THE PETROGRAPHY OF THE LOWER PURBECK LIMESTONES OF DORSET.

by

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Thesis submitted for the Degree of Master of Science
of the University of London.

ABSTRACT

The petrography of the limestone types found in the Lower Purbeck of Dorset is described. Four main types are distinguished namely algal limestones, pellet-limestones, shell-limestones; and replacement-limestones produced by the replacement of gypsum and anhydrite by calcite. The distribution of these limestones especially as revealed by coastal sections, is tabulated. From these studies it is deducted that the principal environment of deposition was a lagoon, the seaward margin of which was restricted by an algal barrier. On the landward side of this barrier evaporites, pellet-limestones and shell limestones were deposited in a lateral sequence. There is evidence to suggest the occurrence of lower salinities to the west than to the east. This lateral change in salinity is probably due to dilution by river water in the west, especially during Hard Cap times. The origin of two post depositional breccias is also discussed.

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ACKNOWLEDGEMENTS

I am most grateful to Dr. W. Smith for his advice, encouragement and especially for his valuable criticism of this text. Dr. D. V. Ager has also been most helpful in reading the text and assisting this work in many other ways. I would especially like to thank Mr. D. J. Shearman for his many stimulating ideas when in the field and for his assistance with petrographic details.

I would also like to thank Mr. R. Curtis for his X-ray identification of celestite, Mr. G. Elliott for confirmation on the identification of some algal genera, and Mr. J. Gee for advice on photography.

CHAPTER I

INTRODUCTION

Situation

Except for inland sections in the areas of Portesham (plate 1) Upwey, Bincombe and Poxwell, extensive exposures of the Lower Purbeck limestones are restricted to the coast of Dorset (fig. 1). The coastal sections display the most complete sequences and have therefore been studied in greater detail than the inland sections. The coastal exposures occur at intervals from Portland Bill to Durlston Head, namely at Burning Cliff (plate 2), Durdle Door, Dungy Head, Stair Hole, Lulworth, Mupe and Worbarrow Bays (plates 3 and 4).

Stratigraphy

The Lower Purbeck everywhere rests on the Portland Stone, and in many places there is no obvious lithological break.

According to Bristow and Fisher (1857), the succession of Lower Purbeck beds is as follows:-

Marly Freshwater Beds
Soft Cockle Beds
Hard Cockle Beds
Cypris Freestones
Broken Beds
Soft Cap
Great Dirt Bed
Hard Cap

\- - - - - - - - - - - -

Portland Stone

Since the Marly Freshwater Beds and Soft Cockle Beds are composed of marls and clays, and not limestones, the author has studied only the succession up to and including the Hard Cockle Beds. At Durlston Head, however, the beds equivalent to the 'Cypris' Freestones and Hard Cockle Beds of Lulworth, are marls and clays, and have not been studied in detail.

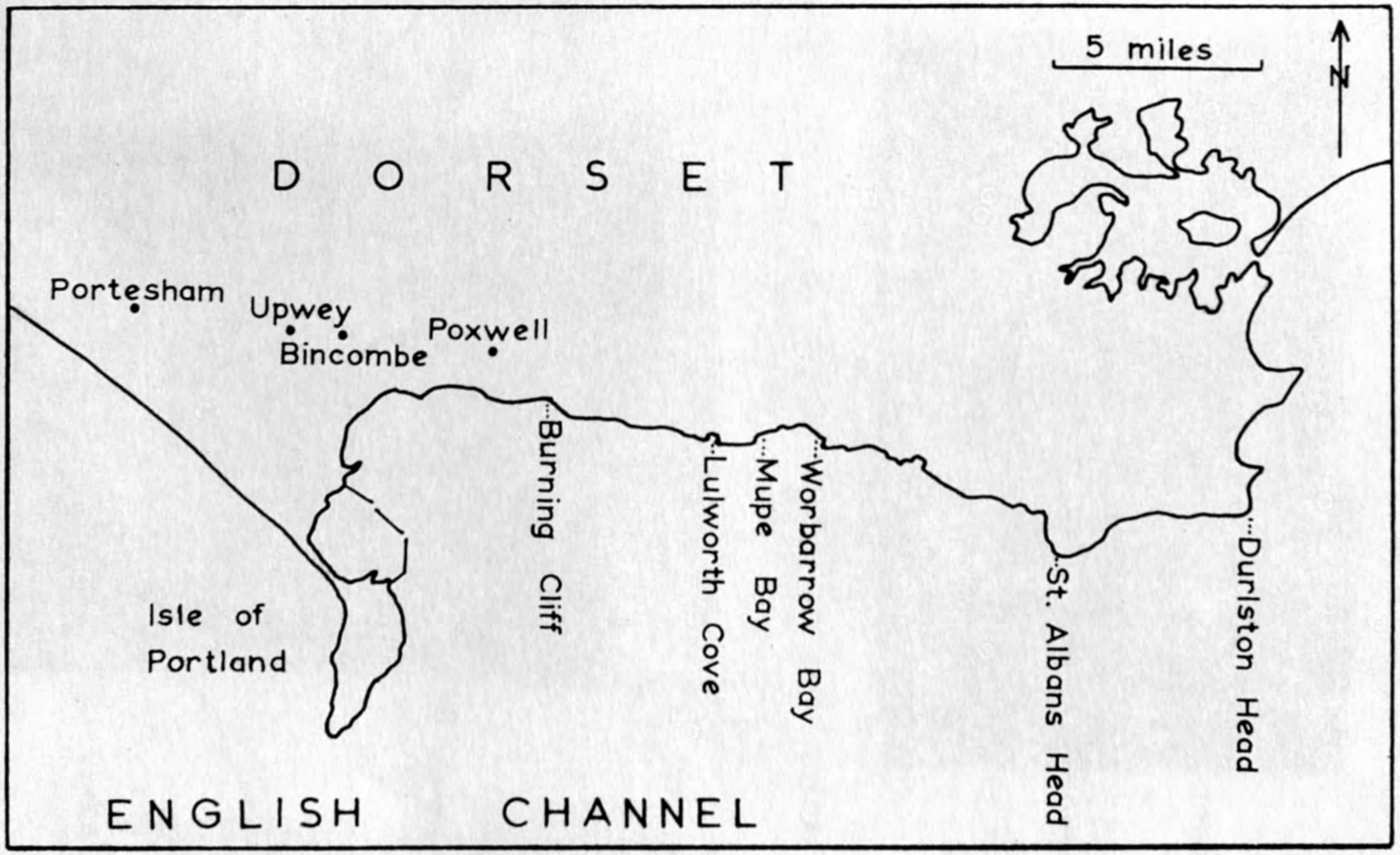


Figure 1. The Lower Purbeck limestone exposures of Dorset.

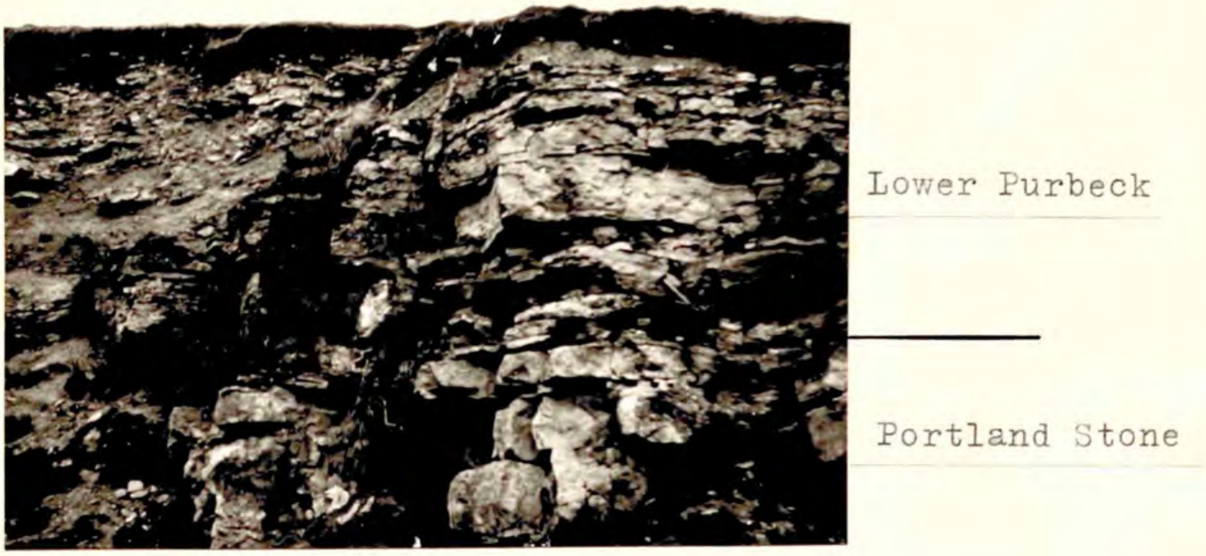


Plate 1. The Lower Purbeck succession in a quarry near Portesham.

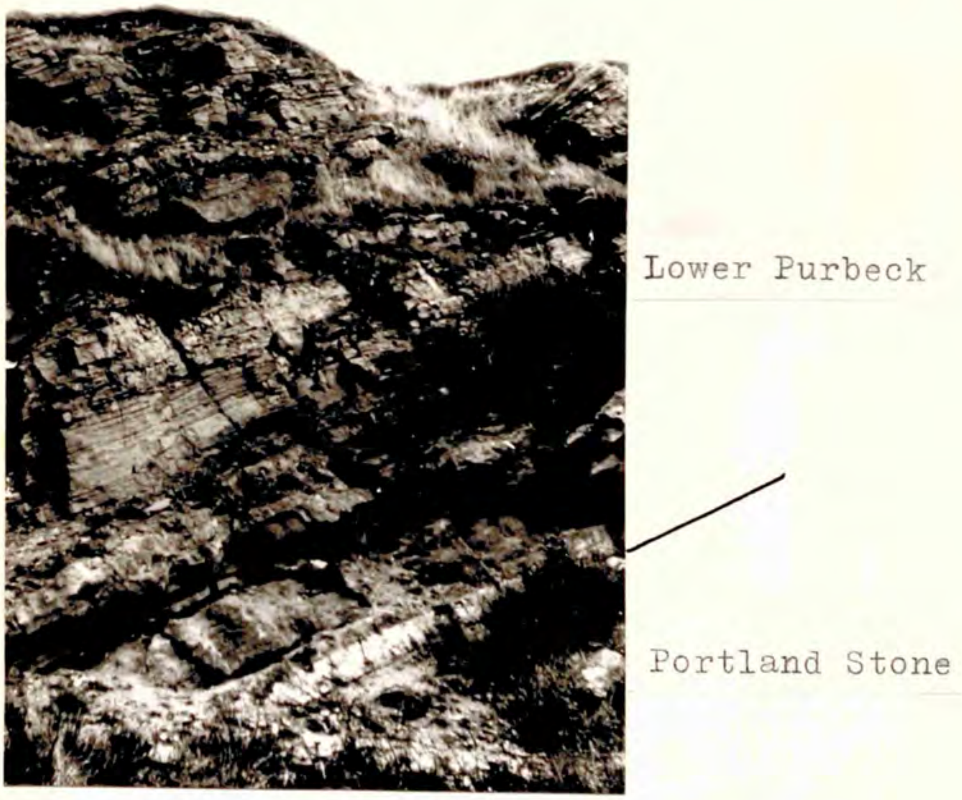


Plate 2. The Lower Purbeck succession at Burning Cliff, Ringstead Bay.

Plate 3. The Lower Purbeck succession at Bacon Hole, Mupe Bay.

Plate 4. The Lower Purbeck succession at Worbarrow Bay.

The total thickness of the Lower Purbeck limestones is not uniform throughout Dorset. A general thinning of the deposits occurs from Durlston Head in the east, to Portesham in the west. According to Bristow and Fisher (1857) the total thickness at Durlston Head is approximately eighty feet. At Worbarrow Bay the present author's sections measure seventy five feet, at Mupe Bay seventy two feet, at Lulworth fifty seven feet, and at Burning Cliff thirty seven feet. On the Isle of Portland and at Portesham the position of the Hard Cockle Bed is not determinable but the total thickness exposed measures forty eight feet and twenty six feet respectively. The upper part of the succession on the Isle of Portland is distinctly argillaceous and may be the equivalent of the Soft Cockle Beds.

Not only does the succession as a whole vary in thickness from place to place but the individual beds also display lateral variations in thickness. However, the diagrammatic section based on the exposures at Lulworth (fig. 2), where all the beds are easily recognisable, portrays the comparative thickness of the beds in a typical sequence.

It has been found that four main limestone types: namely pellet - , algal - , shell - , and replacement-

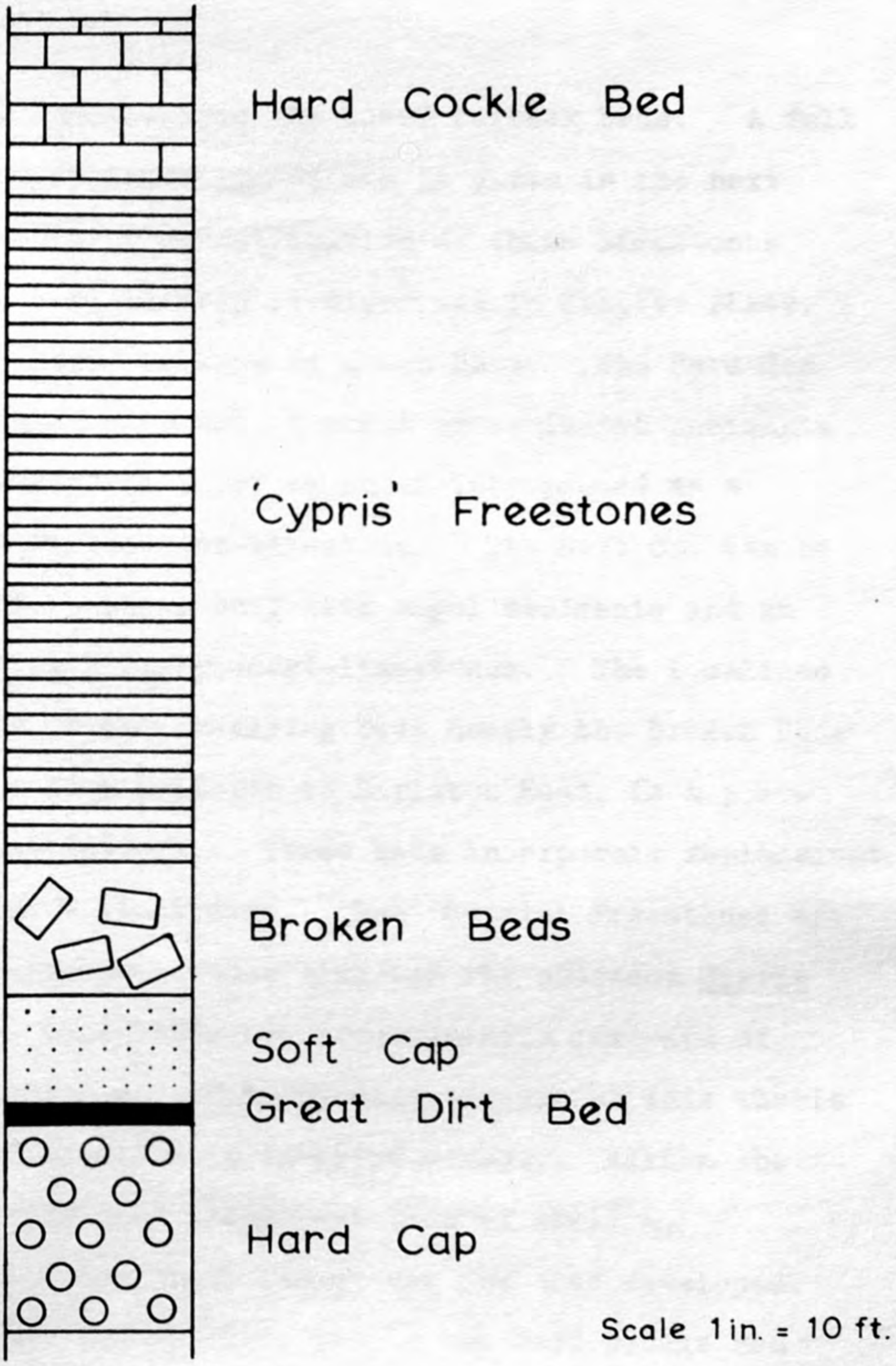


Figure 2. Diagrammatic vertical section showing the relative thicknesses of the beds at the Fossil Forest, Lulworth.

limestones characterise the Lower Purbeck beds. A full description of these limestones is given in the next chapter, whilst the distribution of these limestones within the various beds is discussed in Chapter Three. However, a brief outline is given here. The Hard Cap is essentially composed of algal precipitated sediments with a superficial layer which is interpreted as a "detrital" replacement-limestone. The Soft Cap can be divided into a basal half with algal sediments and an upper half with replacement-limestones. The localised brecciation of the overlying beds namely the Broken Beds which occur from Lulworth to Durlston Head, is a post-depositional feature. These beds incorporate replacement - and pellet - limestones. The 'Cypris' Freestones are really a misnomer because although the ostracod Cypris is present, these beds are predominantly composed of pellet-limestones. Consequently throughout this thesis 'Cypris' is inserted in inverted commas. Within the 'Cypris' Freestones occasional beds of shell -, replacement - and algal limestones are also developed. The uppermost bed studied, namely the Hard Cockle Bed consists, as its name implies, of shell-limestone, together with some pellet-limestones and silt.

Summary of previous literature.

In the past, interest in the Lower Purbeck of Dorset, appears to have developed during three main periods; i.e. from 1826-1906, 1933-47 and recently, from 1960 onwards.

In the nineteenth century, all the descriptions and sections were recorded in detail for the first time. These records were based essentially on field evidence with little or no petrographic description. Nevertheless the thickness and lithology of the various strata were accurately determined. One of the earliest papers was by Webster (1826) describing the junction of the Portland and Purbeck Beds. This was followed by the detailed descriptions and sections of Fitton (1835, 1836), Weston (1848), Forbes (1851), Fisher (1856) and finally Bristow and Fisher (1857) who drew up comparative vertical sections. Apart from the stratigraphy of these beds, other authors concerned themselves with the fauna and flora. The more spectacular fossils were described first, namely the 'Cycads' by Buckland (1828) and the insects by Brodie (1854). Not until thirty one years later, were the ostracods investigated in any great detail. These were identified by Jones (1885), who erected many new genera, and succeeded in dividing the succession into Lower, Middle and Upper Purbeck on the basis of vertical changes in the ostracod assemblages.

Chapman (1896, 1906) also recorded ostracod occurrences.

Finally towards the end of the nineteenth century, even more detailed descriptions were furnished by Woodward (1895), and Strahan (1898) in the first Geological Survey memoirs dealing with the Isle of Purbeck and Weymouth.

From the 1930's onwards, interest was again taken in the Lower Purbeck this time by Arkell, Hollingworth, Sylvester-Bradley and Anderson. A controversy developed between Arkell (1938) and Hollingworth (1938) as to the origin of the Broken Beds. Arkell favoured a tectonic origin, and Hollingworth proposed that the brecciation was due to the collapse following the removal of interbedded evaporites. Meanwhile Anderson (1932, 1940) and Sylvester-Bradley (1940) attempted to correlate the Purbeck in Dorset with that at Swindon, on the basis of the ostracods. During this period Arkell (1933) wrote his classic book on the Jurassic of Great Britain, studied the Purbeckian gastropod fauna (1941) and prepared a revised edition of the Geological Survey memoir covering the Isle of Purbeck, Lulworth and Weymouth (1947).

In the 1960's, the origin of the Broken Beds was again in dispute. West (1960, 1964) favoured the view that the brecciation was due to the replacement of evaporites aided by tectonic movements; whilst Phillips

(1964) considered that tectonic deformation was the only important factor responsible for the brecciation of the beds. The detailed petrology of the limestones was described for the first time, by Brown, (1963, 1964).

The Purbeck Beds lack marine fossils in any quantity, and are therefore difficult to date. As far back as 1822 Conybeare and Phillips classed the Purbeck with the Oolitic Series i.e. as part of the Jurassic. Webster (1826), Fitton (1836) and Topley and Jukes-Browne (1885), however, thought the Purbeck showed closer affinities with the Wealden which they associated with the Cretaceous. In 1851, Forbes and the Geological Survey classified the Purbeck as part of the Jurassic. This opinion has been held upto and including the present day, but Casey (1962, 1963) regarded the Cinder Bed in the Middle Purbeck as the result of the Ryazanian transgression in early Cretaceous times. He therefore took the Cinder Bed as the base of the Cretaceous in Dorset, thus leaving the beds below in the Jurassic. These beds below the Cinder Bed he renamed 'Lulworth Beds', and the remainder of the Purbeck beds above the Cinder Bed he termed 'Durlston Beds'. It should be noted that the strata studied by the present author are part of the Lulworth Beds as defined by Casey, and consequently their Jurassic age is not in dispute.

More recently, however, at the International Stratigraphic Commission the whole of the Purbeck was again associated with the Jurassic; in fact it was decided to regard the Purbeck as a facies of the Portlandian. (Ager, 1963; Lloyd, 1964).

CHAPTER 2

LIMESTONE TYPES

Introduction

The Lower Purbeck limestones can be divided into four main groups; namely pellet-, algal, shell- and replacement-limestones. This classification is however to some extent arbitary because one type readily passes into another, and many beds are composed of a mixture of two or more types of limestone.

Pellet Limestones

The pellet-limestones are by far the most abundant. At Worbarrow Bay (where they are especially well-developed) they account for approximately forty feet out of a total of the seventy five feet of limestone studied. These limestones are characteristic of the 'Cypris' Freestones, the Broken Beds and are occasionally developed in the Hard Cockle Beds (figs. 10, 11, 12).

A pellet-limestone may be defined as a limestone in which fifty per cent or more of the rock is composed of pellets. They are usually set in a clear sparry calcite matrix, or less frequently, in a microcrystalline calcitic matrix. Pellets were described by Folk (1959), as "rounded, spherical to elliptical or ovoid aggregates of microcrystalline calcite ooze, devoid of any internal structure". They are usually less than one millimetre in diameter, and have a well-defined pellet/matrix boundary, though this may be obscured by later recrystallisation. In transmitted light the pellets, unlike the matrix, nearly always appear brownish in transmitted light, but white in reflected light.

It is difficult to classify pellets as they have no internal structure and display only variations in size and shape. However, three genetic categories were recognised by Wolf (1961), namely: faecal pellets, bahamite grains and algal pellets. Unfortunately he gives no information as to how these may be recognised in ancient sediments.

In the past many geologists used to classify most, if not all pellets, as being of a faecal origin. More recently however, Illing (1954) and Beales (1958) after studying the recent sediments in the Bahamas, have stressed the importance of inorganically produced pellets or bahamites. The formation of these bahamite grains is the result of precipitation and aggregation of aragonite and silt particles. They have a minimum size of 20µ, occur in rock building proportions and have few associated macrofossils or ooliths. To distinquish such grains from spherical faecal pellets in ancient sediments is almost impossible. The term faecal pellet can therefore only be ascribed with certainty to pellets with an ovoid shape.

Adopting Folk's (1959) classification the bahamites may be subdivided into two groups; namely pelsparites and pelmicrites. The pelsparites are composed of distinct, rounded, brownish, microcrystalline aggregates set in a matrix composed of clear sparry calcite (fig. 3a). The pellets are nearly always in contact with others and may be associated with quartz silt and intraclasts. In contrast a pelmicrite is characterised by a micrite matrix. The pellets are mostly indefinite in outline and are not in contact with each other (fig. 3b). If the micrite is secondarily replaced by sparry calcite the rock is then termed a pelmicrosparite (fig. 3c).

The algal pellets mentioned by Wolf (1961, 1962) are apparently analogous to the 'grumeleuse' textures described by Cayeux (1935) and to the 'clotted' textures described by Hadding (1958). According to Hadding, the 'clots' of micrite which are often grouped into clusters, result from algal activity, since algal balls when sectioned revealed the same texture. Similarly, the present author has noted the textural resemblance of some laminated limestones, of the Hard Cap at Mupe Bay, to algal balls on the Isle of Portland. Since these limestones are so closely associated with the Spongiostromata, they will be considered under algal limestones, in this thesis.

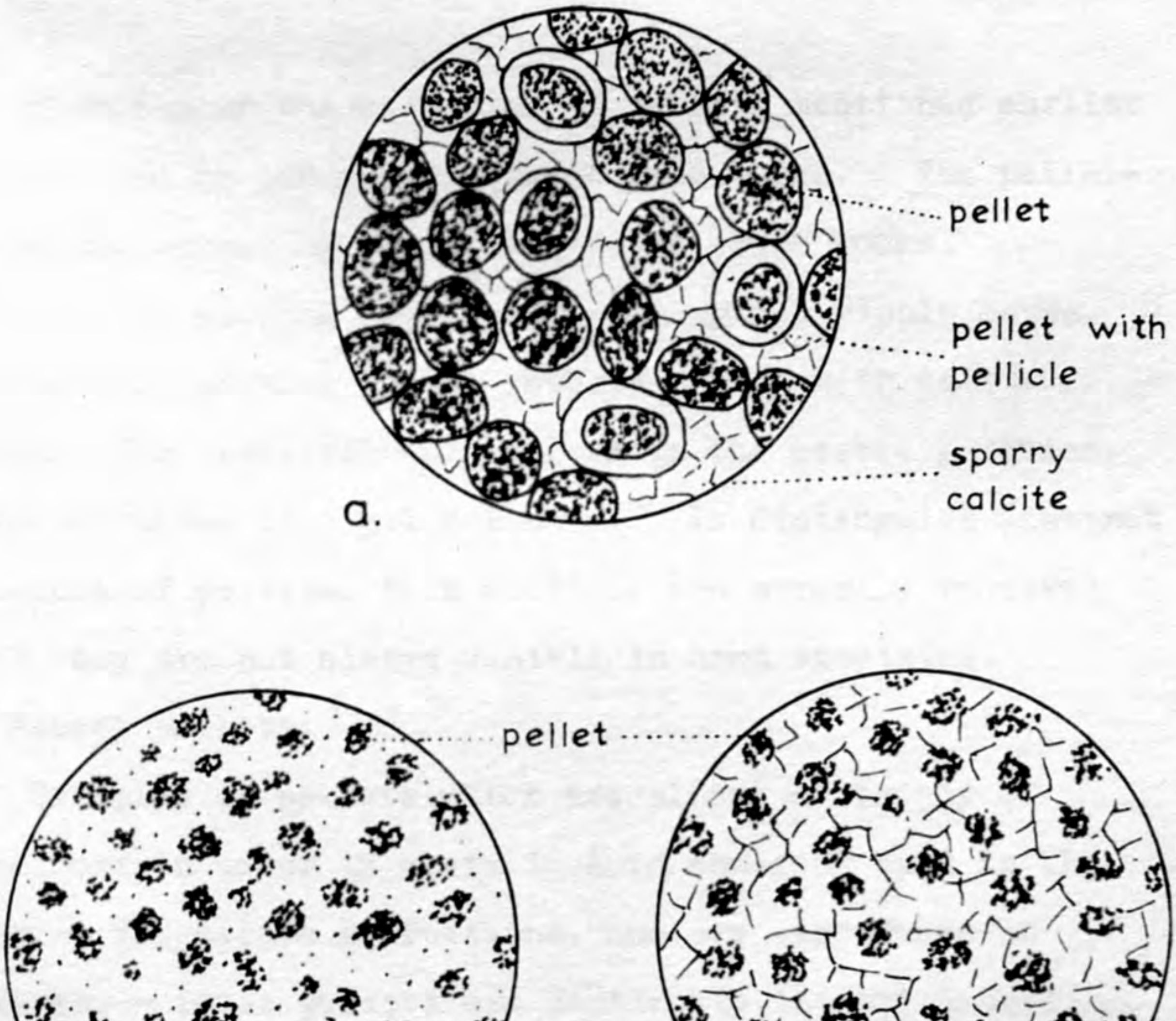


Figure 3. Diagram illustrating the types of pellet limestones; a. pelsparite, b. pelmicrite, c. pelmicrosparite.

Examples of the varieties of pellets mentioned earlier can be found in the Lower Purbeck limestones. The pellet-limestones appear as finely laminated white rocks, occasionally showing some cross-bedding and ripple marks. The bedding surfaces may be covered either with salt pseudomorphs, lamellibranch valves in the stable position, ostracod valves or algal colonies. To distinguish distinct varieties of pellets, thin sections are normally required since they are not always visible in hand specimens.

i) Faecal pellets.

