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SEDIMENTARY ENVIRONMENTS AND DIAGENESIS OF PURBECK STRATA (UPPER JURASSIC - LOWER CRETACEOUS) OF DORSET, U.K.

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Thesis submitted for the degree of Doctor of Philosophy,

Southampton University

________________________ 1979

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

GEOLOGY

Doctor of Philosophy

SEDIMENTARY ENVIRONMENTS AND DIAGENESIS OF PURBECK STRATA (UPPER JURASSIC - LOWER CRETACEOUS) OF DORSET, U.K.

by Ian Michael West

Twelve papers, notes and a contribution to a book, all either published or accepted for publication, constitute this thesis. All parts of the classic, shallow-water, schizohaline Purbeck Formation of the type area are discussed but emphasis is on Lower Purbeck evaporites.

Diagenesis of these involved much conversion of initial small lenticular crystals of gypsum to anhydrite with net-texture. The anhydrite was extensively replaced by calcite and celestite in the Broken Beds, a tectonic evaporite breccia at the base of the Purbecks. Evaporites were almost completely lost in solution from this breccia leaving characteristic relics of "vanished evaporites". Elsewhere, in more argillaceous parts of the formation the sulphate remains, mainly as porphyroblastic secondary gypsum. Nodules and enterolithic veins are abundant in both the calcium sulphate and in the replacements. The similarity to those in Holocene sabkhas of the Trucial Coast (Shearman, 1966) suggested an origin on supratidal sabkhas, but there is a lack of desert sediments and instead the evaporites are interbedded with forest soils. Analogous Carboniferous evaporites, described here, similarly show evidence of sabkha origins but no sign of desert conditions. New evidence has come from sabkhas in northern Egypt where gypsum nodules develop in partly-vegetated environments, dry, but not excessively so, and supports other evidence for a semi-arid origin for the Lower Purbeck evaporites.

The relatively dry climate was temporary and facies of higher parts of the Purbecks seem to result from sub-humid conditions. Throughout the formation lagoonal, "intertidal" and supratidal deposits can be recognised but in the Middle and Upper Purbecks the lagoonal sediments have abundant brackish shelly faunas and, there, "tidal-flat" deposits consist of shell-sand with dinosaur footprints but usually without evaporites. Progressively the proportion of land-derived clastics such as kaolinite and quartz sand increases as the continental Wealden is approached and the final Purbeck sediments contain debris eroded from the underlying Portland Stone Formation, then uplifted at the western margin of the basin.

ACKNOWLEDGEMENTS

Many of the persons who have helped the writer in various ways are acknowledged in the individual papers. This provides an opportunity, however, to thank particularly those who have assisted over a long period of time and those who, for some reason or another, are not fully acknowledged in the papers. I am indebted to my supervisor, Professor Frank Hodson, who suggested that I write the first paper and who, much later, sent me to Egypt correctly predicting the discovery of good analogues of the Purbeck sediments. I thank Mary Long and Eileen Diaper for having typed many versions of the papers and Anthea Dunkley for drawing the diagrams and reconstructions of the environments. I acknowledge the help of past and present technical staff of the Geology Department, Southampton University, particularly Robin Saunders, John Merefield, and Barry Marsh. Trevor Clayton provided much help in the field and in the laboratory and Adam El-Shahat is particularly thanked for his expert guidance with regard to the Middle Purbeck limestones. Jane Francis has provided helpful information regarding "fossil forests". Yehia Ali worked energetically with the writer on comparable Egyptian evaporites and organised field work in Egypt. I fully acknowledge the major contributions of the coauthors of the various papers and gratefully appreciate the very useful criticisms of anonymous referees of the papers. The editors of the various journals have been most helpful, particularly Mr. Lamming of the Yorkshire Geological Society. Robin Bathurst is sincerely thanked for having made it possible to submit this work. Doug. Shearman's published ideas on sabkhas have been the most valuable stimulus and have had an obvious and very considerable influence on the later work. Discussion with the late Professor Sylvester-Bradley has been most helpful. My wife, Cathy, has helped greatly with preparation of the included papers and of the whole thesis.

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PREFACE 1 - STATEMENT

Nature of Publications submitted

This thesis comprises copies of ninepapers and short notes already published, two papers in press and one typescript awaiting publication. They are in chronological order. None of these has already been submitted for a higher degree and papers on carbonate petrography resulting from previous work for an M.Sc. degree (Liverpool University) are excluded. The submitted work represents in concise form a continuing study of Purbeck sediments and of ancient and modern analogues; papers on other topics are not included. All the work was undertaken while the candidate was employed at the Department of Geology, the University of Southampton.

