PETROLOGY OF THE LOWER AND MIDDLE PURBECK BEDS OF DORSET.

by

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ABSTRACT

Petrological study has shown the Lower Purbeck to contain five main facies reflecting variation in the salinity of the water during deposition of the sediment. At this time Dorset was a shelf bordering a shallow saline lagoon in the centre of which evaporites formed. On the shelf, dilution by freshwater at first allowed the growth of an abundant algal flora, and this was followed by an environment that resembled that of the Great Bahama Bank at the present day. Pellet limestones are typical of this facies, and there is evidence of epigenetic anhydrite. This is relevant to the origin of the Broken Beds.

Salinities were reduced by influx of freshwater from the west and an abundant fauna became established. Restriction of this influx and evaporation then caused a return to evaporitic conditions, and carbonate mud was the dominant sediment, with gypsum deposited locally. Algae were again abundant at times. The Lower Purbeck ended with the Dorset area as a freshwater lake in which *Chara* was abundant, conditions that continued into Middle Purbeck time and until ended by a marine incursion which resulted in the formation of oyster banks.

A bioclastic and a terrigenous facies are recognised in the Middle Purbeck. The bioclastic facies comprises shell limestones and pure carbonate-mudstones, and formed under con-

ditions that varied from freshwater to almost normal marine. The terrigenous facies consists of shales and calcareous sandstones formed of land derived sediment originating to the west. This facies probably represents initial phases of Wealden sedimentation.

The dominant sediment of both Lower and Middle Purbeck was carbonate mud. In the Lower Purbeck much of this is believed to have formed by physico-chemical precipitation, some from algal activity. In the Middle Purbeck much of the mud is derived from algae, especially *Chara*, and from shell comminution. Physico-chemical precipitation was much less important.

"Every stratigraphic section in the literature should be accompanied by a petrographic description of at least the major rock types, just as they are always accompanied by lists of fossils. A great many geologic problems might be answered if such a procedure were common practice."

Robert L. Folk (1954).

CONTENTS

I. INTRODUCTION

(a) General

The stratigraphy of the Jurassic system is probably better known in Britain than in any other country. It has been said that "In England, in the sphere of Jurassic geology, we are wardens of a classic area, for our cliffs and quarries are the standards of comparison for the whole world." (Arkell 1933). Nevertheless, when we come to look for petrographic descriptions of the rocks of this classic area, we find that, with a few exceptions, none exist. Palaeontological division of the system into stages, zones and sub-zones has reached a high degree of refinement, but the rocks have often been described in such general terms as "sandstone", "shale", "marl", or "limestone". This was perhaps understandable when the emphasis was on fossil identification and correlation, but that is only a part of stratigraphic synthesis and must be accompanied by descriptions of the rocks themselves if reliable palaeogeographical interpretation is to be attempted.

A reconstruction of sedimentary environments based solely on a study of the fauna depends on accuracy of identification, and should this be faulty then the conclusions drawn will be in error to a greater or lesser extent. The present study serves as an example of this.

The Purbeck has been described as an example of freshwater sedimentation and from it a number of genera of freshwater ostracods have been described. As will be shown, a petrological study of the sediments would have raised doubts as to the validity of some of these identifications before Anderson (1959) showed that the Lower Purbeck ostracods in particular have been mis-identified and are in fact representatives of a super-saline family.

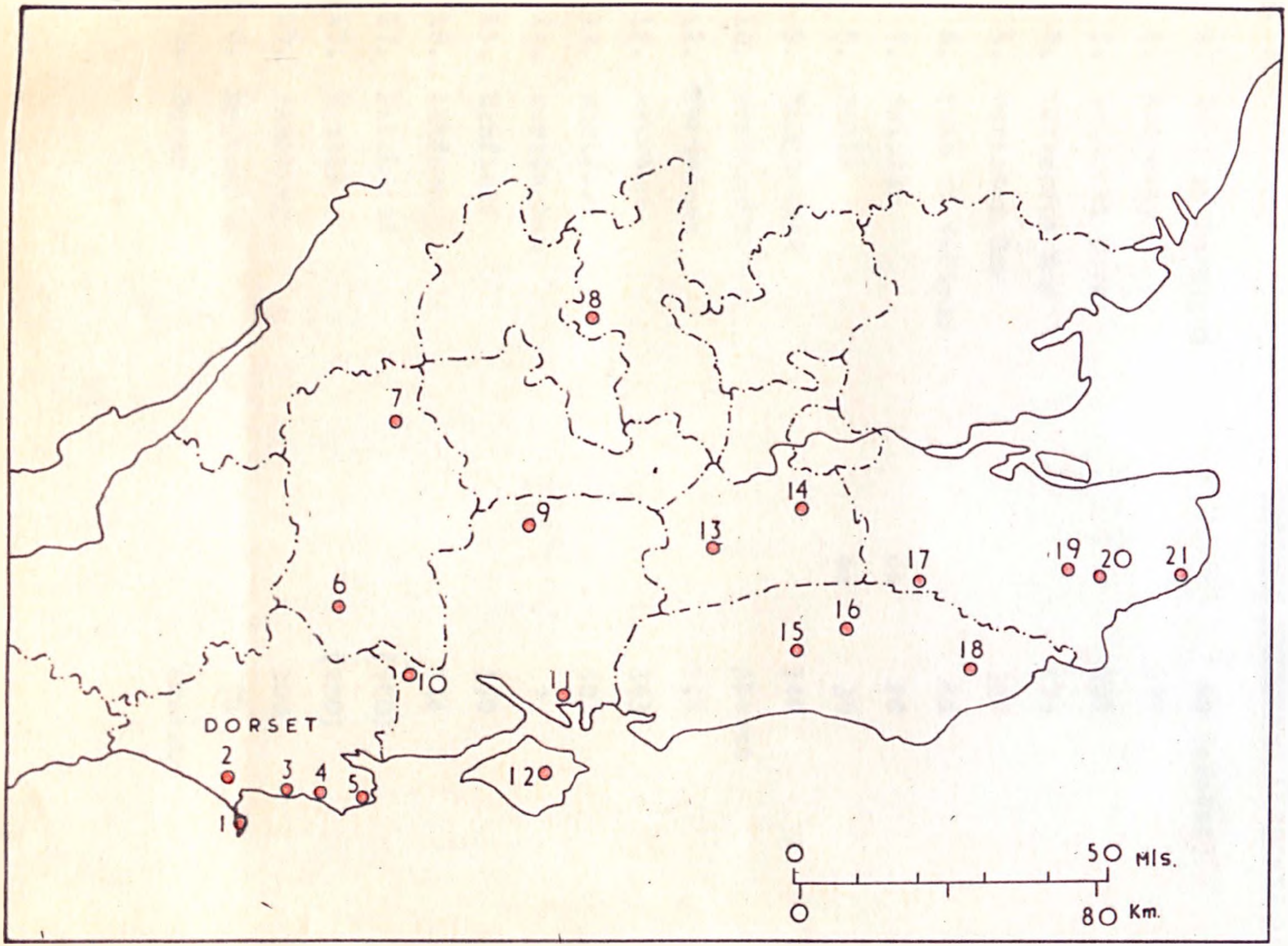
Stratigraphers and petrologists alike have, however, often ignored the petrology of the carbonates, mainly owing to the "recrystallisation" that many of these rocks appeared to have undergone. In recent years, the economic importance of many carbonate rocks - for example as oil reservoirs - has encouraged their study in both economic and academic fields, with the result that an understanding of them is becoming more practicable.

Of particular importance in the development of such an understanding are studies of modern carbonate deposition such as on the Bahama Banks. Recently, for example, Beales (1958) has interpreted the depositional environment of a group of Palaeozoic limestones by applying the observations of Illing (1954) in his study on the Bahaman calcareous sands. A warning against too free an adaption of observations on modern deposits in the interpretation of older carbonates is served by investigations such as those of Cullis (1903) on the mineralogical changes in the Funafuti reef cores, and Ginsberg (1957) in Florida, which show just how complex even early diagenetic changes can be. However, petrographic descriptions can always be given even if the petrogenesis is more uncertain. A current trend in research is towards re-examination of stratigraphically well-known areas with a view to determining the petrology of the rocks within them. The subject of this work is the examination of one particular series of rocks in such an area.

The Purbeckian is the youngest of the Jurassic stages as defined by Arkell (1956). It outcrops in Dorset, Wiltshire, Buckinghamshire and Sussex and is known, from subsurface data, beneath Hampshire and Kent (Map 1.). The Dorset outcrops are the more extensive, occurring from Durlston Bay in the Isle of Purbeck in the east, to Portisham in the west, a distance along the strike of 40 Km., and on the Isle of Portland to the south (Map 2.). This is the type area for the Purbeckian and it is a study of this area that is here discussed.

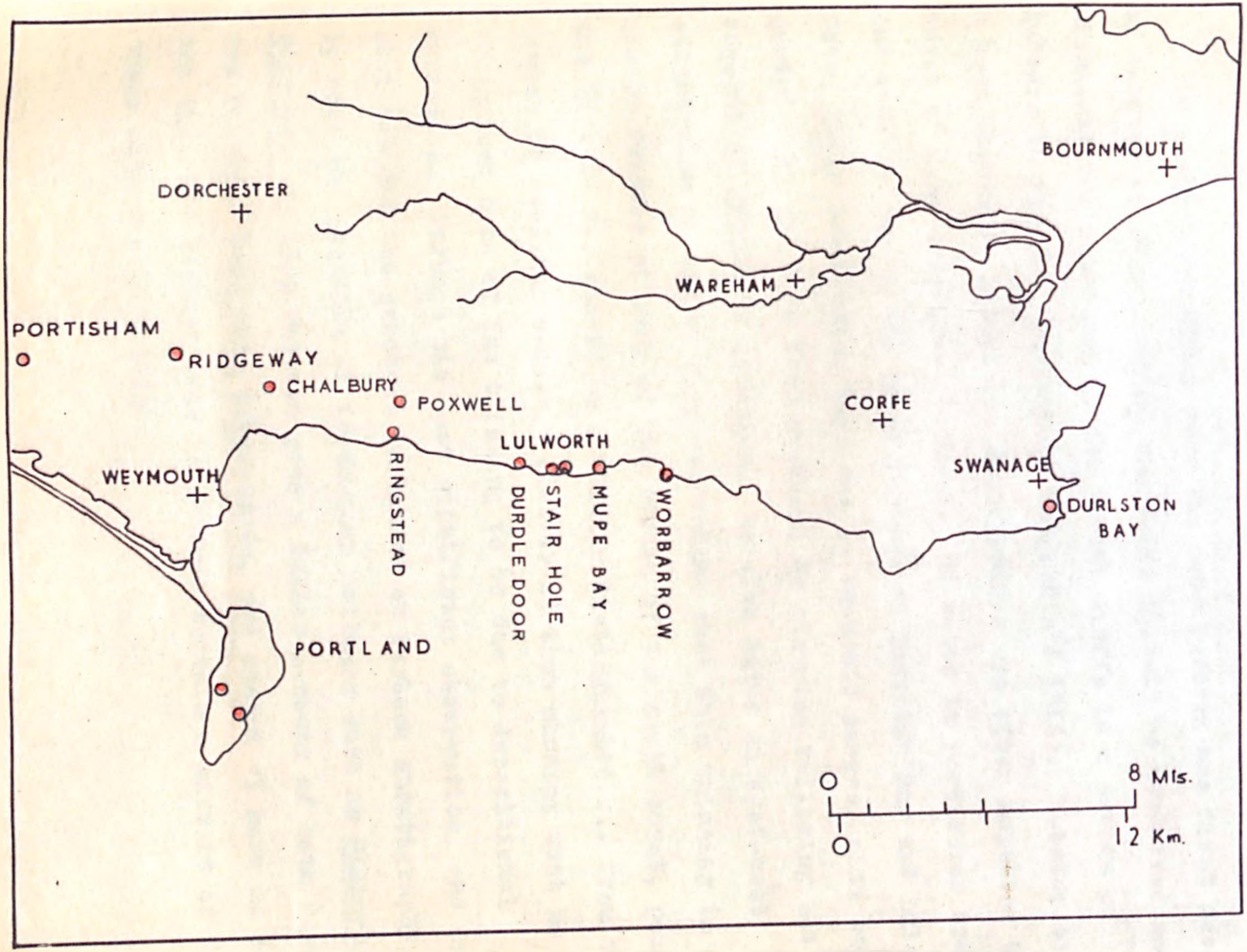
Localities where the beds have been studied are Durlston Bay, Worbarrow Bay, Mupe Bay, Lulworth Cove and on the Isle of Portland, all coastal sections, and inland at Portisham and Ridgeway. These last two localities are now almost completely overgrown and most of the details have been taken from published accounts. Other scattered exposures occur in old quarries on the Isle of Purbeck, and at Chalbury, Poxwell and Ringstead, to the north and east of Weymouth.

MAP I


DORSET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
0
50 Mls.
0
80 Km.

LOCATIONS FOR MAP 1

			Purbeck thickness (approx) in feet.
1.	Isle of Portland		60 (eroded)
2.	Ridgeway		189
3.	Lulworth Cove		198
4.	Worbarrow Bay		273
5.	Durlston Bay		396
6.	Vale of Wardour		85
7.	Swindon	ca	20
8.	Brill	ca	30
9.	Kingsclere		540
10.	Fordingbridge		Absent
11.	Portsdown		248
12.	Arreton		343
13.	Shalford		503
14.	Warlingham		?
15.	Henfield		360
16.	Ashdown		534
17.	Penshurst		(560)
18.	Battle		(400)
19.	Pluckley		100
20.	Brabourne		78
21.	Dover		Absent



DORCHESTER
BOURNMOUTH
WAREHAM
PORTISHAM
RIDGEWAY
CHALBURY
POXWELL
CORFE
LULWORTH
WEYMOUTH
RINGSTEAD
DURDLE DOOR
STAIR HOLE
MUPE BAY
WORBARROW
SWANAGE
DURLSTON BAY
PORTLAND
0
8 Mls.
0
12 Km.

MAP II

(b) History of previous work.

As a stratigraphical term the name Purbeck was first used by Webster in 1811. During the years 1811-15 he described and discussed the exposures in the Dorset cliffs in a series of letters to Sir H.C. Englefield (Englefield 1816). Webster was a keen observer, indeed his descriptions are often superior to those of many subsequent workers. He noted in particular breccias and contortions in the Lower Purbeck of Durlston Bay and Lulworth Cove, while considering them due to tectonic causes, also suggested they may have been produced by slumping following the removal of gypsum by solution. He also noted an east-west attenuation of strata and, commenting that this thinning is a common feature of many of the strata of the south coast, pointed out that it "...should be carefully distinguished ... from the action of denuding causes," (Letter X) thus showing that he recognised some of the thinning to be due to depositional variation. Perhaps his most significant observation, and one that has had the greatest influence on Purbeck stratigraphy, was to note the presence of freshwater molluscs such as <u>Planorbis</u> and <u>Valvata</u>. In 1829 Webster gave a fuller account of both Purbeck and Portland beds with thicknesses, and stated "I have no doubt but that the Purbeck beds in general contain a mixture of freshwater with marine shells".

The junction between the Portland and Purbeck was for some time a matter of controversy. Both Webster and Fitton (1835) placed the boundary at the base of the Caps. (For nomenclature see Table I and fig. 1. in pocket). Buckland and de la Beche (1836) took the base of the main Dirt Bed on the Isle of Portland as the junction saying, "We consider this Dirt Bed as quite decisive in forming the barrier between the Portland and Purbeck formations." It was soon pointed out, however, that other, thinner, dirt beds occur in the Caps below, and ultimately it was generally agreed that the junction be taken as being at the base of the Caps. The first comprehensive account of the Purbeck of southern England was given by Fitton (1836) in his classic paper on the "Strata between the Chalk and the Oxford Oolite".

Most early workers grouped the Purbeck with the conformably overlying Wealden, but in 1850 Forbes separated the two formations, classifying the Wealden with the Cretaceous and the Purbeck with the Oolites (Jurassic). He divided the Purbeck into Upper, Middle and Lower divisions, and, paying particular attention to the fauna, indicated several alternations between a freshwater and marine environment in the Middle Purbeck. The three divisions were in turn subdivided into lithological units by Bristow (1857) most of which are still retained (Table I).

The next account of the Dorset Purbeck was by Fisher (1856) and included detailed tabulation of the strata at Durlston Bay and Ridgeway. He noted that the beds became sandier and contain more terrestrial material from east to west, and introduced the vegetation collapse hypothesis to account for the Broken Beds, a full discussion and criticism of which has been given by Arkell (1938).

The Geological Survey 1 inch map of the area was published in 1850, with detailed vertical sections which remain indispensible in the study of the coastal exposures (Bristow 1957, Bristow and Whitaker 1859). In 1860 Damon published a 'Geology of Weymouth, Portland and the coast of Dorset' which in a 2nd edition of 1884 contains a good account of the Purbeck of Durlston Bay. Andrews and Jukes-Brown (1894) showed that the lithological sub-divisions adopted in Dorset, could, in part, be recognised in the Vale of Wardour.

In 1895 Woodward published a detailed account of the Purbeck beds of England, in Part V of the memoir on the 'Jurassic Rocks of Britain'. The publication in 1898 of the Geological Survey memoir on the 'Geology of the Isle of Purbeck and Weymouth' added little new (Strahan, referred to hereafter as the Purbeck Memoir). These two works remain standard references on Purbeck stratigraphy together with the memoir on the 'Geology of the country around Weymouth, Swanage, Corfe and Lulworth' (Arkell 1947, referred to hereafter as the Weymouth

Memoir).

The Purbeck abounds in ostracods which, in the absence of ammonites, have been used for zoning. The earliest attempt at this was by Lyell (1855) but it was Jones (1885) who first published detailed descriptions of genera and species. He assigned five species to the Lower Purbeck and six to the Middle and Upper. In summarising the earlier work Strahan (1898, p. 90) presented a still acceptable classification which has, however, been refined by Anderson (1941) and Sylvester Bradley (1949) and which is illustrated in Table I.

Ostracods are sensitive indicators of salinity and Anderson (1932) showed how they could be used to trace variations in the salinity of the water during the earlier Middle Purbeck. He has since greatly extended his work to cover the whole formation in England, and the Purbeck of the Jura and Northern Germany, but this is as yet unpublished (personal communication).

The stratigraphic classification of the Purbeck was long a matter of debate, the history of which is given by Strahan (1898) (pp. 72-77) and Arkell (1933, pp. 548-556). It is now accepted as being uppermost Jurassic in age even though it passes conformably into the Wealden, which is regarded as Lower Cretaceous.

(c) The Present Study

(i) <u>Objects</u>. -

Previous study of the Purbeck has been concerned with stratigraphy and various aspects of palaeontology. Nothing has

TABLE I

Purbeck Nomenclature and Ostracod Zones

UPPER	Cypridea setina	Viviparus Clays Upper Cypris Shales Unio Beds Upper Broken Shell Limestone
MIDDLE	C. propunctata	Chief Beef Beds Corbula Beds Scallop Beds
	C. fasiculata	Intermarine Beds Cinder Bed Cherty Freshwater Beds
	C. granulosa	Marly Freshwater Beds
LOWER	Candona bononiensis	Soft Cockle Beds Hard Cockle Beds
	Cypris purbeckensis	Cypris Freestones Broken Beds Hard and Soft Caps

been done on the sediments; indeed, microscope examination appears limited to brief descriptions of some half dozen random thin sections (Sorby 1879, p. 79; Strahan 1898, p. 79; and Chapman 1905, p. 283) and the beds are described in such general terms as shelly limestone or rubbly marl. This tells us very little about conditions of sedimentation, particularly as the Purbeck beds show frequent lithological changes which represent response to environments which changed rapidly, as will be shown, from evaporitic to marine, marine to brackish and brackish to freshwater.

The prime object of the work described here, therefore, was a study of the petrology of the Purbeck sediments in Dorset, and the limestones in particular. In addition, lateral facies changes and sedimentary structures were to be used to develop a better picture of the palaeogeography during Purbeck time. Subsequently an additional object of research developed with the discovery of abundant calcareous algae in the Lower Purbeck. The mode of occurrence and effect of these plants on sedimentation became an important part of the work.

(ii) Methods. -

All sections of the Purbeck in Dorset were remeasured and detailed examination and sampling were carried out. A low power (x5) reading lens of 3" diameter proved very useful in the field for preliminary examination of the strata. Samples of all major beds were examined in the laboratory using standard procedures; thin sections, polished surfaces, stained surfaces and acetate peels. Details of these and other techniques are given in the appendices.

In all some 800 samples were collected of which 450 were either thin sectioned or peeled, and some 300 polished surfaces were prepared. A total of 7 months was spent in the field, the investigation being hampered to some extent by the situation of two of the localities, Worbarrow Bay and Mupe Bay, in a War Department firing range; consequently less time was spent on these sections.

(iii) Nomenclature. -

Carbonates have been more afflicted with confused terminology than perhaps any other class of rocks. The same name is applied to different things, or different names to the same thing, and though attempts have been made to produce unified nomenclature the subject is complex. Currently a committee sponsored by the American Association of Petroleum Geologists is working on the problems of classification and description of carbonate rocks, and perhaps an acceptable scheme may be developed, but it behoves each worker to state clearly the meaning of the terms he uses.

A good discussion of nomenclatorial and other problems has recently been published by Folk (1959) who proposed a classification to be applied to "unrecrystallised" marine limestones, with a nomenclature that indicates the nature of the components and matrix of the rock. Basically it is simple and straightforward and throughout this work, where possible, Folk's terminology is given. As he admits, some rocks will not fit into the classification as it now stands, and where these occur an attempt is made here to name them in a suitable manner. Figure 2 illustrates Folk's terminology.

Figure 2

<table>
<tr><td colspan="5" rowspan="4"></td><td colspan="6">LIMESTONES DOL. LIMESTONES & DOLOMITES</td></tr>
<tr><td colspan="2">>10% ALLOCHEMS
ALLOCHEMICAL ROCKS</td><td colspan="3"><10% ALLOCHEMS
MICROCRYSTALLINE ROCKS</td><td></td></tr>
<tr><td>SPARRY CALCITE CEMENT > MICRO CRYSTALLINE OOZE MATRIX</td><td>MICROCRYSTALLINE OOZE MATRIX > SPARRY CALCITE CEMENT</td><td colspan="2" rowspan="2">1 — 10 %
ALLOCHEMS</td><td rowspan="2"><1 % ALLOCHEMS</td><td rowspan="2">UNDISTURBED BIOHERM ROCKS</td></tr>
<tr><td>SPARRY ALLOCHEMICAL ROCKS</td><td>MICROCRYSTALLINE ALLOCHEMICAL ROCKS</td></tr>
<tr><td rowspan="5">VOLUMETRIC ALLOCHEM COMPOSITION</td><td colspan="4">> 25 % INTRACLASTS</td><td>INTRASPARRUDITE
INTRASPARITE</td><td>INTRAMICRUDITE
INTRAMICRITE</td><td rowspan="5">MOST ABUNDANT ALLOCHEM</td><td>INTRACLASTS:
INRACLAST-BEARING MICRITE</td><td rowspan="5">MICRITE if disturbed DISMICRITE</td><td rowspan="5">BIOLITHITE</td></tr>
<tr><td rowspan="4">< 25 % INTRACLASTS</td><td colspan="3">> 25 % OOLITES</td><td>OOSPARRUDITE
OOSPARITE</td><td>OOMICRUDITE
OOMICRITE</td><td>OOLITES:
OOLITE-BEARING MICRITE</td></tr>
<tr><td rowspan="3">< 25 % OOLITES</td><td rowspan="3">VOLUME RATIO OF FOSSILS TO PELLETS</td><td>> 3 : 1</td><td>BIOSPARRUDITE
BIOSPARITE</td><td>BIOMICRUDITE
BIOMICRITE</td><td>FOSSILS:
FOSSILIFEROUS MICRITE</td></tr>
<tr><td>3:1 — 1:3</td><td>BIOPELSPARITE</td><td>BIOPELMICRITE</td><td rowspan="2">PELLETS
PELLETIFEROUS MICRITE</td></tr>
<tr><td><1 : 3</td><td>PELSPARITE</td><td>PELMICRITE</td></tr>
</table>

II. STRATIGRAPHY AND STRUCTURE

(a) General

Division into Lower, Middle and Upper Purbeck and subsequent sub-division into lithological units was made by Forbes (1850) and Bristow (1857, 1859) in the Dorset type area. These divisions and their modern zonal equivalents are shown in Table I.

In Dorset the Purbeck beds have a maximum thickness of about 121 m. (396 ft.) at Durlston Bay though most of the lower division here is now un-exposed. They are 83 m. (273 ft.) thick at Worbarrow Bay, 71 m. (232 ft.) at Mupe Bay, 60 m. (198 ft.) at Lulworth, 57 m. (189 ft.) at Ridgeway, but thicken to about 67 m. (220 ft.) nearby (Anderson 1958, p. 120). At Stair Hole and Durdle Door, 800 m. west of Lulworth, strike faults have cut out parts of the succession but Arkell (1938, p. 27) calculated their original thicknesses at 45 m. (146 ft.) and 42 m. (138 ft.) respectively, indicating considerable thinning in this area. Only about 25 m. (75 ft.) of Lower Purbeck remains on the Isle of Portland. All these thicknesses must only be approximate owing to (a) lack of continuous exposure in the sections, (b) probable tectonic thinning of some of the softer beds, and (c) the removal by solution of unknown amounts of gypsum. Table II shows the approximate thicknesses of the three divisions at the main localities.

The junction between Upper and Middle Purbeck is taken at the bottom of the Broken Shell Limestone. This is a well defined lithological break easily recognised at each locality. Between Middle and Lower Purbeck the boundary is more difficult to determine. Palaeontologically the first appearance of the ostracod Cypridea granulosa at the base of the Marly Freshwater Beds is taken as the division.

This division, between the Marly Freshwater Beds and the underlying Soft Cockle Beds, is generally not well exposed or is badly weathered, and from a descriptive point of view it would be best to take the boundary between Middle and Lower Purbeck as being the base of the Cherty Freshwater Beds, treating the Marly Freshwater Beds as Lower Purbeck. This has been done in this thesis.

Bristow's sub-divisions have been used to the present day, and are readily distinguishable at each locality. They are not ideal, however, as frequently they differ lithologically from one locality to another. Thus, the Hard Cockle Beds from Lulworth to Worbarrow consist of hard, sandy and shelly limestones (sandy pelsparites), whereas at Durlston Bay the equivalents are composed of shales and calcite-mudstones (micrites). Then too, save for the brecciation, there is no apparent major lithological difference between the Broken Beds and Cypris

TABLE II

Approximate Thicknesses of the Purbeck Divisions

	Lower	Middle	Upper	Total
Durlston Bay	(50.50)	50.60	(19.40)	120.50
Worbarrow Bay	40.20	30.42	(12.40)	83.02
Mupe Bay	37.84	17.45	(15.70)	71.00
Lulworth Cove	37.86	14.99	(7.12)	59.97
Ridgeway	(28.07)	(14.64)	(14.90)	(57.61)

Thicknesses in metres. Brackets indicate sections not remeasured.

Freestones in the Lulworth-Worbarrow area.

It is felt that it would be unwise to introduce a new stratigraphic nomenclature at this late stage, and so in the following sections Bristow's names are retained.

The cross sections, figures 3a and 3b (in pocket) illustrate the bed thicknesses and bed numbers as used in this work. The Durlston Bay numbering is that used by Damon (1884), though the thicknesses obtained on re-measurement are sometimes at slight variance with those given by him. The letters DB, WB, MB, and LC refer to Durlston Bay, Worbarrow Bay, Mupe Bay and Lulworth Cove respectively. Details of the Ridgeway section are taken from Fisher (1856) and of the Portisham area from published work supplemented by personal observation.

(b) The Portland-Purbeck Boundary

The Portland-Purbeck boundary usually appears obvious, but as is so often the case the obvious is not always correct. At most localities there was no break in sedimentation between Portland and Purbeck and no precise boundary can be selected. Invariably, however, there is a sharp break near the base in the form of one of the so called dirt beds, or fossil soils, which have usually been considered to mark the base of the Purbeck. This is well shown in the east cliffs of Lulworth Cove where there is a persistent cherty shale 2-5 cm. thick at the base of bed LC2, which lies on a pronounced ledge and seems a most suitable position to pick as the base of the Purbeck (see fig. 17). Nevertheless, careful examination of the beds beneath reveals that, while most of the rock weathers to the characteristic cream colour of the Portland freestone, the top 30 cm. weathers white and porcellanous like the Purbeck above. Thin sections show that this 30 cm. is a typical Purbeck limestone with clotted algal masses and pellets, quite unlike the oolitic (and shelly) Portland, and there is no doubt that Purbeck-type sedimentation had begun prior to the emergence that produced the first dirt bed.

A similar sequence of Dirt Bed on Purbeck-type limestone on Portland can be found at Mupe Bay and Worbarrow Bay, and though faulting obscures the contact relationships at Durlston Bay, a comparable section can be seen in the cliffs 1000 m. to the west. The exposures at Poxwell and Ringstead show similar characteristics, thus Arkell writes of the Ringstead exposure "The lowest bed, a thin layer of splintery white limestone, ... is cemented tightly to the Portland Roach below". (1947, p. 143). Many of the exposures on the Isle of Portland also show much the same sequence, but there are some differences for in places the Portland was eroded prior to Purbeck deposition. The cross section of a channel cut into the Portland and filled with Purbeck sediment and derived Portland fossils can be seen in the cliffs near Black Nore (Nat. Grid. SY 679710 fig. 4), and evidently emergence took place sooner in some places than others. The dirt beds, in which tree remains are found, indicate emergence and suggest that the change to Purbeck lithology was a function of the shallowing of the water.

(c) Main Stratigraphic Features

The following supplements the Purbeck and Weymouth memoirs which provide adequate general descriptions of the several localities. Here, only some more important features of stratigraphic interest are described, most of which have been used in correlation.

Near the base of the Hard Cap at Worbarrow Bay (WB.3) are developments of spongiostromid algal balls. They are from 0.50 - 1.50 m. in diameter and merge laterally into bedded limestones (pelsparites) /̅figs. 5, 6 and 7_/. These algal balls readily weather white, and have a nodular and porous appearance due to the leaching out of softer carbonate-mudstone. They are built up of smaller (1-2 cm.) spongiostromid algal heads which have developed around a localised nucleus. Similar structures can also be seen near Lulworth, but there the greater development

Fig. 4. - Cross section of a channel cut into the Portlandian, filled by basal Purbeck containing derived Portland fossils and fragments of Chara.

Length of section, 5 m. Isle of Portland.

Fig. 5. - Part of a spongiostromid algal ball passing laterally into, and overlain by, bedded detrital limestones.

Lower Purbeck.
Basal Beds.

Worbarrow Bay.

Fig. 6. - Spongiostromid algal ball passing laterally into bedded detrital limestones.

Lower Purbeck. Worbarrow Bay.
Basal Beds.

Fig. 7. - Spongiostromid algal layers with bedded detrital limestones.

Lower Purbeck. Worbarrow Bay.
Basal Beds.

Fig. 8. - Dirt Bed with ill-sorted blocks of limestone in a black 'earthy' matrix. Underlain by detrital limestones, overlain by porous algal Soft Cap.

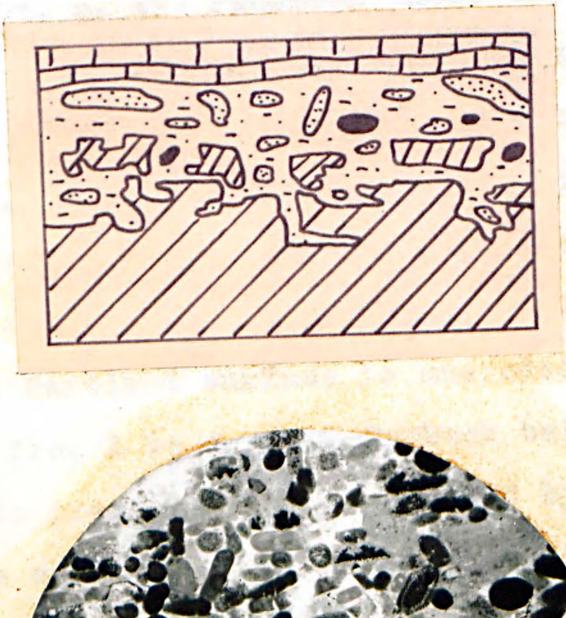
Lower Purbeck. Fossil Forest.
Basal Beds.

Fig. 9. - Diagrammatic sketch showing derivation of blocks in the dirt bed from the underlying Hard Cap. Cross-hatched blocks are derived from sub-adjacent (cross-hatched) Hard Cap. Other blocks and pebbles, dotted or black, are not identifiable as belonging to the Hard Cap owing to their decomposed and weathered nature. (From field sketch)

Lower Purbeck. Fossil Forest.
Basal Beds.

Fig. 10. - 'Pellet Bed'. Micrite pebble (light grey at bottom) with disseminated pyrite specks; matrix of pyritised faecal pellets (black and grey), small micrite fragments and a few shell fragments in a granular calcite cement.

Lower Purbeck. Lulworth Cove.
Soft Cockle Beds.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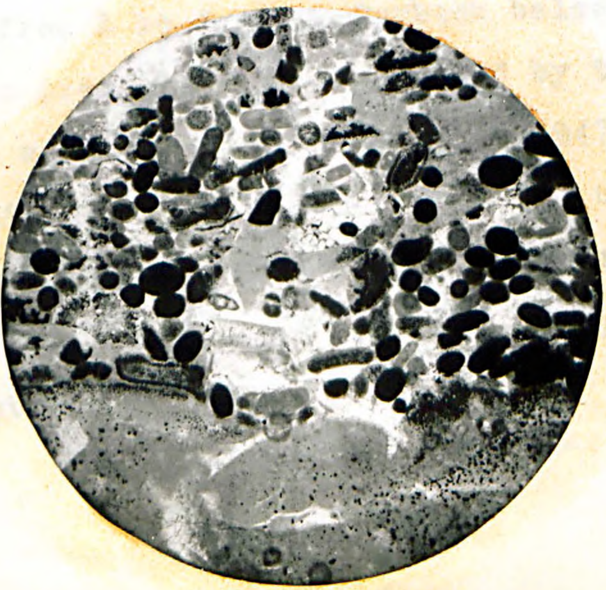
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of algal beds generally obscures such small structures.

Thin impersistent Dirt Beds are present in the lower half of the Hard Cap, but a major period of emergence is shown by the main or Great Dirt Bed that separates the Hard and Soft Caps. This bed can be traced from Portland to Worbarrow Bay. It is best exposed at the Fossil Forest midway between Lulworth Cove and Mupe Bay, where it is a maximum of 30 cm. The bed consists of a brown to black carbonaceous shale full of much weathered grey and black limestone blocks which vary from pea grains to 60 cms. or more in length.

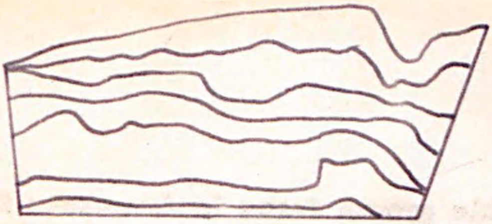
Webster (1829, p. 42) recorded these blocks as "..... belonging to the lower part of the Portland series" and this has been generally accepted since, though with reservations (see Arkell 1947, p. 125). Certainly it is difficult to see how Webster's views can be justified (he gave no evidence to support them), as, save for the minor channelling on the Isle of Portland, the Portland surface is uneroded and in this area there is always from 1 to 4 m. of Purbeck below the Dirt Bed. The similarity to present day soils formed by the weathering of limestone was commented upon by Arkell (1947, p. 125), and it is often possible to trace a sequence from unweathered Hard Cap through partly broken and weathered rock to blocks in the Dirt Bed (figs. 8 and 9), clearly demonstrating derivation from sub-adjacent Purbeck.

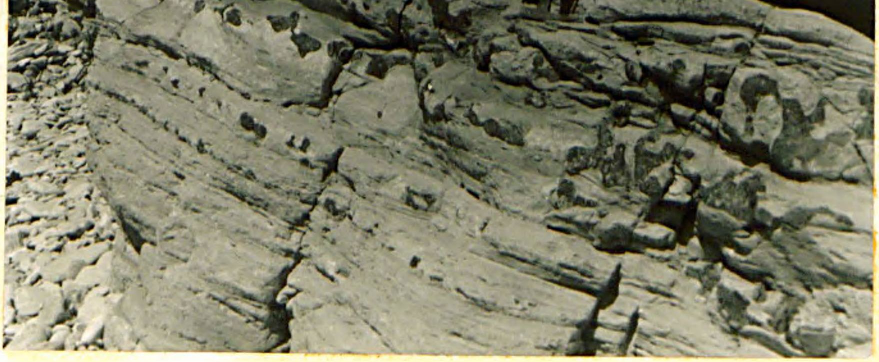
Fig. 11. - Stromatolitic growth forms in fragments from the second pellet bed. The fragments are natural size and the lines represent the laminations visible on the polished rock surface.

Lower Purbeck. Lulworth Cove.
Soft Cockle Beds.

Fig. 12. - Chert nodules (dark) in *Chara* limestone; illustrates the irregular shape of the nodules.

Middle Purbeck. Durlston Bay.
Cherty Beds.





The Soft Cockle Beds comprise a succession of blue-grey calcite-mudstones and calcareous shales which would be difficult to correlate but for the presence of two distinctive pellet beds (LC 22 & 29; WB 45 & 53). The lower, which extends from Durdle Door to Worbarrow Bay, is best developed on the west side of Lulworth Cove where it is nearly 1 m. thick. At Worbarrow the bed is 30 cm. and between these two localities may thin to 5-10 cm. It consists of flat pebbles of calcite-mudstone (micrite) several centimetres in diameter and usually 1-2 cm. thick, in a matrix of small rod-like micrite pellets 100-200 μ in diameter, and granular calcite cement (fig. 10). The pebbles have rounded edges, are blue-grey when unweathered and contain abundant disseminated pyrite specks. A few have a thin cream coating of algal mudstone with faint structure preserved. The pebbles show good planar orientation parallel to the bedding. Some contain small salt pseudomorphs.

The second bed, about 3 m. higher and 20 cm. or less in thickness, is much different, and consists of a breccia of stromatolitic algal fragments set in a granular calcite cement. The fragments are up to 5 cm. in length, though they rarely exceed 1 cm. and show good internal lamination and growth forms (fig. 11). The bed weathers readily to a yellow-brown, but is non-pyritic.

The development of chert nodules in the Cherty Freshwater Beds is characteristic throughout the outcrop. The nodules are variable in size up to 60 cm. diameter, black where unweathered, with a white patina, irregular in shape (fig. 12) and always containing abundant silicified fossils. Associated limestones are a light cream and many were formed by the action of stoneworts of the class Characea. These plants to-day are freshwater and precipitate carbonate around their stems; this sloughs off to accumulate as a calcite-mud, but sometimes the carbonate breaks off as small fragments (1-2 cm.) which become incorporated in the mud and produce a characteristic brecciated appearance in the rock (fig. 13, Pettijohn 1948, p. 309).

Beds LC 52, 53, **MB** 25, WB 73, DB 31.

The most distinctive correlation marker in the Purbeck is the Cinder Bed. So called on account of its rough scoriaceous appearance it is a lumachelle of the oyster *Ostrea distorta*. Small white masses (1-2 cm.) of the calcareous worm *Serpula coacervata* occur as well, the same species as in the Serpulite or Middle Purbeck of Germany. The bed is 2.9 m. thick at Durlston Bay where it has a middle unit composed of valves and fragments of *Protocardia*, together with spines and pieces of test of the echinoid *Hemicidaris purbeckensis*. This middle unit thins, and is absent to the west of Mupe Bay.

A further correlation marker occurs near the base of the Intermarine Beds which overlie the Cinder Bed. It is a bed of blue-grey calcite-mudstone containing Chara. 70 cm. thick at Durlston Bay (DB 48) it can be traced as far as Lulworth Cove (WB 83, MB 29, LC 60).

Although the remainder of the Middle and Upper Purbeck can be correlated in broad outline, only one further bed can be used as a specific datum. This is a thin bed of calcareous sandstone found in the Corbula Beds (DB 63, WB 100, MB 37, LC 66). The bed contains from 50-55% by weight of quartz at each locality. It is attacked by marine borers (probably gastropods) which gives it a distinctive pitted appearance (fig. 14).

The calcite-mudstones of the Corbula Beds often show a gradation of texture. At the base of a unit are well formed, rounded, calcite-mudstone pellets in a very fine grained granular calcite cement. Passing upwards the pellet boundaries gradually merge, with a consequent reduction in granular cement, until at the tops of the unit a uniform calcite-mudstone is present. Then there is a sharp break, and the cycle is repeated. As many as 18 such cycles have been seen in a 30 cm. bed.

Various sedimentary features such as dessication cracks, salt pseudomorphs, ripple-mark and small scale cross-bedding, occur in places throughout the Purbeck and are noted on Bristow's sections (Bristow 1857, 1859). They are used in environmental analysis in later sections of this work.

Fig. 13. - Illustrates the brecciated appearance of many of the Chara limestones. Caused by the incorporation of semi-consolidated carbonate fragments in a carbonate mud, all being derived from the activity of the stonewort alga Chara.
Pencil is 10 cm. long.

Middle Purbeck. Lulworth Cove.
Cherty Beds.

Fig. 14. - Pitted surface of sandstone found in the Corbula Beds. Due to the boring action of modern marine gastropods. Surface is 1 m. long.

Middle Purbeck. Worbarrow Bay.
Corbula Beds.

Fig. 14A. - Tight fold in the Cypris Freestones. Looking more or less directly along the axis.

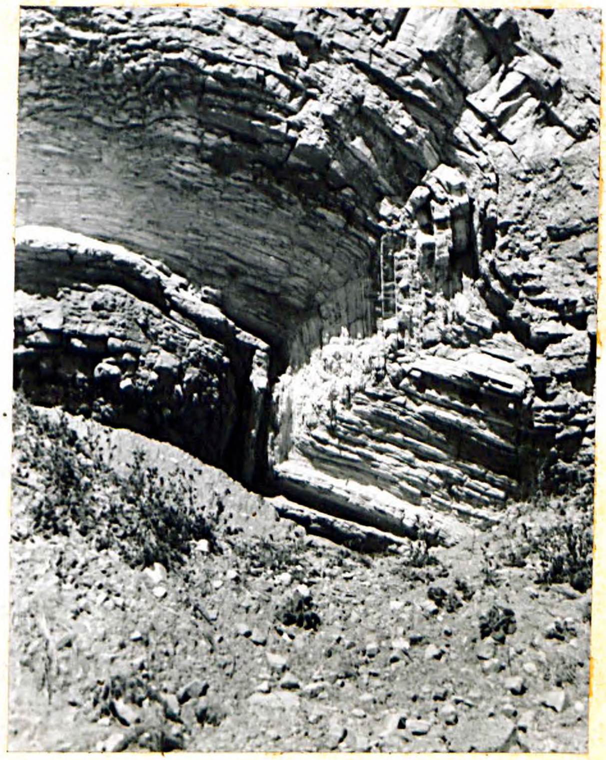
Cypris Freestones. Mupe Bay.
Lower Purbeck.

Fig. 14B. - Small thrust. A 30 cm. bed of calcite-mudstone has been thrust up dip about 2 m. Over and underlying beds are unaffected.

Intermarine Beds. Worbarrow Bay.
Middle Purbeck.

Fig. 14C. - A small crumple or fold in the Broken Beds, typical of many that are found in this division. The axes nearly all run parallel to the main Weymouth anticline.

Broken Beds. Fossil Forest.
Lower Purbeck.



(d) Structure

(i) General. -

The dominant structure of the Dorset area is the Weymouth-Purbeck anticline. This plunges eastward and was formed by folding along an east-west axis during the Tertiary earth-movements. The south limb, best exposed on the Isle of Portland, dips south at a low angle, while the north limb, which is seen in coastal exposures between Durlston Bay and Durdle Door, dips more steeply to the north. Inland, the structure is further complicated by intra-Cretaceous faulting and folding. Axes of minor folds within the Purbeck beds (fig. 14A) are parallel to that of the Weymouth anticline, and were undoubtedly formed during the same period of movement, but in tra-stratal folding is of comparatively minor importance.

A few large faults cut Purbeck beds, most noticeably at Durlston Bay, where two normal dip faults with a combined throw of about 100 m. cause a repetition of the entire Purbeck sequence. Several normal faults of small vertical displacement (1-2 m.) occur here and there in the formation, and a few small thrusts are found in places (fig. 14B) with apparent displacement up dip of about 2 m.

Full discussion of the structure of the Dorset region is given by Arkell (1947, pp. 242-312).

(ii) **Broken Beds.** -

These brecciated limestones are the most striking feature of the Purbeck beds between Durlston Bay and Durdle Door (see figs. 47-49). In a thorough discussion, Arkell (1938, also 1947) concluded that they are " ... a form of adjustment tectonics (drag-folding) resulting from the formation of the Purbeck anticline ..." He was unable to account for the restriction of brecciation to one main horizon, but Hollingworth (1938) suggested that hydration of anhydrite, and the subsequent solution of gypsum, might have formed local areas of weakness at this level that yielded preferentially during the folding.

Prior to the present study no evidence was known for the presence of evaporites in these beds, but as is shown (p. 65) pseudomorphs after gypsum, and replacement textures after anhydrite, indicate that gypsum was at one time present, at least interstitially. Hydration and solution of this gypsum, therefore, could well have initiated areas of weakness as suggested by Hollingworth. Similar brecciated beds in the Permian of Yorkshire have been attributed entirely to collapse following the removal of gypsum. The Purbeck breccia, though at first sight chaotic, contains minor folds and crumples (fig. 14C) the axes of which trend parallel or nearly parallel to the Weymouth anticline, and it seems evident that they were produced during the same period of folding.