Examples of pellets which are almost certainly of faecal origin occur in a six inch to one foot band in the 'Cypris' Freestones at Portland, and are also found at Lulworth. These pellets are distinctly 'cigar' shaped, ranging up to one millimetre in length and approximately 300µ in width. They are set in a sparry calcite matrix (plate 5). At Lulworth, this limestone pseudomorphs crystals of halite.

One can only speculate with regard to the nature of the organism which produced these pellets. In the Bahamas, at the present day similar sized pellets are excreted by the gastropod Batillaria minima (Kornicker and Purdy, 1957). It may be possible that the small gastropod Hydrobia was responsible. However, the moulds of this gastropod are more abundant at the base of the Purbeck and in the Hard

Cockle Beds than in the 'Cypris' Freestones, where the faecal pellets are found. Eardley (1938) attributed similar pellets, in the sediments of the Great Salt Lake, Utah, to a brine shrimp and Ginsburg (1957) states "worms and crustaceans are probably the most important pellet producers today". Therefore some of the Purbeck pellets may be attributed to the associated ostracods. However, the large pellets in plate 5, are only slightly smaller than the ostracods themselves, and could not have been produced in this way and some other organism may have been responsible. It should also be noted that a whole variety of organisms can produce very similarly shaped pellets.

ii) Bahamite grains.

As already mentioned these can be divided into pelsparites and pelmicrites.

Pelsparites. These may be regarded as the typical pellet-limestones of the Lower Purbeck (plate 6). They form the majority of the 'Cypris' Freestones, the Broken Beds from Lulworth to Worbarrow Bay, and part of the Hard Cockle Beds (figs. 10, 11, 12).

The pellets range from 45-100μ in diameter, but in the Lower Purbeck they are associated with

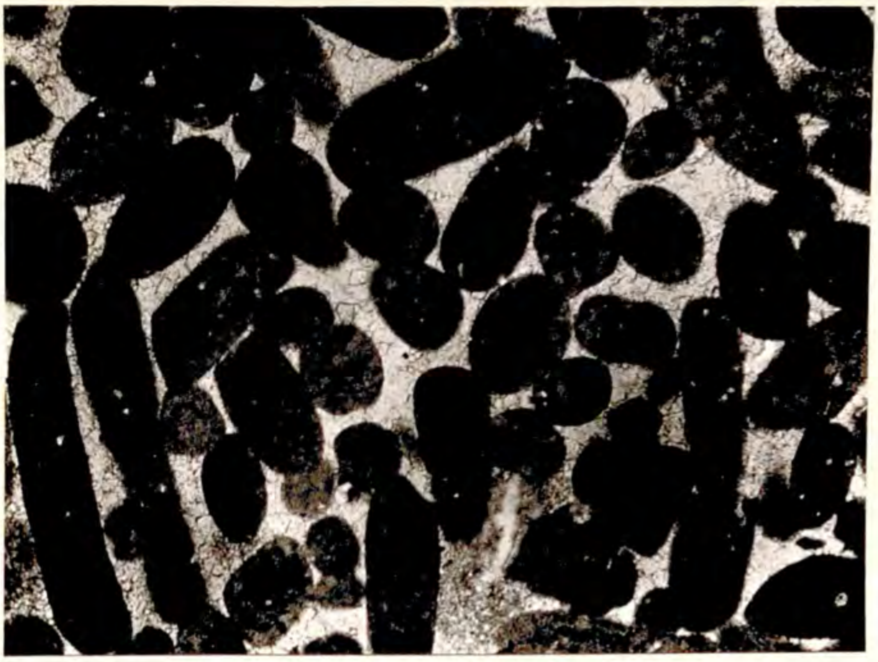


Plate 5. 'Cigar' shaped faecal pellets from the 'Cypris' Freestones, Fossil Forest, Lulworth. X.56. L.138.

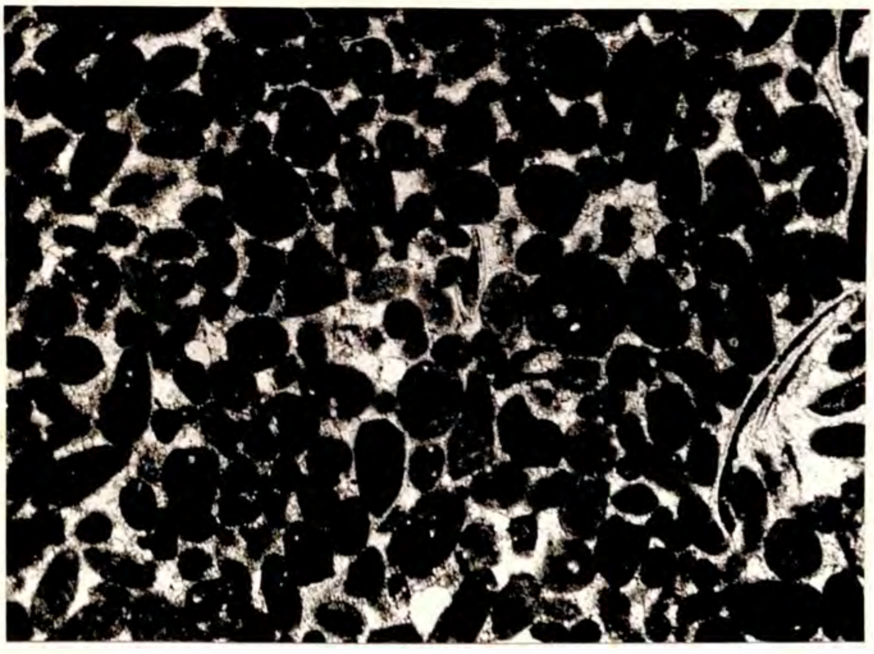


Plate 6. Pelsparite from the 'Cypris' Freestones, Fossil Forest, Lulworth. X.56. L.130.

broken ostracod valves, quartz silt, algal and other intraclasts or may grade into pelmicrite. Generally the pelsparites are almost pure calcium carbonate, the insoluble residue rarely exceeding three per cent.

In some Lower Purbeck strata (figs. 11, 12) the pellets coalesce and appear to have undergone compaction. Ginsburg (1957) observed that pellets, in recent limestones from Florida, tend to lose their individuality a few feet below the surface and deduced that this was the result of compaction before cementation of the deposit.

Frequently the pellets are surrounded by one or two concentric layers of fibrous calcite the long axes of which are normal to the pellet edge; such pellets have been termed 'superficial oolites', (Illing 1954). The present author has observed that in the Lower Purbeck limestones only the larger pellets with diameters of about 170µ have this 'pellicle'. According to Illing, such pellicles form around pellets where carbonate precipitation and tidal currents coincide. At the very base of the Lower Purbeck on Portland, the pellets are apparently held together by fusion of the calcite pellicles (plate 7). The typical sparry calcite matrix is completely absent. On the other hand, at the top of the Hard Cap from Lulworth to Worbarrow Bay it is the pellets which have been removed so that only the pellicles and the sparry calcite matrix remain (plate 8)

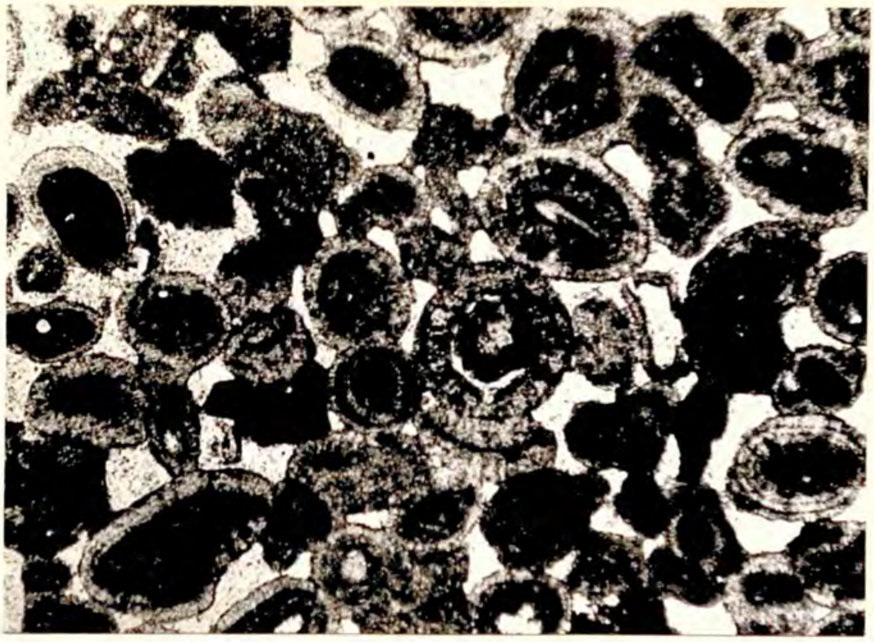


Plate 7. Pellets apparently held in position by fusion of the radial calcite of the pellicles, from the basal Purbeck, Isle of Portland. X.125. P.38.

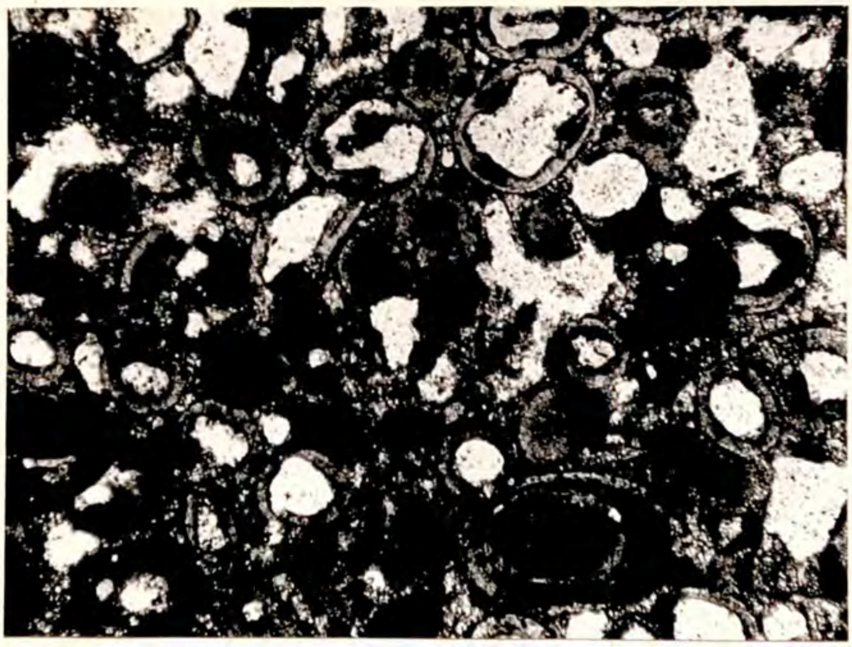


Plate 8. Pellicles of radial calcite surrounding circular cavities, from the Hard Cap, Mupe Bay. X. 56. M. 13.

In such cases rounded cavities were left, some of which may have been filled by single crystals of secondary calcite. It is difficult, however, to distinguish the latter from calcite which has replaced some other mineral. This texture will therefore be discussed more fully later in this thesis.

The association of pellet-limestones with quartz silt occurs in the upper part of the 'Cypris' Freestones and in the Hard Cockle Beds (fig. 10). The quartz silt in these limestones is angular and varies in abundance from 10 - 50 per cent of the rock, the sparite matrix being reduced to a minimum (plate 9).

Pelmicrites. This type of limestone is not very abundant in the Lower Purbeck and is best seen in samples from the Hard Cap. The pellets are small - 50µ - less rounded than in the pelsparites, and not in contact with each other (fig. 3).

Much replacement has taken place in the Purbeck beds and the micrite matrix has often been replaced locally by sparite especially in the Hard and Soft Caps. The resultant texture is termed a pelmicrosparite (fig. 3 and plate 10).

Plate 9. A pelsparite with a high proportion of quartz silt, from the Hard Cockle Beds, Worbarrow Bay. X.105. M.75.

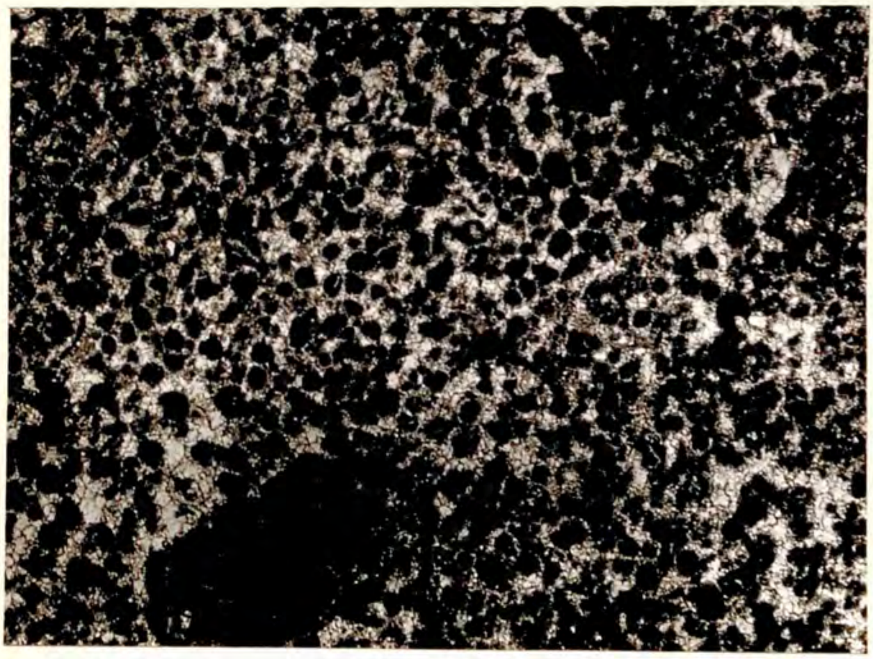


Plate 10. A pelmicrosparite from the Hard Cap, Lulworth Cove. X. 56. L.5.

Algal Limestones

Within the Lower Purbeck there is much evidence of algal activity especially in the Hard and Soft Caps, and locally within the 'Cypris' Freestones. The former presence of algae is indicated by well-defined branching filaments and by crinkled laminations around nodular masses. Also included in this section are the 'clotted' limestones which according to Hadding (1958) and Wolf (1962) are algal precipitated sediments.

Representatives of the three major algal phyta have been recognised from the Lower Purbeck limestones, i.e. Rhodophycophyta (red algae), Chlorophycophyta (green algae) and the Schizophyta (blue-green algae). Of these the blue-green algae were most abundant and produced the greatest thickness of limestone. It is this phyta which is thought to be responsible for the 'clotted' textures both within algal balls and laminated limestones. It must be pointed out, however, that structures resulting from their activity are the most difficult to identify with any certainty. It may be that some textures attributed to algal activity by the author, were formed as a result of other processes.

i) Schizophyta

Pia (1927), divided the Schizophyta into the Porostromata and Spongiostromata. The Porostromata include algae with bundles of well-defined tubes, but lack an obvious branching system, whilst the Spongiostromata lack any definite microstructure but form laminated colonies of varying shapes. The latter are commonly known as Stromatolites. A further subdivision of the Spongiostromata was made by Pia, to differentiate the fixed forms or Stromatolithi from the unattached forms or Oncolithi. It is to the subsection Stromatolithi to which the majority of the Lower Purbeck forms belong.

Porostromata. Some nodular grey limestones from the 'Cypris' Freestones at Lulworth (plate 11) and the Hard Cap at St. Albans Head and Portesham, when sectioned revealed well-defined filaments. These have micrite walls, are often curved and appear circular in cross-section. Occasional branching does take place but no regular pattern was observed. The filaments lack cross partitions and are usually filled with drusy calcite mosaic (Bathurst 1958). Compared with other filamentous

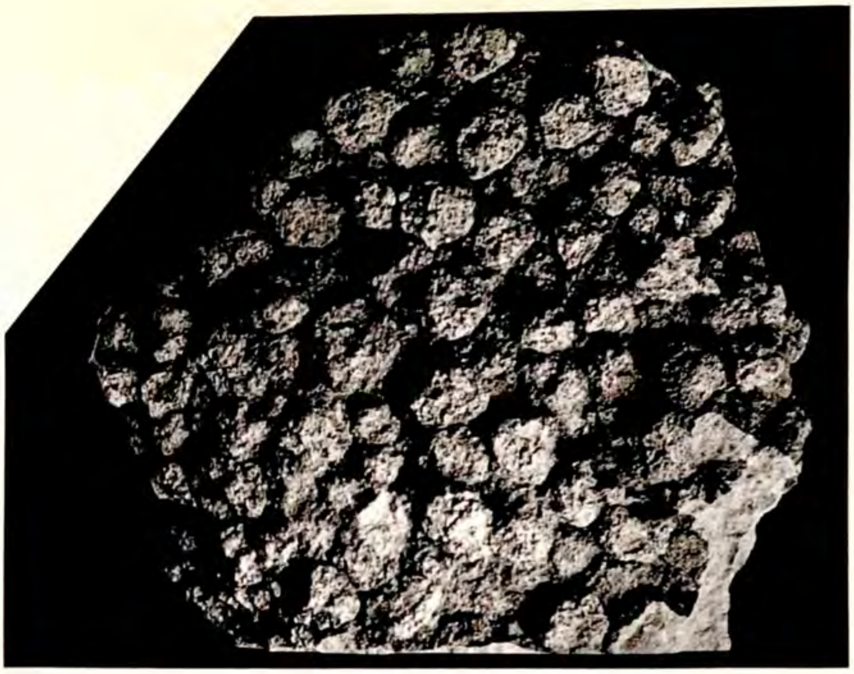


Plate 11. Girvanella colonies on a weathered surface from the base of the 'Cypris' Freestones, Fossil Forest, Lulworth. X. $\frac{3}{4}$. L.126.

Plate 12. Section through a Girvanella colony from the basal Hard Cap, St. Albans Head. X. 25. S. 7.

algae the filaments are quite large in diameter, varying from 85 to 130µ and have micrite walls approximately 14 µ thick (plate 12). This alga is identified as a species of Girvanella.

Also attributed to the activity of Girvanella, by various authors, are algal pisolites (e.g. Wethered 1890). Apparently similar pisolites, occur in the Hard Cap at Freshwater Bay, Isle of Portland. The pisolites appear as bean-shaped dense micrite masses with irregular concentric banding surrounded by a pelmicrosparite matrix. The variable shape and non-continuous banding suggest an algal origin, even though no filaments are visible (plate 13). The pisolites with diameter of 230 to 300µ differ in size from the associated pellets which range from 70 to 100µ in diameter. This difference in size suggests that the calcareous particles adhered to the gelatinous algal matter more readily than to non-gelatinous micrite.

Spongiostromata. Unlike the scattered occurrence of the Porostromata, the Spongiostromata algae grew in colonies or covered the surface of the sediments like a blanket and gave rise to considerable thicknesses of limestone. The majority of the Hard Cap and parts of the Soft Cap resulted from their activity. In the field, the limestones of the Hard Cap are hard, light grey to cream in colour. At Mupe and Worbarrow Bays they appear as laminated calcarenites, but on the Isle of Portland and at Bincombe they are more cavernous. In any one place the limestones of the Soft Cap readily pass from laminated limestones to large rounded cavernous masses or 'burrs'. The laminations often completely overlie the 'burrs'.

At Mupe and Worbarrow Bays the Hard Cap algal limestones when sectioned reveal a texture very similar to that attributed to Spongiostroma maendrinum Gurich. Clusters of dark granules ranging from 200 - 400µ in diameter, with a tendency towards a stellate arrangement occur in a micrite groundmass. The clusters are usually in contact with one another, with a resultant overall dendritic pattern (plate 14).

A similar texture, but with a less definite arrangement of granules, is found in the Hard Cap at Mupe Bay and also in the algal mounds of the Soft Cap. In this case the granules are very small, i.e. approximately 28µ in diameter and scattered randomly within a micrite matrix, which in some cases has altered to sparite (plate 15).

Apparently closely related to this last type, is a form producing algal balls which occurs on the Isle of Portland in a clay above the 'Cypris' Freestones. These balls reach thirty centimetres in diameter (plate 16) and

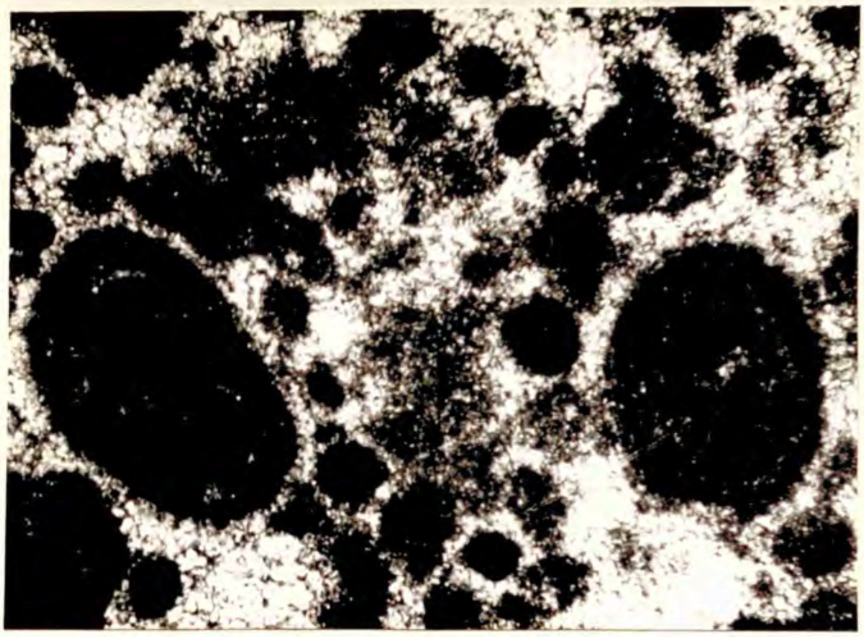


Plate 13. Algal pisolites within a pelmicrosparite, basal Hard Cap, Isle of Portland. X. 280. P.37.

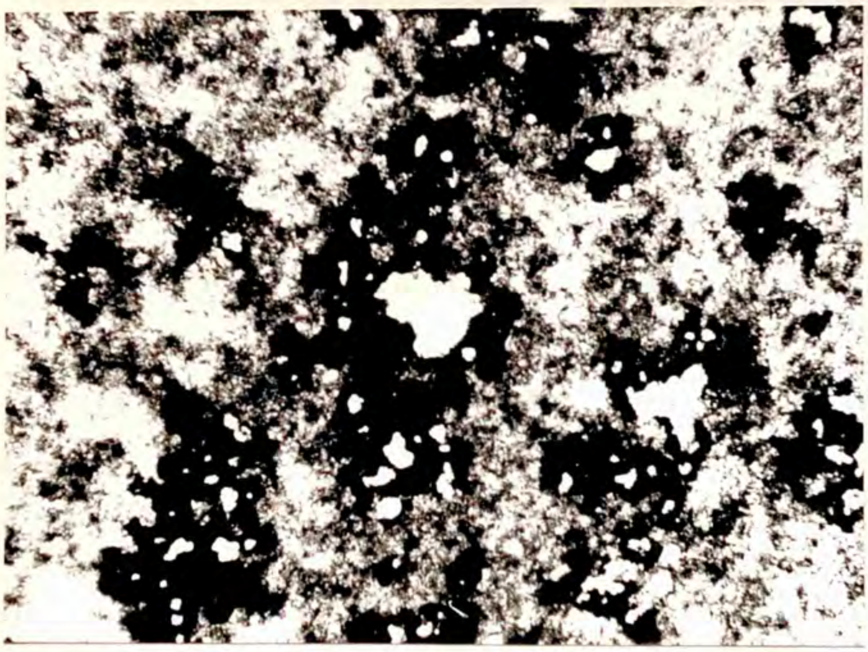


Plate 14. Clusters of granules reminiscent of Spongiostroma maendrinum Gurich from the Hard Cap, Mupe Bay. X 175. M.8.

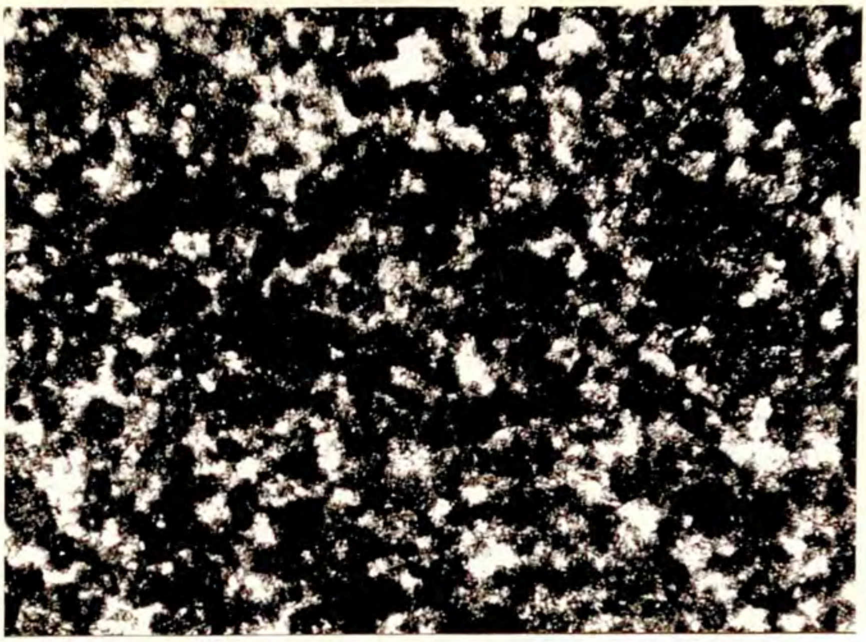


Plate 15. Small granules in a micrite/sparite matrix, from the Hard Cap, Mupe Bay. X. 120. M.4.

Plate 16. Algal colonies attributed to Malacostroma concentricum Gurich, ? Soft Cockle Beds, Perryfield Quarry, Isle of Portland. (Not in situ).

are found only at the one horizon. Only the outermost layer is laminated and this shows varying degrees of corrugation. Centrally the structure has been destroyed by the formation of chert. The sections reveal dense layers with diffuse beige micrite clots, 35µ in diameter, alternating with layers of scattered clots set in sparite. This texture resembles that of Malacostroma concentricum Gurich. The width of the laminations is in the order of 300µ and 300 to 700µ respectively.

The Spongiostromata limestones from the Hard Cap at Lulworth, Bincombe and the Isle of Portland appear porous and often exhibit a radial structure around a central cylindrical hollow. This hollow is thought to be the mould left after the decay of wood. On weathered surfaces, botryoidal masses are revealed either surrounding the cavity or piled one on another. These laminated protuberances reach one centimetre in height and each is capped by mutually interfering small domes (plate 17). The whole appearing as a cauliflower. Coating these protuberances, referred to as Gymnosolen by Brown (1963), is a coarsely crystalline secondary calcite, with occasional barytes crystals.

In thin section, the laminations underlying the crystalline calcite, are seen to consist of fine crystalline calcite bands in the order of 14 - 60µ, which alternate

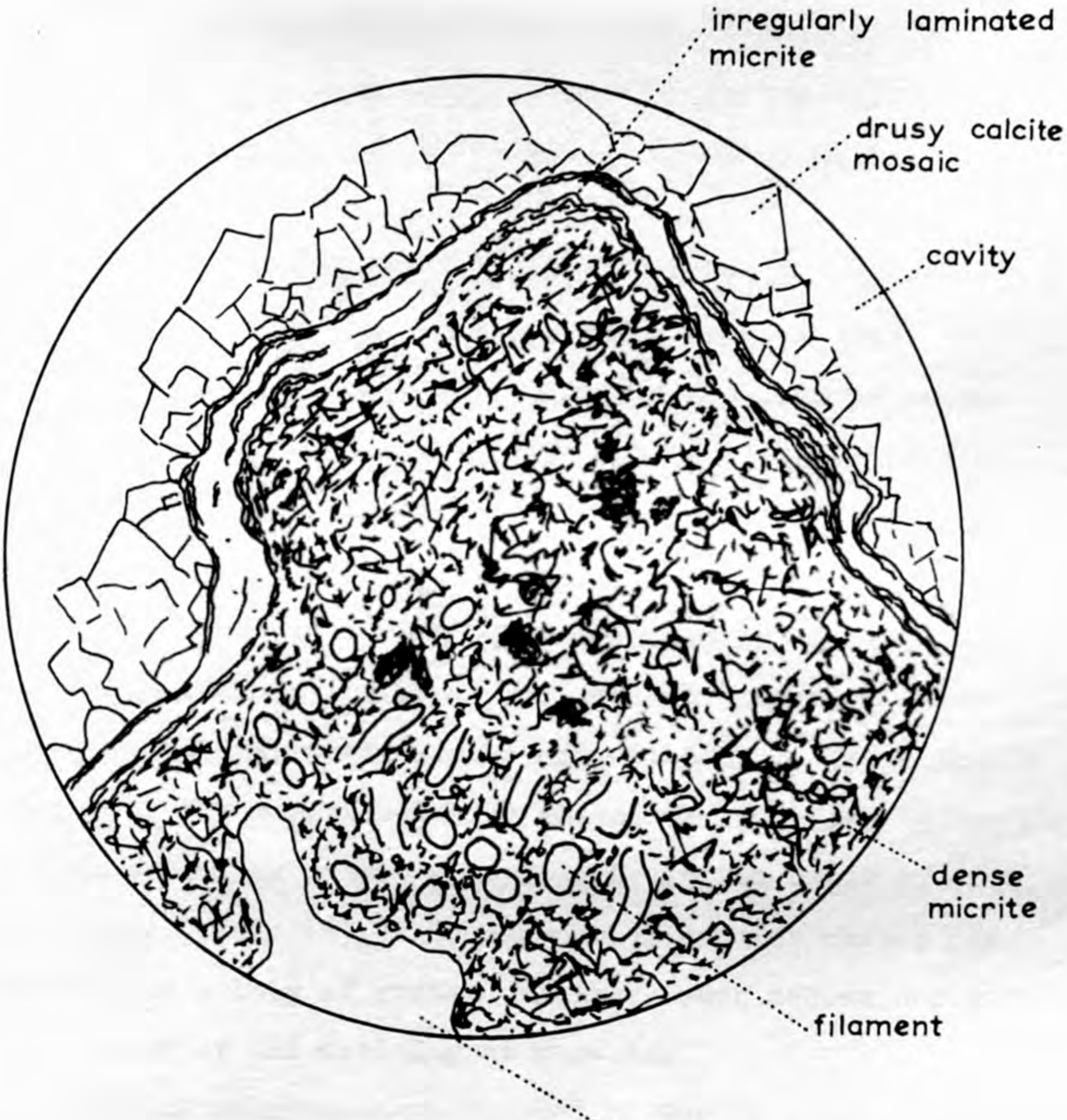


Figure 4. Section through Spongiostromata head from the Hard Cap, Perryfield Quarry, Isle of Portland. X 50.

with organic rich dark bands approximately 35µ thick. The total thickness of the laminated layer is about ½ millimetre.