Four papers with co-authors are included, all of which were written by the candidate but for which substantial work was contributed by the co-authors. For the short Salter and West (1965) paper the XRD work was by Salter, petrography staining and establishment of diagenetic sequence by the candidate. With regard to West, Brandon and Smith (1968), the evaporites were first identified by the candidate. Extensive field mapping for other purposes which had already been undertaken by Brandon and Smith under the supervision of Professor Hodson, facilitated a short period of fieldwork by all three authors to locate the exposed evaporites. Petrography, most of the XRD work and the interpretation was by the candidate, while the co-authors, particularly Brandon, pursued field studies and limited laboratory work. The West and Hooper (1969) results from a field discovery by Hooper. Laboratory work and interpretation is by West.

The paper by West, Ali and Hilmy on a Recent analogue of Purbeck evaporites gives the first results of a project initiated by Professor F. Hodson. Field work in Egypt organised by Professor M. E. Hilmy was planned in detail and undertaken by West and Ali. Subsequent XRD and geochemistry was by Ali while petrography and organisation and preparation of the first paper was mainly by West (Ali continues to pursue this work at Southampton as a visiting scientist from Ain Shams University, Cairo).

The contribution to the book - "A Field Guide to Dorset Mesozoic Environment" is included because it incorporates the results of new field and laboratory investigations and, particularly, gives the writer's conclusions regarding the Purbeck environments. This contribution and each of the papers submitted is a condensed version of more extensive unpublished data.

PREFACE 2 - CONTRIBUTIONS OF THE PAPERS TO PURBECK SEDIMENTOLOGY

1. <u>Introduction</u>

The Purbeck Formation of Dorset is exciting because its interpretation provides an image of shallow lagoonal, shoreline and land environments of Mesozoic Britain that cannot be obtained by studying the marine Jurassic beneath. It is a formation that is particularly interesting, easily accessible, near large centres of population, and long investigated. As a consequence it has become something of a classic lithological unit, described in textbooks (e.g. Till, 1978). It is sometimes, however, rather difficult to interpret because the rocks seem to present excessive information but in an obscure manner. The variety is because it is a shallow water deposit; sedimentation near sea-level is most sensitive to small fluctuations in water-level and to small climatic changes. Thus the lithology and fauna vary rapidly in a vertical section mostly on a scale of about half a metre but frequently within a few centimetres or even millimetres. Thus there are numerous thin beds, usually with considerable lateral continuity. Because of this systematic sedimentological studies on a bed-by-bed basis are slow (eg. West, 1975), and because of initially greater value several papers (eg West, 1964; 1965) are concerned with the decoding of certain specific features.

The emphasis is on Lower Purbeck evaporites (West, 1960; 1961; 1964; 1965; Salter and West, 1965; West, 1973; 1975; in press) but all parts of the Purbeck Formation are dealt with to some extent (West and Hooper, 1969; West, awaiting publication). The Lower Purbeck evaporites have been more investigated by the candidate because (1) new discoveries regarding them were made accidently (2) little work had been done on them (3) they could be studied with very limited equipment (necessary at the beginning). The ultimate objective of the continuing Purbeck study, of which this represents only a part is the understanding of the ancient environments (West, awaiting publication). This is more important than the mechanics of the chemical and mineralogical changes, the study of which is (an interesting) means to an end.

The Purbeck Formation has traditionally been divided into Lower, Middle and Upper. The writer prefers to use these terms, bearing in mind the recommendations for retaining old well-established traditional names expressed by Hedberg (1976) and Holland et al. (1978). The division of the Purbeck into "Durlston Beds" above and "Lulworth Beds" below by Casey (1963) is based largely on tentative correlation of the Cinder Bed with a horizon (the mid-Spilsby nodule bed) regarded as the Jurassic-Cretaceous boundary. The boundary has not, however, been internationally defined and there are problems of correlating the Boreal and Tethyan marine sequences. The lithostratigraphical division of the Purbeck Formation should not, in any case, be governed by chronostratigraphical markers and the writer sees no reason for changing the long-established terminology.

The study commenced when a tabular mineral which was discovered by the writer in the Broken Beds at Durlston Head proved to be celestite (West, 1960). This was the first definite evidence for evaporites at this horizon in Dorset but, at that time unaware of the abundant other evidence for evaporites in the basal Purbecks, the writer commenced research on the pebbles of the Great Dirt Bed. Petrographic evidence showed derivation from the underlying Purbeck limestone and not, as had been suggested (Arkell, 1947), the Portland strata; the misleading black colour of many having been acquired at the margins of hypersaline lakes, as discussed in West (1975). In certain pebbles from Lulworth small lenticular objects were found and then, similar lenses were noticed in the basal Purbeck cherts. These proved to be pseudomorphs after gypsum.

2. Vanished Evaporites

The Broken Beds, the carbonate breccia at the base of the Dorset Purbeck Formation has been ascribed to various regions and the theories can be considered in two major groups (i) collapse theories and (ii) tectonic theories. Arkell (1938) summarised these and showed that the balance of evidence favoured a tectonic origin. Hollingworth (1938) then suggested that evaporites were formerly present at this horizon but did not provide specific evidence from Dorset.