It appears, therefore, that the Broken Beds were produced by a combination of weakening due to the removal of gypsum, and tectonic pressures during the Tertiary folding.

(iii) Differential subsidence. -

Movements during the deposition of the Purbeck beds are indicated by variations in the thickness of the lithological sub-divisions. During Lower Purbeck and earliest Middle Purbeck time, subsidence generally appears to have been greatest in the east, as indicated by the uniformly increasing thicknesses of the divisions from west to east. At Worbarrow Bay, however, the Intermarine and Scallop Beds are thinner than they are at Mupe Bay (3.13 - 3.38 m.), the Durlston Bay section being very thick (16.25 m.), and a slight positive area seems to have existed at Worbarrow. The Corbula Beds, on the other hand, are nearly 1 m. thicker at Worbarrow than at Durlston Bay, and it appears that at this time the Worbarrow area was subsiding more rapidly than elsewhere.

These movements are probably connected with those that affected the Ridgeway and Portisham areas as described by Anderson (1958, p. 119). There, it is suggested that a small basin existed to the west of the main Isle of Purbeck basin, and separated from it by an axis of uplift between Ridgeway and Lulworth that was moving throughout Purbeck time. This axis was responsible for the thin sections of Purbeck now found at Durdle Door and Stair Hole, and it is interesting to note that its strike is parallel to a similar axis that separates the Wessex and Wealden basins of deposition (Taitt and Kent, 1958).

III. THE BASAL BEDS

(a) General Description

The Basal Beds comprise the Hard (or Top) Cap at the base, the main Dirt Bed, and the Soft Cap, though where the Dirt Bed is not identifiable, as to the east of Worbarrow Bay, differentiation of Hard and Soft Cap is impracticable (fig. 15).

The thickness of the <u>Hard Cap</u> is shown in Table IIIa. It is characterised by rapid lateral and vertical variation in lithology and thickness, in places increasing from 2 to 4 m. in as little as 12 m. horizontally. This is best seen along the west cliff sections on the Isle of Portland, and between Lulworth and Mupe Bay. The beds are light to medium brown when fresh, but are usually seen weathered as white to grey, often porcellanous limestone of various types (figs. 16, 17). Many have a finely nodular or botryoidal appearance (fig. 18) and are very porous.

In exposures to the west of Worbarrow Bay there are near the base one or two thin (2-5 cm.) impersistent 'Dirt Beds' which weather and form deep grooves along the outcrop. They are underlain by dessication cracked <u>Ortonella</u> limestones (p. 28).

Some of the limestones developed around a nucleus, usually of wood, and form concretions of from 1-2 m. diameter. These

TABLE III

a) Hard Cap Thicknesses	Metres
Isle of Portland	1-4
Portisham	2
Chalbury	2
Poxwell	2.5
Lulworth Cove	5
Mupe Bay	6.5
Worbarrow Bay	2.5
Durlston Bay	2-3?

b) Dirt Bed Thicknesses	Centimetres
Isle of Portland	0-20
Portisham	4-5
Chalbury	trace
Poxwell	
Lulworth Cove	18-30
Mupe Bay	
Worbarrow Bay	trace
Durlston Bay	absent

IDEALISED SECTION BASAL PURBECK

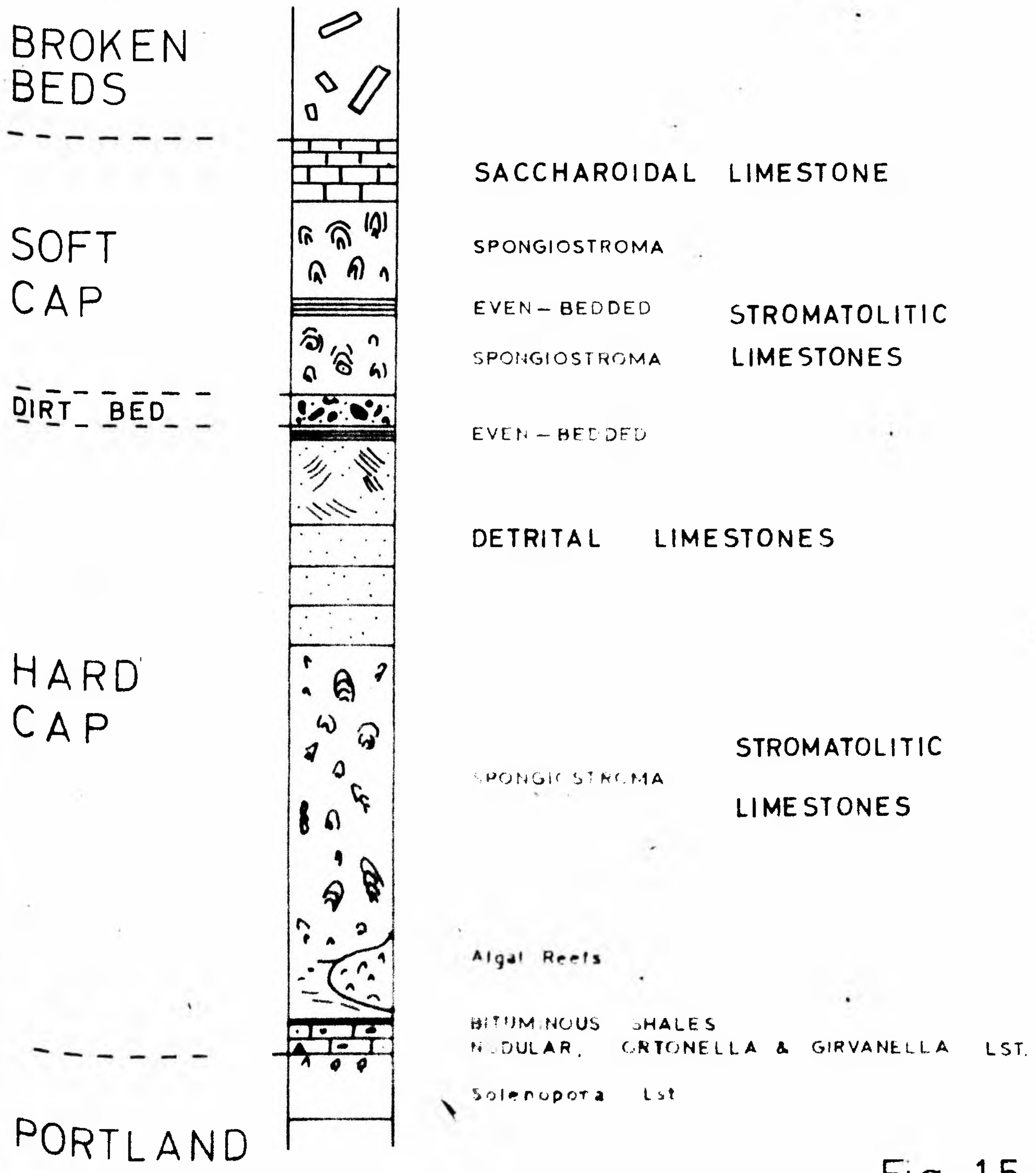


Fig. 15

Fig. 16. - Section of the Hard and Soft Caps. Shows the generally massive appearance of the Hard Cap, here about 3.5 m. thick. Dirt Bed is only poorly developed here at the top of the main massive bed.

Lower Purbeck. Isle of Portland.
Basal Beds.

Fig. 17. - 'Contact' between the Portland and Purbeck, and section of Hard Cap. The apparent contact is at the pronounced ledge which is eroded along a thin dirt bed, but Purbeck type sediment is present for some 30 cm. below this ledge and the contact with the Portland is actually gradational.

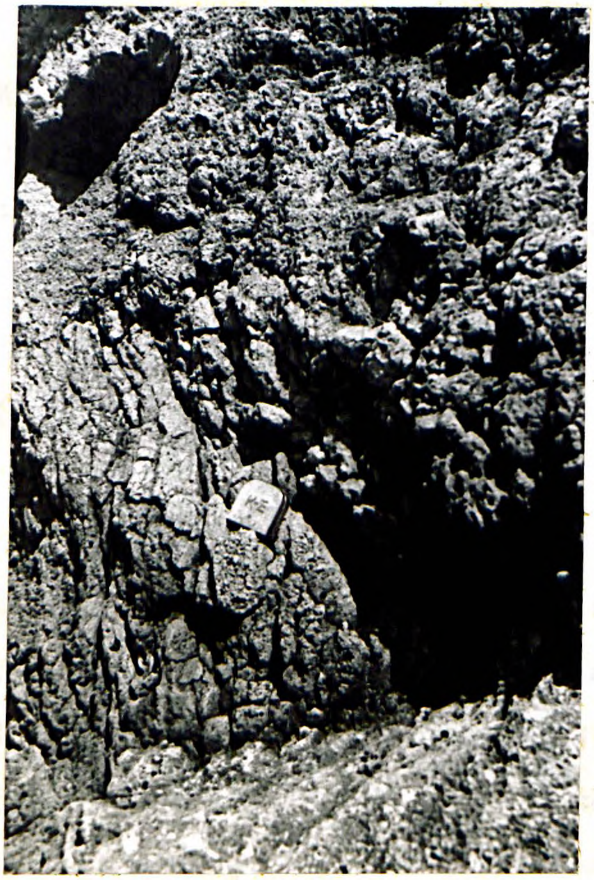
Lower Purbeck. Near Mupe Bay.
Basal Beds.

Fig. 18. - Nodular and botryoidal appearance of some of the Hard Cap limestones. Pocket scale is 3 cm. long.

Lower Purbeck. Lulworth Cove.
Basal Beds.

Fig. 19. - Two large limestone nodules (to the left and right of the hammer) probably formed around a nucleus, passing laterally into bedded detrital limestones.

Lower Purbeck. Lulworth.
Basal Beds.



are surrounded by and overlain by evenly bedded detrital limestones (figs. 19, 20). At Worbarrow Bay there are similar looking masses ½ to 1 m. diameter also passing laterally into bedded limestones, but which do not have a nucleus and were formed by spongiostromatolitic algae (figs. 5, 6, 7, 21). They are true reefs (wave resistant masses built up on the sea floor, p. 12).

At the top of the Hard Cap in the Lulworth area is a 1-1½ m. thick unit consisting of small scale (2-3 cm.) cross-bedded layers of limestone (figs. 22, 23) which contain rounded, spherical to ellipsoidal calcite grains up to ½ mm. in diameter (fig. 40). In places the top of this unit shows dessication cracks but these are usually covered by the main Dirt Bed. Elsewhere, the top of the Hard Cap is a thinly laminated stromatolitic limestone 10-20 cm. thick, also showing dessication cracks. Where the surface of the Hard Cap is areally exposed, as at the Fossil Forest, small collapse structures can be seen. These are roughly circular, 3 m. or so in diameter and about 1 m. deep, (fig. 24) and appear to have formed due to the removal of material from beneath. The inferences to be drawn from this are discussed in detail below (p. 57).

<u>The main Dirt Bed</u> has thicknesses shown in Table IIIb. It consists of a soft black carbonaceous 'earth' filled with ill-

sorted blocks of weathered limestone with colours ranging from light grey to black. All, however, were derived from the Hard Cap which passes gradationally into it (p.16).

Trees that grew in this soil are sometimes found in place and standing about 1 m. high, but more commonly occur broken off in lengths up to 3 m. The wood is silicified with organic textures preserved, and the remains are surrounded by concretionary masses of porous calcareous tufa producing the so called "burrs". This is especially noticeable at the Fossil Forest (fig. 25). These tufa burrs are overlain by, and pass laterally into, bedded algal limestones of the Soft Cap. In places a little bedded chert, up to 10 cm. thick, may be present (fig. 26).

The Soft Cap passes irregularly upwards into the Broken Beds so thicknesses vary. All the beds are very porous and weathered. They are light grey or white, though brown when fresh (fig. 26). The basal 30-50 cm. is essentially similar in appearance to the porous nodular Hard Cap, but above this bed the similarity ends.

On the Isle of Portland and to the west of Durdle Door the limestones above the basal bed are thin bedded (2-5 cm.), pseudo-oolitic and fossiliferous, typical of the Broken Bed lithology (p. 62). In the Lulworth area and to the east the change is

Fig. 20. - Algal balls of about 1½ m. diameter, probably formed around a nucleus. Underlain by massive Hard Cap limestones.

Lower Purbeck. Lulworth cliffs
Basal Beds. (inaccessible)

Fig. 21. - Spongiostromatolitic algal ball passing laterally into, and overlain by bedded detrital limestones.

Lower Purbeck. Worbarrow Bay.
Basal Beds.

Fig. 22. - Cross-bedded detrital limestones infilling an irregular surface on spongiostromatolitic Hard Cap.

Lower Purbeck. Fossil Forest.
Basal Beds.

Fig. 23. - Close up of the cross-bedded units seen in Fig. 22.

Lower Purbeck. Fossil Forest.
Basal Beds.

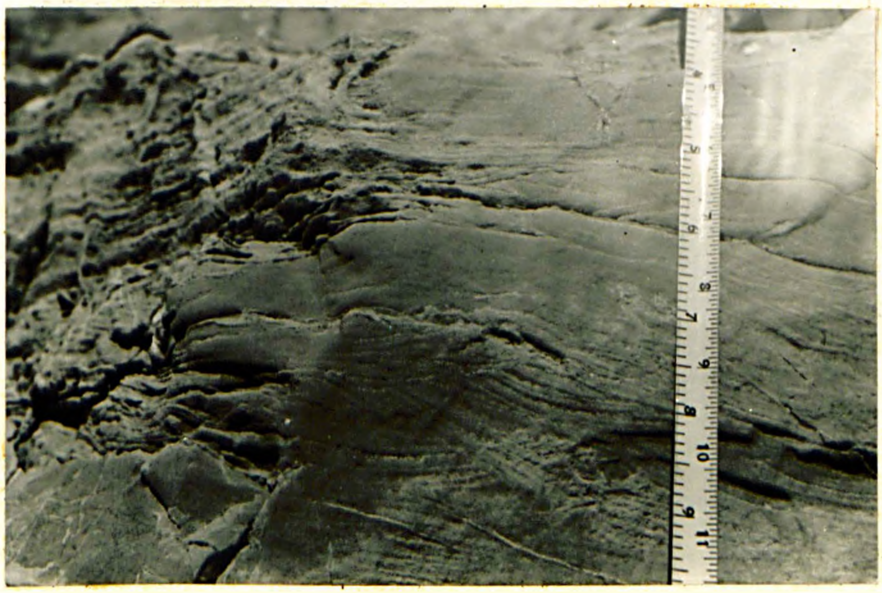


Fig. 24. - Collapse structure in the Hard Cap. Diameter is about 3 m., and depth about 1 m. Probably caused by the removal of gypsum during the formation of the Dirt Bed.

Lower Purbeck. Fossil Forest.
Basal Beds.

Fig. 25. - Algal tufa 'burr'. These formed around tree trunks and stems, the remains of which are now found silicified. Hammer marks the site of the central tree trunk.

Lower Purbeck. Fossil Forest.
Basal Beds.

Fig. 26. - Irregular, porous Soft Cap (below hammer). The beds by the hammer are weathered saccharoidal limestones. The bed immediately below the weathered groove is bedded chert which occurs rarely at this horizon.

Lower Purbeck. Fossil Forest.
Basal Beds.

to a white saccharoidal limestone that thickens progressively from about 15 cm. at Lulworth Cove to 3 m. at Durlston Bay, where it is involved in the brecciations of the Broken Beds.

The basal Purbeck beds in Dorset can be divided into six main lithological types whose general stratigraphic positions are shown on figure 15. They are:-

- Ortonella and Girvanella limestones
- Nodular limestones
- Stromatolitic limestones -
    - Spongiostromata type
    - Even-laminated type
- Bedded detrital limestones
- Bituminous calcareous shales
- Saccharoidal limestones

(b) Petrology of Ortonella and Girvanella Limestones

(i) *Petrography*. -

These occur at the base of the Hard Cap as beds of variable thickness up to 0.75 m. They consist of sub-spheroidal nodules of *Ortonella nodosa* (Anderson) up to 3-4 cm. diameter, though usually smaller, with less abundant *Girvanella* nodules (*G. intermedia* Weathered) of the same order of size. The nodules are in a matrix of pellets of calcite-mudstone with a few ostracod shell fragments, all in a granular calcite cement

(Bathurst, 1958, pp. 14-20). When fresh the nodules are medium brown and give a clotted appearance to fractured rock surfaces. They weather to a porcellanous white or grey.

Ortonella belongs to the family Codiaceae of the green algae. The members of this family have a freely branched tubular thallus of interwoven, continuous branching filaments. To-day, all are marine and the majority are restricted to warm seas. Ortonella is crustose or nodular and forms rounded or irregular masses. In thin section the nodules here show branching filaments of calcite spar, averaging 40μ diameter, with well defined walls of algal dust (Wood, 1941). Filaments are best developed towards the periphery of the nodule, merging to clotted calcite-mudstone at the centre (fig. 27). This mudstone may in turn surround a small (100-200μ) irregularly shaped nucleus of calcite spar. The mudstone is light grey, with patchy grain size varying from 2-10μ. Grains in the mudstone are sometimes acicular but more commonly equant, while grain boundaries are mostly plane, though a few are curved. The calcite forming the filaments shows many characteristics of a drusy cavity filling (Bathurst, 1958).

Girvanella, though a well known genus, is of uncertain affinities. It has generally been placed with either the green or the blue-green algae, though this may need revision (Wood, 1957, p. 27). Nevertheless, as a facies indicator Girvanella nodules can be reliably taken to indicate shallow clear water (Wood 1957, p. 23). The Girvanella nodules here consist of unbranched, twisted, vermiform filaments of calcite spar 60-100μ diameter, with more rarely a second form, of diameter 45-50μ, in a calcite-mudstone similar to that of the Ortonella nodules, though in this case preservation of algal filaments is usually not as good.

Most nodules contain in addition variable amounts of yellow-brown, translucent, crypto-crystalline calcite, sometimes as a thin fibrous rim (fig. 27), but more usually as irregularly shaped patches within the nodule. The rims may be as much as 300μ thick, fibres forming them being 2-3μ wide and up to 45μ long, oriented normal to the nodule surface.

Inter-nodule spaces are quite large, up to 2-3 mm., and the nodules are in a typical granular calcite cement of fairly coarse crystal size (up to 500μ). The cement crystals have straight boundaries, some show twinning, and many contain irregularly scattered whisps and inclusions of calcite-mudstone. Some of the crystals contain tubes, 18-20μ diameter and finer, often partly filled with calcite-mudstone, which can sometimes be followed from the cement into algal nodules. This presumably indicates early cementation while the sediment was still subject to attack by boring organisms. The calcite-mudstone inclusions in the cement also suggest that it formed while calcite-mud was still in suspension and capable of being included within the precipitate.

Associated with the nodules are irregularly shaped calcite mudstone pellets 60-150 μ longest diameter. The mud grains within these pellets are morphologically similar to those of the nodules and in places it is evident that the pellets are derived from the nodules by abrasion. A few ostracod shells and very rare foraminifera are also present in the rock, together with small rectangular pieces of yellow-brown, isotropic collophane bone fragments. Sometimes, thin, 5-10μ , very irregular, brown bituminous shale laminae occur which, if they were originally more or less horizontal, indicate some movement to have taken place within the rock, perhaps due to pressure solution.

In places chalcedonic quartz is found to have replaced the calcite-mudstone of the nodules. Initially, replacement was irregular, but euhedral quartz crystals were developed, 200 μ or so in length, zoned with specks of unaltered mudstone. Replacement is not common in this type of rock and it confined to small areas.

(ii) Origin. -

The fine-grained carbonate precipitated around certain

Fig. 27. - Photomicrograph of an <u>Ortonella</u> nodule with thin rim of fibrous calcite. The filaments are here not well preserved. Light areas are granular calcite cement or drusy fillings.

Lower Purbeck. Mupe Bay.
Basal Beds.

Fig. 28. - Photomicrograph of nodular limestone. Medium grey spherulitic and botryoidal masses are yellow-brown calcite formed by crystallisation of an algal gel. Syneresis cracks are only faintly visible in the photograph. Dark grey areas are micrite, light grey to white areas are granular calcite cement.

Lower Purbeck. Isle of Portland.
Basal Beds.


1000 µ

algal threads, as in Ortonella and Girvanella, was termed "algal dust" by Wood (1941), who showed that it was composed of angular calcite crystals 2-3 μ long. He presented evidence that the original precipitate was of calcite, and not aragonite, as is the case in some modern calcareous algae (Lowenstam and Epstein, 1957). The mechanism by which calcareous algae precipitate calcium carbonate is not well understood. According to Jones (1925) it is due to the life processes of the plant causing a local deficiency of CO_2 in the water surrounding the filaments. This in turn lowers the solubility of $CaCO_3$, which precipitates upon the filaments as minute crystals of calcite.

Upon the death of the plant the filaments decay, leaving a cylindrical cavity that may be subsequently filled by drusy calcite. Where this occurred, the algal dust was obviously lithified prior to the decay of the filaments, but it is likely in many cases this was not so, and that the fine calcite crystals were dispersed to accumulate as a mechanically deposited mud, the origin of which would be obscure.

The nodules in these beds developed around a nucleus, and the frequently symmetrical appearance shows them to have been unattached and rolling about, thus allowing equal growth in all directions. This also resulted in their having a relatively smooth outline, and occasionally led to the formation of a thin oolitic rim.

The calcite grains of the filament walls are slightly coarser here than those described by Wood, up to 10μ diameter in some cases, but this may well be a peculiarity of the particular algal species. On the other hand, the merging to a clotted mudstone at the centre of the nodule may indicate a different mode of precipitation. It is possible that decaying algal threads at the core of a nodule produced ammonia, which would cause the precipitation of $CaCO_3$ (Reis, 1923), perhaps of slightly different grain size to that on the filaments.

The calcite-mudstone sometimes associated with the nodules, either as pellets or thin layers, is formed of grains of similar size and shape as the algal dust, and it almost certainly derived from the breaking up of the unlithified filament walls. Turbulance and abrasion of lithified nodules could have provided both discrete grains and some of the irregular pellets.

Ortonella and Girvanella are both well known in Carboniferous limestones where they commonly occur with ostracods and worms in a lagoonal facies (George, 1960, pp. 354-6). The restriction of plants to two main genera of algae, and their association with an impoverished fauna of ostracods, and possibly worms, suggests that in the basal Purbeck too, conditions other than normal marine prevailed. They were perhaps also lagoonal or, in view of the dessication cracks (p. 25), and the presence of thin dirt beds, it may be more accurate to picture a tidal-flat environment on the border of a lagoon.

The topmost Portlandian is richly algal, containing for example abundant Solenopora and, in addition, bryozoa. It is evidently more truly marine, and the transition to Purbeckian seems to be due to a continued restriction of the Portland sea, and a consequent raising of salinity and probably temperature. The regional aspects of this are discussed below (p. 199).

(c) Petrology of the Nodular Limestones

(i) Petrography. -

In outcrop this type is similar to the Ortonella limestone, also occurring near the base of the Hard Cap, with beds of from 0.5 - 0.75 m. Brown when fresh, weathering to a porcellanous white or grey, the nodules differ from the matrix in being more resistant to erosion, and consequently stand in relief with a characteristic knobbly appearance. They vary from pieces of 50-100 μ , up to lumps 4-5 cm. in diameter. Very irregular in shape they are unlike the Ortonella nodules which generally have a smooth outline.

The nodular limestones are usually associated with a more abundant fauna than the Ortonella limestone, chiefly of ostracods, but in addition gastropods such as <u>Hydrobia</u>, and, more rarely, broken pelecyped shells. The fauna is found in thin bands between layers of nodules, though ostracods may occur throughout the rock.

The nodules consist of translucent, crypto-crystalline or finely acicular calcite, light to dark yellow in colour. This colour is characteristic. It is retained on acetate peels and would seem to be due to very fine disseminated organic matter, the intensity of colour depending upon the concentration of the organic material. A few nodules have well developed fibrous rims similar to those described above (p. 30), but more usually they are botryoidal (fig. 28). The botryoidal exteriors develop from spherulites. These average 200 μ diameter and develop around variously sized calcite-mudstone cores. The calcite of the spherulites is acicular, with needles about 1-2 μ wide and 25-30 μ long. Elsewhere, in non-spherulitic patches, crystal size is 1.5 μ or less, and frequently cannot be resolved even with the help of acetate peels.

An important feature is possible syneresis cracks which occur throughout the nodules. These are mostly microscopic, 80-100 μ long, but may reach 1-1½ mm. length and 20 μ width. These larger cracks are often filled with calcite-mudstone.

Replacement by silica is more common than in <u>Ortonella</u> limestones, as much as 5% by volume of quartz being present in some beds. The frequent development of euhedral quartz crystals zoned with carbonate-mudstone shows that the silica replaced the calcite.

The matrix of this type of rock is more often of calcite-mudstone, either as layers or pellets, than in the Ortonella limestone. Here again, however, inter-nodular spaces are large and often filled with coarsely crystalline calcite (fig. 28). This is typically drusy (Bathurst 1958, pp. 14-20), the crystals may contain mudstone inclusions, but no borings are present.

The calcite-mudstone is sometimes grey but is more usually brown. It often contains abundant ostracod shells and their fragments. Grains are from 2-4 μ diameter, noticeably smaller than in the Ortonella limestone, and are mostly equi-dimensional with apparently planar boundaries. The mudstone sometimes formed a thin coat on nodules before spar cementation occurred. The fauna could account for the form of aggregation of the mud, either by producing faecal pellets, or by the breaking up of semi-consolidated mudstone layers. The pellets vary from 50-150 μ diameter. Some have a length diameter ratio of 2 or 3:1. All are rounded and some are spherical, though these may be transverse sections of rods.

(ii) Origin. -

The light to dark-yellow calcite of these nodular limestones shows a number of features that have bearing on its possible origin. They are: the spherulitic and botryoidal structures, the colour due to probable organic matter, the fragmental appearance of many pieces, the large calcite-filled cavities or vugs, and particularly the possible syneresis cracks. These criteria strongly suggest formation by the crystallisation of an organic gel. One of the characteristics of such crystallisation is auto-brecciation and the expulsion of water (Lindgren, 1925); this would account for the irregular shape and fragmental appearance of the nodules. The crystallisation of the gel took place around small calcite-mudstone nuclei which may have been enclosed by the gel during its formation, or were simply centres of crystallisation within the gel.

The association of these beds with the Ortonella and Girvanella limestones at the base of the Purbeck and the occasional presence within Ortonella nodules of small areas of yellow calcite (p. 30), suggests that the gel was produced by algal activity. Thin sections of these rocks closely resemble algal structures at Searles Lake (Scholl, 1960, pp. 420-421, figs. 4 and 6), which were formed by unicellular algae. There, however, it is not suggested that any gel stage was present though botryoidal structure is common. Thomas and Glaister (1960) describe structures in limestones from the Mississippian of Saskatchewan produced by blue-green algae, and illustrate a section (Plate Ic, p. 575) that is almost identical with some of the Purbeck nodular limestones. They suggest that calcium carbonate is precipitated as a colloidal gel encrusting leaves and stems of plants, and that crystallisation produces a crypto-grained limestone with syneresis cracks and vugs.

These Purbeck beds too, were perhaps formed by the development of algal gels up to a few centimetres thick, and of limited areal extent, in an environment similar to that of Ortonella limestones, but with perhaps a more abundant fauna (p. 35). The gels alternated or were associated with thin layers of calcite-mudstone and upon crystallisation, auto-brecciation and the expulsion of water sufficed to mix shells, shell fragments and mudstone with the pieces of crystallised gel.

The calcite-mudstone associated with these limestones is more usually brown than grey, and is finer grained (2-4 μ) than that present in the Ortonella limestones. Its common occurrence in small ellipsoidal pellets suggests faecal pelleting, and this may correlate with the observed increase in fauna. During the passage of a calcite silt or mud through the gut of a mud ingesting animal, any change is likely to be towards a reduction in grain size of the calcite and, perhaps, to the dispersal of unassimilated organic matter in a very fine or even colloidal form throughout the excreted pellet. This mudstone may therefore originate as an algal dust, as in Ortonella limestones, but have its grain size reduced and colour altered by the action of invertebrates.

(d) Petrology of the Stromatolitic Limestones

(i) Petrography. -

The term stromatolite is used to describe laminated but otherwise structureless masses and beds. They are believed to have been formed by the action of lime-secreting and perhaps filamentous algae. Although organic in origin, they are not themselves organisms or parts of organisms, but represent, when best preserved, the casts produced by algae precipitating calcium carbonate about their thalli (Cloud 1942).

In the Purbeck, two types of stromatolite are recognised, Spongiostromata type, and Even-laminated type.

1. Spongiostromata type -

This is the most abundant rock type of the Hard Cap, though it is present also in the Soft Cap. It occurs in beds of from 0.5 - 3.0 m. with rapid lateral variations (figs. 5-7, 29). Fresh or weathered, it is usually light grey or cream, but may be light brown. It sometimes has a conchoidal fracture, but small (½-1 cm.) spongiostromata heads frequently stand in relief on weathered surfaces (fig. 30). There are two distinct forms of spongiostromata. Firstly, those built up in place and producing distinct layers 5-10 cm. thick that can be traced laterally for 15-20 m., and sometimes, as at Worbarrow, formed reef like masses ½-1½ m. diameter (fig. 5); and secondly, those that formed individual nodules ½-2 cm. diameter around a rolling or fixed nucleus.

Spongiostromata is a family erected by Pia (1927) to cover a large number of fossil algal forms showing little or no microstructure, but which develop colonies of constant shape. Most are artificial form-genera probably produced by several species or genera of algae in close association. Numerous form-genera have been described (e.g. Anderson, 1950). Externally the Purbeck forms resemble Ottonosia Twenhofel, and Pycnostroma Gurich, but they generally lack the internal structure associated with these and it is best, therefore, to refer all the Purbeck material to the general form "Spongiostroma".

Typical growth form of the first type is illustrated by figures 11 and 31. The nodules, or heads, vary from ½-5 cm. diameter, and in this type they coalesce into sheets or small reef like masses (figs. 5-7, 30). The heads consist of laminae 1-2 mm. thick built convex upward from a small nucleus, successive laminae almost enclosing the previous ones. This

Fig. 29. - Stromatolitic limestone showing the irregular weathered appearance, and the rapid lateral changes in thickness.

Lower Purbeck. Lulworth Cove.
Basal Beds.

Fig. 30. - Thin stromatolitic layer with characteristic nodular appearance due to the small algal 'heads'. Overlain and underlain by detrital limestones. Thickness of layer is about 5 cm.

Lower Purbeck. Mupe Bay.
Basal Beds.

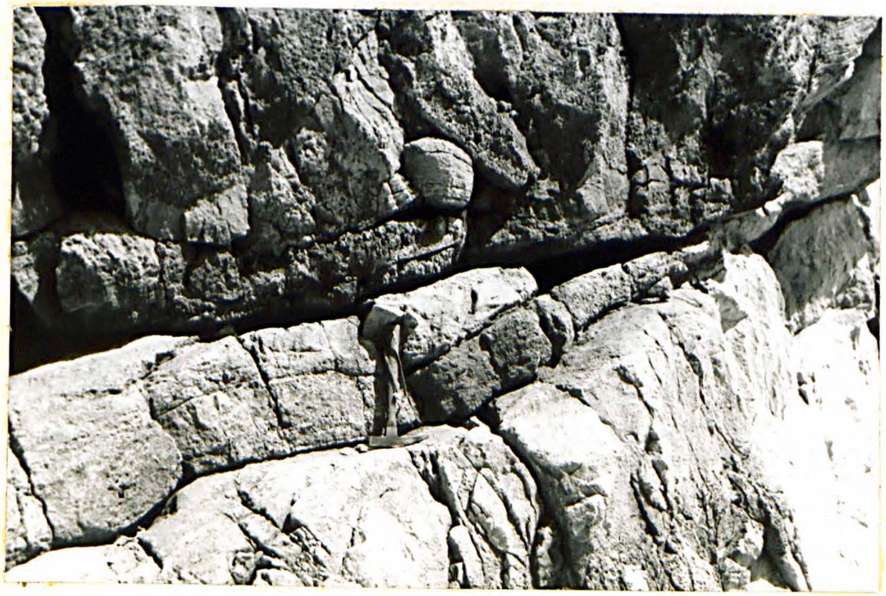


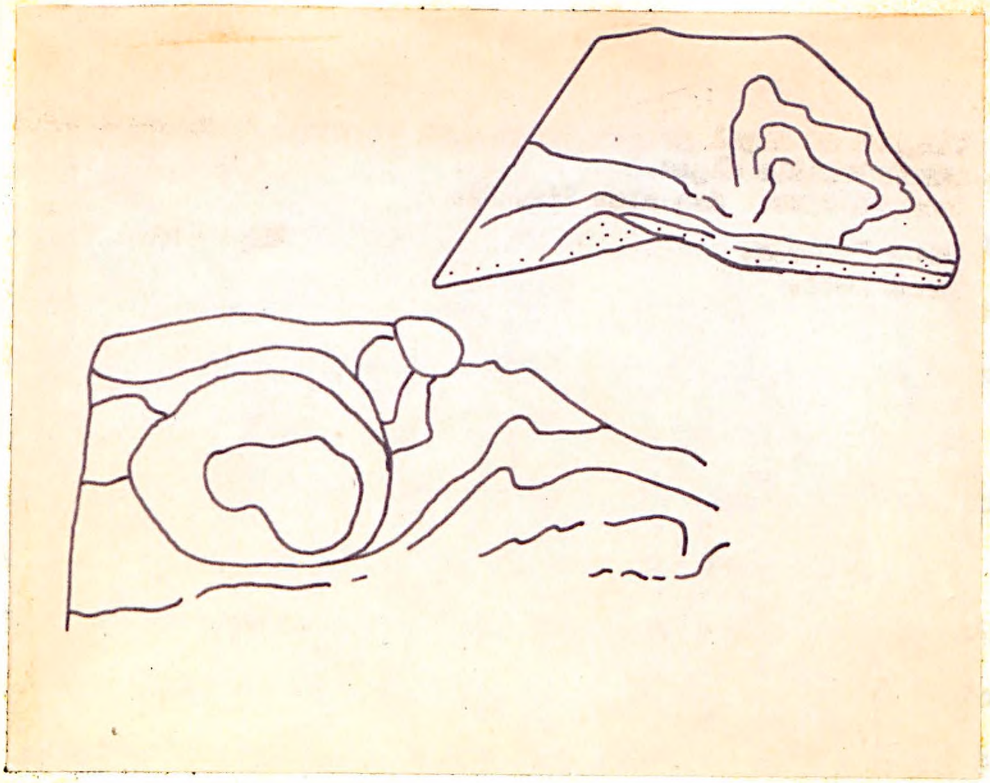
Fig. 31. - Diagram of algal growth forms seen in small nodules, produced by stromatolitic algae.
Natural size. See also Fig. 11.

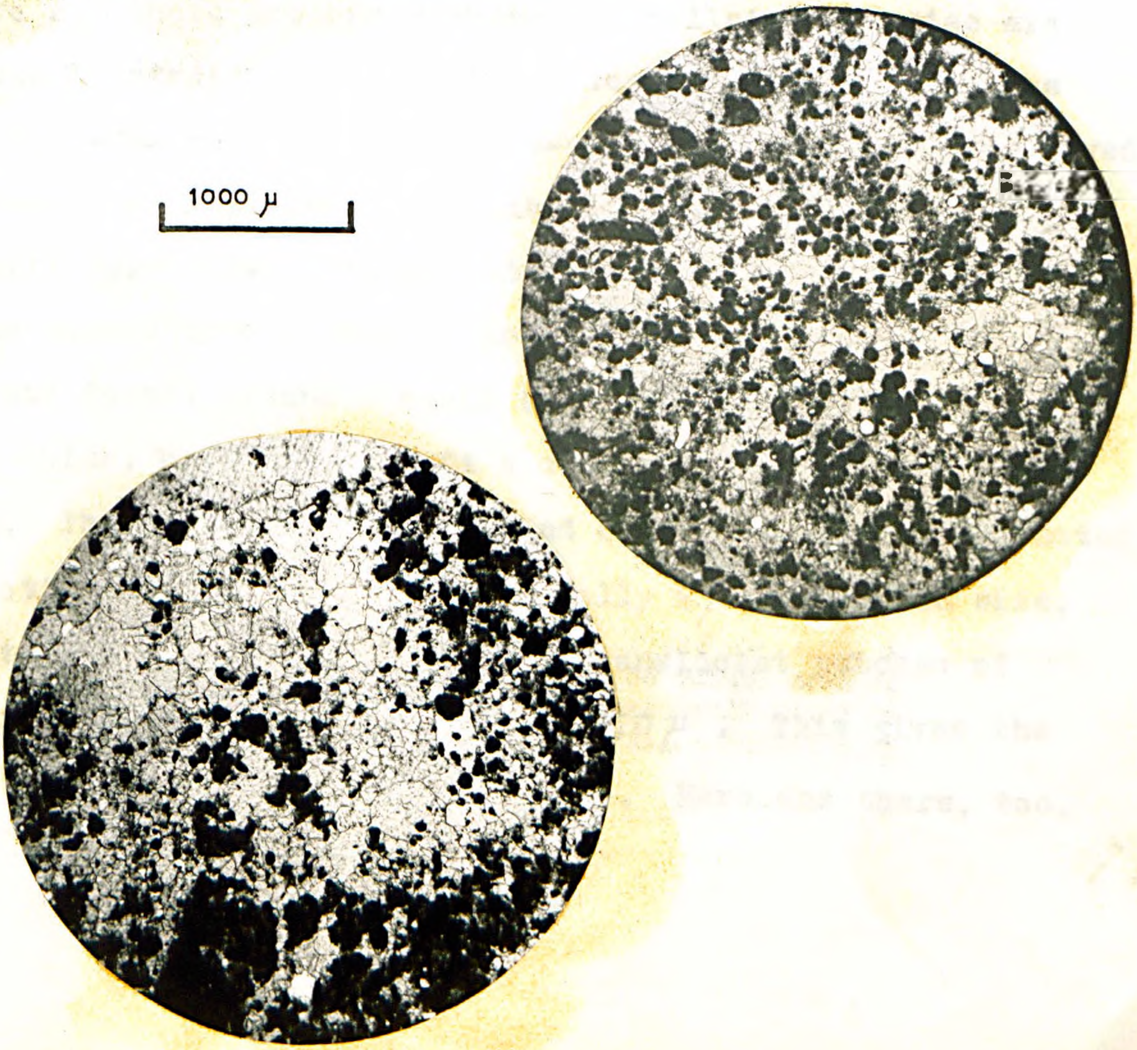
Lower Purbeck. Mupe Bay.
Basal Beds.

Fig. 32. - Photomicrograph of loosely packed micrite pellets showing faint lamination, in a granular calcite cement. These are thought to be algal bound accumulations of pellets, shell fragments and silt or mud grade calcite.

Lower Purbeck. Mupe Bay.
Basal Beds.

Fig. 33. - As Fig. 32. but illustrating coarse patches of calcite cement. Many pellets appear to 'float' in these patches though most are probably in three dimensional contact, but it is thought that in many cases this coarse calcite is a replacement of an original anhydrite cement.




1000 μ

results in the formation of a roughly concentric nodule. In thin section the laminations are seen to consist of alternations of ill-sorted and loosely packed calcite-mudstone pellets 50-250 μ diameter, in a coarsely crystalline calcite cement (figs. 32, 33). There are also layers of clotted silt and mud-grade calcite (10-2 μ) in which faint, spar-filled tubules, probably of algal origin, may rarely be made out.

The pellets consist of mud to fine silt-grade grains (1-8 μ), roughly equant in shape, with plane grain boundaries. They are grey in colour. Most are rounded though not spherical, but here and there are areas where the pellet boundaries are surprisingly straight, and in the sides of them are numerous small, spar-filled, rectangular re-entrants. These are believed to be caused by replacement by anhydrite, subsequently replaced by calcite (p. 56). This calcite is typically drusy.

The second type occurs as nodules and lumps ½-2 cm. diameter, and formed around a small (200-400 μ), probably organic nucleus which, upon decay, left a cavity now filled by drusy calcite. The nodules are opaque and consist of poorly laminated accumulations of calcite grains, usually 2 μ or less in size, but scattered throughout are small, translucent patches of granular cement with grains of from 5-20 μ. This gives the nodules a clotted appearance (fig. 34). Here and there, too,

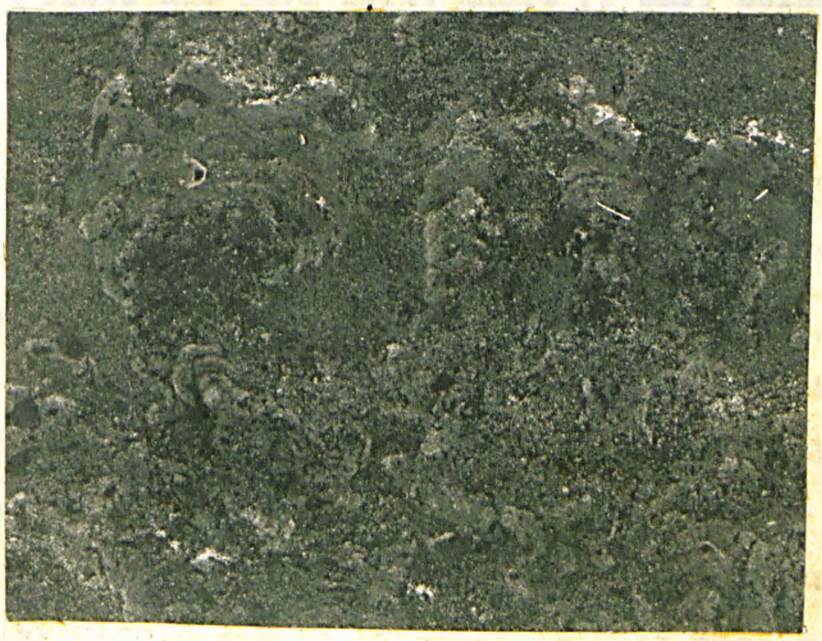
Fig. 34. - Photomicrograph of an algal button that formed around a small nucleus, now filled by micrite pellets and calcite cement. The button consists of a poorly laminated accumulation of calcite mud and silt grains retaining, in this case, no direct evidence of algal origin.

Lower Purbeck. Lulworth Cove.
Basal Beds.

Fig. 35. - Columnar shape of small algal 'heads' that grew in place. They are formed of alternations of calcite-mudstone, calcite siltstone and small micrite pellets.
Negative print of an acetate peel, magnification 2x.

Lower Purbeck. Mupe Bay.
Basal Beds.


500μ



rounded calcite mudstone pellets up to 100 μ diameter are present within the clotted material. In rare cases poorly defined spar-filled tubes 50 μ or so in diameter can be seen within the finer grained groundmass, but this is uncommon. It does, however, strongly point to algae as the originators of the structures. They were perhaps non-calcareous forms that trapped suspended carbonate grains, and sometimes pellets, on a mucilaginous surface. It has been noted that such algae preferentially trap finer grained sediment (Black 1933) and this appears to have been the case here.

Some nodules are symmetrical suggesting that they are formed around an unattached nucleus that rolled about and allowed growth to take place in all directions. Others appear to have been fixed and have built short (2 cm.) columns (fig. 35).

The nodules are in a matrix of calcite-mudstone pellets and granular cement. The micrite pellets (Folk, 1959) are 50-140 μ diameter, light grey in colour, are round and frequently appear spherical. They are formed of calcite grains of the same size as the clotted *Spongiostroma* layers and this lends support to the view that these layers were formed by the trapping of grains. The cause of pelleting is not clear. A few have a thin superficial oolitic coat indicating movement in an environment saturated with $CaCO_3$, and it is possible that they were produced by aggregation of discrete grains in a manner similar to that described by Illing (1954). A faecal origin seems unlikely because of the similarity of habit of the calcite grains in the pellets and in the Spongiostroma (p. 41) and, though less convincingly, because of the almost complete lack of fauna in these sediments. A few ostracod valves and fragments are all that is present.

2. Evenly-laminated type -

These are rare, occurring in places just below, or at a short distance above, the main Dirt Bed (fig. 36). They are formed of 2-5 mm. thick layers of millimeter laminated calcite-mudstone, alternating with 5-10 mm. layers of dense to porous Spongiostroma type limestone. The slight relief developed on the top surface of these Spongiostroma layers is eliminated within the next calcite-mudstone layer.

The mudstone layers are grey, but with a brown tinge. Some laminae are of a uniform structureless calcite-mudstone; others have a very finely clotted texture. These both alternate with laminae composed of irregularly shaped calcite-mudstone pellets and fragments, up to 50 μ diameter, set in a patchy, granular calcite cement. The cement patches are of very irregular shape, and some may be replacements after gypsum.

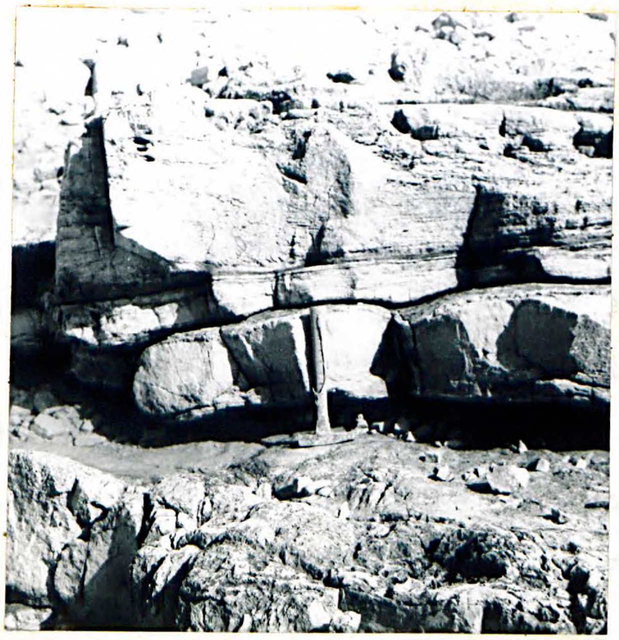
The Spongiostroma layers contain small lumps and nodules 1-2 mm. diameter composed of clotted, unlaminated calcite-mudstone. In addition, abundant well-formed calcite pseudomorphs

Fig. 36. - Even-laminated stromatolite (behind the hammer) just above the main Dirt Bed. Here it is overlain by porous, weathered saccharoidal limestone.

