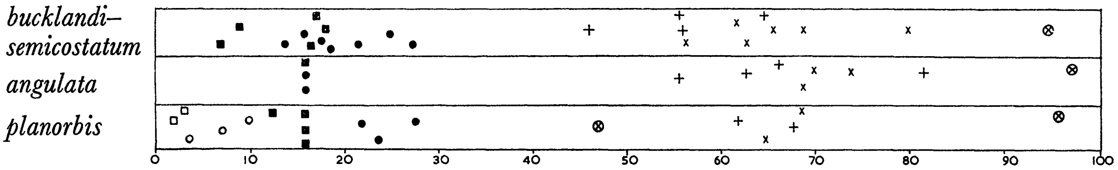


Figure 2. Diagram showing percentages of insoluble residue of 52 Blue Lias samples.

Key

- ● Normal calcilutite, Dorset.
- ○ Laminated calcilutite, Dorset.
- ■ Normal calcilutite, Glamorgan.
- □ Skeletal limestone, Glamorgan.
- × Normal marl or marly shale, Dorset.
- + Normal marl, Glamorgan.
- ⊗ Laminated marl or bituminous shale, Dorset.

Table 3

	CaO	MgO	SiO_2	Al_2O_3	$FeO+Fe_2O_3$	P_2O_5	MnO	TiO_2
laminated limestone, (a) Dorset	53·33	0·58	3·4	0·48	0·28	—	0·034	0·002
laminated limestone *(b)* Dorset	51·05	0·52	4·2	1·48	0·44	0·05	0·032	—
normal limestone, *(a)* Dorset	46·90	0·51	12·0	4·21	0·74	0·15	0·095	0·005
normal limestone, *(b)* Dorset	45·41	0·54	14·8	4·66	1·24	0·02	0·062	0·012
normal limestone, *(a)* Glamorgan	44·52	0·49	15·2	3·21	0·74	—	0·053	0·006
normal limestone, *(b)* Glamorgan	46·48	0·18	—	—	—	—	0·084	—
oolite, Glamorgan	50·83	0·36	7·0	1·25	0·70	0·01	0·038	—
Sutton Stone *(a)*	53·06	0·18	3·4	1·38	0·14	—	0·076	—
Sutton Stone *(b)*	52·64	0·41	3·0	1·30	0·22	0·01	—	0·002
normal marl, *(a)* Dorset	16·80	0·38	39·2	11·69	3·48	0·30	0·054	0·048
normal marl, *(b)* Dorset	20·56	0·40	37·1	10·13	3·80	0·40	0·027	0·048
laminated marl, Glamorgan	17·22	0·45	48·4	10·10	3·00	0·03	0·031	0·049
normal marl, Glamorgan	24·08	0·29	35·6	6·29	1·40	0·28	0·005	0·029

It is clear from table 3 that nearly all the soluble carbonate is present as $CaCO_3$, for MgO is consistently lower than 1 %. The Ca:Mg ratio is notably less in the marls. Excepting this main variable ($CaCO_3$ content) and its consequent influence on the clay content the chemical composition appears to be very uniform. P_2O_5 and TiO_2 tend to be more abundant in the marls. Most of the MnO in the limestones is found in the carbonate fraction but apparently the reverse is true of the marls.

Several analyses of carbon content were undertaken separately for the insoluble residues of some Dorset samples. The results are given below.

	% carbon		% carbon
limestone (43)	1·1	laminated marl (H 1)	8·0
marl (48)	1·6	bituminous shale (H 71)	7·0
marl (H 91)	1·9	bituminous shale (52)	3·9

As expected, the carbon content of the laminated rocks is appreciably higher than for the normal-type limestones and marls.

A separation of carbonaceous matter was obtained in a few samples of marl and shale by treatment with HF and dilute KOH. Examined under the microscope the great bulk was seen to be structureless, but plant spores and hystricosphaeroids occur rarely.

The clay mineral content of nine samples of insoluble residues from different parts of the succession in Dorset and Glamorgan, three of limestones, and six of marls and shales, was determined by means of an X-ray technique described by Perrin (1957). All contained between 90 and 100% of illite, and up to 10% of kaolinite. Four samples contained traces of vermiculite, but only one a faint trace of smectite. The rocks are therefore shown to exhibit remarkable uniformity. There is no suggestion of variation either up the succession, or between different areas or lithological types. The composition of the Blue Lias rocks bears a fairly close resemblance to that of marine Mesozoic clays in the Paris Basin, studied by Millot (1949). The latter differ principally in containing a higher proportion of kaolinite. A closer and more detailed comparison can be made with the results obtained from Oxford and Kimeridge Clays by Perrin (1957).

Spectrographic analyses to determine the strontium content of the soluble carbonate fraction of several samples were kindly undertaken by Mr R. Allen. The results given below are expressed in the usual way as the Sr/Ca ratio. In calculating the ratio, the small Mg content of the rocks has been neglected and the soluble fraction taken as $CaCO_3$:

	Sr/1000Ca		Sr/1000Ca
laminated limestone, Dorset	0·38	normal marl, Dorset	2·00
laminated limestone, Dorset	0·38	normal marl, Dorset	2·00
normal limestone, Dorset	0·38	normal marl, Glamorgan	2·00
normal limestone, Dorset	0·80	Sutton Stone, Glamorgan	0·38
normal limestone, Glamorgan	0·38	primary calcite, Dorset	0·80

The most interesting feature of the results is the consistently higher Sr content of the marls, a fact for which no satisfactory explanation can be offered. Many more results of this type are needed to confirm whether this is a normal feature. The Sr/1000Ca ratios of the limestones are consistently close to the average (0·71) determined for a large number of limestones of different ages by Kulp, Turekian & Boyd (1952), and are similar to that determined for a specimen of calcite from a drusy cavity in one of the Blue Lias limestones. The results for the marls, though notably higher, fall well within the range established by Kulp *et al.* (1952). All the results are consistent with the $CaCO_3$ having been precipitated originally as calcite; but, as the Sr content decreases markedly when aragonite recrystallizes into calcite (Revelle & Fairbridge 1957), the possibility cannot be excluded that the $CaCO_3$ was originally aragonite. If, however, this were the case it might be expected that strontium would be retained within the rock as strontianite or celestite.

Several samples from the White Lias of Devon have also been analyzed and give extraordinarily high values for the Sr/1000Ca ratio, up to 10·0 (Hallam 1960*a*). These results are held to suggest strongly an original deposition of aragonite.

(*b*) *Vertical and lateral variation*

Just as the essential source of variation between the different rock types is $CaCO_3$-content, so changes within the succession as a whole may be expressed as ratios of limestone to shale and marl (or 'shale'). For the purpose of comparing successions composed of hundreds of small-scale units of unvarying lithology, the conventional technique of drawing illustrative sections is unsatisfactory for, unless each unit is represented, variation can only be expressed in crude terms and lines of division tend to be arbitrary. Instead a graphical method based on the limestone–'shale' ratio has been adopted. For this it was necessary to measure the Glamorgan succession more or less inch by inch, as Lang had done for Dorset. The section has to be composite, but careful correlation between the different coastal sections is reassuring in revealing that lateral variation between Dunraven and Lavernock is negligible. Sections were measured at Lavernock and Bull Cliff (*planorbis–angulata*), Stout Bay (*angulata–conybeari*), Nash Point (*angulata–bucklandi*) and Sea Mouth (*angulata–gmuendense*). The columns for the different regions under consideration were then divided up into units of constant thickness, and the percentage of limestone present in each unit calculated. On grounds of practicability and convenience 33 in. units were used. Although the Dorset column is shorter than that of Glamorgan the limestones themselves are not appreciably thinner, so there is no point in using a smaller unit. Consequently, the graph for Dorset gives a cruder representation. The graph (figure 3) also gives details of successions at Tolcis, near Axminster in Devon, and in north Somerset, as geographically intermediate areas. The Tolcis section was measured in detail comparable to Lang's section (Hallam 1957*b*); the Somerset section is taken at Saltford Cutting, as measured by Donovan (1956). Despite the disadvantage of variable thicknesses, the salient features of the different successions are brought out clearly. In all regions there is a pronounced decrease in the limestone–shale ratio from the *planorbis* to the *angulata* zone. Though least marked on the Dorset coast it becomes striking a few miles inland at Tolcis. The change in Somerset is probably exaggerated a little, since, although Donovan mentions that thin limestones are present in the Saltford shales, they are not represented in his section. From the base of the *angulata* zone there is, generally speaking, a gradual rise of the limestone–shale ratio into the *bucklandi* zone. In Dorset there is a sharp drop above the *conybeari* subzone. This cannot be seen in the condensed Somerset succession, but is present in Glamorgan, though as the *rotiforme* sub-zone is condensed it is not a striking feature. Everywhere the change from the *bucklandi* to the *semicostatum* zone is marked by a sharp fall in the curve, especially pronounced in Dorset. If the curves are compared as a whole, Somerset and Glamorgan are seen to resemble each other fairly closely, whereas Dorset stands apart, principally because of the low limestone–shale ratio in the *rotiforme* and *bucklandi* sub-zones.

If individual horizons in Dorset and Glamorgan are compared, some striking similarities emerge. First there are the local comparisons. Tolcis and the Dorset coastal section are separated by a distance of 7 miles. In both these localities the beds maintain their distinctive lithological characters and thicknesses, often to within an inch. The evidence for this remarkable fact is recorded elsewhere (Hallam 1957*b*). Within Glamorgan a similar constancy holds. Bed-by-bed correlation in the *planorbis* zone between Lavernock and Bull Cliff, which are 5½ miles apart, is an easy matter given one or two key horizons. Similarly, the thickness of the *conybeari* sub-zone between Stout Bay and Sea Mouth (7 miles apart) differs by only 1½% of the thickness at the former locality, while, as noted earlier, individual horizons can be followed in the cliffs. Secondly, Dorset and Glamorgan may be compared directly. As already noted, two groups of laminated limestones,

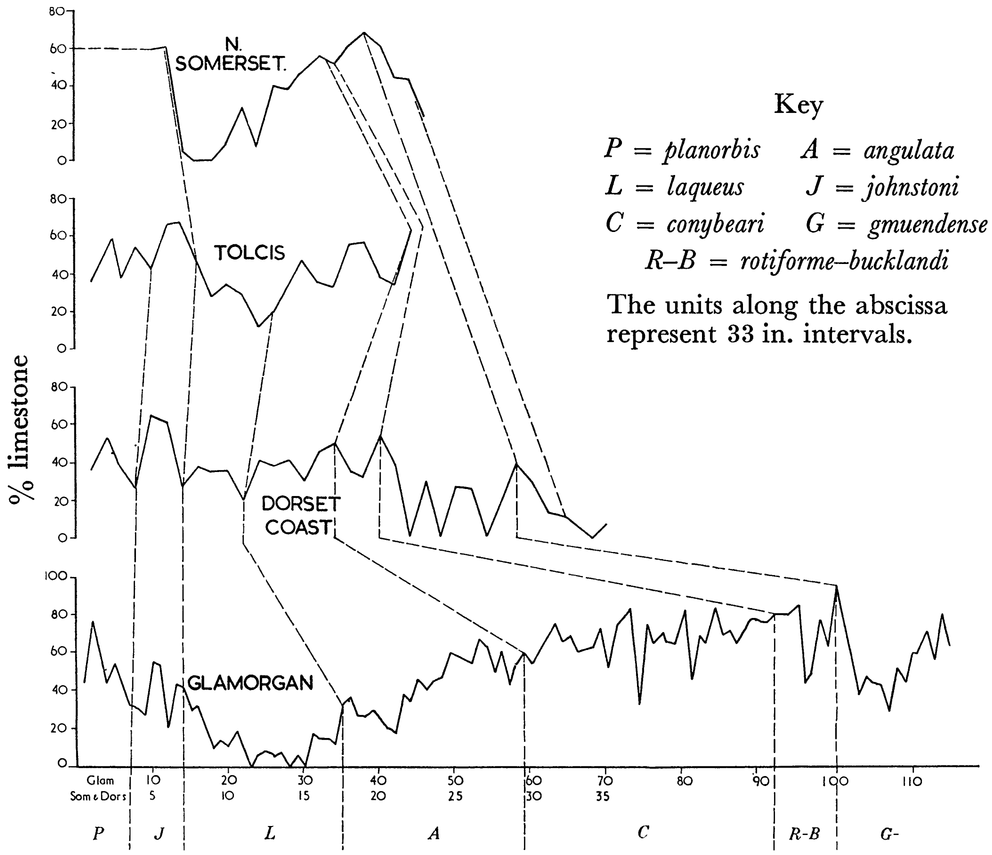


FIGURE 3. Diagram of the limestone–shale ratio, a graphical method of comparing different areas in the off-shore facies.

distinctive from their neighbours, occur in the *johnstoni* sub-zone of Dorset (H 30, 32, 34, 36: H 46, 48, 50, 52). These two groups are also present in Glamorgan. The first group, of four limestones, occurs at Lavernock 7 m above the base of the Lias, and immediately above the thick shale rich in *Psiloceras planorbis* (as in Dorset). The second group, of three limestones, comes in 4 m higher. Besides this striking similarity in detail, which can be proved because the limestones are unusually distinctive, other more general ones may be noted. For example, the basal '*Ostrea*' Beds are very similar in the two areas despite their different thicknesses, and the lower beds of the *angulata* sub-zone have highly irregular surfaces.

(*c*) *Diagenetic changes*

(1) *Calcite*

Before the conditions of deposition of the original sediments can be considered the results of diagenesis must be disentangled.

For a long time there has been a controversy about the origin of the Blue Lias limestone–shale rhythm, whether it is *primary*, and caused by original differences in sedimentation, or *secondary*, and caused by some form of diagenetic segregation of $CaCO_3$ in originally homogeneous marl. Published work has favoured the latter view, but the alternation of normal-type shelly limestones and marls with finely laminated shales, the wide lateral extent of many individual limestone beds and the presence of trace-fossil mottling provide convincing evidence that the rhythm is primary (Hallam 1957*a*). This is not to say that there has been no secondary segregation. The swelling of limestones around large fossils and the existence of complementary limestone pairs are good evidence that nodular limestones and the nodule bands into which they might grade owe their origin, in part, to changes that took place after deposition. Particularly convincing evidence of secondary segregation is seen in the marly shale H 5 in the cliffs of Pinhay Bay, west of Lyme Regis. This contains some extraordinary ridge or dome-shaped limestone protuberances which project from the underlying limestone H 4 at high angles (figures 9 and 11, plate 1). It is inconceivable that such structures could have remained unsupported on the sea floor. In a few cases these prominences can be observed to lie on the line of small faults in the immediately underlying White Lias and basal Blue Lias (figure 9). Tarr's suggestion (1933) that the Lower Lias nodules are primary in origin must therefore be rejected. The $CaCO_3$ segregation must have been comparatively early-stage for, as Richardson (1923) first pointed out, it precedes the compaction which crushed fossils in the shales.

The most important problem to be faced concerns the conditions under which uniform bands of lime mud were subjected to diagenetic changes which resulted in the formation of nodular limestones or bands of nodular concretions. The following facts must be accounted for. Laminated limestones are always planar, and nodular structures are confined to the normal type. Seams of laminated limestone as thin as 3 mm have been observed (in H 1, Dorset), but normal limestones are never less than 3 cm, and thin normal-type limestones in a thick shale sequence (e.g. *laqueus* sub-zone, Glamorgan) are generally represented by strings of nodules. Nodular structures in a given bed are similar in size and more or less equally spaced over a wide area. Although it is generally true that less fossiliferous limestones tend to have planar surfaces there is no intimate relationship with shell content. More often than not nodules or nodular protuberances do not contain fossils at their core.

Presumably the obliteration of fine lamination by organisms permitted greater ease of migration of $CaCO_3$. Usually, however, this would take place only under the influence of chemical gradients created by the existence of inhomogeneities within the sediments. One superficially plausible possibility is that involving fragments of decaying organic matter. Weeks (1953) suggested an explanation along these lines. The release of NH_3 from rotting organisms would increase the pH locally and promote precipitation of calcite. This solution is unquestionably an oversimplification and is not satisfactory in the case under consideration. The loss of NH_3 is likely to be accomplished within a matter of months or at most a few years, whereas concretions may have developed hundreds or even thousands of years after the deposition of the original limy bed. For example, the strange protuberances from H 4, described above, could not have formed until after the deposition of the overlying marly shale which in its compressed condition is 23 cm thick. Similar considerations apply to the complementary limestone pairs. Moreover, concretionary development does not bear the intimate relationship to body-fossils that the theory requires. The association of limestones with irregular, nodular surfaces and the presence of trace-fossils does, however, suggest an indirect relationship between organic content and concretionary development. Presumably the excavation and infilling of ramifying burrows created inhomogeneities in sediment-porosity which controlled subsequent chemical migration. The uniform spacing of concretionary structures suggests that perhaps local segregation around a few centres could set off a trigger action under the influence of concentration gradients.

As concretionary development is closely bound up with the early recrystallization history, more light can be shed on mechanisms by a study of primary textures. A very satisfactory classification of limestone textures and discussion of their formation has recently been undertaken by Bathurst (1958) and his terminology is adopted in the following account. As recrystallization leads to an increase in grain size the original lime mud must have been composed of numerous mud-grade particles of $CaCO_3$ separated by films of water and clay minerals. Concomitant with compaction the pore spaces were progressively filled out by a process of local solution and redeposition until a firm mosaic was produced and the limestone consolidated. Where cavities were originally present or were created through shrinkage a coarser mosaic was produced through *drusy growth*. *Grain growth* in the solid state possibly took place to a limited extent but cannot be proved. Shell pockets were consolidated by *granular* and *rim cementation*. The uniformly coarser mosaic of the marls is probably due to the higher proportion of clay minerals to calcite particles, which could expand further without meeting their neighbours.

During the process of mosaic formation carbonaceous laminae were disrupted by the force of crystal growth. On a larger scale, specimens of *Lima gigantea* were cracked and fragments forced apart by the local expansion. Clearly, concretionary structures could not have formed later than the mosaic, so the process of primary recrystallization must have been accompanied by active migration of calcareous solutions, both laterally and vertically. The amount of vertical migration, in so far as it involved depletion of the calcareous rocks, must have been limited, for the delicate structures of trace-fossils, which are only recognizable because of an original difference in sediments, are not obliterated, except locally in some nodules. On the other hand, the dark marly infillings in limestones, due to trace-fossils, tend to be slightly more calcareous than the overlying marl. A certain amount of vertical migration would also help to explain the sharp transition from marl to limestone.