Enclosed within the laminated portion is a dense micrite with filaments and/or radial calcite. The filaments with dense micrite walls are circular in cross-section with an average diameter of 80µ. The filaments may be curved but rarely appear long in the plane of the section (fig. 4).

The associated radial calcite is easily distinquished from the matrix by its brown colouration, rosette appearance and slightly denser central area. The circular outline of the rosettes may be polygonal where two interfere but the diameter is usually in the order of 115 - 230µ (plate 18). Occasionally, nodular masses may be composed solely of radial calcite; such masses occur in the base of the Hard Cap at Mupe Bay.

Similar structures were noted by Gurich (1906), who attributed it to an inorganic origin, but associated with Chondrostroma, another genus within the Spongiostromata. Muir and Walton (1957) thought the dark colour to be the result of the crystal structure, but P.R. Brown (1963) definitely attributed it to contained organic matter. Further confirmation of its organic association is its occurrence around Codiaceae filaments. Though not strictly comparable, crystals forming a rosette appearance were

Plate 17. Handspecimen of Spongiostromata limestone from the Hard Cap, Isle of Portland. X 1½. P.90.

Plate 18. Radially arranged calcite crystals and siliceous spherulites, from the Hard Cap, Isle of Portland. X 140. P.7.

recorded by A. Brown (1894), around canals leading to the conceptacles of Lithothamnion. No such pores are visible in the Purbeck specimens.

Scattered within the radial calcite are siliceous spherulites. These vary in size from 44 - 250μ and show brown concentric banding. Where two or three are in contact the outer bands are then continuous (plate 18). One example of banding was seen in radial calcite and this may suggest that the siliceous spherulite was originally composed of radial calcite. Scholl (1960) described very similar textures from algal deposits in Searles Lake, California:- "Optically orientated calcite possibly aragonite, fills many of the cells, but many are rich in organic matter and are dark brown. Most of the cells are encircled by dark-brown bands containing organic matter which closely follow the configuration of the cell. Where cells are closely grouped the outer banded zone surrounds the entire cluster rather than the individual cell". Apart from the fact that the Purbeck examples are now siliceous this description could equally be applied to them.

The algal limestones of the Soft Cap are either laminated or nodular. Small algal colonies, 7.5 - 25 centimetres in width, seen on the Isle of Portland are referred to the Cryptozoon - form genus, by Brown (1963).

At the Fossil Forest, Lulworth, however the mounds reach up to six feet in diameter. The clotted texture of both these mounds and the laminated sediments is similar. The 'clots' vary in size from 60 - 200 μ and are fairly well-defined. They are of no regular shape and often form clusters (plate 19). The matrix varies from a micrite to a microsparite in which the 'clots' appear to float.

The mounds are usually circular with either a convex upper surface or a central depression. The mounds with a central depression or 'burrs' vary from four to six feet in diameter and are usually three feet high (plate 20), whilst the convex mounds vary from one to five feet in diameter (plate 21). The 'burrs' were previously thought to indicate fossilised tree trunks

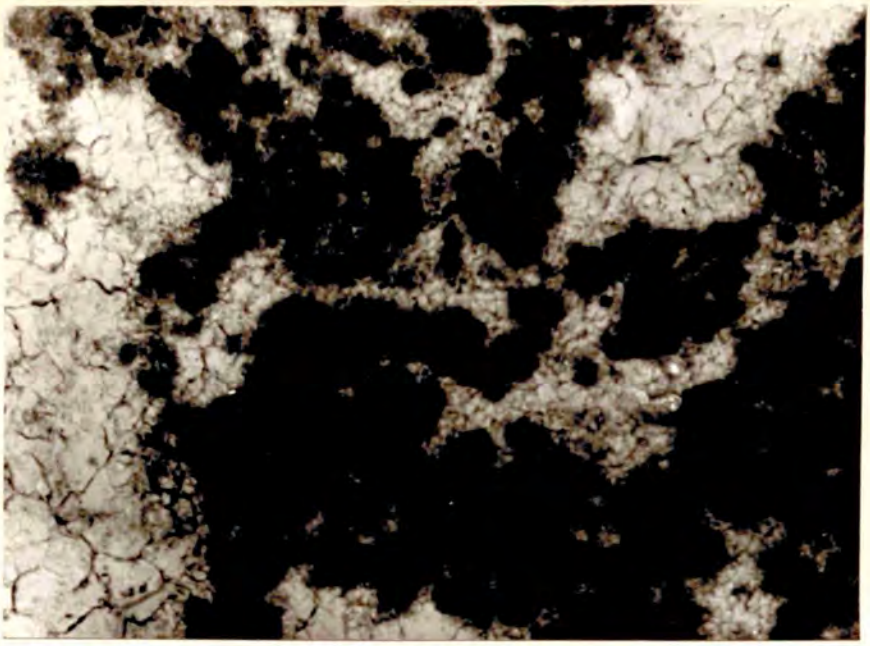


Plate 19. 'Clotted' algal limestone from the Soft Cap, Lulworth Cove. X 360. L. 7.

Plate 20. Algal 'burr' from the Soft Cap, Fossil Forest, Lulworth.

surrounded by encrusting algae - for Strahan (1898) stated "The structure, however, may have been due to the action of filamentous freshwater algae growing from the stump and radiating from it as a centre". His opinion was based solely on field evidence. With the assistance of thin sections however it is evident that the algae were not filamentous and probably not freshwater forms. The associated gypsum pseudomorphs indicate hypersaline conditions, as do the replacement-limestones. Furthermore the present author disputes the view that the algae were entirely encrusting types, but instead suggests that the 'burrs' were produced as individual algal colonies.

The main feature favouring the view that the algae were merely encrusting forms is the similarity in shape of the 'burrs' to tree boles and fallen trunks (plate 22). Only one example was seen by the author of wood protruding centrally. Silicified wood is found in the Great Dirt Bed, but in these instances it lacks any encrusting algae. The apparent lack of wood, may have resulted from zealous collecting by geologists, or to the rotting of the wood before silicification took place. It is also a well-known fact that algae will encrust submerged logs (Bradley 1929).

It is not, however, necessary to postulate that the 'burrs' could only be formed around tree boles and logs because Eardley (1938) described similar algal heads growing on the shore of the Great Salt Lake, Utah. These appear as circular mounds varying from one to four feet high, and with a diameter from six to twenty seven feet. In detail they consist of firm white crusts between which are pellets and silt, with no evidence of unicellular algae. This description agrees well with the Purbeck forms, except that the latter lack small scale laminations, although large scale concentric growth rings are seen in the field (plate 23). Furthermore Eardley continues "the porous and somewhat friable nature of the bioherms has led engineers and others familiar with the lake to call the deposit "tufa" but this name is inappropriate because of its implication of spring origin". Likewise earlier authors refer to the Purbeck Caps as tufaceous limestones (Strahan 1898, Arkell 1933, 1947).

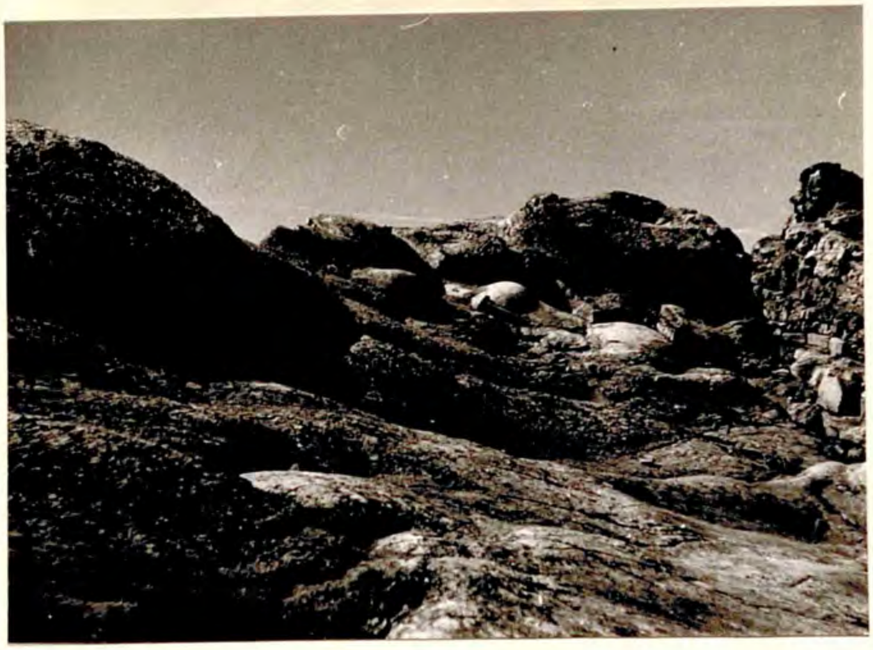


Plate 21. Algal mounds of varying sizes from the Soft Cap, Fossil Forest, Lulworth.

Plate 22. A supposedly algal encrusted fallen 'trunk' from the Soft Cap, Fossil Forest, Lulworth.

However, Scholl (1960) mentions that "recent tufas can be shown to be a precipitant of algae". The environment in which Eardley's colonies grew, namely the Great Salt Lake, is also similar to that which is believed to have existed during Soft Cap times in Dorset. Furthermore algal heads of the same proportions have been recorded in Western Australia in hypersaline bays (Logan 1961, 1964).

Not only do circular mounds occur at the Fossil Forest, but mounds are also seen to coalesce (plate 4) or to form parallel ridges (i.e. "the so-called trunks"). The circular nature of the 'burrs' suggests that the supposed trees were standing upright. It is however, most unlikely that two fairly large trees could grow so close together that algae encrusting them could coalesce. Instead it is possible to explain these structures as of an entirely algal origin. Carozzi (1962) has described similar algal

Plate 23. Vertical section through an algal mound showing laminations, from the Soft Cap, Fossil Forest, Lulworth.

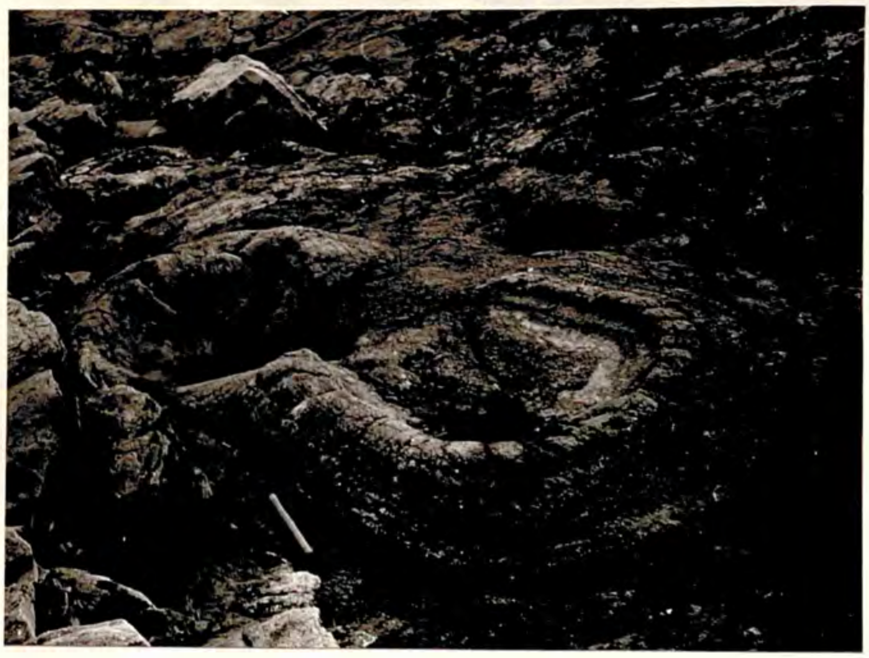


Plate 24. Coalescing 'burrs' from the Soft Cap, Fossil Forest, Lulworth.

patterns from the Great Salt Lake, Utah, although these are much shorter than the Purbeck examples. Similar proportioned algal heads however, coalescing near the summit were described from Australia by Logan (1961) (fig. 5). According to Carozzi the variation in shape of the colonies from circular, to coalescing and to elongate ridge-like forms is related to the location of the algae on the shore. The circular forms characterise the landward region whereas the elongate forms are closer to the sea and related to erosional gullies. Unfortunately there is no evidence of gully erosion in the Lower Purbeck and the origin of the so-called 'tree trunks' cannot be explained in this way. The central chert found in one of the 'trunks' did not reveal any cell structure, although this is well preserved in silicified wood from the Great Dirt Bed. No satisfactory explanation for the origin of the 'trunks' can be suggested.

Bradley (1929), besides mentioning log encrusting forms of algae, also described Chlorellopsis coloniata Reis, a more common form which builds reefs consisting of "an aggregate of more or less dome-shaped or puff-ball shaped masses of algal limestone. These will be referred to as heads. They may be entirely separate one from another or they may be merely botryoidal convexities or arches in a continuous layer". Such a description is applicable to the convex mounds at Fossil Forest which lack a central depression (plate 21).

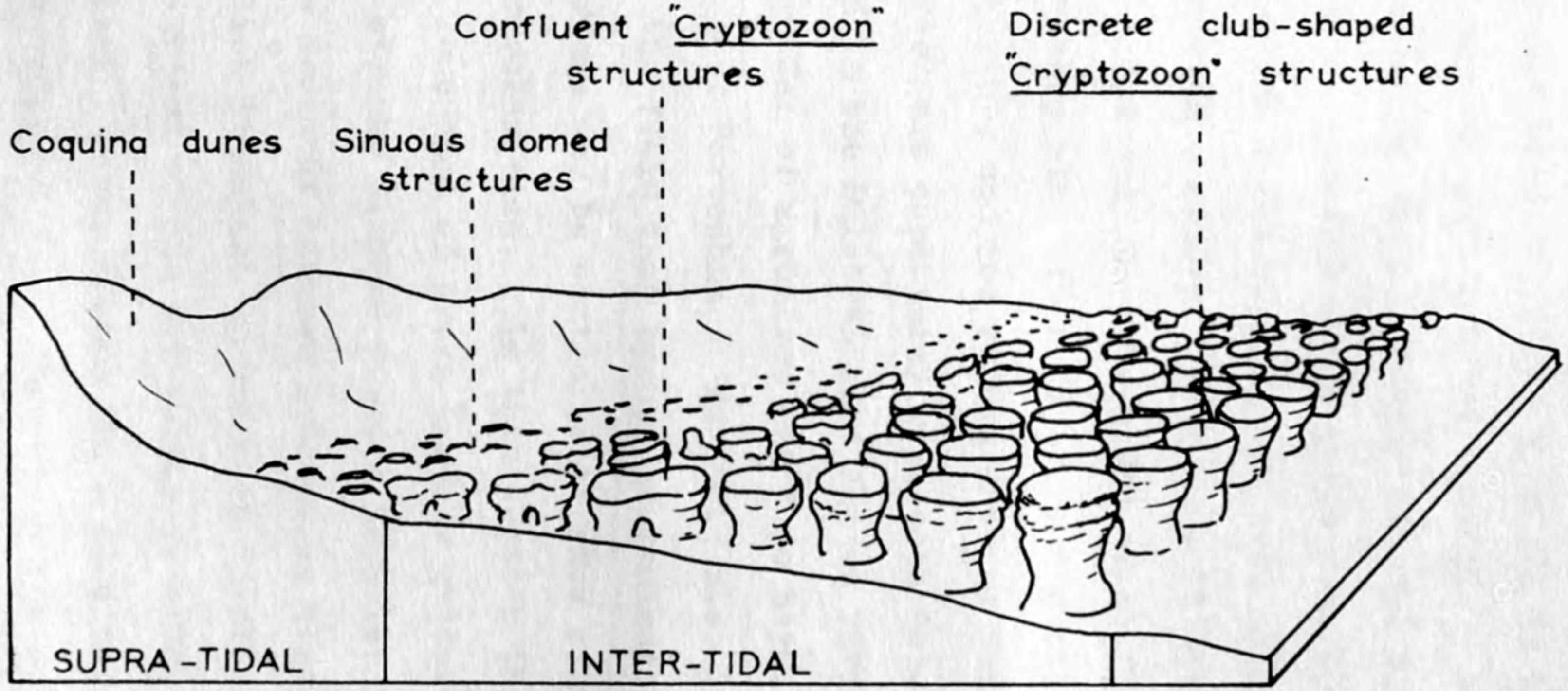


Figure 5. Idealised zonation of stromatolite forms across an inclined beach, Hamelin Pool, Australia, (after Logan).

These are obviously not formed by encrusting algae because they are often so small as to suggest the absence of any underlying plant remains. Furthermore rounded mounds are characteristic of many types of algal colony and it therefore seems quite reasonable to postulate that the Purbeckian 'burrs' are also really algal mounds but with a central depression (plate 20).

Not only do blue-green algae form discrete colonies, but they also often occur as a continuous blanket on the sediment, and are referred to as "algal mats". Such "mats" are especially well seen below the Great Dirt Bed in the Lulworth area and at various intervals in the Hard Cap of Worbarrow and Mupe Bays, at Burning Cliff and also at Portesham. Examples also occur in the Soft Cap. In the field they appear as laminated limestones or the surface may be weathered to show crinkled and nodular irregularities. In thin section they are recognised by an abundance of brown organic matter and by a laminated or streaky clotted texture parallel to the bedding (fig.6). The sediment between successive algal mats is usually a pellet limestone or one with "clotted" texture. The thickness of the mat varies from 700 - 1400μ, whilst the pellet laminae are only 450 - 600μ thick, with pellets in the order of 50μ. Sometimes the mats show evidence of desiccation (fig. 7) since vertical cracks occur filled at the base with pellets and overlain by secondary calcite.

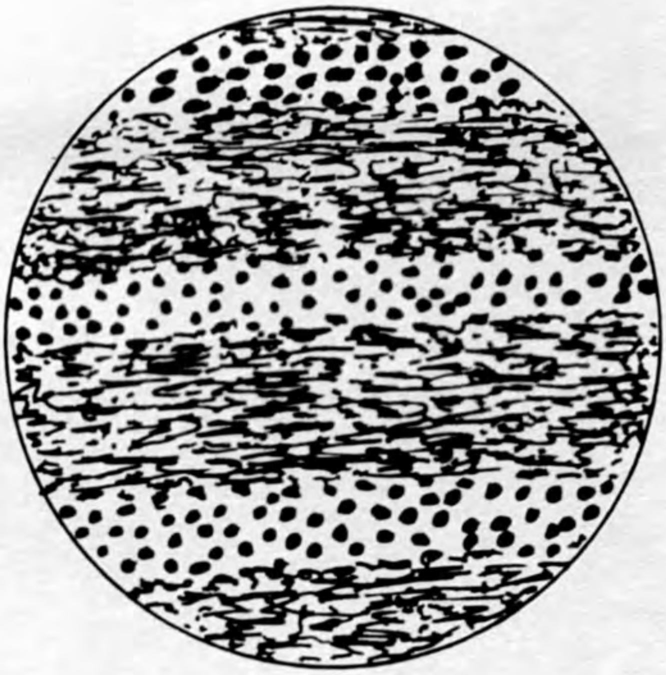


Figure 6. Diagram of alternating algal mats and pellets from the Hard Cap, Burning Cliff. X 26. P. 206.

Figure 7. Diagram of a vertical section through a ?dessiccation crack in an algal mat, Hard Cap, Mupe Bay. X 14. M. 11.

At the Fossil Forest laminated algal sediments are in places traversed by large polygonal cracks with raised edges (plate 25). Such structures would appear to be the result of desiccation as observed by Fisk (1959) from the Laguna Madre Flats, Texas. Similar structures were recorded by Black (1933) from the Bahamas but he regarded them as an algal growth form, The growth of blue-green algae over a mud crack has also been observed by Shearman and others working in the Persian Gulf.

The unattached forms of Spongiostromata algae or Oncolithi are not so abundant in the Lower Purbeck. The examples seen closely resemble Pycnostroma Gurich but on a smaller scale. It should be noted that Johnson (1961) includes this in the Stromatolithi, but according to Gurich it is an unattached form. Ginsburg (1960), Johnson (1954) and Logan (1964) also refer to Pycnostroma as an Oncolithi, which indeed it seems to be (plate 26). In hand specimens the nodules appear as large pellets in a loosely cemented limestone. This is confirmed in this section where the nodules are seen to measure 850 - 1140µ in diameter, compared with the associated oolitic coated pellets of diameter 140µ. The Pycnostroma nodules are irregular in shape with alternating wide and narrow concentric laminations of 140µ and 30µ respectively. The wide laminations are of either micrite or sparite and alternate with thin bands

Plate 25. Algal mat surface showing initial uplifting around the edges of the polygonal desiccation cracks, from the Fossil Forest, Lulworth.

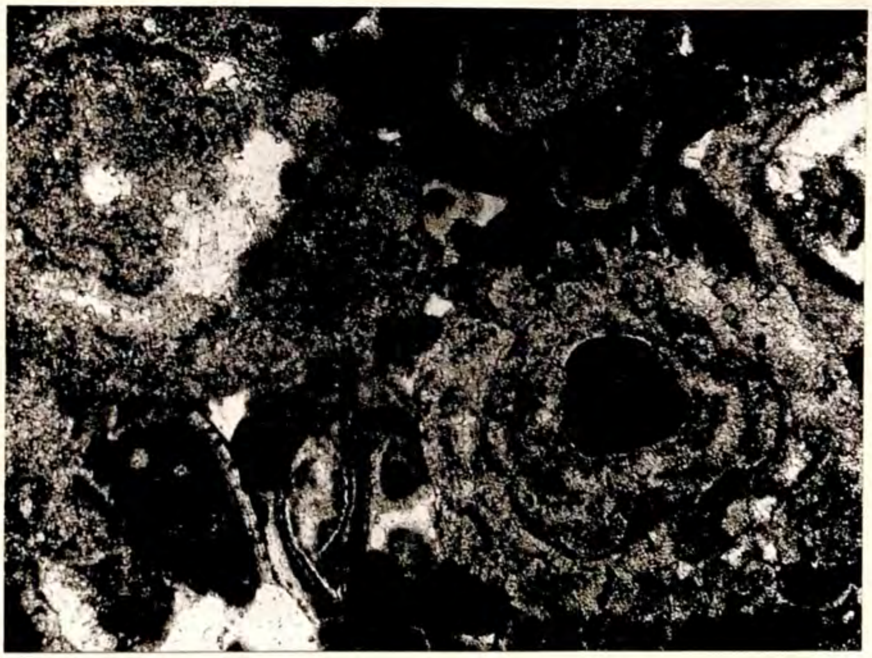


Plate 26. Section through two Pycnostroma colonies, The left one is partially obliterated by secondary calcite, 'Cypris' Freestones, Mupe Bay. X 56. M. 20.

of black matter. In the micrite portions there is a fine clotted granular appearance similar to those described previously. At the centre of the nodule is either a pellet or a shell fragment. Examples of this were found near the base of the 'Cypris' Freestones at Mupe and Worbarrow Bays and also from the uppermost exposed limestone at Portesham.

ii) Chlorophycophyta.

In contrast with the Spongiostromata, the green algae are relatively easy to recognise by their well-defined filaments. However, their distribution and abundance in the Lower Purbeck is much more restricted than the other groups described. The genera that are represented all belong to the family Codiaceae. This family includes algae with freely branching filaments which are grouped to form a definite shaped colony. Johnson (1961 and 1964) subdivided the Codiaceae into nodular forms, with closely packed filaments and erect forms, with loosely-packed usually segmented filaments. The nodular forms predominate in the Lower Purbeck limestones.

The various genera are identified by the mode of branching of their filaments. The most common genus is that with a simple bifurcating filament namely <u>Ortonella</u> Garwood. Another genus which at first appears very similar to Ortonella, is Cayeuxia Frollo. In this genus there is an initial acute angled bifurcation, but the filament then bends so that for the majority of its length it is parallel to the primary filament. In contrast with this simple bifurcation, the genus Hedströemia Rothpletz, produces a multiple forked arrangement of filaments from one point.

Ortonella. Nodular colonies of this genus are found in the Hard Cap and 'Cypris' Freestones. In the Freestones at Worbarrow Bay, the nodules appear as blisters of approximately 2 cm. diameter on the bedding planes. Centrally the nodules are composed of an indeterminate micrite in which are scattered tubes of circular cross-section, diameter 42 - 70µ. Radiating outwards from these are more filaments that branch dichotomously at approximately every 300µ or less, and at an acute angle from 25°-70° (plate 27). (Though strictly Ortonella filaments should branch at 40° according to Garwood 1914). No cross partitions were seen.

Often a complete colony is not seen, but instead isolated filaments occur, (but showing the simple bifurcation) within intraclasts.(plate 28). Where filaments are visible, such intraclasts can be termed algal intraclasts. These are sometimes associated with Stromatolites, an association which was also noted by Garwood.

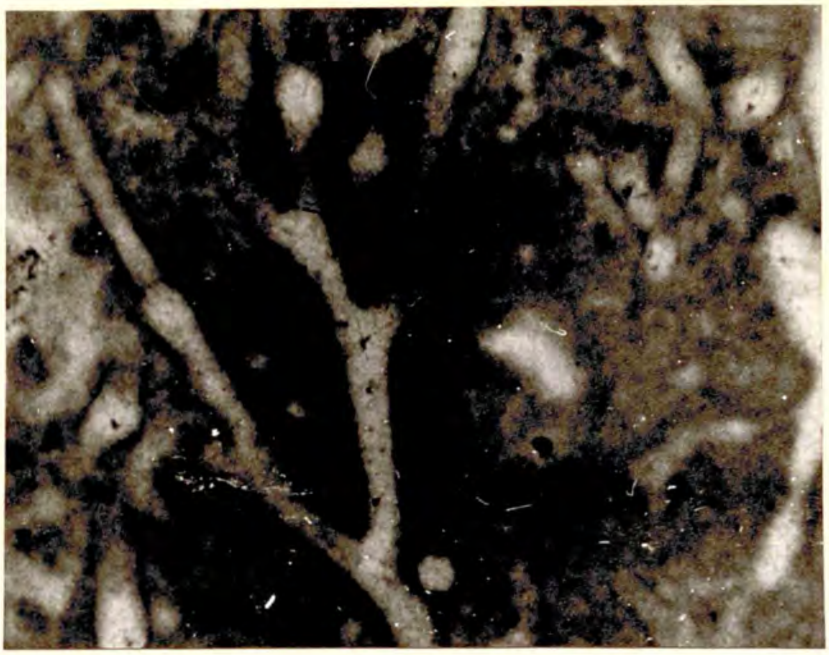


Plate 27. Branching filaments from an Ortonella colony, from the 'Cypris' Freestones, Worbarrow Bay. X 360. M.70.