Lower Purbeck. Fossil Forest.
Basal Beds.

Fig. 37. - Photomicrograph showing a typical appearance of calcite pseudomorphs after gypsum. The rhomboidal shape is characteristic, and many are filled by a single calcite crystal. The matrix is micrite.

Lower Purbeck. Poxwell.
Basal Beds.




500μ

after gypsum are present (fig. 37), their leaching out producing the porosity in outcrop.

In places, the calcite-mudstone layers are traversed by thin, downward narrowing, spar-filled cracks probably caused by dessication. This, the gypsum pseudomorphs, and the close association with the sub-aerial dirt bed, indicates very shallow water conditions and occasional emergence during the formation of these beds. Except for the gypsum pseudomorphs they are similar to the beds described, for example, by Ginsberg and Lowenstam (1958), which are formed by mats of microscopic blue-green algae (see below).

(ii) Origin. -

In discussing the origin of stromatolites, most authors have concluded that they are algal structures formed in shallow waters, with depth of penetration of light as the most important factor controlling their growth. Modern stromatolites are usually found only above low-water mark (Black 1933, Ginsberg 1955), where they are formed by the action of blue-green and green algae. The blue-green algae described by Black on Andros Island in the Bahamas are filamentous types that permeate and bind calcareous sediment, but do not themselves precipitate calcium carbonate. During periods of non-deposition, thin algal mats are formed which are in turn covered by more sediment. Continued repetition of this process results in the formation of a laminated deposit the appearance of which depends largely on such factors as periods of dessication and of flooding. Black illustrated 4 types of deposit (A - D) characteristic of various environments. Similar structures have been described from Florida (Ginsberg and Lowenstam, 1958), where they occur in association with small, unattached, spherical bodies resembling Ottonosia.

Stromatolites are not exclusively marine and may form under wide ranges of salinity. Fresh-water types have been described by Clark (1900), Bradley (1929) and others. Russell (1885) described and illustrated several varieties of calcareous tufa that formed in variable salinities along the shore of the pre-glacial Lake Lahontan in Nevada. His work was developed by Jones (1925) who showed, by comparison with modern deposits in the remnants of this lake, that most of these tufas are of algal origin.

While some algae produce stromatolites by binding sediment together, others form structures by precipitating calcium carbonate around their stems, either as a loose precipitate adhering to the mucilaginous algal sheathes, or as a hard stony incrustation around the colony (Jones 1925). This type may retain some micro-structure in fossil forms, but the commonly porous nature of the deposit render it susceptible to diagenetic changes, and only in favourable circumstances can algal filaments be seen.

Rezak (1957) presents a good discussion of the origin of stromatolites, and gives a table (pp. 145-146) listing the environments in which the various structural types are likely to have been formed.

More recently Ginsberg (1960) has compared ancient forms with the modern stromatolites of Florida and the Bahamas. He considers stromatolites described by Black (1933) to be characteristic of mud flats periodically flooded and exposed. Ginsberg describes unattached stromatolites, the onkolites of Pia (1927), forming in marine environments. Previous descriptions of this type of modern stromatolite have only been of fresh or brackish water forms.

These modern onkolites closely resemble ancient forms such as Pynenostroma and Ottonosia, and consist of laminations around a nucleus. They may develop on a fixed protuberance and build up small hemi-spherical masses, but they are more often broken off by scavengers or by wave action and continue growth symmetrically to form a rounded nodule.

Many onkolites have internal cavities which are commonly tubular in shape and are made by boring polychaetes, while central cores may often be almost completely destroyed by boring and burrowing animals. Frequently the algal bound laminations have been converted to loose faecal pellets and have been removed. Originally some laminae were composed of particulate sediment of sand size, others of finer grade.

The Purbeck stromatolitic limestones previously described can be compared with many modern and fossil forms. In particular, they closely resemble both the photographs and description of calcareous tufas of Lake Lahontan (Russell 1885). These are porous laminated deposits formed in the beach zone of a warm, shallow saline lake, where they were subject to fluctuating lake level and to wave action. More compact, laminated tufas developed in shallow water on the lake floor. They were produced by both carbonate precipitating and sediment-binding algae, with only minor amounts of physico-chemical precipitates.

Continued restriction of the basal Purbeck Ortonella lagoon would lead to an increase in salinity, and perhaps of temperature, sufficient to inhibit the growth of Codiacean algae. Green and blue-green algae on the other hand would still be able to grow and become the dominant rock builders in producing the stromatolitic limestones. The rapid lateral variations, and the irregular distribution of these beds, reflects local changes in environment, such as depth of water, wave activity, and, perhaps, variations in salinity.

Individual Spongiostroma balls were formed in shallow agitated waters, while the porous Spongiostroma sheets and reefs developed in areas that were sometimes above water level, but kept wet by wave action. Wave action, too, helped produce some of the material for the detrital limestones. Even-laminated stromatolites were formed by sediment-binding algae in places near or above sea level and subject to frequent innundation. This generally prevented complete drying out of the layers and preserved the laminated appearance.

(e) Petrology of the Detrital Limestones

(i) Petrography. -

These are laminated and generally evenly bedded limestones of variable character and thickness. Most abundant are well bedded pelsparites (Folk, 1959), that grade in places to pelmicrite. The beds are of from 3-30 cm. thickness, generally horizontally laminated except where the sediment has accumulated between Spongiostroma heads, where concave lamination is common (fig. 38). The rocks are composed of micrite pellets and lumps, round and often apparently spherical when less than 100 μ diameter, but the larger lumps, up to 500 μ size, are irregularly shaped (fig. 39). The pellets and lumps are light grey in thin section and are formed of aggregates of calcite grains of from 4-8 μ diameter, only rarely smaller. The grains are mostly equant and appear to have plane boundaries. The pellets are well sorted along individual layers, but show considerable vertical variation. Their packing determines the nature of the calcite cement which varies from fine to coarsely crystalline

Fig. 38. - Concave lamination of detrital limestones infilling a gap between spongiostromatolitic algal nodules. Length of section, 15 cm.

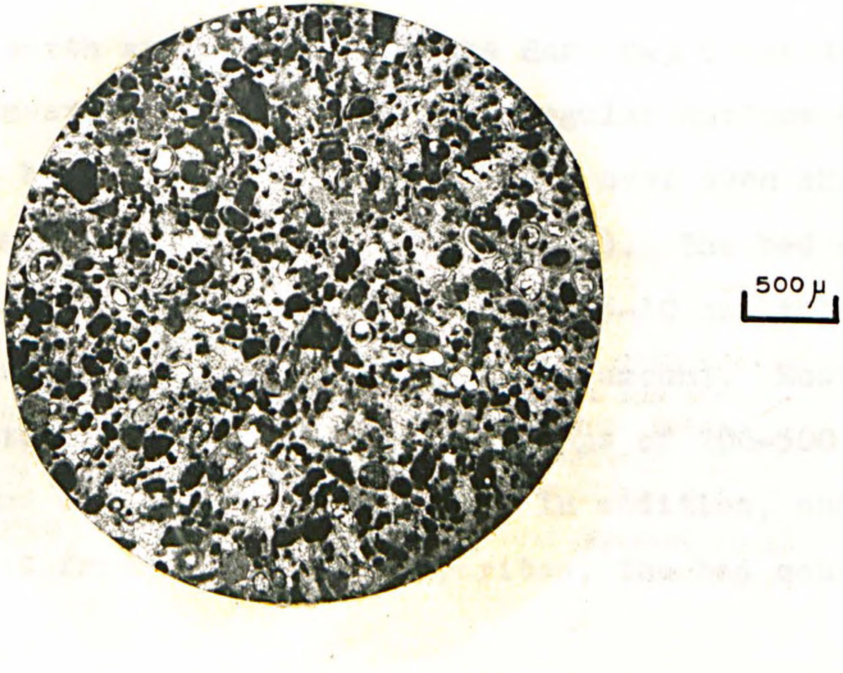
Lower Purbeck.
Basal Beds.

Fossil Forest.

Fig. 39. - Photomicrograph of a detrital limestone. It consists of micrite pellets and lumps with some superficial oolites and rare shell fragments, set in a granular calcite cement. There is some evidence for the micrite cores of oolites having been replaced, first by anhydrite and then by granular calcite (see Fig. 41.).

Lower Purbeck.
Basal Beds.

Worbarrow Bay.


500 μ

(10-100 μ). In places a micrite matrix is present, probably where winnowing was insufficient to remove algal mud. The micrite areas are composed of grains which are similar in size and shape to those forming the pellets and lumps; these areas sometimes contain small pseudomorphs after gypsum.

Most of the micrite lumps show little or no internal structure, but in places it is possible to follow a lateral graduation from amorphouscarbonate lumps, through lumps with vague structure, to pieces of distinct <u>Spongiostroma</u> limestone, and, particularly at Worbarrow these beds can be followed until they merge into a <u>Spongiostroma</u> reef (fig. 21). It is evident that the pelsparites are contemporaneous with algal beds, and are mostly derived from them. The variation in shape and loss of internal structures is dependent upon the amount of transport and abrasion.

In the Lulworth area the top of the Hard Cap consists of a cross-bedded limestone that infills an irregular surface of spongiostromata beds. Thickness is variable over even short distances but is a maximum of 1.5 m. (fig. 22). The bed consists of cross-strata (McKee and Weir, 1952) 5-10 cm. thick, with dip very variable in both direction and amount. Most of the rock consists of micrite pellets and lumps of 200-500 μ size, rounded and often quite spherical. In addition, and distinguishing it from the other pelsparites, the bed contains an abundance of often spherical to ellipsoidal calcite grains of from 7 -500 μ diameter, many of which are optically single crystals (fig. 40). Some have a more irregular shape similar to ex-foliated ooliths (Cayeux, 1935, Plate 14); others, though mostly consisting of one clear calcite crystal, also contain small inclusions of micrite; while a few contain small marginal crystals characteristic of drusy growth.

In places there are small patched 8-10 mm. long, 1-2 mm. wide consisting of large (500 x 800 μ) inclusion-filled calcite crystals. These are light yellow in polarised light and resemble selenitic gypsum crystals in shape (Ogniben, 1957). The inclusions are of micrite. These crystals may have replaced gypsum (p. 58).

Detrital limestones are abundant only towards the top of the Hard Cap, though present between algal heads in the lower part. They were probably produced by the destruction of algal beds and from calcite mud produced by algae. Their increased importance at the top of the Hard Cap seems to reflect a shallowing of the water and the increased effect of wave action and, partly, sub-aerial erosion of pre-existing limestones.

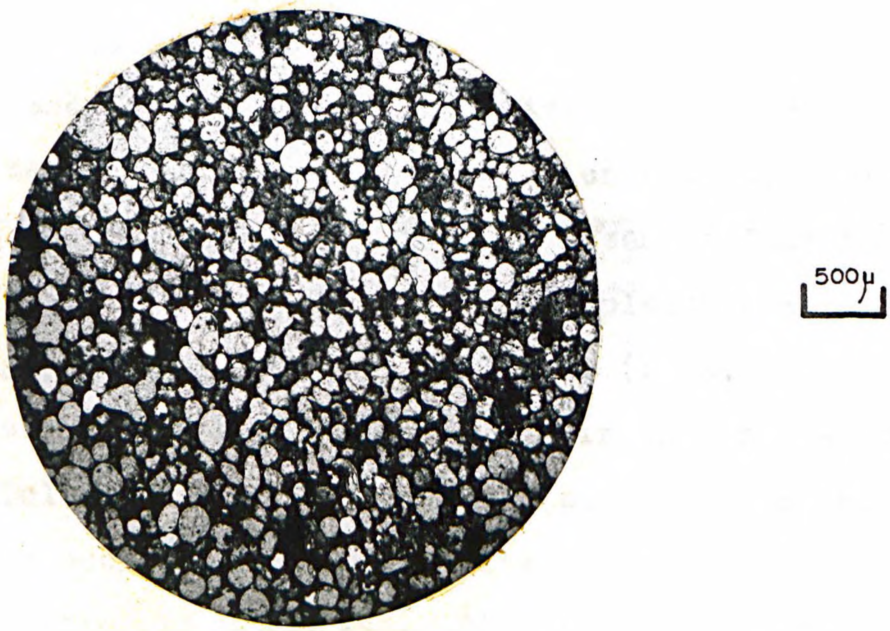
(ii) Origin. -

For the reasons given above most of these limestones are believed to be derived from the erosion and break up of spongiostromata limestones. Agitation by waves or currents is

Fig. 40. - Photomicrograph of round, often almost spherical calcite grains, many of which are optically single crystals, in a micrite matrix. A few show irregular shape similar to exfoliated ooliths.

Lower Purbeck. Lulworth Cove.
Basal Beds.

Fig. 41. - Diagram to illustrate stages in the replacement of the micrite nucleus of an oolite. Initially the micrite was replaced by anhydrite or gypsum, and this in turn was replaced by drusy calcite after the sulphate had been leached away. The end result of this process is a superficial oolite with a nucleus consisting (apparently) of a single calcite crystal.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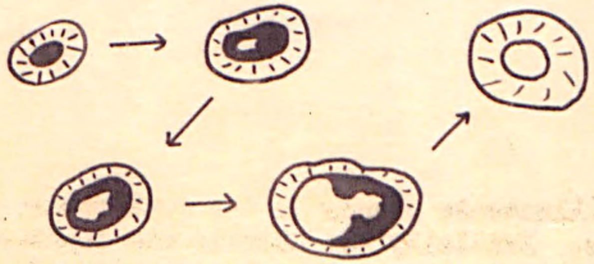


shown by the rare presence of ooliths, mostly superficial. The nuclei of these vary from single calcite crystals to spherical micrite pellets with every gradation between. Examination reveals that these calcite crystals seem in fact to be replacements of anhydrite that had in turn replaced a micrite core. Many stages of replacement can be seen (figs. 39, 41).

This process was carried to completion in the cross-bedded strata between Lulworth Cove and Mupe Bay (p. 50). Here, the entire oolite has been replaced by calcite crystals, and only rarely is any oolitic rim preserved. Pictures of this type of rock and a discussion of its origin are given by Cayeux (1935, pp. 229-232, Plate 14, fig. 53), who concluded that the spherical-ellipsoidal calcite grains were formed by the alteration of ooliths. An earlier replacement by anhydrite suggests a possible mechanism for this.

(f) Petrology of the Bituminous Shales

(i) Petrography. -

From west to east the basal Purbeck limestones become darker in colour, and thin laminations of black calcareous shale appear within them, especially near the base of the Hard Cap, until at Durlston Bay finely laminated layers of black, brittle calcareous shale are 2-3 cm. in thickness. In thin section these show light yellow laminae 6-10 μ thick, alternating with dark brown laminae of 15-20 μ thickness. The colour change is due to an increase in the carbonate content in the lighter layers, shown by increased intensity of stain with Alizarine Red. The total carbonate content averages 48% (3 determinations), the remainder being mostly organic material readily oxidised in Schultz solution, and leaving a residue of fine quartz silt and brown mud. Some of the carbonate is ostracod shells. These are flattened and lie parallel to the lamination. Small carbonaceous plant and insect fragments are present, and interstitial yellow-brown collophane sometimes common. More often, however, this is in the form of small bone fragments. Powdered and heated these shales yield small quantities of brown, oily distillate, readily soluble in organic solvents such as acetone and xylol.

In the more calcareous layers there is evidence of replacement of gypsum. Small patches (up to ½ mm. square) of coarsely crystalline calcite spar occur which contain inclusions of the shale. In rare cases the cores of the calcite crystals contain relict patches of gypsum.

Quantitatively the shales are of minor importance, but are interesting for environmental interpretation.

(ii) Origin. -

No bituminous shales are present in the west of Lulworth Cove, and their increase eastwards can be correlated with a decrease in the thickness of the Hard Cap.

The environment of formation of the Hard Cap limestones, as deduced on previous pages, examined in relation to the basal Purbeck deposits of the Isle of Wight and similar areas to the east of Durlston Bay, provides an explanation for the origin of these shales.

During basal Purbeck time the Dorset and Hampshire area appears to have been a part of a shallow evaporite lagoon, in or near the centre of which anhydrite deposits were forming. Near the border of this lagoon in Dorset salinities were such as to allow algal growth and here the calcareous tufas were formed. This may have been due to the influence of a stream entering the area from the S.W., evidence for which is presented later (p. 97). Plankton, insect larvae and such like entering the area would encounter increasingly saline conditions from west to east, eventually sufficient to kill all but the most tolerant forms. With the decrease in the amount of carbonate deposition, the accumulation of organic material becomes more noticeable. The saline environment may also have encouraged anaerobic conditions, thus leading to the preservation of the organic compounds responsible for the bituminous nature of the shales.

(g) Petrology of the Saccharoidal Limestones

(i) <u>Petrography</u>. -

These are very characteristic in the field and are confined to the Soft Cap (fig. 26). At Lulworth they are 15 cm. thick and thicken eastwards to about 3 m. at Durlston Bay where they are partly involved in the Broken Beds. They consist of rim-cemented calcite crystals 50-200 μ diameter, interlaminated with whisps of pellety micrite or single micrite pellets, and some paper thin partings of black shale. Most of the micrite pellets are floating and must therefore have accumulated as detrital grains with the calcite crystals. Many of the crystals contain rod shaped, inclusion rich cores, which are roughly parallel to the lamination (fig. 42).

(ii) Origin. -

These crystalline limestones are unlike any other rock found in the Purbeck. There seems little doubt that they were detrital; this is shown by the lamination and floating pellets. At Durlston Bay the beds contain small amounts of celestine (West, 1960), a mineral commonly associated with gypsum (Murdock and Webb, 1940), and the progressive eastward thickening of these beds in a direction of increasing anhydrite deposition, supports a view that this limestone is connected with evaporitic conditions.

No comparable type has been found described in the literature, but C. Pendexter (personal communication) reports similar limestones as being associated with evaporites in parts

Fig. 42. - Photomicrograph of saccharoidal limestone. Rim cemented calcite crystals with rod-shaped inclusion rich cores which are roughly parallel to the lamination in the hand specimen.

Lower Purbeck.
Basal Beds.

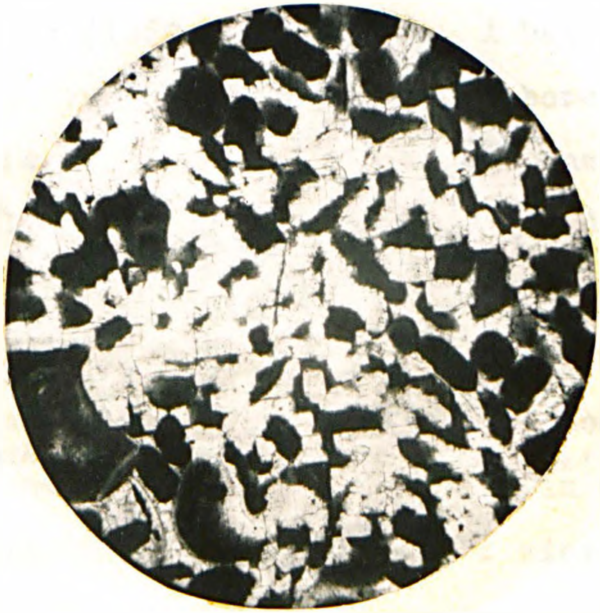
Durlston Bay.

Fig. 43. - Photomicrograph of replacement texture. The dark grey areas are micrite pellets and lumps. The light grey and white patches are anhydrite, all one single optical crystal. This anhydrite has replaced much of the micrite and original calcite cement. Note the development of rectangular sides to the pellets, and the apparently 'floating' appearance of some of the small fragments. Compare with figure 33.

Lower Purbeck.

Arreton borehole.

500 μ



of the U.S.A. A tendency for calcite in association with gypsum to be of a coarse grain size has also been noticed in the Broken Beds (p. 66). Using the criteria given below (p. 57) there is, too, evidence of anhydrite replacement having taken place in some of the inter-laminated micrite layers.

(h) Diagenesis

(i) Replacement textures. -

Several textures in the Basal Beds are believed to be formed by the replacement of calcite by anhydrite. Most apparent are the rectangular re-entrants and straight sided micrite pellets (p. 41), similar examples of which have been described by Murray (1960, pp. 79-80). A better comparison here is with Purbeck material from the Arreton borehole, in the Isle of Wight. In this, the original sediment consisted of micrite pellets and shell fragments (mostly ostracods) in a granular calcite cement. In places the cement, shell fragments and much of the micrite has been replaced by anhydrite (fig. 43). Each anhydrite patch is one optically continuous crystal up to 5-6 mm. long and 2-5 mm. wide, but when in extinction it is seen that, although the calcite of the micrite pellets has been replaced, small non-carbonate specks, possibly micas, are unaffected and their polarization colours indicate the original extent of the pellet. This is shown too in ordinary light by a faint yellow colour in the anhydrite that has replaced micrite or shell fragments, contrasted to colourless anhydrite replacing granular cement.

The replacement anhydrite attempts to develop its crystal form and is controlled by the three cleavages at right angles. This results in straight sided crystals and in the formation of the rectangular re-entrants in the sides of micrite pellets (fig. 43). Sometimes the crystal shape is controlled by the fabric of the rock element being replaced, particularly by shell fragments, and rectangular outlines do not develop.

Were this anhydrite in turn to be replaced by calcite, the resultant texture would closely resemble that seen in places in the Hard Cap (fig. 33), and it is proposed that this has occurred. During such replacement the anhydrite would first probably hydrate to gypsum and this process may have destroyed some of the texture. Subsequently, the gypsum was leached away and replaced by drusy calcite. During this process the non-carbonate inclusions wuld, for the most part, be carried away in suspension and redistributed. This removal of gypsum may be the cause of the collapse structures seen in the Hard Cap (p.26).

In only one case has gypsum been found still present as a cement in the Basal Beds. This is on the Isle of Portland in a bed known by the quarrying term of "slat". Two specimens of this bed have been examined. One, from a quarry, has a dominantly gypsum cement (fig. 44). In the other, from the cliff outcrop, this gypsum has been replaced by calcite (fig. 45).

The gypsum crystals vary in size up to 500-600 μ length. Many show one good cleavage. They have replaced micrite, shell fragments and calcite cement, but rectangular shapes are not common. There is, however, a tendency for the gypsum crystals to be rimmed by thin films of micrite, and for the distinctive rhomboid crystal form to develop (fig. 45).

In the outcrop specimen this crystal form is readily recognised, now composed of calcite crystals. Areas containing whisps of dispersed micrite show where calcite has replaced micrite rimmed gypsum, but there is little evidence from rectangular shapes that gypsum was once present. Similar coarse mosaics of calcite with whispy micrite inclusions occur in the cross-bedded Hard Cap at Lulworth Cove (p. 50), and, by comparison with the beds on Portland, it is reasonable to assume that these patches too are replacements after gypsum.

(ii) <u>Silicification</u>. -

This is of minor importance in the Basal Beds. A little

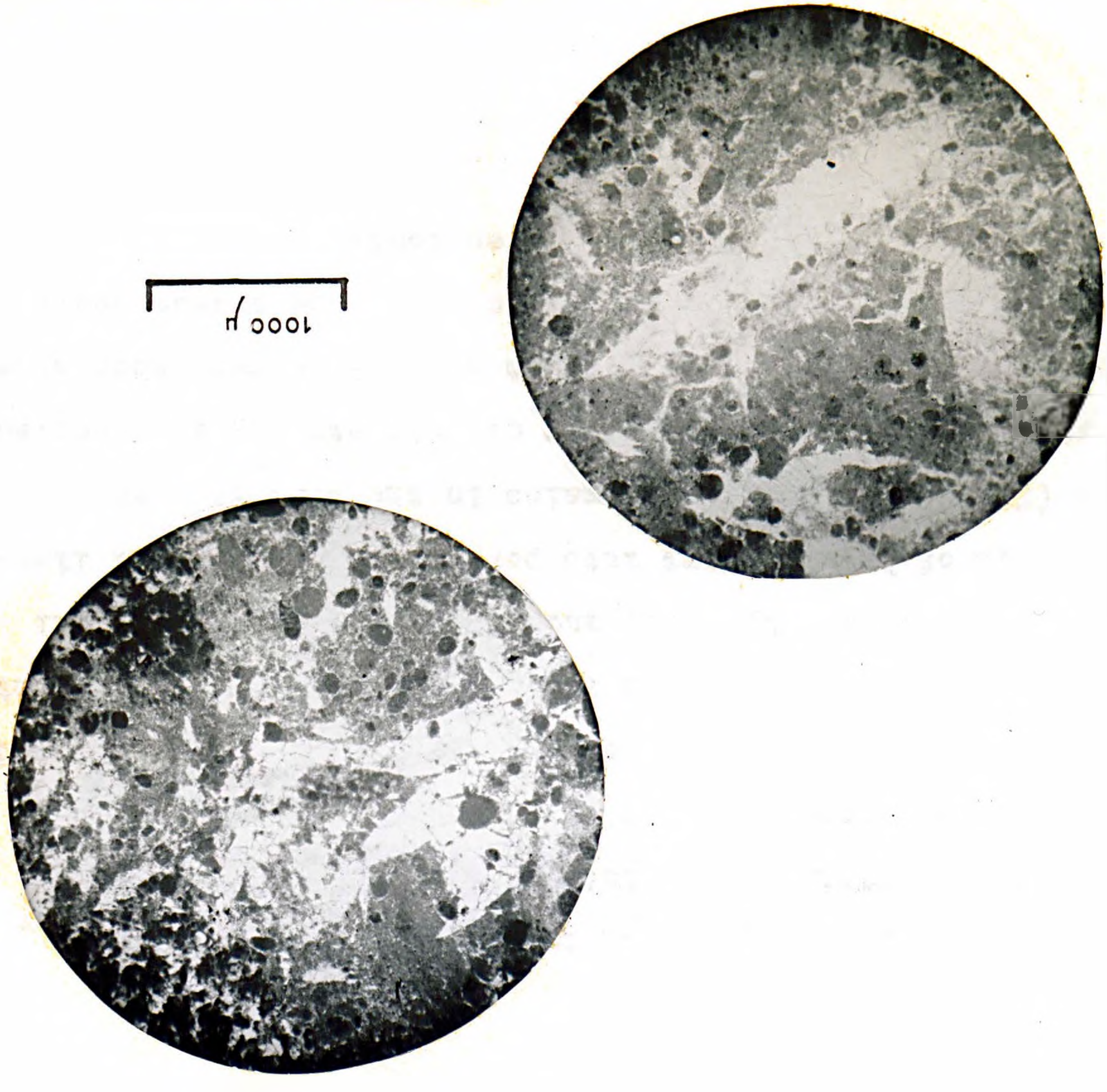
Fig. 44. - Photomicrograph of 'slat'. Micrite pellets and lumps, here with a dominantly gypsum cement which has partly replaced the micrite and has partly developed a typical rhomboidal shape.

Lower Purbeck. Isle of Portland.
Basal Beds.

Fig. 45. - 'Slat' as in fig. 44. Here, however, the gypsum cement has been replaced by calcite. The rhomboidal shape is still evident.

Fig. 46. - To the left of the hammer the middle layer is a porous, tufaceous limestone which passes laterally at the hammer into bedded chert, evidentally a replacement of the limestone.

Lower Purbeck. Fossil Forest.
Basal Beds.


1000 μ

chert is present in places at the base of the Soft Cap (p. 27), but otherwise silicification is confined to small (1-2 cm.) chert lenticles, or to microscopic patches. In all cases the silica can be clearly seen to have replaced carbonate. This is shown in thin section by the development of euhedral quartz crystals, and in outcrop by the lateral transition of bedded chert into porous tufaceous algal limestone (fig. 46). The tree remains in the Dirt Bed are invariably silicified with their organic structure preserved. This indicates that silicification took place very soon after the death of the tree, otherwise decay of the tissue would have occurred and the structure been lost.

IV. BROKEN BEDS

(a) General Description

To the east of Durdle Door the Broken Beds form a distinct lithological unit, a study of which is complicated by the brecciation. West of Durdle Door the beds are unbrecciated, but, except on the Isle of Portland, exposures are poor. In many of the brecciated sections the beds consist of a jumble of limestone blocks in complete disorder (figs. 47, 48, 49). In some places, however, where brecciation is less intense, it is possible to sample the beds in an approximately stratigraphic sequence. Inevitably this sampling is biased, as only the more competent beds, the limestones, yield satisfactory specimens. Any shales or mudstones originally present were squeezed out during the brecciation, or are highly weathered. Comparison with the unbrecciated beds on Portland indicates that such beds are likely to have been quantitatively small, but their original presence cannot be ruled out.

The dominant field characteristic is the brecciation, the general appearance of which is well described by Arkell (1947, p. 298). The limestone blocks weather to a light grey or tan, sometimes with a white efflorescence. Uniform, laminated evenly-bedded units 2-5 cm. thick are typical, but a few layers show small scale cross-bedding. These layers are usually richer in detrital quartz than are the others.

Fig. 47. - Broken Beds. Shows the occasional preservation of thick units in an approximately stratigraphic order.

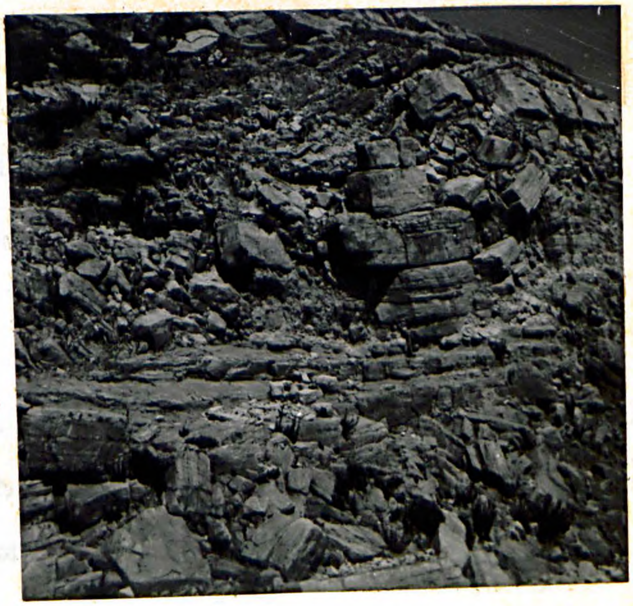
Lower Purbeck. Fossil Forest.
Broken Beds.

Fig. 48. - View of Mupe Rocks. Much brecciated at the base, overlain by unbroken Cypris Freestones and capped by brecciated Hard Cockle Beds.

Lower Purbeck. Mupe Bay.

Fig. 49. - Close up showing the jumbled nature of much of the Broken Beds.

Lower Purbeck. Lulworth Cove.
Broken Beds.



Lamination is due to variation in the size of calcite-mudstone pellets, which form the bulk of the limestones, but is only apparent on weathered surfaces. Other than ostracods, no fossils appear to be present, though some layers are covered with black carbonaceous specks, possibly insect fragments. Black chert occurs here and there, usually towards the base, and is more common at Durdle Door and Lulworth than further east.

The top of the Broken Beds is irregular, higher horizons being affected by the brecciation in some places than in others. From Worbarrow to Lulworth however, there is a thin, very distinctive bed that can be taken to mark the top of the lithological unit, even though in places beds above it are brecciated. This bed is about 5 cm. thick and weathers to an orange-brown that is clearly defined in the grey-tan limestones. The bed contains about 25% by weight of sand-size quartz grains, many of which have over-growths giving them euhedral shape. The rest of the bed is a soft calcite-mudstone with a very few ostracod shell fragments and black carbonaceous specks. It acted as a slip plane during the folding, and in places slickenslides are still present on its surface. Its main importance, though, is stratigraphic in providing a correlateable marker at an important horizon. By using it as such it is possible to compare the petrography of the beds below from section to section and, over such a limited area, to be reasonably sure that we are comparing time equivalents.

(b) Petrology

(i) Petrography. -

Throughout the Broken Beds the dominant sediment is calcite-mudstone in the form of pellets and lumps set in a granular calcite cement (figs. 50, 51 52). In addition, algal mudstone fragments, superficial and true oolites are also present, but in minor amounts. Bioclastic material is sparse, usually consisting of thin ostracod valves and fragments and only rarely whole shells. Very rare foraminifera occur, and, except in the beds on the Isle of Portland, pelecypods and gastropods are absent. The reason for this faunal poverty is adduced below (p. 70). Quartz of silt-sand grade is ubiquitous but seldom abundant. Interstitial collophane is present in places, and calcite-pseudomorphs after gypsum are common in some beds.

1. The Pellets. -

The calcite-mudstone pellets mostly appear light-medium grey in thin section, but some have a distinct golden-brown tinge, a feature that is more common in some beds higher in the Lower Purbeck (p. 90) and that may have a significant connection with their mode of origin or diagenesis. The mud grains in the pellets are 3 μ or less in size, boundaries appear to be mostly plane but some seem slightly curved. The pellets are very homogeneous, only rarely showing a faintly clotted texture caused by the inclusion of small patches of the golden-brown mudstone. These patches are of very fine grain size, but sometimes show a radial extinction. Inclusions, such as shell fragments and quartz grains, are completely absent from the pellets (fig. 50).

Pellets are of sand size, varying from 70-250 μ diameter, though usually well sorted in any particular bed, with the smaller pellets showing the better sorting. Though round there is none the less considerable diversity of shape with variation fro spherical to square and pentagonal. Many pellets appear as small rods with length-diameter ratio of about 2:1. These too would appear as spherical pellets if cut transversely and care must be taken to watch for any suggestion of orientation of rods with long axes lying more or less parallel to one another. This occurs in some of the Soft Cockle Beds (p. 116) but does not seem to be present in these rocks.

Only rarely do pellets interpenetrate one another, or do two or more pellets merge their boundaries. When either of these occurs it is usually common throughout a particular layer

Fig. 50. - Photomicrograph of pellets and lumps with granular calcite cement. A few ostracod fragments. Note the absence of inclusions within the pellets.

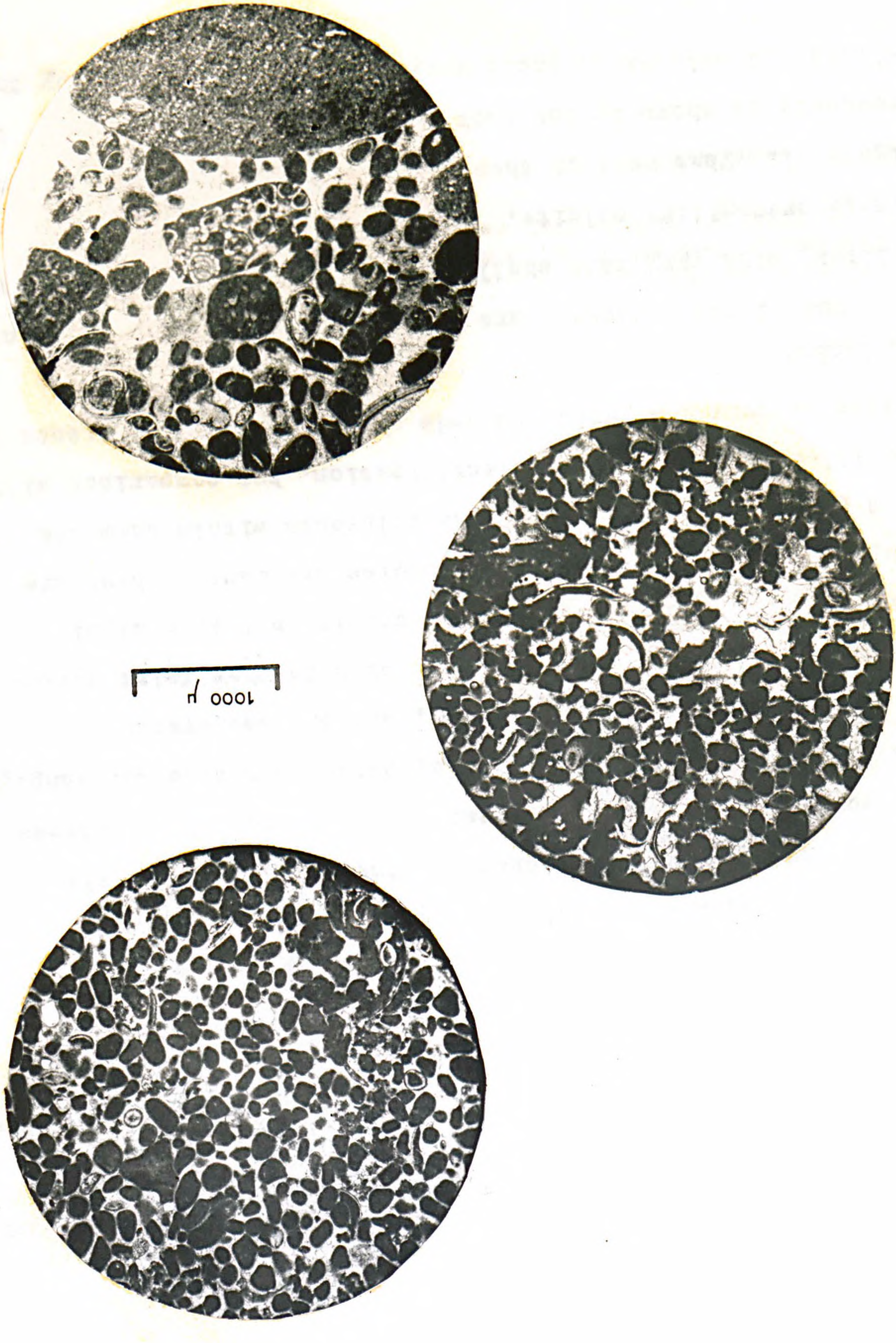
Lower Purbeck. Worbarrow Bay.
Broken Beds.

Fig. 51. - Pellets and lumps with granular calcite cement. Most of the lumps are formed either by algae or by accretionary processes, as shown by the absence of truncated internal structures (see fig. 52).

Lower Purbeck. Lulworth Cove.
Broken Beds.

Fig. 52. - Pellets and intraclasts in granular calcite cement. Note particularly the well-rounded intraclast at the centre, containing oolites, some of which have been truncated at the margin of the fragment.

Lower Purbeck. Stair Hole.
Broken Beds.


1000 μ

of 1-2 cm. thickness.

2. The Lumps. -

The term lump is used both in the sense of Illing (1954), that is, masses formed by the aggregation of two or more pellets, and also includes fragments that may be intraclasts in the sense of Folk (1959). Differentiation often depends upon the recognition of diagnostic structures within the lumps, and upon the relationship between the lump and the surrounding cement. In many cases, when internal structures are absent, there are no criteria, other than size and shape, to distinguish lumps from pellets, and the two overlap.

Many lumps of from 150-500 μ size do show faint structures indicating a possible algal origin, but true algal fragments with recognisable structures are rare. These are from ½-2 mm. in diameter and the filaments within them are too ill-defined to permit identification, but comparison with better preserved material in beds above indicates reference to Ortonella.

Most lumps, however, are built up of distinct pellets and oolites, with very rare shell fragments, cemented together by finely crystalline calcite. Typical lumps are illustrated in figure 51. That most of these lumps are formed by accretionary processes is shown by the lack of truncation or erosion of the pellets and oolites at their margins. Had they formed by the erosion of previously deposited beds of pellets far more should show erosional edges. That this process did occur is shown by the rare presence of just such eroded fragments (fig. 52). These are true intraclasts but their rarity indicates that pene-contemporaneous erosion was not a major factor in lump formation.

3. The Cement. -

The cement shows many of the characteristics of granular cement as given by Bathurst (1958, pp. 19-20). The calcite crystals are in mosaics with plane intergranular boundaries, and with grain size dependent upon the tightness of packing of the pellets. Around the pellets the cement forms a border of small grains, nucleated presumably upon the mud grains of the pellets. These small grains are overgrown by larger ones that occupy the main inter-pellet spaces, and grains may reach 200 μ in longest dimension, but this is unusual. Twinning in the crystals is rare and such as does occur can perhaps be ascribed to the grinding of the thin section.

Towards the top of the Broken Beds there is sometimes a variation in the fabric of the cement. This is particularly so where pseudomorphs after gypsum occur. These pseudomorphs have the distinctive rhomboid shape of gypsum (fig. 37), but have usually been replaced by single crystals of calcite, or sometimes by two crystals joined along the shorter diagonal of the rhomboids. They are set in a calcite mosaic of irregular grain size varying from 120 μ down to an average of 5-15μ, though in any one area grains are of fairly uniform size. The grains possess apparently plane boundaries. The mosaics separate pellet layers by as much as 1 mm., and contain isolated pellets that are not in three dimensional contact with one another; criteria that suggest a rim cemented detrital deposit, and perhaps indicate a tendency for carbonate to be precipitated as silt-size crystals rather than as mud under particular environmental conditions, as noted previously. (p. 56).

4. The Accessories. -

The chief of these is quartz, which is ubiquitous but seldom abundant. A thin bed at Lulworth contains 20% by weight, with the quartz grains averaging 100 μ size, but this is exceptional. The grains are usually of fine silt to sand size. They are angular, but show indications of some replacement by calcite, so it would be unwise to draw conclusions as to the amount of transport or abrasion they have undergone. Stable heavy minerals such as tourmaline and zircon are associated with the quartz.

Here and there in the beds are small (50-100 μ) patches of light yellow to brown mineral. It is isotropic with a R.I.

slightly less than that of calcite o-ray (1.658). It is probably a form of collophane, derived perhaps from bone fragments.

Unlike many of the Lower Purbeck rocks, the Broken Beds appear devoid of pyrite. This partly accounts for the light colour of the beds.

(ii) Origin of the carbonate-mudstone. -

Much of the calcite-mudstone forming the pellets and lumps was originally a mechanically deposited mud. That unpelleted mud was available is shown by two main criteria. Firstly, the presence in some cases of floors of calcite-mudstone in whole ostracod shells; this mudstone, with an essentially flat topped surface, is overlain by drusy calcite and must have been introduced prior to the formation of this druse, and of the cement. Secondly, by the presence in some oolitic coats of small patches of mud-size calcite grains, a criterion used by Wood (1941, p. 194) to show the presence of 'algal dust' in suspension during oolith formation. Here, the dust is not necessary algal. Several conceivable modes of origin for such a mud may be considered. It could be:

A physico-chemical precipitate
A purely biological precipitate
A combination of these two
Formed by the comminution of shell debris
Formed by erosion of pre-existing calcite-mudstone

The last of these is limited by the absence of possible source areas containing calcite-mudstone, and more particularly by the fact that erosion of such rocks would be likely to proceed by solution, and transportation of $CaCO_3$ as solute. Ultimate precipitation would thus place the formation of the mud into the first category.

It is more difficult to decide to what extent the breaking up of shells contributed to the production of mud. The lack of fauna in the beds may suggest that shell debris was quantitatively unimportant. On the other hand, the very lack of skeletal material may be due to its total disintegration. That shells can so disintegrate and produce mud size particles was first noted by Sorby (1879 p. 70) and has been frequently commented upon since. It depends primarily upon the shell being aragonite. It seems unlikely that such complete disintegration of shells could have occurred here, particularly as those layers where deposition was most rapid - shown by pellet merging - are also devoid of shell fragments, even though some preservation might be expected in these cases. Although, therefore, some mud may be derived from shells, it is considered unlikely that the amount was great.

Biochemical precipitation of calcite (and aragonite) by animals is usually confined to the formation of a hard exoskeleton, and consequently need not be considered here. Plants, however, especially some algae, often precipitate carbonate on or within their tissue. Examples of this have been discussed previously (p. 39). Upon the death of the plant the carbonate may be released and act as a detrital deposit, or, as often happens, small fragments are produced which retain some outline of the plant's cellular structure. During the life of the plant carbonate deposition may be so great that fragments slough off to form a mud. This is well known in the case of the stoneworts, but can also occur in other classes (Lowenstam, 1955).

Recognisable algal fragments are present in the Broken Beds though the amount is small, a maximum of 2-4%, and consequently it is likely that some at least of the mud is of algal origin. It is impossible at present to say how much is so derived.

Physico-chemical precipitation of calcium carbonate is well known, and has been described particularly from the Bahamas by, for example, Drew (1914), Vaughan (1913, 14), Black (1933), Illing (1954), and Newell and Rigby (1957). Precipitation from solution is dependent on a number of variables, the most important of which are, the degree of saturation with respect to $CaCO_3$, the partial pressure of CO_2, temperature and salinity. Carbonate precipitation is favoured by an increase in temperature (which in turn lowers the concentration of CO_2). The temperature increase also results in a raising of salinity due to evaporation. This is well shown in the Bahamas where salinities over the Banks are in the region of 38.5% compared with the 35% of the open ocean. In enclosed shallow waters such evaporation could ultimately lead to the deposition of gypsum either as beds, or interstitially as a cement. Evidence of interstitial gypsum is present in the Broken Beds, in the form of calcite pseudomorphs and leads to the conclusion that saturation with respect to $CaSO_4$ occurred.

No direct evidence of depth of water is present, but the presence of occasional cross-bedded units rich in detrital quartz, the presence of algae, the occurrence of oolites and lumps indicating turbulence on the sea floor, and the persistence of conditions of saturation with respect to $CaCO_3$ and sometimes $CaSO_4$, strongly suggest shallow water, possibly of only a few metres depth.