At a subsequent stage, after much compaction of the shaly rocks had taken place, 'beef' seams developed. Richardson (1923) was the first to prove that the 'beef' post-dates the nodules. Crystals of calcite developed within bedding planes in the shales, forcing them apart as they grew. Detailed mechanisms have been suggested by Richardson (1923) and Tarr (1933).

It is opportune at this stage to discuss briefly the nomenclature of the fine-grained limestones. Bathurst (1958) avoids using the term calcilutite, since he wants to distinguish between carbonate muds and silts. This distinction in the case of the Liassic rocks is impossible, since diagenesis has played such an important role in effecting secondary enlargement of the original $CaCO_3$ grains. Therefore, the general term calcilutite is adopted here. There is little reason to believe that any of the original precipitated grains were of silt grade.

The formation of woody lignite, with jet, in the limestones and jet in the marls and shales is a diagenetic phenomenon dealt with elsewhere (Hallam & Payne 1958).

(2) *Pyrite*

Iron sulphide was formed within the sediments under anaerobic conditions, presumably as the colloid hydrotroilite, and subsequently crystallized into pyrite. Its characteristic association with shells is related to the liberation of H_2S from decaying organic matter by sulphate-reducing bacteria. The process probably took place fairly soon after deposition, for mud samples obtained by surface dredging in the Black Sea contain pyrite as small lumps and infillings of shells (Archanguelsky 1927). The association of calcite and pyrite in many drusy cavities is interesting. As the pyrite is interstitial it must have formed after the bulk of the calcite had crystallized out. The most plausible explanation is that there was a local fall in pH as calcite came out of solution. If the fall was from about 8 to 7·5 or thereabouts the precipitation of pyrite would be favoured (Krumbein & Garrels 1952).

(*d*) *Conditions of deposition*

(1) *Origin of the microlamination*

The presence of abundant carbonaceous matter in a sediment signifies anaerobic conditions usually, since otherwise it would be oxidized and the carbon lost as CO_2. Fine, undisturbed lamination signifies that no organisms burrowed within the sediment. Nor did macro-organisms crawl about on the surface, since even this would suffice to destroy laminae less than 1 mm thick. These facts are well known and bituminous shales like those of Dorset are sometimes referred to as euxinic deposits. On the other hand, the absence of lamination in fine-grained sediments is clear evidence that material has been reworked by burrowing animals (Dapples 1942; Schäfer 1956). In the case of the Blue Lias the interpretation is straightforward, for the normal limestones and marls usually contain ample evidence of organisms, both as body and trace-fossils. Clearly, they were laid down in an aerobic environment. It should be observed that the presence of pyrite in the non-laminated rocks in no way invalidates this interpretation, which involves the bottom waters, since anaerobic conditions develop *within* nearly all fine-grained sediments (ZoBell 1946). Significantly, only below the bituminous shales and laminated limestones and marls is mottling due to trace-fossils absent. It is apparent that the rhythmic alternation of anaerobic with aerobic deposits (except for the few laminated limestones and marls) is of considerable significance for palaeogeographical interpretations.

Strong evidence exists that the carbonaceous layers were deposited annually, the product of the heavy fall each spring of diatoms from the plankton. When Archanguelsky (1927) made this suggestion for the very similar laminae in the Black Sea muds he was unable to clinch his argument. Conclusive evidence was forthcoming, however, from the work of Moore (1931) in the Clyde Estuary. The deposition of sediment was studied over several years and each year correlated with the formation of a thin, peaty layer not more than 2 mm and a light band from 3 to 7 mm thick. Apparently the silica of the diatoms is quickly dissolved so that all trace of organized structure disappears at an early stage. This explains why the bulk of the material in the Liassic rocks is structureless. Further indications that the Blue Lias laminae are annual deposits come from the work of Seibold (1958) on euxinic sediments in an isolated bay in the Adriatic. He recognized fine laminations in the deepest part of the bay, with laminae averaging about 0·25 mm. These can be proved by historical events and seasonal variations to be annual deposits. The light layers are considered to be deposited in summer and the dark (rich in organic matter and FeS_2) throughout the remainder of the year.

(2) *Origin of the sedimentary rhythm*

The $CaCO_3$ must have been precipitated originally as a fine mud, either inorganically or through the agency of bacteria. If it were detrital in origin it would show a closer relationship to undoubted terrigenous fragments. Quartz grains in the off-shore facies are, however, considerably larger than those of the calcite mosaic, which would not be expected if grains of $CaCO_3$ came from the land as detritus. Moreover, as the rocks are traced into the Southerndown Beds of Glamorgan, quartz and chert fragments of considerable size enter the sequence but the calcareous 'mud base' remains unchanged. Studies in Scotland confirm this independence from terrigenous sedimentation.

Precipitation of $CaCO_3$ is favoured by increase of temperature, salinity and pH, and by decrease of pressure. Good reviews of knowledge of the complex CO_2–$CaCO_3$ system can be found in the works of Sverdrup, Johnson & Fleming (1942) and Harvey (1955).

The next matter to decide is whether the rhythmic alternation of limestone and shale–marl is due to the periodic increase of $CaCO_3$ precipitation against a constant 'background' of clay deposition or vice versa, or whether both types of deposition fluctuated considerably. The evidence favours the first alternative because in the limestones (1) the 'varve' lamination, where it can be seen, is coarser, (2) quartz grains are more widely spaced and (3) shells tend to be less densely distributed than in the closely associated marls, e.g. the top of H 53 and H 54, Dorset. Therefore Lombard's view, that small-scale limestone–marl rhythms are due to the periodic influx of pulses of terrigenous clay (1956, pp. 518, 523) can be excluded in the case under consideration, particularly as the proportion of limestone actually increases towards land.

There remain two possibilities, that the rhythm owes its origin to epeirogenic oscillations or to climatic changes. (The latter alternative was suggested for rocks of Blue Lias age in Lorraine by Klüpfel (1917) but he adduced no evidence in support of his view.) Both possibilities satisfy physico-chemical requirements. If the sea bottom alternates between shallower and deeper water more $CaCO_3$ will be precipitated in the shallower water since temperatures will be higher and pressures lower. Further, if bacterial action be admitted, the increased amount of light will also favour a higher rate of precipitation (Lalou 1957). Two sorts of climatic change have been suggested. First, in periods of greater precipitation on the land, more terrigenous mud would be carried to sea by rivers. The more calcareous bands would then signify relatively arid periods (Trask 1936). This idea can be excluded in the present case since the evidence points to a rhythmic increment of $CaCO_3$, not clay. Alternatively, variations in temperature would suffice, with more $CaCO_3$ precipitating in the warmer periods (Brückner 1953).

The following evidence is held, somewhat tentatively, to favour the view that the Blue Lias rhythm owes its origin to small-scale epeirogenic oscillations, with the more argillaceous beds being laid down in periods of deeper water.

(i) In its typical full development in Dorset, 'anaerobic' bituminous shales, low in $CaCO_3$, alternate with 'aerobic' calcareous rocks (figure 7). This invites comparison with the Black Sea deposits (Androussov 1897; Archanguelsky 1927; Caspers 1957). The shallower waters are sufficiently oxygenated to support benthonic life, but below a certain depth (varying from 100 to 180 m) the waters are anaerobic and contain free H_2S. In this deeper zone, barren, finely laminated muds are laid down. Admittedly, anaerobic conditions can exist in the shallowest of waters, neighbouring the coast, but this possibility cannot be entertained for the Blue Lias, since the bituminous shales are strictly marine and disappear towards the old shore-line. Further, they contain no signs of periodic emergence. The climatic theory fails to account for this correlation between carbonate content and aeration of the original sediment.

(ii) The near-shore rocks of Glamorgan are notably more calcareous than their offshore equivalents a few miles away. This is easily explained by shallowing towards land if $CaCO_3$ deposition is controlled by depth, whereas the climatic alternative demands either that water temperatures increased sharply towards land or that coastal waters were considerably enriched in dissolved $CaCO_3$. Neither possibility is plausible, for modern oceanographic studies have established that sea temperatures and the concentration of dissolved carbonates change only slightly over large areas. Of especial interest is the oolite at Castle-upon-Alun, to be described later, which is overlain by a non-oolitic marl band. It is hard to avoid the conclusion that the change from one to the other was the result of sinking of the sea bed.

Accepting the theory of epeirogenic oscillations, the large increase in rhythmic units from Dorset to Glamorgan has to be accounted for. It is unlikely that the number of oscillations differed much over such a comparatively small area and important breaks appear to be lacking, so the lithological evidence for some rhythms in the succession must have been lost. Figure 4 illustrates in diagrammatic form how this might have come about. The Glamorgan succession often consists of alternations of groups of marly shales and thin limestones with limestones and thin marls. If such a succession were condensed the thin beds would be reduced to mere partings. In the earlier sections it was shown that, except for the comparatively uncommon 'anaerobic' beds, finely laminated structures are destroyed by the action of organisms and the diagenetic migration of $CaCO_3$. Thus, for the common rock types, thinning of the succession is likely to result in fewer beds being distinguishable. In support of this idea it may be noted again that there is a critical size of about 3 cm below which no normal-type limestones have developed. Also, if the laminated limestones of Dorset are examined closely, they may be found to contain thin seams of darker, impurer material which are probably the condensed equivalents of marls elsewhere which have been partly obliterated during diagenesis.

It might be objected that it is unreasonable to invoke an epeirogenic oscillation, however minor, for each small alternation between limestone and shale. This, however, is merely a subjective argument. Further detailed work elsewhere might well necessitate modifications to the ideas expressed above, but at the present stage of investigations they may be retained provisionally.

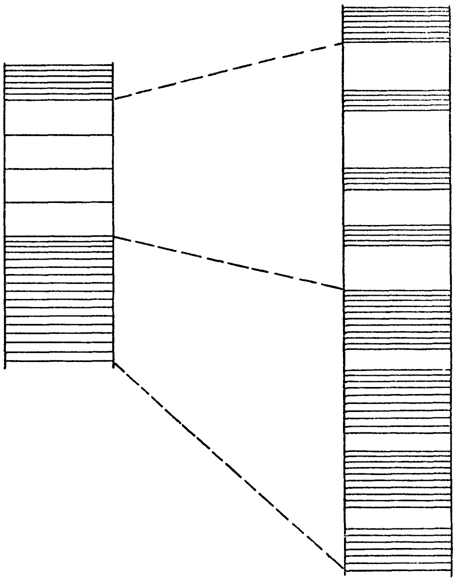


Figure 4. Diagram to illustrate the proposed explanation of the loss of limestone and shale units in a thin succession. Full explanation in text.

4. The rocks of the near-shore facies

(a) *General description*

The Blue Lias of Glamorgan, notably the Hettangian, shows signs of an approach to a shoreline in the neighbourhood of Southerndown, Cowbridge and Bridgend. Calcarenites, consisting of both oolites and skeletal limestones (in the sense of Illing 1954), conglomerates and chert beds are found within the succession, and the rocks locally transgress on to Carboniferous Limestone. A good general account of these changes is given by Trueman (1922) who succeeded to a large extent in working out the main stratigraphical relationships of the different facies.

The most familiar of the near-shore deposits is the Sutton Stone of the *planorbis* zone, which makes a fine display in the coastal cliffs south-west of Southerndown. Between Pant y Slade and Fairy Cave (857739) it forms a massive lithological unit resting unconformably on Carboniferous Limestone and varying between 10 and 13½ m in thickness. It also forms the prominent headland of Witches Point where it is brought up by a fault (figure 12, plate 1). The rock is distinctly crystalline in appearance and ranges from massive to thin-bedded. It is conglomeratic at certain horizons and stylolites are ubiquitous. Two main divisions are recognizable. The lower division ranges up to 10 m and is pale blue-grey in colour when fresh but weathers to a locally cavernous, creamy-white rock. The basal 1½ m contain abundant pebbles of Carboniferous Limestone, chert and subsidiary sandstone, together with occasional boulders up to 1 m in diameter. The overlying rock is only slightly conglomeratic. Fragments of limestone and chert are mostly under 2·5 cm in diameter and tend to be confined to several layers directly overlying irregular partings. Partings increase in frequency towards the top so that the upper rock, as seen in the weathered state in Black Rocks Quarry (868743), is markedly thin-bedded. Stylolites may be associated with these partings but generally they occur independently, varying about irregular horizontal planes by as much as 15 cm. Some horizons are rich in shells and shell fragments easily visible to the naked eye. Corals are quite common but rarely distinct; they are associated with drusy cavities infilled by calcite. The top of this lower division of the Sutton Stone is sharp. It is marked by an irregular surface containing subvertical borings, up to 3 cm long, infilled by limestone of sand grade and shell detritus.

The upper division has a constant thickness between Pant y Slade and Witches Point of some 4 m. It is composed of a number of thin calcarenites and differs from the lower division in its darker colour and in the abundance of small fragments of detrital limestone and chert of gravel grade. It is overlain by ½ m of marls with thin, nodular calcilutites containing *Waehneroceras*.

Microscopic examination reveals that the typical Sutton Stone has a pseudo-oolitic structure, being composed essentially of semi-rounded, equant or elongate particles of coarse calcite mosaic, generally rimmed by a dark layer of very fine calcite crystals in a similar matrix of coarse calcite mosaic (figure 24, plate 2). The fragments are fairly well sorted and range mostly between 0·125 and 0·350 mm but extend up to 1·00 mm in length. The rim thickness varies between 10 and 15 μ with the grains less than 5 μ. Sometimes recognizable echinoderm and pelecypod fragments are observed. The dominant detrital constituents of the conglomeratic bands are subangular fragments of brown and grey calcilutites and oolites. The interstitial mosaic is always coarser than in the calcilutites of the off-shore facies, though individual crystals may range down to 10 μ. Drusy patches and veins are fairly common. Quartz occurs as grains extending up to 0·28 mm in diameter but, like pyrite, is very rare. Barite is fairly common as prismatic crystals in the basal conglomerate. Galena is also fairly common and may be visible to the naked eye in drusy cavities.

The Sutton Stone is overlain in the Southerndown cliffs by a limestone group known as the Southerndown Beds, of the *angulata* and lower *bucklandi* zones. These consist of a series of thin, bluish grey, brown-weathering calcilutites and subsidiary shelly calcarenites, each bed ranging up to 0·6 m in thickness and separated by partings of marl never more than 1½ cm thick. The marl is generally hard and might be described sometimes as argillaceous limestone. Frequently the individual limestones are only recognizable on weathered faces where the marls weather back. Irregular, nodular surfaces are commoner than regular ones and often have a labyrinthine pattern due to trace-fossils. There are numerous bands of conglomerate a few centimetres thick, composed of poorly sorted, angular fragments of chert and limestone, mostly oolitic, up to 13 cm but usually under 2 cm long, set in a matrix of calcilutite. Detrital fragments of sand and gravel grade occur in virtually all the beds but tend in contrast to be sparsely distributed. There is no distinction between the detrital content of limestones and marls. Many thin horizons are sufficiently siliceous to be called chert bands. It can be seen from examination of thin sections that extensive silicification of fossils and limestone pebbles has taken place.

Unlike the Sutton Stone the Southerndown Beds exhibit lateral variation and transition into the off-shore facies in the Southerndown region. Some 15 m of these beds between Dancing Stones and Fairy Cave are the equivalent of about 27 m of calcilutites and marls of the off-shore facies of the *angulata* zone less than a mile to the south-east, on the other side of Witches Point. The latter lacks the shaly development of the *laqueus* sub-zone at Lavernock and Barry and contains a few thin seams of fine gravel, composed of chert and limestone. It is thus transitional to the near-shore facies of the Southerndown Beds. Detailed changes can be traced within the Southerndown Beds themselves. At Dancing Stones, on the north side of Sea Mouth, the top bed is of distinctive lithology, containing scattered ooliths. Its hummocky surface is overlain by a shale containing abundant boulders of this lithology, often encrusted by Liassic oysters. In addition there are boulders of Carboniferous chert and limestone up to 0·3 m in diameter. The boulder surfaces are frequently coated with red Fe_2O_3. Overlying the shale are alternations of calcilutite and marly shale typical of the off-shore facies. The boundary between the two facies corresponds approximately with the top of the *angulata* zone. Some 400 yards west of this locality the boulder bed has disappeared; the overlying beds contain chert fragments and the amount of shale is reduced, i.e. the near-shore facies has extended a few feet higher in the succession. Still further west, in Pant y Slade gully, the Southerndown Beds facies extends well up into the *bucklandi* zone, as Trueman recognized.

Lateral changes in the Southerndown Beds can also be traced inland. At the quarry at Castle-upon-Alun (915747), 2 miles east-north-east of Southerndown, the following section was measured in metres.

4. Calcilutites and subsidiary shales. *Montlivaltia guettardi* Blainv. at top	*ca.* 8·750
3. Calcilutites with marl partings and bands rich in chert gravel	*ca.* 6·000
2. Non-oolitic marl band	0·025
1. Beds of oolite *ca.* 1 ft. thick	5·830

The Southerndown Beds here reach a level about 2 m lower than at Dancing Stones. Bed 1 contains ooliths ranging from 0·30 to 0·65 mm in diameter, with nuclei of shell and limestone fragments set in a coarse mosaic of calcite (figure 23, plate 2).

In the Cowbridge district rocks of the *planorbis* zone, i.e. the lateral equivalent of the Sutton Stone, may be studied. The *angulata* zone has been reported but not confirmed in the present work. Sections are still visible in the neighbourhood of Welsh St Donats, Maindy, Alberthin, Newhouse, the Herberts and in the old railway cutting at Cowbridge. Details of these and other sections are given in the Survey Memoir (Strahan *et al.* 1904) and other works referred to by Trueman (1922).