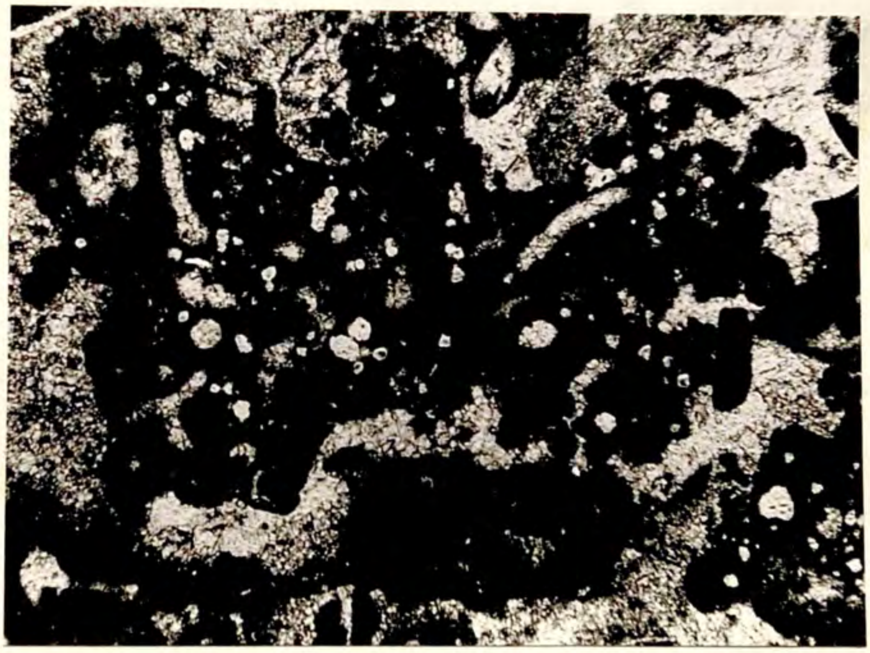


Plate 28. Algal intraclast, containing Ortonella filament, from the 'Cypris' Freestones, Suckthumb Quarry, Isle of Portland. X 105. PA. 16.

Cayeuxia. This genus is very much like Ortonella in macro- and microstructure. It forms almost spherical colonies of 10 - 15 mm. diameter, in the Hard Cap, at Perryfield Quarry, Portland. In the hand specimen these colonies show irregular concentric banding. This is probably due to the simultaneous branching of the radially arranged filaments. The angle of branching varies from 26°-35°, and the filaments are circular in cross-section with diameter of 60µ, (plate 29). No cross partitions were seen and since the filaments have a uniform width, this particular example is believed to be C. piae, as described by Frollo (1938).

Another species of Cayeuxia is seen in a specimen from the basal Hard Cap at St. Albans Head. This was identified as C. nodosa Anderson (1948) owing to the irregular width of the filaments which alternately bulge and contract (plate 30). Furthermore the angle of branching is 33°, which is in the range for the genus Cayeuxia.

Hedströemia. Only one example of this genus was found, and that was from the Hard Cap at Stair Hole. The genus apparently lacks the nodular form of the previous genera, since the filaments are very long and branching. The filaments have a diameter of 30 - 70 µ and lack cross partitions (plate 31).

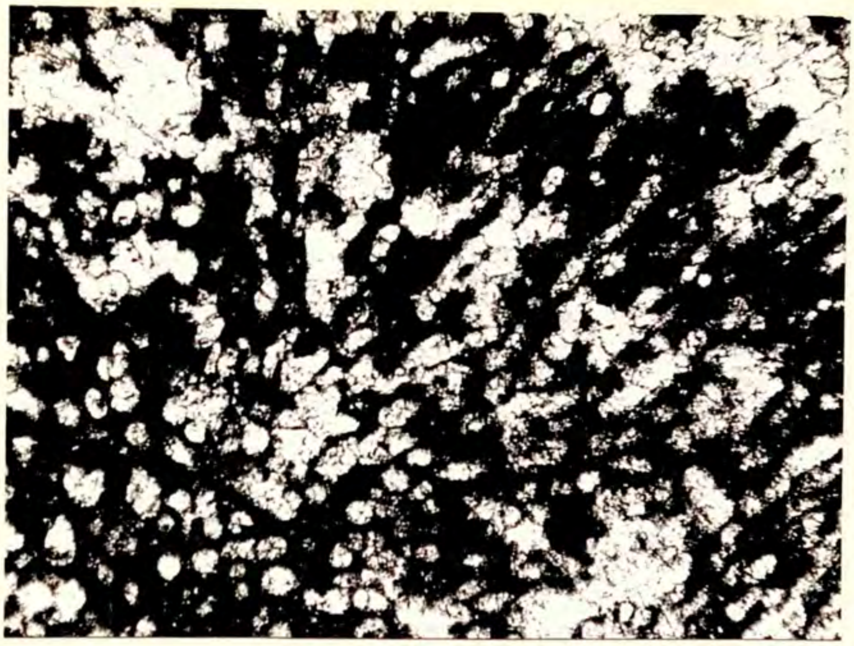


Plate 29. Part of Cayeuxia piae colony from the Hard Cap, Perryfield Quarry, Isle of Portland. X 140. P. 9.

Plate 30. Cayeuxia nodosa colony from basal Hard Cap, St. Albans Head. X 56. S.7.

iii) Rhodophycophyta

The only representative from this phytum belongs to the family Solenoporaceae namely Solenopora.

Solenopora. Examples of this are seen from the basal Hard Cap especially at Worbarrow Bay. The colonies appear as clusters of closely packed circular or polygonal shaped filaments (plate 32). The colony is usually about 3 mm. in diameter, and individual filaments vary from 36 to 80µ in diameter. In longitudinal section, cross partitions are seen (plate 33). The size and form of the filaments correspond closely to S. melobesoides as described by Pfender (1930). The colonies are associated with Girvanella and with some Codiacean algae.

Replacement-limestones

This name is applied by the present author, to limestones in which the calcium carbonate shows evidence of having replaced original evaporitic calcium sulphate minerals. Pseudomorphs of both euhedral gypsum and anhydrite are numerous, thus suggesting previously existing hypersaline conditions. Interlocking anhedral crystalline calcite identified by staining methods described by Friedman (1959) and Evamy (1963), is common in the replacement-limestones. This calcite is often intimately associated with euhedral pseudomorphs after calcium sulphate, and it is therefore tentatively suggested

Plate 31. *Hedströemia* sp, showing triple forked branching of filament, Hard Cap, Stair Hole, Lulworth. X175. L.51.

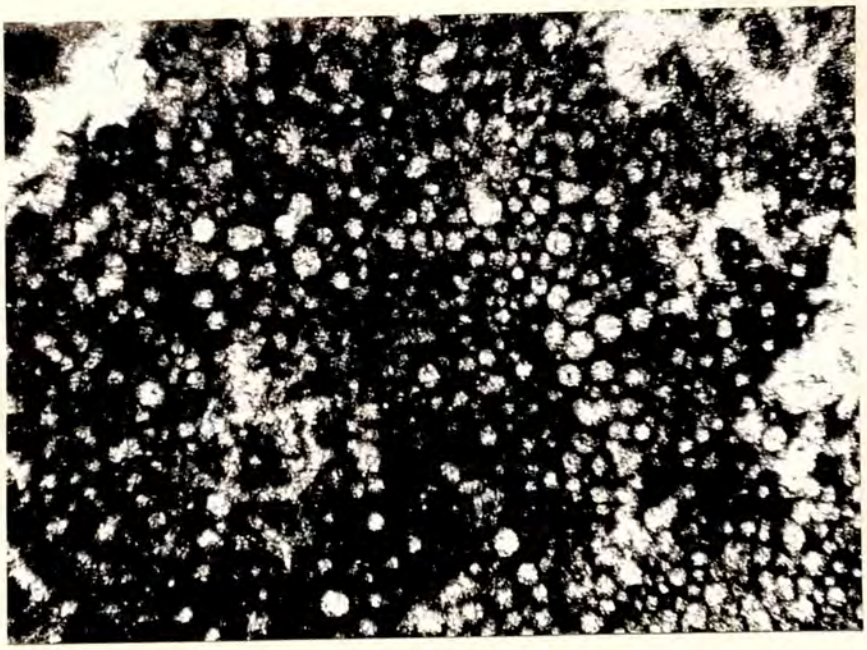


Plate 32. *Solenopora* *melobesoides* colony sectioned transversely, basal Hard Cap, Worbarrow Bay. X175. M51.

Plate 33. *Solenopora melobesoides* sectioned vertically to show cross partitions within the filaments, from the basal Hard Cap, Worbarrow Bay. X 315. M.51.

Plate 34. Hand specimen of laminated replacement-limestone , from the Soft Cap, Fossil Forest, Lulworth. X$\frac{3}{4}$. L. 101.

that this anhedral calcite represents replaced anhedral gypsum or anhydrite.

Locally within these limestones chalcedony and celestite is seen to replace both gypsum and anhydrite. Secondary e~~n~~uhedral quartz is also abundant especially at Worbarrow Bay.

Various stages in the diagenesis of the evaporite minerals have already been intensively studied by West (1960, 1964). This author distinquished five stages. Firstly lenticular gypsum was precipitated, which on compaction and crystal growth gave rise to anhedral gypsum. Subsequently with increasing overburden the gypsum altered to anhydrite, but this hydrated to gypsum on the removal of the overburden in Tertiary times. At first gypsum porphyroblasts occurred in the anhydrite but these grew until eventually no anhydrite was left. The sequence of gypsum altering to anhydrite and then hydrating back to gypsum is well known (Murray, 1964 and Borchert and Muir 1964). It was possible for West to recognise all these stages by reference to the Soft Cockle Beds and borehole material, as well as to the Lower Purbeck limestones (as defined here). It must be stressed at this point however, that no gypsum or anhydrite is now present in the Hard Cockle Beds or in the underlying Purbeck beds of Dorset since calcite, or chalcedony or celestite have completely replaced the evaporite minerals. The former presence of gypsum and anhydrite is deduced solely by the occurrence of pseudomorphs and 'ghosts' i.e. inclusions left after the removal of the original mineral but retaining the shape of this mineral.

The replacement limestones are to be found in the upper part of the Soft Cap from Portesham to Worbarrow, and in places are involved in the Broken Beds. The thickness varies from 2 to 4 feet. At Durlston Head, however, a much greater thickness is reached (approximately fifteen feet), but this is thought to include the Hard Cap and also much of the Broken Beds. Two thin strata, not more than one foot thick are also seen in the 'Cypris' Freestones, especially at Lulworth Cove. Tentatively classed with the replacement limestones are a few feet of strata at the top of the Hard Cap, from Portland to Mupe Bay which have rounded calcite grains and are therefore termed "detrital".

In the field the replacement limestones appear porous and/or laminated. Often they contain small lens shaped hollows arranged parallel to the bedding; such rocks have a spongy appearance and possess porosities varying from 13 to 27 per cent. Sometimes the rocks are well laminated and hard (plate 34) but sometimes they are soft, brown and crumbly. Typical examples of the latter type, which contain much quartz, are developed at Worbarrow Bay.

The replacement limestones are predominantly composed of crystalline calcite and anhydrite pseudomorphs. At Durlston Head, however the limestones show anhydrite ghosts and at the Fossil Forest euhedral gypsum pseudomorphs are abundant below the strata containing anhydrite pseudomorphs. The gypsum pseudomorphs, although easily recognisable and occurring in different situations are not really characteristic of the replacement limestones other than those at Lulworth, but are more often associated with pellet and algal limestones. Since gypsum and anhydrite both indicate hypersaline conditions and both have been replaced they are considered together. Furthermore halite is another evaporitic mineral and this also has been dissolved and its former presence is now indicated solely by pseudomorphs.

i) Anhydrite.

Pseudomorphs of anhydrite are found in the porous and laminated replacement limestones. They appear as well-defined rectangular or square crystals now replaced by a single crystal of calcite and set in a matrix of fine to coarsely crystalline calcite or occasionally micrite (plate 35 and plate 36). The scattered distribution of the euhedral anhydrite pseudomorphs within a crystalline groundmass suggests that the anhydrite was a secondary mineral.

Admittedly the evidence for identifying these pseudomorphs as anhydrite is not very convincing, but it should be remembered that anhydrite is abundant in the Lower Purbeck of Sussex (Howitt 1964), in the boreholes at Portsdown and Henfield (Taitt and Kent 1958) and from the Soft Cockle Beds of Dorset (West 1964). Therefore its occurrence in Dorset is not unlikely. In addition, the texture of these rocks greatly resembles that of the cap rocks overlying salt domes (Brown. L, 1931). In the cap rocks euhedral anhydrite crystals are scattered in a calcite groundmass and this has been referred to as net-texture.

Associated with the limestones with pseudomorphs, are limestones composed solely of clear crystalline calcite. It may be very fine grained, i.e. about 30 µ

Plate 35. Pseudomorphs of anhydrite in a crystalline calcite matrix, Soft Cap, Fossil Forest, Lulworth. X 25. L. 89.

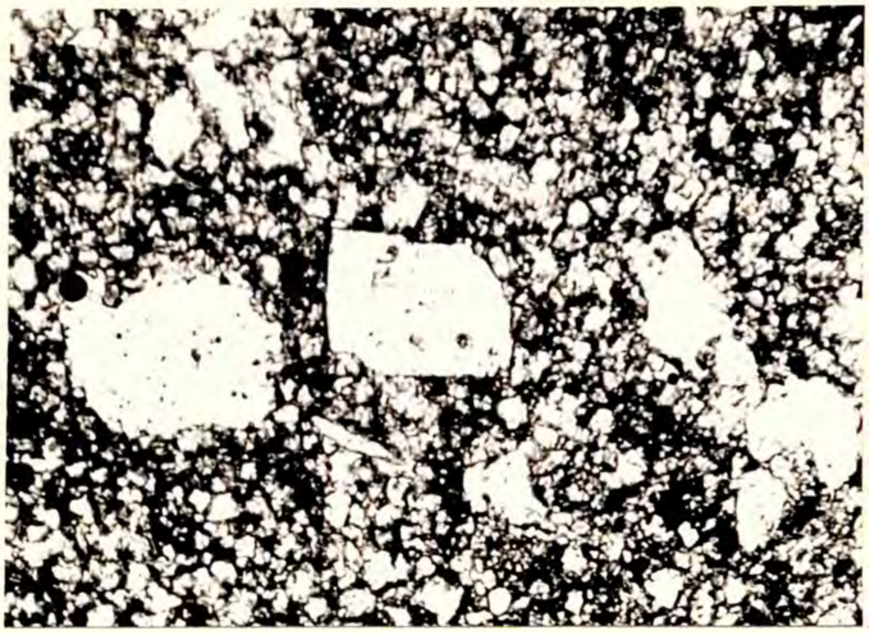


Plate 36. Enlarged view of pseudomorphs of anhydrite from the Soft Cap, Fossil Forest, Lulworth. X 245. L. 89.

in diameter, or coarse grained, with diameters ranging up to 250 µ. The purity of this calcite suggests that it is a replacement product as does the presence of pellets 'floating' within it. It is not possible, however, to determine the precise nature of the mineral or minerals, which have been replaced by the calcite. The original groundmass may have been fine-grained calcite, gypsum or anhydrite.

To return to the quartz-rich limestones at Worbarrow these are very porous and have a groundmass of coarsely crystalline calcite. Scattered within the groundmass are well-defined often doubly terminated quartz crystals, which may be up to 700 µ in length (plate 37). Sometimes the quartz crystals are arranged in rosettes (plate 38) and there is very little matrix so that the rock is crumbly. The presence of euhedral quartz does not in itself indicate hypersaline conditions, but according to Brown (1931), Tarr (1929) and Goldman (1952) such forms are often associated

Plate 37. Euhedral quartz crystals in crystalline calcite, Soft Cap, Worbarrow Bay. X. 360. M.60.

Plate 38. Rosettes of quartz crystals, Soft Cap, Worbarrow Bay. X. 460. M. 58.

with evaporite deposits or replaced evaporites.

As already mentioned the replacement limestones at Durlston Head, show anhydrite ghosts. The hard laminated limestones are composed of interlocking calcite crystals. Placed roughly within the centre of each calcite crystal is a patch of dark inclusions with a rectangular arrangement (plate 39). These patches are up to 500μ long and 70μ wide. In one part where the rock has been silicified the 'ghosts' are still visible in the chert.

Again, the clear calcite suggests replacement. It may be replacing either calcite or possibly gypsum, but since anhydrite readily hydrates to gypsum, the 'ghosts' left within the centres of the crystals could indicate the former presence of residual anhydrite. This would then favour gypsum as the replaced mineral.

Associated with these replacement limestones at Durlston Head, there is much celestite. This has already been described by West (1960). Euhedral rectangular blades of celestite occur within the crystalline calcite . Celestite is also seen to replace gypsum and also a rhomboidal mineral from the Freestones on Portland (plate40). No evidence is available as to the original nature of this replaced mineral.

Plate 39. Crystalline calcite with each crystal showing centrally placed anhydrite ghosts, Hard Cap, Durlston Head, X. 140. S.9.

Plate 40. A rhombic mineral now replaced by celestite 'Cypris' Freestones, Perryfield Quarry, Isle of Portland, X. 360. PA. 8.

ii) Gypsum.

As already mentioned this has a scattered and varied distribution. It may occur as isolated pseudomorphs, as randomly arranged groups within algal limestones or as orientated pseudomorphs parallel to the bedding. Only when found orientated parallel to the bedding, does it give rise to a recognisable stratum.

Isolated pseudomorphs are of a restricted distribution. Usually they are relatively large (up to 3 mm. in length), with well-defined boundaries and often associated with a crystalline matrix. Sometimes they are seen to enclose pellets or patches of micrite. The replacing mineral is most commonly granular calcite, but an example from the Isle of Portland was infilled by crystalline celestite (fig. 8). In one pseudomorph the centre was of celestite whilst the outer edges were of calcite. Large gypsum pseudomorphs are to be found scattered in the Soft Cap and 'Cypris' Freestones.

According to West (1964) the original gypsum was formed syngenetically within the sediment. That this was so is suggested by; their comparatively large size, their sharp outlines and the occurrence of pellets within them. In the case of both calcite and celestite replacing gypsum, it is possible that the calcite partially replaced the celestite which had previously replaced the gypsum.

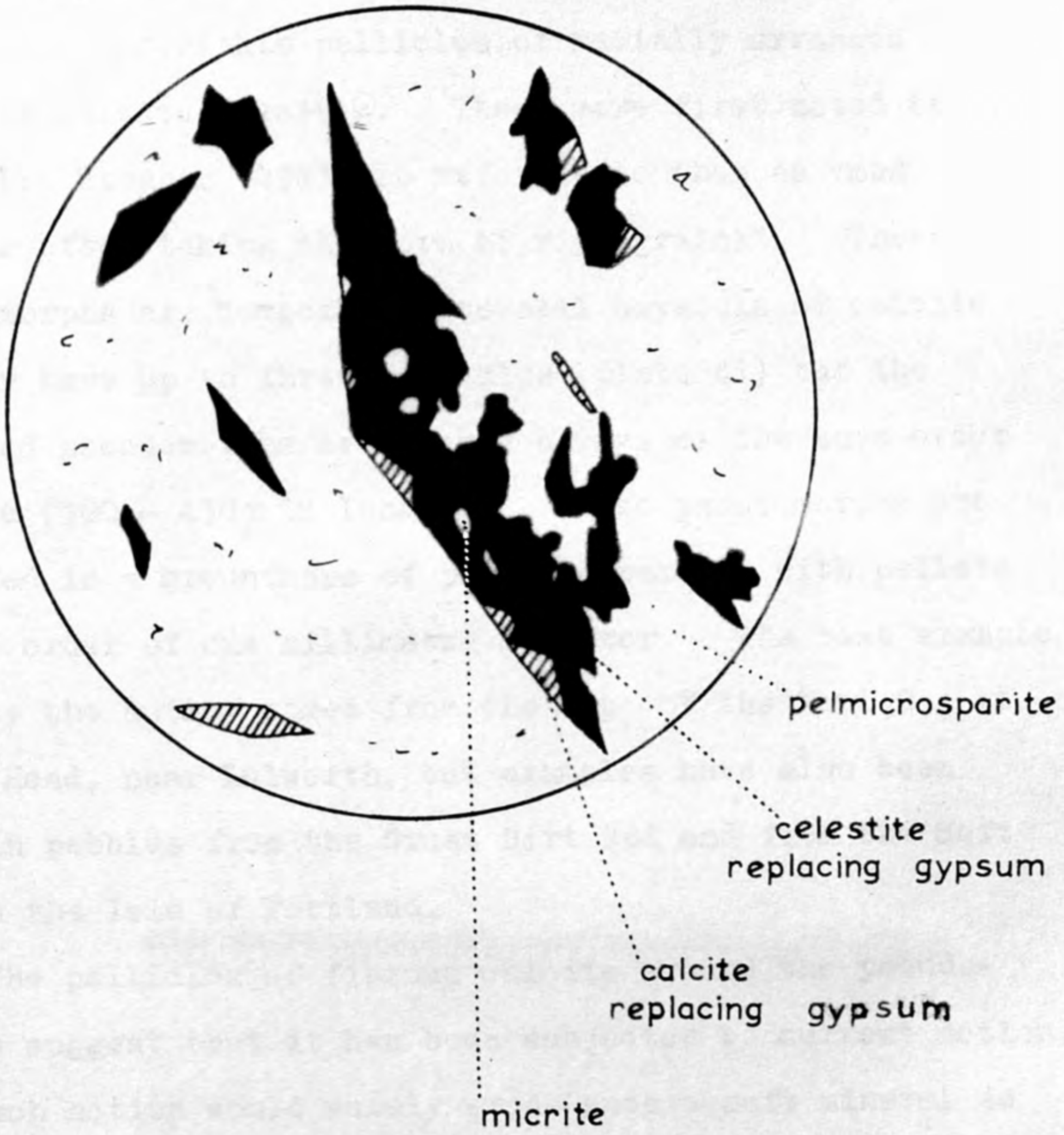


Figure 8. Diagram of a gypsum pseudomorph replaced largely by celestite, from the 'Cypris' Freestones, Perryfield Quarry, Isle of Portland. X 30. Pa.7.

Single or pairs of gypsum pseudomorphs are to be found enclosed within pellicles of radially arranged acicular calcite crystals. These were first noted by Teall (in Strahan 1898) who referred to them as "mud pellets often taking the form of rice grains". These pseudomorphs are composed of several crystals of calcite and may have up to three pellicles (plate 41) but the enclosed pseudomorphs are nearly always of the same order of size (300 - 430 μ in length). These pseudomorphs are situated in a groundmass of pelmicrosparites with pellets in the order of one millimetre diameter. The best example seen by the author comes from the top of the Hard Cap at Dungy Head, near Lulworth, but examples have also been seen in pebbles from the Great Dirt Bed and from the Soft Cap on the Isle of Portland.

The pellicles of fibrous calcite around the pseudomorphs suggest that it has been subjected to current action, yet such action would surely erode such a soft mineral as gypsum. It therefore seems likely that the gypsum was replaced by calcite prior to transportation.

Distinct from the pellicle coated pseudomorphs, are pseudomorphs enclosed within micrite intraclasts. These intraclasts are irregular in shape, occasionally with an outer pellicle of radial calcite, and are set in

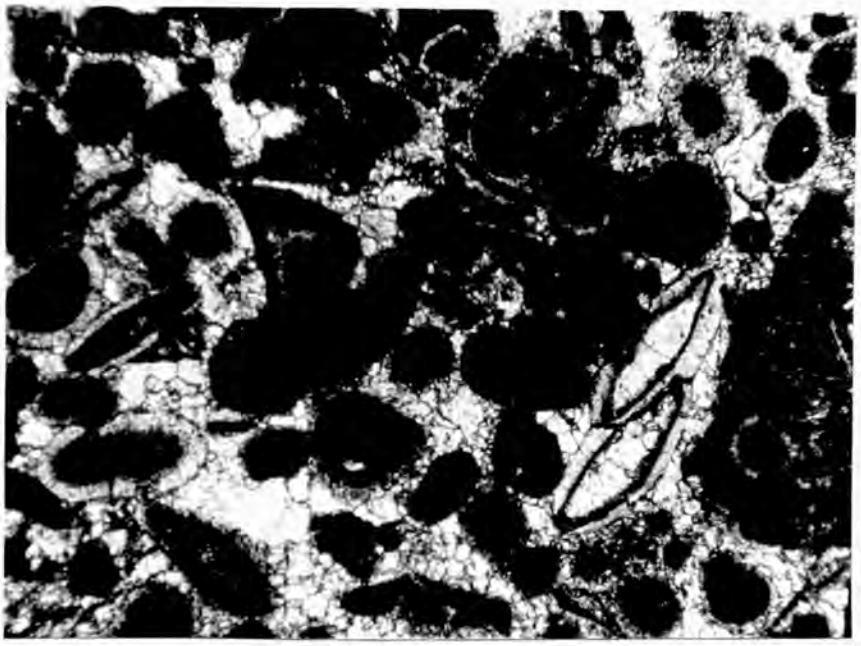


Plate 41. Two gypsum pseudomorphs enclosed by radial calcite in a pelsparite, from the Hard Cap, Dungy Head, near Lulworth, X. 56. L. 79.

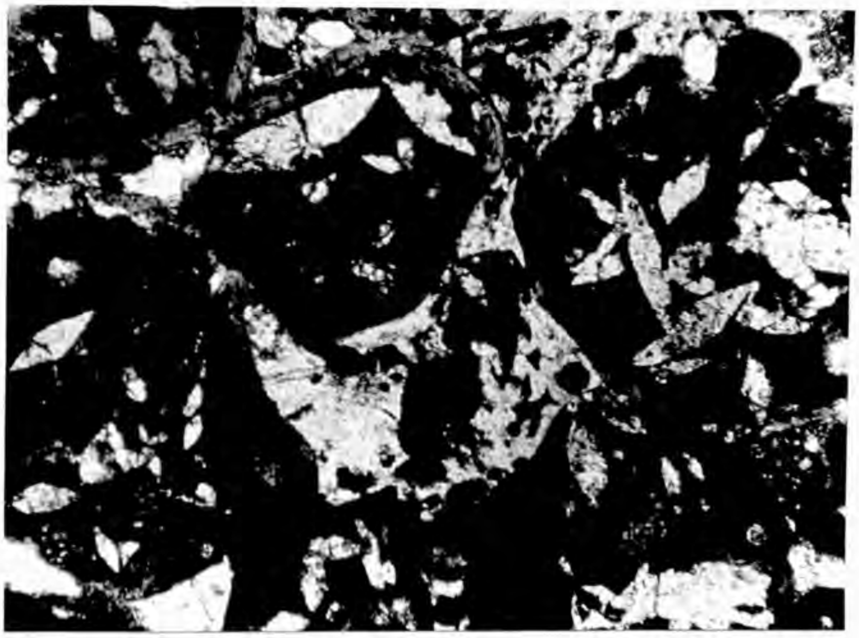


Plate 42. Gypsum pseudomorphs within intraclasts, now replaced by calcite which is in optical continuity with matrix. Hard Cap, Worbarrow Bay. X. 56. M.55.

a fairly porous, coarsely-crystalline calcite matrix. The enclosed gypsum pseudomorphs are generally composed of a single crystal of calcite which is often in optical continuity with that of the groundmass surrounding the intraclasts (plate 42). Examples of this texture occur in the Hard Cap at Worbarrow Bay (fig. 10). Very similar pseudomorphs were also observed from a sample from the same horizon at Mupe Bay. In this case, however, multi-granular calcite has replaced the gypsum.

The presence of gypsum pseudomorphs within micrite intraclasts, and not within the surrounding matrix, suggests the erosion of gypsiferous mud. During transportation the mud became rolled into intraclasts and coated with a calcite pellicle, by a mechanism similar to that producing the calcareous layers in ooliths. Assuming the micrite was impermeable, the gypsum could have survived transportation within the intraclasts and then have been replaced by calcite after deposition. In fact, the optical continuity of the calcitic matrix surrounding the intraclasts, with that of the gypsum pseudomorphs suggests that replacement by calcite took place after deposition.

Numerous examples of clusters of gypsum pseudomorphs are to be found within the Spongiostromata limestone. The pseudomorphs are small (up to 285μ long) and replaced by polycrystalline calcite. The pseudomorphs are distinquished from the groundmass by their micrite boundaries. Preferred orientation is apparently lacking (plate 43). Examples were seen in samples from the Hard Cap from Worbarrow to Lulworth Cove, from the Soft Cap at Lulworth and from a band in the 'Cypris' Freestones on the Isle of Portland.