It is proposed, therefore, that much of the carbonate-mud was formed by physico-chemical precipitation in warm, shallow, slightly super-saline waters subject to gentle agitation, and with a sparse fauna controlled by the salinity and particularly the temperature (Adams and Rhodes, 1961). An indeterminate amount of mud was additionally contributed by algae.

(iii) Mode of aggregation. -

The original mud is now in the form of pellets and lumps of mudstone and three modes of origin for these are considered. The first, that they may represent eroded fragments of older rocks has already been discussed and considered unlikely (p. 68). There remain the possibilities that they were produced by the activity of organisms, as faecal pellets, or by some process of progressive aggregation of grains, as "bahamites" (Beales 1958).

The identification of faecal pellets in rocks has been and still is a vexing problem of petrology. It is known from observation on modern deposits that large amounts of such pellets may be produced by invertebrates, especially those living in a mud environment. The preservation of these pellets however is dependent firstly upon the speed at which they become lithified, and secondly upon the rate of burial. Rapid burial causes squashing and merging of the pellets and the production of a structureless mud. Pellets formed in an environment saturated with $CaCO_3$ are likely to be lithified rapidly, as are faecal pellets on the Bahama Banks (Illing, 1954, p. 24), and thus preserved as discrete pellets.

The shape has been used in efforts to distinguish faecal from other pellets, the more rod like ones being assumed as faecal. However, this is by no means certain for, as shown by Moore (1951), faecal pellets, which may initially reach 2.0 mm. length, rapidly break up into lumps 0.2 mm. long which would be indistinguishable from spheres when rounded. Perhaps a more important distinction may be the presence of small "chitinous" specks disseminated throughout the internal parts of faecal pellets (Illing, 1954, p. 25). In addition, there is the possibility that the pellet will contain a proportion of organic matter which may, under conditions of rapid burial, produce a localised reducing environment within the pellet and result in the formation of pyrite. This is discussed in a later section (p. 71) where such pyritised pellets are concluded to be faecal. Folk (1959, p. 7) mentions that faecal pellets are usually rich in organic matter and show up with a brownish colour in thin section when viewed with convergent light.

In the present case, however, pyrite is absent, as are any traces of the chitin specks. Furthermore, as previously adduced, there was an impoverished fauna while the presence of lamination indicates little turnover by worms, and so, while some of the pellets may be of faecal origin, it is thought that most were formed by some process of grain aggregation. The postulated conditions of origin of the mud lead directly to comparison of the pellets and lumps with those described by Illing (1954, p. 31), and it is here suggested that they were formed in a similar manner, this is, by the accretion and progressive cementation of mud particles. Continued cementation produced some lumps (grapestones of Illing), while increased local turbulence led to the formation of the rare oolites.

(c) Diagenesis

Whatever its origin, much of the carbonate-mud must have been deposited mechanically, as shown by its presence in the lower half of the shells; it would therefore have been a porous deposit. During or following aggregation this porosity was lost, and the present non-porous fabric developed. The proposed mode of origin for the pellets and lumps, by accretion of grains, would likely result in the precipitation of interstitial carbonate (aragonite ?) cement which would effectively eliminate the porosity. Some rim-cementation (Bathurst, 1958, p. 21) may have occurred, as might pressure solution of some of the smaller grains but this is not determinable.

The cement shows all the characteristics of a granular chemical deposit (Bathurst, 1958). There is no evidence of any pre-existing aragonite, though in view of the proposed environment this must be a distinct possibility. If such a cement existed and was later removed by solution, then calcite deposited in the pore space would appear to be 'primary'. Aragonite inverting to calcite is not likely to produce the characteristics of a chemical deposit.

Bioclastic material is chiefly of ostracods which, having a calcite shell, have undergone little change. The calcite of the shells is arranged as prisms normal to the shell wall. These acted as nuclei for granular and drusy cement, and helped to produce oriented crystals around the shell fragments. Gastropods are present only in beds on the Isle of Portland and are only recognisable as calcite-mudstone casts of the body chamber. The aragonite shell has completely disappeared, and this must have been removed prior to the cementation of the rock. This is shown by the fact that pellets and lumps are now in contact with the mudstone gastropod casts, and must therefore have moved into place after the shell had dissolved, and prior to the deposition of calcite cement.

Here and there is some evidence of anhydrite replacement having occurred, mostly in the form of rectangular shaped pellets as described on page 57 , but this is not common and does not appear to have been extensive.

V. CYPRIS FREESTONES

(a) General Description

The Cypris Freestones are a maximum of 8.44 m. thick at Worbarrow Bay. They are about 5-5.50 m. at Mupe Bay and Lulworth, while the equivalent beds on the Isle of Portland are only 1 or 2 m. thick. The Durlston Bay section is now covered, but according to Bristow (1857) the beds there are 11.0 m. thick. The Freestones are best exposed at Worbarrow Bay and at the Fossil Forest; elsewhere exposure is only partial.

The beds are cream, white or tan weathering, and form relatively thick units (60-100 cm.) (figs. 53, 54), often finely cross-bedded and with ripple mark common. Where cross-bedding is absent, the beds are well laminated. Shales are absent at the base of the sequence and it is their incoming, together with that of sandy limestone, that marks the top of the unit.

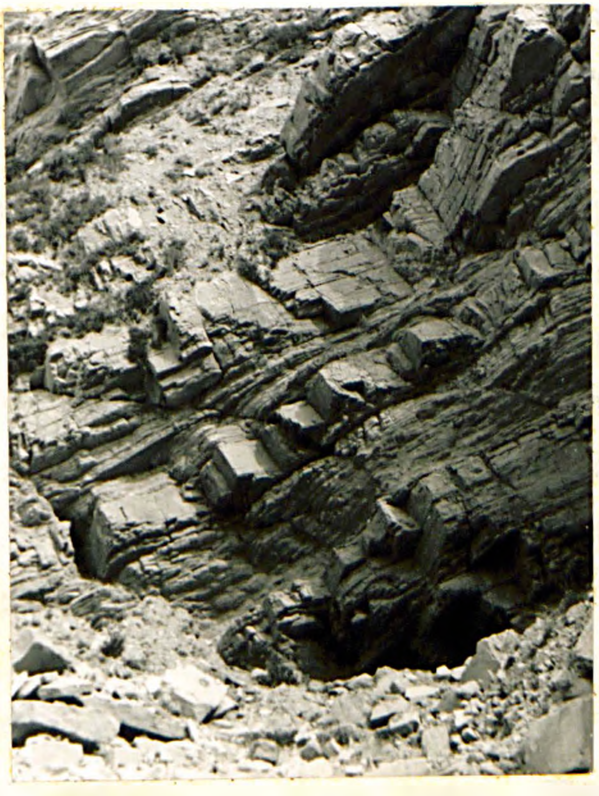
As in the Broken Beds the dominant sediment is calcite-mudstone, in the form of pellets, lumps, and more commonly than in the Broken Beds, oolites. In addition, algal fragments are more abundant and better preserved, and though ostracods are again the most abundant fauna, gastropods and pelecypods become common, especially towards the top of the sequence. The algal fragments often weather out as nodules ½-2 cm. diameter. The

Fig. 53. - View of the topmost Portland and basal Purbeck at Worbarrow Tout. The cave is eroded into the Broken Beds, and the prominent beds overlying belong to the Cypris Freestones and in part to the Hard Cockle Beds.

Lower Purbeck. Worbarrow Bay.

Fig. 54. - Shows the well bedded, relatively thick units of the Cypris Freestones.

Lower Purbeck. Worbarrow Bay.
Cypris Freestone.



pelecypods, mostly fragments but sometimes whole valves, lie parallel to the bedding, and are invariably concave down. Quartz grains are again scattered throughout, occasionally forming thin sandy laminae, but quartz is not common until near the top of the sequence.

(b) Petrology

(i) Petrography. -

1. The pellets and oolites —

Many of the pellets are a light grey, but a far higher proportion are golden-brown, and this becomes more pronounced towards the top of the sequence. Individual grains forming the pellets are less than 3 μ size, and in the brown pellets the grains are frequently too small to be readily distinguished even with peels. There is a greater range of pellet size than in the Broken Beds, with pellets from 50-300 μ diameter, though the larger pellets pass into lumps. As in the Broken Beds, individual layers are fairly well sorted. Smaller pellets are in general more spherical than those larger than 150 μ (fig. 55), but many are rod shaped with ratios of about 2:1 or, rarely, as much as 4:1. Below 150 μ most pellets have an homogeneous texture, though where a brown colour is present they are strongly mottled in appearance. There is more uniformity in their shape than in the Broken Beds.

Ooliths are mostly superficial, that is, they possess only one layer of radial growth around a nucleus. A few true ooliths occur but in small amounts. Composite ooliths are more abundant. When present, ooliths are common throughout a particular bed - up to 20% by volume in cases - but elsewhere are rare. Oolith nuclei are usually mudstone pellets, very rarely they are foraminifera or small quartz grains. The oolitic layers are composed of radially oriented calcite fibres 1-1.5 μ width and 20-35 μ long, that yield a characteristic black cross under crossed nicols. 'Dust' inclusions are common within the oolitic layers. Ooliths are always associated with the larger sized pellets and lumps, and with a granular calcite cement (fig. 56).

In general, the boundaries of pellets and ooliths are clearly defined, though where the pellets are of fine size they are closely packed and some merging of boundaries occurs. In a few thin layers (½ cm.) merging is sufficient to produce grumuleuse texture, but uniform, structureless mudstone is not present.

2. The lumps. --

Many of these are algal, and are both abundant and large in some layers which may contain as much as 63% by volume algal fragments. They may be up to 3 mm. in length, and very irregular in shape, with algal structure in variable states of preser-

Fig. 55. - Small micrite pellets and ostracod fragments in a granular calcite cement. The pellets are quite well sorted, and the shell fragments lie more or less parallel to the bedding.

Lower Purbeck. Lulworth Cove.
Cypris Freestones.

Fig. 56. - Larger pellets, lumps and oolites in a granular calcite cement. Some of the lumps are probably of algal origin.

Lower Purbeck. Worbarrow Bay.
Cypris Freestones.

Fig. 57. - A large algal nodule containing well preserved filaments of Ortonella.

Lower Purbeck. Worbarrow Bay.
Cypris Freestones.


1000 µ

vation (fig. 57). These structures are similar to those described for the Ortonella limestones of the Basal Beds, with circular, spar filled tubules averaging 35-40 μ diameter in a clotted, mudstone matrix. This is often spongiostromid in texture, and contains small fragments of shells, pellets and quartz grains which the algae enclosed during growth. The fragments show signs of having been bored, perhaps by non-calcareous worms, which produce small eyes of spar within the mudstone. Rarely, these may be circular, similar in appearance to the algae but of much larger dimension, about 120 μ .

These large algal lumps grade downwards to pieces of 350 μ or so which retain less structure, and eventually no doubt to still smaller pieces now unrecognisable as algal (fig. 56). The calcite-mudstone of the fragments is usually light grey in this section. Brown colour is only rarely present. The mud grains are in the order of 2-4 μ size, slightly coarser than in the pellets. This may perhaps be used to identify algal fragments that have lost all structure.

In addition to the algal mudstone lumps, there are those formed by the aggregation of two or more pellets. In most respects these are similar to the lumps described in the Broken Beds, and the same criteria can be used to differentiate them from the intraclasts which are here slightly more common.

3. Bioclastic material and accessories. -

Bioclastic material consists of ostracods, pelecypods, rare gastropods and foraminifera. Ostracods occur throughout the sequence and occasionally form thin layers (¼-½ mm.) of valves lying parallel to the bedding. The shells are light yellow in thin section and are composed of radially oriented calcite prisms. Whole shells often have a drusy calcite filling with the crystals in optical continuity with the walls. Some of the shell fragments are obviously intraclasts, and the concave portion contains small gobbets of brown carbonate-mud and sometimes two or more shell fragments occur within such a gobbet.

As ostracods decrease, pelecypods increase. At first these are rare, occurring as thin valves about 6 mm. length, concave down. These give way to abundant fragments of thicker shells. These are 1-2 mm. long and are from ¼-½ mm. thick, and consist of mosaics of calcite of variable crystal size, but seldom less than 50 μ . Most of the fragments are outlined by a fine 'dust line' of silt or mud sized calcite crystals. Many of the shell fragments have been bored and the borings filled with calcite-mud (fig. 58). These borings are from 20-40 μ diameter and up to 100 μ long. Sometimes only one side of the shell is affected, but mostly it is bored equally on both sides. No trace of original shell structure now remains. The ends of the fragments are sometimes rounded but often angular, though the bored shells are more abraded and rounded than others.

Fig. 58. - Pelecypod fragments containing micrite filled borings; micrite filled gastropods, pellets and lumps in a granular calcite cement.

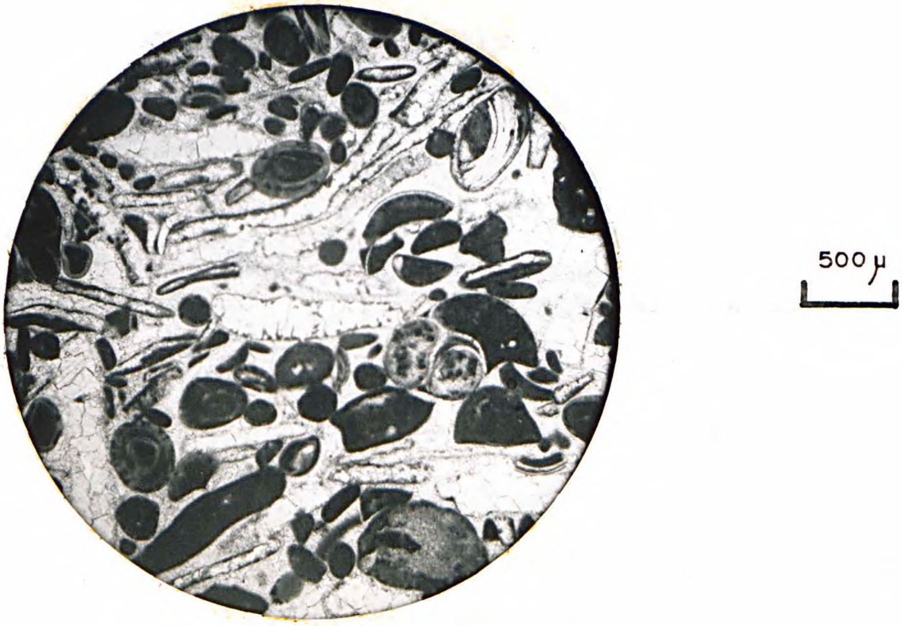
Lower Purbeck.
Cypris Freestones.

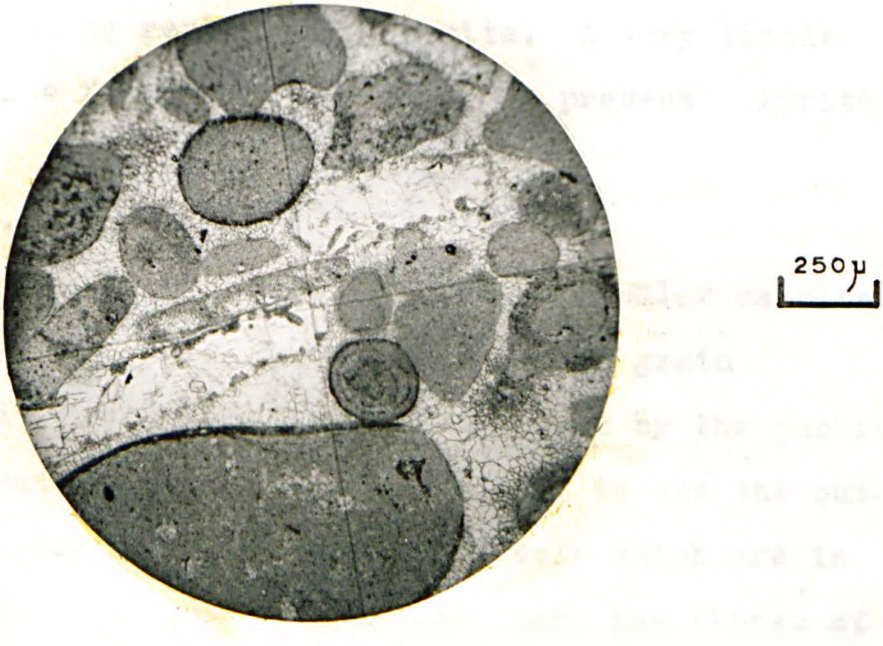
Worbarrow Bay.

Fig. 59. - Photomicrograph of an acetate peel showing micrite filled borings in pelecypod shell fragments; micrite pellets and lumps rimmed by small crystals of calcite cement which grew into empty space between pellets.

Lower Purbeck.
Cypris Freestones.

Worbarrow Bay.


500μ


250μ

Gastropods are rare. They are only recognisable as casts where the body chambers were filled by mud (fig. 58). All trace of the shell has gone, and it is quite possible that some of the pellets may in fact be gastropod chamber casts. This is not believed to be common in this sequence, however, though it is elsewhere.

Rare, too, are foraminifera. These are usually present as the core to an oolith, only rarely as separate fossils. Little can be said about them except to note the presence of a finely granular wall with spar filled chambers.

Of the non-carbonates, quartz is the most common. Again it occurs in small amounts in most beds, and in only a few does it reach 2-3% by weight. The grains are usually less than 125 μ size, are angular (Pettijohn, 1948) but once more show evidence of being replaced by calcite. A very little collophane, as bone fragments, is sometimes present. Pyrite is absent.

4. The cement. -

As in the Broken Beds this is mainly a granular calcite cement consisting of crystal mosaics with plain grain boundaries and with the crystal size controlled by the packing of the rock elements (fig. 59). It is common to see the outside of a oolite rimmed by small spar crystals which are in optical continuity with, and were seeded upon, the fibres of the oolite. This shows the radial fibres to have been in that form prior to cementation.

There are some layers in which the matrix is a calcite silt, or sometimes mud, with grain size 5-15 . This is readily distinguishable from the mudstone of the pellets by its light grey colour and greater translucency. This type of matrix is frequently associated with concentrations of algal fragments and may be algally produced carbonate.

(ii) Origin of the carbonate mud. -

Much of the discussion of the origin of the carbonate-mud of the Broken Beds applies equally here and will not be repeated. It must be recognised, though, that algae have been much more important in mud formation in the Cypris Freestones. Excluding granular calcite cement, algal fragments frequently form nearly 100% of a rock. They consist of irregular masses of calcite-mudstone, disintegration of which would have yielded abundant mud grains. This calcite is often of sightly coarser grain size than usual, sometimes up to 10 μ with a resultant increase in translucency. Accumulations of such mud, or of small pellets not recognisably algal but which have grains of similar habit may reasonably be considered as of algal origin. Invertebrate activity on the other hand may well cause a decrease in the grain size of the carbonate, and once such a break down has occurred it would not be possible to detect an algal origin from observations on the grain size.

A second important difference from the Broken Beds lies in the much more prolific fauna, especially in the increase in pelecypods and gastropods. Their increasing numbers upwards throughout the sequence at once suggests an altering environment, perhaps less saline than that previous. Lowered temperatures, too, may have helped in providing a more favourable environment. Both of these factors, however, would increase the solubility of $CaCO_3$ and hence reduce the likelihood of physico-chemical deposition taking place. While at the base of the sequence, therefore, it is probable that chemical precipitation was common, as shown by "bahamites" and other accretionary lumps, this became less important as time went on, and biochemical mud, chiefly algal, became dominant.

(iii) Mode of aggregation. -

Most of the lumps and many of the pellets retain sufficient structure to be identified as algal. At the base of the sequence some of the pellets appear to be identical with many of those in the Broken Beds, and are probably formed by accretion - as bahamites. Most pellets, however, show other characteristics. Chief among these is the strong golden-brown colour many possess. Other features include the frequent rod shape with length-diameter ratios of up to 4:1, the very good sorting along the individual layers, and particularly the presence of small chitinous ? inclusions. The change in environment coupled with increased fauna suggests that most of these pellets are faecal.

In some layers oolites are common. They are mostly superficial around mud pellet nuclei. The oolitic coats are of radially oriented calcite fibres, occasionally cut by concentric bands of calcite-mudstone (Wood's algal dust inclusions). The oolites are invariably cross-bedded on a small scale.

(c) Diagenesis

A third criterion for the presence of a mechanically deposited mud is present in these beds, in the form of the bored shell fragments (figs. 58, 59). These shells were bored by plants or animals and the borings infilled by a mud. This must, nevertheless, have been lithified prior to the solution of the aragonite shells, as the casts were preserved and enclosed in the drusy calcite cavity fillings. This also points to the mud having been of calcite and not aragonite, otherwise the casts too would have dissolved and been destroyed.

The shell mosaics show typical drusy characteristics, and solution of the aragonite shell must have occurred in a rigid fabric, that is, post cementation, otherwise any cavity would presumably have been desotroyed.

There is no evidence in these beds of replacement by anhydrite, and no silicification has occurred.

(d) Aragonite - or Calcite - mud

In the Broken Beds and Cypris Freestones it has been shown that a carbonate mud was the dominant sediment. Little has been said as to whether this was originally aragonite or calcite. It is now entirely calcite.

There is sufficient evidence to show that any algally produced mud was calcite. The criteria used by Wood (1941, p. 194) apply equally here, and there is in addition the evidence from the preservation of borings in shells cited above. Physico-chemically precipitated mud on the other hand is more likely to have been aragonite, as in modern environments of carbonate precipitation. This applies also to oolites, the concentric and radial layers of which are usually entirely aragonitic in modern deposits. Aragonite mud is usually in the form of needle like crystals, but as has recently been shown (Hathaway and Robertson, 1960), these may soon loose this appearance by a rounding of the ends, and coalescence to form larger grains. This is normally accompanied by inversion to calcite and the resultant fabric cannot be distinguished from that of many aphanitic limestones. It is impossible, therefore, at present to differentiate between mud originally aragonite and mud originally calcite, though there is a strong probability that both kinds were present, particularly in the Broken Beds sequence.

VI. HARD COCKLE BEDS

(a) General Description

The upward change from Cypris Freestone lithology is marked by the appearance in the section of alternating sandy limestones and dark grey calcareous shales. At Worbarrow Bay at least 60 such alternations occur in a bed 80 cm. thick. Except for the bottom 1-1.5 m., the sequence is best exposed there, and has a thickness of 6.07 m. Only the top 2-2.5 m. are exposed at Mupe Bay and Lulworth Cove, while the beds at Durlston Bay are entirely covered. It is impossible to correlate any beds on the Isle of Portland, and elsewhere there are no exposures.

The beds are generally light tan-yellow weathering and are difficult to obtain fresh (fig. 60). Small scale cross-bedding (2.5 cm.) and ripple-marked surfaces are common, while cubic salt pseudomorphs are not infrequent. In the sequence at Worbarrow Bay are two thin (5 cm.) bands of calcite-mudstone breccia. Individual beds range from 20-165 cm. thickness.

There is a much more abundant fauna than in the beds below, and this shows a variation between Lulworth and Worbarrow that is of significance in interpreting the environment.

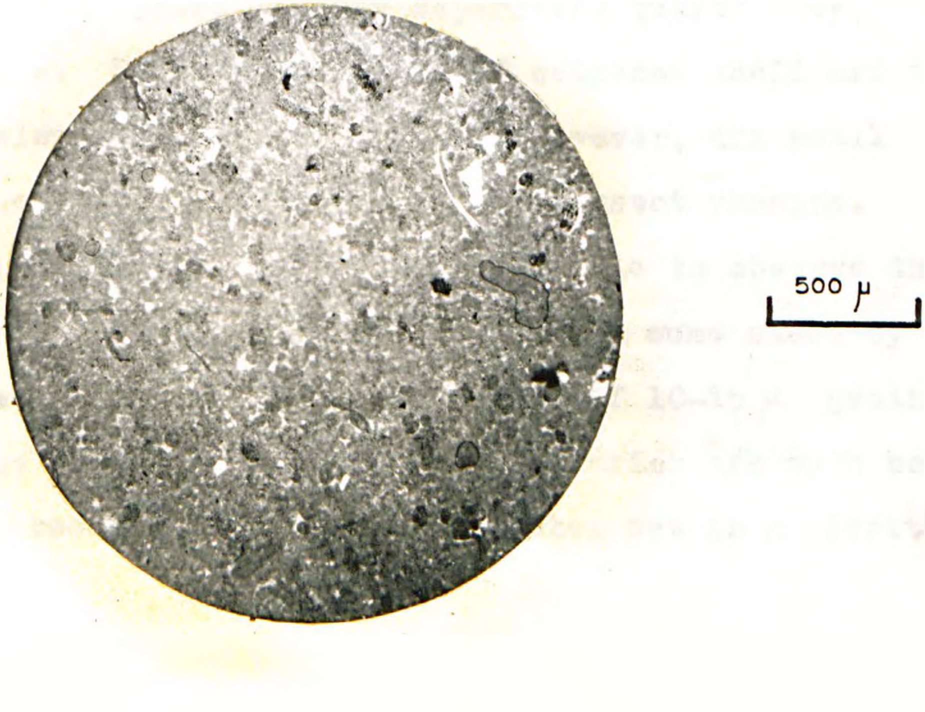
The Hard Cockle Beds contain a variety of sediments distinct from those previously described, ranging from calcite-mudstones (micrites) to calcareous sandstones, and from

Fig. 60. - Outcrop of the Hard Cockle Beds.

Lower Purbeck. Lulworth Cove.

Fig. 61. - Photomicrograph of a typical pelmicrite. Outlines of small pellets can be discerned within the micrite matrix. Finely disseminated pyrite, quartz silt and some small shell fragments are also present.

Lower Purbeck. Lulworth Cove.
Hard Cockle Beds.


500 μ

biomicrite to biosparite. The petrography of each type is given without reference to its stratigraphic distribution which is discussed below (p. 99).

(b) Petrology of the calcite-mudstones (Micrites) and biomicrites

(i) Petrography. -

There is every gradation between homogeneous calcite-mudstones (micrites) and rocks with mudstone pellets in a dominantly mud matrix (pelmicrites). In thin section the micrites are mottled grey and brown, and are usually full of small black specks and granules of finely disseminated pyrite. A little silt and fine sand-size quartz is present, usually as thin, irregularly spaced laminae separating quartz free mudstone layers. Rare, thin pieces of ostracod shell are the only faunal elements present. Common, however, are small black carbonaceous fragments that may be insect remains.

Where silty laminae occur it is possible to observe the vague boundaries of mud pellets, outlined in some cases by pyrite specks, in others by a spar cement of 10-15 μ grain size. In true pelmicrite the pellet boundaries are much better preserved and readily discernable even when set in a micrite matrix (fig. 61). The pellets are well rounded, some appear spherical, others elongate but of the same diameter as the spheres, suggesting that these may in fact be the transverse section of rods. Most pellets are grey, but a few have the mottled brown appearance, seen in the Cypris Freestone, while in any bed about 10% of the pellets contain abundant black pyrite specks. Shell fragments are again rare, but quartz of sand-size is a little more common than in the micrites.

Pellets vary from 70-140 μ diameter, while the length - breadth ratios are from 2 or 3.5 to 1. The mud grains in the pellets are of very fine size, generally 2 μ or less. In most of the uniform micrite the mud grains are of a similar habit, but here and there are small patches in which the grain size is 5-8 μ . This produces a slight mottling effect. In some layers pellet merging can be seen, and it is this process that is probably responsible for all of the micrites.

The biomicrites are essentially a variation of micrite in which shells and shell fragments become important constituents of the rock (fig. 62). The micrite is a uniform grey, generally non-pyritic, and is often pelleted. Its grain size is rather variable from true mud grade of about 2 μ , to a fine silt of about 10 μ . Plane grain boundaries are the rule with many grains roughly pentagonal. Scattered throughout this fine mosaic are single calcite crystals 20-30 μ diameter, probably derived from the comminution of shells. The micrite usually constitutes from 45-60% of the rock.

Shells are mostly pelecypod, but some gastropods and rare ostracods are also present. Pelecypods are often valves of variable size though seldom exceeding ½ cm. in length, and in places whole shells are present. Where broken, the ends of the shells are angular. Shell thickness is very variable, up to 250 μ , but depends on orientation which is usually roughly planar parallel to the bedding. The original shell has been replaced by a mosaic of calcite showing characteristics of a drusy cavity filling (Bathurst, 1958). The boundary between this druse and the surrounding micrite is sharp, and replacement must have post-dated lithification of the micrite.

Gastropods, too, have had their shell replaced by a mosaic of drusy calcite. The body chambers were often filled with micrite and their casts now outline the shape of the shell, most of which are still whole (fig. 62). In a few cases the body chambers were filled by drusy calcite, and subsequent replacement of the shell means that they are now seen as circular to elliptical patches of granular calcite surrounded by micrite.

Calcareous worm-tubes are common, often as fragments but also as whole tubes with diameters up to 1 mm. They have a

Fig. 62. - Biomicrite: Shell fragments, now composed of drusy calcite crystals, in a micrite matrix. Mostly pelecypods, but a gastropod cast is seen in the centre of the photograph.

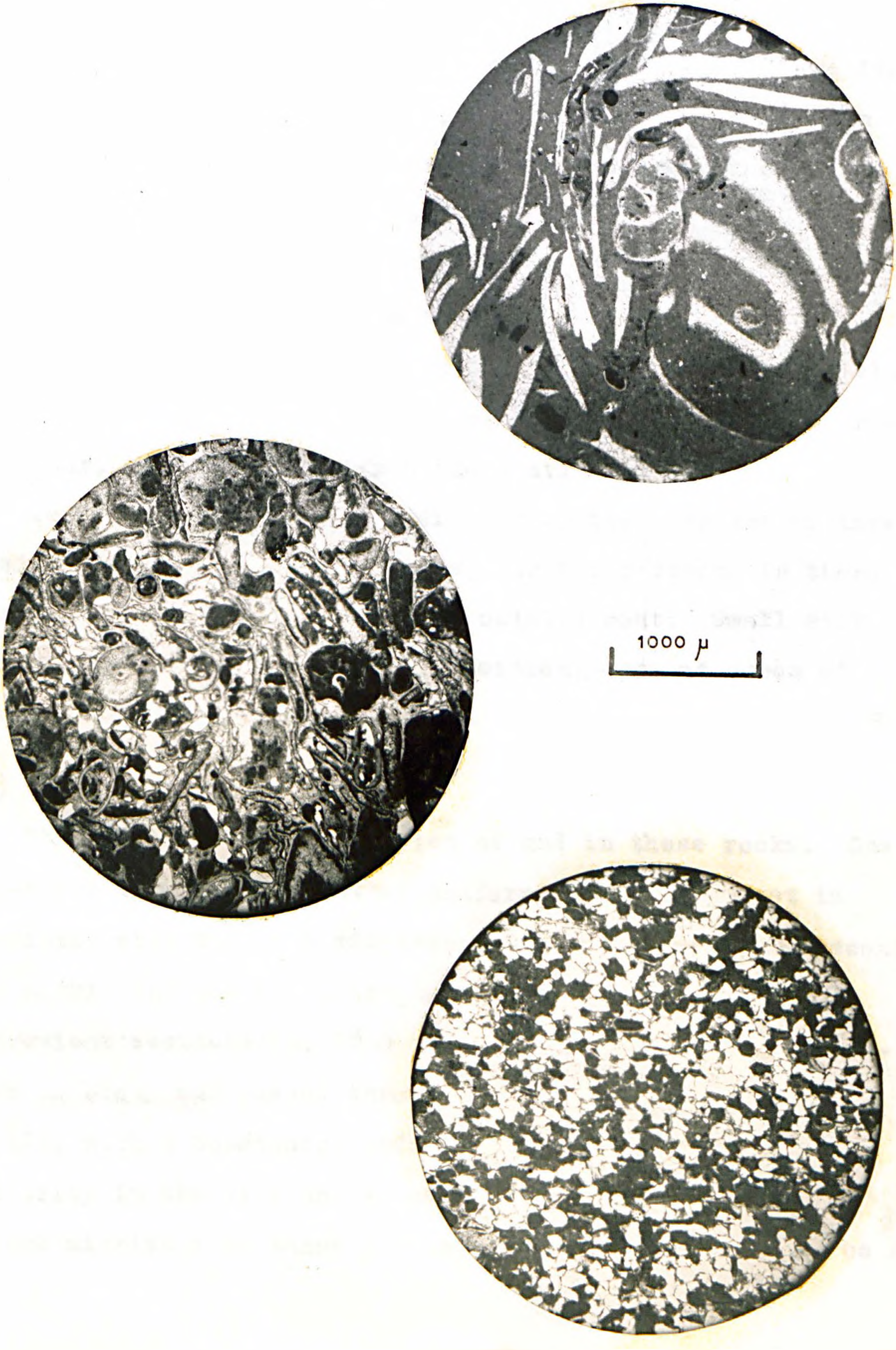
Lower Purbeck. Mupe Bay.
Hard Cockle Beds.

Fig. 63. - Biosparite: Pelecypod fragments with a thin micrite envelope, gastropod casts, micrite pellets, lumps and quartz grains in a granular calcite cement.

Lower Purbeck. Mupe Bay.
Hard Cockle Beds.

Fig. 64. - Calcareous sandstone: Angular quartz grains and small micrite pellets in a granular calcite cement.

Lower Purbeck. Lulworth Cove.
Hard Cockle Beds.


1000 µ

distinctive lamellar structure in transverse section, are dark brown in ordinary light, but show a strong pleochroism from straw yellow to brown in polarized light. This enables even small fragments to be recognised. These worms may have produced some of the micrite pellets though the pelecypods and gastropods would also have contributed.

The pellets are of the same order of size as in the pelmicrites, and are notable for being strongly mottled and brown in colour, quite distinct from the micrite matrix.

Periodic turbulence is indicated by the presence of layers of silt - sand size quartz grains, and the presence in these layers of mud pellets with a thin oolitic coat. Small salt pseudomorphs are present in thin section, seen as cubes of granular calcite.

(ii) Origin. -

There are two distinct types of mud in these rocks. One, grey-brown to brown, the other uniform grey. The first is associated with the pure micrites and with pellets, the second is a matrix for the shell fragments. For the reasons given in previous sections (p. 38) it is considered that the grey-brown to brown mud passed through the gut of mud ingesting animals, with a consequent reduction in grain size. The similarity in the size and shape of the mud grains in the uniform micrite with those forming the pellets appears to be a possible confirmatory factor, and the origin of the micrite by pellet merging seems clear as all gradations from pelmicrite to pure micrite can be found.

The pyritisation of many of the pellets due perhaps to a high organic content, and the consequent formation of a localised reducing environment also indicates their probable faecal origin, and accounts for the pyrite disseminated throughout the micrite as being derived from the merging of these pellets. The formation of micrite as distinct from pelmicrite presumably depended upon the respective rates of sedimentation and lithification (Dapples, 1942).

This micrite is likely to have been derived from the grey mud seen in the biomicrites, which has noticeably coarser grain size and is almost invariably non-pyritic. There seems little doubt that some of this mud is derived from the comminution of shells. Downward gradation from large shells to smaller fragments to single crystals of 20-30 μ diameter can be readily followed. It is impossible to say just how much mud was so derived. Algal fragments are very scarce, and it is unlikely that plants contributed very much to the formation of mud. On the other hand, the presence of salt pseudomorphs points both to evaporation and to salinity, and suggests that some of the mud at least was a physico-chemical precipitate.

The two types of mudstone are characteristic of two distinct environments. One, with grey-brown mud, in which shell fragments are generally absent, the other, with grey mudstone and abundant fossil remains. The planar orientation of the shell fragments, and the generally uniform nature of their micrite matrix, indicates little disturbance by scavenging or burrowing organisms. In the micrites and pelmicrites on the other hand, the sediment was evidently turned over and ingested, perhaps many times, and any faunal remains destroyed. The lack of shell fragments here need not be indicative of conditions inimical to life, probably the contrary, but merely that scavenging was sufficiently great to destroy any remains. Such thorough turnover could only occur if deposition were sufficiently slow, faster deposition generally resulting in the preservation of shell fragments and lamination (Dapples, 1942). The two types of rock therefore seem to reflect variations in the rate of deposition of the carbonate mud, fast deposition leading to the production of biomicrites, slow deposition leading to the formation of micrites or pelmicrites.

(c) Petrology of the biosparites

(i) Petrography. -

Palaeontologically these are similar to the biomicrites, but the fauna is generally in a granular calcite cement, though a little micrite may be present. The fossils are pelecypods, more abundant gastropods than in the biomicrites, ostracods and serpulid worms. There is considerable variation in both fossil content and in its state of preservation. Micrite pellets, algal fragments and quartz grains are also present (fig. 63).

The pelecypods are of all sizes from fragments of 100-200 μ length up to valves 8-10 mm. long. Shape is mostly irregular and in general the edges of the fragments are rounded - distinct from those in the biomicrites. Some fragments consist of mosaics of calcite crystals, others of calcite crystals and micrite. All, however, are outlined by an envelope of micrite or 'dust line' usually about 25 μ thick but varying from 5-100 μ, though this depends upon the angle that the thin-section cuts the shell.

The calcite mosaics have crystals of about 30 μ size with plane grain boundaries, and exhibit many of the features of drusy cavity fillings. Often, the micrite envelope is broken and the drusy fillings merge with the granular calcite cement. Breakage must have occurred prior to the final cementation of the rock, as the presence of thin, whole valves shows that little compaction took place and it would be difficult to account for breakage in a rigidly cemented fabric. The occasional presence along the edge of unbroken micrite envelopes of small drusy crystals, which are absent from the broken edges, does indicate that a little cementation had probably occurred, but insufficient to prevent breakage.

The partial micrite filling seen in some of the shell fragments is most probably an infilling of borings in the shell caused by algae or some invertebrate (fig. 63). Glancing sections through the micrite envelope may, in some cases, produce the false impression that much of the shell has been replaced by micrite.

Gastropods are identifiable as casts surrounded by granular calcite cement (fig. 63). Several genera are present, including species of Hydrobia and Planorbis. Some beds contain an almost exclusively gastropod fauna, others only a few individuals. The casts may be of micrite, micrite and spar, or light yellow calcite spar only. In this latter case a fine 'dust line' outlines the original shell, as with pelecypods. No trace of the shell now remains as it has been replaced by a drusy calcite mosaic that merges into the granular cement, and but for the casts of the body chambers and the 'dust line', no trace of the gastropod would now be visible.

Ostracods are rare, and when present are whole, spar-filled shells. Worm tubes are fragmentary and are frequently seen inside small lumps of micrite - as intraclasts. The pieces are readily distinguished by their brown colour and pleochroism.

Micrite pellets and lumps occur throughout but never make up more than 5-10% by volume of any rock. Many of the smaller pellets, 50-80 μ size, may be faecal, and black pyrite specks are common within them though not invariable. Others are algal, retaining vague filament outlines, while some are true intraclasts showing eroded and truncated internal structures; About 5% by weight of most rocks in this group is of sand-sized quartz grains distributed evenly throughout. Many grains show small overgrowths of quartz on an original sub-rounded grain, which now appear to be angular.

The cement is usually of typical granular calcite, though in a few places a little micrite is present. This is uncommon and presumably occurs where winnowing was insufficient to remove it, or perhaps where it filtered down from above.

(ii) <u>Origin</u>. -

The biosparites have every appearance of being coquinas swept together by current and wave action. Their field appearance, where they are frequently cross-bedded and ripple-marked, is in agreement with this. It certainly appears that most of the shells are not in their original life enviornment. Their fragmental nature and rounded appearance supports this view, but it is also possible that abrasion was caused not so much by continued lateral transport, as by repeated turnover in place, in a surf or breaker zone, similar to the rounded calcarenites of the Persian Gulf (Houbolt, 1957). Strong currents are indicated by the mudstone intraclasts, apparently torn up from semi-consolidated layers of mud; and, also, by the ubiquitous sand-size quartz scattered throughout the beds. The rare presence of micrite shows carbonate mud to have been present, but usually unable to be deposited permanently because of the winnowing action of the currents.

(d) Petrology of the calcareous sandstones

(i) Petrography. -

The distinction between sandy limestone and calcareous sandstone is usually placed at 50% quartz and carbonate. As pointed out by Pettijohn (1948, p. 304), a more 'natural' boundary would be at 18% quartz, which is the least common occurring quartzose limestone. In the Hard Cockle Beds the quartz content of this class varies from 35-55% and so they may be called calcareous sandstones. They are usually cross-bedded on a small (2-3 cm.) scale.

The quartz grains are well sorted with a median size of 110 μ varying from 90-130 μ. In thin section the grains are angular (fig. 64). This is due both to replacement of quartz by calcite, and, in some cases, to the development of quartz overgrowths on originally rounded grains. Most grains are clear, but a few contain abundant dark and unidentifiable inclusions. Stable heavy minerals are present including tourmaline, zircon, garnet and kyanite.

The remainder of the rock consists of micrite pellets, ostracod fragments and, especially, broken Serpula tubes. Occasionally a whole tube is present showing the diameter to be about 1 mm. The micrite pellets are of the same size range as the quartz. They are grey or brown and are frequently penetrated by quartz grains. The cement is granular calcite, the grain size depending upon the packing of the quartz and pellets.

(ii) Origin. -

These sandstones probably result from an increased supply of detrital quartz and accessories. The small scale cross-bedding and micrite intraclasts point to strong currents prevailing during deposition. In following any one bed from west to east, it is found that the quartz content decreases, suggesting a general westerly origin for the quartz, but this is not definite without north-south control as well.

The rapid alternations between calcareous sandstones and calcareous shales at the base of the sequence is cyclic deposition, but it is impossible to say what the cause might have been.

(e) Diagenesis

As with the mudstones described previously (p. 73) lithification of the micrites and biomicrites in the Hard Cockle Beds was probably by inter-granular deposition of carbonate, perhaps as a rim cement. The preservation in places of thin unbroken pelecypod valves shows little compaction to have occurred, so that pressure solution of grains is unlikely. Lithification of the biosparites and calcareous sandstones appears to have proceeded in a similar manner, by the deposition of a granular calcite cement.

Apart from the lithification, the most obvious diagenetic effect is the total loss of the internal structure of the shell fragments and their replacement by granular calcite mosaics. In the biosparites pelecypods are often only recognisable because of the presence of a thin micrite envelope outlining the original fragment. At some time the aragonite of the shell was removed and replaced by drusy calcite. As adduced above (p. 93) this must have been prior to the complete cementation of the rock, but quite probably after some initial cementation had occurred. In the biomicrites, on the other hand, the absence of any sign of collapse of the micrite matrix into the presumed cavity left by the removal of the aragonite, points to its having been at least partially lithified prior to solution.

(f) Lateral variation

There is a distinct lithological variation in the Hard Cockle Beds between Worbarrow Bay and Lulworth Cove. At both localities the base of the sequence is poorly exposed, but appears to consist of inter-bedded calcareous shales and calcareous sandstones. At Lulworth Cove, and Mupe Bay, the succeeding sequence is one of micrites, biomicrites, calcareous sandstones and biosparites, the latter containing abundant pelecypods and gastropods. The Worbarrow Bay sequence, though containing abundant micrites and calcareous sandstones - with some brecciated layers in the micrites - is almost devoid of a fauna other than Serpula and ostracods. Pelecypods and gastropods are very rare. It is also apparent from the common presence in the micrites of cubic salt pseudomorphs that dessication and high salinity was a feature of the environment at Worbarrow, and these factors may well have been decisive in determining the paucity of fauna there. The brecciated mudstone layers probably reflect the action of currents breaking up semi-consolidated and perhaps sun-cracked micrite layers, after periods of dessication.

The relative abundance of fauna in the Lulworth - Mupe Bay region, although it may not all be actually in its life environment, indicates that there, or nearby, salinity was such as to enable pelecypods and gastropods to survive. Their small size may indicate, however, that even here conditions were not ideal for growth. This change of salinity may have been due to dilution by river water, or by run-off from the land. The suggestion (p. 96) that the biosparites were abraded in a breaker zone would agree with there being a coast-line nearby.

It is unfortunate that it is no longer possible to examine the equivalent beds further west, for the published descriptions of the section at Ridgeway (Fisher, 1956; Woodward, 1895) give only very general accounts of lithology. The beds are described as 'granular limestones, shales and marly limestones, hard shell limestones and compact crystalline limestone', which would seem to suggest affinity with the Lulworth area rather than Worbarrow. At Durlston Bay, likewise now covered, the beds were described as 'marly limestones and shales' (Bristow, 1857), more like the Worbarrow section, but an exact correlation of Durlston Bay with beds to the east seems doubtful.

These lateral variations, and their significance, are discussed further in section XIV.

VII. SOFT COCKLE AND MARLY FRESHWATER BEDS

(a) General Description

About 18.5 m. thick at Lulworth Cove and Mupe Bay, these beds thicken to 21 m. at Worbarrow and up to 32 m. at Durlston Bay, where, however, only the Marly Freshwater Beds are now well exposed. At any one locality these beds make up about one-half of the Lower Purbeck. They show a considerable change in sedimentation from the beds below consisting, in general terms, of calcite-mudstones, soft calcareous shales and, rarely, of thin beds of shelly limestone. Due to their softness they are not well exposed and are readily weathered (figs. 65, 66). Composite sections of closely associated exposures can, nevertheless, be made to give an accurate picture of these beds at each locality.

They are generally even-bedded with beds of from 5 - 50 cm. thickness, though their friable nature upon weathering may obscure this. Fresh, most of the rocks are blue-grey, though a few are cream, but all weather to a light grey that is in marked contrast to the beds below and above this sequence. The recurrence of thin beds of black calcareous shale affords evidence of cyclic deposition in parts of the sequence. At Worbarrow and Durlston Bay, nodular masses of gypsum are present near the lower part of the section, but the ease of

Fig. 65. - Section of the Soft Cockle Beds showing the comparatively poor exposure.