The rocks are predominantly calcilutite beds from 5 to 20 cm thick, with slightly irregular surfaces and partings of marl. There is a subsidiary development of skeletal limestone and oolite. Seams of chert-limestone gravel and bands of chert nodules occur at a few horizons and stylolites are present in the more massive rocks. A few bands rich in corals have been reported. The base is seen only in Cowbridge Cutting, where calcilutites and skeletal limestones with *Liostrea* and *Modiolus* rest upon marls and limestones of the White Lias. The rock facies resembles to some extent that of the coastal Southerndown Beds but there is much less gravel. No accurate estimate of thickness can be made since detailed correlations have not proved possible, but there is no reason to believe that the *planorbis* zone is abnormally thick or thin. Without doubt, the 45 m of conglomerates found in a borehole near Llangan belong to the Trias and not, as Trueman thought, to the Lias.

The *bucklandi* zone gives less evidence of the proximity of a shore-line. Apart from the higher Southerndown Beds at Pant y Slade the only important deposit related to the near-shore facies is an oolite at Bridgend. This is exposed in the south-west corner of Trueman's quarry no. 5 (1922, fig. 64), for which the grid reference is 909798. A careful examination of the local succession leaves little doubt that this oolite is the equivalent of the thick limestone which marks the top of the *bucklandi* zone on the coast. The rock is more or less massive and exhibits current bedding, with ooliths ranging from 0·125 to 0·475 mm. Quartz of fine sand grade is fairly common and forms most of the nuclei of the ooliths. At Wick, Trueman assigned a small exposure of skeletal limestone of Sutton Stone type to the *bucklandi* zone. In addition, there has been described from a small quarry near Brocastle a bed of conglomeratic Lias with *Gryphaea* and small arietitids resting upon Carboniferous Limestone (Moore 1867). The main changes in the Hettangian from off-shore to near-shore facies on the coast are illustrated in figure 5.

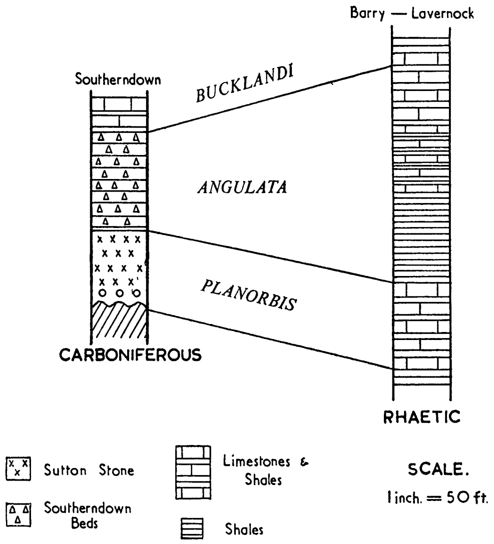


FIGURE 5. Diagram to illustrate the change in the Hettangian of Glamorgan from off-shore to near-shore facies.

The rocks rich in silica deserve special mention. They are of two types, bands and nodule layers of chert and rocks with selectively silicified pebbles and fossils. Chert bands about 5 cm thick are characteristic of the upper part of the coastal Southerndown Beds. Both thin bands and nodules occur at St Fagan's. The bands terminate sharply both upwards and downwards and sometimes transgress bedding in the limestones and marls. The nodules are up to 15 cm in diameter and are alined in rows parallel to the bedding, which they transgress. Chert nodules may be ellipsoidal (e.g. Cowbridge Cutting, bed 8 in Survey Memoir) or roughly sphaeroidal (e.g. *bucklandi* Beds, Bridgend). Thin sections show the silica to be usually pale brown chalcedony. Much of the cherty rock is composed of a patchy mixture of this with calcite, but in some instances chalcedony is concentrated at the borders. Calcareous fossils are at most only slightly silicified. In one section it was observed that the canals of calcareous sponge spicules were infilled within the most siliceous rock by colourless chalcedony.

Silicified pebbles are common in parts of the Southerndown Beds. Coarse radial fibrous crystals of brown chalcedony occupy central areas (figure 21, plate 2). Coarse calcite mosaic may also be partly replaced but the fine-grained matrix is unaltered. Silicified fossils are common in the *bucklandi* zone of Gwter Fawr and partly beekitized specimens of *Gryphaea* and *Liostrea* occur as far east as Stout Bay. The fossils have been patchily replaced by a mosaic of large or small fibrous, brown or colourless crystals. The fibrous structure may be complex (figure 22, plate 2). In specimens of *Gryphaea* silicification appears to have taken place from the outside, in contrast to the silicification of the pebbles.

The reader is here referred to the results of three chemical analyses of calcarenites from the near-shore facies (§ 3*a*, table 3).

(*b*) *Diagenesis*

(1) *Calcite*

The calcarenites consist of calcareous particles of sand grade cemented by a granular mosaic of calcite. The process of *granular cementation* is familiar and comparatively well understood (Bathurst 1958) and calls for no special comment. The important problem about the Sutton Stone concerns the nature of the embedded particles. Flett examined a thin section for the Geological Survey and concluded that they were recrystallized shell fragments coated by calcite mud (Strahan *et al.* 1904, p. 60). Trueman, on the other hand, took them to be recrystallized grains of detrital limestone. However, undoubted detrital cacilutite grains are numerous at certain conglomeratic horizons and are never recrystallized to a coarse mosaic. But the recrystallized grains show transitions to unaltered pelecypod and echinoderm fragments and often have an irregular shape incompatible with an inorganic origin (figure 24, plate 2). These facts, taken with the macroscopic evidence of abundant shelly matter, provide conclusive evidence for Flett's interpretation. The intense recrystallization to which the shelly matter has been subjected is probably related to the freedom of movement of fluids in the original porous sand. The calcite mud rim invites comparison with the concentric laminae of ooliths and it would not be misleading to describe the grains of the Sutton Stone as incipient or superficial ooliths.

At a comparatively late stage, when the rocks were consolidated, stylolites developed, presumably through a process of pressure solution, as is generally assumed.

(2) *Silica*

Whatever its origin it must be presumed that certain layers were unusually enriched in silica. Under certain circumstances silica in such layers segregated to form nodules. This could take place under the influence of locally varying pH. A lowered pH (8) compared with the surroundings would favour the local solution of calcite and the precipitation of silica (Correns 1950). Migration through diffusion could take place and the dissolved calcite be reprecipitated in the spaces vacated by the silica. However, it is interesting to note that Davis (1918), in a number of experiments, was able to effect an apparently mechanical segregation of layers of silica nodules, but there can be no confidence that this process is more than merely analogous. The origin of the marginal zones rich in silica is another puzzle but further work is needed to establish if this is more than an uncommon feature. Furthermore, it is far from clear why under certain circumstances shelly fossils and detrital fragments are attacked while the fine-grained matrix is not.

The formation of silica nodules post-dates the diagenetic changes involving the formation of irregular limestone surfaces, at least near St Fagan's.

(*c*) *Conditions of deposition*

By comparison with present-day sedimentary conditions on the Bahama Banks and in the Persian Gulf (Illing 1954; Houbolt 1957) it may be inferred that the calcarenites were laid down in very shallow, clear water subject to strong current or wave action and reasonably free from an influx of terrigenous detritus for most of the time. This interpretation is confirmed for the Sutton Stone by the presence of colonial corals. The skeletal limestone is similar in most respects to the *rounded calcarenite* of Houbolt. He considers that the rounded grains are the product of abrasion in zones of breaker activity. Periodic emergence is the most likely explanation of the interruptions of deposition which are marked by irregular surfaces overlain by conglomeratic bands. Stylolites might have been initiated along similar uneven surfaces. The division between the lower and upper parts of the Sutton Stone is marked by borings into *consolidated* limestone, indicating an important break. The occurrence of isolated patches of coral also suggests the pene-contemporaneous development of hard surfaces. Virtually all the rudaceous sediment appears to have been derived from the Carboniferous Limestone.

The poorly sorted gravel and pebble bands of the Southerndown Beds are totally out of sedimentary harmony with the fine calcilutites in which they are normally embedded. Presumably they represent separate pulses of coarse sediment brought from the neighbouring land by density currents, though no convincing case of graded bedding has been recognized. Judging from the coastal exposures, gravel was never carried more than a few miles from the land. Considering the Southerndown Beds as a whole, the thin-bedded character suggests periodic minor epeirogenic oscillations with the sparse development of marl pointing to shallower water than in the case of the off-shore facies. Just as the basal marly development implies a pronounced sinking after the formation of the Sutton Stone, so the coarse conglomerate containing cobbles of the underlying bed at the top of the succession at Dancing Stones is clear evidence of emergence. The rapid disappearance of this conspicuous bed westwards into a normal Southerndown Beds succession suggests either very shallow water or that emergence above sea level might often have left no trace.

In summary, the passage of off-shore into near-shore facies is marked, first, by a progressive decrease in the amount of argillaceous rocks and by an incoming into the succession of rudaceous sediment, then by the development of more or less pure calcarenites which must have been laid down in shoal areas comparatively free from terrigenous sedimentation. An interpretation of the near-shore environment is given in figure 6.

The silicification phenomena are of exceptional interest and warrant separate treatment. One of the main controversies about the formation of chert layers involves the source of the silica, whether it was derived directly from the land or from the remains of siliceous organisms embedded in the sediment. It is rare to find the evidence so unequivocal as in the present instance. Sponge spicules are of only sporadic occurrence in the Lias of Glamorgan and are, moreover, calcareous, with no indications of an earlier replacement of silica. Even in intimate association with chert nodules these spicules tend to retain their calcareous character. Only by the most tenuous arguments could an organic origin be upheld for the chert. On the contrary, there is a close correlation between silicification in general (chert, fossils, pebbles) and the proximity of a land source rich in silica, as testified by the abundance of detrital chert from the Carboniferous Limestone. This is not a general phenomenon when land is approached, for the rocks of the near-shore facies in the succession of the Skye area do not exhibit silicification, nor is there more than a small fraction of detrital chert (Hallam 1959*b*).

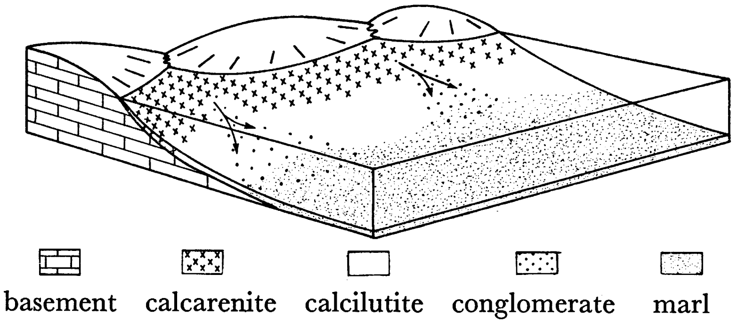


FIGURE 6. Suggested reconstruction of the near-shore environment in Glamorgan.

Silicification is strictly local in development, for while it extends on a small scale a few miles into the off-shore facies (e.g. the beekitized oysters of Stout Bay) it appears to be absent from the Cardiff district. Periodic enrichment of the coastal waters in silica gave rise to cherty layers which sometimes segregated afterwards into nodules.

5. THE FAUNA

(*a*) *Stratigraphical distribution*

In this section the broad features of the vertical and lateral variation are described as they would be in a purely stratigraphical account. The most important elements quantitatively in the off-shore facies are pelecypods, ammonites and echinoderms. Microfossils are abundantly represented by foraminifera and ostracods. Table 4 gives a complete invertebrate faunal list for the off-shore facies except in the case of the foraminifera, for which only the common species are recorded. A detailed study of the foraminifera of the whole Lower Lias was made fairly recently by Barnard (1949). He recorded a total of thirty-five species from the Blue Lias. The data for Dorset are given on the left side of each column and for Glamorgan on the right.

The stratigraphical value of the non-ammonite fauna has already been commented on. Each area has a number of distinctive horizons characterized by the abundance of particular species and these often prove very useful for local bed-to-bed correlation. The most important horizons in Dorset include H 5 (*Meleagrinella fallax*), H 28–9 (*Psiloceras planorbis*), the base of H 67 (*Psilophyllites hagenowi*), the top of H 67–8 (*Waehneroceras* spp.), 7 (*Spiriferina pinguis*), 15–17 (*Gryphaea*, *Schlotheimia lymensis*, *Pseudolimea harburyensis*), 29 (large

Coroniceras aff. *conybeari*), 31 (*Gryphaea*) and 49 (*Coroniceras reynesi*, *Nannobelus*). Of these, only the *Psiloceras* and *Coroniceras* aff. *conybeari* horizons can be located in Glamorgan, at the top of the *planorbis* and *conybeari* sub-zones, respectively, but the fossils extend through a greater thickness of rock. Thus, large specimens of *Coroniceras* are much less densely distributed than on the top surface of bed 29 in Dorset. The principal Glamorgan horizons include, in addition, two with *Montlivaltia*, in the middle of the *laqueus* and *conybeari* sub-zones, bed 49 of Trueman (1930) (*Charmasseiceras*), bed 55 (*Coroniceras rotiforme*, *Ptychomphalus*) and two crowded with *Gryphaea*, one at the top of the *angulata* sub-zone, and the other close to the base of the *gmuendense* sub-zone.

Though the broad similarities are apparent enough a number of important general differences between the two successions of off-shore facies may be noted. The rocks in Glamorgan tend to be less fossiliferous, though this statement needs qualification. For example, the basal '*Ostrea*' Beds are crowded with oysters at a number of horizons, no less than in Dorset. *Gryphaea*, *Mactromya*, *Pholadomya*, *Pinna* and minute gastropods (probably *Bourguetia* spp.) are much commoner in the *bucklandi* zone of Glamorgan, while brachiopods are much rarer and *Placunopsis* has not been found. The *bucklandi* zone of Glamorgan abounds in minute, compound, tubular structures which resemble the bryozoan *Bidiastopora* (figure 10, plate 1), and *Montlivaltia* is common at two horizons, while neither form has been discovered in Dorset. Finally, the rich *Schlotheimia lymensis*–*Pseudolimea harburyensis* fauna of the topmost *angulata* zone is found only in Dorset.

Next, the faunal characteristics of the near-shore facies will be considered. The most striking feature of the Sutton Stone, as exposed at present, is the great abundance of the two ribbed pectinids *Chlamys valoniensis* and *Terquemia arietis*, both of which are only subsidiary elements in the off-shore facies. In addition, the pelecypods *Lima succincta*, *Pseudolimea hettangiensis* and *Cardinia* sp. and the patellid gastropod *Acmaea schmidti* (Dunker) have been discovered. *Caloceras* cf. *johnstoni* (= *Ammonites suttonensis* Tawney) has been found about 6 m above the base (Strahan *et al.* 1904, p. 83). However, present exposures of the Sutton Stone give a poor idea of the richness and variety of the fauna and recourse has to be made to accounts of old, strongly weathered exposures. The old pits a few miles inland, at Brocastle and Ewenny, have yielded a rich fauna of corals, pelecypods and gastropods together with serpulids and bryozoa (Duncan 1867). The corals belong to the genera *Isastrea*, *Montlivaltia* and *Thecosmilia*.

The fauna of the Southerndown Beds bears a closer resemblance to that of the off-shore facies, but gastropods including the genera *Coelostylina*, *Katosira*, *Procerithium* and *Pseudomelania* are commoner and larger. Several bands of gastropods are present in the coastal section but the fossils are extremely difficult to extract.

Of the greatest interest is the discovery near Brocastle by Moore (1867, p. 521) of a small exposure of conglomeratic Lias, resting upon Carboniferous Limestone, which, judging from the presence of *Gryphaea* and small arietitids, belongs to the *bucklandi* zone. This exposure yielded an extremely rich and highly interesting fauna including numerous corals, gastropods, pelecypods, fragmentary echinoderms and serpulids together with bryozoans, brachiopods, ostracods, foraminifera and the triradiate spicules of calcareous sponges. Cirripedes have been found commonly nearby at Llangan and Ewenny in similar deposits.

TABLE 4

× = common ○ = occurs

	planorbis		*johnstoni*		*laqueus*		*angulata*		*conybeari*		*rotiforme*		*bucklandi*		*gmuendense*	
CEPHALOPODA																
Alsatites liasicus (d'Orbigny)	.		.		○	×	.		.		.		.		.	
?*Arietites* aff. *bucklandi* (J. Sow.)	.		.		.		.		.		.			○	.	
Arnioceras aff. *semicostatum* (Young & Bird)	.		.		.		.		.		.		○		×	○
Charmasseiceras spp.	.		.		.		.			○		×	×		.	
Coroniceras aff. *conybeari* (J. Sow.)	.		.		.		.		×	×	.		.		.	
C. (*Primarietites*) cf. *caprotinum* (d'Orbigny)	.		.		.		.		.		○		.		.	
C. (*P.*) *reynesi* (Spath)	.		.		.		.		.		.		.		×	×
C. (*P.*) *rotiforme* (J. de C. Sow.)	.		.		.		.		.		×	×	.		.	
C. sp. = *Arnioceratoides* spp. in Trueman (1930)	.		.		.		.		.			×	.		.	
Euagassiceras resupinatum (Simpson)	.		.		.		.		.		.		.			×
Pararnioceras aff. *parthenope* (Reynes)	.		.		.		.		.		.		.			○
Psiloceras (*Caloceras*) *johnstoni* (J. de C. Sow.)	.		×	×	.		.		.		.		.		.	
P. (*C.*) sp.	.		.			○	.		.		.		.		.	
P. (*Laqueoceras*) aff. *laqueus* (Quenstedt)	.		.		○	×	.		.		.		.		.	
P. (*Psiloceras*) *planorbis* (J. de C. Sow.)	×	×	.		.		.		.		.		.		.	
Psilophyllites hagenowi (Dunker)	.		.		○	○	.		.		.		.		.	
Schlotheimia (*Schlotheimia*) *extranodosa* (Waehner)	.		.		.		○	○	.		.		.		.	
S. (*S.*) *lymensis* (Spath)	.		.		.		×		.		.		.		.	
S. (*S.*) *pseudomoreana* Spath	.		.		.		○	○	.		.		.		.	
S. (*S.*) *similis* Spath	.		.		.		×	○	.		.		.		.	
S. (*Waehneroceras*) *megastoma* (Gümbel)	.		.		○	×	.		.		.		.		.	
S. (*W.*) cf. *portlocki* (Wright)	.		.		×	○	.		.		.		.		.	
Nautilus striatus J. Sowerby	.			○	○	○	○	○		○		○	○		×	○
Nannobelus brevis (Blainville)	.		.		.		.		.		.		.		×	
PELECYPODA																
Astarte sp.	.		.			○	.		.		.		.		.	
Bakevellia hagenowi (Dunker)	.		.		.		.		.		.		○		.	
Cardinia listeri (J. Sow.)	○	○	×	×	○	×	○	○	.			×	.		.	
Chlamys (?) *calva* (Goldfuss)	.		.		.		.			×	○	×	×	×	×	×
C. subulata (Münster)	.		×	×	×	×	×	×	.		.		.		.	
C. textoria (Schlotheim)	.		.		.		.		○		○		○		×	×
C. valoniensis (Defrance)	○	○	.		.		.		.		.		.		.	
Gervillea lanceolata (J. de C. Sow.)	.		.		○		.		○		.		.		.	
Gryphaea arcuata Lamarck	.		.		.		×	○	○	×	×	×	○	○	×	×
Lima (*Plagiostoma*) *gigantea* (J. Sow.)	×	×	×	×	×	×	×	×	○	○	○	○	○		×	
L. (*Antiquilima*) *succincta* (Schlotheim)	○			○	○		○	○	.		.		.		.	
Liostrea irregularis (Münster)	×	×	×	×	×	×	×	×	○	○	○	○	.		○	
Lucina limbata Terquem	.		.		.		.		.			○	○		.	
Mactromya unionides (Goldfuss)	.		○	×		×	○	×		×		×		×		×
Meleagrinella fallax (Pflücker)	○		.		.		.		.		.		.		.	
M. cf. papyria (Quenstedt)	.		.		.		.		.		.		.		×	
Modiolus hillanus J. Sow.	×	×	×	×	×	×	×	×	.		.		.		.	
Nuculana complanata (Quenstedt)	.		.			○	.		.		.		.		.	
Oxytoma inaequivalve (J. Sow.)	.		.		.		.		.		.		×		×	
Parallelodon hettangiensis (Terquem)	○	○	○		.		.		.		.		.		.	
Pholadomya ventricosa (Agassiz)	.		.		.		○	○		×		○		○		×
Pinna hartmanni Zieten	×	×	×	×		×	○	×		×		×		×		×
Placunopsis striatula (Oppel)	.		.		.		○		○		×		×		.	
Pleuromya galathea Agassiz	.		.		.		○	×	.		.		.		.	
P. striatula Agassiz	.		○		.		.		.		.		.		.	