The small size of the pseudomorphs, the micrite walls, together with micrite matrix, all suggest a primary origin for the original gypsum. The association of gypsum with algae is not unusual because Evans and others working in the Persian Gulf refer to the close association of gypsum and algal mats (personal communication). A similar association apparently occurred in Purbeck times. The explanation may be that saline water trapped between the algal mats, on evaporation became increasingly saline, until eventually gypsum was deposited. However, Hecht quoted in Revelle and Fairbridge (1957) stated that rotting organic matter releases sulphuric acid which reacts with the surrounding carbonate to give gypsum. This may account for some of the gypsum but since certain stromatolites are known to be restricted to hypersaline bays in W. Australia at the present day (Logan 1961), the explanation given previously seems more likely.

Finally, gypsum pseudomorphs either as hollows or replaced by other minerals, occur orientated with their c-axes parallel to the bedding. The best examples are

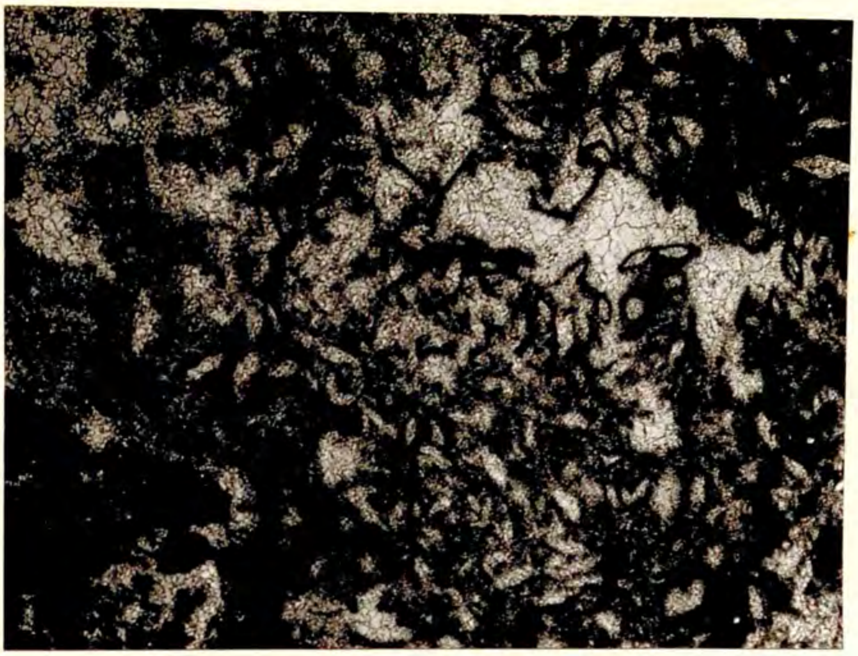


Plate 43. Gypsum pseudomorphs within pockets of Spongiostromata limestone, from the Soft Cap, Lulworth Cave. X.80. L.7.

Plate 44. Pseudomorphs of gypsum replaced by chalcedony, Soft Cap, Fossil Forest, Lulworth. X.360. L.86.

seen in the Soft Cap at the Fossil Forest, Lulworth, where a siliceous band, of gypsum moulds up to 3 mm. in length, occur. In places this band passes into a chert layer which 'laps' around the "burrs" and when sectioned reveals orientated gypsum completely replaced by granular chalcedony (plate 44). In places silicification has not occurred and the gypsum has been replaced by polycrystalline calcite.

The preferred orientation of the gypsum pseudomorphs suggests that these were deposited as crystals from standing water, and together with associated algal mats gave rise to laminated limestones (plate 34).

iii) Halite.

Pseudomorphs of this mineral are quite widespread throughout Dorset, but they are usually associated with pellet limestones and do not give rise to replacement-limestones. It is included here merely for convenience and because it is characteristic of hypersaline conditions, as are both gypsum and anhydrite.

Salt pseudomorphs are most common in the 'Cypris' Freestones, but they are also seen in the Broken Beds and Soft Cap. They occur in the Freestones from Portland to Worbarrow, especially in the upper part.

These pseudomorphs differ from the others previously described in that they are not replaced by another mineral, but are infilled with sediment, usually pellets. The complete pseudomorph is never seen, only the lower or upper part, which protrudes from the bedding plane (plate 45). Specimens are seen in which pseudomorphs protrude both on the upper and lower surface of the rock sample. The pseudomorphs on the lower surface are much more common and are readily explained as sediment infilled moulds, which were left after the salt dissolved. The pseudomorphs on the upper surface are more difficult to account for, because one would expect them to appear as depressions rather than projections. It may have been that the salt crystals were full of impurities which remained in situ after the salt was leached away.

The pseudomorphs are often hopper-shaped, and as pointed out by Shearman (personal communication) are arranged in groups with the pseudomorphs in a particular group, all having the same orientation (plate 45). Since no sun-cracks have been seen in the 'Cypris' Freestones, it is thought that the halite crystals must have been precipitated in shallow water. Salt however, usually crystallizes out as a crust on the surface of standing water. The salt crystals in this crust,

Plate 45. Hand specimen showing halite pseudomorphs arranged in groups, 'Cypris' Freestones, Fossil Forest, Lulworth. X 1 1/6.

presumably have a preferred orientation. It is therefore suggested that when the crystals became sufficiently large they sank to the bottom. In so doing groups of crystals became detached from the crust and in settling lost the overall preferrred orientation. Within each crystal fragment however, the preferred orientation was maintained.

iv) "Detrital".

Throughout the Dorset coast except at Durlston Head, the top of the Hard Cap shows some lamination, and was referred to by Brown (1963) as a bedded "detrital" limestone. These limestones are considered here, rather than with the pellet limestones because some of the pellets appear to have been replaced by calcite. In thin sections, these limestones are seen to vary from pellet limestones to those containing pellets associated with round calcite grains. These grade into porous bands containing circular hollows and finally into rocks containing rounded areas of granular calcite within a micrite groundmass.

At Mupe Bay, the limestones are predominantly pelsparitic but scattered throughout are rounded grains now composed of a single calcite crystal, with diameters ranging from 140 to 300 μ (plate 46). Sometimes these rounded grains are surrounded by a pellicle of radial calcite. Quite often the central calcite grain or pellet has been leached out so that the pellicle is left surrounding a circular hollow (plate 8). Laminae of similar rounded calcite grains, and circular hollows without a pellicle are seen at Lulworth.

Both from the field and thin section evidence these sediments would appear to be mechanically deposited limestones. The occurrence of large round clear calcite grains is unusual. Since several kinds of pseudomorph now composed of calcite have been recognised, it seems quite possible that the clear calcite is pseudomorphing some other mineral. According to Dunham (1948) and Sloss (1953) evaporites may be deposited mechanically from pre-existing evaporites, such as the saccaroidal dolomites which show cross-bedding and features typical of quartz sand. Since samples from the same horizon at Dungy Head show pellicle coated gypsum pseudomorphs, as already described, there is the possibility that the rounded grains of clear calcite may have replaced eroded grains of evaporite minerals.

However, other samples collected from the same horizon show multigranular crystalline calcite patches within a micrite. In one instance these patches had developed to such an extent, that the rock was almost entirely composed of finely crystalline calcite with irregular brown markings separating one area from another. In general, the appearance is that of a pelmicrite in which the pellets have been replaced by calcite.

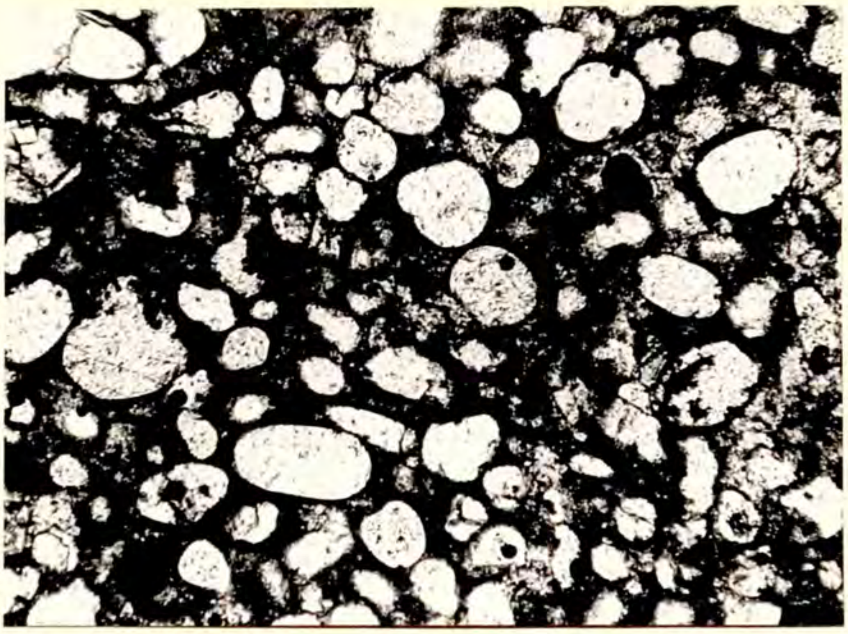


Plate 46. Rounded grains of single calcite crystals, Hard Cap, Fossil Forest, Lulworth. X. 100. L.105.

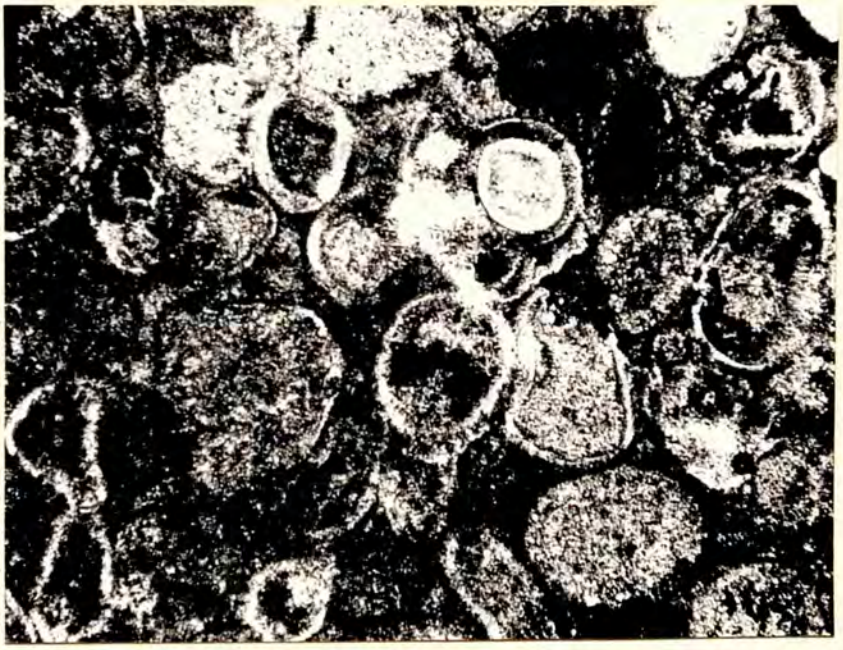


Plate 47. Silicified portion of limestone fragment from the Great Dirt Bed, showing preservation of pellets, Fossil Forest, Lulworth. X.140. L.121.

In fact, a fragment of limestone collected from the Dirt Bed showsevidence that the pellets had been replaced. Most of the fragment was seen to be full of rounded hollows, but one small portion had been silicified. In this, pellets of the same order of size as the hollows, are abundant. Some of the pellets have pellicles and in some the micrite core has apparently undergone grain growth giving rise to finely crystalline calcite (plate 47). In addition, some of the fibrous calcite of the pellicles has recrystallised to sparry calcite, thus suggesting that silicification preserved some of the original textures. In the unsilicified part, subsequent leaching out of the minerals occurred and left circular cavities.

This concept of grain growth may also account for the unigranular, often angular, calcite grains with diameters of approximately 70 to 300µ, which occur in pelmicrite (plate 48). The frequent occurrence of cavities of similar size and shape suggests that such grains were formerly even more abundant but that many were subsequently leached out.

After considering this other evidence, it is possible to suggest that the rounded calcite grains mentioned earlier, are a result of grain growth, followed by erosion and deposition of the beds. In which case an evaporitic origin is ruled out. The sequence of events may have been as follows:- for some unknown reason, initial grain growth began within a pelmicrite or micrite and patches of slightly coarser crystalline calcite were formed. Continual grain growth eventually resulted in large single grains of calcite scattered within a matrix of micrite. These beds may then have been eroded, the large calcite grains rounded or coated with a pellicle of radial fibrous calcite and finally deposited to give a calcarenite.

Brown (1963) suggested that the 'detrital' limestones were the result of replaced ooliths. Yet again this may be the explanation, but the only convincing oolicasts seen by the author were from Dungy Head. In these the original concentric layering is still visible, because the sparry calcite replacing the radial fibrous carbonate is restricted in crystal size to the width of a particular layer (plate 49). Furthermore, the micrite pellet which formed the nucleus of the oolith is often present, but is not always centrally placed. Textural evidence suggesting the former existence of ooliths has not, however, been found by the author in the majority of specimens from the top of the Hard Cap.

In conclusion, it may be said that no really satisfactory explanation can be found to account for the "detrital" limestones, but of those considered, the concept of grain growth prior to erosion and redeposition seems the more likely explanation to the present author.

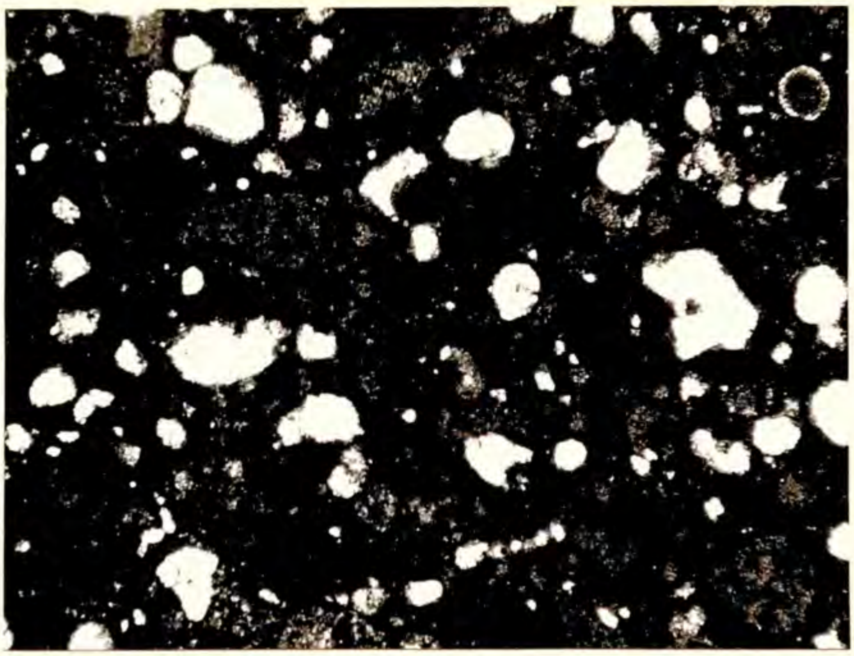


Plate 48. Angular calcite grains within a pelmicrite, from the Hard Cap, Isle of Portland, X. 100. P.92.

Plate 49. Ooliths replaced by crystalline calcite, except for the nucleus of micrite, from the top of the Hard Cap, Dungy Head, near Lulworth. X. 175. L.80.

Shell-Limestones

These limestones consist essentially of shell debris which is usually associated with a sparry calcite matrix. The coarse variety or 'coquina' is composed of lamellibranch and gastropod shell fragments together with a few serpulid tubes. The finer variety or 'microcoquina' consists largely of ostracod valves and a few gastropods. Shells are not very abundant throughout the Lower Purbeck and only occur in rock building proportions in the Hard Cockle Beds or locally in the 'Cypris' Freestones. More frequently the shells are restricted to certain bedding planes; for example the bedding planes strewn with lamellibranch valves in the 'Cyrpis' Freestones. Hydrobia moulds and lamellibranch valves have a similar arrangement in the basal Hard Cap of Portland.

i) Coquina.

True coquina limestones are seen in the Hard Cockle Beds from Worbarrow to Lulworth. These limestones are hard and grey, but have often weathered so as to give a porous appearance. The hard coquina limestones form two prominent ledges along the cliff tops, and are separated by either a soft band of quartz silt or a pellet limestone with associated quartz silt.

The majority of the shelly material is composed of fragmental lamellibranch valves and these are therefore difficult to identify. At the base of the Hard Cockle Beds at the Fossil Forest unbroken lamellibranchs with their valves united are seen in a silty pellet limestone, and these can be identified as <u>Protocardia purbeckensis</u> de Loriol. Much of the fragmental shell material appears to be derived from this genus and the name 'Cockle Bed', refers to its abundance in the coquinas.

Other shelly material is derived from species of <u>Hydrobia</u> and <u>Planorbis</u> (plate 50). The <u>Hydrobia</u> spp. are often preserved as complete specimens, probably on account of their small size since their length rarely exceeds two millimetres. Also scattered within these limestones are serpulid tubes and algal intraclasts.

The matrix of these limestones is usually sparry calcite, and rarely micrite. It has been observed that the shell material is usually composed of sparite in the form of a drusy mosaic irrespective of the nature of the nature of the matrix (plate 51). In the case of a sparite matrix the shelly material is only visible because of a dense micrite sheath which surrounds it. According to Bathurst, in Imbrie and Newell (1964) this micrite sheath is the result of micrite infilling borings made by algae in the outer layers of the shell. Associated with the shelly debris are pellets and quartz silt.

For convenience, mention is made here of the lamellibranches seen on the bedding planes in the 'Cypris' Freestones. Although these are preserved only as moulds, they are thought to be species of <u>Neomiodon</u>. Similar moulds occur at the very base of the Purbeck, especially on the Isle of Portland, together with Hydrobia moulds. In addition, Hydrobia shells were seen to cover a bedding plane in the 'Cypris' Freestones near Freshwater Bay, Portland. These shells were nearly all positioned with their apices pointing in one direction, as if orientated by current action.

ii) Micrococquina.

This type of limestone rarely forms a thick stratum in the Lower Purbeck. The ostracods which typify it, do however, form limestone bands in the 'Cypris' Freestones especially at Worbarrow Bay, where complete ostracod valves are found. Micrococquina also occurs in the Hard Cap at Burning Cliff and in exposures west of this. The ostracods present have been identified as Cypris purbeckensis Forbes and Candona ansata Jones.

The ostracod valves are usually present as single valves as seen in samples from the Isle of Portland. The valves in this instance however, are seen to cap a small area of micrite (plate 52), and are set in a groundmass of sparite. This suggests erosion of a micrite rich in ostracods, with the subsequent removal of all the micrite except that protected under the ostracod valves. Quite often the valves may be piled one on top of another like stacks of inverted saucers (plate 53). Presumably, after being washed around by currents they came to settle in this manner.

Plate 50. *Hydrobia* sp. and shell debris in a sparite matrix, from the Hard Cockle Beds, Fossil Forest, Lulworth. X. 100. L.136.

Plate 51. Secondarily replaced lamellibranch valves in a micrite matrix, from the Hard Cockle Beds, Fossil Forest, Lulworth. X. 100. L. 133.

The valves are composed of fibrous calcite and are often set in a sparite groundmass. Associated with the ostracods are pellets, gastropods and sometimes algal intraclasts.

Plate 52. Ostracod valves capping patches of micrite, from the Hard Cap, Isle of Portland. X. 25. P.29.

Plate 53. Ostracod valves piled together presumably as a result of current action, from the 'Cypris Freestones', Mupe Bay. X.150. M.22.

CHAPTER 3

DISTRIBUTION OF LIMESTONE TYPES

The fourfold division of the Lower Purbeck limestones into algal, replacement-, pellet- and shell-varieties corresponds roughly to the Hard Cap, Soft Cap, 'Cypris' Freestones and Hard Cockle Beds respectively. However, the detailed succession is not quite so simple since bands of other limestone types occur in sequences which are predominantly of a particular type. For example, thin layers of replacement-, algal- and shell-limestones are interbedded with the pellet-limestones which are characteristic of the 'Cypris' Freestones.

In order to appreciate the thickness and especially the vertical distribution of the limestones, the reader is referred to the detailed sections of figs. 9-15. The lateral variation is seen in the comparative sections of fig. 16, but it is felt that minor details which are not readily visible in this figure need more attention. The variations within the successive beds is therefore given in more detail.

The Hard Cap

Unfortunately the basal Hard Cap is not readily accessible at Durlston Head, the easternmost exposure, because of the sheer sea cliffs. It has also been subjected to much faulting. The basal Hard Cap is more easily seen west of Winspit or at St. Albans Head, where the beds are laminated for a few inches and then overlain by '**tu**faceous' limestone. The lowermost beds contain algal filaments possibly of *Girvanella* sp. and

VERTICAL SECTION AT DURLSTON HEAD

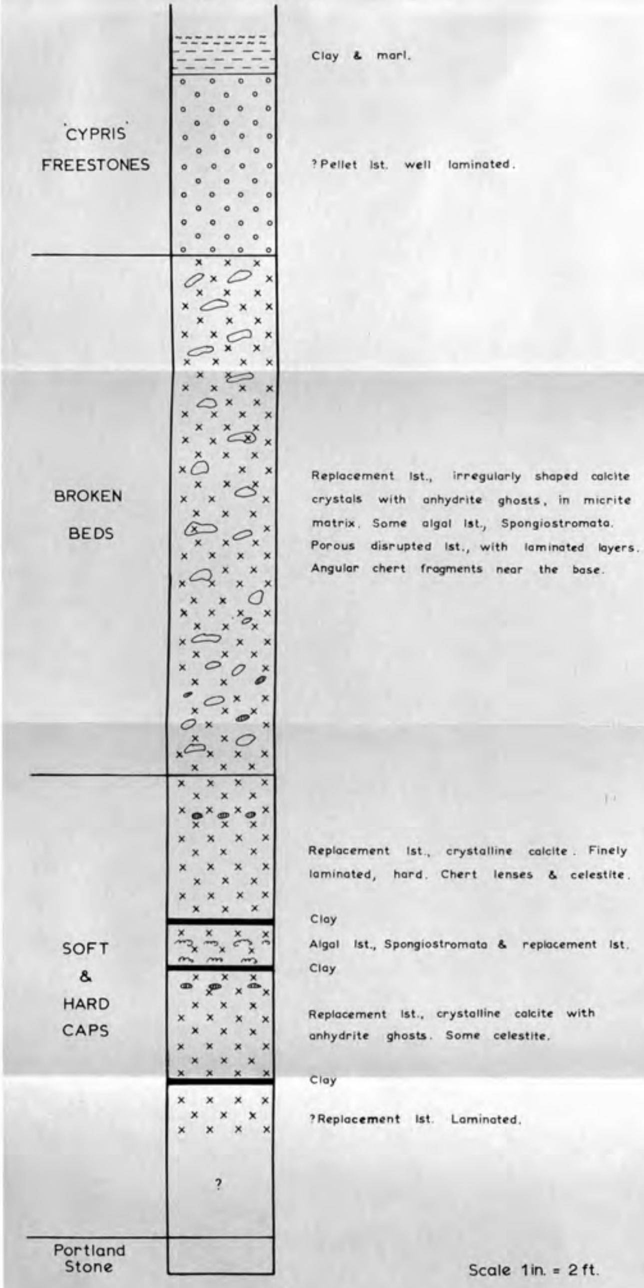
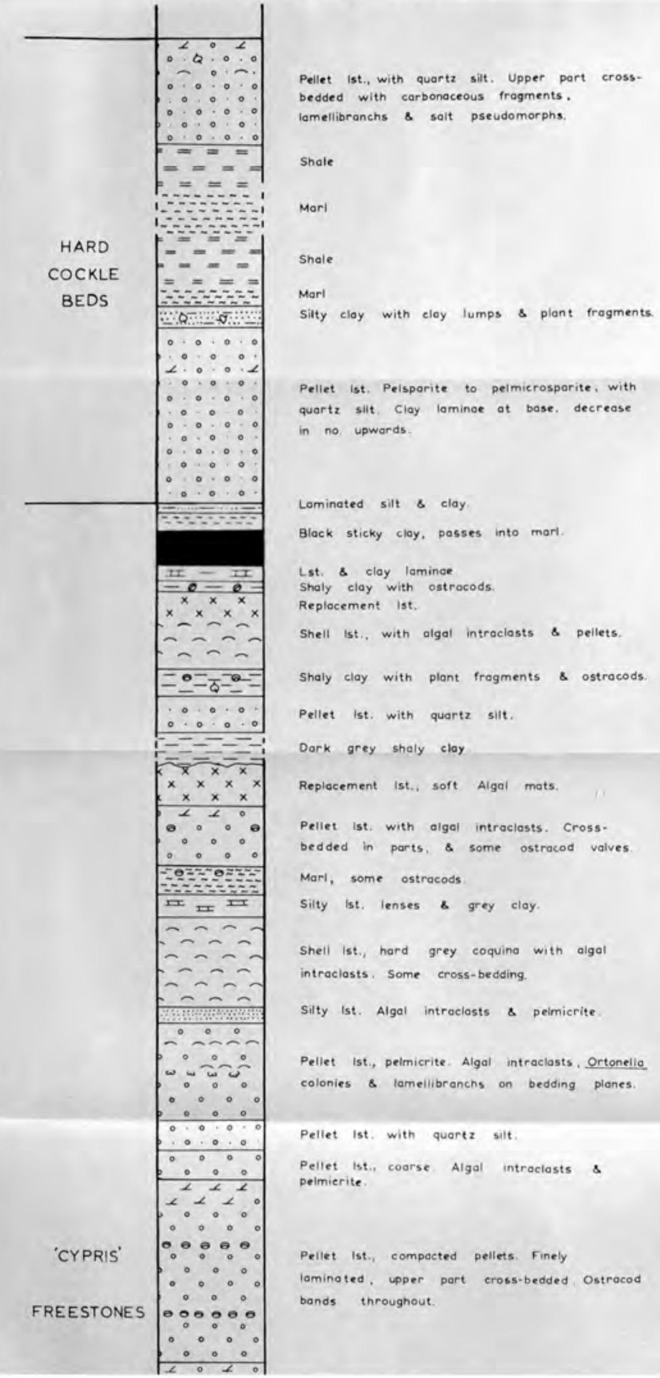


Figure 9. Vertical section at Durlston Head.