Lower Purbeck. Lulworth Cove.

Fig. 66. - Poorly exposed section of Soft Cockle Beds. A few harder 'marl' bands stand out.

Lower Purbeck. Mupe Bay.

solution of the calcium sulphate results in poor exposure, and obscures the relationship with the surrounding rocks. The occurrence of pellet, or breccia beds has been previously described (p. 17).

The beds in this sequence can be conveniently grouped into six classes.

Calcite-mudstones (Micrites)
Ostracodal and pellety mudstones
Pelecypod and ostracod limestones
"Pellet" beds
Gypsum deposits
Shales

(b) Petrology of the calcite-mudstones (Micrites) and ostracodal and pellety mudstones

(i) Petrography. -

These are the most abundant rocks in the sequence, especially in the Soft Cockle Beds, though becoming subordinate to pelecypod-ostracod limestones in the Marly Beds. Usually described as marls in previous studies, presumably on account of their soft and easily weathered nature, they rarely are.

At Worbarrow and to the west most beds contain only 5-10% by weight of material insoluble in dilute hydrochloric acid, and frequently only 1-2%. The beds at Durlston Bay (the top 2-3 m. of the Soft Cockle, and the Marly Freshwater Beds), however, usually contain about 20-30% insoluble matter, and in one case 43%, and may be more accurately described as marls.

They are true mudstones with grain size of less than 3-4 μ , only rarely larger. Grain boundaries appear to be plane. Commonly the mudstones are light-brown in thin section due perhaps to fine dispersed organic matter, which remains as a brown slimy residue after solution in dilute acid. This organic material is readily oxidised in Schultz' solution leaving behind a residue of very fine quartz silt and clay. Very finely disseminated pyrite granules 10-15 μ size are abundant in some layers but are not generally common. Far more common are round to irregular shaped granules 8-14 μ in size, that are translucent and red-brown in thin section. The appearance and colour suggest that they are organic and some may be spores, but they are more probably parts of insect fragments, the carbonised wings and elytra of which are abundant on many bedding planes.

A few thin ostracod valves and fragments may be present, but are rare. The mudstones in general are devoid of lamination, though the occasional shell and insect fragments do produce faint lamination on a limited scale. Salt pseudomorphs are common in some beds and appear in thin section as drusy-calcite filled cubes. Some internal disturbance of the mudstone is indicated by the occasional presence of small 'eyes' of calcite spar. These must have been formed after at least partial lithification of the mud as their borders are sharp, and small mudstone fragments are often present within them.

A few beds are noticeable for their slightly coarser grain size. These have grains of from $4-8\mu$ and are characteristically cream coloured in outcrop, and more translucent in thin section. They have a conchoidal fracture.

The ostracodal and pellety mudstones are, in part, gradational from the calcite-mudstones, but in typical development are mudstones containing either abundant ostracods, or calcite-mudstone pellets. The ostracods may be complete shells, valves or fragments (fig. 67). Where whole shells are present they tend to be concentrated in distinct layers, while intervening layers of mudstone contain only a few fragments. Most shells are spar-filled but a few have thin floors of light grey calcite-mudstone. This is much lighter in colour than the mudstone matrix. Scattered throughout the matrix are small (5-20μ) single crystals of yellow- calcite, usually square or rectangular, that are believed to be pieces of broken ostracod shell. Rarely, a few small foraminifera are present, usually concentrated in thin laminae rather than dispersed throughout the rock, together with calcispheres of about 30 μ diameter. Quartz grains of up to 80 μ size, though usually less, are often present in the ostracod layers, but are absent in the mudstone laminae.

Pellets within a mudstone matrix (pelmicrites) often form well defined layers ½-1 cm. thick. In thin section the pellets have a golden-brown colour that enables them to be easily seen even though surrounded by micrite (see Folk, 1959, p. 7). There is a slight difference in grain size between pellets and matrix. The pellets are formed of grains of 2 μ and less, the matrix of grains 2-6 μ size. Pellet size is variable, but they are commonly from 120-250 μ diameter, and up to 700 μ long. Many of the pellets are almost completely pyritised, usually with a thin outer rim unaffected. This, and the brown colour suggest the presence of organic matter. Unlike other examples of pelmicrite (p. 88) there is no boundary merging or interpenetration to produce uniform mudstone, and pellet bands are overlain by mudstone bands with sharp junctions between. In places where pellets are abundant a finely granular calcite cement is often present. Etching with dilute acetic acid shows non-pellety layers to be richer in non-carbonates, and it is possible that periodic influxes of non-carbonate mud inhibited pellet formation.

There is generally little fauna in the pelmicrites. A few ostracods may be present, and here and there fragments of Serpula tubes, while in a very few cases these tubes are abundant and form thin (2 cm.) layers. These often contain casts of small Hydrobia as well as a few pelecypod fragments. Serpula is usually associated with stabilised bottoms where little deposition is occurring (Illing, 1954, p. 22), and these layers therefore represent temporary breaks in sedimentation.

(ii) Origin. -

It is likely that much, if not all of the mud, was a physico-chemical precipitate, at least in the lower half of the sequence. The common salt-pseudomorphs show evaporation to have occurred, which implies conditions conducive to precipitation. Contribution of mud from plants appears to have been minor, though as will be shown (p. 114), algae are occasionally common in the Soft Cockle Beds, and in places, therefore, algal mud may have been an important contributor to the sediment. The conditions of salinity and evaporation, possibly with increased temperatures, makes it unlikely that there was a very abundant fauna - as the paucity of shells indicates - and shell comminution would not have been important in the formation of mud.

Fig. 67. - Spar filled ostracod shells and fragments in a micrite matrix. Black specks are finely disseminated pyrite.

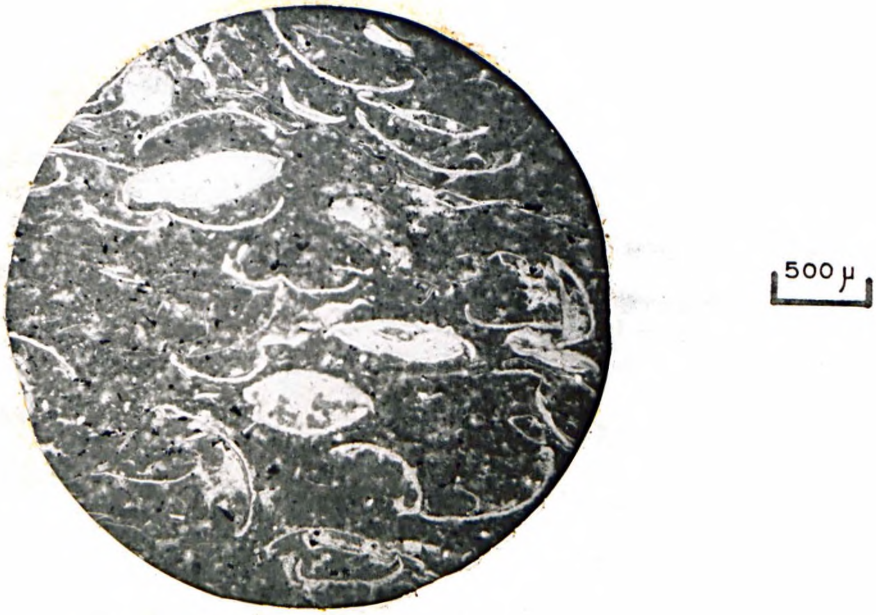
Lower Purbeck. Worbarrow Bay.
Soft Cockle Beds.

Fig. 68. - Diagram of burrows in a micrite layer, one of which contains the cast of a small spired gastropod. The burrowing evidently took place in at least a semi-consolidated mud. Natural size.

Lower Purbeck. Mupe Bay.
Soft Cockle Beds.

Fig. 69. - Thin sandy laminae (stippled) in a micrite bed showing micro-scours or washouts. Small contemperaneous fault in thin micrite band (black). Natural size.

Lower Purbeck. Mupe Bay.
Soft Cockle Beds.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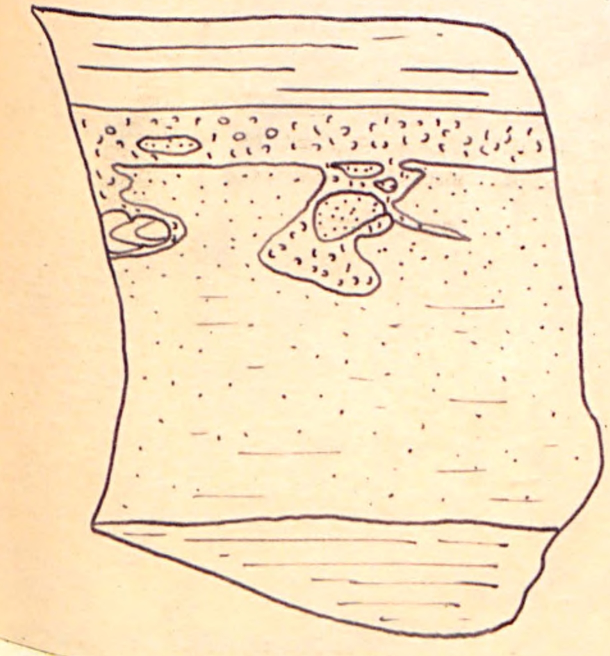
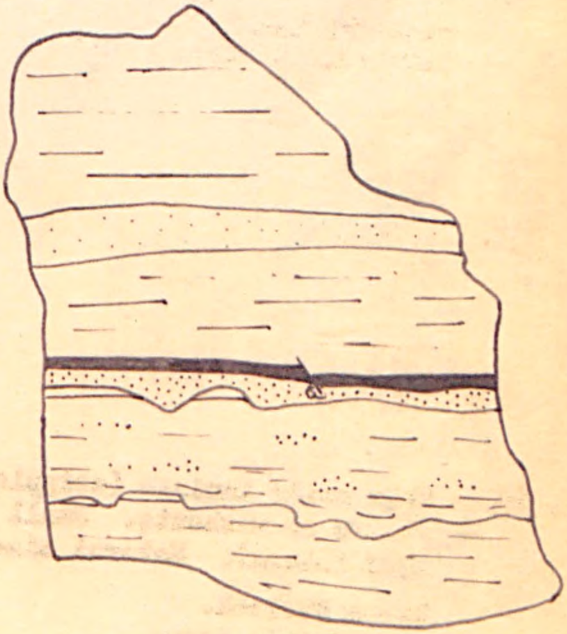



a

The micrites differ but little from those described in the Hard Cockle Beds (p. 87), though they are perhaps more uniform and generally less pyritic. The comparatively high organic content may be due to turnover by burrowing and mud ingesting organisms, as in cases previously described. Certainly, there is a distinct difference between the mud of the matrix, and mud trapped within the cavities of ostracod shells. The latter, presumably protected from the outside environment, is always light grey and of a coarser grain size than the mud matrix. If this matrix had been ingested one or more times before final lithification, this may well account for the fine size and colour. Evidence of burrowing is only preserved where it took place in an at least partially lithified mud (fig. 68), but may well have occurred previous to this. It is noticeable that in beds lacking organic matter, cream coloured in outcrop, the grain size is coarser, suggesting that little turnover of sediment occurred. There is no direct evidence that the micrites formed as a result of pellet merging, but this is very likely in view of the proposed origin of grain size and colour.

Pelmicrites originated in a similar manner, but here the pellets had sufficient time to become firm or partially lithified before final burial. Breaks in sedimentation are indicated both by the Serpula layers, and by the presence in some beds of micro-washouts and scours along laminae (fig. 67).

(c) Petrology of the pelecypod and ostracod limestones

(i) Petrography. -

These are common only in the Marly Freshwater Beds. They are variable in character but usually consist of either pelecypod valves and fragments, or of ostracods, usually in a micrite matrix but sometimes in a granular calcite cement.

Pelecypods occur as fragments, single valves and, rarely, as whole shells. Fragments are generally large (up to 6 mm.) with valve hinges often preserved, while the edges of the valves are angular; all criteria pointing to the lack of abrasion. The occasional presence of small-scale (1-2 cm.) cross-bedding, shows that some bottom traction did take place. Fragments invariably show good planar orientation to the bedding (fig. 70). Only rarely is any original shell structure preserved, the fragments now being mosaics of calcite crystals, which may be clear, or opaque and brown with a strong pleochroism. This pleochroism is especially noticeable in the Marly Beds and is only rarely seen below them.

When cemented in spar, the pelecypod fragments always have a thin micrite envelope which may be on one side of the valve only, but is usually on both. A little pyrite is present in localised patches such as the underside of a shell fragment, but is generally absent. This is in marked contrast to beds with a micrite matrix where disseminated pyrite is common. This micrite is often brown in thin section, apparently rich in organic matter. It may be in the form of a uniform mud or as pellets, while micrite intraclasts are often common. Any micrite found within a shell cavity is always a much lighter colour than that outside of the shell. In some beds, however, all the micrite is light grey.

Gastropods occur in these rocks, chiefly Planorbis, with some spired types, but they are not common. Very rarely, foraminifera are present. The amount of shell material varies from as little as 5% to as much as 80% by volume of the rock. While not mutually exclusive, it is a general rule that an abundance of pelecypods means few ostracods, and vice-versa.

Ostracods occur both whole and as valves or fragments. Whole shells are generally spar filled, though a few contain micrite. Where abundant, shells are well oriented with their longest axis parallel to the bedding. Valves and fragments, too, are planar oriented. Many beds contain little else but ostracod shells and fragments, with but a minimum of cement. A few shells may be slightly flattened indicating rapid burial and compaction, but most are not and were perhaps quickly filled by drusy calcite spar which provided rigidity.

Small bone fragments occur in places and most beds contain small amounts of quartz grains. These are usually of fine sand to silt size (less than 65μ), and often very well rounded. Chert is present in small amounts in some of the pelecypod limestones. It is secondary, and has replaced both shells and cement in two different ways. Shells have been replaced by fibrous chalcedonic quartz, brown in colour and often spherulitic. Calcite cement is replaced by colourless microcrstalline quartz, often with wavy-fibrous extinction. Chert is confined to thin layers, seldom more than 2 cm. thick, with the remainder of the rock showing shell fragments and some micrite pellets in a spar cement. Micrite pellets are replaced by micro-crystalline quartz producing an almost isotropic aggregate. Chertification appears to be confined to beds in which the cement was granular calcite. Full discussion of this process is given below (p. 142). A few beds in the Marly Beds contain fragments of the stonewort <u>Chara</u>, a carbonate secreting alga. These occur near the top of the sequence.

(ii) <u>Origin</u>. -

These types are not common, but the comparative abundance of fauna is related to changes in the environmental conditions, reflected to some extent in the original naming of the Marly Freshwater Beds. Thin beds of shell limestones are, however, also present in places in the Soft Cockle Beds.

Many of the pelecypods would seem to be in, or close to, their life environment, as they are whole shells with the valves still closed. The ease with which pelecypod valves normally open and are separated after death shows that in these cases little or no transportation could have occurred.

As in the Hard Cockle Beds, variation in salinity, or temperature, or both, is the most probable cause of the increase in fauna, an amelioration of conditions allowing pelecypods and gastropods to inhabit previously unfavourable areas. This change is particularly shown in some of the beds near the top of the sequence where fragments of the freshwater alga <u>Chara</u> are found in the mud matrix. Much, if not all, of the mud was, in these cases, produced by algal activity. Elsewhere, particularly in some of the ostracod limestones, it is evident that shell comminution was an important agent in the formation of mud, as all gradations from discrete shell fragments down to mud can be seen. Mostly, however, there is a noticeable lack of breakage of pelecypod shells, and the mud in these cases is again more probably a physico-chemical precipitate. Where whole shells and valves are present, the mud matrix is nearly always light grey with a grain size of 4-6μ, and does not appear to havebeen disturbed or ingested. This would certainly agree with the lack of breakage of the shells. Where broken pelecypod shells and shell fragments are common, then the mud is more often a brown colour with grains of less than 4 μ size, suggesting turnover by mud ingesting animals. It is evident from the preceeding discussion that no single origin can be given for these beds. Several different environments appear to be involved, and each bed must be examined on its own merits. What is indicated, is that the generally evaporitic conditions of the lower half of the sequence give way to a less saline and eventually almost freshwater environment in the Marly Freshwater Beds.

(d) Petrology of the "Pellet" beds

(i) Petrography. -

Some of these are very similar to the pellety mudstones previously described (p. 106), but there are sufficient differences to warrant separate description. The beds vary from pelsparites to the large-intraclast beds described on pages 117. The one constant feature is their association with algae.

In the pelsparites, pellets vary from 100-250μ in diameter, are round, and spherical to ellipsoidal. Characteristically they are golden brown and somewhat mottled in thin section, and some contain silt sized (10-15 μ) quartz grains (fig. 71). Pellets sometimes interpenetrate one another due to pressure solution, but true merging is rare. Mud grains in the pellets are almost always less than 2 μ size. Scattered throughout the beds are lumps of calcite-mudstone ½ mm. and upwards in size, containing well preserved spar-filled algal filaments. The mud is a light grey and of slightly coarser grain size (4-5 μ). Several kinds of algae are present. An **Ortonella**, with well branched and separate filaments 25-30 μ diameter, a different form from that of the Hard Cap (p. 29), a **Girvanella** of about 100 μ diameter, and stromatolitic types, though these are rare in beds with finer sized pellets. Salt-pseudomorphs are abundant in hand specimens, and are often found as well developed hopper crystals up to 1½ cm. length. Rarely, too, small dessication cracks can be found.

In other beds pellets are subsidiary to intraclasts. These may be formed of accumulations of pellets or, more commonly, of uniform micrite. They are up to 2-3 cm. length and almost ½ cm. thick, frequently with a thin algal mudstone coating. This is readily distinguishable by its grey to cream colour as compared to the brown of the intraclast. It may almost completely enclose the intraclast, or usually be developed only on one side. Very well preserved filaments of **Ortonella**

Fig. 70. - Micrite rimmed pelecypod fragments showing good planar orientation and some micrite pellets, in a granular calcite cement.

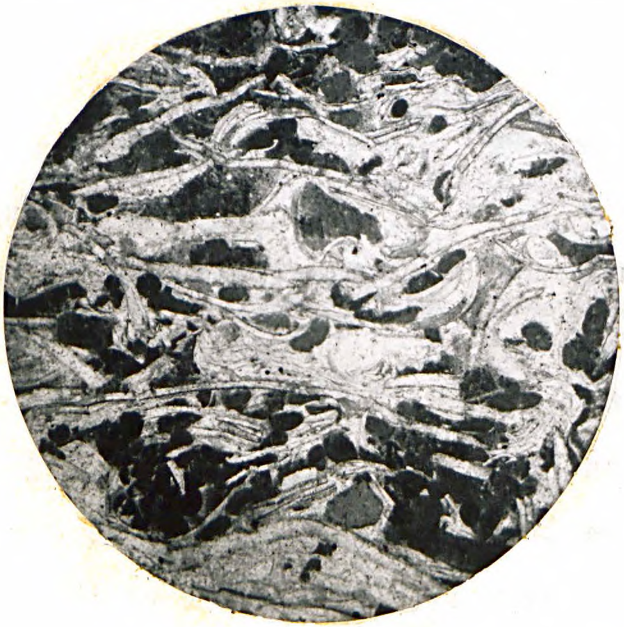
Lower Purbeck. Durlston Bay.
Marly Freshwater Beds.

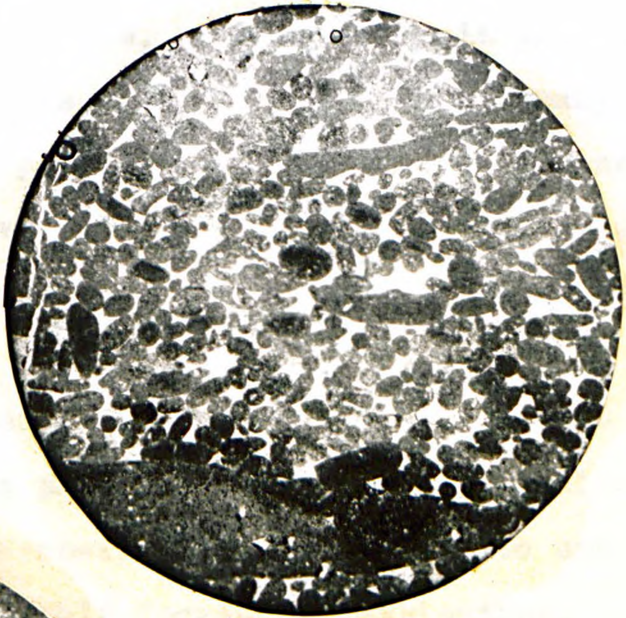
Fig. 71. - Fairly well-sorted micrite pellets with a few larger micrite lumps in a granular calcite cement. Note the presence of small inclusions of silt size quartz grains in the pellets.

Lower Purbeck. Fossil Forest.
Soft Cockle Beds.

Fig. 72. - Coating of Ortonella around a micrite lump in a 'pellet' bed.

Lower Purbeck. Mupe Bay.
Soft Cockle Beds.





1000 μ

are common (fig. 72), while stromatolitic layers are not infrequent. Many of the intraclasts and associated pellets contain abundant disseminated pyrite. This type of bed is intermediate between the pelsparites and the first pellet bed used for correlation (LC 22; WB 45).

In this bed intraclasts are more abundant and much larger, up to 5 cm. in length and occasionally more, and 1-2 cm. thick. The majority are of micrite with sometimes a few thin shell fragment inclusions, and in places, small cubic salt pseudomorphs. Disseminated pyrite is common throughout and many have thin (10-20 μ) rims of pyrite, usually confined to one side of the intraclast. A very few have a thin coat of algal mudstone but this is uncommon. The intraclasts are in a matrix of rod like micrite pellets 100-200 μ diameter which are also highly pyritised. Broken worm tubes, small <u>Hydrobia</u> and a few pelecypod fragments are also present. The larger intraclasts often show fine, downward-narrowing cracks confined to one surface of the fragment, probably formed by dessication.

The second bed used in correlation (LC 29; WB 53), contains large algal intraclasts and only a few micrite pellets. The algal fragments are up to 5 cm. long and ½-1½ cm. thick. Stromatolitic forms are very common (fig. 11), as well as <u>Ortonella</u> (diameter 35-40 μ) and possibly <u>Girvanella</u>. Many of the fragments contain worm borings. These were formed prior to fragmentisation, as the worm tubes are often truncated by the intraclast boundaries. Broken worm tubes occur in the matrix, with smaller algal fragments and some light grey micrite pellets.

The cement in all these forms of pellet bed is almost invariably of typical granular calcite. Only rarely is any calcite-mudstone present, presumably where unwinnowed.

(ii) Origin. -

In the pelsparites, shape, colour, grain size and internal structure of the pellets point to their being faecal. The fact that they are generally fairly well-sorted and in a spar cement, seems to show that they accumulated under the influence of some form of current, and this is to some extent confirmed by a tendency for the pellets to develop a preferred orientation - seen on bedding planes - with their long axes sub-parallel to one another. Their association with recognisable algal fragments does suggest a second possible origin. The pellets may be the mud filled cells and gametocysts of Dasycladacean algae. Mud pellets so formed have recently been described by Osgood and Fischer (1960). From their description it is evident that the mud forming the pellets is generally of similar morphology to the mudstone now surrounding them. In the present case, the difference in the colour and grain size (2μ or less) of the pelleted mud, and that of many associated unpelleted mud ($4-5\mu$), does point to their having been produced by some process causing grain reduction, such as faecal pelleting, rather than by mere infilling of cavities.

The origin of the mud itself is problematical. The presence of calcareous algae shows that some must certainly have been derived from algal activity. Evidence of evaporation in the form of salt pseudomorphs and dessication cracks also indicates that physico-chemical precipitation was likely too, but the relative importance of these processes cannot be determined.

Increase in the amounts of micrite intraclasts present implies conditions of increased turbulence, during which the fragments were torn from previously deposited and probably partially lithified beds. Ultimately, conditions were such as to lead to the formation of the correlation bed LC 22 - WB 45. This is in effect a flat-pebble conglomerate, with the pebbles being micrite intraclasts. The abundance of pyrite in these, although they are now in a spar cement and were presumably deposited under conditions of free movement of water, implies anaerobic conditions when the micrite was first deposited, prior to the formation of the intraclasts. This is reflected, too, in the pyritised pellets. The probable dessication cracks and occasional algal coats suggest that we are here dealing with an inter-tidal mud flat environment. Layers of carbonate mud laid down in shallow water were periodically exposed and sun cracked, and the resultant fragments torn up and redeposited during subsequent submergence.

A similar environment is proposed for the second correlation bed (LC 29, WB 53). Here, however, it is evident that rather than mud being deposited mechanically, sediment trapping stromatolite-producing algae were abundant, and formed structures comparable to those described by Black (1933) and Ginsberg (1960). Worms, both soft bodied and calcareous, are often abundant and burrow through algal deposits (Ginsberg, 1960), and it is evident that in the present case calcareous serpulid worms were common. Subaerial dessication of the stromatolites, followed by re-submergence, was sufficient to cause fragmentation of the layers.

The algae present in these beds, stromatolites, <u>Girvanella</u> and <u>Ortonella</u>, although of different species are of similar genera to those found in the Hard Cap (p. 28), and it is not unreasonable to postulate similar environmental conditions. That is, tidal flats on the border of a lagoon, with salinities slightly above those of normal marine conditions.

(f) Petrology of the gypsum beds

(i) Petrography. -

Gypsum occurs as nodular and layered masses near the base of the sequence at Durlston Bay and Worbarrow Bay (fig. 73). Much weathered and covered, it is impossible to determine the true relationships to the surrounding beds. Two types of gypsum are present. Fibrous selenitic 'beef' or satin spar, and coarse mosaics of alabastrine gypsum. Both are readily distinguishable in hand specimens.

In thin section, the alabastrine variety shows as coarse crystals 4-5 mm. in length, with very irregular sutured grain boundaries (fig. 74). These crystals are full of small inclusions (up to 100 μ long), many of which are anhydrite, as shown by shape, refractive index and high birefringence; but some, showing low birefringence colours, are perhaps minerals such as celestine. These inclusions are often well oriented, sometimes in one direction, but frequently in two directions at right angles. These almost certainly indicate the rectangular cleavage directions of anhydrite. Around nearly all of the crystals is a thin (35-40μ) inclusion free border, a phenomenon also noted by Forbes (1958, p. 354) in gypsum crystals from the Permian of Yorkshire. The sutured contacts of these crystals are rectangular and follow the cleavage directions indicated by the inclusions (fig. 74). A few of the smaller crystals are inclusion free.

Fig. 73. - Outcrop of fibrous-nodular gypsum. The white bands are fibrous layers.

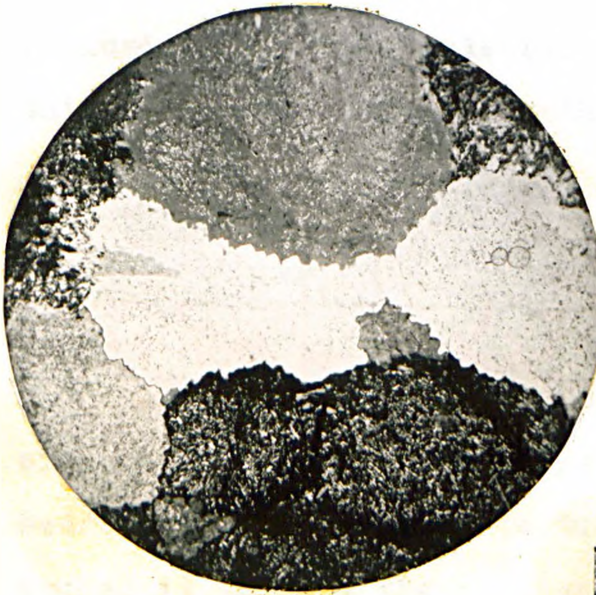
Lower Purbeck. Worbarrow Bay.
Soft Cockle Beds.

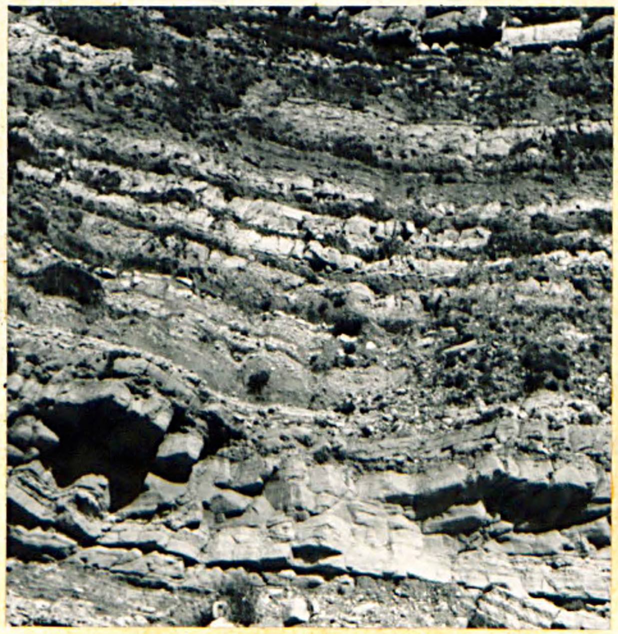
Fig. 74. - Photomicrograph (crossed nicols) of alabastrine gypsum. Note the large number of inclusions within each crystal, and the sutured crystal boundaries showing rectangular form.

Lower Purbeck. Worbarrow Bay.
Soft Cockle Beds.

Fig. 75. - Shales and 'marls' of the Soft Cockle Beds. The dark beds crossing the centre of the photograph are black-weathering clay shales.

Lower Purbeck. Fossil Forest.
Soft Cockle Beds.


500 μ



The fibrous gypsum is in the form of bands up to several centimetres thick, fibres are normal to the apparent bedding. Fibres are 8-10 μ width, and up to 50 μ long; they are free of inclusions. The fibres are not straight, but are slightly flexured, and sometimes rupturing has occurred with the production of small scale cone-in-cone structure. Crossed nicols and a sensitive tint show a good preferred orientation to be present. A few small twinned (swallow tail) crystals occur, following Mottura's rule (that is, the top V of the swallow tail points downwards) but these are not common.

(ii) <u>Origin.</u> -

It is unfortunate that these gypsum masses are so poorly exposed, as it would be interesting to know their contact relationships with the surrounding rocks. It is always possible, for instance, that the gypsum was originally uniformly bedded, but that during Tertiary folding flow took place that caused it to form the nodular masses. None the less, it is evident that there is a large amount present, sufficient at one time to have been mined at Durlston Bay for the preparation of Plaster of Paris, and it is necessary to account for its presence. The calcite pseudomorphs after gypsum noted elsewhere in the Lower Purbeck, and the evidence of anhydrite replacement (p. 56), shows calcium sulphate to have been commonly present in those rocks prior to leaching and its removal by ground water. The sub-surface Purbeck sections shown on Map I nearly all contain anhydrite or gypsum in the sequence, so we are not dealing in Dorset with a purely local phenomenon.

Sea water must be concentrated by a factor of 3.35 to obtain saturation with respect to calcium sulphate (Posnjack, 1940), when it has a chlorinity of about 65‰. At this concentration, and below 34°C, gypsum commences to crystallise out, and continues until the chlorinity has risen to 119‰ when anhydrite precipitates. At temperatures above 34°C, anhydrite is the first formed salt. In water containing no other salts, however, gypsum precipitates at temperatures below 42°C, while in saturated sodium chloride solutions it forms only below 14°C.

The depth at which gypsum is stable in nature is a function of the temperature gradient over the region, and also depends on the composition of the pore water and on the hydrostatic pressure (Mac donald, 1953). Gypsum is rarely found at depths below about 2000 ft. having lost its water of crystallisation and changed to anhydrite. The Permian deposits of Yorkshire, at depths of over 3200 ft., consist, for example, of anhydrite, halite and polyhalite, but at least some of the anhydrite was deposited as gypsum (Stewart, 1949, p. 629).

According to Arkell (1938, p. 11), the Purbeck in Dorset was buried to a depth of about 2000 ft., though this appears to be a conservative estimate. It would, however, have been sufficient to convert any primary gypsum to anhydrite. This anhydrite would, in turn, have re-hydrated to gypsum during or after uplift and folding in Tertiary times, and the relict crystals of anhydrite in the alabastrine gypsum show this to have occurred. In the Wealden Basin, too, it is noticeable that in boreholes where the Purbeck beds are found below about 2000 ft. (i.e. Portsdown, Arreton, etc. Map I), anhydrite is present in the Lower Purbeck, whereas in those holes where the Purbeck is at shallow depth (Henfield, Battle, etc.), gypsum is found. It is , unfortunately, impossible to say if there was any primary anhydrite formed in the Dorsetshire Purbeck, or whether all the calcium sulphate was deposited as gypsum.

The presence of these $CaSO_4$ deposits does, nevertheless, show that evaporation was an important factor during Lower Purbeck times. It also requires a continual replenishment of mineral rich waters to supply the sulphate. The possible inferences to be drawn from this are discussed in detail below (p. 202).

(g) Petrology of the Shales

(i) Petrography. -

Shales in the sequence are usually highly weathered and covered, and it is hard to obtain good samples. They weather to a dark blue-grey or black and consequently, when exposed, stand out from the light grey micrites (fig. 75). This is well seen at Fossil Forest where several black-weathering shales indicate some form of cyclic deposition. Four such shale beds can be seen in the lower half of the sequence, separated by friable to blocky calcite-mudstones.

Weathered, the shales are soft and plastic; fresh, they show fine-scale lamination and are usually lighter in colour. Sampling was carried out in order to determine the amount of non-calcareous material in these shales. It is important to know if any decalcification has occurred as otherwise erroneous results are obtained. When well preserved calcite shell fragments can still be found in a shale it is reasonable to assume that little decalcification has taken place, but unfortunately these shales here are generally non-fossiliferous and so this criterion cannot be used. Efforts were made to secure as fresh and unweathered a specimen as possible, but it cannot be ruled out that the results of the non-carbonate determinations may be higher than they should be.

One black-weathering shale which dried to a medium grey, gave an analysis of 39% by weight non-carbonate. Another, which dried to a dark blue-grey gave 75%. The non-carbonate is chiefly clay grade material with some fine quartz silt, but organic matter is also present. The residue in the second case when oxidised in Schultz' solution lost a further 7% by weight, leaving a much lighter coloured residue of mud and silt. No determination of the clay grade minerals have yet been carried out.

Figure 76 shows a complete cycle as seen in the Soft Cockle Beds. There are five such cycles up to the base of the second pellet bed (LC 29, WB 53).

(ii) <u>Origin</u>. -

The high percentage of non-carbonate in the shales at first suggests sudden influx of terrigenous material. On the other hand, their fine lamination, and the lack of coarse detritus, so common at other horizons where terrigenous material is found, seems to indicate quiet depositional conditions. What appears more likely, therefore, is that the supply of terrigeneous matter remained more or less constant, but that carbonate deposition varied.

During the formation of the shales very little carbonate was precipitated and consequently the terrigenous material forms a high percentage of the rock. They formed in quiet

IDEAL CYCLIC UNIT
SOFT COCKLE BEDS

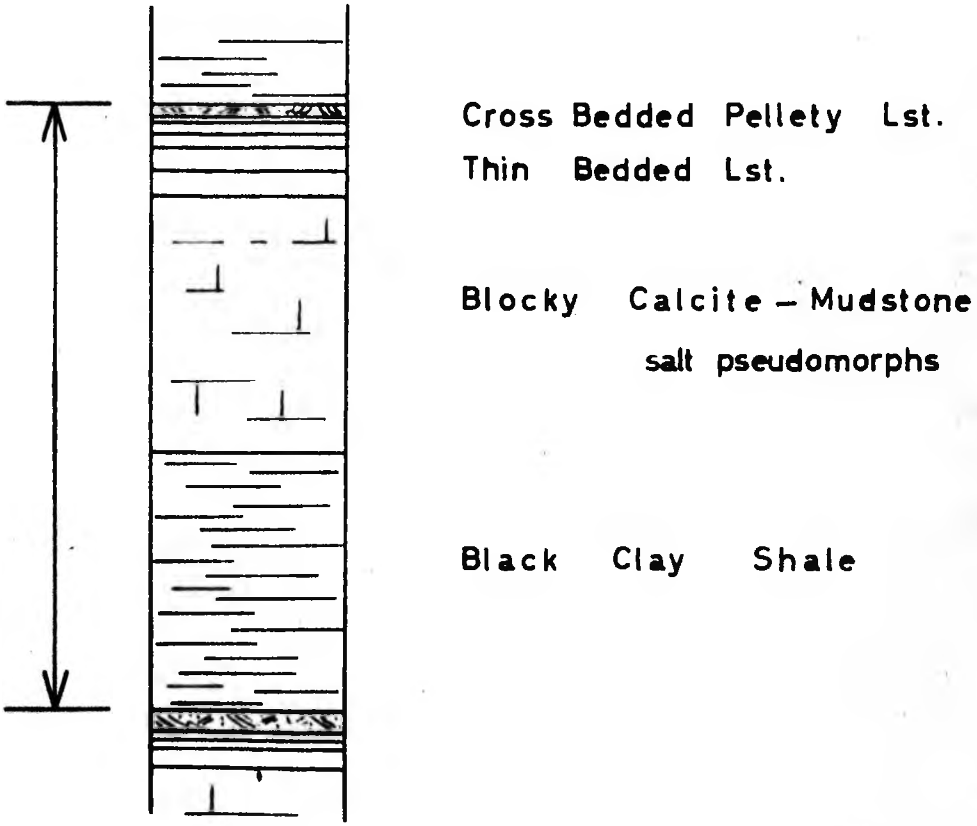


FIG. 76

conditions, perhaps even stagnant, as the paucity of fauna and high organic content would indicate. This may possibly be related to a freshening of the water and to lowered salinities which inhibited the precipitation of calcium carbonate. Subsequently, salinity increased once more until carbonate precipitation was again common, and the blocky calcite-mudstones were formed, often with salt pseudomorphs indicative of evaporation and dessication. The top of the cycle is usually a bed of pelsparite of variable thickness, similar to that described previously on page 114.

VIII. CHERTY FRESHWATER BEDS

(a) General Description

The Cherty Freshwater Beds are 8.05 m. thick At Durlston Bay and thin westwards to 5.43 m. at Worbarrow Bay, 2.70 m. at Mupe Bay, 1.85 m. at Lulworth Cove and 1.55 m. at Ridgeway. They consist of interbedded shell limestones, calcite-mudstones and calcareous shales, weathering to a light grey and cream, often with a white efflorescence, and containing nodular black chert. Most distinctive in this sequence is a bed of white-cream limestone, in which most of the chert is found. This bed is 150 cm. thick at Durlston Bay and is present at all localities in Dorset, forming a useful marker horizon. It often appears to be brecciated (fig. 13), but ths is an apparent brecciation caused by the incorporation in a carbonate mud of fragments of mudstone sloughed off the stems of *Chara* (Pettijohn, 1948, p. 308). The chert nodules are up to 50-60 cm. diameter, often have a thick white patina and contain abundant silicified fossils. This, and their irregular shape (figs. 77, 12), show the chert to have replaced limestone.

The chert appears to be associated with a possible erosion surface. This is at the top of the *Chara* limestone at Durlston Bay, where the bed is irregular and hummocky (fig. 78) and covered with large chert nodules lying in a dark grey 'earthy'

Fig. 77. - *Chara* micrite containing irregularly shaped chert nodules (black). Tape measure case on top of bed is 5 cm. long.

Cherty Freshwater Beds. Durlston Bay.
Middle Purbeck.

Fig. 78. - Irregular, hummocky surface (at hammer head) possibly erosional, at the top of the *Chara* micrite layer. No chert visible.

Cherty Freshwater Beds. Durlston Bay.
Middle Purbeck.

shale full of broken shells. An apparently identical layer is present at Worbarrow Bay where, however, it lies in the middle of the *Chara* limestone. At Mupe Bay and Lulworth Cove the same type of break is near the bottom of the limestone bed.

The calcareous shales and calcite-mudstones often show dessication-cracked surfaces and occasionally ripple-mark. Most beds are abundantly fossiliferous containing ostracods, pelecypods and especially gastropods. *Planorbis*, *Valvata* and *Physa* are very common in the chert nodules and in the associated limestones. It is of interest to note that some of the pelecypod shells in the shale layers retain a nacrous appearance and are still aragonitic (stain and X-ray).

The Cherty Freshwater Beds can be divided into three broad lithological groups, micrites and calcareous shales, biomicrites and biosparites. It is not possible to delineate sharp boundaries between these groups and to some extent they overlap one another, but they are convenient divisions for the purpose of petrographic description.

(b) Petrology of the micrites and calcareous shales

(i) *Petrography*. -

The micrites generally form firm and blocky beds up to 50 cm. or more thick. They may or may not show lamination, and fossil content is variable. The beds are either light-dark grey or tan-cream, colour depending both upoh the presence of *Chara*, and upon variation in the amount of non-carbonate mud in the rock, the more non-carbonate present the darker is the colour. It is possible to distinguish two main types of micrite rock.

1. Chara micrites -

These are tan to cream coloured rocks of fairly high purity, only about 1-2% of non-carbonate - mostly organic material - being present. They form the main chert bearing horizon mentioned above (p. 126), and are readily distinguished in the field both by their colour and by their apparent brecciation (p. 18). In thin section the beds are seen to consist of light brown to grey micrite, which is a matrix to ostracod shells and fragments, and to the stems and oogonia of *Chara* (fig. 79). [These are mainly species of *Clavator* and *Perimneste*, which were monographed by Harris, 1939]. A few gastropods are usually present but pelecypods are rare, though they do occur as micrite filled complete shells as well as fragments. The brecciated nature can often be seen in thin section where large (up to 1 cm. sq.) fragments of uniform micrite are found enclosed in a matrix of micrite containing shell fragments.

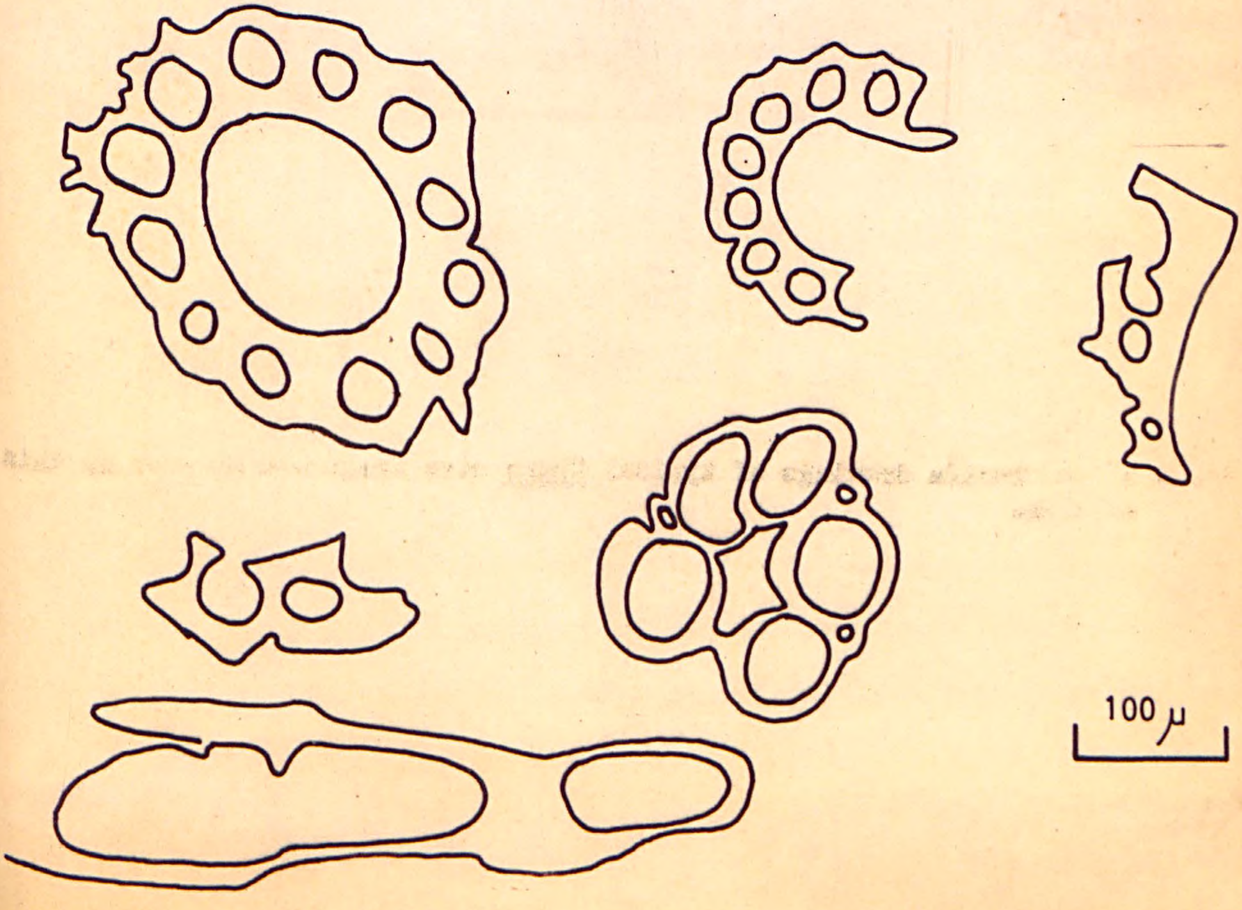
The mud grains in the matrix are rather irregular in size,

Fig. 79. - Photomicrograph of Chara micrite. Several Chara stem fragments are visible, also pelecypod valves and much fine shell debris in a micrite matrix (grey).

Cherty Freshwater Beds. Durlston Bay.
Middle Purbeck.