Table 4 (*cont.*)

× = common ○ = occurs

	planorbis		*johnstoni*		*laqueus*		*angulata*		*conybeari*		*rotiforme*		*bucklandi*		*gmuendense*	
Pelecypoda (*cont.*)																
P. tatei var. *altior* Richardson & Tutcher	○	○	.		.		.		.		.		.		.	
Protocardia phillipiana (Dunker)	○		○		.		.		.		.		.		.	
Pseudolimea harburyensis Cox	.		.		.		○		○		.		.		.	
P. hettangiensis (Terquem)	.		×	×	×	×	○	×	.		.		.		.	
P. pectinoides (J. Sow.)	.		.		.		.			○	.		○		○	
Terquemia arietis (Quenstedt)	○	○	○	×	○	×	○	×	.			○	.		.	
Gastropoda																
Bourguetia zenkeni (Dunker)	.		.		.			×	○	×		×		×	○	×
Coelostylina (?) cf. *minuta* (Terquem & Piette)		○	.			○	.		.		.		.		.	
Pleurotomaria anglica (J. Sow.)	.		.		.		○		○	○		×	.		○	○
Pseudomelania (*Oonia*) *globosa* (d'Orbigny)		○	○	○	.		○		.		.		.		.	
Ptychomphalus expansus (J. Sow.)	.		.		.		.		.			×	.		.	
Brachiopoda																
Calcirhynchia calcaria Buckman	.		.		.		×		×	×	○		×		.	
Discinisca holdeni (Tate)	.		.		.		○		○		○		.		.	
Lingula beanii Phillips	.		.		.		.		○		.		.		.	
Piarorhynchia juvenis (Quenstedt)	.		.		.		.		.		.		×		×	
Spiriferina pinguis (Zieten)	.		.		.		○		.		.		.		.	
S. walcotti (J. Sow.)	.		.		.		.		.		.		.		○	
Zeilleria perforata (Piette)	.		.		○	○	○		.		.		.		.	
Echinodermata																
Isocrinus tuberculatus (Miller)	○		×	×	×	×	×	○	×	○	×	○	×	○	×	○
Echinoid spines, probably including species of *Diademopsis*, *Eodiadema*, *Polycidaris* and *Procidaris*	×	×	×	×	×	○	×	×	○	○	○	○	×	○	×	×
Hexacoralla																
Montlivaltia guettardi Blainville	.		.			○	.			×	.		.		.	
Foraminifera																
Bullopora globulata Barnard	○		.		×		○		○		.		×		×	
Dentalina pseudocommunis Franke	.		○		×		×	○	×		×		×		×	○
Frondicularia brizaeformis Bornemann	.		○		×		×		×		.		○		×	
F. sulcata Bornemann	.		.		×	○	×		○		.		.		.	
Lenticulina spp.	.		○	○	○	○	×	○	×		○		×		×	
Lingulina tenera Bornemann	.		.		○		×	○	×		×		×		×	
Marginulina prima d'Orbigny	.		.		×		×		×		×		×		×	
Nodosaria metensis Terquem var. *robusta* Barnard	.		.		○	○	×		○		.		○		○	○
Planularia inaequistriata (Terquem)	.		.		×	○	×		×		○		○		○	
Crustacea																
Bairdia spp.	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Pseudoglyphea ancylochelis (Woodward)	.		.		.		.		○		.		.		.	
Polychaeta																
Serpula sp.	.		.		.		.			○		○	.		.	
Bryozoa																
Bidiastopora (?) sp.	.		.		.			×		×		×		×		×
Stomatopora antiqua Haime	.		.		.		○		.		.		.		.	
Trace-Fossils																
Chondrites Sternberg	.		○		×		×		×	○	×	○	×		×	
Gen. nov. (Hallam 1960*b*)	.		.		.		×		○	○	○	×	○	○	×	○
Rhizocorallium Zenker	.		○		○		×	○	×	○	○		○		×	
Thalassinoides Fiege	○		×	○	×		×	○	○	×	○	×	○		×	

One of the most remarkable features of the Blue Lias is the gradual increase in size up the succession of many elements of the macrofauna. This is more than a local phenomenon. Table 5 gives for each sub-zone the amount in centimetres of the maximum dimension of a number of common fossils, except in the case of *Gryphaea*, for which the maximum length of the right valve is used instead. It has been shown for *Gryphaea* that, provided a large number of specimens is used, the measurement of such a dimension is a reliable index of size and has the advantage of being convenient to deal with (Hallam 1959*a*). The results in table 5 have been compiled from data collected all over Britain and, judging from personal observations in south-west Germany and study of the literature, are valid for the whole of north-west Europe at least. The most reliable results are those for the commonest fossils, *Gryphaea*, *Lima* and *Liostrea*. In addition, size increase has been observed in the common species of *Cardinia*, *Mactromya*, *Pholadomya* and *Pleurotomaria* but no satisfactory quantitative data are available. The ammonite genus *Psiloceras* and the subgenera *Waehneroceras*, *Schlotheimia*, *Metophioceras* and *Primarietites* all show pronounced increases in diameter up the succession but, except perhaps in the case of *Metophioceras*, the changes are probably not confined to one Linnaean species.

TABLE 5

	planorbis	*johnstoni*	*angulata*	*conybeari*	*bucklandi*	*gmuendense*
Gryphaea arcuata	—	—	3·8	—	4·5	5·2
Lima gigantea	5·5	10·0	15·0	20·0	—	20·0
Liostrea irregularis	4·0	5·0	6·5	—	—	—
Modiolus hillanus	2·7	3·7	—	—	—	—
Nautilus striatus	—	—	11·0	—	—	69·0
Pinna hartmanni	—	11·0	19·0	32·0	—	33·0
Pseudolimea hettangiensis	—	2·3	3·2	—	—	—

(*b*) *Stratinomy*

An essential requirement in most palaeoecological investigations is a study of the nature of the distribution of fossils in the enveloping rock. For example, information is sought on shell orientation and degree of valve disarticulation. Such a study, which treats organic remains as part of the sedimentary environment, is embraced by the subject known as stratinomy. One hopes in this way to determine as much as possible about the spatial distribution of the original living organisms and to distinguish fossil *life assemblages* from *death assemblages*, to use the terminology of Boucot (1953). In the present work it has been found desirable to develop this distinction further, and the following general classification of fossil assemblages is proposed.

(i) *Life*

This category includes such examples as burrowing pelecypods *in situ*, undisturbed reef associations and clusters of colonial organisms. The essential requirement is that disturbance after death has been negligible. So restricted, true life assemblages are rare and generally confined to small areas.

(ii) *Death*

(*a*) *Indigenous.* In this case organic remains have been removed (e.g. by current action) from their original life positions but have not been transported far. The important point is that the organisms lived in the one broad environment reflected in the sediments of the matrix. For example, many shales contain disarticulated valves of pelecypods and it may be possible to prove by regional studies that the fossils concerned, though undoubtedly disturbed from their life positions, were mud-livers and were not introduced from another environment.

(*b*) *Exotic*. This includes assemblages consisting of material introduced from a contemporary environment not reflected in the local sediments, for example, coarse reef debris swept into neighbouring muds and shells of shore-livers carried into subtidal sediments.

(*c*) *Remanié*. If the exotic material consists of fossils reworked from older rocks the resultant assemblage deserves to be so distinguished.

(iii) *Mixed*

This is the general case and by far the most important. It will be found useful to talk of, for instance, mixed life and indigenous death, or mixed indigenous and exotic death assemblages.

First, the off-shore facies will be examined, as normally developed, with each major group being treated in turn.

Amongst the **pelecypods** both *Liostrea* and *Gryphaea* tend to occur in clusters but right and left valves are rarely found adjacent. *Liostrea* is generally found attached to the shells of ammonites and other pelecypods and to pieces of lignite, but the '*Ostrea*' Beds of the *planorbis* sub-zone contain bands crowded with elongate, cup-shaped oysters with only small areas of attachment, which must have grown in mud. Shells of *Gryphaea* appear to be randomly orientated and left valves may interlock.

The valves of pectinids are usually disarticulated, unlike the majority of valves of *Modiolus*. A number of forms are found almost invariably inclined at high angles to the bedding, anterior downwards. These positions would be unstable unless the shells were embedded in sediment and must represent growth positions. This category includes the burrowers *Pholadomya*, *Pleuromya* and *Mactromya* together with *Pinna*. The last need occasion no surprise, since modern pinnas live vertically half-embedded in mud with their byssi attached to some firm object (Yonge 1953). In addition, *Lima gigantea*, *L. succincta* and *Cardinia* are frequently found anterior downwards, indicating growth positions. Even when they lie parallel to the bedding they tend to have their two valves together. The myas seem invariably to be preserved as moulds; the shells were presumably dissolved during diagenesis. Encrusting oysters are usually restricted to the posterior parts of the shells. Shells of *Placunopsis*, which are very common in the *rotiforme* sub-zone of Dorset, appear to be free-lying, and the smaller valves, frequently found in association with the larger, convex valves, rarely show signs of having been attached at some stage to hard surfaces.

Certain pelecypods including *Gervillea lanceolata*, *Lima gigantea*, *Liostrea irregularis*, *Modiolus hillanus* and *Placunopsis striatula* occur on planes within the generally barren bituminous shales. Except for occasional oysters moulded on ammonites they are thin-shelled and smaller than the same species in the limestones and marls and without much doubt are genuinely dwarfed. Quantitative analysis proved impracticable, since it was difficult or impossible to collect large numbers of fossils from a given shale. However, it may be noted that even when in the limestones *Lima gigantea* exceeds 15 cm in length the same species in the interbedded bituminous shale is never more than 3 cm long. At any rate, nothing larger has been found after thorough examination. Within the bituminous shales the valves are always together.

Above a diameter of about 5 cm **ammonites** lie parallel to the bedding. Below this diameter they may be inclined at high angles. This is readily explicable on mechanical grounds. It is reasonable to compare the bottom muds with present-day deposits and assume a surface layer of several centimetres of soft sediment. A small ammonite shell falling randomly would stand a good chance of being embedded obliquely if the diameter did not greatly exceed the thickness of the soft layer. As all the Blue Lias ammonites are platycone or serpenticone in shape they would tend to fall under their own weight to the position of greatest stability, i.e. parallel to the sediment surface. It is otherwise with *Nautilus*, which has a sphaerocone shell. Even large shells of this form could remain upright embedded in only a few centimetres of mud and, indeed, they are often found in this position. Bohlin (1949, p. 560) referred in a footnote to the occurrence of large ammonites at Lyme Regis orientated at high angles to the bedding. He seems to have confused ammonites with *Nautilus*. The shells in the limestones and marls are infilled to a varying degree by mud and sometimes only the internal mould remains. If cavities remained in the upper parts they were infilled by calcite or pyrite. Within the bituminous shales ammonites can often only be recognized as faint calcitic or pyritic films or as rib-moulds on oysters. In some large specimens of *Coroniceras reynesi* in Dorset the last chamber is enriched with crinoid ossicles compared to the surroundings, suggesting perhaps that they were swept in by currents.

Echinoderm remains are extremely common but complete tests are scarcely ever found. Although characteristically distributed randomly as spines, plates and ossicles, small patches unusually rich in crinoid ossicles are not rare and are presumably close to the original life positions.

Whenever the abundance of **brachiopods** is reasonably great it is seen that they tend to be aggregated into clusters. The individuals in a given cluster cover a wide range in size but apparently show no preferred orientation. The best examples are found in bed 53 in Dorset, taken by Lang, following the Survey, as the top of the Blue Lias, which is crowded with *Piarorhynchia*. These shell clusters are familiar features in many brachiopod deposits and represent colonial associations. The shells are rarely disarticulated and are almost invariably infilled by drusy calcite. Very few brachiopods have been found in the bituminous shales. It cannot be assumed that brachiopods living in a mud environment were invariably attached by their pedicles to a hard surface. It is therefore interesting to note that Dell (1951) has observed living rhynchonellids lying loose on the sea floor.

The **simple corals** in Glamorgan are distributed fairly evenly in the limestone beds and are nearly always right-way up, presumably close to what was their growth position.

Ostracods and **foraminifera** are distributed randomly. They are infilled by calcite often or less commonly by pyrite or even glauconite. There is a rough correlation between the abundance of the two groups in different beds, a point noted by Barnard (1949). Ostracods are the only group common in the bituminous shales. Usually, when the valves are together, as is almost invariable in these shales, the shells are infilled by calcite.

Very important keys to the character of the original environment are provided by **trace-fossils**, the structures produced by organisms moving on and within the soft sediment. The systematic study of trace-fossils has been dealt with excellently by Seilacher (1953), whose work provides an admirable starting point for modern investigations.

Four highly distinct and clearly recognizable types are common in the Blue Lias. All have the taxonomic status of ichnogenus. One owes its origin to an aggregation of shell fragments and to associated phosphatic structures, but the other three have been preserved because of original differences in sedimentation and are recognizable as the piping down of light-coloured material into dark and vice versa (figure 7). This has been termed *bed-junction* preservation (Simpson 1957).

Chondrites is the fine, tubular, branching structure which is responsible for the conspicuous mottling in the limestones and marls of Dorset (figure 16, plate 2). It has been the subject of a thorough study by Simpson (1957), who interpreted the tubes as infillings of tunnel systems excavated by organisms, possibly sipunculoids, which swallowed the sediment.

Rhizocorallium is the name accepted here for the U-shaped structures with a median laminal portion known as the septum or *Spreite*. A detailed morphological account is given by Richter (1926). They are common in Dorset, notably in beds 17 and 49 but, like *Chondrites*, are much less in evidence in Glamorgan. The U ranges up to 21 cm in length and 4·5 cm in width, with a tube diameter of 0·7 cm, in bed 49, but in bed 17 no more than 5 × 2·7 cm. The orientation is generally subvertical but may vary to almost horizontal. They are best viewed on vertical joint planes of limestones (figure 15, plate 2), but are more likely to be seen on bedding planes as pairs of circular markings joined by a zone exhibiting laminal structures (figure 16, plate 2).

Seilacher interprets *Rhizocorallium* as the product of excavations of small organisms which fed on the sediments, probably worms or crustaceans (personal communication). They are not to be confused with *Arenicolites*, as was done by Coysh (1931), who appears to be the first to have recorded U-structures from the Blue Lias. In work not yet published Seilacher distinguishes two ichnospecies, *Rhizocorallium jenense* Zenker and *R. parallelum* (Torell), according to whether the structures are horizontal (or oblique) or vertical respectively.

Thalassinoides consists of a ramifying network of tubular structures never wavering much from the plane of the bedding, which usually appear as ridges on the undersides and as grooves on the upper sides of limestones. Sometimes, however, calcite has been concentrated within these structures by segregation, a phenomenon also observed in nodules containing *Chondrites* (Simpson 1957). Although generally preserved as half-relief it is not uncommon to find full-relief structures which are circular or elliptical in cross-section. At least two distinct size grades are recognizable. The larger type has a tube diameter of about 1·5 cm, ranging up to 2·5 cm, and can be well studied in the *conybeari* sub-zone of Glamorgan. Branching is occasionally observed, with a branching angle usually about 20 to 25°, rapidly expanding away from the junction. The area at such junctions is frequently expanded by an enlargement of the proximal parts of the tubes. The smaller type, in the *johnstoni* and *laqueus* sub-zones of Dorset, ranges up to 0·8 cm in diameter. Good examples are seen on the surfaces of H 60 and H 68.

The interpretation of *Thalassinoides* has been gone into by Fiege (1944), who first described the ichnogenus from the Trias. The structures are the infillings of complicated tunnel systems, produced in all probability by callianassid crustaceans, the key feature being the triradiate branchings. Beautifully preserved examples from the Lias of south-west Germany have been figured by Rieth (1932), who thought they were the impressions of sponges.

A new name is to be proposed for stumpy, subvertical, phosphatic cylinders enriched in shell fragments. These will be fully considered elsewhere (Hallam 1960*b*).