VERTICAL SECTION AT WORBARROW BAY



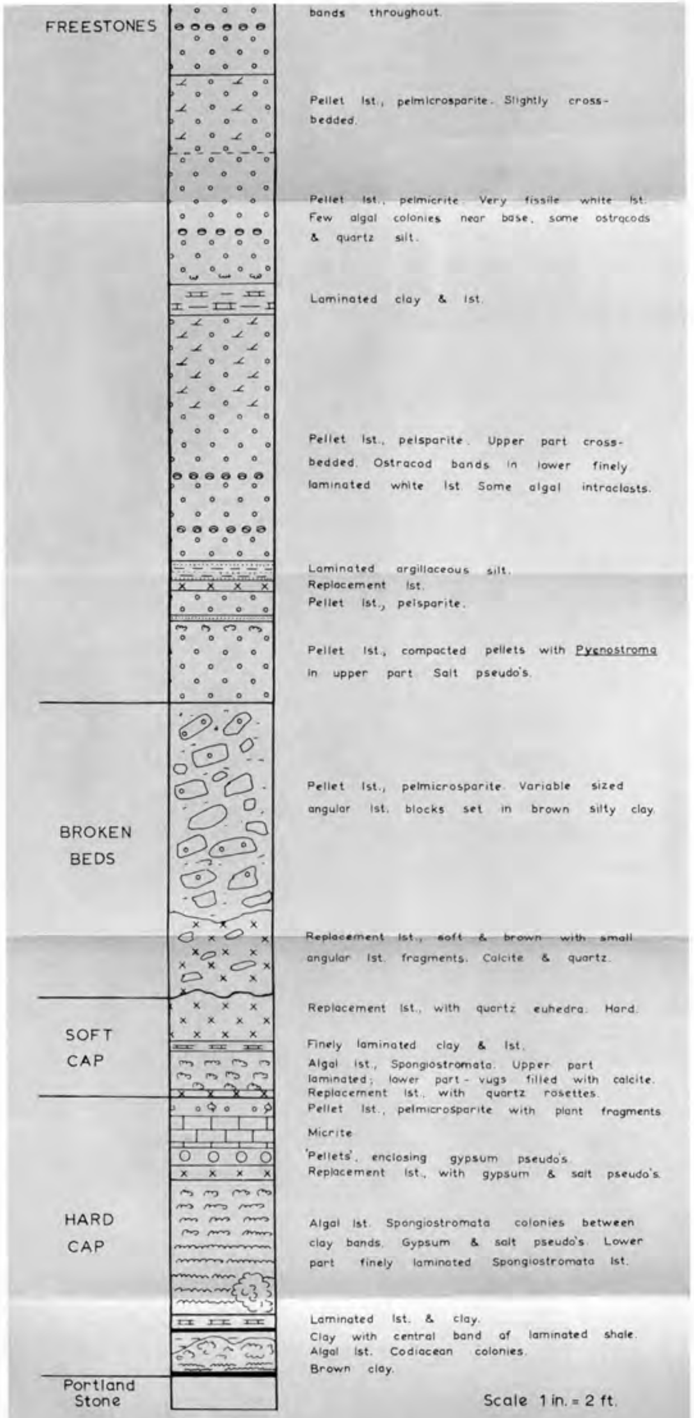
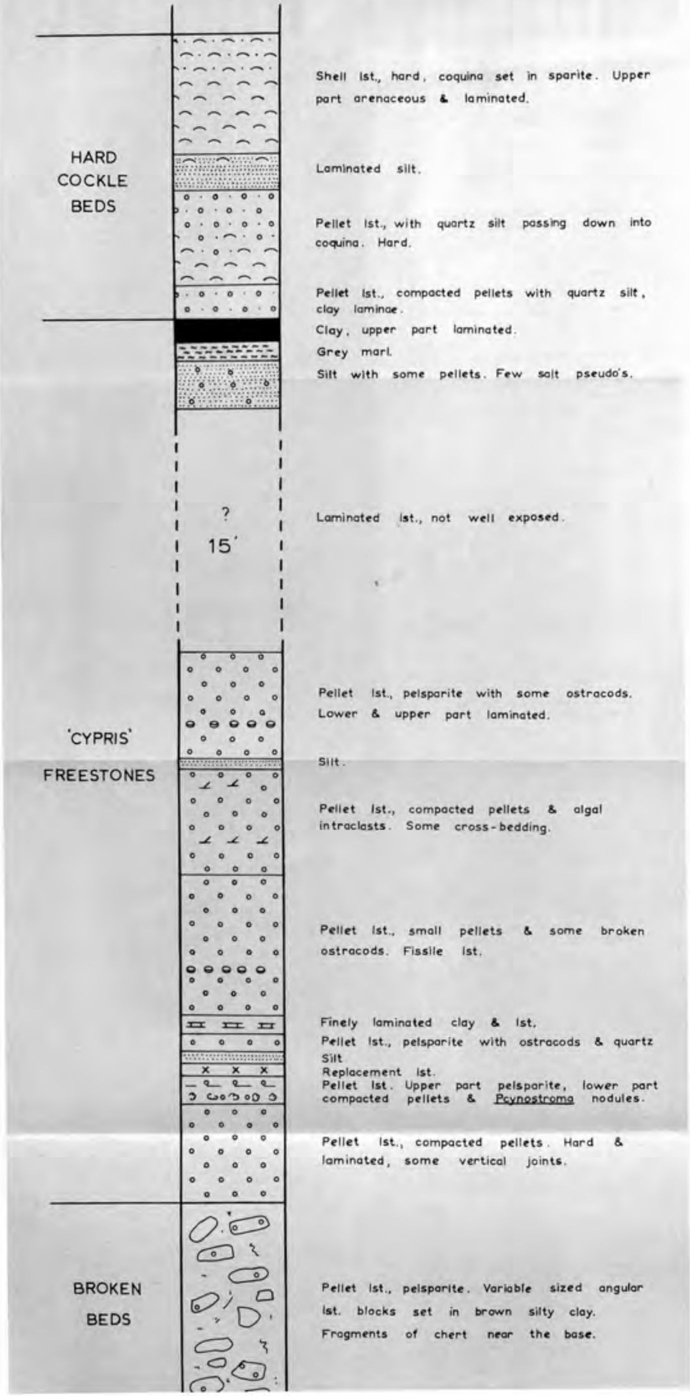


Figure 10. Vertical section at Worbarrow Bay.

VERTICAL SECTION AT MUPE BAY



Shell lst., hard, coquina set in sparite. Upper part arenaceous & laminated.

Laminated silt.

Pellet lst., with quartz silt passing down into coquina. Hard.

Pellet lst., compacted pellets with quartz silt, clay laminae.

Clay, upper part laminated.

Grey marl.

Silt with some pellets. Few salt pseudo's.

Laminated lst., not well exposed.

Pellet lst., pelsparite with some ostracods. Lower & upper part laminated.

Silt.

Pellet lst., compacted pellets & algal intraclasts. Some cross-bedding.

Pellet lst., small pellets & some broken ostracods. Fissile lst.

Finely laminated clay & lst.

Pellet lst., pelsparite with ostracods & quartz silt

Replacement lst.

Pellet lst. Upper part pelsparite, lower part compacted pellets & Pcynostroma nodules.

Pellet lst., compacted pellets. Hard & laminated, some vertical joints.

Pellet lst., pelsparite. Variable sized angular lst. blocks set in brown silty clay. Fragments of chert near the base.

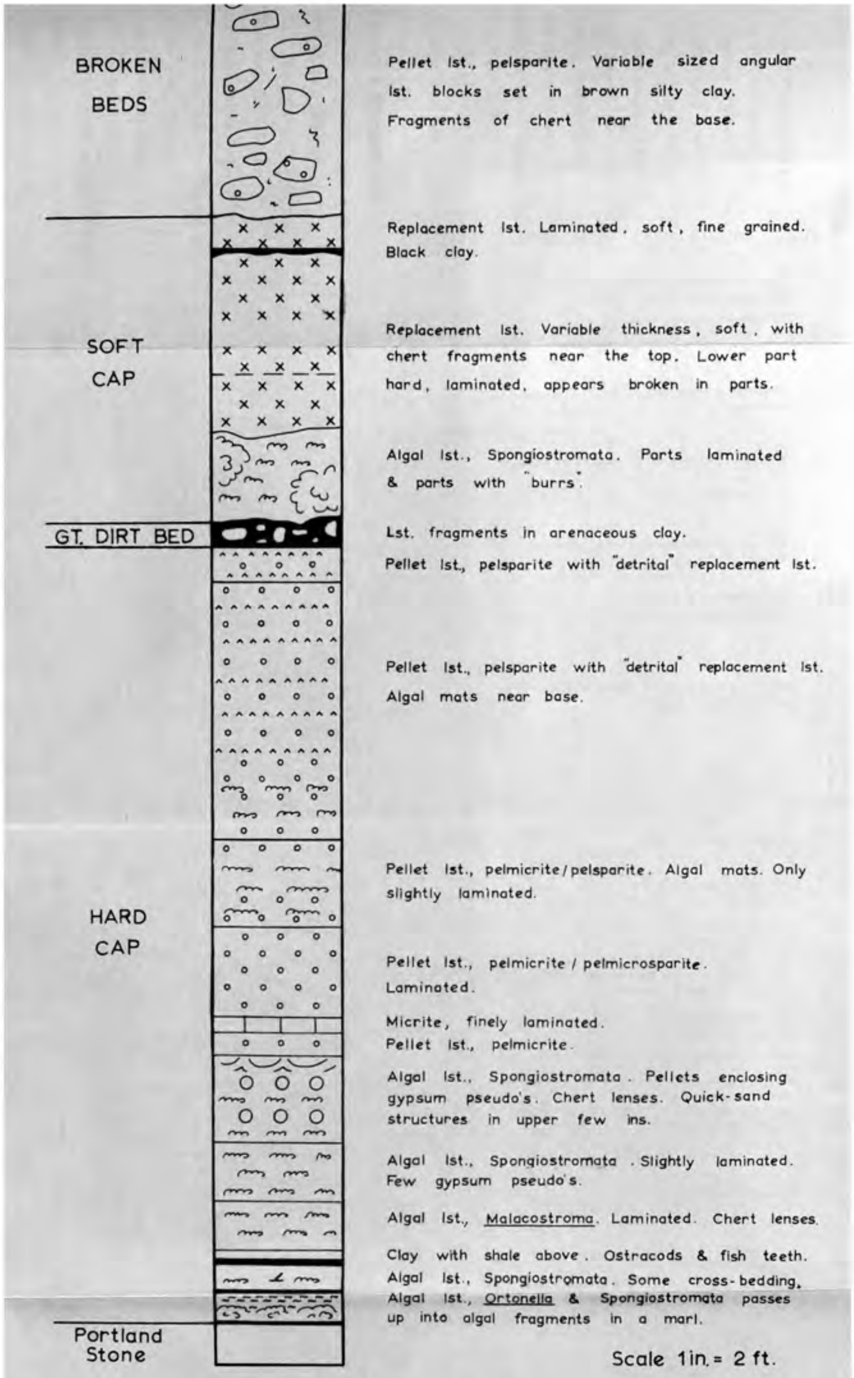


Figure 11. Vertical section at Mupe Bay.

the overlying limestone is undoubtedly algal with Spongiostromata and Solenopora colonies. A similar algal base is seen at Worbarrow and Mupe Bays. At Worbarrow it is approximately one foot thick but at Mupe Bay thins to six inches and is not seen at Lulworth Cove. Besides Spongiostromata algae, there are also Ortonella colonies in this basal limestone. At Lulworth and Dungy Head the basal Purbeck consists of five to six feet of continuous hard limestone, again with Spongiostromata, but at Lulworth the one example of Hedstroemia so far found by the author came from this level.

Farther westwards at Burning Cliff, Poxwell, Bincombe and Portland the basal Purbeck is not algal. It is essentially a calcilutite band one or two feet thick, with moulds of Hydrobia and Planorbis. At Portesham, the westernmost exposure, the base of the Purbeck is apparently a three inch clay seam with carbon fragments and fish scales.

Throughout Dorset the remainder of the lower part of Hard Cap is largely composed of Spongiostromata limestone but with local variations. At Durlston Head there is only a small amount of this limestone since replacement limestones reach a considerable thickness and are thought to extend down into the Hard Cap. At Lulworth, Mupe and Worbarrow Bays the algal limestone is largely laminated (plate 54) and is associated with gypsum pseudomorphs which occur either within pockets in the limestone or within intraclasts. From Burning Cliff to Portesham minor clay seams occur in the lower half, and have been called dirt beds. Interbedded with these is the Spongiostromata limestone, but this is a more nodular form than that at Mupe and Worbarrow Bays. Individual algal heads (plate 18), are visible and surround cylindrical hollows, believed to have been left after the decay of vegetation. Gypsum pseudomorphs are absent, but instead bands of ostracods and colonies of Codiacean algae are more widespread, for example, the Cayeuxia colonies on the Isle of Portland.

At Burning Cliff and Portesham the nodular Spongiostromata limestone is reduced to a one foot band or less near the base of the Hard Cap. The succeeding beds are similar to those at Portland, being composed of pellets, ostracods and at Portesham, Girvanella colonies.

In contrast with the local variation of the lower part of the Hard Cap, the upper two to three feet are not so varied. From Worbarrow to Portland the upper part consists of micrite followed by the 'detrital' replacement-limestones. These do not occur at Durlston Head, but reach a maximum thickness from Worbarrow to Lulworth and thin towards the Isle of Portland. At Mupe Bay, the 'detrital' limestones are exceptionally thick and result in the Hard Cap being thicker there, than either at Lulworth or Worbarrow (plate 55).

At Portesham the 'detrital' limestones are absent, but the upper part of what is believed to be the top of the Hard Cap is composed of a laminated pelmicrite with chert lenses.

Plate 54. Irregularly laminated algal limestone from the Hard Cap, Worbarrow Bay.

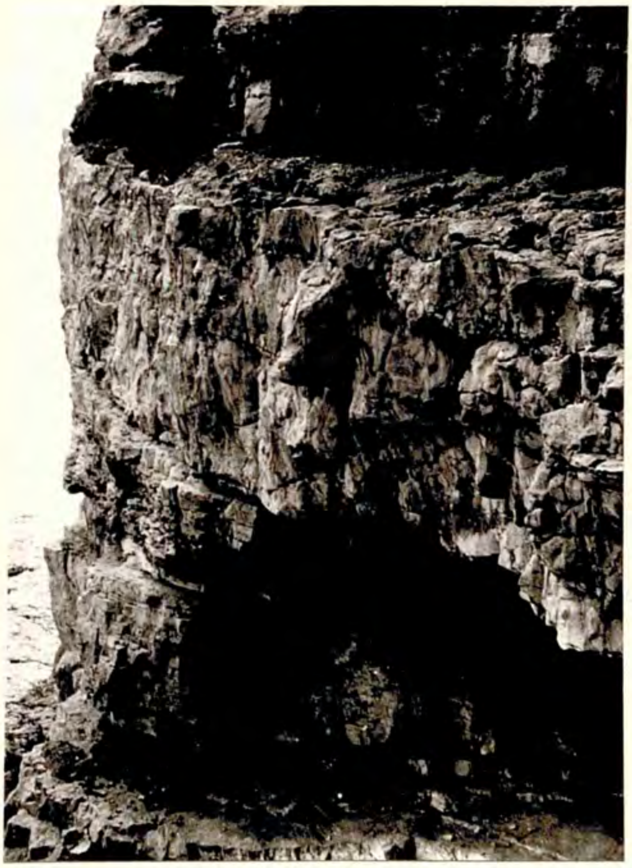


Plate 55. The Hard Cap, as seen at Bacon Hole, Mupe Bay.

In parts the chert apparently replaces small gypsum pseudomorphs.

Great Dirt Bed

Resting on the Hard Cap there is frequently a poorly sorted essentially argillaceous band known as the Great Dirt Bed. Its characteristic feature is the presence of irregular shaped limestone fragments scattered within the dark brown argillaceous matrix. When these limestone fragments are sectioned they reveal very little texturally, but one fragment did contain a pellicle-coated gypsum pseudomorph and therefore probably originated from the Hard Cap below.

Fragments of silicified wood lacking any surrounding algal sediments have been found by the author, in the Dirt Bed. These, however, were only found on the Isle of Portland and at Portesham. Cycadeoids have also been recorded from Portland and many are on display in the Natural History Museum, but unfortunately none ~~were~~ was found by the author.

The Dirt Bed forms a fairly continuous horizon throughout the Dorset outcrops, but is absent from Durlston to Worbarrow Bay. At Worbarrow Bay a six inch pellet limestone with plant fragments is thought to indicate its easternmost limit. Locally on the Isle of Portland it thins to a clay seam, likewise at Burning Cliff. At Portesham only a lower dirt bed is clearly recognisable but at a slightly higher level a two foot band of marly clay with carbon fragments and *Planorbis* sp. is thought to be equivalent to the Great Dirt Bed of the Isle of Portland.

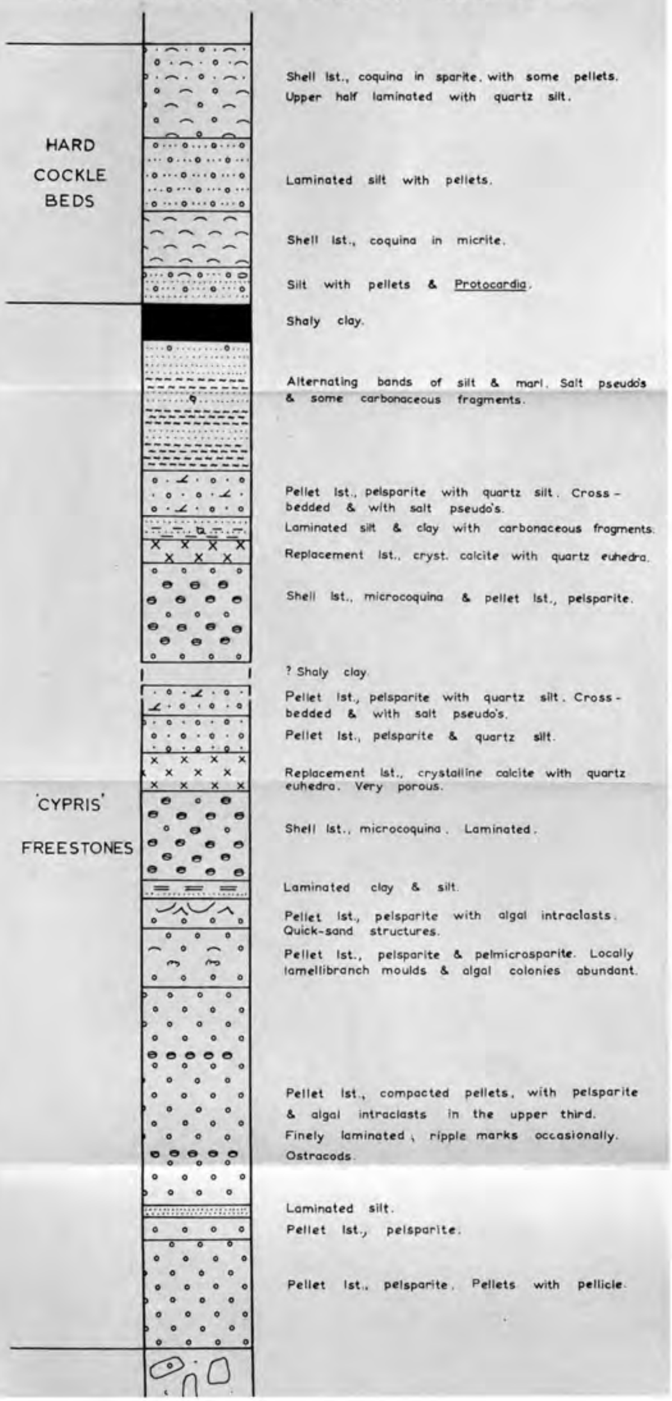
The Soft Cap

The Soft Cap throughout the Dorset outcrops, except at Durlston Head, consists of part algal and part replacement limestone. The lower algal limestone may be laminated and/or 'nodular' and is overlain by laminated crystalline replacement limestone. From Durlston to Mupe Bay this replacement limestone is incorporated in the base of the Broken Beds (figs. 9, 10, 11).

The algal base of the Soft Cap at Worbarrow Bay is composed of laminated Spongiostromata limestone. At Mupe Bay, in addition to the laminated limestone there are 'tufaceous' algal masses which reach an apparent maximum development at the Fossil Forest. These have been weathered out to show several complete 'burrs' or algal colonies (plate 21). At Burning Cliff the algal colonies are not seen, but reappear in a one foot thick stratum on the Isle of Portland, and **are referred** to as *Cryptozoon*-type algal heads (Brown 1963). Farther to the west at Portesham a similar stratum occurs but it is composed essentially of laminated algal limestone.

The laminated Spongiostromata limestones are reminiscent of successive layers of algal mats. Alternating with the

VERTICAL SECTION AT THE FOSSIL FOREST, LULWORTH



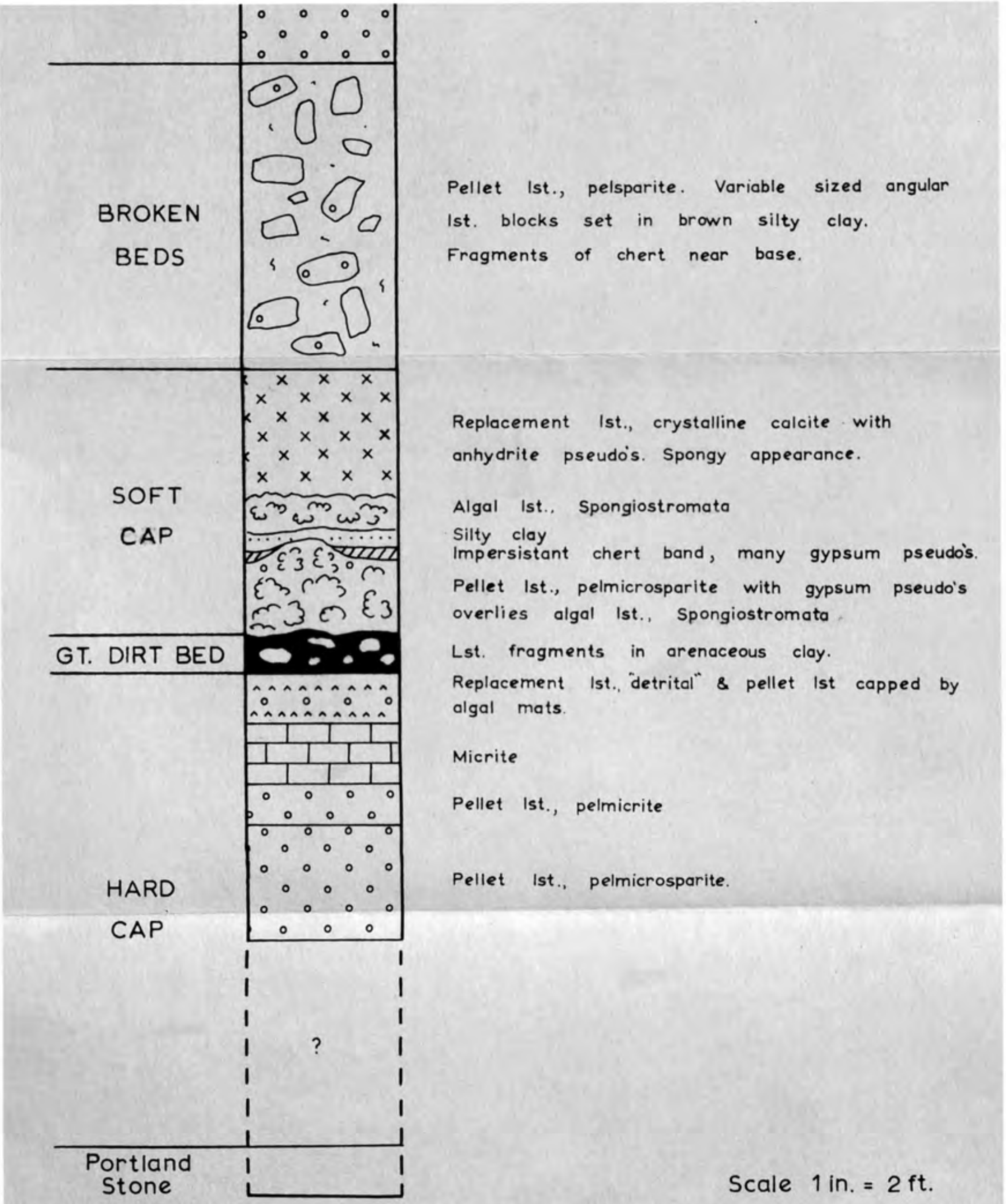


Figure 12. Vertical section at the Fossil Forest, Lulworth.

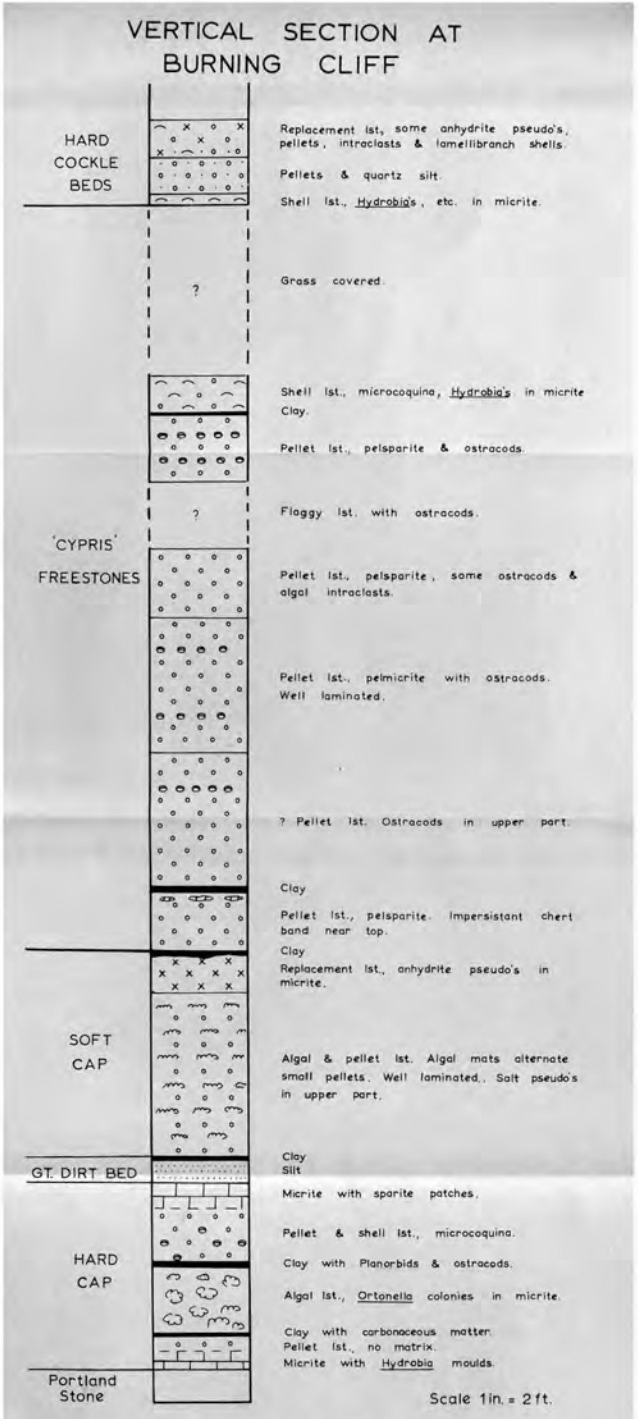
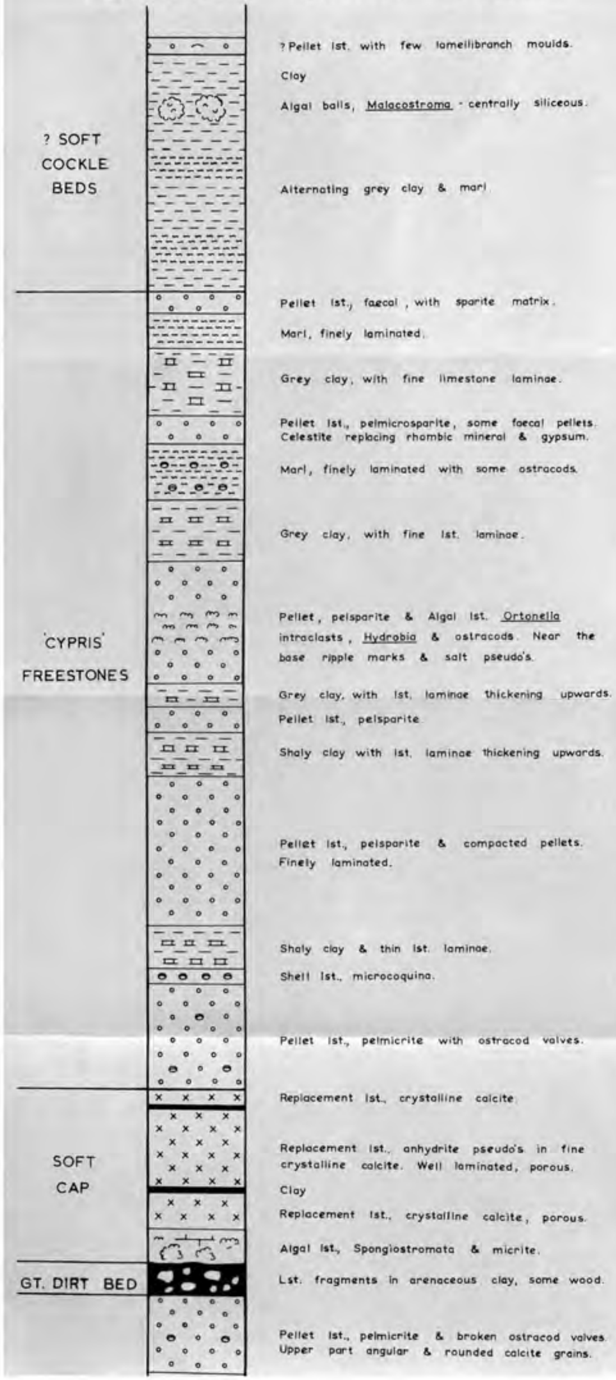


Figure 13. Vertical section at Burning Cliff.