Fig. 80. - Camera lucida drawings of typical Chara stem fragments as seen in thin section.


500μ


100μ

varying from 10 μ down to less than 2 μ. The larger grains, though, are probably derived from the comminution of ostracod and pelecypod shells, as all gradations up to recognisable fragments can be seen. Grain boundaries, though apparently plane, are none the less very irregular, giving an interlocking mosaic of crystals. Micrite is often present in whole ostracod shells as a distinct floor overlain by drusy calcite. Generally this micrite is of the same colour and grain size as the matrix, but may sometimes be a lighter grey and more uniform in texture, apparently with little or none of the coarser inclusions. In any one area of the slide the mudstone floors indicate a uniform 'way up' direction, but this direction may vary from fragment to fragment within a single thin section.

<u>Chara</u> fragments are mostly confined to the stems of the plants; the oogonia are rare in most rocks, but may locally be abundant. This is perhaps due to current sorting, for as noted by Carrozi (1948) on the Purbeck of the Jura, it is unusual to find both oogonia and stems together. Stem pieces may be up to 3 to 4 mm. long but are usually less, and frequently are only partial fragments. They generally retain their cylindrical appearance but are sometimes seen to have been crushed. Typical stem sections are shown in figure 80. The stem walls were calcified during life (Harris, 1939) and now consist of small

radiating calcite fibres, usually 1-2 μ wide and 10-12 μ long, though this varies. The cavities within the cortical tubes may be filled by micrite or by drusy calcite. These stem fragments appear very susceptible to silicification and are often found replaced by chalcedonic quartz even when little or none of the remainder of the rock is silicified.

Ostracods are occasionally common, usually spar filled and sometimes with mud floors, but are usually fragmental and rare. Gastropods, chiefly <u>Planorbis</u>, are well preserved. The shell is now a coarse mosaic of drusy calcite, evidently a cavity filling, and solution of the aragonite shell must therefore have taken place after lithification of the matrix. Pelecypod shells, too, consist of drusy mosaics of calcite. Pyrite is not common, but is sometimes present, associated particularly with ostracod shells which it hasoften replaced. There is little or no detrital quartz.

2. Argillaceous micrites -

These contain variable amounts of non-carbonate material, usually about 5-10% by weight. They are generally much darker than the <u>Chara</u> micrites, with the actual colour appearing to depend on the amount of argillaceous material present, the more they contain the darker grey is the rock. In thin section, too, the micrite is a dark brown-grey. It is more uniform in texture, containing, as a rule, far less shell material than the <u>Chara</u>

micrites. Lamination is often very well preserved and is indicated by rare, thin layers of fine quartz silt, as well as by a planar orientation of shell fragments where present. The calcite-mud grains have, however, much the same size and shape as those in the Chara beds.

The non-carbonate material is very fine quartz silt and mud, chiefly argillaceous mud, but no determination of its composition has yet been made. Organic matter is virtually absent. In spite of the apparent difference, some of these beds may also contain Chara remains, but in very small amounts and always much fragmented. Pieces of shell, too, may locally be common; ostracod valves and fragments (frequently highly pyritised), well preserved gastropods with micrite and spar filled body-chambers, and thin pelecypod valves with hinges intact now preserved as mosaics of calcite crystals, often brown and pleochroic. In other beds the shells may also show signs of having been flattened, and the gastropods are broken.

Detrital quartz is again rare or absent except in rare thin laminae.

3. Calcareous shales -

These are always highly weathered and usually much covered, occurring in beds up to 60 cm. thick. The shales may be soft, friable, blocky weathering with a white efflorescence, or olive grey and plastic. Lamination is often good, but sometimes absent. The shale may be full of finely comminuted shells, or, sometimes, whole pelecypod valves are present; white and aragonitic (stain test) these valves are complete but squashed and broken in the plane of the lamination.

There is usually about 25-30% by weight of non-carbonate in the shale, somewhat higher than in the argillaceous micrites which they otherwise resemble, but there appears to be every gradation between the two classes. The non-carbonate is again chiefly mud with some fine quartz silt. Coarse detritus is absent. Pyrite granules occur in localised patches but are not common.

(ii) Origin. -

In spite of the importance of the argillaceous material in these beds, carbonate mudstone still forms the bulk of the sediment. The originally particulate nature of this mud is well shown by its presence as the infilling of gastropod body-chambers, pelecypod shells, and as floors in ostracod shells. There is no evidence of pelleting having occurred, most of the mudstone being very homogenous, and lithification must presumably have been by some process of intergranular cementation - perhaps rim-cementation.

It seems unlikely that much, if any, of this carbonate mud was derived from physico-chemical precipitation. The fauna and flora are indicative of a fresh to brackish-water environment throughout, and even though evidence of dessication is present in the form of mud-cracked layers, no salt or gypsum pseudomorphs are found that would indicate salinity. Purely physicochemical precipitation of carbonate in freshwater is known, but usually takes place with the formation of crystalline deposits such as travertine and calcareous tufa. These are not present here. Many freshwater limestones are, however, produced by biochemical precipitation, due to the action of plants. Of these plants, the stoneworts (algae) are particularly well known examples (Pettijohn, 1948, p. 308). In the present case stonewort remains are abundant, and it seems probable that much of the carbonate mud has been formed by their action. The carbonate produced by these plants is calcite, so no inversion from aragonite has occurred. Some mud is likely also to have been derived by the comminution of shells, as indicated in the petrographic description (p. 129). How much was so derived is indeterminable, but it seems unlikely that such mud ever formed a large part of the deposit, for as indicated below, scavenging does not appear to have been thorough, and turbulence and strong currents were absent.

There is little or no coarse ($>50\mu$) detritus in these beds, but argillaceous material is always present in greater or lesser amount. As in the Soft Cockle Beds (p. 124) the variation in the amounts present may be due either to a sudden increase in the supply of non-carbonate, or to a temporary decrease in the amount of carbonate mud being formed. The even-lamination, especially in the argillaceous micrites and shales, shows depositional conditions to have been quiet and undisturbed, with little scavenging action. There is no evidence of strong currents, the brecciation in the Chara micrites being due to the accumulation, in places, of sloughed off fragments (p. 18). This would suggest the second of the two possibilities to be most likely. However, the presence in places of flattened pelecypod and ostracod shells, shows that deposition was at times fairly rapid, and led to a compaction of the sediment, and in those beds the non-carbonate percentage is high (25% +). In most cases no shell crushing has occurred, perhaps indicating slower depositional rates, and here the non-carbonate content is usually lower (15% or less). The higher non-carbonate contents do, therefore, seem to be related to increased rates of deposition, that is, to an increase in the supply of argillaceous material. This appears to be generally so, though of course the rate of deposition of carbonate may also have varied.

The environment of deposition of the Chara micrites seems clear. To quote from Harris (1939, p. 4), " ... there was, in Dorset, a very large lake shallow enough (1-10 m. deep) for these gregarious plants to grow over large areas. The rather local occurrence of the different species suggests that they were deposited near the place where they grew." The rare presence of finely fragmented Chara in the argillaceous micrites, on the other hand, suggests that these rocks were formed in areas removed from active Chara growth. Perhaps the argillaceous materials in suspension were sufficient to inhibit the development of the plants in some areas. Further increase in the supply of argillaceous sediment resulted in the formation of the calcareous shales.

(c) Petrology of the biomicrites

(i) Petrography. -

Gradational from shelly argillaceous micrites, this class may be taken as comprising those rocks with greater than 15% by volume of fossil fragments in a micrite matrix (fig. 81). They may be silicified to a greater or lesser extent, and in some the shell material is still aragonite. There are fragments of Chara present but these are much rarer, while detrital quartz of fine sand-size occurs in small amounts. In the outcrop the biomicrites are usually shades of grey and form firm beds up to 40 cm. thick. They sometimes show lamination but are often devoid of it.

The micrite matrix is of two types. The first is similar to that in the argillaceous micrites: grey, with grains of 4-5 μ and with the same larger inclusions up to 10-15 μ size noted previously (p. 129). The second type is golden-brown with a very fine grain size, usually less than 2 μ, and is present as small lumps, pellets and fragments - apparently intraclasts - but sometimes also arranged in thin laminae. It is never very abundant. In some rocks the matrix is not a true micrite but a calcite-siltstone with grain size of 10-15 μ and larger. This has much greater clarity in thin section, though often the grains have a yellow tinge. Grain boundaries are plane. This siltstone matrix is associated with those rocks in which ostracods form the bulk of the bioclastic debris, and the siltstone is often present as fillings or as 'floors' to ostracod shells, overlain by drusy calcite.

Shell fragments are generally similar to, but more abundant than, those found in the *Chara* and argillaceous micrites. Some beds, especially those with a siltstone matrix, contain mostly ostracod fragments, valves and whole shells, with very few pelecypods or gastropods. Coarse silt to fine sand-size quartz grains are often present scattered throughout the beds. These rocks are quite well laminated, and the ostracod fragments lie parallel to the bedding. In peels it is seen that some cement is present as a thin rim of small grains around the ostracod shells, seeded upon the calcite prisms of the shell. In thin section it is hard to distinguish this rim cement from calcite-siltstone matrix.

Pelecypod fragments are preserved in two ways. Where found with ostracods and calcite-siltstone matrix, the pelecypod fragments are clearly drusy calcite filled casts showing the usual characteristics (Bathurst, 1958). Fragments are thin, but up to 8-10 mm. long, evidently not much broken. Where ostracods are rare, and the matrix is micrite, most pelecypod fragments are preserved as mosaics of brown pleochroic calcite, often with faint 'ghost' shell structure still present. These shells do not appear to have dissolved as the brown calcite mosaic does not show any criteria of a cavity filling. Some of the shells are silicified and these are white by reflected, mottled brown by transmitted light. The fragments are large, usually angular, and are mostly oriented roughly parallel to the bedding, though with some indication of disturbance. In some thin beds with a micrite matrix the shell is still aragonite (X-ray and stain tests), also brown and pleochroic.

Gastropods are not very common, occurring only rarely as drusy filled shell casts, with micrite or spar filled body-chambers. Small bone fragments are also sometimes present.

Pyrite is frequently abundant in these rocks, both disseminated throughout the micrite, and as a lining to, or a replacement of, shell fragments - particularly ostracods. It is very rarely found as a replacement of the pleochroic pelecypod shells. The pytite is usually in the form of small cubes 10μ or so in size, or as aggregates of very fine grain size.

(ii) Origin. -

Most of the micrite in these rocks seems clearly to have been derived in a manner similar to that of the Chara and argillaceous micrites. That is, mostly from the activity of Chara, but with lesser amounts possibly derived from shell comminution. The origin of the golden-brown micrite is less clear. It has not been found in the outcrop in rock forming quantities, only as intraclasts or as thin laminae, though this may be due to chance sampling. On the basis of colour and grain size, and following the argument of previous sections (p. 38), it would follow that this is micrite that has undergone some process of grain reduction, such as may be produced during ingestion by mud eating animals. There is no evidence of pelleting in this particular mud (there is in the biosparites), though in the larger areas it does have a faintly clotted texture suggestive of pellet merging, and it is quite probable that it has been derived from the coarser-grained micrite by a process such as faecal pelleting.

The calcite-siltstone was originally particulate, as is shown by its presence inside ostracods. The variable grain size, together with the common yellowish tinge, is indicative of its origin by shell comminution. It is possible to follow a gradation from the grains of 10-15 μ size upwards to recognisable ostracod fragments, and much, if not all of the silt seems to have been derived from the breakdown of ostracod carapaces. This break down could have been due to scavenging, to decay of organic tissue within the shell, or to mechanical abrasion. The lack of micrite and of pyrite, together with the presence of some fine quartz sand, does suggest current action which may have assisted in breaking the shells.

Pelecypod shells are always broken and angular, but are usually in quite large fragments. The micrite matrix, and the common presence in it of pyrite, certainly does not indicate current or wave action as the cause of breakage. On the other hand, the usual presence of planar orientation of the shell fragments seems to preclude scavenging, at least below the sediment surface. The lack of complete shells in those rocks suggests that the fragments may not be auto-chthonous, and what seems possible is that the shell fragments and the micrite intraclasts were periodically swept into what was essentially a mud environment. In other words, the pelecypods and the golden-brown micrite are characteristic of one environment, that of a prolific, mud ingesting community, that was occasionally swept by strong currents which removed shell fragments and tore up intraclasts, re-depositing them in a mud environment containing little fauna other than ostracods.

(d) Petrology of the biosparites

(i) Petrography. -

There are few true biosparites in the Cherty Beds. All contain variable amounts of micrite, but, except in some thin laminae, the micrite is always subordinate to the granular calcite cement. This cement is in the form of plane sided crystals of variable size, up to 150 μ and rarely larger. It has the characteristics of a granular cement (Bathurst, 1958), and is sometimes seen to form a thin border of small grains around ostracod fragments, in optical continuity with the shell.

Micrite is usually dispersed and tends to be trapped between shell fragments, but may also form an envelope to the fragments (fig. 82). This micrite is typically grey and of 4-5 μ grain size with occasional coarser grains. Here and there too, it may pass into a calcite siltstone of 10-15 μ size, but this is not common. More common in some layers are pellets and fragments of golden-brown micrite, frequently pyritic. The pellets are ellipsoidal with spherical cross-section, but are often broken. They are sufficiently abundant in places for the rock to be termed a biopelsparite (Folk, 1959). The pellets and fragments are in a granular cement together with shell fragments that are themselves intraclasts. This is shown by many of the fragments having gobbets of brown

Fig. 81. - Photomicrograph of a biomicrite. Mostly pelecypod fragments in a micrite matrix. Black specks are finely disseminated pyrite.

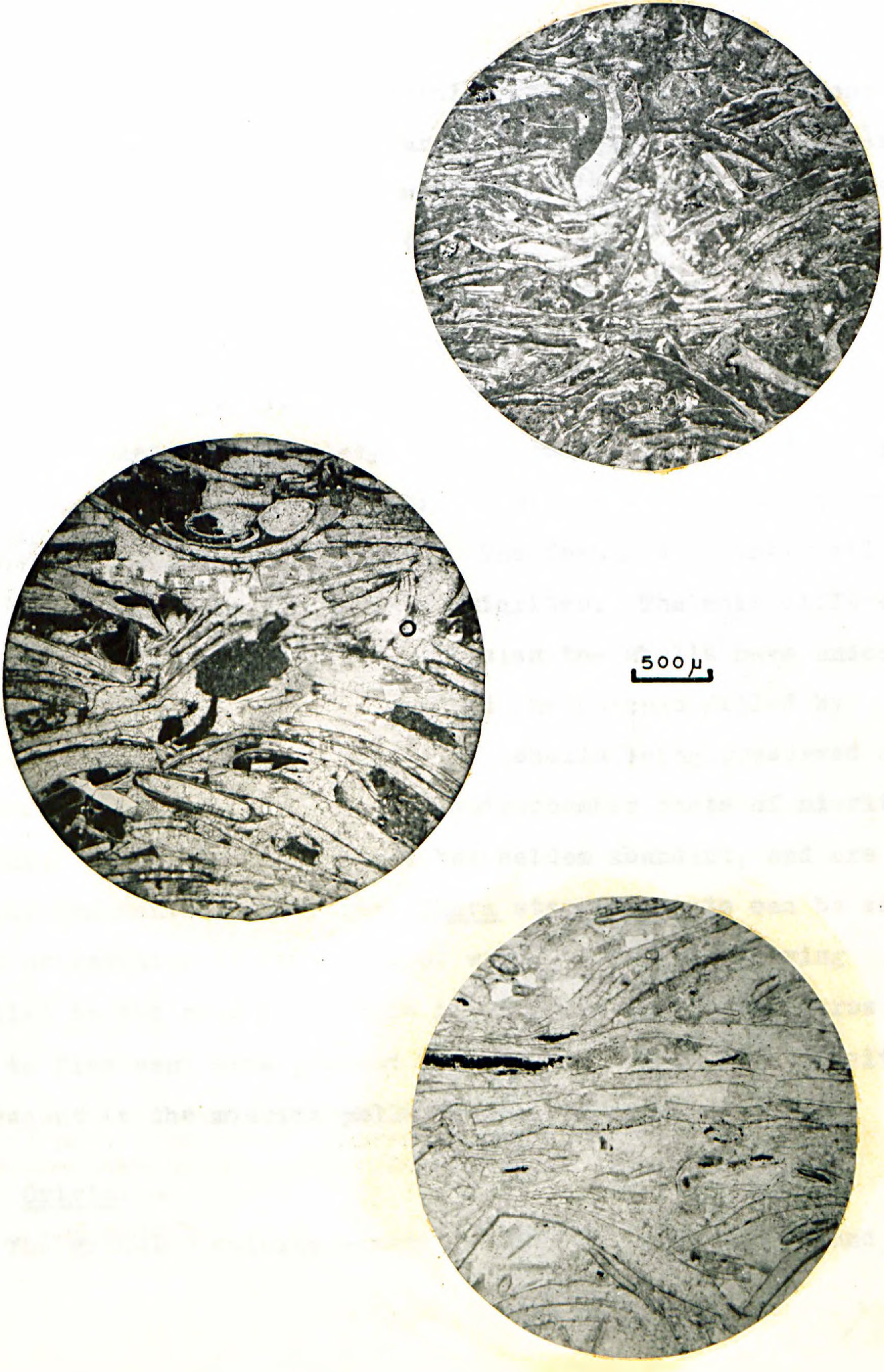
Cherty Freshwater Beds. Worbarrow Bay.
Middle Purbeck.

Fig. 82. - Photomicrograph of biosparite. Pelecypod valves and fragments, some bored or abraded, with micrite pellets and lumps and a few ostracods in a granular cement. Some shells have small gobbets of micrite attached to them indicating that they are intraclasts.

Cherty Freshwater Beds. Durlston Bay.
Middle Purbeck.

Fig. 83. - Photomicrograph of biosparite. Pelecypod fragments with a thin micrite envelope (grey) in a granular cement. Black specks are pyrite. Note the breakage of some of the shells giving angular ends, ends are otherwise rounded.

Cherty Freshwater Beds. Durlston Bay.
Middle Purbeck.


500μ

micrite attached to them, especially in the concave portions (fig. 82). Where the pellets are abundant shell fragments are small and more abraded than elsewhere. Their edges are rounded and the pieces are seldom greater than 3-4 mm. long, often less. Where pellets are rare or absent the shell fragments are commonly greater than 8 mm. length, though often still with rounded edges (fig. 83).

Shells are mainly pelecypod, now mostly mosaics of calcite, often brown and strongly pleochroic, but in a few cases aragonite shells are still preserved. The features of the shell mosaics are the same as in the biomicrites. The main difference apparently is in the amount of abrasion the shells have undergone. A few have been bored and had the borings filled by micrite. Gastropods are again rare, shells being preserved as drusy calcite fillings outlining body-chamber casts of micrite or spar. Ostracods are present but seldom abundant, and are usually fragmented. Very rare Chara stem fragments can be seen. Shell orientation is usually good with the fragments lying parallel to the bedding. There is a little quartz of coarse silt to fine sand size present but it is never common. Pyrite is present in the micrite pellets, but otherwise absent.

(ii) Origin. -

The granular calcite cement, lack of micrite matrix and presence of intraclasts point to depositional conditions in which some current action was continually effective. This is also indicated by the good planar orientation of the shell fragments. Most of these shells are not autochthonous, as is shown by their fragmental and abraded appearance, and by the fact that many are themselves intraclasts. They were torn up from their initial place of deposition - as a biomicrite, with carbonate fragments still attached, and re-deposited with micrite pellets and intraclasts. The environment of deposition may originally have been one of mud, but most of this was winnowed away by the currents. Some, however, remained trapped beneath and between shell fragments, and is visibly of a different type from that forming the pellets and intraclasts. There cannot have been very much abrasion as generally the size and preservation of the fragments precludes this; it was sufficient though to produce a rounding of the edges of the shell fragments.

(e) Silicification

Although present in limited quantities at other horizons in the Purbeck, chert is common only in this sequence of beds.

It occurs as nodules and thin lenticles, never as a bedded deposit. The nodules are very irregular in shape (figs. 77, 12) and up to 60-70 cm. diameter. They are often heavily patinated, with a grey patina ¼-½ cm. thick, clearly divided from the black-brown chert. The nodules usually contain abundant fossils, often very well preserved, and may also contain fragments of unsilicified limestone. Most nodules are traversed by thin irregular cracks, filled by quartz. Lenticular chert is confined to layers 2-5 cm. thick, but these may extend several metres laterally parallel to the bedding.

In thin section several different petrographic types of silica can be seen; they are:

Radial or fibrous mosaics of chalcedonic quartz, partly spherulitic.

Microcrystalline quartz.

Brown chalcedony - this is very rare.

Anhedral quartz crystals.

There is, too, an order of preference for silicification: this generally follows

Large pelecypod and gastropod shells, preceeded by *Chara* fragments if present.

Smaller shell fragments.

Drusy calcite shell-fillings and granular cement.

Micrite matrix.

Ostracod shells.

Many of the pelecypod shells, and most gastropods, are replaced by fibrous quartz. The fibres are straight and oriented normal to the shell wall showing a good preferred orientation (gypsum plate). They are in the order of 10-40 μ wide and seldom exceed 150 μ length, usually being much less. In other cases the shell is a mosaic of microcrystalline quartz, almost isotropic in aggregate. The cavities inside both gastropod and ostracod shells frequently have a thin lining of fibrous quartz, up to 50 μ thick, which is covered by spherulitic or radially oriented chalcedonic quartz (Folk and Weaver, 1952). The spherulites are usually mutually interfering and meet along straight compromise surfaces (fig. 84). This obviously postdates the fibrous type.

Microcrystalline quartz aggregates, other than those replacing shells, are usually found occupying what may have been cavities or pore space in the rock, but sometimes are found in small areas between mutually interfering spherulites. The quartz crystals are highly sutured, with very irregular wavy extinction, and this is a stage that appears to be intermediate to the formation of unstrained quartz crystals of 120-150 μ size, sometimes found at the centre of spherulitic masses. Figure 85 is a diagrammatic representation of the types of chert fabric seen in these rocks.

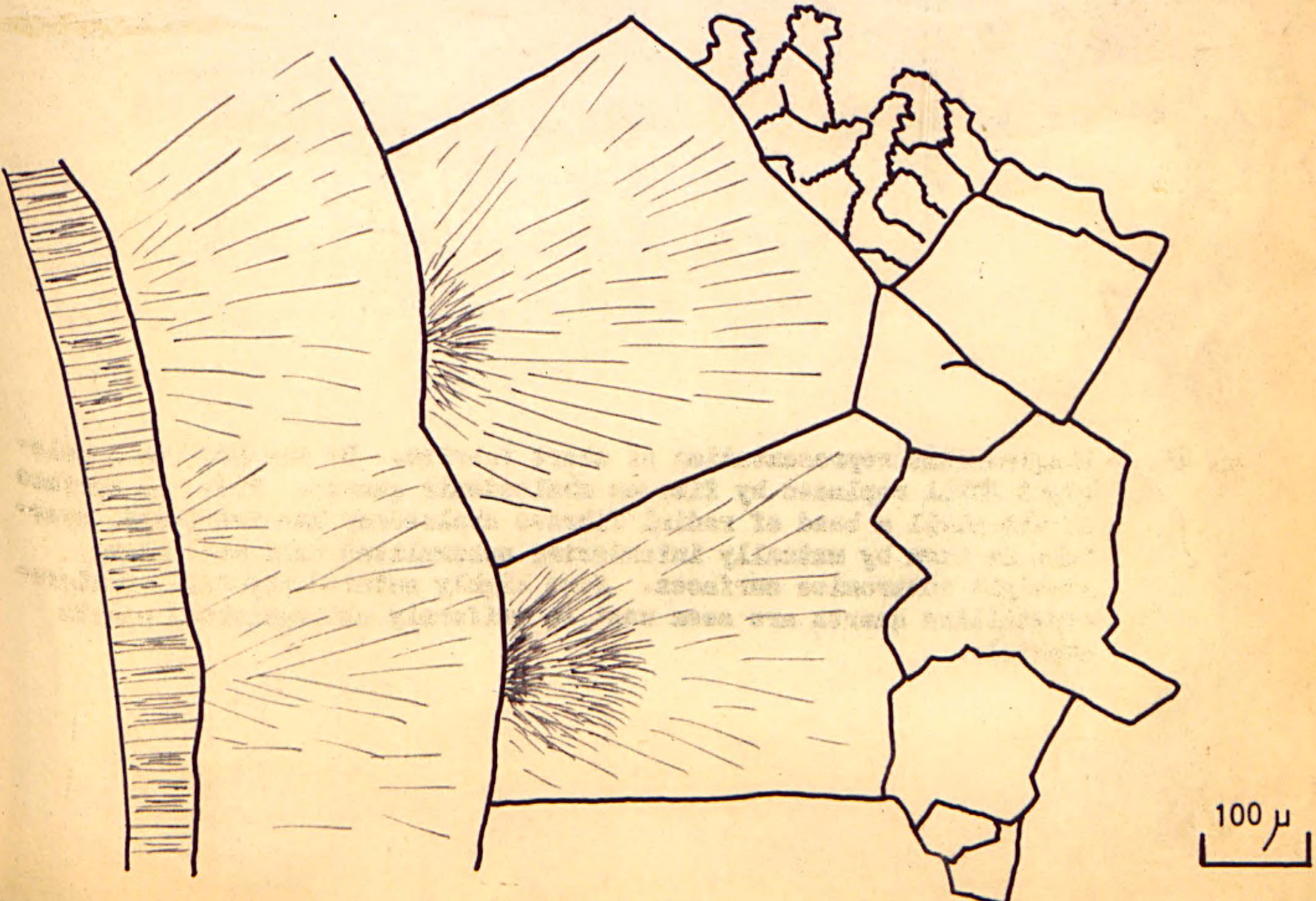
The problems raised by the presence of chert in limestone

Fig. 84. - Photomicrograph of chert (crossed nicols). Chert spherulites can be seen to meet along straight compromise surfaces. Microcrystalline quartz is present in spaces between mutually interfering spherulites, and also as a replacement of micrite pellets. Remainder of rock is calcite.

Cherty Freshwater Beds. Worbarrow Bay.
Middle Purbeck.

Fig. 85. - Diagrammatic representation of chert fabrics. On the left is a pelecypod shell replaced by fibrous chalcedonic quartz. From the surface of the shell a band of radial fibrous chalcedony has developed, overlain in turn by mutually interfering spherulites that meet along straight compromise surfaces. Some highly sutured crystals of microcrystalline quartz are seen next to uniformly extinguishing quartz crystals.


500 µ


100 µ

have been the subject of much speculation and discussion. In the Purbeck rocks we can list three main problems to be considered. They are:-

(i) The origin of the silica.
(ii) The time of silicification.
(iii) The cause of the localisation of most of the chert.

(i) The origin of the silica. -

The three main possible origins of the silica in these rocks are (1) detrital quartz grains (2) organisms (3) inorganic precipitation. There is very little detrital quartz in the Cherty Beds, but where present it can be seen that some of the grains have been embayed by calcite. This replacement of quartz has not been extensive, however, as many grains still appear to have original rounded boundaries partly preserved, and it seems most improbable that sufficient silica could have been obtained in this manner to account for all of the chert.

Organisms can provide silica from the solution of the siliceous tests of animals such as sponges and radiolaria, and of plants such as diatoms. Radiolaria and diatoms have not been found in the Purbeck rocks, though in view of their small size and possible replacement by calcite, they may have been overlooked, especially as diatoms are often present to a minor extent in gastropod-bearing lacustrine limestones (Swineford and Franks, 1959). However, diatoms appear in quantity only in late Cretaceous times (Lohman, 1960) and are unlikely, therefore, to have supplied much silica here. Siliceous sponges, too, are not common, though one species has been described from the Lower Purbeck, (Spongillia purbeckensis), and calcified spicules have been found associated with small chert lenticles in the Soft Cockle Beds. No evidence of their presence has been found in the Middle and Upper Purbeck, and it seems unlikely that siliceous organisms contributed much to the supply of silica in the Cherty Beds.

Inorganic precipitation of silica depends largely upon the presence of both suspended matter and electrolytes in the water. Soluble silica is absorbed upon the suspended matter as it comes into contact with the electrolytes (Bien, Contois and Thomas, 1959). Although the palaeontological evidence indicates that the water at this time was fresh or brackish, some elctrolytes might be expected to have been present. The presence of suspended matter is shown by the high argillaceous content of the beds. It seems likely, therefore, that much of the silica was formed as an inorganic precipitate, probably as a stable colloidal sol as is usually the case to-day, and too dispersed through the sediment to form gel-like masses (Krauskopff, 1959).

Subsequently, this dispersed silica was concentrated to form chert nodules and lenticles, during which time a replacement of carbonate occurred. The underlying cause of this concentration and replacement was undoubtedly pH change that affected the equilibrium of interstitial solutions. An increase in pH causes silica to dissolve. This may be brought about by, for example, decay of organic matter resulting in the liberation of ammonia. A release of carbon dioxide or hydrogen sulphide by bacterial action would lower the pH and favour a precipitation of silica and solution of calcite. Sediment is not usually homogenous, and consequently it is quite possible for silica to be dissolved at one point and precipitated at a closely adjacent point simultaneously. A silica trap can thus be formed which continues while pH differentials last. Any other process likely to upset equilibrium, such as renewal or commencement of ground water circulation, may start a similar cycle. The broken and cracked appearance of the chert nodules suggests that they may have formed as a hard silica gel. Expulsion of water during crystallisation was sufficient to cause breakage, and may account for the strained and undulose extinction of the microcrystalline quartz (see Pittman, 1959, p. 134).

(ii) Time of replacement. -

If the formation of the chert was due to pH changes brought about by organic decay, then this must presumably have occurred soon after the sediment was deposited. On the other hand, none of the cracks in the nodules, if due to crystallisation of a gel, have been filled by sediment as would be expected if this were an early phenomenon. That this does occur was shown by Pittman (1959) in chert nodules from Cretaceous limestones in Texas. In the Purbeck, the cracks are quartz filled. In a few beds pyritized micrite pellets occur, many of which are silicified. Here, silicification evidently post-dates pyritization.

The preferential replacement of pelecypod and gastropod shells compared to ostracods, may be explained if silicification took place before or during the inversion of aragonite shells to calcite. In very rare cases it is possible to see quartz that has apparently preserved a lamellar shell fabric. Mostly, however, it appears to have been a crystalline calcite mosaic that was replaced. Why the silica should replace these calcite mosaics and drusy fillings in preference to the calcite ostracod shells, is as yet unexplained. It may be due to properties of orientation in the ostracod shell prisms.

Generally, then, it appears that silicif ication post-dates the calcitisation of aragonite shells.

Modern studies seem to show that the change from aragonite to calcite is dependent upon the circulation of fresh-groundwater. This suggests that silicification may not have occurred until uplift during intra-Cretaceous movements, and possibly not until after Tertiary folding. It must be remembered, though, that the connate water of these sediments was fresh or brackish. How would this have affected the rate of calcitisation?

Not without significance, perhaps, is the almost complete absence of chert from the subsurface Purbeck rocks (e.g. Arreton) even though lithologies are so similar. These rocks have not been subject to near-surface groundwater circulation.

(iii) <u>The cause of localisation</u>. -

The high concentration of chert in these beds is almost certainly related to the fresh-brackish water environment of deposition of the sediments. Fresh-waters contain higher concentrations of silica than sea waters, in the form of monomeric silicic acid (Krauskopff, 1959). The sediments may thus have had a higher silica content initially than others in the Purbeck.

IX. CINDER BED

(a) General Description

This is the most distinctive bed in the Purbeck. 2.90 m. thick at Durlston Bay it thins westwards to 1.65 m. at Worbarrow Bay, 1.28 m. at Mupe Bay, 1.20 m. at Lulworth Cove and 0.90 m. at Ridgeway. For the most part the bed consists of masses of oyster shells (Ostrea distorta) in a fine grained carbonate matrix, preservation of the shells varying from complete valves to small fragments. At Durlston Bay it is readily divisible into three units based upon the nature of the matrix and on the amount of Ostrea present (fig. 86).

The basal unit consists of small Ostrea fragments, blue-grey in colour, set in a grey carbonate-mudstone. There is no apparent bedding, though the shell fragments show a rough orientation parallel to the regional bedding. Near the top of the unit small (1-2 cm.) masses of white calcareous Serpula tubes become common (S. coacervata). The middle unit is characterised by a general lack of oysters. Tan coloured, it contains valves and fragments of Protocardia and, more rarely, Trigonia, while spines and in places tests of Hemicidaris purbeckensis are found. Serpula is common. There is less matrix than in the lower unit, but is again a carbonate mud. The upper unit comprises three beds (each 15 cm. thick) of large oyster shells, many unbroken, in a matrix of grey carbonate mudstone. The shells vary from blue-grey to white in colour.

The middle unit with its non-oyster fauna thins rapidly westward and is only just recognisable at Worbarrow and Mupe Bays, where a few Hemicidaris spines may be found. It is absent at Lulworth, where the bed consists only of oysters and rare Serpula in carbonate mudstone.

(b) Petrology

(i) Petrography. -

The lower and upper units of the Cinder Bed at Durlston Bay are alike petrographically and similar to the bed as a whole further west. Differences are mainly due to the size and preservation of the oyster shells.

Although the hand specimen has a dull argillaceous appearance, there is only about 5-6% by weight non-carbonate present, chiefly silt to sand-size quartz, mud and bone fragments. The matrix is of light grey silt-size calcite grains, not, however, a granular cement (fig. 87). Grain size is irregular, varying from about 5 μ up to 15 or 20 μ , with fairly common larger grains scattered throughout. These are usually single crystals and appear to be derived from shell comminution. Grain boundaries are plane.

Fig. 86. - Cinder Bed. The bottom two units are not distinguishable on the photograph, though the middle one is at the hammer head. The bedded upper unit is clearly visible.

Cinder Bed. Durlston Bay.
Middle Purbeck.

Fig. 87. - Photomicrograph of Cinder Bed. Lamellar *Ostrea* fragments in a grey micrite matrix of patchy grain size (up to 20μ).
Cinder Bed. Mupe Bay.
Middle Purbeck.


500µ

Shells are mostly pelecypods but with some ostracods. The pelecypods are largely *Ostrea* fragments with variable amounts of other genera. The oyster fragments are often quite large (½ cm. and upwards) though mostly smaller pieces are present in the lower unit. They retain very good lamellar structure as the original shell is calcite and not aragonite, and this serves to identify readily even small fragments (fig. 87). The ends of the fragments are usually rounded, but may sometimes have a frayed appearance which seems to be controlled by the shell structure.

Non-oyster pelecypod shells are present as brown pleochroic mosaics of calcite crystals, with very irregular grain boundaries. They are mostly smaller than the oyster fragments, and have a rounded abraded appearance. Generally, the boundary of the fragment merges with the calcite siltstone of the matrix so that there is an apparent blurring of the edges of the shells. Ostracods are usually present as single valves but there are rare, whole, spar-filled shells. Quartz grains of 100-200 μ size are scattered throughout, but are not common, while here and there are small bone chips.

Small (10-20 μ) granules of an opaque mineral with metallic lustre are scattered throughout the matrix and appear to have replaced parts of the shell fragments. This is possibly marcasite.

The middle unit differs in having a greater volume of shell fragments and less matrix, and a dominantly non-oyster fauna. The matrix is again mostly a calcite-siltstone apparently identical to that in the other two units. Here and there though a little micrite is present in the form of small intraclasts. These are more opaque and a brown-grey in section with grains of less than 4μ. A few small oyster fragments can be recognised by their lamellar structure, but are very rare. Of the remainder of the pelecypod shells, two distinct types of preservation can be recognised.

Some shells have been bored - by pelecypods, algae or such like - and the borings are filled by micrite. The remainder of the shell is a typically drusy mosaic of calcite. The borings are confined to the smaller fragments of more abraded shells and are found on both sides of the fragment. Ends are rounded, and often a thin micrite envelope is present.

Larger fragments (up to ½ cm.) are unbored. They consist of mosaics of calcite having very irregular grain boundaries. The calcite grains may be brown and pleochroic, or colourless, and do not show drusy characteristics. In peels the difference in the grain boundaries between the types is most marked (fig. 107 A.B.).

Ostracods appear to be absent. There is more quartz than in the lower and upper units, of about 100-200 μ size. Marcasite or pyrite is absent.

(ii) Origin. -

The abundance of oysters in this bed indicates an environmental change of some significance. Oysters require shallow water for development, and can survive temporary exposure to the air, but need a good supply and exchange of water for maximum growth. They are very variable in size and shape, and this often depends on the substratum. On soft bottoms, they tend to be long and narrow; on hard bottoms they are round and flat. They are sessile, and usually grow in clusters, which in turn helps to produce misshapen shells. Various species are tolerant to different ranges of salinity. Modern oyster reefs along parts of the Texas coast, for example, are of two types. A low salinity reef in waters of from 12 to 25%, and a high salinity reef with a different species in salinities greater than 25% (Parker, 1959).

In the Purbeck, complete oyster shells are mostly confined to the upper unit where they average 3 x 2 x 1 cm. size. That is, they tend to be round and flat, indicative of a firm substrate. The basal unit contains for the most part only fragments, and does not appear to be a true 'reef' but an accumulation of debris from some nearby oyster mass. Increasing salinity resulted in the development of marine pelecypods and Hemicidaris, but these conditions do not appear to have extended much to the west of Durlston Bay.

In the west salinity was presumably lower, modified perhaps by proximity to a coast. Shell boring and abrasion may indicate slower rates of deposition. Subsequently this marine phase was succeeded by brackish conditions permitting the redevelopment of oysters. At Durlston Bay these are now seen in place with abundant complete shells.

The calcite-siltstone matrix is largely derived from shell comminution. The downward gradation from recognisable shell fragments is clear, and the irregularity of grain size seems to preclude origins such as inorganic precipitation. Biochemical precipitation by plants may have produced some silt, but plant remains have not been found in this bed, and so such origin is unlikely for most of the grains. There appears to have been little scavenging of the sediment in the lower and upper units. In the middle unit the micrite filled borings and intraclasts indicate that some grain size reduction occurred which may have been due to scavenging activities.

X. INTERMARINE BEDS

(a) General Description

The Intermarine Beds are 14.88 m. thick at Durlston Bay, and thin westwards to 2.49 m. at Worbarrow Bay. They thicken slightly at Mupe Bay to 2.65 m. and then thin again to about 2.25 m. at Lulworth Cove and 2.28 m. at Ridgeway.

Broadly speaking, the beds are a succession of shelly limestones (biosparites and biomicrites), micrites and shales. The outcrop shows uniform, parallel beds (figs. 88, 89) accentuated by differential weathering. Medium grey to tan in colour the beds vary from about 5-75 cm. thickness, and show a variety of sedimentary structures such as ripple-mark and cross-bedding. Biological structures like sediment-filled borings (fig. 90) and small oyster reefs (fig. 91) are also present.

The fauna is dominantly one of pelecypods, the shells of which form the bulk of the limestones, but gastropods and ostracods are also common in places, and <u>Chara</u> fragments are locally abundant. One bed near the base of the sequence seems to be correlatable throughout the coastal exposures. It is a light blue-grey <u>Chara</u> micrite (DB 48, WB 84, MB 29, LC 56). Coarse quartz grains are common in beds near the top of the sequence, but no calcareous sandstones are present.

There are a variety of rock types in the Intermarine Beds,

Fig. 88. - Intermarine beds illustrating the uniform parallel bedding.
Middle Purbeck. Durlston Bay.

Fig. 89. - Intermarine beds illustrating the uniform parallel bedding.
Middle Purbeck. Durlston Bay.

Fig. 90. - Sediment filled vertical boring that has weathered out. The generally disturbed appearance of the sediment is apparent and is probably due to scavenging.

Intermarine Beds. Durlston Bay.
Middle Purbeck.

Fig. 91. - Small 'reef' composed of fragments and shells of *Ostrea*. These fragments occur in abundance along the bedding plane on which the hammer rests.

Intermarine Beds. Durlston Bay.
Middle Purbeck.

but most are formed by variation in the amounts present of three 'end members'; pelecypod fragments, ostracod and quartz, and matrix. This latter may be micrite or typical granular spar cement, while the pelecypods may be drusy casts or brown, pleochroic mosaics of calcite. In spite of the apparent variety it is possible to group the sediments into three broad divisions, each of which may be sub-divided to a greater or lesser extent.

(b) Petrology of Chara-ostracod micrites

(i) Petrography. -

This is the most heterogeneous group and comprises *Chara* micrites, ostracod limestones and calcareous shales. Some of the beds are detrital; they show small scale cross-bedding (2-5 cm.) and contain 5-10% by weight of sand-size quartz. Shales are dark grey or black, rocks composed of *Chara* fragments are mostly brown when fresh but weather to a blue-grey or white, and the ostracod limestones are generally light-medium grey. Bedding is well developed and most of these rocks split readily into layers 2-5 cm. thick. The thinner beds sometimes show dessication cracks, while in others, vertical, sediment filled borings weather out (fig. 90), as do small *Chara* stems.

In thin section Chara is readily recognisable (fig. 92) usually as small stems or fragments of stems, and only rarely are oogonia seen. Amounts present vary from isolated pieces scattered throughout the rock, to beds that are composed almost exclusively of Chara fragments and matrix. The fragments have a light-yellow colour in section and consist of inter-locking aggregates of plane sided calcite crystals of from 4-20 μ size. They are acicular in places and this is seen particularly in longitudinal sections of the stems. Nodal cavities are usually filled with colourless calcite spar, but a very few contain micrite.

Where Chara fragments are common, ostracods are rare, but do occur as whole, spar-filled shells (fig. 92). Pelecypods too, are rare, occurring either as pleochroic calcite mosaics, or sometimes as drusy casts, the boundaries of which tend to be blurred and merge with the matrix. The matrix is a light-grey micrite essentially similar to that of the Chara micrites in the Cherty Beds (p.128), with grain size variable but mostly about 3-4 μ , though containing inclusions of single calcite crystals up to 30-40 μ size, especially where ostracods are more abundant.

The ostracod limestones are firm, very evenly bedded rocks, usually a few centimetres thick and often containing thin (mm.) clay partings. In thin section whole, spar-filled shells, valves and fragments are abundant (fig. 93), valves often nesting one inside the other, while some of the whole shells are partially flattened. Most of the shells are of light yellow calcite, but some are opaque and pyritised. The valves and fragments are always planar oriented parallel to the bedding.

In some beds, calcite crystals seeded upon the prisms of the ostracod shell, and a thin border of clear cement can be seen surrounding the yellowish shell. In favourable circumstances this proceeded further and acicular crystals developed producing a 'beef' structure on a micro-scale (see fig. 101). The matrix is a calcite-siltstone. Translucent in section the grain sizes are from 6 μ to 15 μ, with plane grain boundaries. The presence of siltstone as a floor inside some whole ostracod shells points to its having been of discrete grains and mechanically deposited, not as having been a cement.

Quartz is ubiquitous in the ostracod limestones which contain up to 10% by weight in some cases. The grains are mostly angular or sub-angular and of 70-120 μ size, though some secondary enlargement of the grains appears to have occurred. Associated with the quartz are micrite pellets of 100-150 μ diameter. These are usually brown or grey and are clearly differentiated from the matrix. A few grains of a light green, isotropic, glauconite-like mineral are also present, apparently authigenic as it is seen to have irregular form and, sometimes, to have formed between two mechanically deposited grains. Pelecypods are rare in thin section and are more usually seen in the hand specimen as thin layers of valves.

Shales are present as thin beds up to 35-40 cm. thick. They are generally soft and plastic and readily weather to grey or black; some, however, form firm, thin, well-laminated layers. Non-carbonate content is variable from about 25-55% by weight, consisting chiefly of clay grade material and a little quartz silt. Organic matter is usually low, but a few beds are highly bituminous and yield a viscous brown oil on heating. Ostracods are abundant in the shales, and pelecypod valves and fragments are sometimes common in layers, and may be entirely aragonitic (X-ray). The pelecypods are thin shelled and up to 1 cm. width but mostly smaller. Many are broken but the fragments have not been moved and still form the entire valve. Small comminuted fragments are also present in thin layers.

(ii) Origin. -

The similarities between this group and the micrites and shales of the Cherty Beds (p. 128) are evident. The micrites here contain, perhaps, more fragments of Chara and less calcite-mud, which may indicate that they have been transported from their place of growth, and to some extent sorted by current action, but otherwise very similar environmental conditions must have prevailed. The ostracods, species of *Cypridea*, evidently accumulated in conditions of gentle agitation, sufficient to winnow away any micrite that may otherwise have settled. Occasional more turbulent conditions are indicated by increased quartz content and small scale cross-bedding.

The lamination in the shales generally imparts a good fissility to the plane of the bedding, and seems to indicate comparatively slow deposition, as fast depositional rates usually produce blocky mudstones with unoriented clay minerals (Dr. F. Broadhurst, personal communication). This slow deposition, in turn, implies that the formation of the shales is likely to be due to a decrease in the amount of carbonate accumulating, rather than to an increase in the supply of terrigenous material. The shales probably formed in sheltered areas away from the site of active *Chara* growth, where only the finest carbonate was able to accumulate in more or less equal amounts with terrigenous mud.

(c) Petrology of pelecypod-gastropod limestones

(i) Petrography. -

The rocks in this group are light grey-tan in outcrop, and form well defined beds up to 80 cm. thick. They are shelly limestones in which the matrix can be micrite, granular cement, or a mixture of both. The shells are mostly pelecypod fragments, planar oriented parallel to the bedding, with occasional whole valves (fig. 94). Gastropods are locally common, but ostracods comparatively rare. The pelecypod fragments often have a thin micrite envelope, and some have micrite-filled borings. Most of the fragments are now mosaics of colourless calcite that show characteristics of a drusy cavity filling. A few, however, are of a slightly pleochroic brown calcite, and in these it is still possible to see lines of inclusions that mark original shell structure. Here and there, too, are small pieces of <u>Ostrea</u> shell, recognisable by their lamellar calcitic structure. The fragments generally have rounded ends, especially those with a micrite envelope, but some pieces are up to ½ cm. length and hinge areas are often well preserved.