The sediments have manifestly been subjected to repeated reworking, with later trace-fossils partly obliterating or otherwise modifying the earlier. Figure 15, plate 2, for example, shows *Rhizocorallium* transgressing older structures, while the dark sediments in the U have been penetrated in their turn by *Chondrites* from a higher, more calcareous horizon. Significantly, no sediment pipes down from the laminated rocks (figure 7). Indeed, the lamination could not have been preserved if excavating organisms had lived on or in the sediment.

Although Seilacher has made it clear that an ichnospecies need not correspond with a normal Linnaean species it is probable that within the limited stratigraphical range of the Blue Lias each trace-fossil represents a distinct Linnaean species. Possibly, for instance, *Thalassinoides* was the product of *Pseudoglyphaea ancylochelis*, a callianassid-like crustacean described from Lyme Regis by Woodward (1863). In this connexion it is noteworthy that *Rhizocorallium* and the undescribed trace-fossil, at least, exhibit a gradual size increase up the succession, just as in the case of the molluscs considered earlier.

Considering the fauna of the off-shore facies as a whole, the occurrence of burrowing pelecypods in growth positions, the poor degree of sorting and random orientation of shells, the tendency towards clustering and the preservation of delicate trace-fossils all signify elements of a life assemblage, excepting ammonites that floated in, little disturbed by water movements. This interpretation is in keeping with the lithological evidence, for fine muds are only deposited in areas of weak current activity. On the other hand, the disarticulation of the valves of surface-living pelecypods and the large amount of widely disseminated shell debris point to a fair amount of disturbance after death. Therefore the fauna may be classified as a *mixed life and indigenous death assemblage*. Organisms presumably played a large part in effecting the break-up and redistribution of shells, for there must have been many soft-bodied forms which left no recognizable trace. Even large shells like *Lima gigantea* could have been undermined and displaced by tunnelling. In addition, there were probably short periods of increased turbulence and non-deposition. Certainly there is evidence from several distinctive horizons that such conditions operated on a pronounced scale. The tops of beds 29 and 49 in Dorset are crowded with shells and shell fragments, notably ammonites (figure 13, plate 1) and are enriched in glauconite and collophane, an association characteristic of condensed deposits. Pelecypod shells are mostly disarticulated and moulds of burrowers may lie randomly parallel to the bedding. Independent palaeontological evidence of condensation in the case of 49 is strong and mention has already been made of signs of erosion on the upper surface. In the marly shales plastered on to this surface thin layers crowded with *Arnioceras* have sharp lower boundaries and alternate with thicker, less fossiliferous rock. All this may be taken to indicate reduced deposition, periodically stopped, and a considerable reworking of bottom sediment by comparatively strong currents, giving rise to an *indigenous death* *assemblage*. (There is no evidence of exotic or derived elements in the fauna.) Similarly, in Glamorgan, both the *rotiforme* and *bucklandi* sub-zones are abnormally thin in relation to the rest of the succession and the stratinomic data suggest condensation. Thus the top bed of the *rotiforme* sub-zone is enriched in shells and glauconite. *Pinna* shells over 27 cm long are common lying parallel to the bedding—sure evidence of pronounced reworking by currents. Many of the shells are encrusted by serpulids, which are rare elsewhere and presumably favour only slight sedimentation. Uprooted *Pinna* shells are common also on the upper surface of the highest *bucklandi* bed which passes laterally into an oolite.

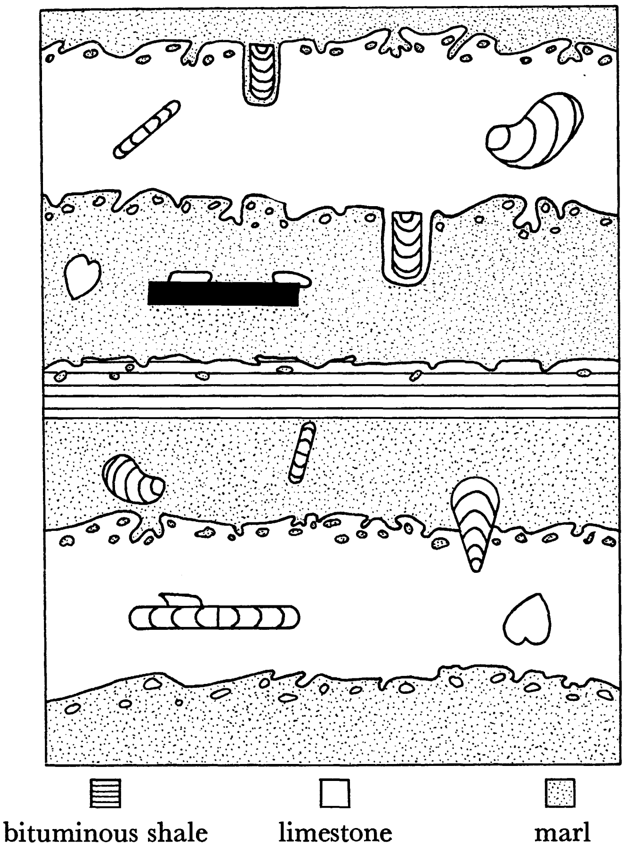


FIGURE 7. Diagram to illustrate the main lithological and faunal characteristics of the Blue Lias in the fullest cyclic expression. The black object represents a piece of lignite (driftwood) with encrusting oysters. The fossils represented diagrammatically include ammonites, pelecypods, *Chondrites* and *Rhizocorallium*.

It should be noted, however, that the majority of the richly fossiliferous layers in the off-shore facies are not of this sort. Nearly all the common species are found in abundance only at a limited number of horizons which rarely coincide for different forms. Rich shell layers as a whole may occupy several centimetres in the limestones and marls but little more than planes in the bituminous shales. Figure 7 is an attempt to represent diagrammatically the 'typical' off-shore Blue Lias facies in its fullest cyclic expression.

The stratinomy of the near-shore facies need not be treated at length. In the Sutton Stone the completeness of the disarticulation amongst the unbroken pelecypod valves and the innumerable shell fragments of sand grade clearly signify a death assemblage. *Acmaea* *schmidti* lived on a hard surface and was washed into the shell sand, and the same is probably true of many other gastropods. As the two common pelecypods were, in contrast, indigenous and adapted to the local shell–sand environment the fauna should be classified as a *mixed indigenous and exotic death assemblage*. The colonial corals that are found are often only fragmentary and no true reefs have been discovered during the present work. The oolites are poorly fossiliferous except for isolated shell fragments. In this they compare well with present-day deposits of constantly shifting calcareous sands which form a precarious environment for almost any benthonic organisms.

(*c*) *Ecological classification*

With such a bewildering variety of forms to deal with, ecological studies of the benthos are severely handicapped without some sort of classification based upon mode of life rather than morphology. In level-bottom communities an important distinction can be drawn between organisms that live within and organisms that live on the surface of the sediment. Similarly, there is a pronounced difference between organisms which move about freely and those which remain more or less rooted to one spot for the whole of their adult lives. The classification adopted here is a modification of one proposed for living organisms by Schäfer (1956) which is based essentially on these two criteria.

(i) *Vagile endobionts*

Active movers within the sediment, notably sediment eaters including probably many worms, crustaceans, etc., few of which left any organized trace.

(ii) *Sessile endobionts*

Includes forms ranging from those occupying more or less permanent burrows (the myas, *Lingula*) to pelecypods normally sessile but with a capacity for slow movement (probably, for example, *Cardinia*, *Lucina* and *Protocardia*) and pelecypods attached by their byssi to hard objects several centimetres below the surface of the sediment (*Pinna* and at least some of the Limidae). The two small, high-spired gastropods *Bourguetia zenkeni* and *Pseudomelania globosa* are abundant in what were soft sediments and might well have inhabited burrows like the modern *Turritella communis* (Yonge 1946).

(iii) *Sessile epibionts*

Surface-living forms variously free-lying (*Gryphaea*, simple corals) or attached. The latter may be cemented (oysters, serpulids, colonial corals, some bryozoa) or fixed by byssi or pedicles (*Gervillea*, *Meleagrinella*, *Modiolus*, and brachiopods) to a hard surface or rooted in soft mud (crinoids, which might also have been attached to floating wood).

(iv) *Vagile epibionts*

Active crawlers on the surface of the sediment. Includes many gastropods, worms, crustaceans, echinoids, foraminifera, ostracods, etc.

(v) *Nektobenthos*

Forms swimming close to the sea bottom, in some cases resting periodically on the surface of the sediment. Includes cephalopods, pectens and perhaps ostracods, though the latter might have been crawlers.

Naturally these divisions are not always clearly defined. For example, some vagile endobionts might behave at times as epibionts. Most 'sessile' endobionts are capable of movement if forced to by violent changes in the physical environment, a phenomenon acknowledged by Schäfer's term for this group—*bedingt vagile Endobionten.* Again, should *Pinna* be separated from the other pelecypods with byssal attachments because it lies half buried in mud? Despite such inevitable disadvantages the classification does express important ecological relationships. Applied to the Blue Lias it enables the differences described earlier to be expressed in a succinct and illuminating way. Thus the 'anaerobic' laminated rocks differ from the others in the complete absence of endobionts and the commonest fossils, ammonites and ostracods, had perhaps only transient contacts with the surface of the sediment during life. Considering the upper *angulata* and *bucklandi* zones of the off-shore facies, epibionts such as brachiopods and *Placunopsis* are much commoner in Dorset, whereas in Glamorgan endobionts including *Pinna*, the myas and *Bourguetia* (?) come to the fore. The comparative abundance of the epibionts *Montlivaltia*, *Calcirhynchia* and *Chlamys* in several layers in the upper *conybeari* sub-zone of Glamorgan is likely to be significant. The condensed bed at the top of the *rotiforme* sub-zone in Glamorgan is greatly enriched in epibionts including *Ptychomphalus*, *Liostrea* and serpulids, the latter encrusting uprooted endobionts (*Pinna*). Finally, the transition to the near-shore facies is marked by a great increase in the proportion of both sessile and vagile epibionts.

(*d*) *Relationship between the fauna and the sediments*

A positive relationship can be demonstrated and interpretations suggested in several cases.

(i) The faunal impoverishment of the laminated rocks as compared with their normal-type associates is precisely what one would expect from anaerobic bottom conditions. The chief problem concerns the thin bands containing dwarf epibionts. The possibility that the shells drifted in from another environment may be discounted, at least for the pelecypods, since the bottom waters were stagnant and there are few signs of all but the slightest disturbance of bivalved shells. There is no good reason to doubt that the small pelecypods are dwarfed adults, since poor aeration is known to be a potent factor in inhibiting molluscan growth (Humphrey & Macey 1930; Robertson 1941).

The dwarfed organisms would probably be well adapted to living under conditions of oxygen deficiency like, for instance, *Nucula* at the present day (Moore 1931). Even still, this specialized existence was apparently possible only for surface-living forms and these only occur at comparatively few horizons, suggesting perhaps a periodic slight improvement in oxygenation. The necessary surfaces of attachment could have been provided by fish scales and subsequently by shells of the same species.

The comparative abundance of ostracods need occasion no surprise, since they are remarkably tolerant organisms and many may live almost indefinitely in very foul waters (Ulrich & Bassler 1923, p. 279). On the other hand, their minuteness and lightness of shell makes them the likeliest candidates for drifting in from another environment. Ammonites too are comparatively common. Although their gas-filled shells are likely to have been carried long distances, in some cases it is questionable whether more than the occasional shell would have drifted into the stagnant waters. Moreover, the oxygen problem is much less serious for the nektobenthos because experiments by Brouardel & Fage (1955) have shown that the oxygen content of water undergoes a rapid decrease in the immediate vicinity of the bottom (0·5 m). This decrease is related to the very rapid oxidation of the bottom sediment and the very slow diffusion of the dissolved gas. It follows that swimming ammonites might have survived even when life was impossible for epibionts. Dwarfing could not be proved for ammonites but remains the likeliest explanation for the numerous small specimens of *Arnioceras* and *Euagassiceras* in the Dorset bituminous shale 52, in a rock sequence containing giant arietitids in the limestones. Unfortunately, it is usually impossible to make a satisfactory comparison between the limestones and shales because the former are hard to break up and there are only limited exposures of the latter.

(ii) In the condensed beds there is a relationship between enrichment of shells, many of them slightly worn, and glauconite and collophane. This has been dealt with in the section on stratinomy. The increased importance of encrusting epibionts should be noted.

(iii) As far as the differences between the off-shore facies of the upper *angulata* and *bucklandi* zones are concerned, observations are too general to allow more than a few tentative suggestions to be made and the conditions do not favour a detailed quantitative treatment. The Glamorgan rocks differ from those in Dorset essentially in the higher limestone–shale ratio and the greater thickness, even allowing for compression of the more argillaceous Dorset sequence. From the interpretations adopted in this paper the Glamorgan succession signifies shallower water conditions and a higher sedimentary rate in general, and it remains to be seen how far these may account for the faunal differences. Some control is provided on interpretation by personal observations in other areas.

Gryphaea is common in the thick successions of Glamorgan and the Skye district and in thin shell beds, signifying well-aerated conditions, in Yorkshire. It is fairly common in the thin sequences of limestone and marl of north Somerset and Württemberg, but rare in the thick shaly sequences of Warwickshire and Yorkshire and not especially common in Dorset. Probably the shallow, well-aerated water was the most important factor controlling distribution, but *Gryphaea* was apparently well adapted to high rates of sedimentation.

Pinna is far commoner in Glamorgan and the Skye area than in Dorset, north Somerset and Württemberg, suggesting strongly that it favoured a high rate of sedimentation. The same is probably true of the myas but the evidence is less convincing. While common enough in Glamorgan only *Pleuromya galathea* is abundant in the *semicostatum* zone of Scotland. Myas are not especially common in the thin successions, nor in the shaly sequences of the Midlands and Yorkshire.

Brachiopods are distinctly commoner in the thin, limestone-rich successions of Dorset, Somerset and Württemberg than in the thick limestones of Glamorgan and they are rare in the thick shales of the Midlands and Yorkshire. They are almost totally lacking from bituminous shales. All this suggests that the brachiopods favoured low rates of sedimentation and good aeration but the issue is complicated somewhat by their abundance in a number of bands in the thick *semicostatum* zone of Skye and Raasay. A brief examination suggests that these might be shell beds related to short interruptions in sedimentation but a more thorough study is needed for confirmation.

(iv) The transition from off-shore to near-shore facies is accompanied by some striking faunal changes. The sharp rise to dominance, accompanied by a size increase, of *Chlamys valoniensis* and *Terquemia arietis* in the Sutton Stone is of considerable interest, for their shells are corrugated by ribbing and would presumably be well adapted to withstand the strong current activity to which they were undoubtedly subjected. In contrast, their likely ecological equivalents dominant in the off-shore facies, *Chlamys subulata* and *Liostrea irregularis*, are both smooth-shelled. This state of affairs may be compared with what is known of living pectens. Mud-living forms are generally thin-shelled, whereas those that thrive on shallow-water sands and are subjected to stronger currents tend to be robust and are nearly always ribbed (Roger 1939). The better aeration could account for the size increase.

The other important change to be accounted for is the great increase in epibionts. Though now essentially a death assemblage the fossils must have come from near-shore environments. Colonial corals require very shallow, warm, clear water and a hard surface for attachment. A hard substratum is also necessary for cirripedes, serpulids and most bryozoans and sponges. Most gastropods require a firm surface, which could have been provided by shell sand; the patellid *Acmaea* must have lived on hard rock. An association of representatives of these groups with an abundance of shelly matter and an erosion surface of Carboniferous Limestone is therefore readily explicable. Moore (1867) made the interesting observation that corals and gastropods frequently occur in contact with the Carboniferous Limestone surface. Unfortunately, it is not possible to make any generalizations on the relation between shell shape in gastropods and the nature of the substratum (C. M. Yonge, personal communication).

There are several instances in which faunal change cannot be correlated with lithology.

(i) The pronounced size increase up the succession in a number of molluscan genera and species is unquestionably independent of facies. As exemplified by the best-documented case, *Lima gigantea*, there is a gradual change, the same in different areas, regardless of the rock types in the off-shore facies. The important point to be discussed is whether or not the size changes are the result of environmental factors for which there is no lithological evidence. The principle environmental factors influencing size appear to be degree of aeration (Humphrey & Macey 1930; Robertson 1941), amount of available food (Robertson 1941; Tasch 1953), temperature (Tasch 1953) and salinity (Goldring 1922; Gunter 1947). The first factor has already been discussed in connexion with the laminated rocks and is intimately related to lithology. There is no reason to suppose that the earlier faunas suffered from a relative deficiency of food, since it is evident from the petrological studies that there was an annual rain of plankton as in present-day seas. The evidence relating to temperature is equivocal. For most animals there is a tendency for size to increase with latitude, but there are notable exceptions which preclude the formulation of a general rule. It is relevant that among these exceptions are molluscs with shells, which exhibit gigantism only in tropical and subtropical waters. Therefore, if temperature were the controlling factor in the Blue Lias, the seas must have got progressively warmer as time passed. But as the corals and the oolites in the *planorbis* zone signify warm water at an early stage such temperature increase would be limited to a few degrees. There is, however, absolutely no evidence that a fourfold increase of size can be effected in molluscan species by a small temperature change.

There remains the possibility of a gradual salinity change from brackish water to marine conditions, since the underlying Rhaetic Beds have been regarded from time to time as deposits laid down in waters of low salinity (e.g. Elliot 1953), partly to explain the absence of ammonites and brachiopods. Such quantitative data as are available (e.g. Hesse, Allee & Schmidt 1937, p. 166) suggest a direct relationship between size and salinity. If table 5 is consulted it will be seen that this would imply brackish water throughout much of the Hettangian. This cannot be accepted because both echinoderms and corals, which are markedly stenohaline, are abundant in particular facies of the *planorbis* zone. Echinoid spines are actually present in the basal shale. Furthermore, if such a salinity change did take place it would be expected that in the north-east Alps, a classic area for unquestioned marine Rhaetic (containing both ammonites and brachiopods), there would be no sign of molluscan 'dwarfing' in the overlying *planorbis* zone. This, however, is not the case, according to Dr W. Blind (personal communication). The largest specimens he has found of *Lima gigantea* and *Nautilus striatus* measure only 4·7 and 9·2 cm in length and diameter, respectively, well within the limits established for north-west Europe.