VERTICAL SECTION AT PERRYFIELD QUARRY, PORTLAND



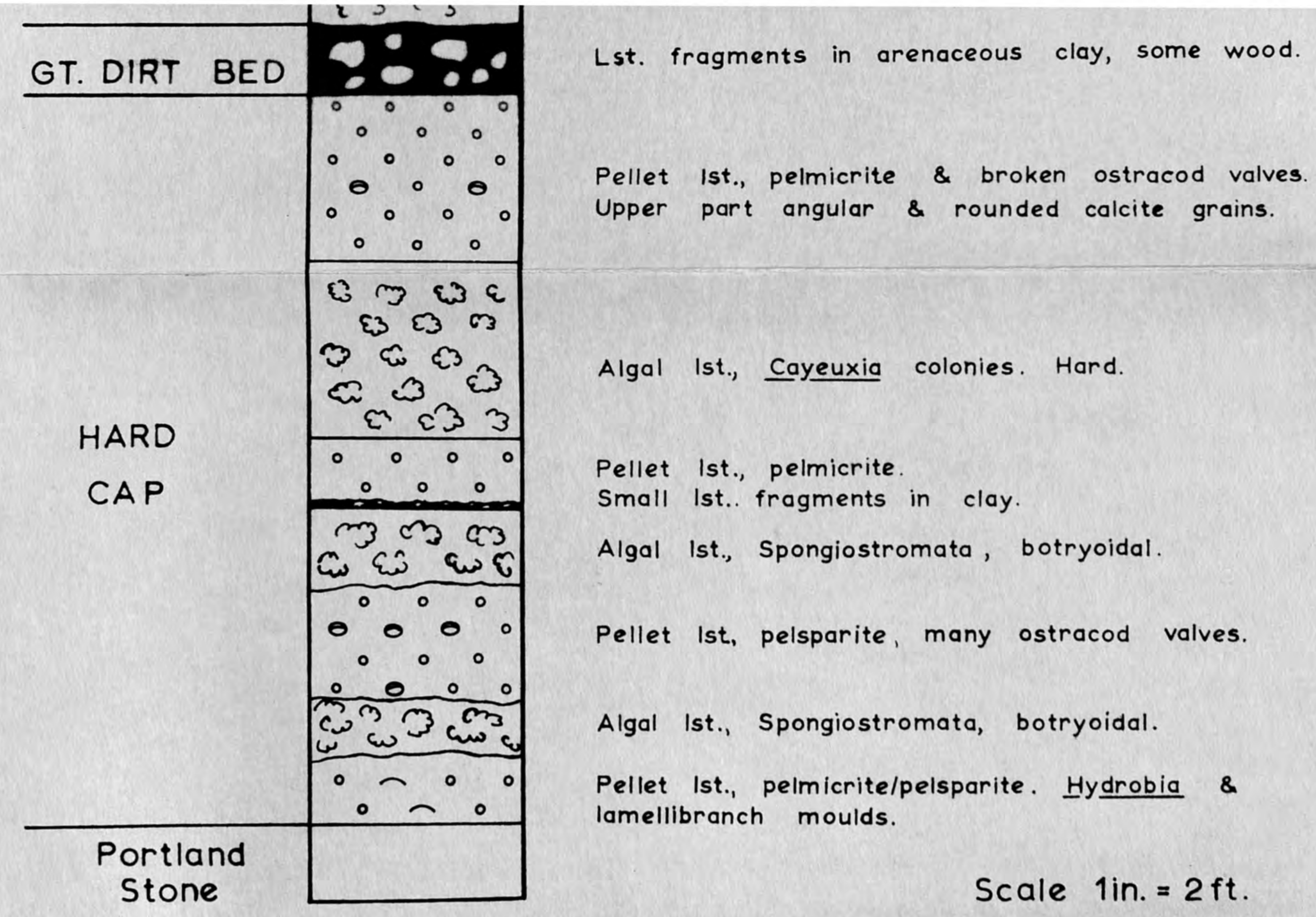


Figure 14. Vertical section at Perryfield Quarry, Portland.

VERTICAL SECTION AT PORTESHAM

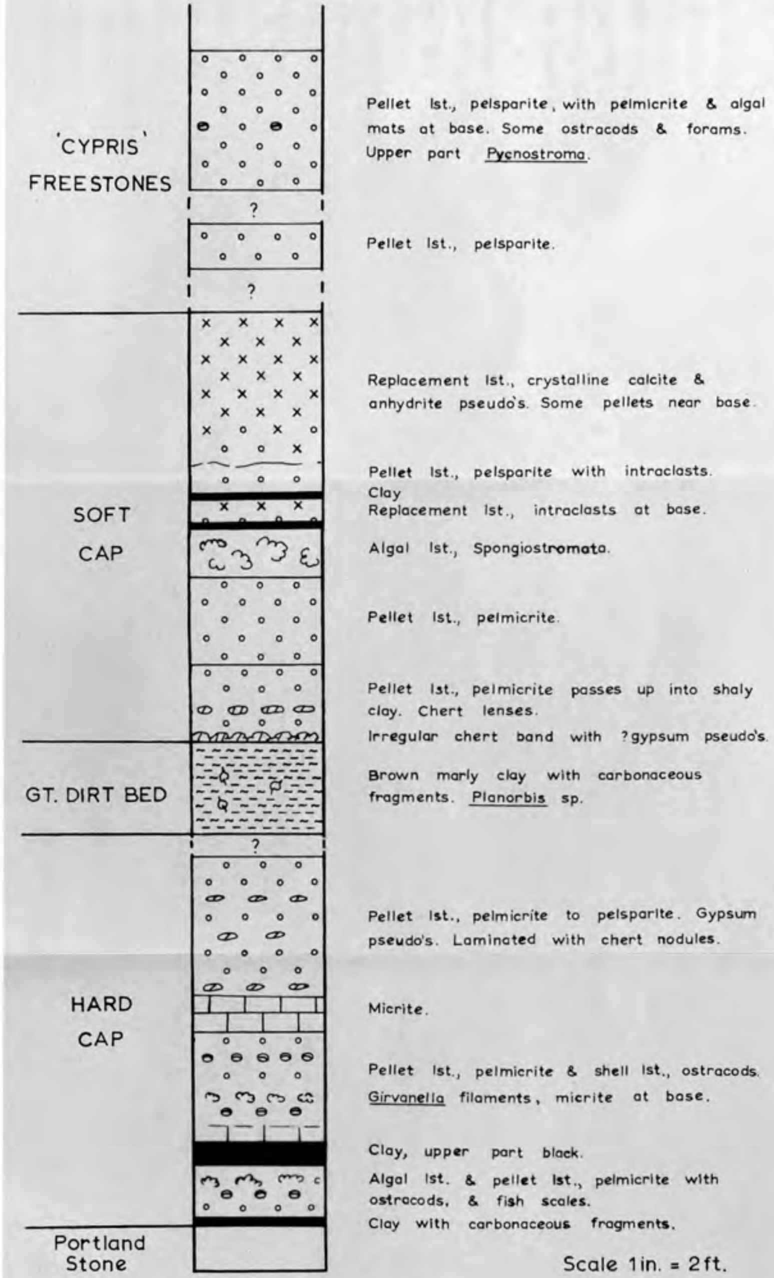


Figure 15. Vertical section at Portesham.

algal layers are limestones rich in gypsum pseudomorphs especially at Worbarrow Bay and the Fossil Forest. In fact, at the Fossil Forest one such horizon, composed almost entirely of gypsum pseudomorphs, has been silicified to form an impersistent chert band.

The overlying replacement-limestones are well laminated, and throughout the Dorset outcrops show anhydrite pseudomorphs. At Durlston Head, the replacement-limestones reach approximately fifteen feet in thickness but since the Great Dirt Bed is not present, no real distinction can be made between Hard and Soft Cap and it is thought that the replacement-limestones are equivalent to **the** algal limestones deposited to the west. Furthermore these limestones differ from other replacement-limestones in that anhydrite ghosts are present, together with much secondary celestite. At Worbarrow Bay, the replacement-limestone is much reduced in thickness, but contains a high proportion of secondary euhedral quartz. The replacement-limestones of Mupe and Lulworth show a spongy texture, whereas from Burning Cliff westwards they appear as well-laminated limestones, three to five feet in thickness. However, at Portesham slightly different conditions apparently prevailed because clay seams are interbedded with the replacement-limestones. Furthermore the base of each replacement-limestone band contains many intraclasts, (fig.15) which appear as small pebbles in hand specimens.

The Broken Beds

The Broken Beds are composed of replacement- and pellet-limestone fragments set in a soft brown silty matrix. They only occur from Lulworth to Durlston Head and are thought to be a post-depositional feature, and so will be considered in more detail in Chapter 5.

The 'Cypris' Freestones

The 'Cypris' Freestones are largely pellet-limestones, grading from pelmicrites to pelsparites. The upper part of the sequence incorporates a considerable proportion of quartz silt which reaches a maximum in the Hard Cockle Beds. Within the Freestones variations are considerable both vertically and laterally; correlation is therefore made difficult.

In the east of Dorset, at Durlston Head, the pellet-limestones are poorly developed, the 'Cypris' Freestones being represented by a thick sequence consisting mainly of marls and clays.

In contrast, at Worbarrow Bay, where the Freestones reach their maximum thickness, pellet limestones are well-developed. At the base occur compacted pellets and **Pycnostroma** algal colonies, which are also found at Mupe Bay, Lulworth and again at Portesham. The overlying pellet limestones for the succeeding twenty feet show a repetitive

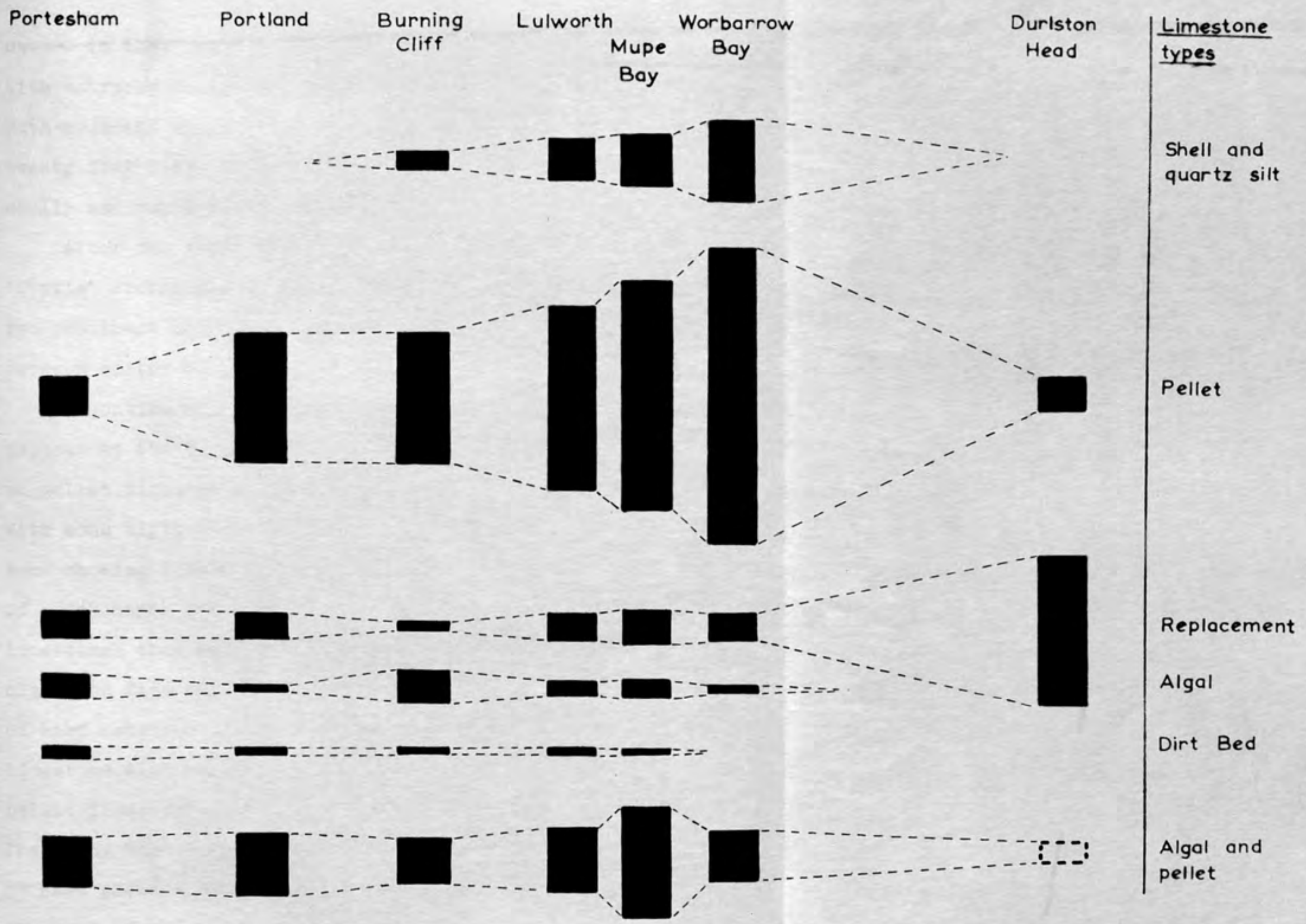


Figure 16. Diagram to show the lateral variation in the thickness of each limestone type.

? scale

nature in that three distinctive strata occur each capped with ostracod bands and with cross-bedded pellet limestone with abundant algal intraclasts at the base. The uppermost twenty feet lacks this repetitive nature, but contains algal, shelly and replacement-limestone bands.

After the first twelve feet or so at Mupe Bay, the 'Cypris' Freestones are obscured by loose rock debris, but two prominent hard limestone bands can be distinquished between softer strata.

A continuous 'Cypris' Freestone succession is well exposed at the Fossil Forest. The lower twelve feet consist of pellet limestones, either pelsparites or compacted pellets with some algal intraclasts. Above this comes a ten inch band showing festoon structures (plate 56) similar to those of quick sands described by Selley (1963). The succeeding limestones then show a cyclic pattern. At the base is a clay with fine silt laminae followed by two to three feet of hard ostracod-limestone. This is capped by replacement-limestone.with anhydrite pseudomorphs and is overlain by a pellet-limestone with an abudance of quartz silt (fig.17). The silty band may be cross-bedded and contain plant fragments or salt pseudomorphs. A clay band then follows and marks the base of the next cyclothem. The two hard limestone bands seen at Mupe Bay at this level are ostracod-limestones which probably form part of similar cyclothems.

West of the Fossil Forest, at Burning Cliff, the cyclic

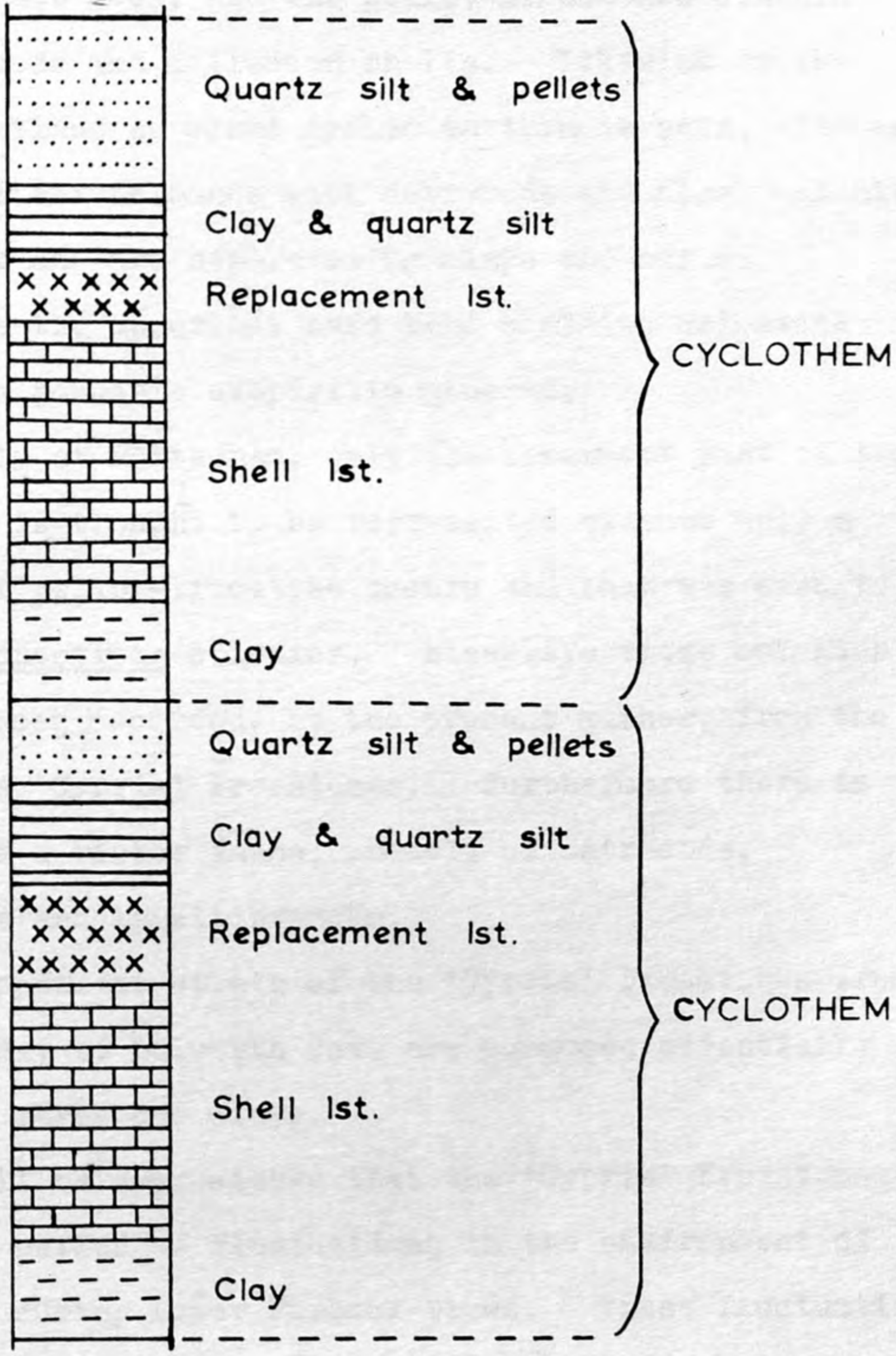


Figure 17. Sequence of sediments in the cyclothems of the 'Cypris' Freestones, Fossil Forest, Lulworth.

pattern is not seen, and the pellet-limestones contain more ostracods and molluscan shells. Likewise on the Isle of Portland no clear cyclic pattern is seen, although two hard limestone bands with ostracods and algal colonies are present and are separated by clays and marls. Furthermore the uppermost hard band contains celestite replacing a possible evaporitic mineral.

Finally at Portesham, only the lowermost part of the Freestones is thought to be represented because only a few feet of pellet-limestone occurs and that was seen to contain *Pycnostroma* colonies. Elsewhere these colonies have only been recorded, by the present author, from the base of the 'Cypris' Freestones. Furthermore there is evidence of a richer fauna; namely of ostracods, foraminifera and lamellibranchs.

The uppermost strata of the 'Cypris' Freestones from Worbarrow Bay to Lulworth Cove are composed essentially of shales, marls and clays.

It will be appreciated that the 'Cypris' Freestones indicate a period of fluctuations in the environment of deposition during Lower Purbeck times. These fluctuations were probably only of a minor nature, but sufficient to change the sedimentary sequence from one locality to another.

The Hard Cockle Beds

The Hard Cockle Beds can be traced from Worbarrow Bay to Burning Cliff. At Worbarrow Bay they are predominantly pellet-limestones with quartz silt separated by shales and marls. The upper pellet-limestone, however, contains some shelly material, together with carbonaceous fragments. At Mupe Bay, as at Worbarrow Bay, the lowermost hard limestone bed contains a considerable proportion of pellets and quartz silt. In contrast, at the Fossil Forest it is the upper hard bed which contains more pellets than the lower coquina.

To the west of Lulworth, at Burning Cliff, the two hard limestone strata are reduced in thickness and are separated by quartz silt but, as at Worbarrow Bay, the amount of shell debris is low, when compared with the proportion of pellets.

Mention was made at the beginning of this chapter of the various stratigraphical units which correspond roughly to the four main limestone types. The present author's detailed study of the distribution of these limestone types show, however that their relationships are more complex. There is considerable variation in the local sequences as the result of lateral and vertical facies variations. These facies variations must therefore be characteristic of a general environment of deposition envisaged for the whole area.

CHAPTER 4

DEDUCED ENVIRONMENT OF DEPOSITION

The Lower Purbeck limestones have a relatively poor fauna. This restricted range of the palaeontological evidence available has led to difficulties in deducing the environment of deposition. Many workers in the nineteenth century believed that all the Lower Purbeck sediments were deposited in freshwater, but later the ostracod fauna was considered to indicate brackish or marine conditions. Furthermore the presence of evaporitic minerals or their pseudomorphs in certain beds indicates the existence of hypersaline conditions, during at least part of Lower Purbeck times. Such a wide range in the salinity is not however, impossible and can be explained by postulating the former presence of a lagoon in the Dorset region.

Physical Conditions

At the commencement of Purbeck times shallow water conditions prevailed. This conclusion is based on the fact that algae will only grow in water which is sufficiently shallow to allow the penetration of light which is required for photosynthesis. Shallow water conditions presumably continued into 'Cypris' Freestone times, because the presence of hopper-shaped salt psuedomorphs indicate at least temporary shallow conditions. In fact, there is evidence to suggest aerial exposure prior to the deposition of the Soft Cap. Underlying the Great Dirt Bed at the Fossil

Forest is an algal mat which is traversed by large desiccation cracks (plate 25). For such cracks to form, the sediments must have dried out. Furthermore the overlying Dirt Bed has long been thought to represent a fossil soil. The main evidence for this opinion being the occurrence of Cycadeoids and silicified wood in the Dirt Bed. However, the irregular shapes and sizes of the enclosed limestone fragments, suggests to the author that the Dirt Bed is a subsoil rather than a true soil. This opinion is supported by the low organic content of the insoluble residues from the deposit and the absence of carbonaceous streaks.

The emergence of the sediments to form dry land is not at all unlikely because evidence from other levels within the Lower Purbeck indicates the presence of nearby land, especially to the west of Lulworth. On the Isle of Portland and at Bincombe, cylindrical moulds encrusted by algae are numerous in the Hard Cap and are presumably the hollows left after the decay of wood. This wood is thought to have been drift wood because the moulds usually lie horizontally and are completely encircled by algal sediments. If it had been a submerged forest, one would have expected the algal sediments to cover only the upper surface. Deposition close to the land is also indicated by the occasional seams of abundant carbonaceous fragments, especially in the 'Cypris' Freestones and to some extent in the Hard Cockle Beds.

Throughout the Lower Purbeck limestones the amount of clastic material is small, and since the sediments were presumably deposited near to the land, one assumes that the surrounding land was generally of low relief. This assumption would also coincide with Casey's (1962, 1963) theory of the Spilsby sea overflowing from the north into the Dorset basin in Middle Purbeck times, because for such an overspill to take place the intervening land must presumably have been low-lying.

In the 'Cypris' Freestones and Hard Cockle Beds there is evidence that the water underwent gentle current action. The Freestones especially, are characterised by calcarenites, and the pellets sometimes have a 'superficial' oolitic coating, ripple marks are common on some bedding (plate 57) planes and cross-bedding occurs especially at Worbarrow Bay. Likewise the coquinas of the Hard Cockle Beds and the frequent occurrence of single valves of both ostracods and lamellibranchs in a stable position indicate some agitation

Plate 56. Festoons similar to those produced in quick sands, from the 'Cypris' Freestones, Fossil Forest, Lulworth.

Plate 57. Cross-bedding of the pellet limestones from the upper part of the 'Cypris' Freestones, Worbarrow Bay.

of the water and transportation of material.

Climatic conditions during Purbeck times are thought to have been more equable than those prevailing in this country at the present time. Warm temperate to sub-tropical conditions are suggested by the presence of evaporites, especially those in Sussex. The abundance of Cycadeoids, which today are restricted to sub-tropical and tropical regions, also supports this opinion. Furthermore Nairn (1960) on the basis of paleomagnetic data showed that the late Jurassic seas lay in latitudes from 30 to 35°N.

Many of the above mentioned features could have resulted from deposition in a lacustrine or estuarine environment. However, the important factor of salinity, of the water in which the sediments accumulated, has not been discussed. At the beginning of this chapter mention was made of various salinities that were thought to be prevalent throughout Lower Purbeck times, but the author believes that the salinity was variable. The very basal

Purbeck at Portland, Poxwell and Portesham contains many Hydrobia moulds, whilst shells of Hydrobia and Planorbis are common in the Hard Cockle Beds. Living representatives of these gastropods inhabit brackish environments and it is assumed that their ancestors did likewise. According to Brown (1963) the algae are marine forms, and Anderson (1958) considered that the ostracods belonged to a marine to hypersaline suite. The beds containing pseudomorphs of evaporitic minerals are also indicative of hypersaline conditions. Such a range in salinity is fairly characteristic of lagoonal environments. Restricted circulation of the sea together with intensive evaporation would give rise to hypersaline conditions (Scruton, 1953) and these could pass into brackish water near to the land, as the result of dilution by freshwater brought in by streams.

Lagoonal Environment

With reference to the comparative sections (fig.16) the general succession of limestones from the base of the Lower Purbeck is as follows:- algal limestones, dirt bed, algal limestones, replaced evaporites, pellet-limestones, quartz silt and shell-limestones. A similar sequence of limestones could represent the various sediments found on passing from the open sea, across a lagoon to its landward margin (fig.18).

The oolitic Portland stone with its large ammonites and other marine fossils indicates deposition in a shallow sea. The succeeding algal limestones of the Lower Purbeck are thought to represent a minor biostrome especially as Pettijohn (1957)

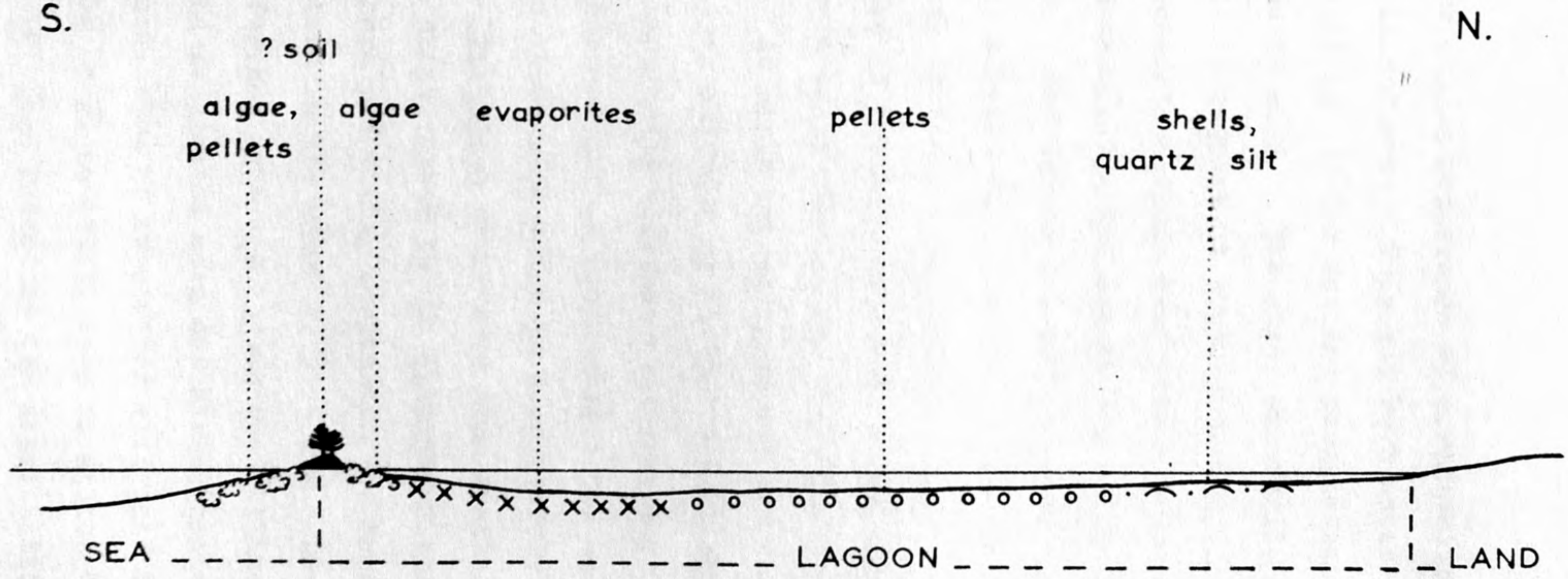


Figure 18. Idealised section across the postulated Lower Purbeck lagoon.

mentions the common occurrence of stromatolites in biostromal limestones. This may have acted as a barrier, partially cutting off the sea and restricting circulation on the landward side. The algae apparently thrived and became aerially exposed at some localities. On these emergent sediments certain land plants could have established themselves and eventually a type of soil may have formed. The Cycadeoids and other plants probably gave rise to scenery very similar to that of miniature barrier reefs of today with their scattered palm trees.

Landward of the bar, evaporation probably exceeded inflow of salt water through the underlying porous algal sediments. At first the salinity was not too extreme and large algal colonies or 'burrs' established themselves. These were apparently tolerant of fairly hypersaline conditions because gypsum pseudomorphs are associated with them, a conclusion which is supported by the fact that recent <u>Cryptozoon</u> structures from Australia are "limited in distribution to the intertidal zone of the bay-heads where prevailing conditions are hypersaline with salinities in the range of 56 - 65‰." (Logan, 1961). On passing further into the lagoon the salinity apparently increased and evaporites were deposited (plate 34). The frequent association of evaporites with reef type deposits was mentioned by Sloss (1953) when he stated "that reef exploration is often guided by the distribution of evaporites".