Gastropod shells are always seen as drusy cavity fillings surrounding body-chambers that may be filled with micrite or drusy spar. Very rarely a <u>Chara</u> fragment can be found, more especially in the beds at Worbarrow. Quartz grains are ubiquitous, and in places small (15-20μ) circular-walled bodies that may be Hystrichosphaerids are not uncommon.

Micrite matrix is both grey and brown in thin section. The brown micrite occurs as small lumps or clots and has grains of 2 μ or less in size. The grey micrite, which occurs in more homogenous layers or patches, has grains of 4-5 μ. The distribution of the micrite is very irregular, often none is present, and a coarse-grained granular calcite cements the shell fragments. Micrite is always subordinate to granular cement.

(ii) Origin. -

The presence generally of a good planar orientation to the shell fragments, indicates current action as well as a lack of scavenging below the depositional surface. On the other hand, the occurrence in places of a micrite matrix shows that currents were not continuous, and that periods of quiescence occurred during which the mud was deposited. It was, perhaps, during such periods that shell fragments were bored - by gastropods, pelecypods, algae or such like - and the borings filled by micrite, but such boring is rare.

The round ends of some of the fragments may have been produced by abrasion during movement by currents. Accumulation of these shell fragments resulted in a porous deposit. Some pore space was filled by micrite, the remainder was ultimately filled by chemically deposited granular calcite cement. The preservation of the shells indicates that solution of their aragonite shell and filling of the resultant cavity by drusy calcite took place after cementation had occurred.

Although a few pieces of Ostrea are present in these rocks, they are rare, and the bulk of the fauna appears to be of non-marine pelecypods such as Neomiodon, with occasional gastropods like Viviparus. Thes , together with the Chara fragments, suggest a fresh or brackish water environment. The development of small amounts of possibly authigenic glauconite may, perhaps, indicate brackish conditions, as glauconite is normally associated with more marine environments (Cloud, 1955). This environment would indicate that much of the micrite in the rocks was derived from shell comminution or abrasion, though the presence of the rare Chara also indicates some algally produced mud to be likely as well.

(d) Petrology of pelecypod limestones

(i) Petrography. -

This group consists of rocks with abundant brown, pleochroic pelecypod shell fragments in either a micrite matrix or a granular calcite cement (figs. 94, 96).

The rocks with micrite matrix are firm and well-bedded, medium grey in outcrop. In thih section the micrite is seen to be variable in quantity, from as little as 5% by volume to as much as 50%. Generally it is a uniform grey, with grains of from 2-4 μ , but in places inclusions of larger crystals are common, yellow in colour. In addition, there are rare pellets and thin layers of brown micrite in which grains are less than 2 μ size, but these are not common. Occasionally the micrite grades into calcite-siltstone with grains of 6-10 μ . This is usually present in thin layers, perhaps where finer-grained material was winnowed away.

The shell fragments are almost entirely of pelecypods. They are usually broken and only rarely are whole valves or shells found - best seen in the hand specimen. Ostracod valves are also present, often pyritised, and whole, spar-filled shells occur in places. Rare fragments of <u>Ostrea</u> are recognisable by their lamellar structure, but all other pelecypods are mosaics of brown pleochroic calcite (fig. 95). Lines of small inclusions marking original shell structure are common in these mosaics. The ends of the shells are generally rounded, though a few angular pieces are also present. Some of the fragments are opaque having been replaced by very fine-grained pyrite or marcasite (fig. 96). Others, contain micrite-filled borings about 20 μ diameter which permeate the whole of the shell fragment.

Some pressure solution has occurred in these rocks as frequently shells can be found that have pressed into other fragments without breakage but with a loss of shell material

Fig. 95. - Photomicrograph of pelecypod fragments with micrite matrix. The mottled appearance of the shells is due to the patchy brown colour of their mosaic crystals.

Intermarine Beds. Durlston Bay.
Middle Purbeck.

Fig. 96. - Photomicrograph of brown coloured pelecypod fragments, some heavily pyritised, with a granular cement. The mottled appearance is due to the patchy brown colour of the mosaic crystals.

Intermarine Beds. Durlston Bay.
Middle Purbeck.

Fig. 97. - Pressure solution between two shell fragments. The smaller fragments are seen to have been pressed into the larger. It retains the micrite envelope thus indicating the original shape.

Intermarine Beds. Durlston Bay.
Middle Purbeck.


500µ
250µ

(fig. 97). This would indicate compaction prior to complete cementation. Angular to sub-angular quartz grains of up to 250 μ longest diameter are scattered throughout the beds, but are not abundant. Small collophane bone chips are also present. Common, too, in hand specimen, though rarely seen in thin section, is the light green glauconite-like mineral described previously (p. 160). This is very soft and is usually torn out of the thin section during preparation.

Beds with a granular calcite cement are blue-grey in outcrop and contain abundant blackened shells. The fragments exhibit the same features as in the rocks with micrite matrix, though they are more pyritic, and there is more variation in their size. In some beds the shell pieces are relatively large, up to 5-6 mm. long, though the ends are rounded. In other beds, however, particularly where quartz is common, the fragments are much smaller and may even be single crystals of 45-50 μ size, still strongly pleochroic. Quartz is generally more abundant in these beds and reaches 5% by weight in some cases.

The cement is a typical granular calcite, though the grains may be of small size (10-20 μ). The amount present varies considerably, and in some beds the shell fragments are so abundant and so well layered that it is hard to distinguish any cement.

(ii) Origin. -

The two rock types in this group differ only in their matrix, and this in turn reflects the presence or absence of currents during deposition, which periodically winnowed much micrite away. The abundance of pelecypods, and the rarity or absence of other groups of animals, is indicative of non-marine conditions. The pelecypods, though generally too broken to permit identification, appear very uniform in thin section, and this may itself be due to a restriction of the species present. Restriction of species and abundance of individuals is usually interpreted as indicating conditions other than normal marine such as saline, lagoonal or brackish (e.g. Beales, 1955). In the present case the occasional presence of Ostrea, and in places of recognisable valves of Neomiodon, suggest brackish-water conditions as being the most likely.

In general the shell fragments have a good planar orientation parallel to the bedding, and show relatively little evidence of disturbance. Such disturbance as is present affects only small areas and thin (½ cm.) layers, and may be due more to increased local turbulence than to scavenging. In any one bed the fragments are of much the same size, though there is considerable variation from bed to bed. Coarse detrital quartz grains, and the absence of micrite in some beds, show current action to have been appreciable at times. This all suggests that most of the shell fragments are current sorted, and mechanically deposited. The rarity of whole shells, and even of valves, supports the view that these are transported assemblages, not life ones.

At the same time, the common pyritisation of the shells could hardly have occurred if organic matter were not still present, and it appears unlikely, therefore, that the fragments were transported for long before final burial. Burial was then rapid enough for reducing conditions to develop below the sediment surface. This may account, too, for the formation of the glauconite. This is present as thin platy layers inside shell fragments, never as discrete grains. There is a rise in chlorinity of interstitial waters of a sediment (Shepard and Moore, 1955), and this, together with the presence of organic matter and reducing conditions (Cloud, 1955) might have been sufficient to allow its formation even if the depositional environment were not truly marine. It is, of course, possible that shells from a brackish environment were transported and deposited in a more marine one, but some evidence of a more marine fauna might then be expected.

The micrite matrix appears to have been largely derived by shell comminution, with some, perhaps, having been modified by faecal pelleting. Accumulation of shells must at times have been fairly rapid. This is indicated by the pressure-solution effects (p. 165) which show that a sufficient weight of sediment (shells) was available, prior to cementation, to cause solution. This is also indicated by the formation of reducing conditions in what was otherwise a high energy, and presumably well oxygenated environment.

XL. SCALLOP BEDS

(a) General Description

The Scallop Beds are a thin but distinctive group of limestones. They are 1.37 m. thick at Durlston Bay, 0.64 m. at Worbarrow Bay, 0.73 m. at Mupe Bay, 0.50 m. at Lulworth Cove, but are not recognisable at Ridgeway. The beds are well defined shell-limestones (biosparites and biomicrites). Cream, tan or grey in outcrop they are clearly differentiated from the beds below and above which are usually grey calcareous shales or micrites. The fauna is mostly of pelecypods, but here species are more numerous and several genera are present. They include Ostrea, Gervillia, Corbula and Protocardia. Small gastropods are also present, though rare, and include marine species such as Pachychilus manselli. Whole valves are often common, though complete shells are rare, while thin layers of finely comminuted shells separate the main beds, which are up to 65 cm. thick.

(b) Petrology

(i) Petrography. -

In thin section the Scallop Beds are very similar to the pelecypod-gastropod and pelecypod limestones of the Intermarine Beds. They are biomicrites and biosparites, but with no clear distinction between the two. Shells are mostly of pelecypods, and may vary from well-preserved valves down to small (50-100μ) fragments, though in any one bed the pieces are fairly well-sorted. Ostracod valves and fragments are quite common in beds where the pelecypod fragments are small, but are absent from beds made up of large pelecypod fragments and valves. Angular detrital quartz grains of 100-200μ size are also common in beds with smaller fragments. Shells are usually oriented parallel to the bedding. Ends are well rounded.

Pelecypod shells often have a thin (5-10μ) micrite envelope surrounding them and some contain micrite-filled borings, though this is rare. These shells are now calcite mosaics that show the characteristics of a drusy filling. In a few cases the micrite envelope has been broken by inward collapse evidently into a cavity (fig. 98). None of these micrites coated fragments shows any evidence of pressure-solution, unlike those without an envelope. Those latter consist of mosaics of patchily pleochroic brown calcite, often with thin lines of micrite inclusions indicating original shell structure. Here the effects of pressure-solution can be clearly seen where two fragments have pressed together (e.g. fig. 97). A few of these shells are pyritised, and some have an irregular, thin coating of golden-brown micrite, quite unlike a normal micrite envelope and this is possibly organic in origin. The colour is retained on acetate peels.

Micrite is present both as a matrix and as pellets and intraclasts. As a matrix it is a light to medium grey, and is rather inhomogeneous and patchy in appearance due to an irregular grain size. This varies from true mud-grade of 3-4 μ up to fine silt of 10-15 μ , occasionally larger. Pellets and intraclasts, on the other hand, are golden brown with grains of less than 2 μ. The pellets, which are about 50-100 μ diameter, are sometimes pyritised, and comparison with previously described forms (p. 91) suggests them to be faecal. The intraclasts often show internal structures such as superficial oolites, which have been truncated during the tearing-up process. They are most common where detrital quartz is abundant. A few shell fragments, too, appear to be intraclasts, containing gobbets of micrite in the concave part of the shell.

Calcite spar in the biosparites is a typical granular cement. It is best developed in those thin (5-10 cm.) beds where quartz is common (up to 5% by weight) together with small angular pelecypod fragments, ostracods and intraclasts. These thin layers separate the thicker beds with large shells, and seem to represent periods of much greater current activity.

(ii) Origin. -

The chief differences between these limestones and those of the preceeding Intermarine Beds, are the more marine nature of the fauna, and its better preservation. Although complete shells are rare, whole valves are abundant and well preserved, and it seems unlikely that they can have undergone much transport and that they are essentially autochthonous. Some scavenging is indicated both by the micrite filled borings in shells, and by the micrite (faecal ?) pellets, but the planar orientation and lack of angular edges of the fragments indicate that this was not extensive. Most shell breakage, therefore, is likely to have been caused by wave or current action, the presence of which is shown by the detrital quartz and intraclasts. Periods of diminished currents are indicated by the presence of micrite matrix. Pressure solution and pyritisation show that deposition was rapid at times.

The similarity to groups (c) and (d) of the Intermarine Beds suggests comparable depositional environments, modified only by the higher salinity and by less transportation of the shells. These beds may, in fact, be the offshore equivalents of Intermarine Beds that formed under the influence of lowered salinities closer to land.

XII. CORBULA BEDS

(a) General Description

The Corbula Beds are a heterogeneous sequence of shelly limestones (biomicrites and biosparites), calcite-mudstones, calcareous shales and calcareous-sandstones. They have a maximum thickness of 11.82 m. at Worbarrow Bay, and are 10.92 m. at Durlston Bay, 5.73 m. at Mupe Bay, 4.84 m. at Lulworth Cove and 5.62 m. at Ridgeway. Faunally they are, perhaps, the most interesting of the Purbeck sub-divisions, containing abundant Corbula, together with Pecten, oysters (? Ostrea) and other unidentified pelecypods. In addition, marine gastropods such as Pachychilus and Promathildia are locally common, and species of Hydrobia are often abundant.

The beds are dark grey and often iron-stained, with the limestones standing out from the intervening weathered and usually covered shales. Near the base of the sequence quartz sand is common, and one bed of calcareous-sandstone (DB 63, WB 100, MB 37, LC 65, fig. 14) seems correlative throughout the coastal exposures, serving to illustrate that the greater thickness at Worbarrow Bay is largely due to an increased thickness of sediment at the base of the sequence. Of interest, too, is a 'graded' micrite found near the top of the Beds (DB 66, WB 113, MB 49, LC 73). Here, as in the Hard Cockle Beds (p. 88) a succession of thin (1-2 cm.) layers of pelmicrite gradually merge boundaries upward to produce a uniform mudstone. A sharp break then occurs and a pelmicrite layer follows and the sequence is repeated. As many as 18 such units have been seen in a bed 20 cm. thick.

Broadly speaking the beds may be divided into four main groups; micrites and pelmicrites, biomicrites, biosparites and calcareous sandstones, sandy limestones and shales. These show many of the characteristics of the Scallop and Intermarine Beds, but with modifications and differences.

(b) Petrography of the micrites and pelmicrites

(i) Petrography. -

These vary from almost homogeneous micrites to the 'graded' pelmicrites described above. In outcrop, the beds are blue-grey, and up to 40 cm. thick. In thin section they are medium to dark grey depending on the grain size. This is variable from true mud-grade of 2-5 μ up to a fine silt of 6-10 μ . Very fine (4-10 μ) opaque specks, possibly pyrite or marcasite, are disseminated throughout. Calcispheres of 30 μ diameter are also quite common, and thin shell fragments and small spar or micrite filled ostracod shells may also be present. Where these are more abundant a few angular pelecypod fragments and rare, very thin-shelled valves may be present. Silt-size (20 μ) quartz grains may occur throughout this micrite, but are more usually found in thin (50 μ) laminae.

Pellets of 90-150 μ diameter are usually present even in the more homogeneous micrite, but more commonly occur in layers. They are frequently pyritised or are often much denser and darker grey than the matrix. Elongate, with length-breadth ratios of 2 or 3 to 1, many pellets have been partly flattened in the plane of the bedding. This ultimately led to the formation, by merging, of almost uniform micrite which, however, still retains a faintly clotted appearance. Merging of the pyritised pellets probably accounts for the disseminated opaque specks. There is a variable amount of argillaceous material in the beds, but it is always less than 5% by weight.

(ii) Origin. -

There is no indication from the fauna that salinities in the Corbula Beds were ever greater than, if as high, as in normal marine conditions (35-36‰). Gypsum or salt pseudomorphs are lacking where dessication-cracked surfaces occur, even though they might be expected in these circumstances. The dessication cracks do show that at times evaporation was sufficient to cause surface drying, and some mud may possibly have been produced by physico-chemical precipitation during this evaporation. In general, however, the abundance of fauna and lack of dessication features would seem to preclude the probability of much precipitated carbonate mud being formed. Plants, too, may have contributed to mud formation, but evidence is lacking, and it appears, therefore, that most of the fine-grained carbonate was derived by shell disintegration and comminution.

A transition from well-formed micrite pellets, through flattened pellets to vaguely clotted mudstone frequently occurs, and there seems little doubt that much of the micrite was at one time pelleted. This pelleting, apparently faecal, has destroyed most of the evidence regarding the origin of the mud.

It is probable that mud and fine silt-size carbonate grains derived from shells was winnowed away by gentle currents to accumulate in less turbulent areas, where a bottom dwelling fauna caused pelleting and further loss of structure. Rapid burial resulted in pyritisation of pellets, and cyclic variation in the environmental conditions seems to be responsible for the gradation of pellets to uniform mudstone.

(c) Petrology of the biomicrites

(i) Petrography. -

The biomicrites are of two basic types that depend on the mode of preservation of the shells. These consist mostly of pelecypods, but with gastropods sometimes common and with rare ostracods, in a matrix mainly of micrite or calcite-siltstone, but at times with a granular cement also present. The micrite is generally uniform and grey in appearance but with some inclusions of single calcite crystals 20-30 μ size, and occasionally contain small brown micrite-pellets. Grain size is variable from 4-10 μ, grains being irregular in shape but with plane boundaries. In general, therefore, it is similar to the micrite described in the previous section (b).

Pelecypod shells are preserved in two ways. In the first, fragments have a thin micrite envelope (fig. 99) which is much darker and finer-grained than the matrix. The envelope surrounds the shell fragments except in the few cases where the end of the fragment is angular; mostly, the ends are round. In places the envelope has been broken as if by inward collapse (e.g. fig. 98). The shells are coarse mosaics of calcite, mostly showing typical drusy features. In a few instances, however, inclusion lines show relict shell structure and here, calcitisation seems to have occurred in place , even though the pleochroism usually associated with this phenomenon is not developed. Fragments are of all sizes up to whole valves 1-1½ cm. long which are common in some layers. Very rare pieces of <u>Ostrea</u> or <u>Pecten</u> can be seen which show their original lamellar

Fig. 98. - Photomicrograph of pelecypod shells with micrite envelopes. The envelope under the cross-wires has broken and partly collapsed, believed to be indicative of solution of the original aragonite shell.

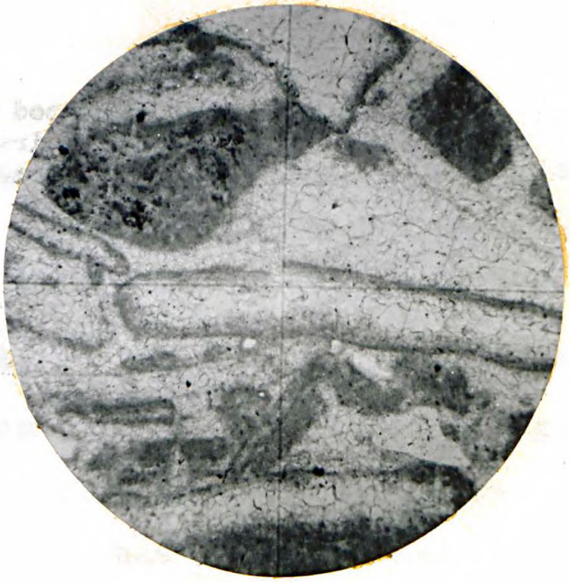
Scallop Beds. Lulworth Cove.
Middle Purbeck.

Fig. 99. - Photomicrograph of pelecypod fragments and shells in a micrite matrix. Most of the fragments appear to be worn and abraded and most are drusy mosaics. The large valve in the centre, however, shows faint inclusion lines and is an in place calcitised shell.

Corbula Beds. Worbarrow Bay.
Middle Purbeck.

Fig. 100. - Photomicrograph of an in place calcitised shell, the crystals of which are outlined by pyrite. This indicates that calcitisation occurred early in diagenesis, in this instance.

Corbula Beds. Durlston Bay.
Middle Purbeck.


500 μ


250 μ


500 μ

Fig. 101. - Incipient development of 'beef'. Small pillar-like calcite crystals have developed between shell fragments and forced them apart.

Corbula Beds. Durlston Bay.
Middle Purbeck.

Fig. 102. - Pelecypod valves and fragments that are intraclasts and contain attached gobbets of micrite (dark grey). Micrite pellets and lumps, some quartz grains and a granular cement. Shells and pellets are partly pyritised (black).

Corbula Beds. Lulworth Cove.
Middle Purbeck.

Fig. 103. - Quartz grains and ostracod fragments in a granular cement. The quartz grain under the cross-wires has been partially replaced by calcite.

Corbula Beds. Worbarrow Bay.
Middle Purbeck.


500 μ


500 μ


500 μ

structure.

The second state of preservation of the pelecypod shells is similar to that described for some of the Intermarine Beds (p. 164). The fragments show brown pleochroic mosaics of calcite, with relict shell structure preserved, and must have been calcitised without a solution stage. Although the fragments in both cases have a general planar orientation parallel to the bedding, it is often somewhat disturbed and irregular. The occasional angular edges indicate that this disturbance was due to scavengers, as currents would have removed much of the micrite matrix.

Some of the shells are pyritic. Often the pyrite is concentrated along an edge, but is usually disseminated throughout the fragment. Pyritisation must have post-dated alteration of the shell structure, as the pyrite is sometimes concentrated along the boundaries between the crystals of the mosaics (fig. 100).

Gastropods are recognisable as micrite or spar-filled body-chamber casts. The shell walls are now typical drusy mosaics. Most of the gastropods are broken, but a few are complete.

Quartz grains of 30-50 μ size are scattered throughout, and yellow, isotropic bone fragments are common.

(ii) Origin. -

These rocks are generally ill-sorted with every gradation from micrite up to complete valves of shells present. The presence of these unbroken valves in some abundance implies that many of the shells may be at or close to their life environment. At the same time, the well rounded fragments also suggest that abrasion was often effective, as rounding of shells appears to require turbulence (Houbolt, 1957). Such granular cement as is present in these rocks is found where the fragments are smallest and most abraded, as might be expected if turbulent conditions existed to winnow away any micrite.

It appears, therefore, that somewhat variable conditions prevailed during the formation of these beds. Generally quiet and non-turbulent, the fauna accumulated at or near where it died in a micrite matrix which, like that described in section (b) , would seem to have been derived largely from shell disintegration. Periodic turbulence broke and rounded shells and removed much micrite, while disturbance by scavengers, though rare, helped to produce a 'mixed' and poorly sorted rock. Deposition appears to have been rapid at times, allowing reducing conditions to form below the sediment surface, and resulting in the formation of pyrite.

(d) Petrology of the biosparites

(i) Petrography. -

As in the biomicrites, there are two distinct types of biosparite. The first consists of pelecypod valves and fragments having strong brown pleochroism. These are often densely packed one on the other with a consequent reduction in the amount of granular cement. The shell mosaics are coarsely crystalline with relict shell structure well preserved in places indicating recrystallisation in place. A few shells are completely pyritised but this is rare. More commonly, pyritisation is patchy and seems to follow original shell structure rather than the recrystallised mosaic. Coarse quartz grains of 200-300 μ size are scattered throughout. They are mostly sub-round or round, though not spherical. Yellow bone fragments, too, are fairly common.

A few beds can be seen in which there is an incipient development of 'beef' (Richardson, 1923), that is, an arrangement of calcite prisms or crystals with long axes normal to the bedding or, in this case, to shell fragments. The crystals are from 50-300 μ long and 10-50 μ wide. Here, they seem to have developed from the surface of thin and often pyritised shell fragments, and, in some cases, appear to have broken shells or forced them apart by growth from the centre of a fragment (fig. 101). This could not have occurred in a rigidly cemented fabric and the development of 'beef' here may be an early diagenetic effect. Associated with the 'beef' is a soft, green, isotropic mineral similar to that seen in the Intermarine Beds (p.160) and perhaps a form of glauconite. It is found as small irregular lumps, and also along the boundaries of beef crystals and is thus seen to post-date beef formation.

The second type of biomicrite consists of shell fragments that are intraclasts. They may be colourless drusy mosaics, or mosaics of pleochroic calcite recrystallised in place, but most are enclosed within, or contain attached gobbets of, grey-brown micrite that may itself contain smaller shell fragments (fig. 102). The pieces are well rounded and many of the smaller (300-500 μ) fragments have a thin (10 μ) coat of light yellow calcite, possibly oolitic or perhaps algal. Pelecypods and gastropods are present, and whole valves are common with complete shells not infrequent. Many of the fragments are pyritic. Coarse quartz grains of 250-300 μ size are scattered throughout, rounded but not spherical, but a few have overgrowths giving angular shape. The cement is typically granular but with some inclusions of single crystals derived from shells, as shown by their pleochroism.

(ii) <u>Origin</u>. -

The granular cement and coarse quartz grains in these rocks seem to indicate deposition conditions in which currents were continually effective, preventing deposition of micrite.

The biosparites are, in effect, coquinas, accumulations of current sorted and deposited pieces. Accumulation must have been rapid at times, so that reducing conditions were developed locally beneath the sediment surface and some of the shells pyritised. Here, pyritisation appears to have mostly occurred before calcitisation of the shells. Lack of identifiable shells in the beds precludes estimation of salinity from the fauna, but the post-depositional development of glauconite-like mineral suggests that salinities could not have been far removed from normal marine.

The intraclast-biosparites clearly appear to be derived from normal biomicrites previously described (p. 178). They represent accumulations of fragments and lumps torn up from semi-consolidated biomicrite during, presumably, periods of stronger turbulence. The development of thin oolitic coats on some of the fragments points to continued agitation in waters saturated with calcium carbonate.

(e) Petrology of calcareous sandstones, sandy limestones and shales

(i) Petrography. -

The calcareous sandstones contain from about 50-55% by

Fig. 101. - Incipient development of 'beef'. Small pillar-like calcite crystals have developed between shell fragments and forced them apart.

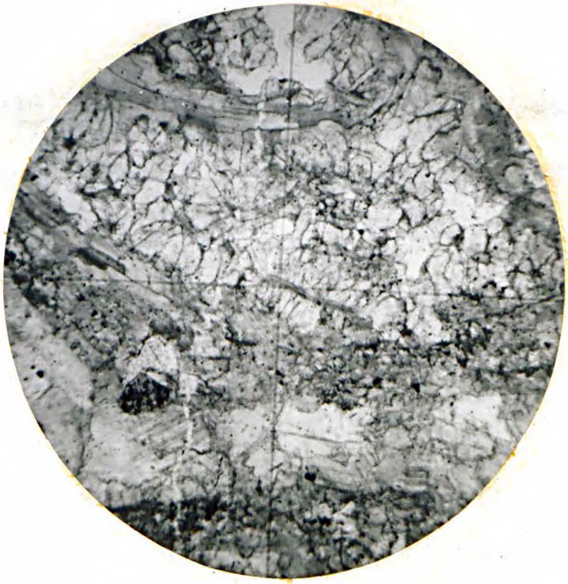
Corbula Beds. Durlston Bay.
Middle Purbeck.

Fig. 102. - Pelecypod valves and fragments that are intraclasts and contain attached gobbets of micrite (dark grey). Micrite pellets and lumps, some quartz grains and a granular cement. Shells and pellets are partly pyritised (black).

Corbula Beds. Lulworth Cove.
Middle Purbeck.

Fig. 103. - Quartz grains and ostracod fragments in a granular cement. The quartz grain under the cross-wires has been partially replaced by calcite.

Corbula Beds. Worbarrow Bay.
Middle Purbeck.


500 μ


500 μ


500 μ

weight of quartz. Grains are well-sorted with a median size of about 150-200μ. They are generally sub-angular but many grains have been replaced by calcite (fig. 103) so that the shape is not a primary feature. Most grains are clear, but a small percentage are filled by minute dark, unidentifiable inclusions. Heavy minerals present include stable forms such as tourmaline, zircon, kyanite, garnet and rutile. In the main sandstone bed near the base of the sequence there is a slight but distinct decrease in the quartz content from west to east, 56% by weight at Lulworth, 54% at Worbarrow and 52% at Durlston Bay. Also present are small shell fragments, mostly pleochroic, that are most abundant in the bed at Lulworth Cove. The cement is granular calcite.

There are all gradations from calcareous sandstone to sandy limestone with about 25% by weight of quartz, and to beds in which thin sandy laminae with granular cement alternate with micrite. The main difference is in the increase of shell debris and decrease in the amount and size of the quartz detritus, the grains of which generally average 80-100 μ diameter. Shell fragments may be ostracods, or pelecypods which are both pleochroic and drusy mosaics, the latter more commonly being associated with the micrite layers.

At Durlston Bay about a quarter of the sequence is formed of dark grey to black clay shales. These decrease in importance to the west and are almost absent from the sections at Mupe Bay and Lulworth Cove. They are mostly covered and much weathered. The shales are finely laminated. Some layers are crowded with well preserved ostracods; others contain crushed pelecypods that retain a white nacrous appearance and are still aragonite (stain test). Excluding shell material, the shales contain very little calcium carbonate (about 1-2%). They consist of terrigenous clays and fine quartz silt, with a little organic matter. Small crystals of selenite are abundant in places, probably formed from iron sulphide in the shale.

(ii) Origin. -

The calcareous sandstones and sandy limestones, formed by influx of detrital quartz grains, are indicative of periods during which the deposition of coarse terrigenous sediment overshadowed the chemical and biochemical accumulation of carbonate. Shales, on the other hand, represent periods during which little carbonate at all was formed and fine grained, land derived sediment alone accumulated. The fine lamination of the shales shows a lack of disturbance by burrowing organisms, perhaps due to stagnant bottom conditions. Undisturbed micrite bands in the sandy limestones also show lack of scavenging, and indicate that the shells in these rocks are not autochthonous, but that they accumulated with the quartz grains - as detrital particles.

The upward increase in terrigenous sediment in the Corbula Beds may well represent an initial phase in the development of Wealden-type sedimentation. A decrease in the quartz content, and the increase in the amount of finer-grained material from west to east, suggest a westerly origin for this sediment, though lack of north-south control (as in the Hard Cockle Beds, p. 97) makes this only speculative. Work on the Wealden (Bathurst, 1953, Allen, 1959) has shown a westerly source for much of the Wessex Wealden sediment, and this may well have been initiated in late Purbeck time. The earliest Wealden sediments in this area (Dorset) are muds and fine sands, which at first alternated with periods of limestone deposition (Bathurst, op. cit., p. 99), conditions apparently little different from those prevailing at times in the Corbula Beds.

XIII. CHIEF BEEF BEDS

(a) General Description

This is the topmost division of the Middle Purbeck. 8.32 m. thick at Durlston Bay the beds thin to 5.48 m. at Worbarrow Bay, 1.97 m. at Mupe Bay, 2.85 m. at Lulworth Cove and 1.36 m. at Ridgeway.

As the name implies, a feature of the sequence is the presence of bands of 'beef', or fibrous calcite (fig. 104). These are up to 20 cm. thick at Lulworth, where they are best seen. Cone-in-cone structure is well developed. The beds are alternations of dark clay shales, much covered and weathered, 'beef' bands and thin, hard, shell-limestones. These latter are sometimes cross-bedded (fig. 105) and have ripple-marked surfaces. They are darker coloured than in the Corbula Beds, and all are biosparites. Thin layers of 'perished' pelecypod shells occur in the shales, and ostracods are abundant.

In Durlston Bay the section is much covered as shales make up about ¾ of the sequence. These are less in amount relative to the limestones in the other localities, though at Mupe Bay and Lulworth Cove the beds are disturbed by folding and are again poorly exposed.

Fig. 104. - Layers of fibrous calcite, or 'beef'.

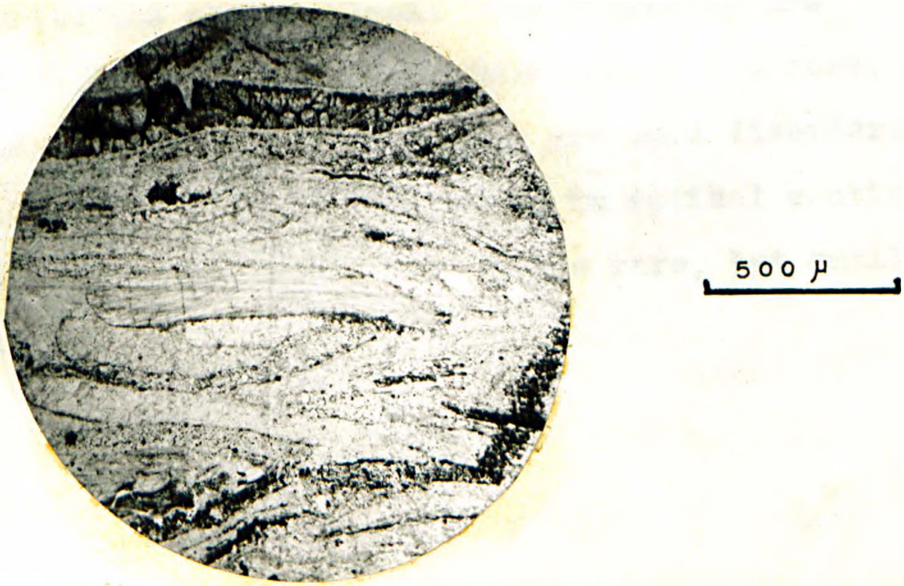
Chief Beef Beds. Mupe Bay.
Middle Purbeck.

Fig. 105. - Small scale cross-bedding in shell limestone.

Chief Beef Beds. Worbarrow Bay.
Middle Purbeck.

Fig. 106. - Photomicrograph showing small Ostrea fragment with its lamellar structure surrounded by pelecypod fragments with, in this case, in place calcitised mosaics. Note how the pyrite outlines the mosaic crystals of the large fragment at the top and compare with figure 100.

Intermarine Beds. Durlston Bay.
Middle Purbeck.


500 μ

(b) Petrology of the biosparites

(i) Petrography. -

There are two main types. One, in which pelecypod fragments are abundant, and the other with ostracods as the chief fauna. The pelecypod biosparites are very similar to those of the Corbula Beds (p. 181) consisting of closely packed shells and fragments with a granular calcite cement. The shells are 'in place' calcitised mosaics with and without brown pleochroism, but with inclusion lines showing original structure. Micrite envelopes often outline the fragments which are sometimes pyritic, the pyrite generally outlining the mosaic crystals and therefore post-dating the calcitisation. Shell fragments generally have round ends, and are well oriented parallel to the bedding. Shell size varies from bed to bed, but is relatively uniform within each bed.

Ostracods are present as whole, spar-filled shells, valves and fragments. Slightly yellowish in thin section, some of the fragments are pyritic and appear black. The fragments are oriented parallel to the bedding where whole shells are rare; where whole shells are common the fragments are more disordered. The shells are filled by spar which is often in optical continuity with the prisms of the shells. Quartz is rare, but small bone chips are common.

(ii) Origin. -

Both kinds of biosparite accumulated rapidly under conditions of gentle current activity. Currents are indicated by the absence of micrite or silt, and also by ripple-mark commonly associated with these limestones, but they were evidently insufficient to transportmuch quartz detritus. Rapid accumulation is shown by the pyritisation, indicative of anaerobic conditions and organic matter below the sediment surface. The pelecypods are, for the most part, too fragmentary to permit identification, though in the shales there are shells of Neomiodon. Ostracods are species of Cypridea which include C. granulosa. These are indicative of predominantly fresh or brackish water conditions. The variations from pelecypod to ostracod limestone reflects local differences in environment, and to some extent, perhaps, sorting of shells by currents.

(c) Shales and 'Beef'

Shales are insufficiently exposed and too highly weathered for adequate sampling and examination. They appear to be similar to those described in the Corbula Beds (p. 184), that is, containing very little carbonate other than as shell fragments. Unlike the Corbula Beds, no coarse quartz detritus is present.

The shales are again thickest in the eastern part of the area.

Formation of 'beef' and cone-in-cone structure is described by Richardson (1923) from the Lias, who ascribes it to growth of calcite along planes of rupture, the crystals growing outwards in both directions from the plane. He attributes the development of cone-in-cone structure to the stresses set up during the growth of the calcite fibres. Planes of rupture from which growth commenced here must have developed prior to the main tectonic movements, as the beef layers are folded and in places faulted. It is possible that they formed during the intra-Cretaceous movements which, in the coastal areas at least, were of a relatively mild nature.

XIV. DIAGENESIS

(a) General

Diagenesis is here taken to include both the processes leading to lithification of a sediment, and those later changes that take place within the sediment at relatively low temperature and pressure. Problems concerning such aspects as compaction, cementation, pyritisation and silicification, have been discussed as appropriate in the sections on petrology (e.g. P. 56,73,83). One of the most interesting problems has only been mentioned briefly, and concerns the preservation and alteration of shell fabrics. Shells that were originally calcite (e.g. Ostrea, Pecten) retain their prismatic or lamellar structure and are essentially unaltered except for occasional silicification (fig. 106). In rare cases, too, aragonite shells are found unaltered in layers of impervious calcareous shale. These two cases are not considered further here. There are two remaining types of shell fabric found in the Purbeck rocks. They are: mosaics of drusy calcite, and mosaics of calcite or aragonite containing lines of inclusions that mark original shell structure. The crystals of this latter mosaic are frequently brown and pleochroic.

(i) Drusy shell mosaics. -

These are calcite casts, filling cavities left by solution of an original aragonite shell. They are generally found in the biomicrites, but when seen in biosparites are always surrounded by a thin micrite envelope, or dust line. The calcite mosaics show most of the criteria listed by Bathurst (1958) as characteristic of drusy growth. In particular, they show uniformly extinguishing grains whose intergranular boundaries are regular plane interfaces (fig. 107 A). There is generally an increase in grain size inward from the margin, but sometimes single crystals extend from one wall to the other. No original shell structures are preserved.

The fabric criteria leave little doubt that these mosaics are cavity fillings, further evidence for which is supplied by the common inwards fracture of the micrite envelope, suggesting collapse into a cavity (Mr. R.G.C. Bathurst, personal communication).

In biomicrites, solution of the aragonite must have occurred after at least partial lithification, as the borders of the cavity are sharply defined, and could hardly have been preserved had the sediment been unlithified. Breakage of the micrite envelopes in biosparites is usually attributable to another fragment (of shell, or an oolite, etc.) having been pressed against it. This could not have occurred in a rigidly cemented mosaic, and aragonite solution must here often have occurred prior to complete cementation. It seems likely, therefore, that solution of aragonite shells was an early diagenetic phenomenon.

(ii) Pleochroic shell mosaics. -

This second type of shell mosaic first becomes apparent only in the Middle Purbeck (it is also present in the Upper Purbeck). Crystals forming the mosaic may be roughly equant or columnar but are often of very irregular shape. They vary from about 10-350 μ in size, though columnar grains may reach nearly 500 μ length and often show a preferred orientation with the long axis normal to the shell walls. As in drusy mosaics, the smallest grains are often found along the margins of the shell wall, but there is a distinct difference in the intergranular boundaries. Plane boundaries are uncommon, and the grains have characteristically irregular outlines that appear curved, consertal, or made up of short straight lines. Figure 107 B. is a camera lucida drawing that illustrates these boundaries and compares them with those of a drusy mosaic (fig. 107 A).

In ordinary light the mosaic crystals vary from colourless to medium brown, and in polarised light these brown crystals are strongly pleochroic from pale straw to dark brown, with maximum pleochroism in the E - W position. The pleochroism may be localised, even within a single calcite crystal, a part of which may be colourless, and a part dark brown.

Common, too, in these mosaics, are lines of small inclusions which appear to outline original shell structure, and

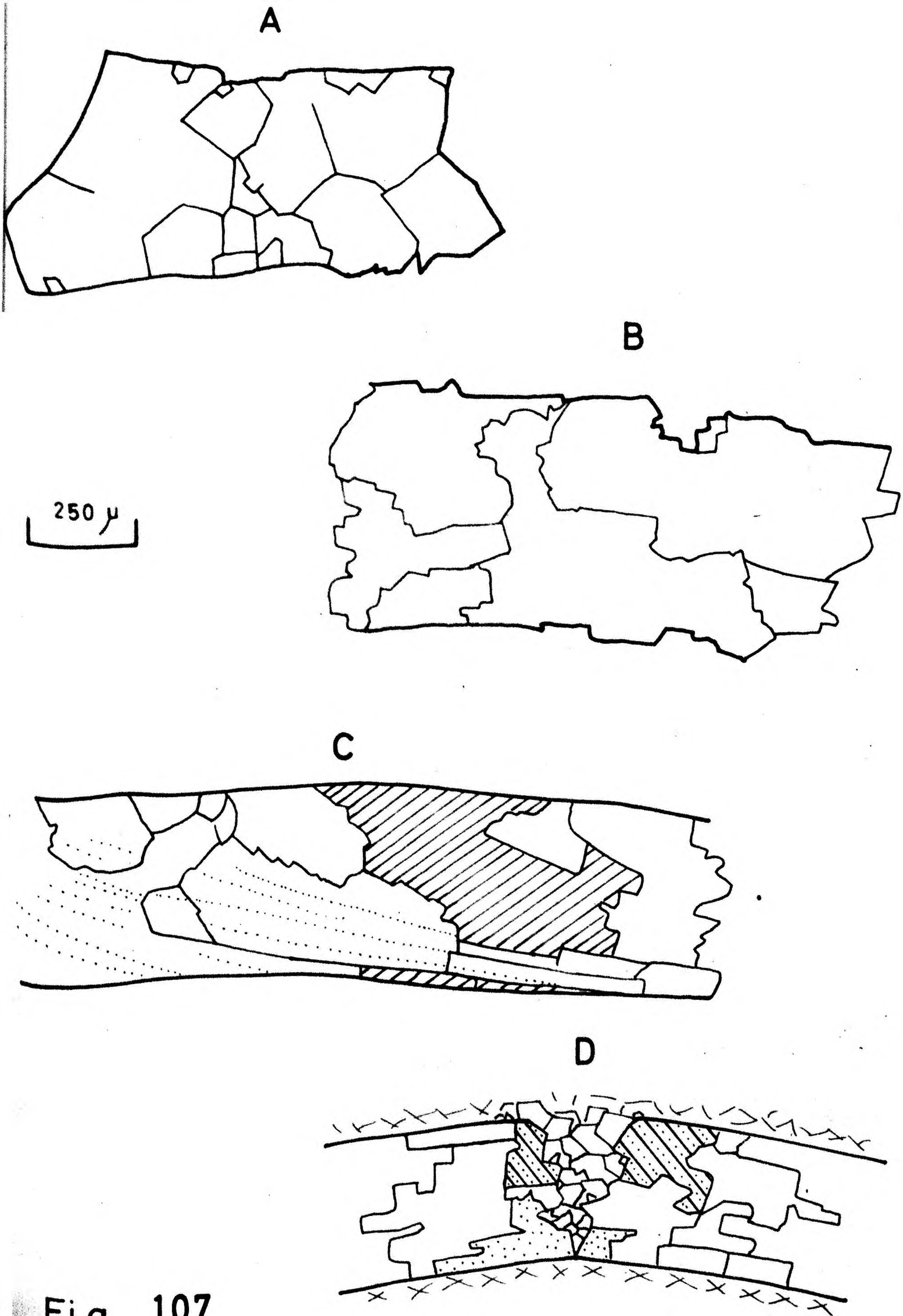


Fig. 107

upon which the anhedral crystal mosaic is superimposed (fig. 107 C). This phenomenon has been commented upon by Nelson (1959, p. 66) who cites it as evidence that the shell has undergone a solid state recrystallisation from aragonite to calcite. That is, no solution stage occurred. It is significant that this mosaic is found only in originally aragonite pelecypods and gastropods, never in ostracods, or in calcite pelecypods such as <u>Ostrea</u>.

Although this mosaic is usually of calcite, one specimen examined, that shows similar features, was found by stain tests (confirmed by X-ray) to be still mostly aragonite. Here, therefore, seems to be a half-way stage in the development of the mosaic. The original aragonite shell with prismatic or lamellar structure, changed to an anhedral aragonite mosaic which subsequently became calcitised. No solution stage occurred, and though this type of mosaic is often devoid of a micrite envelope, in those cases where one does occur it is always entire, no evidence of collapse being present.

The cause of the brown colour is not clear. According to Dr. J. Hudson (personal communication) it is related to minute inclusions within the calcite crystals. This is supported by the observations of Emery (1954, p. 223) who notes the occurrence of brown or yellow-brown calcite in sediments from the cores on Bikini atoll, and comments that under crossed nicols it contains "matted needle like birefringent crystals about 1μ long". He also records a brown lineation, parallel to shell walls but formed of interlocking, roughly parallel crystals perpendicular to the shell wall (op. cit., p. 231). Emery suggests, however, that the colour is due to a small percentage of organic matter in the shell.

The common association of pyrite with this mosaic suggested that the brown colour might be due to high iron content, and several thin sections were treated with potassium ferricyanide in 1% HCl. Most of the brown shell fragments stained to a dark blue showing the presence of iron. Granular cement, ostracod shells and drusy mosaics remained unstained. Colourless calcite veins cutting some sections also stained blue, suggesting that the calcite in them was derived from iron rich shell fragments, while the granular cement was not.

Whatever the cause of the brown colour, it is significant that it first appears in the Marly Freshwater Beds and is present only in the Middle and Upper Purbeck, where brackish water conditions were so common, and it seems possible that the colour is related to factors such as the salinity at the time the shell was forming. However, further study is needed, particularly to determine the range of genera or species that show this colour: are they restricted, or is there wide variation?

Calcitisation generally seems to have occurred early in the history of the rock (the aragonite mosaic notwithstanding), certainly before final cementation, as a rule. This is shown by broken shells that have separate crystals on either side of the fracture that would be in optical continuity if reunited. The calcitisation evidently occurred prior to the fracture and hence prior to cementation, otherwise movement of the two parts would have been impossible (fig. 107 D.).