One is forced to the conclusion that the size increase is evolutionary. Size increase is an important evolutionary trend in the majority of invertebrate groups and is considered to be adaptive, i.e. due to orthoselection for greater size (Newell 1949; Simpson 1953, p. 252). The changes described above in the molluscs appear to be further examples of this sort. The most interesting point is that the size changes affected individual Linnaean species, which apparently remained constant in their other characters.

(ii) The progressive replacement of ammonites up the succession is due to the evolution and migration of new forms and extinction of the old. Similar evolutionary changes took place in the other groups, but the results are frequently difficult to disentangle from temporary appearances and disappearances due to migration. A comprehensive survey of these different types of faunal change must await more work on the Lias as a whole in widely different parts of the world. In a few instances there are reasonable grounds for believing in replacement of species by ecologically similar organisms entering the succession for the first time. Such are the effective replacements of *Chlamys subulata* by *C.? calva* (both smooth-valved), *Liostrea irregularis* by *Gryphaea arcuata* and *Placunopsis striatula* by *Oxytoma inaequivalve*. All these changes took place at about the same horizons over wide areas.

(iii) The enrichment in fossils in some beds compared to their neighbours is not always to be ascribed to non-deposition, nor to a general improvement in living conditions, e.g. better aeration, since often only one or perhaps two species are involved. It would be a fair generalization to state that all common species are really common only at a limited number of thin horizons. Ascending the succession first one and then another will be seen to jump into prominence. Such a pattern brings to mind the annual population fluctuations in different benthonic species, well known to marine biologists. Such fluctuations are the rule rather than the exception. The shell bands in the Lias, however, probably represent larger-scale fluctuations more comparable with those in which a certain species establishes dominance for many years.

The remarks in this section are not intended as a complete analysis of the pattern of faunal distribution in the Blue Lias. This is a highly complex matter involving a large number of interacting variables. The present contribution is to be considered only as an introductory study which may provide a suitable framework for further detailed quantitative work.

6. The Blue Lias environment

A summary can now be made of knowledge about environmental conditions as deduced from sedimentary and faunal data.

Temperatures were high and probably similar to those in present-day tropical and subtropical regions. This is clear from the presence of colonial corals and giant molluscs. The occurrence of coal measures in southern Sweden (Troedsson 1951) and the abundance of fossil driftwood signify a humid climate. There is no good evidence that salinities ever dropped below those normal for marine conditions.

The average rate of deposition for the bituminous shales in Dorset, as measured from the laminations, was 0·03 mm/year. The only satisfactory measurement on a laminated limestone gives 0·23 mm/year. Higher sedimentary rates usually operated in Glamorgan, where an increased proportion of terrigenous matter tended to prevent the development of finely laminated shales. As the limestone–shale balance in the off-shore facies of Glamorgan was not markedly upset a higher sinking rate may be presumed.

Not even approximate quantitative data are available on depths of deposition, but certain qualified comments may be made. The interpretation adopted in this paper favours regular, small-scale oscillations every few thousand years between shallower and deeper water but these might have had amplitudes of only a few tens of feet. None of the rocks of the off-shore facies need have been deposited in ‘deep’ water, the important condition being quiescent bottom conditions. On physico-chemical grounds alone, depths of water greater than, say, 150 m for the calcilutites are unlikely and some were probably laid down in much shallower water. Conditions were often remarkably constant over wide areas. The calcarenites of the near-shore facies were probably deposited in very shallow water, less than 20 m in depth.

Bottom currents during the deposition of the off-shore facies were generally weak in shallower water, while at greater depths circulation was frequently so poor that there was little to no oxygen renewal. In both areas a greater tendency towards periodic stagnation can be recognized in the *planorbis* zone, with laminated and associated poorly fossiliferous limestones and marly shales signifying poorly oxygenated bottom conditions even in shallower water. As the seas shallowed towards land current strengths increased considerably and pulses of coarse, terrigenous sediment were swept in from time to time. Signs of the proximity of land in Glamorgan diminish progressively up the succession, pointing to the gradual transgression of the Liassic sea. The virtual absence in the conglomeratic layers of anything but fragments derived from the Carboniferous Limestone suggests that by the beginning of the Lias the local Coal Measures had been removed by erosion.

I should like to record my gratitude to the following persons who have assisted me at different times: Dr W. D. Lang, F.R.S., for his much-valued interest and encouragement; Professor F. H. Stewart, for his helpful criticisms of the typescript; the late Dr W. J. Arkell, F.R.S., and Mr M. Black, supervisors at different stages of the research. Dr R. M. S.

Perrin gave instruction, with great willingness, in techniques that he had developed for rapid inorganic chemical analysis and also supervised the clay mineral analyses. Dr L. R. Cox and Dr D. T. Donovan gave help in several taxonomic matters relating to pelecypods, gastropods (L. R. C.) and ammonites (D. T. D.). Finally, Dr S. R. Nockolds and Mr R. Allen kindly undertook a number of spectrographic analyses of strontium.

The research was carried out during the tenure of a D.S.I.R. Maintenance Grant at Cambridge.

References

Androussov, N. 1897 La Mer Noire. *VIIth Int. Geol. Congr.* **29**, 1–13.

Archanguelsky, A. D. 1927 On the Black Sea sediments and their importance for the study of sedimentary rocks. *Bull. Soc. Nat. Moscow*, **35**, 264–289.

Arkell, W. J. 1956 *Jurassic geology of the world.* Edinburgh: Oliver and Boyd.

Barnard, T. 1949 Foraminifera from the Lower Lias of the Dorset coast. *Quart. J. Geol. Soc. Lond.* **105**, 347–388.

Bathurst, R. G. C. 1958 Diagenetic fabrics in some British Dinantian limestones. *Liverp. and Manchr Geol. J.* **2**, 11–36.

Bohlin, B. 1949 The *Asaphus* Limestone of Öland, Sweden. *Bull. Geol. Instn Univ. Uppsala*, **33**, 529–570.

Boucot, A. J. 1953 Life and death assemblages among fossils. *Amer. J. Sci.* **251**, 25–40.

Brouardel, J. & Fage, L. 1955 Variation, en mer, de la teneur en oxygène dissous au proche voisinage des sediments. *Deep Sea Research*; supplement to vol. **33**, 40–44.

Brückner, W. D. 1953 Cyclic calcareous sedimentation as an index of climatic variations in the past. *J. Sediment. Petrol.* **23**, 235–237.

Caspers, H. 1957 'Black Sea and the Sea of Azov' in Treatise on marine ecology and paleoecology. *Mem. Geol. Soc. Amer.* **67**, 1, 803–890.

Correns, C. W. 1950 Zur Geochemie der Diagenese. *Geochim. et cosmoch Acta*, **1**, 49–54.

Coysh, A. W. 1931 U-shaped burrows in the Lower Lias of Somerset and Dorset. *Geol. Mag.* **68**, 13–15.

Dapples, E. C. 1942 The effect of macro-organisms upon near-shore marine sediments. *J. Sediment. Petrol.* **12**, 118–126.

Davis, E. F. 1918 The radiolarian cherts of the Franciscan Group. *Univ. Calif. Publ. Bull. Dep. Geol.* **11**, 366.

Dell, R. V. 1951 Some animal communities of the sea bottom from Queen Charlotte Sound, New Zealand. *N.Z. J. Sci. Tech.* **33**B, 19–29.

Donovan, D. T. 1952 The ammonites of the Blue Lias of the Bristol district. *Ann. Mag. Nat. Hist.* (12), **5**, 629–655; 717–752.

Donovan, D. T. 1956 The zonal stratigraphy of the Blue Lias around Keynsham, Somerset. *Proc. Geol. Ass. Lond.* **66**, 182–212.

Duncan, P. M. 1867 On the Madreporaria of the Infra-Lias of South Wales (chiefly from the Sutton and Southerndown Series). *Quart. J. Geol. Soc. Lond.* **23**, 12–28.

Elliot, G. F. 1953 The conditions of formation of the Lower Rhaetic at Blue Anchor, Somerset, and of the western European Rhaetic generally. *Proc. Geol. Soc. Lond.* 1494, xxxii.

Fiege, K. 1944 Lebensspuren aus dem Muschelkalk Nordwestdeutschlands. *Neues Jb. Min. Geol. Paläont.* B, **88**, 401–426.

Goldring, W. 1922 The Champlain Sea. *Bull. N.Y. St. Mus.* 239–240; 153–194.

Gunter, G. 1947 Paleoecological import of certain relationships of marine animals to salinity. *J. Paleont.* **21**, 77–79.

Hallam, A. 1957*a* Primary origin of the limestone–shale rhythm in the British Lower Lias. *Geol. Mag.* **94**, 175–176.

Hallam, A. 1957*b* The Rhaetic and Liassic beds at Tolcis, near Axminster. *Proc. Dorset Nat. Hist. Fld Cl.* **78**, 58–63.

Hallam, A. 1959*a* On the supposed evolution of *Gryphaea* in the Lias. *Geol. Mag.* **96**, 99–108.

Hallam, A. 1959*b* Stratigraphy of the Broadford Beds of Skye, Raasay and Applecross. *Proc. Yorks. Geol. (polyt.) Soc.* **32**, 165–184.

Hallam, A. 1960*a* The White Lias of the Devon coast. *Proc. Geol. Ass. Lond.* **71**. (In the Press.)

Hallam, A. 1960*b* A new trace-fossil from the Lias. *Palaeontology*, **2**. (In the Press.)

Hallam, A. & Payne, K. W. 1958 Germanium enrichment in lignites from the Lower Lias of Dorset. *Nature, Lond.* **181**, 1008–1009.

Harvey, H. W. 1955 *The chemistry and fertility of sea water.* Cambridge University Press.

Hesse, R., Allee, W. C. & Schmidt, K. P. 1937 *Ecological animal geography.* New York: Wiley.

Houbolt, J. J. H. C. 1957 'Surface sediments of the Persian Gulf near the Qatar Peninsula.' Doctorate thesis, Utrecht.

Humphrey, R. R. & Macey, R. W. 1930 Observations on some of the probable factors controlling the size of certain tidal pool snails. *Puget Sound Biol. Sta.* **7**, 205–258.

Illing, L. V. 1954 Bahaman calcareous sands. *Bull. Amer. Ass. Petrol. Geol.* **38**, 1–95.

Klüpfel, W. 1917 Über die Sedimente der Flachsee im Lothringer Jura. *Geol. Rdsch.* **7**, 97–109.

Krumbein, W. C. & Garrels, R. M. 1952 Origin and classification of chemical sediments in terms of pH and oxidation-reduction potentials. *J. Geol.* **60**, 1–33.

Kulp, J. L., Turekian, K. & Boyd, D. W. 1952 Strontium content of limestones and fossils. *Bull. Geol. Soc. Amer.* **63**, 701–716.

Lalou, C. 1957 Studies on bacterial precipitation of carbonates in sea water. *J. Sediment. Petrol.* **27**, 190–195.

Lang, W. D. 1914 The geology of the Charmouth cliffs, beach and foreshore. *Proc. Geol. Ass. Lond.* **25**, 293–360.

Lang, W. D. 1924 The Blue Lias of the Devon and Dorset coasts. *Proc. Geol. Ass. Lond.* **35**, 169–185.

Lombard, A. E. 1956 *Géologie sédimentaire; les Series marines.* Paris–Liège: Vaillant-Carmanne.

Millot, G. 1949 Relations entre la constitution et la genèse des roches sédimentaires argileuses. *Geol. appl. prosp. min.* **2**, 11–352.

Moore, C. 1867 On abnormal conditions of secondary deposits when connected with the Somersetshire and South Wales Coal-basins, and on the age of the Sutton and Southerndown Series. *Quart. J. Geol. Soc. Lond.* **23**, 449–568.

Moore, H. B. 1931 Muds of the Clyde Sea area. III. Chemical and physical conditions; rate and nature of sedimentation; and fauna. *J. Mar. Biol. Ass. U.K.* **17**, 325–366.

Newell, N. D. 1949 Phyletic size increase—an important trend illustrated by fossil invertebrates. *Evolution*, **3**, 103–124.

Perrin, R. M. S. 1957 The clay mineralogy of some tills in the Cambridge district. *Clay Mins. Bull.* **3**, 193–205.

Quenstedt, F. A. 1883 *Die Ammoniten des Schwäbischen Jura.* I. *Der schwarze Jura* (*Lias*). Tübingen:

Revelle, R. & Fairbridge, R. 1957 'Carbonates and carbon dioxide' in Treatise on marine ecology and paleoecology. *Mem. Geol. Soc. Amer.* **67**, 1; 239–295.

Richardson, W. A. 1923 Petrology of the 'Shales-with-Beef'. *Quart. J. Geol. Soc. Lond.* **79**, 88–98.

Richter, R. 1926 Flachseebeobachtungen zur Paläontologie und Geologie. XII. Bau, Begriff und paläogeographische Bedeutung von *Corophioides luniformis* (Blanckenhorn 1917). *Senckenbergiana*, **8**, 200–219.

Rieth, A. 1932 Neue Funde Spongeliomorpher Fucoiden aus dem Jura Schwabens. Mit einer zusammenfassenden Übersicht ähnlicher Gebilde aus triassischen und cretasischen Schichten Deutschlands. *Geol. paläont. Abh.* **19**, 257–293.

Robertson, J. D. 1941 The function and metabolism of calcium in the Invertebrata. *Biol. Rev.* **16**, 106–133.

Roger, J. 1939 Le genre *Chlamys* dans les formations Neogènes de l'Europe. *Mem. Soc. géol. Fr.* **17**, mem. no. 40, 1–294.

Schäfer, W. 1956 Wirkungen der Benthos-Organismen auf den jungen Schichtverband. *Senckenbergiana Leth.* **37**, 183–263.

Seibold, E. 1958 Jahreslagen in Sedimenten der Mittleren Adria. *Geol. Rdsch.* **47**, 100–117.

Seilacher, A. 1953 Studien zur Palichnologie. I. Über die Methoden der Palichnologie. *Neues Jb. Min. Geol. Paläont. Abh.* **96**, 421–452.

Simpson, G. G. 1953 *The major features of evolution.* New York: Columbia Univ. Press.

Simpson, S. 1957 On the trace-fossil *Chondrites*. *Quart. J. Geol. Soc. Lond.* **112**, 475–495.

Spath, L. F. 1942 The ammonite zones of the Lias. *Geol. Mag.* **79**, 264–268.

Spath, L. F. 1956 The Liassic ammonite faunas of the Stowell Park borehole. *Bull. Geol. Surv. G.B.* **11**, 140–164.

Strahan, A. *et al.* 1904 The geology of the South Wales Coalfield. Part IV. The geology around Bridgend. *Mem. Geol. Surv. G.B.* H.M. Stationery Office.

Sverdrup, H. U., Johnson, M. W. & Fleming, R. H. 1942 *The oceans, their physics, chemistry and general biology.* New York: Prentice-Hall.

Tarr, W. A. 1933 Origin of the 'beef' in the Lias shales of the Dorset coast. *Geol. Mag.* **70**, 289–294.

Tasch, P. 1953 Causes and paleoecological significance of dwarfed fossil marine invertebrates. *J. Paleont.* **27**, 356–444.

Trask, P. D. 1936 Relation of salinity to the calcium carbonate content of marine sediments. *U.S. Geol. Surv. Prof. Paper* 186–N, 273–299.

Troedsson, G. 1951 On the Höganas Series of Sweden. *Lunds Univ. Årsskr. N.F. Avd.* **2**, 47, 1–268.

Trueman, A. E. 1920 The Liassic rocks of the Cardiff district. *Proc. Geol. Ass. Lond.* **31**, 93–107.

Trueman, A. E. 1922 The Liassic rocks of Glamorgan. *Proc. Geol. Ass. Lond.* **33**, 245–284.

Trueman, A. E. 1930 The Lower Lias (*bucklandi* zone) of Nash Point, Glamorgan. *Proc. Geol. Ass. Lond.* **41**, 148–159.

Ulrich, E. O. & Bassler, R. S. 1923 Palaeozoic Ostracoda: their morphology, classification and occurrence. *Maryland Geol. Surv., Silurian Volume*, 271–391.

Weeks, L. G. 1953 Environment and mode of origin and facies relationships of carbonate concretions in shales. *J. Sediment. Petrol.* **23**, 162–173.

Woodward, H. 1863 On a new macrurous crustacean (*Scapheus ancylochelis*) from the Lias of Lyme Regis. *Quart. J. Geol. Soc. Lond.* **19**, 318–321.