Succeeding the replaced evaporite beds and grading into them are the pellet limestones. The preservation of faecal pellets, salt pseudomorphs and bahamites within these beds indicates sedimentation under the quiet conditions which are characteristic of lagoonal sedimentation. In addition, the absence of a truly marine fauna, together with a paucity of genera, suggests that normal marine salinities were not established (Hudson, 1963). Conditions were obviously not hypersaline because some horizons are rich in ostracods, Codiacean colonies and Neomiodon moulds. A similar faunal assemblage was mentioned by Wood (1941) from a lagoonal phase in the Carboniferous of South Wales. It is therefore suggested that dilution of the former hypersaline environment was brought about by inflowing freshwater from the land to the north and west. This produced rather unusual salinities which only certain organisms could tolerate.

However, conditions did not remain constant throughout 'Cypris' Freestone times as there is some evidence of cyclothemic deposition. These cyclothems may have been caused by cyclic changes in either the rate of evaporation or in the rate of freshwater inflow.

Finally the increasing amounts of quartz silt together with coquina bands suggests deposition of sediments fairly close to the land. The presence of ripple marks and broken shells set in sparite are indicative of agitated water. It is therefore suggested that the shell bands represent an offshore shell bank, similar to that mentioned by Rusnak (1951-58) along the shore line of the Laguna Madre.

The succession of limestone types can therefore be compared very readily with the sequence of sediments deposited across a lagoon. In order to establish the vertical succession as seen in Dorset the various facies belts are thought to have migrated seawards. Unfortunately the absence of exposures in the north of Dorset prevents evidence being obtained to substantiate this theory.

Local Variations

Within the general framework of the postulated lagoonal sedimentation, local variations from east to west can be detected in the successive beds. Unfortunately exposures to the north of Dorset are rare, and the north-south variation cannot be studied in similar detail.

i) Hard Cap.

In the last chapter it was pointed out that from St. Albans Head to Lulworth the basal band was composed of algal colonies, i.e. Ortonella, Solenopora, Girvanella. These indicate saline conditions. At Durlston Head, the succeeding beds are predominantly formed of replaced evaporites. While on the other hand at Worbarrow Bay, only a narrow band of replaced evaporites occurs and just to the west, at Mupe Bay, it is completely absent. This suggests a decreasing prolongevity of hypersaline conditions in a westward direction. This is also indicated in the sediments from Worbarrow Bay to Dungy Head since only gypsum pseudomorphs are found in the upper part of the Hard Cap.

In contrast, to the west of Lulworth, conditions are thought to have been brackish to marine. The basal band with Hydrobia moulds at Poxwell, Portland and Burning Cliff gives the first indication. In addition the growth-form of the Spongiostromata algae at Portland, is very reminiscent of that of freshwater algae described from the Oligocene by Johnson (1937), and Cloud (1942) states that the 'Gymnosolen' form is nearly always recorded from freshwater deposits. The presence of ostracods, wood and fish scales also suggest brackish to marine conditions. At Portesham, however, there is an anomalous occurrence of gypsum pseudomorphs in what is thought to be the upper part of the Hard Cap. This is difficult to explain since the other evidence indicates higher salinities to the east than to the west.

The higher salinities in the east of Dorset may have been caused either by the lack of inflowing freshwater into the area or possibly by seepage or overspills of hypersaline water from the Sussex Basin.

ii) The Great Dirt Bed.

At Durlston Head, where evaporite deposition was apparently continuous from Hard Cap to Soft Cap times, the Great Dirt Bed is absent. It is also absent at Worbarrow Bay, but at Mupe Bay, it is well developed and can be traced all the way to Portesham, except for local absences at

Burning Cliff and Poxwell. It is interesting to note that at these latter localities the Spongiostromata limestone is also not well developed. At Portesham, the horizon interpreted as equivalent to the Dirt Bed, lacks the limestone fragments, but is argillaceous with some Planorbis spp. and carbonaceons fragments (fig. 15).

Assuming that the Dirt Bed indicates the former presence of land, it would appear that a bar or chain of islands occurred only to the west of Mupe Bay. This is to be expected if dry land lay in the Devonshire area.

iii) Soft Cap

The algal limestones of the Soft Cap are relatively uniform throughout Dorset. The replacement-limestones are also continuous, but local variations occur. From Durlston Head to Lulworth they appear extremely porous, but from Burning Cliff to Portesham they appear as well laminated limestones. This may be due to the higher percentage of algal material interlaminated with the replaced evaporites to the west. Furthermore the two successive replacement-limestone bands, at Portesham, both with intraclasts at the base suggests that the western limit of hypersaline conditions during Soft Cap times was not far away. The successive influxes of hypersaline water apparently disturbed the bottom sediments, so causing intraclasts to form.

iv) 'Cypris' Freestones.

Lateral variation within the Freestones, is pronounced, but throughout these beds the sediments and fauna are similar. Though as before, replacement-limestones, denoting the previous existence of evaporites, are more frequent to the east of Lulworth. This may result from the proximity of the Sussex basin which was characterised by hypersaline conditions throughout the lower part of the Lower Purbeck.

v) The Hard Cockle Beds.

The distribution of the shelly matter and silt in these beds is irregular. On the Isle of Portland these beds are not seen, but are well developed at Lulworth. At Worbarrow Bay, the shell and silt content is much reduced and the limestones are predominantly composed of pellets. These features may indicate deposition farther from the land than those of Lulworth, and according to Brown (1964) the amount of quartz silt increases to the west again suggesting that land lay to the west.

A predominant feature of the lateral facies variation is that they indicate higher salinities in the east than farther west. This variation in the salinity may be attributed to the fact that only a low ridge separated the hypersaline Sussex basin from Dorset. Furthermore the west of Dorset was in closer proximity to land, which could have provided a source of freshwater.

<u>The Lower Purbeck deposits of Dorset in relation to the surrounding areas</u>.

An isopachyte map of the Lower Purbeck deposits (fig. 19) reveals that the beds thin to the west of Dorset and also to the north around Swindon and Oxford, and to the east of Kent. In central Kent, however the Purbeck deposits as a whole, reach their greatest thickness - five hundred and sixty two feet is recorded at Penshurst. These thin eastwards to sixty feet at Brabourne (Lampugh and others, 1923) and westwards to two hundred and ten feet

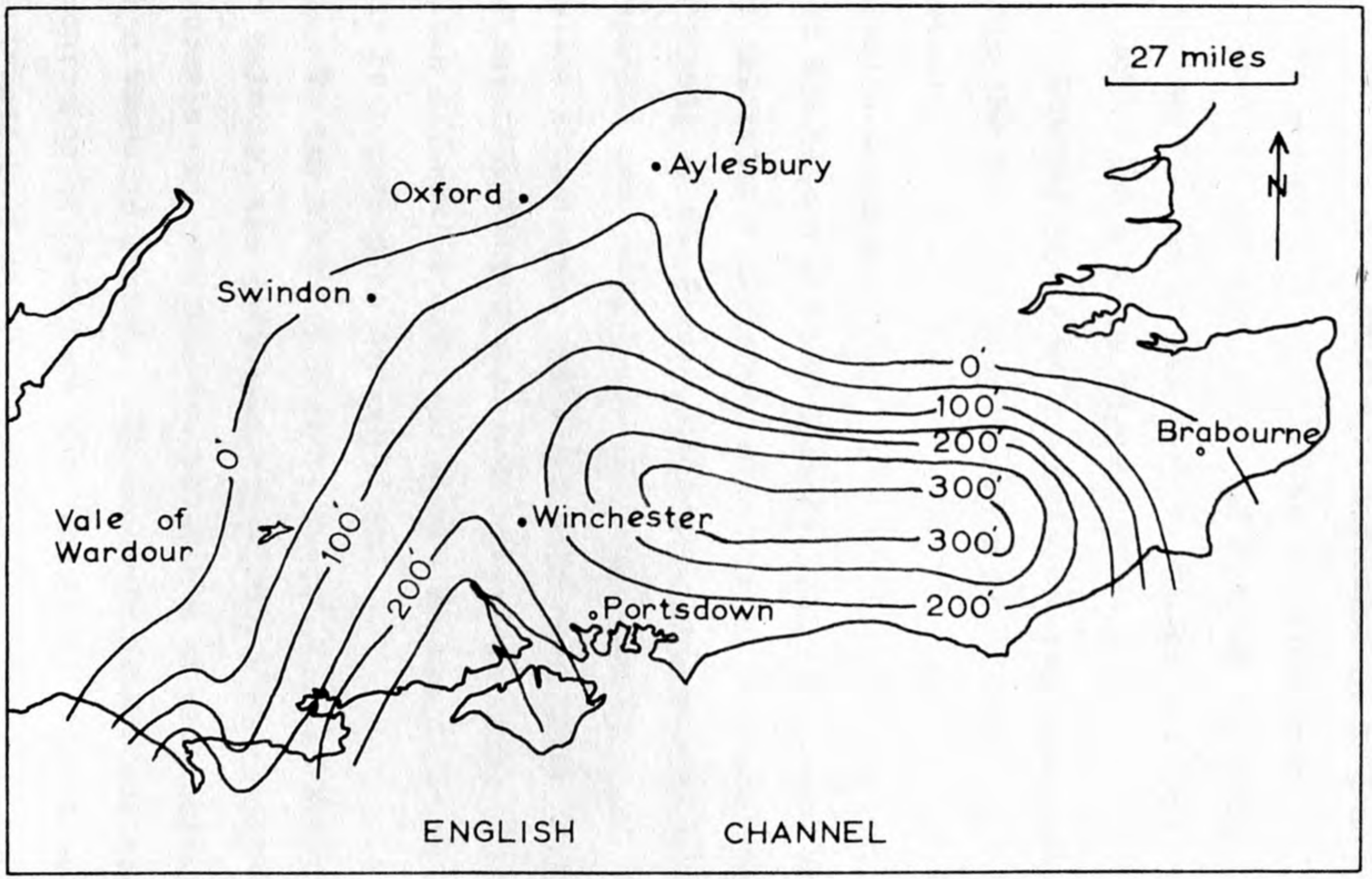


Figure 19. Isopachyte map of the Purbeck Beds, from the base to the Cinder Bed. (after Howitt)

at Portsdown in Hampshire (Taitt and Kent, 1958). According to Howitt (1964) a north-west to south east ridge extended from Portsdown to Winchester. This he thought separated the area of Purbeck deposition into two basins, one to the east in Sussex and Kent, and the other to the west in Dorset.

The variation in the sediment sequence also supports this theory. In Sussex, the basal Purbeck is composed of seventy one feet or so of gypsiferous beds overlain by shallow water clays and shales, similarily at Portsdown and Henfield the Lower Purbeck consists almost entirely of anhydrite interbedded with marls. In contrast, the majority of the Dorset exposures, whilst having some replaced evaporites, are characterised by algal and pellet limestones. However, the succession at Durlston, of essentially replaced evaporites and clays, indicates close affinities with the Sussex facies. It therefore may be regarded as transistional.

To the north of Dorset, in the Vale of Wardour and at Swindon, the sediments apparently lack evaporitic minerals and resemble the sediments of west Dorset rather than those of Sussex. In the Vale of Wardour the occurrence of dirt beds and 'tufaceous' limestone is very reminiscent of the Portland Caps (Andrews and Jukes Browne 1894). Local variation does occur, but it is of no greater difference than of that between Upwey and Portland.

To the north, at Swindon the beds are similar to those at Portesham, according to West (1961). Arkell (1940) noted intercalations of marine and freshwater allochthonous fossils and believed that the sediments were deposited in a shallow sea, possibly near to some marshes. Close proximity to land for this region, is also suggested by the frequent occurrence of pebble beds mentioned by Sylvester-Bradley (1940). However, the presence of both marine and freshwater fossils has led to difficulties in dating these beds and Sylvester-Bradley (1962) suggested that the so-called Purbeck Beds at Swindon were the time equivalent of the Upper Portland Beds of Dorset.

Lower Purbeck Beds, identified by their ostracod fauna (Chapman 1900), are also recorded from Oxfordshire. They are best seen at the Bugle Pit, Stone, where they are characterised by thin bedded limestones and marls.

Isolated outcrops of Lower Purbeck are also found near Brill, Buckinghamshire and according to Brodie (1867) the beds resemble the Hard Cap of Portland.

Unfortunately to the south of Dorset Purbeck outcrops are even fewer. Although the Purbeck is known to occur below the English Channel (Donovan and Stride 1961), the author has found no record of dredged samples.

In France, the Purbeck Beds are absent along the Normandy coast, and at Boulonnais the so-called Lower

Purbeck is very thin and arenaceous (Pruvost and Pringle 1924). In all the exposures of Lower Purbeck Beds outside Dorset, there is apparently little evidence that would contradict the postulated existence of a lagoon within the Dorset region. Thus the author envisages a lagoon in the area of Dorset and Wiltshire, with a subsidiary, possibly more land-locked, basin in the Wealden area. Since the Portsdown-Winchester ridge was less pronounced to the north, perhaps it was in this area that the two basins were connected.

CHAPTER 5

BRECCIAS

Breccias can be subdivided into two types depending on whether they were deposited as breccias or whether the rocks were brecciated after deposition. From the field evidence, the Lower Purbeck breccias belong to the latter group. The descriptions of the beds involved are therefore treated separately because they have no bearing on the palaeogeography.

Two brecciated horizons occur within the Lower Purbeck limestones, namely the Broken Beds proper and the 'broken beds' which are only found at Portland Bill. The Broken Beds can be considered as 'fold breccias' since the maximum brecciation occurs where the overlying beds are steeply inclined. Whereas when the dip is slight the equivalent beds are only crumpled. The other 'broken beds' first recorded by Arkell (1947, p.298) are restricted to the region around Portland Bill and according to Shearman (personal communication) originated as the result of frost action in late Pleistocene times.

Broken Beds

As mentioned in the first chapter these beds have been extensively studied by other authors. For concise descriptions the reader is referred to Arkell (1938, p.12 and 1947, p.297). There is one point, which the present author would like to add, and that is that the equivalent beds west of

Lulworth are not brecciated but only crumpled. The sediments effected by the brecciation are mostly pellet limestones, but at Worbarrow Bay and at Durlston Head the underlying replacement limestones are incorporated. According to Hollingworth (1938) and West (1964) the brecciation resulted from tectonic movements along a plane of weakness caused by the hydration of inter-bedded anhydrite. There is much to be said for this line of reasoning because both the maximum inclination and the maximum thickness of replacement limestones coincide. Phillips (1964), however, stresses the importance of the tectonic origin. This opinion is favoured by the author because the Broken Beds at Bacon Hole display drag-folds (plate 58) which all have the same orientation as a very pronounced fold (plate 59). If folds had been produced by the increase in volume which accompanies the hydration of anhydrite, surely they would lack orientation and display less angular types of folding. Furthermore on the Isle of Portland, where the effect of folding is negligible, the equivalent beds are only crumpled, although replacement limestones are present. Such minor crumpling would seem to be more in keeping with the deformation which one would expect to accompany changes in the volume of the evaporitic minerals resulting from hydration. It would seem therefore that the brecciation was essentially the result of stresses producing during folding, although the location of the brecciation may have been determined by earlier formed planes of weakness, as suggested by Hollingworth and West. The present

Plate 58. Drag folds produced in the Broken Beds, Bacon Hole, Mupe Bay.

Plate 59. Pronounced fold from the base of the 'Cypris' Freestones, Bacon Hole, Mupe Bay.

author, however, postulates the reverse sequence of events. At Ringstead Bay, the unconformity between the Jurassic and Cretaceous rocks indicates M. Albian pre-Cretaceous folding. This pre-dates extensive denudation of the area, which according to West was when the Purbeckian anhydrite was hydrated to give gypsum. So it can be argued that the brecciation resulted in a greater degree of porosity which allowed the easier percolation of solutions which were responsible for the hydration and calcification of anhydrite. Mille and others (1964) suggested a similar sequence of events as an explanation of breccias in the Prairie Formation, Saskatchewan, which also occur above evaporites. Furthermore the permeability of the underlying reefs of the Prairie Formation appears to have aided movement of water and hence the dissolution of the salts.

Cryoturbation Structures.

These structures are confined to the southern tip of the Isle of Portland where they are exposed in the eastern cliff top from Portland Bill to the Longstone Ope Quarries (fig.20). The Lower Purbeck only forms a relatively thin horizon between the Portland Stone below and raised beach material above. All three horizons have been effected by the frost action but the brecciation is most pronounced in the Lower Purbeck strata.

Characteristic structures which result from frost-action according to van Leckwijck and Macar (1949) are involutions, wedge-shaped fissures, polygonal soils,

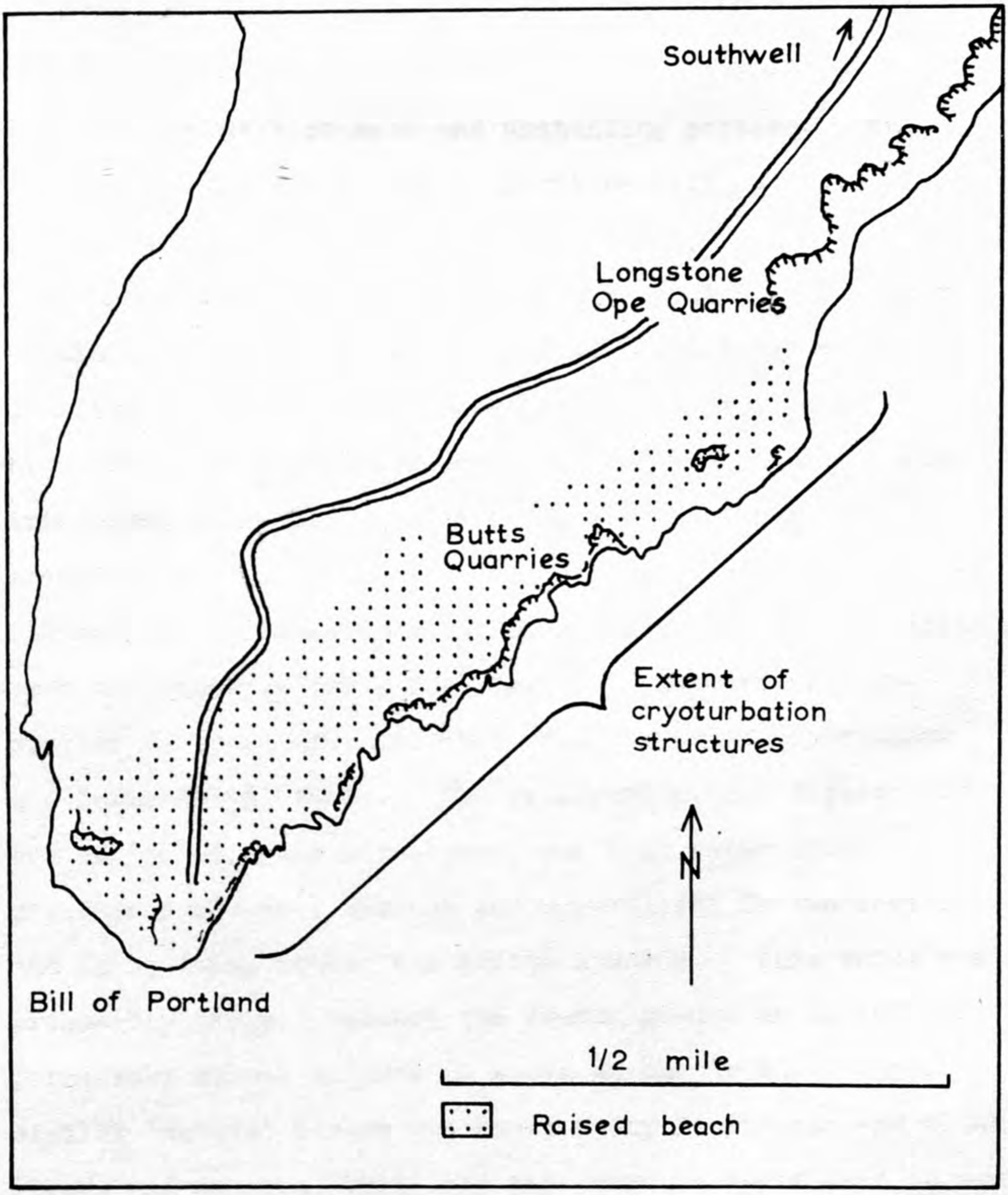


Figure 20. Location and extent of cryoturbation structures on the Isle of Portland.

solifluction disturbances and upstanding pebbles. Many of these features are seen at Portland Bill.

i) Involutions or festoons.

These structures are seen in the basal Hard Cap near Portland Bill, and are especially well-developed at Butts Quarries. At intervals the almost horizontal laminated beds become disrupted (plate 60). The strata are broken into slabs which become tilted upwards on either side of a central area of completely disorientated limestone blocks (plate 61). The upthrust portion often extends for three feet and measures three feet across. Structures very similar to these are described from Glamorgan by Bradshaw and Ingle Smith (1963). The explanation, put forward for the origin of these structures, was that water under pressure was forced through the superficial frozen layer, and in so doing heaved the strata upwards. This water was presumably trapped between the frozen ground above and the permafrost below, in what is known as the 'active' layer. Similar 'active' layers are known today in Siberia and Alaska (Brown and Johnson, 1964) and this zone is restricted to a depth of two to three metres. The brecciated zone with festoon structures at Portland Bill, is similarly restricted to the upper nine to twelve feet of the cliff (plate 62).

ii) Frost wedges.

Only one possible frost wedge is seen near Portland Bill, in the Lower Dirt Bed. A wedged shaped fissure filled with pale silty clay and limestone fragments from the brecciated part above, extends downwards through dark clay for approximately eighteen inches (plate 63).

iii) Opening of joints.

The lowermost Purbeck stratum of calcilutite usually forms a fairly continuous band occasionally broken by vertical cracks. When viewed on the upper surface those cracks are seen to combine to form a polygonal network.

However, the most impressive opening of joints is seen in the underlying massive Portland Stone (plate 64). At the top of the cliff the limestone blocks are small and disrupted to form a breccia, but pass downwards into an extremely well jointed band, in which the blocks are still in position. Continuing downwards the blocks

Plate 60. Festoon produced as a result of ice action, from the basal Lower Purbeck, Butts Quarries, Isle of Portland.

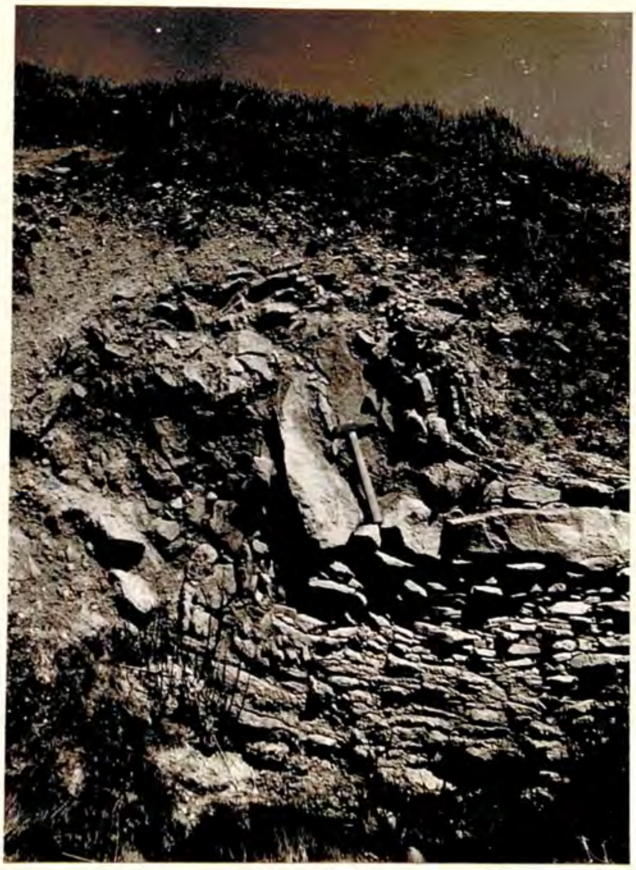


Plate 61. Festoon in which the central core has become completely disrupted. Lower Purbeck, Butts Quarries, Isle of Portland.

Plate 62. The brecciated zone at the cliff top, Butts Quarries, Isle of Portland.

Plate 63. ? Ice wedge in the Lower Dirt Bed, Isle of Portland.

decrease in number and only the master joints are open, until finally massive Portland Stone occurs. This whole zone of open joints probably indicates the extent of the 'active' zone which was subjected to repeated freezing and thawing. The top of the cliff was undoubtedly subjected to greater extremes of temperature than lower down, and therefore suffered more disruption.

iv) Upright pebbles.

Pebbles orientated with their long axis vertical to the bedding occur in the unconsolidated raised beach deposit (plate 65). This orientation is usually brought about by frost heaving, and therefore the cryoturbation structures must have been formed in post-raised beach times, probably the late Pleistocene. According to Te Punga (1957), the whole area of southern England south of a line from London to Bristol was situated in the periglacial zone during Pleistocene times. Furthermore the deposits

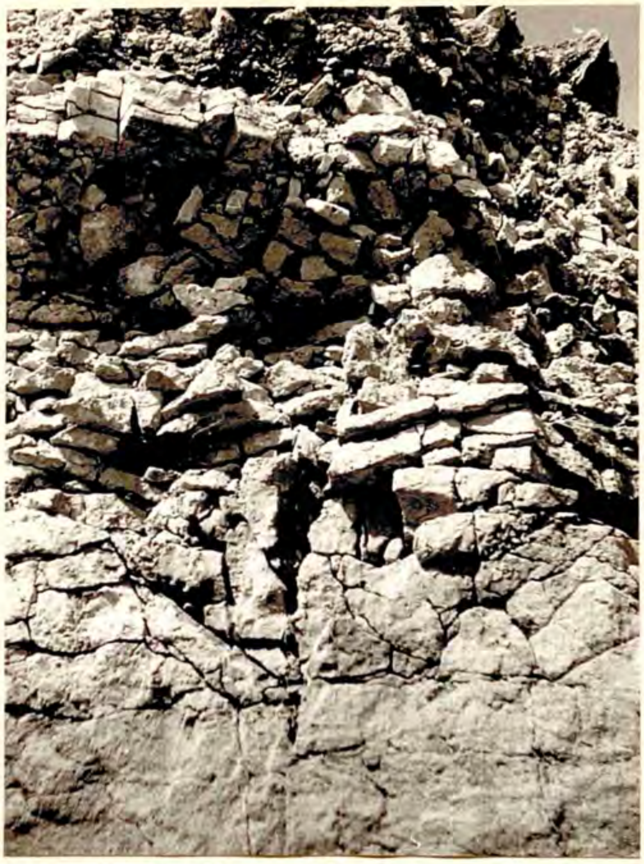


Plate 64. Opening of joints within the massive Portland Stone at the cliff top, near Portland Bill.

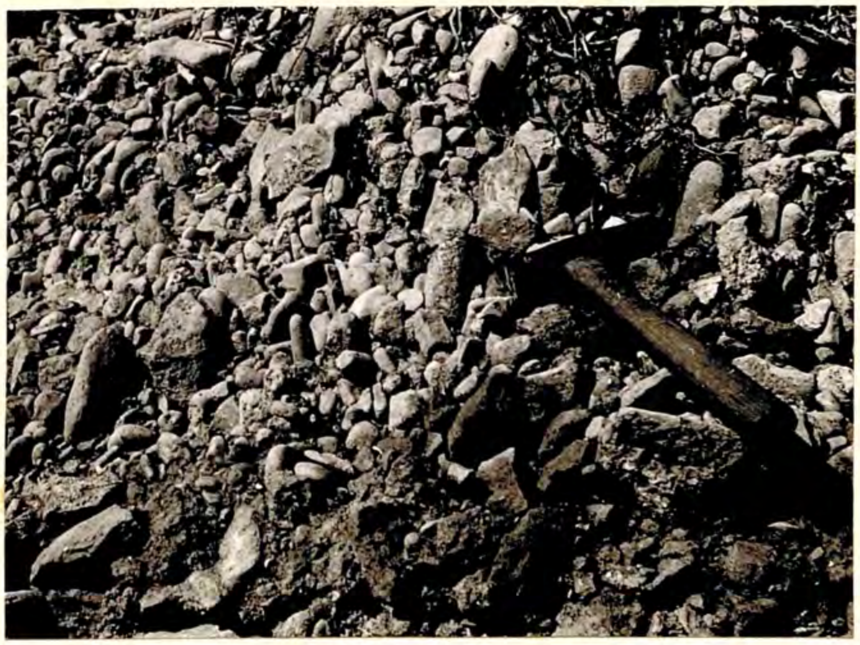


Plate 65. Upright pebbles of the raised beach deposit, near Portland Bill.

above the raised beach which Prestwich (1875) considered to be the result of solifluxion, have not been effected by frost heaving.

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