(b) Dolomitisation

No dolomite has been found in the Dorset Purbeck, and this is somewhat surprising in view of the environment proposed for the Lower Purbeck. It has recently been said, for instance, that " ... limestones closely associated with contemporaneous evaporite lagoons seldom escaped extensive dolomitisation" (Adams and Rhodes, 1960, p. 1913). Dolomite is present in the Purbeck of the Swiss Jura (Carozzi, 1948), and also the French Jura, though there dedolomitisation has often occurred (Shearman <u>et. al</u>., 1961). No evidence of dedolomitisation has been seen in the Dorset rocks, and it is considered as unlikely that any dolomite was ever present in them. It may be that there was insufficient magnesium, but this seems unlikely in view of the presence of high magnesian calcite in some of the algal beds (p. 11), and it is thought more probable that the evaporitic conditions did not persist long enough for dolomitisation to occur.

(c) Diagenetic History

It is now possible to give a somewhat generalised summary of the diagenetic history of these Purbeck rocks. Naturally, with varying conditions diagenesis proceeded differently from place to place, but none the less the following scheme is suggested as being generally applicable.

1. Deposition of the sediment.
2. (a) Modification by scavengers, formation of faecal pellets and of burrows. Infilling of some shells by sediment. Bahamite formation.
2. (b) Compaction, expulsion of connate waters and some pressure-solution as burial proceeds.
3. Commencement of pyritisation (p. 183).
4. Initial formation of granular cement rims in biosparites, partial lithification of micrites (p. 94).
5. (a) Solution of aragonite shells, breakage of micrite envelopes (p. 93), infilling of cavities by drusy calcite (p. 89).

5. (b) Calcitisation in place of aragonite shells (p. 196).
6. Further pyritisation, development of 'beef', formation of glauconite? (p. 179, 181).

   (3-6 probably more or less contemporaneous)
7. Final cementation, drusy infilling or most remaining cavities.
8. Epigenetic replacement of calcite by gypsum (or anhydrite) (p. 56). Deep burial.
9. Gypsum dehydrates to anhydrite. Folding and uplift.
10. Main period of silicification (p. 148).
11. Hydration of anhydrite to gypsum (p. 58).
12. Replacement of gypsum by calcite (p. 58).

XV. CONCLUSIONS

(a) Lower Purbeck

In previous sections (III - VII) various suggestions were made for the probable origin of the several rock types. These rocks have been described in detail and it is possible to place them into five broad groups that correspond approximately, but not absolutely, with the lithological sub-divisions of Bristow. These groups are here called:-

Algal facies
Bahamite* facies
Gastropod - pelecypod facies
Saline facies
Mudstone - shale facies

The algal facies at the base of the Purbeck represents a continued restriction of the Portland lagoon in which Solenopora had occurred in reef-forming quantities (fig. 108). Increased salinity generally limited the invertebrate fauna of the basal Purbeck, but was suitable for the growth of some carbonate precipitating and stromatolitic algae. A coast line close to the west of Portland and Portisham is indicated by the occasional presence of a brackish-water fauna in some of these algal beds, by the development at times of land surfaces in the western part

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*The term bahamite was introduced by Beales (1958) to apply to pellets and lumps of carbonate-mudstone, believed to be formed by accretion in the manner described by Illing (1954). It is, perhaps, an unfortunate term, as it necessarily implies a close comparison with Bahaman environments, which might not always apply. Nevertheless, it is retained, for the present, as comparison with the Bahamas has here been suggested (p. 70).

of the area, and by erosion of the topmost Portlandian on the Isle of Portland. The sediment filling the channel previously mentioned (p. 15 , fig. 4) contains not only derived Portland fossils, but also fragments of Chara, brought in, perhaps, by a freshwater stream from the west or south-west. Chara is also found in the basal beds at a higher horizon at Portisham (West, 1961).

Thickness of the algal beds shows optimum conditions of growth and preservation to have been in the Lulworth Cove - Mupe Bay area. The beds are thinner to the west, possibly because of lower salinity, and to the east because of higher salinity though other, local factors, such as clarity of the water would undoubtedly have been equally important in controlling algal growth. Nearer to the coast for example, it is possible that greater opacity of the water limited algal development even though salinity may have been optimum.

Published descriptions of the Purbeck beds once exposed in the Vale of Wardour (now mostly covered) and at Swindon, provide little information with which to compare the Dorset rocks. Woodward (1895, p. 269) remarks that the Lower Purbeck beds at Wardour "... resemble in some respects the lower beds at Lulworth Cove, and Worbarrow". The evaporite forms of ostracod 'Cypris' purbeckensis and 'Candona' bononiensis are recorded, however, suggesting that saline conditions were present, at times at least. The age of the Swindon Beds is controversial (see

Sylvester-Bradley, 1940). According to Anderson (personal communication) the beds represent only marine phases of the Middle Purbeck. Recently, West (1961) has cited evidence in support of a Lower Purbeck age for those beds. Both at Swindon and Wardour the thickness of the beds is much reduced from that of the main Dorset outcrops, and it does appear that they were situated not far from the border of the Purbeck (Wessex) lagoon.

The main Dirt Bed provides evidence of a land surface over much of the Dorset area. Although well developed at the centre of the Isle of Portland it thins and is absent at the south end of the island where sub-aerial conditions do not appear to have developed. It is also absent to the east of Worbarrow Bay. Figure 109 A. shows the distribution of the Bed and an approximate shore-line at this time. A return to algal lagoon facies followed the formation of the Dirt Bed, even-laminated stromatolites below and above it being indicative of tidal-flat environments.

Continued evaporation led to the development of saline conditions over much of the Dorset area. Replenishment of the water must have been continuous, however, as there does not appear to have been any lowering of water level and re-development of land surfaces, such as might be expected around the borders of an enclosed lagoon. Connection with the sea would therefore seem to be indicated - to the south? Actual evaporite deposition (anhydrite or gypsum) did not extend much to the west of Lulworth Cove, and increased in thickness eastwards. This saline phase was of relatively short duration but is important in providing an explanation for the origin of the Broken Beds (p. 21). Figure 109 A. summarises the information for the algal facies and first saline phase.

The succeeding bahamite facies was widespread. It is considered that at this time most of the Dorset area was a shelf that bordered a shallow saline lagoon, in the centre of which evaporites continued to form. Upon the shelf, physico-chemical precipitation of calcium carbonate mud occurred, which, owing to agitation of the waters, formed pellets and lumps in a manner similar to that on the Bahama Banks. Figure 110 shows such pellets from the bahamite facies at Portisham. They compare very closely with those from the Bahamas figured by Illing (1954, p. 34). This facies appears to have had its maximum development in the Worbarrow region, decreasing both to the west and east. The poor exposure at Durlston Bay limits recognition of the facies there, but similar beds are certainly present in the Arreton borehole, where they occur above a thick basal anhydrite, and are associated with epigenetic anhydrite replacement (see fig. 43).

Conditions necessary for the formation of bahamites seem to be relatively shallow, warm, agitated waters with salinities slightly higher than normal marine (Beales, 1958). High salinities are certainly indicated by replacement textures after anhydrite, and too, by the sparse fauna of this facies. Algae, however, continued to grow through their recognisable remains are not plentiful. There is no direct evidence as to the position of the coast line at this time. Ripple-mark in the Cypris Freestones from Durdle Door to Worbarrow Bay, if approximately parallel to the coast, show it to have been to the north west and west, but the exposures are really insufficient to justify any firm conclusions.

The period of bahamite formation on the Dorset shelf was ended by a lowering of salinity due, most probably, to influx of freshwater from the west. This is indicated by the appearance of detrital quartz in sediments west of Worbarrow Bay, quartz content increasing to the west. The lowered salinity enabled a gastropod and pelecypod fauna to establish itself. Brief periods occurred, however, during which bahamite conditions returned, but ultimately the gastropod-pelecypod facies - in which detrital quartz is common - spread over much of the Dorset shelf, and is present to a limited extent also at Arreton.

As described on pages 99-100, there is a distinct faunal

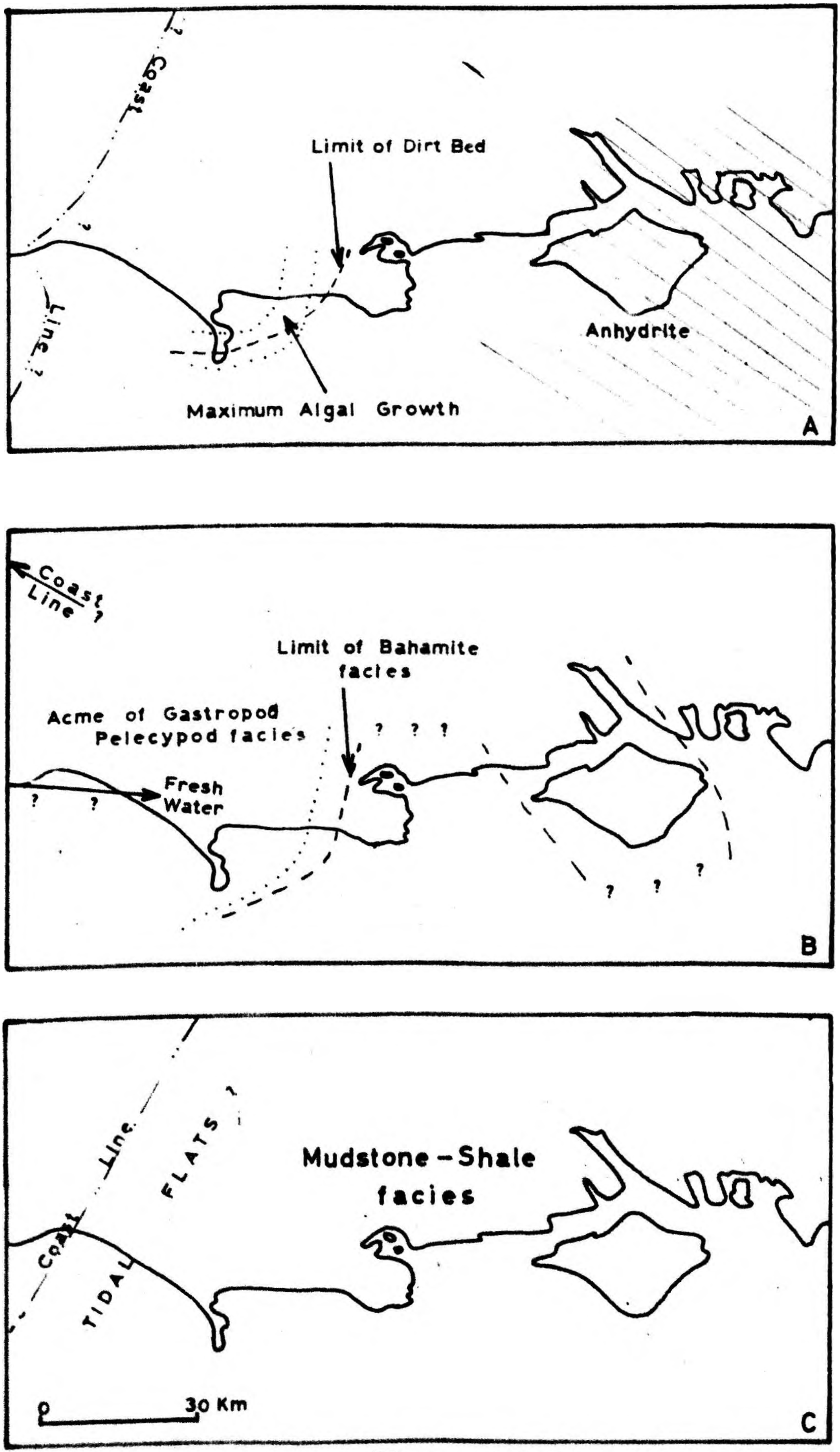

Coast Line ?
Limit of Dirt Bed
Anhydrite
Maximum Algal Growth
A
Coast Line ?
Limit of Bahamite facies
Acme of Gastropod Pelecypod facies
Fresh Water
? ? ?
B
Coast Line
TIDAL FLATS ?
Mudstone – Shale facies
0 30 Km
C

Fig. 109

difference between Mupe Bay and Worbarrow Bay. It was suggested that this was due to higher salinity in the east, and points to the freshwater as coming from the west. Figure 109 B. summarises information for the bahamite and the gastropod-pelecypod facies.

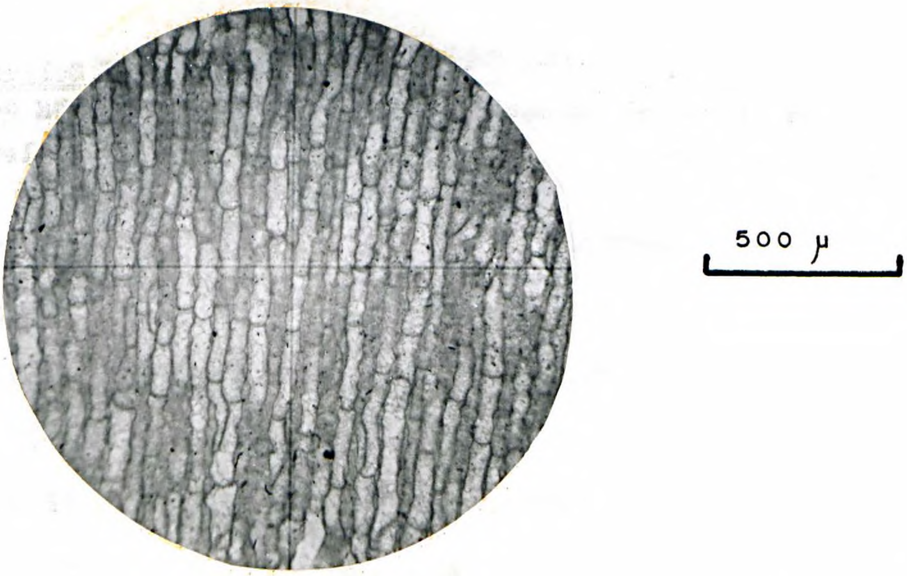
Maintenance of conditions suitable for an abundant fauna depended upon continued influx of freshwater from the west to counterbalance influx from the open sea, probably to the south or south east. When this freshwater supply ceased, then evaporation and concentration of the water led to the re-development of a saline facies. Carbonate precipitation was again widespread on the Dorset shelf but lack of agitation inhibited bahamite formation. Instead, calcite-mudstones formed, which were modified at times by the activity of a sparse fauna to produce pelmicrites. Locally, salinity was high enough to lead to the deposition of gypsum, as at Worbarrow and Durlston Bay. At times conditions must have closely resembled those of the Basal Beds, as Codiacean and stromatolitic algae are present, notably in the pellet beds (p. 114). These beds, which thicken to the west, are formed of fragments of either algal coated micrite, or stromatolitic lumps. Dessication cracks preserved in some of these fragments point to their origin on mud flats, probably tidal.

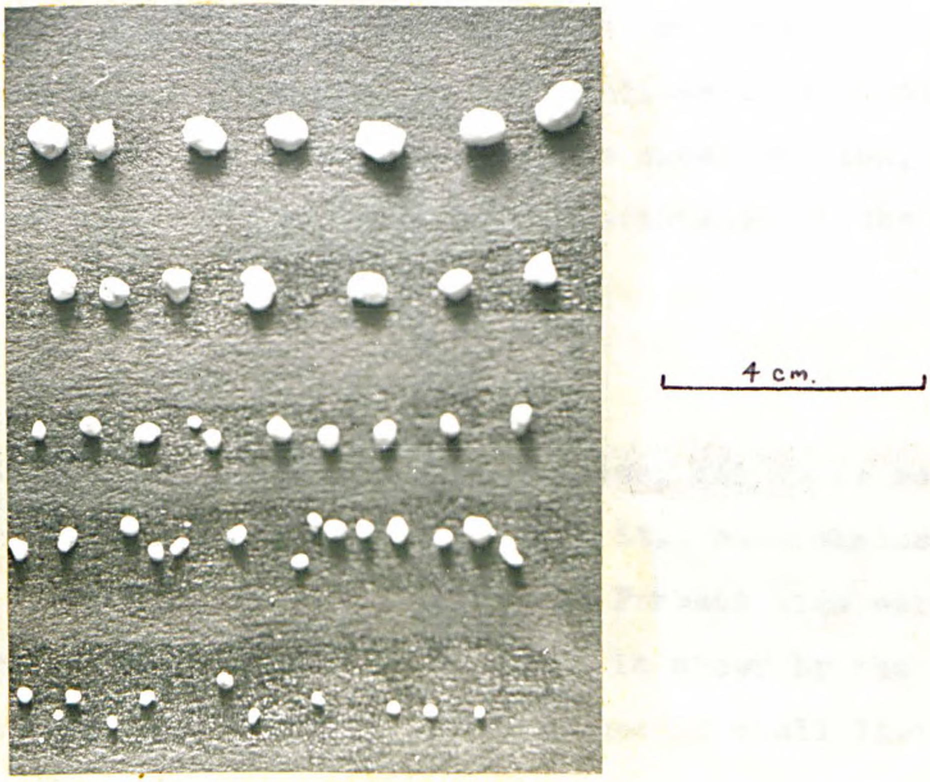
This second saline phase was ended by a lowering of the

Fig. 108. - Photomicrograph of a longitudinal section of Solenopora. Well defined walls of 'algal dust', with irregular but strong cross partitions.

Upper Portland. Durlston Bay.

Fig. 110. - 'Bahamite' pellets and lumps from the Cypris Freestones at Portisham. Compare with the photographs of Illing, 1954, p. 34.


500 µ


4 cm.

salinity which culminated in freshwater conditions over the whole of the Dorset area by the end of Lower Purbeck time. It seems likely that by this time contact with the sea had finally been broken, and that the Purbeck lagoon had become a freshwater lake in which the mudstone-shale facies was deposited. Figure 109 C. summarises the information for the mudstone-shale facies.

Figure 111 is a generalised cross section from Worbarrow Bay to the Lulworth Cove area and shows the overall relationship of the various facies in this region. Correlation to the east and west would be only tentative, but the five facies can be recognised at the various localities. Superimposed upon these main lithological units, which represent the response to major changes in environmental conditions, are small-scale variations due to local environment, not shown upon the cross section, and best studied, probably, by observation of variations in the ostracod species (see Anderson, 1932).

(b) Middle Purbeck

The Middle Purbeck is harder to summarise, for it is not as easy to recognise distinct facies within it. Nevertheless, it is evident that conditions during Middle Purbeck time were much different from those preceeding. This is shown by the large increase in the fauna, and the abundance of shell lime-

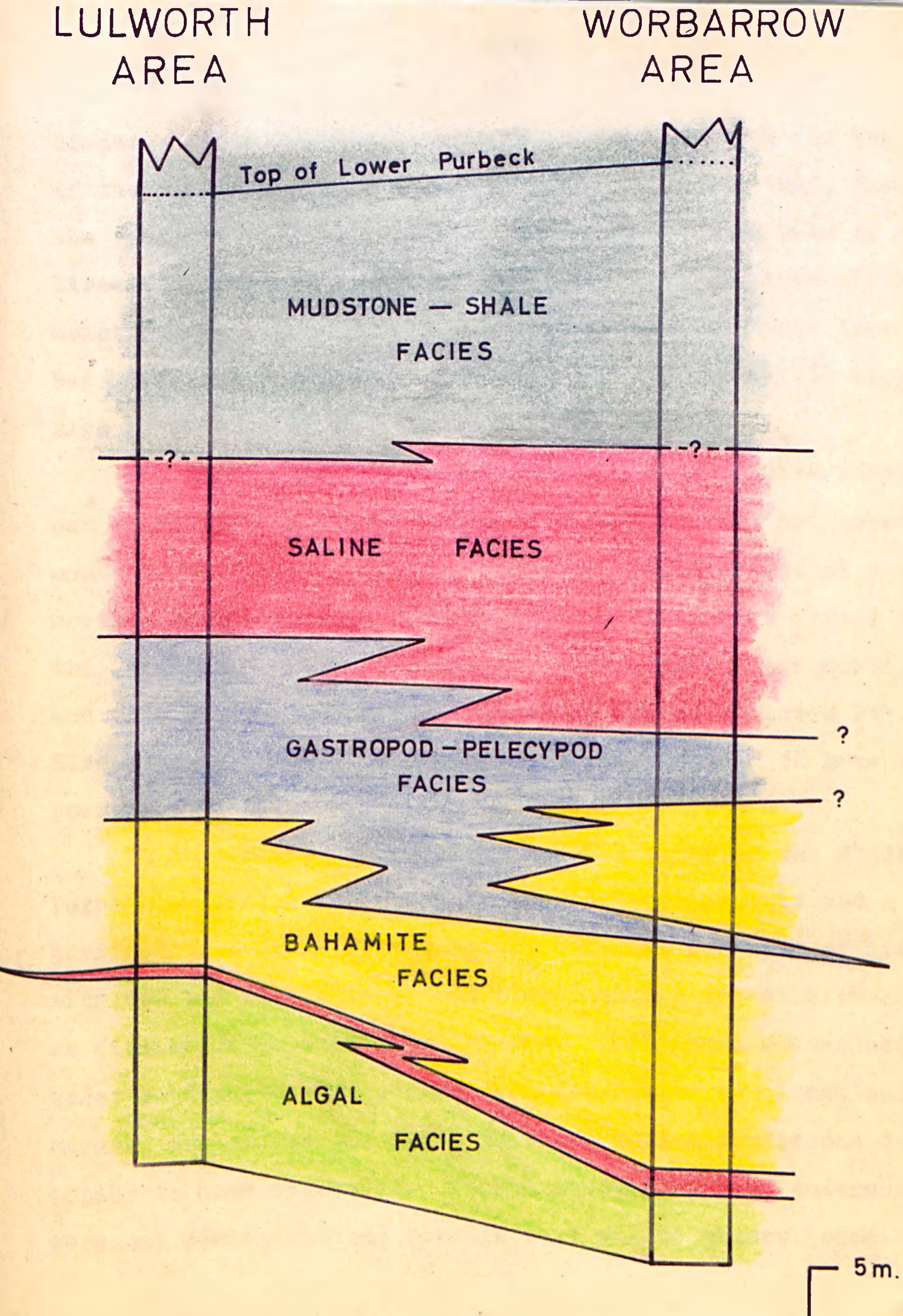

LULWORTH AREA
WORBARROW AREA
Top of Lower Purbeck
MUDSTONE — SHALE FACIES
-?-
-?-
SALINE FACIES
?
GASTROPOD – PELECYPOD FACIES
?
BAHAMITE FACIES
ALGAL FACIES
5 m.
0

Fig. 111

stones - so noticeably rare in the Lower Purbeck. At the base of the Middle Purbeck, however, below the Cinder Bed, save for the presence of <u>Cypridea granulosa</u> and some thin beds of shell limestone, conditions differed but little from those of the mudstone-shale facies of the Lower Purbeck and these lowest beds may well be grouped with that facies. Certainly they are also of freshwater origin, with <u>Chara</u> abundant.

The Cinder Bed was formed during a major marine phase that can be recognised throughout N.W. Europe (though not necessarily containing oysters), and marks the re-establishment of a connection with open sea. The phase appears to have spread into the Dorset area from the east, or more probably the south east, and true marine conditions reached as far as Durlston Bay. Elsewhere in Dorset, estuarine conditions appear to have been present.

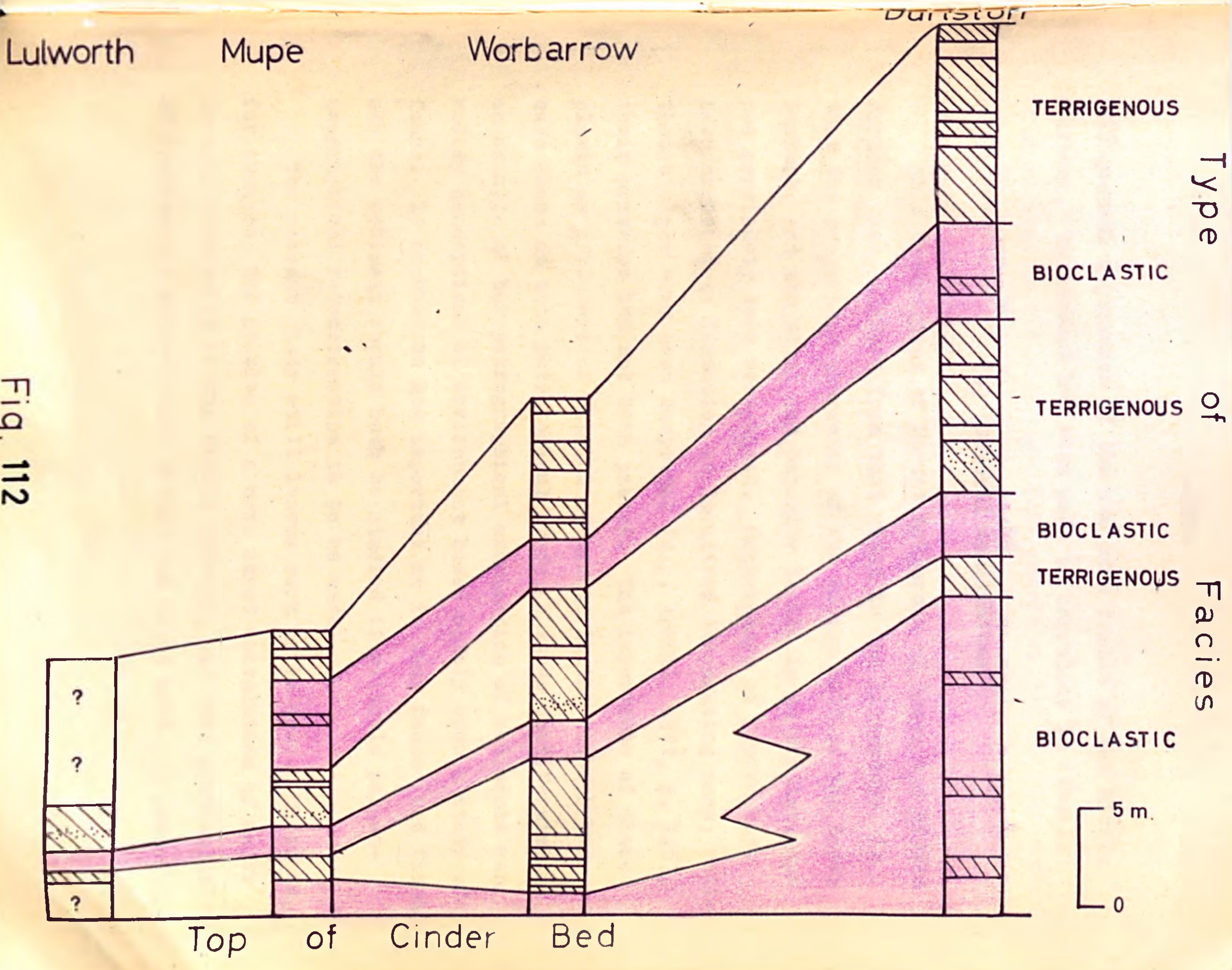
It is possible to consider the remainder of the Middle Purbeck as comprising two main facies, a bioclastic and a terrigenous facies. The bioclastic facies consists of biomicrites and biosparites, but also includes the calcite-mudstones - as distinct from calcareous shales. These beds accumulated under conditions that varied from freshwater to almost normal marine, but unlike the Lower Purbeck, saline conditions do not appear to have developed. Faunal study (Dr. F.W. Anderson, personal communication) reveals that marine phases (some of very brief duration) periodically raised the salinity of what was generally a brackish water environment in which pelecypods and gastropods were abundant.

The terrigenous facies includes the calcareous sandstones and shales and becomes increasingly important towards the end of Middle Purbeck time, and, as previously suggested (p.186), may well represent initial phases in the development of Wealden type sedimentation.

During much of Middle Purbeck time, conditions appear to have been closely comparable to, for example, some of the coastal lagoons of the Gulf Coast of the U.S.A. These lagoons are almost separated from the open sea by barriers, and salinity of the lagoonal waters depends chiefly on such factors as the rate of inflow of freshwater from streams, and on evaporation. Periods of drought lead to an increase in the salinity of the lagoons (sometimes as high as 40‰) and allow a marine fauna gradually to establish itself. Floods then cause a rapid lowering of salinity and mass mortality of the marine fauna (Parker, 1959, p. 2105). Cycles similar to this have been shown to occur at the base of the Middle Purbeck (Anderson, 1932) and may well have occurred throughout. There is no evidence here, however, that salinities ever increased to the extent recorded on the Gulf Coast.

Figure 112 is a diagrammatic cross-section to illustrate

Fig. 112


Lulworth
Mupe
Worbarrow
Durlston
?
?
?
TERRIGENOUS
BIOCLASTIC
TERRIGENOUS
BIOCLASTIC
TERRIGENOUS
BIOCLASTIC
Type of Facies
5 m.
0
Top of Cinder Bed

the general appearance of the two main facies of the Middle Purbeck. No attempt has been made to correlate in detail.

(c) General conclusions

This description of Dorset sediments of Lower and Middle Purbeck age, differs from that given in the literature, in that the evaporitic character of the bottom half of the Lower Purbeck, and the algal and bahamite facies in particular, has not previously been recognised. Occurrences of gypsum have been ascribed to formation in localised evaporating pans; while though algae have been suspected (e.g. Arkell, 1947, p. 126), their presence had not been proved. The importance of these plants as producers of calcium carbonate in the Purbeck has been shown in this petrological study, a study that furnishes an example of how petrographical examination of sediments can modify conceptions of environment based solely upon a study of fauna. It emphasises how important it is that fauna (and flora) and the sediment should both be studied if reliable palaeogeographical reconstruction is to be made.

The present study still leaves work to be done. There is, for example, the problem of a more exact correlation of major facies, especially in the Middle Purbeck, and more particularly of determining micro-facies within the major ones. A geochemical study, too, might provide valuable information on salinity changes during deposition that could perhaps be correlated with changes in the ostracods (cf. Anderson, 1932). The highly weathered nature of the coastal exposures, however, may make this study difficult.

Diagenetic problems discussed are not specific to the Purbeck but are common to most limestone sequences. Calcitisation of aragonite shells 'in place' is recorded elsewhere (Nelson, 1959), but the development of pleochroism on such a large scale seems to be due to peculiarities of environment that were common during Purbeck time.

APPENDIX A. - METHODS

Petrological study was carried out with standard thin sections used in conjunction with binocular examination of polished surfaces. Comparison of thin sections with the surface from which they were cut, soon enabled direct interpretation to be made from polished surfaces alone; this appreciably reduced the number of thin sections required.

Sections of fine-grained carbonate rocks are often hard to interpret owing to Becke line effects and internal dispersion of light due to the high refractive indices and birefringence of the carbonate minerals (e.g. see Wood, 1941). Use of acetate peels overcame this difficulty. These were prepared by first smoothing a surface of the rock with number 600 carborundum powder, and then etching this surface for 3 minutes in 1% hydrochloric acid. This etching period was found to be generally satisfactory for most specimens. The etched surface was dried, covered with a film of acetone, and a sheet of cellulose acetate pressed firmly down on to the surface, care being taken to ensure that too much acetone was not present, otherwise the sheet crinkled. The specimen was then left, preferably overnight, though the sheet may be peeled off after 15 minutes if required. It was washed in dilute HCl to remove excess carbonate, dried, trimmed and mounted dry under a cover slip. The peel retains the outlines of the etched crystals (and cleavages), and even mud grains of 1-2 μ size can be clearly seen under high-power magnification. Photomicrographs of peels are illustrated by figures 35 & 59

The mineralogy of carbonate rocks is readily determined by means of various selective staining techniques. Initially, Lemberg's solution was used to test for the presence of dolomite, but subsequently a scheme was adopted following that outlined by Friedman (1959). Calcite was distinguished from aragonite by means of Fiegl's solution, in which aragonite turns black after a few minutes, calcite (and dolomite) being unaffected. Calcite and aragonite may be distinguished from dolomite by means of Alizarine Red S in 0.1% HCl. Calcite turns deep red after a few minutes; dolomite is unaffected. The main carbonate mineral found in the Purbeck was calcite. Aragonite is present in shell fragments in a few places, but no dolomite was detected. Some algal limestones are highly magnesian, and analysis of two Purbeck samples gave 10.8 and 11.2% MgO respectively (analyst, D. Powell), but stain tests for high magnesian calcites were not satisfactory. A high iron content in calcite can be detected with potassium ferricyanide in 1% HCl. This stains iron rich calcite blue, and was found in several places in the Purbeck beds, mostly in the brown, pleochroic mosaics (p.195).

APPENDIX B. - PALAEOBOTANY

CHLOROPHYCOPHYTA

Codiaceae

Ortonella Garwood 1914.

Ortonella nodosa (Anderson) 1948.

Figure 27

Small sub-spheroidal nodules up to 2-3 cm. diameter but usually smaller. The nodules are medium brown on fresh surfaces imparting a clotted appearance to the rock, but weather to a porcellanous white or tan. In thin section the nodules show radiating filaments, circular in cross section and separate from one another. Filament walls are composed of fine-grained calcite (less than 4μ, the algal dust of Wood, 1941), and enclose coarse grained, typically drusy calcite. In any one nodule filament diameter is quite regular, and variation between nodules is from $30-55\mu$, the average being about 40μ. Filaments are straight or slightly sinuous, subparallel with marked dichotomous branching which appears to be more regular than in Cayeuxia Frollo.

Horizon: Basal Beds.

Ortonella cf. furcata Garwood 1914.

Figure 72

An encrusting form usually found as a thin coating to large micrite pebbles or intraclasts. The filaments are completely separated and widely spaced.

Straight or slightly sinuous, they are circular in cross section with diameters of from 30-40 μ, averaging 35 μ. There is irregular but marked dichotomous branching from both sides of the main filament, usually at an angle of about 40°.

This form differs from *O. furcata* Garwood (1914) in its encrusting rather than nodular habit, and in its more frequent and irregular branching. Here, it occurs with *Girvanella* sp. of diameter 80-100 μ, and is intimately associated with stromatolitic forms.

Horizon: Soft Cockle Beds.

CHLOROPHYCOPHYTA ?

Porostromata

Girvanella Nich. and Eth. 1880.

Girvanella intermedia ? Wethered.

Found in nodules of up to 2 cm. diameter that resemble those of *O. nodosa* in hand specimen. In thin section they show twisted, vermiform filaments with thick well-defined walls of algal dust. Filament diameters vary from 60-100 μ they are separate and unbranched. This form closely resembles *G. intermedia* but preservation is insufficient to confirm the diagnosis.

Horizon: Basal Beds.

Girvanella spp.

Several indeterminate forms probably referable to *Girvanella* are found in the Basal Beds and the Soft Cockle Beds. Filament diameters vary from 45-50 μ

up to 80-100μ, rarely up to 120μ. There is insufficient material to attempt further specific identification.

CYANOPHYCOPHYTA

Spongiostromata

Spongiostroma Gürich 1906.

"Spongiostroma" s. lato.

Figures 32 - 35.

This occurs as small button-like fragments of up to 1 cm. size which formed around a nucleus, or as larger, more or less continuous layered structures several centimetres thick. Little or no microstructure is preserved, though very rarely traces of thin filaments may be seen. The buttons are similar to Pycnostroma, though they are generally not so distinctly laminated as the forms figured by Gürich (1906).

Spongiostroma s. l. differs from Spongiostroma Gürich in having less well preserved filaments, otherwise the structures are closely comparable.

Horizon: Basal Beds.

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Philip R. Brown: Petrology of the Lower and Middle Purbeck Beds of Dorset.

SUMMARY

This petrological study of Dorsetshire sediments of Lower and Middle Purbeck age was carried out to determine their depositional environments, and to see how this changed with time. Five major facies are recognised in the Lower Purbeck, and two in the Middle. The Lower Purbeck facies chiefly reflect variation in the salinity of the water during deposition, and probably its temperature. During this period Dorset was a shelf area, usually covered by shallow water, but sometimes land. It lay on the border of a saline lagoon, the waters of which gradually became brackish and finally fresh by the end of the Lower Purbeck time.

There is no break in sedimentation between the Portland and the Purbeck. The basal Purbeck is composed of algal limestones, chiefly stromatolitic, but also containing species of *Solenopora*, *Ortonella* and *Girvanella* similar to those in the Upper Portland. There is evidence of epigenetic formation of anhydrite in some of these limestones. The succeeding beds (Broken Beds and Cypris Freestones) are mostly pellety limestones that resemble some of those forming at the present day in areas such as the Great Bahama Bank. A similar depositional environment is proposed for these Purbeck sediments, as a 'bahamite' facies. Here, too, there is evidence of epigenetic anhydrite, and it is hydration of this, and the subsequent solution of gypsum during Tertiary folding, that is thought to have localised the Broken Beds.

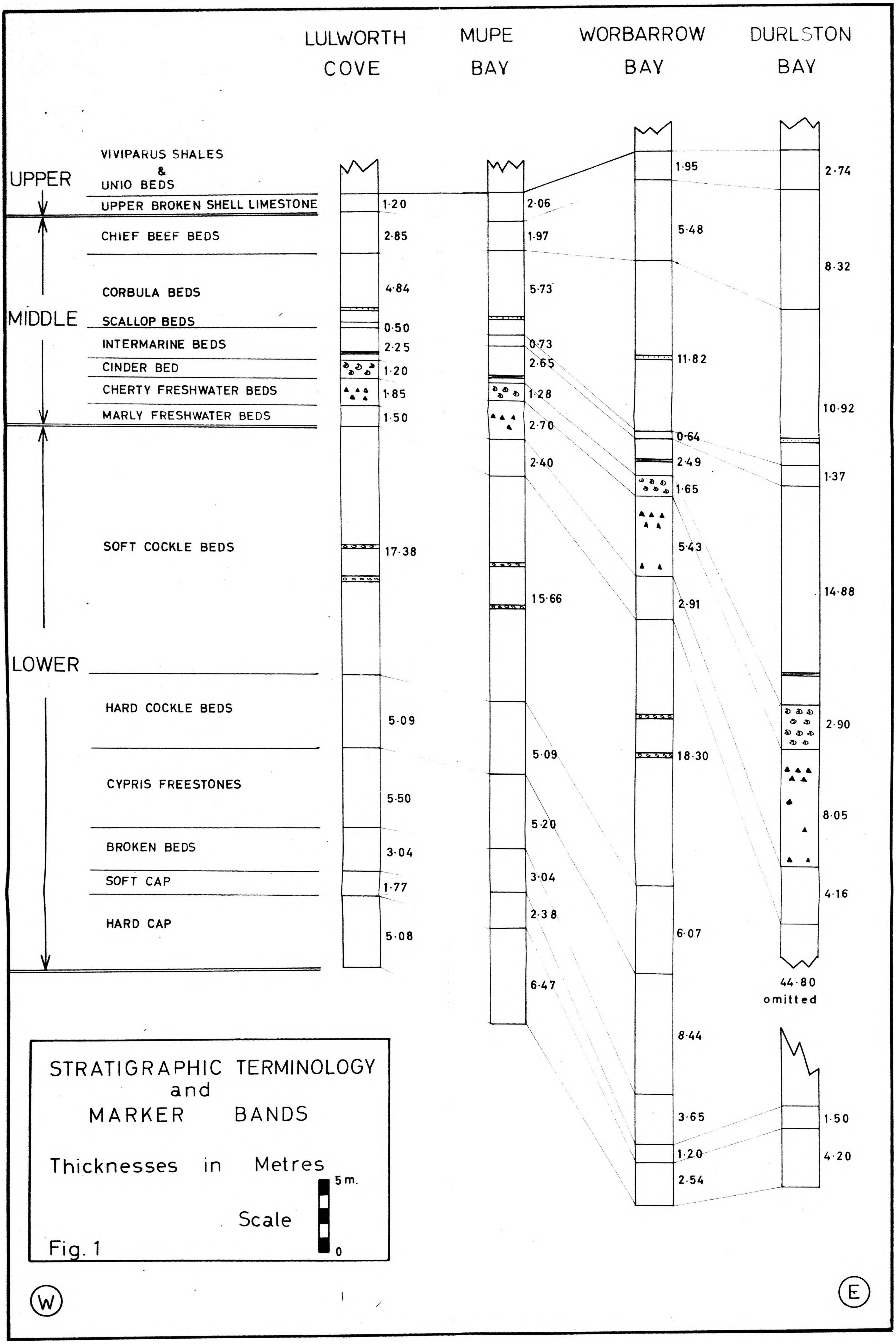
Lowered salinities, apparently caused by influx of freshwater from the west, enabled a brackish water fauna of gastropods and pelecypods to spread throughout the area (Hard Cockle Beds). Restriction of this freshwater, and evaporation, then raised the salinity again. Precipitation of carbonate mud was widespread, gypsum being deposited locally. *Ortonella*, and stromatolitic algae were common at times, perhaps growing on tidal flats, but a 'bahamite' facies did not develop, possibly owing to lack of agitation of the water.

There then followed a gradual decrease in salinity until, by the end of Lower Purbeck time, freshwater conditions prevailed over the whole Dorset region. Carbonate mud was still the dominant sediment, but was formed by the action of freshwater algae such as *Chara*. These freshwater conditions continued during the early part of the Middle Purbeck but were terminated by a marine incursion that led to the formation of large oyster banks (Cinder Bed).

The two facies of the Middle Purbeck, called the bioclastic and the terrigenous facies, are unlike those of the Lower Purbeck. The bioclastic facies formed under conditions that varied from freshwater to almost normal marine, the rocks consisting mainly of shells and shell fragments in micrite or spar cement, but including pure calcite-mudstones formed by shell comminution

or by the action of plants. The terrigenous facies formed during periods of reduced carbonate deposition when land-derived sediment of mud to sand grade was brought into the area, probably from the west. It is suggested that these influxes were the initial phases in the development of Wealden type sedimentation.

Most diagenetic problems discussed are not specific to the Purbeck. Fabrics are described that are believed to be formed by calcite replacement of epigenetic anhydrite, while pleochroic shell mosaics are thought to be aragonite shells that calcitised in place, without solution. This phenomenon is well developed in Middle Purbeck rocks.



STRATIGRAPHIC TERMINOLOGY
and
MARKER BANDS

Thicknesses in Metres

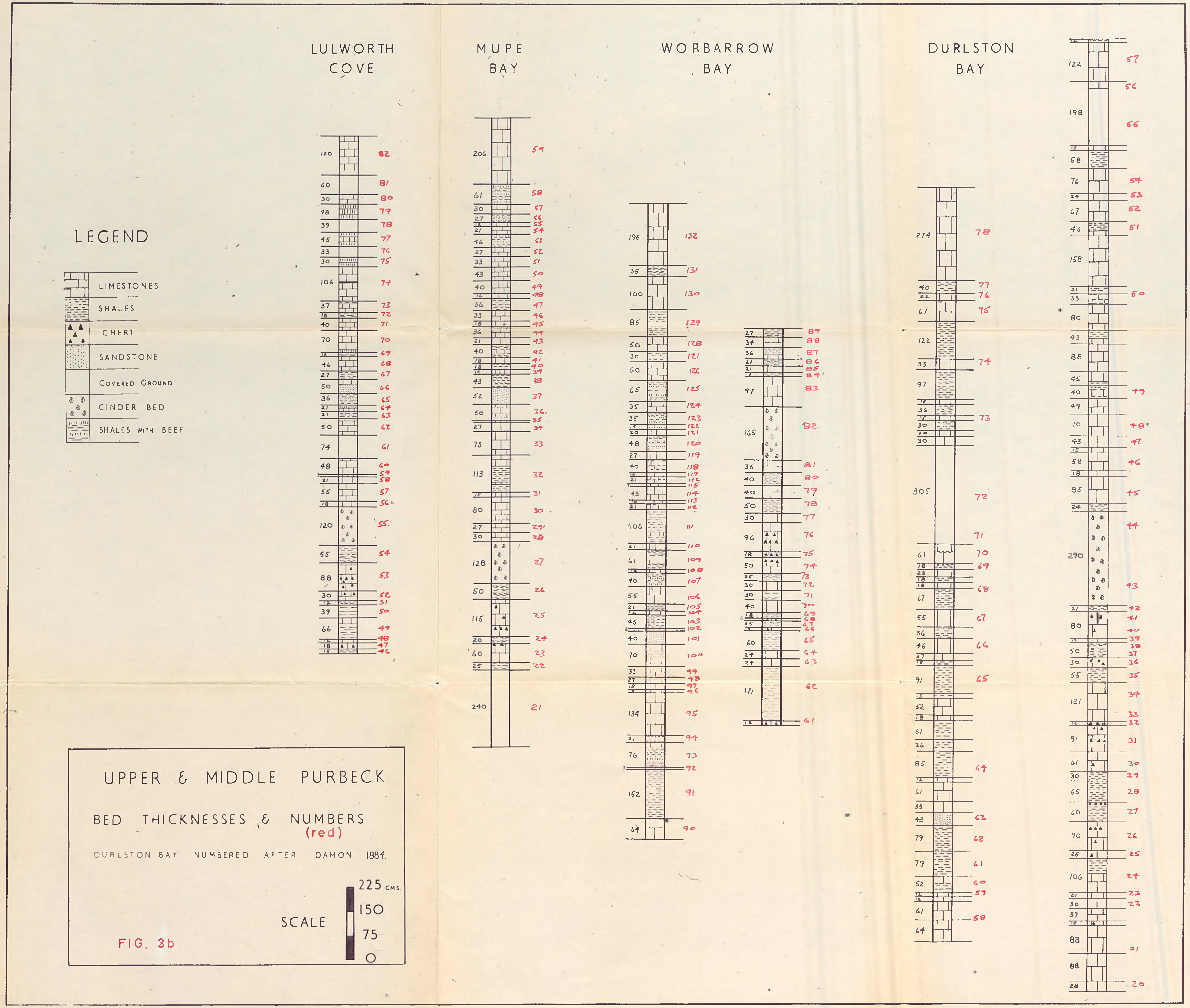
Scale

Fig. 1

LOWER PURBECK

BED THICKNESSES & NUMBERS (red)

FIG. 3a



UPPER & MIDDLE PURBECK

BED THICKNESSES & NUMBERS (red)

DURLSTON BAY NUMBERED AFTER DAMON 1884

FIG. 3b