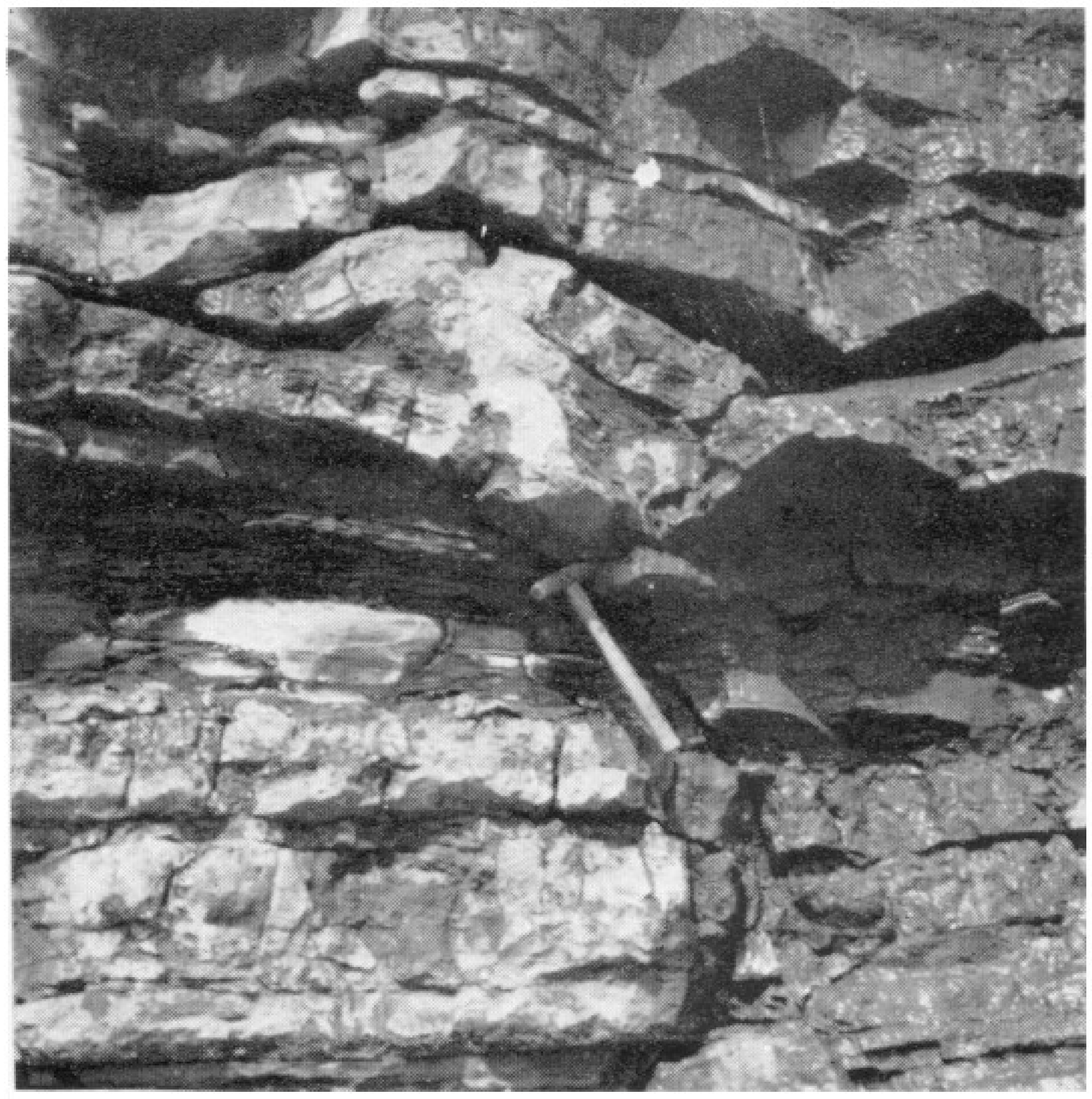
Yonge, C. M. 1946 On the habits of *Turritella communis* Risso. *J. Mar. Biol. Ass. U.K.* **26**, 377–380.

Yonge, C. M. 1953 Form and habit in *Pinna carnea* Gmelin. *Phil. Trans.* B, **237**, 335–374.

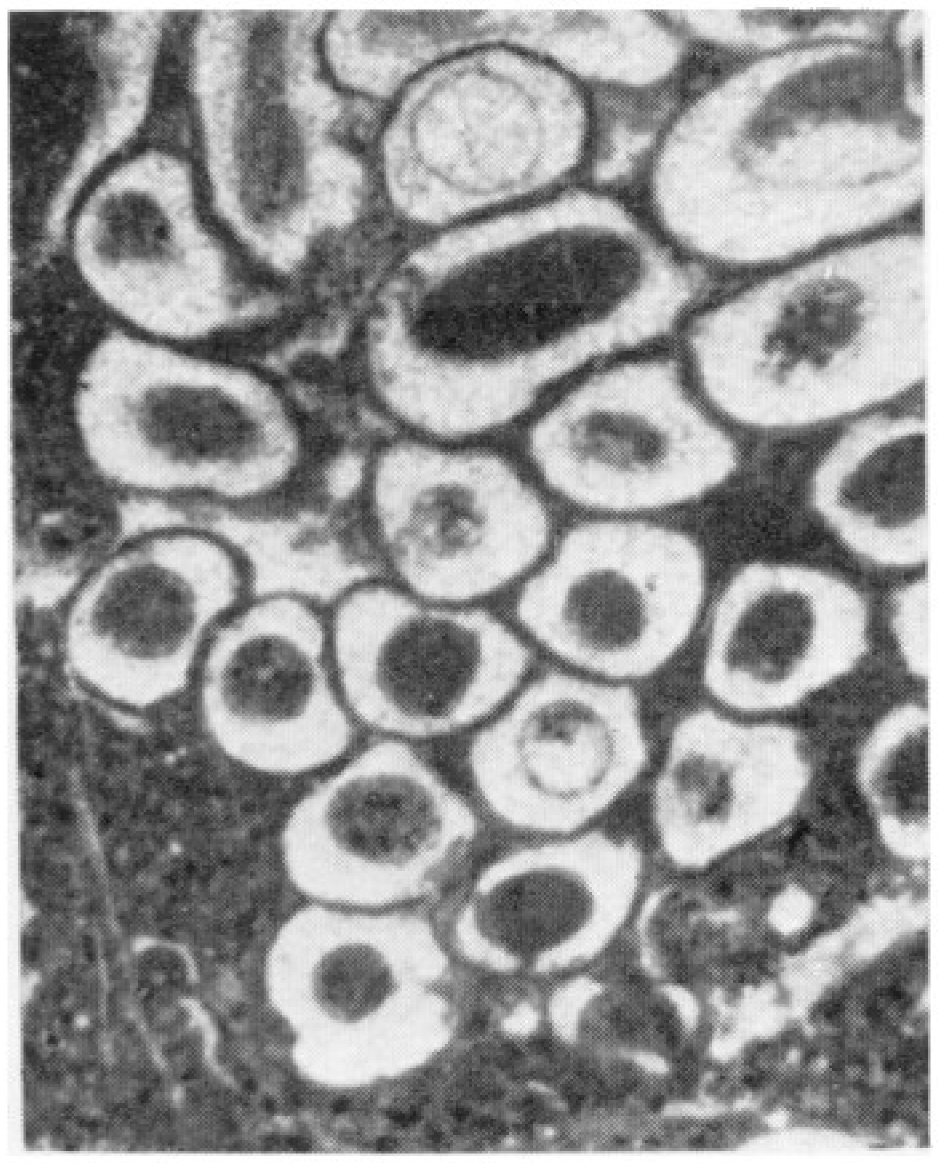
ZoBell, C. E. 1946 Studies on redox potential in marine sediments. *Bull. Amer. Ass. Petrol. Geol.* **30**, 477–513.

8

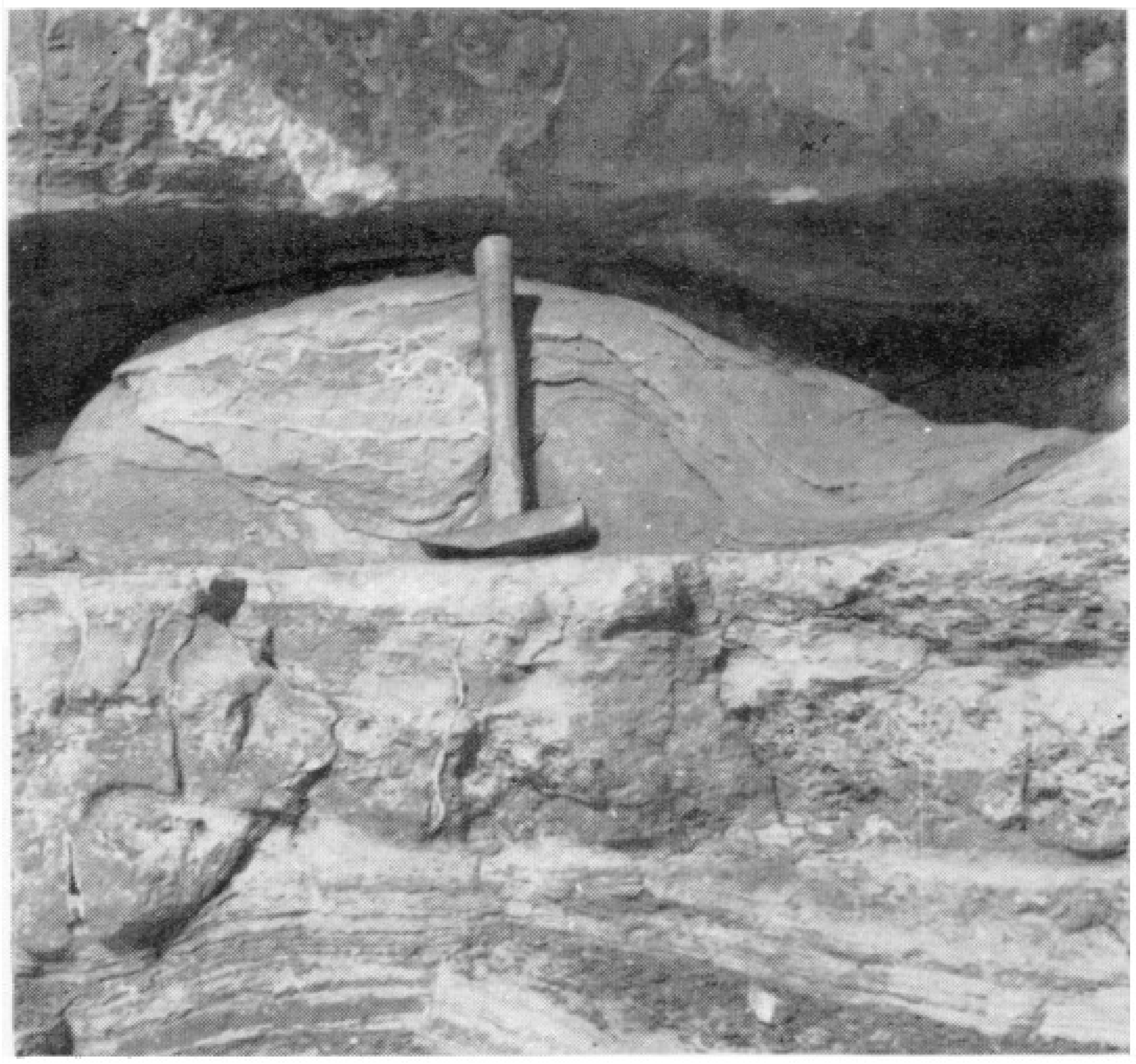
9



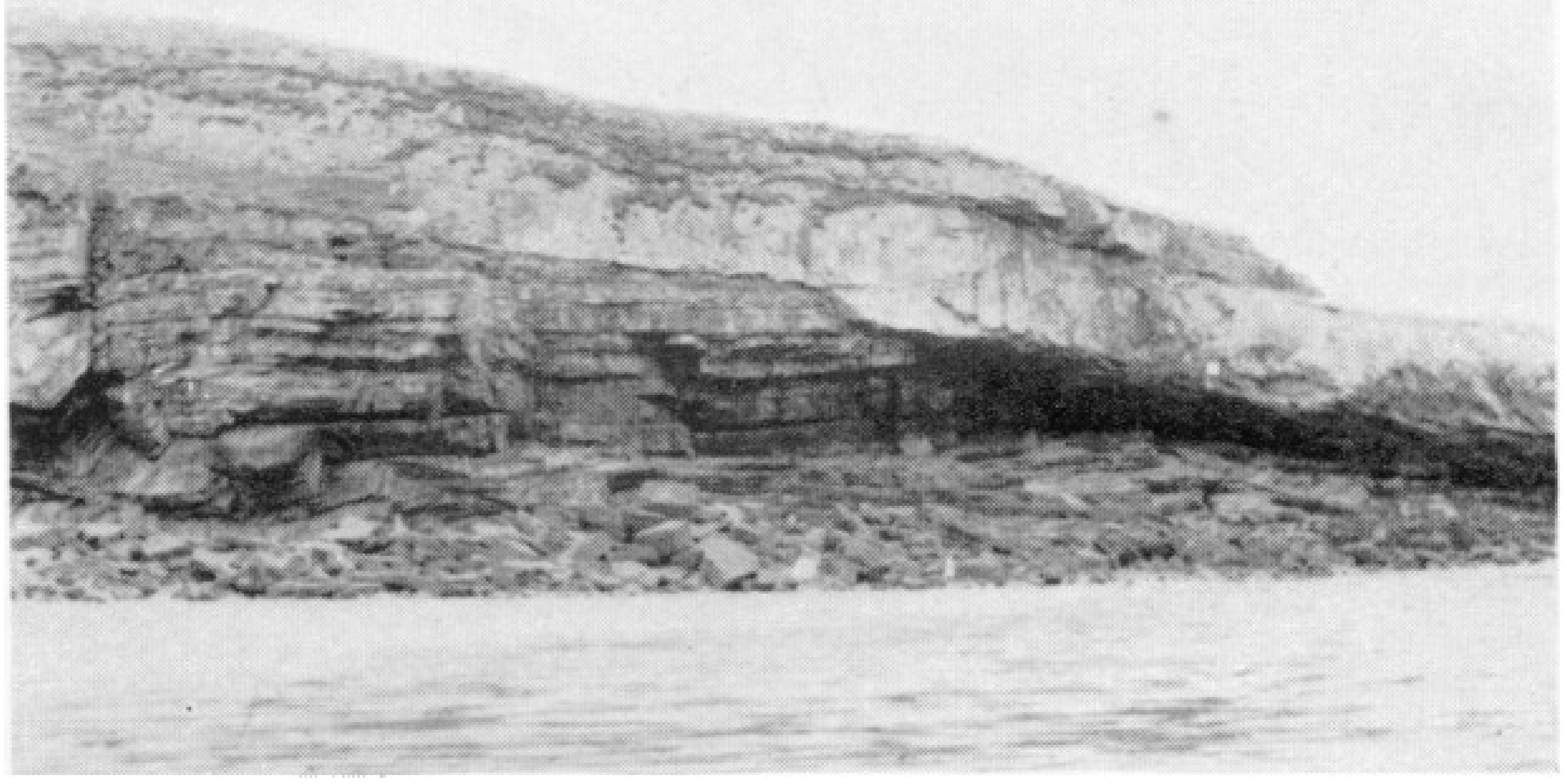
10



11



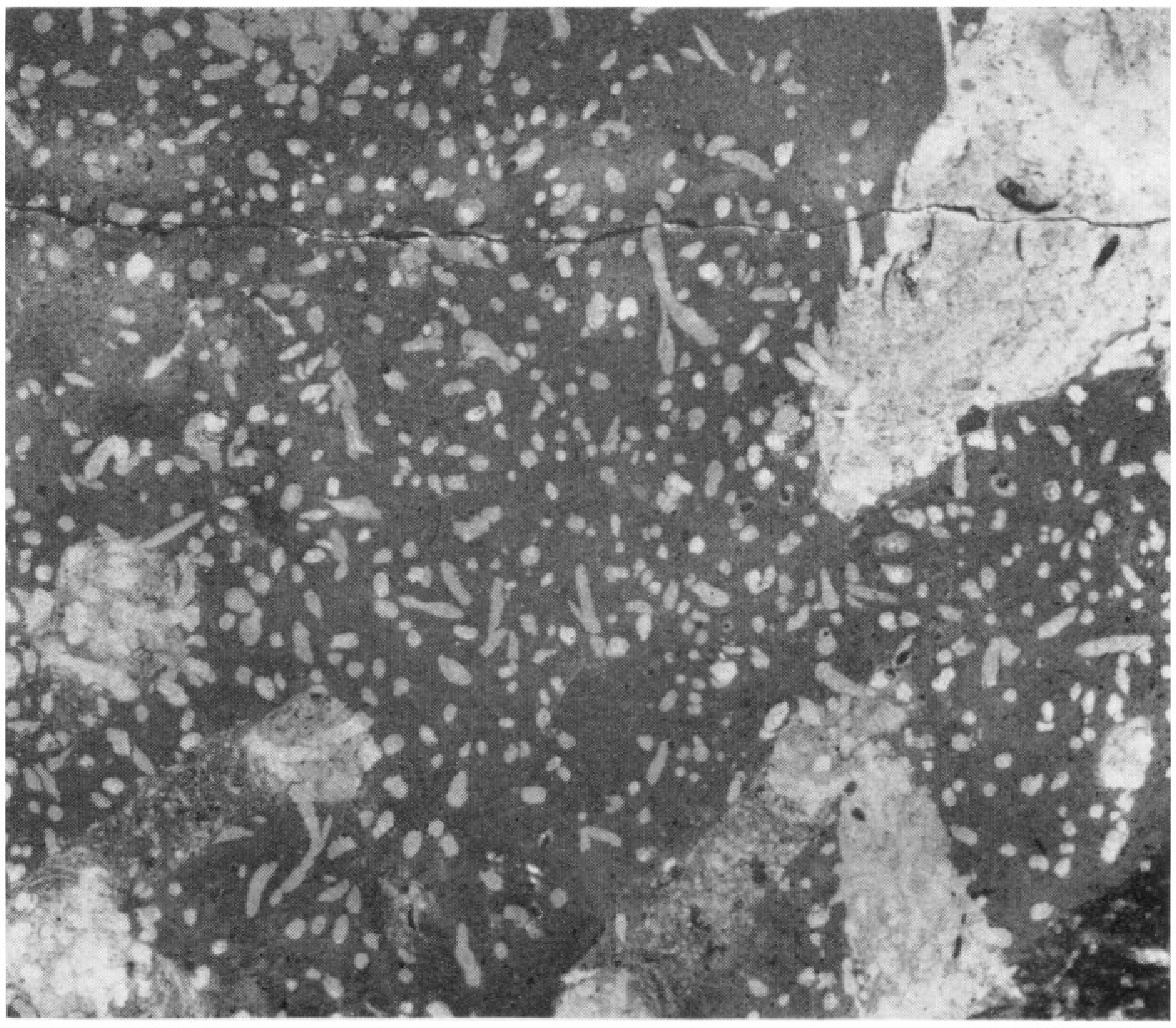
2



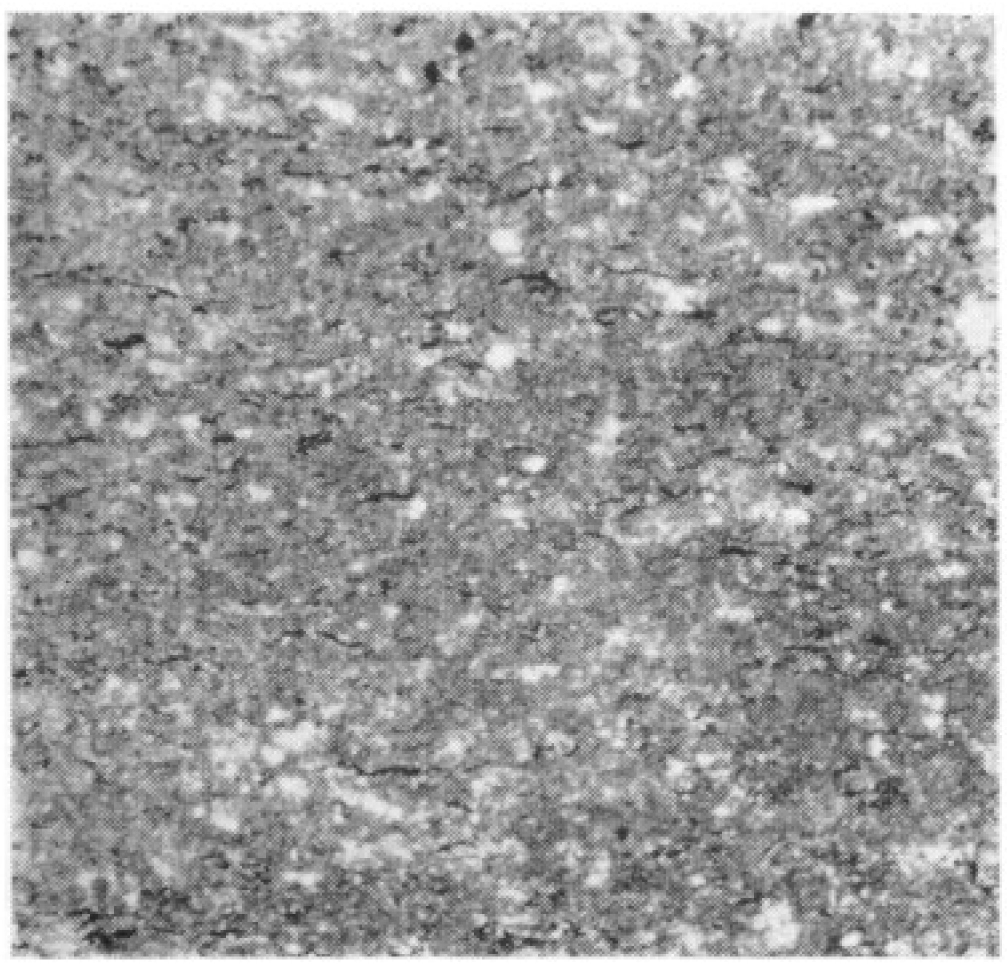
13

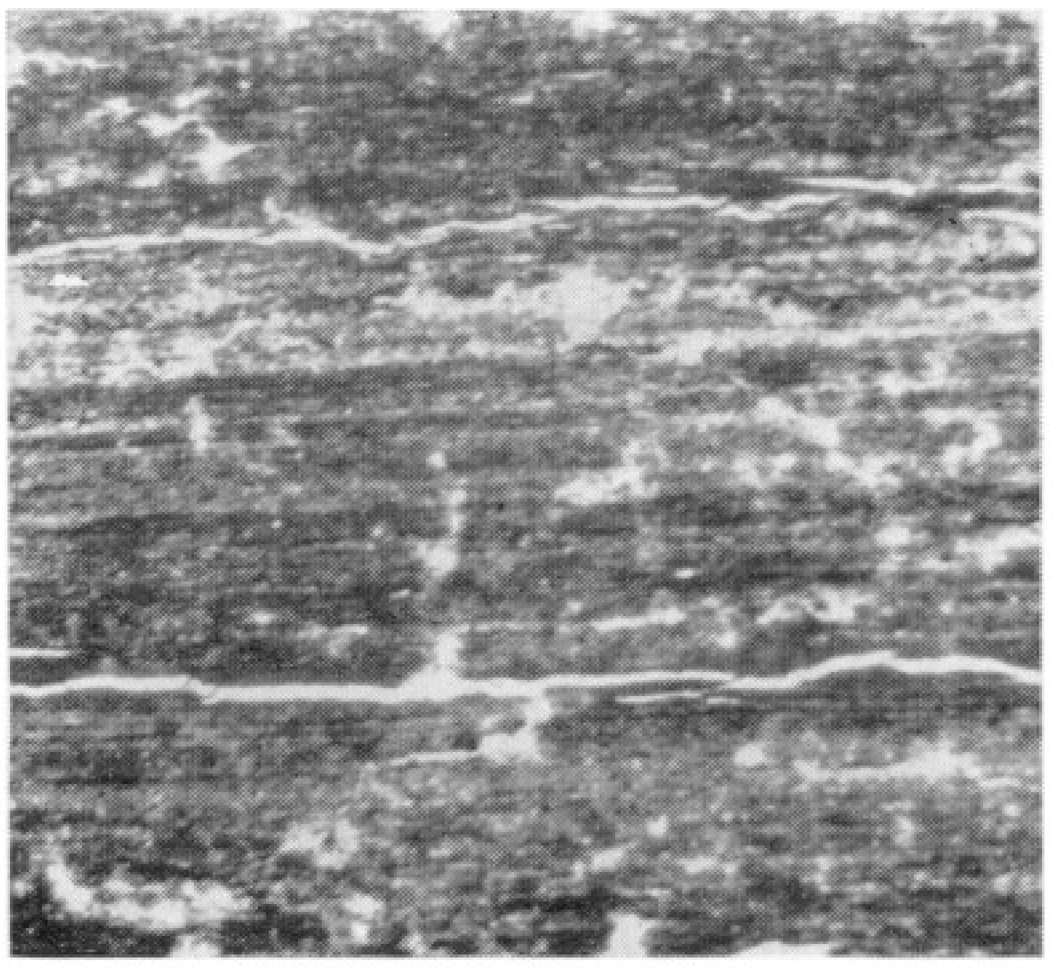
14

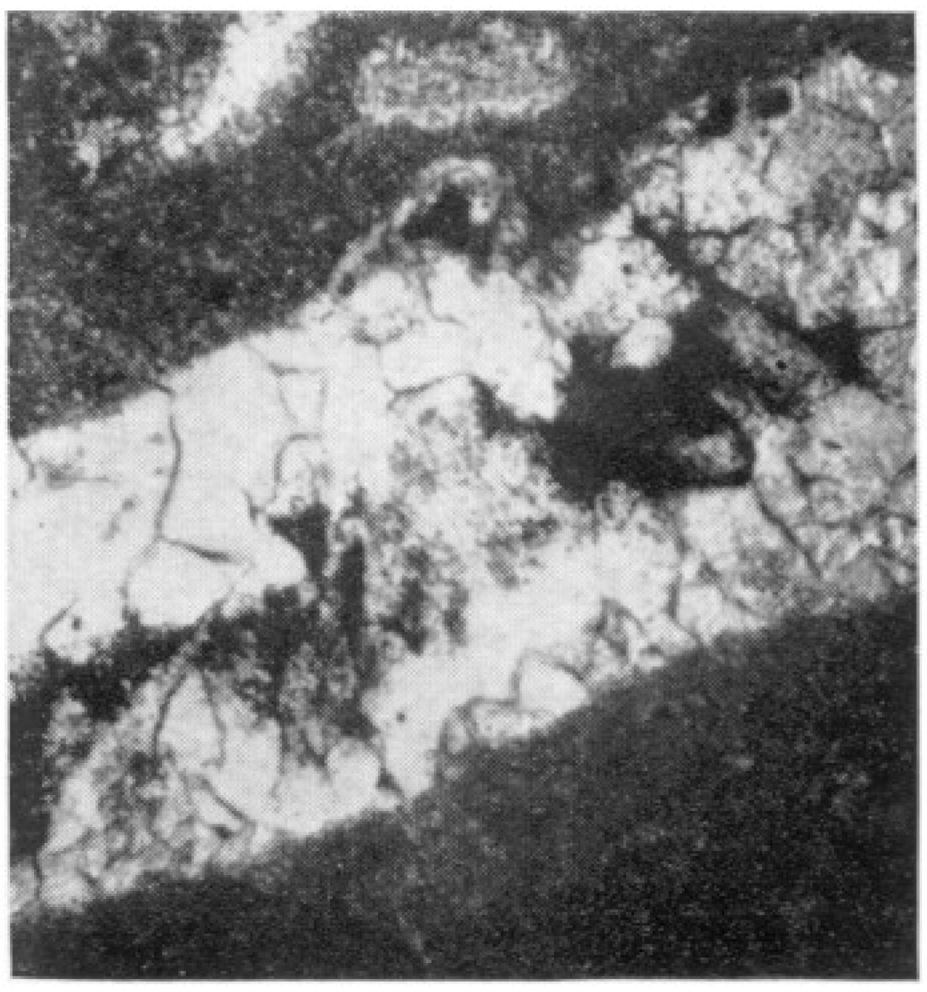
15



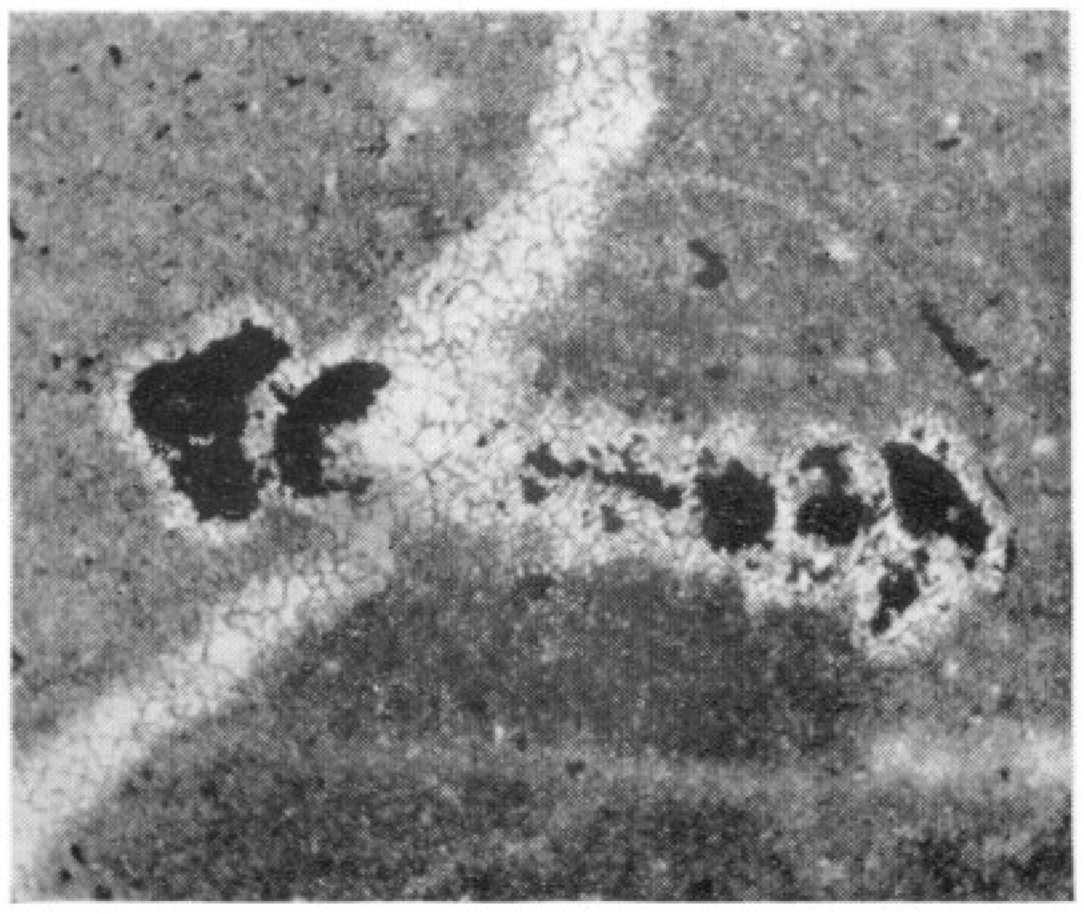
17

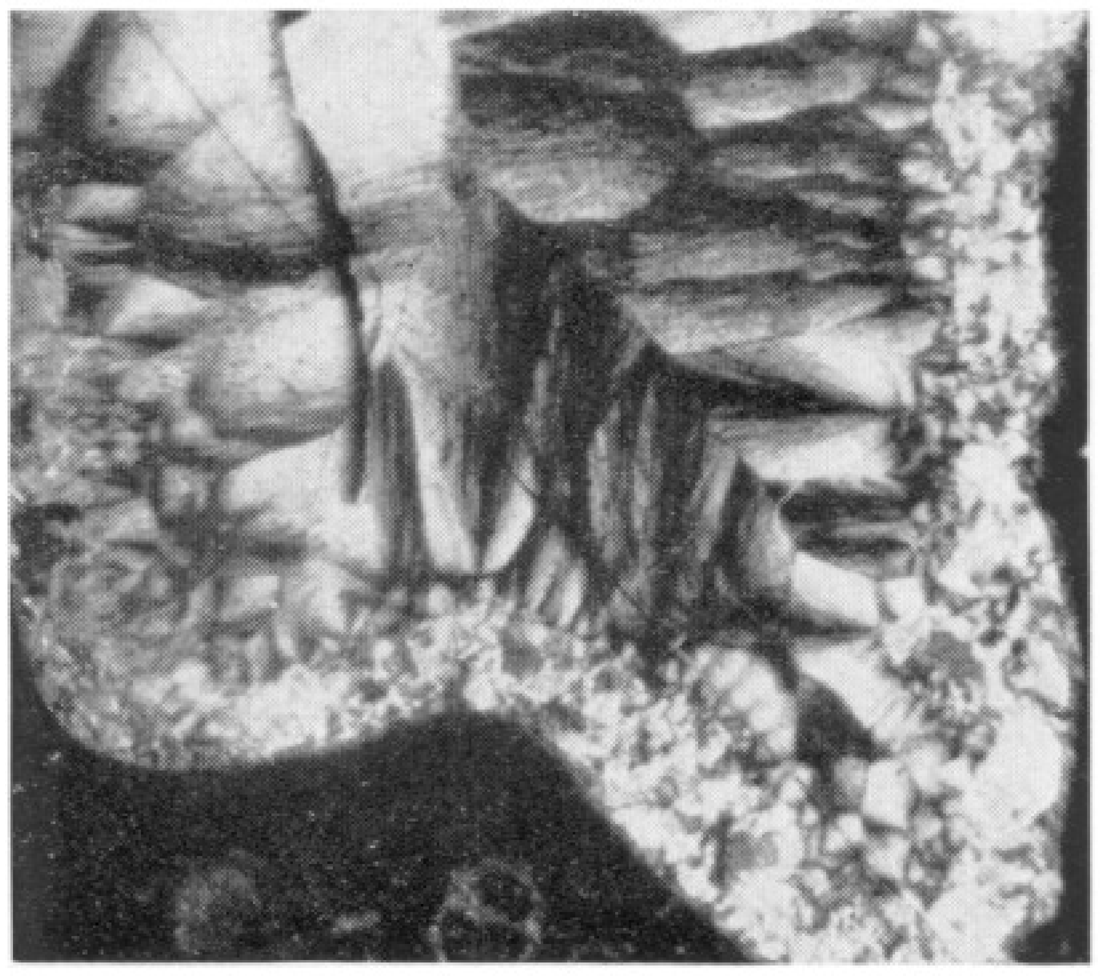


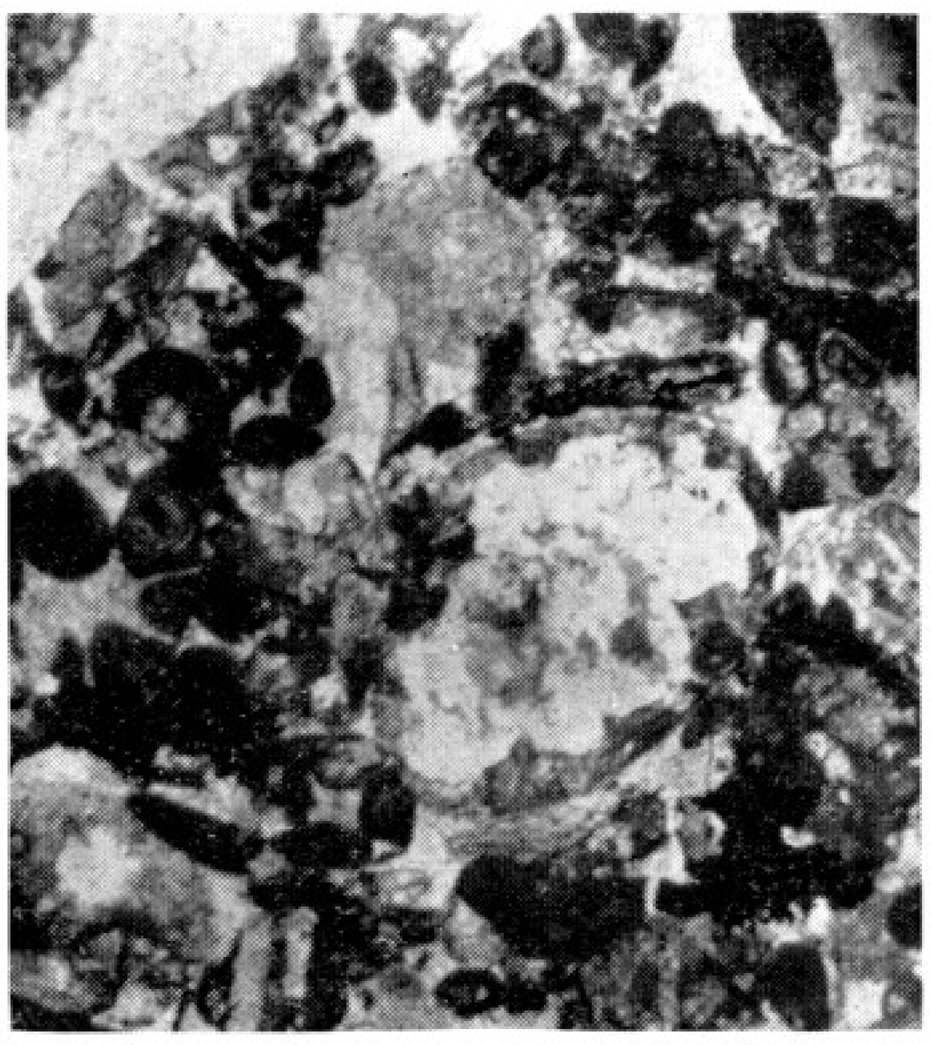




20







23