The first paper (West, 1960) provided the first mineralogical evidence for former evaporites in the Broken Beds but at this initial stage, however, the extensive calcitisation of anhydrite was not recognised and most of what were considered to be calcite replacements of celestite crystals later proved to be calcite pseudomorphs after anhydrite (West, 1964). It was noted (p. 399) that the celestite occurs as small lenticular concretions and that therefore "a replacement origin for the celestite in the lower bed is clearly impossible unless the original material was itself in the form of a concretion". It was not realised that calcium sulphate was once present in major quantities here and this indeed had been in the form of concretions which were, of course, nodules.

The nodular character of the Durlston Head celestite and its origin by replacement of anhydrite is shown in the later paper (West, 1965 pl. 3, fig. 10). Nevertheless the 1960 paper suggests local abundance of calcium sulphate deposits adjacent to the celestite. It was appreciated that reaction between strontium-bearing water and calcium sulphate was involved in the formation of the deposit but in this first paper an unlikely theory of strontium-bearing water derived from Triassic celestite deposits was put forward. A more probable explanation is that strontium-rich groundwaters mainly derived from the underlying Portland Stone has flowed up the fault plane and reacted with anhydrite.

This was followed by the discovery of lenticular crystals of gypsum replaced by chalcedony beneath the Broken Beds at Portesham, at Stair Hole, Lulworth and later at many other localities (West, 1961; 1964) beneath and within the Broken Beds. As in the Portland Formation (West and Hooper, 1969), the chert is not only replacive but is also of early origin and preserves the initial stages of diagenesis. Other indicators of the former presence of evaporites such as net-texture and lutecite (West, in press) were found in basal Purbeck strata. The distribution of the evaporites using such criteria was found to bear a close relationship to the distribution of the Broken Beds and it was shown that replaced evaporites form the lower part of the breccia and the immediately underlying beds (West, 1975).

The criteria for vanished evaporites have been put to the test successfully in West, Brandon and Smith (1968). It is important, however, to stress that recognition of the former presence of evaporites on the basis of a single criterion is not a satisfactory procedure, a view expressed in West (1973).

3. Diagenesis

The basic scheme of Purbeck evaporite diagenesis excluding that of nodular structure was given in West (1964). Lenticular crystals of gypsum formed the initial deposits of calcium sulphate which on burial changed to gypsum with "net-texture" which was then in turn converted to anhydrite under further burial. Much later, on exhumation, this was hydrated usually via a porphyroblastic (porphyrotopic) stage.

In a second paper on diagenesis (West, 1965) gypsum with nodular structure was investigated and this was termed "macrocell structure", the name having been applied to distinguish it from the finer-grained net-texture (this the writer had intended to call "cell texture" but proved to have been already named "net texture" by Brown in 1931). The name "macrocell structure" has not been adopted and nodular or chicken-wire are the terms usually applied. In this paper it was suggested that nodular anhydrite developed from nodular gypsum and a more complete diagenetic scheme was developed. Later in West (in press) written before working in Egypt, this view was modified so as to consider the possibility of displacive primary anhydrite, the presence of which was suggested by Shearman (1966) and his co-workers on the Trucial Coast of the Persian Gulf.

Providing new evidence with regard to the crucial problems of primary anhydrite or gypsum is the preliminary paper by West, Ali and Hilmy (1979). The basic evidence for primary gypsum is put forward here, and further evidence has since emerged to support views expressed in the paper. Discussion of this controversial matter is likely, however, and further investigation certain.

The fixing of strontium at certain horizons and localities is an important aspect of Purbeck diagenesis. The strontium-bearing groundwaters have reacted with calcium sulphate (Salter and West, 1965; West, 1973) largely during calcitisation of the anhydrite of the Caps and Broken Beds. The work of Evans and Shearman (1964), however, had shown that some celestite can develop early to a small extent, and this has been confirmed by West, Ali and Hilmy (1979). Carbonate replacement of the strontium sulphate has taken place in one case to produce calciostrontianite (Salter and West, 1965). Analogous large-scale celestite replacement takes place in the Viséan of Ireland (West, Brandon and Smith, 1966) and is developed at the top and bottom of the Soft Cockle gypsum of Dorset and in the basal Purbeck evaporites of the Mountfield Mine, Sussex.

4. Sedimentary Environments

There has been suggestion in the past that much of the Lower Purbeck Formation originated in freshwater conditions and the stromatolites were originally described as freshwater "tufas" (Strahan, 1898). The absence of marine forms was so explained. The abundance of evaporites, the details of which are discussed in the papers here, though, explains both both the presence of stromatolites and the abundance of ostracods which are not of freshwater type (Anderson in Wilson et al, 1958) Identifiable algae studied by Brown (1963) and Pugh (1969) seem to have originated in hypersaline water. Thus it became clear that hypersaline conditions prevailed in Dorset throughout much of the time during which the Lower Purbecks were deposited (West, 1975).

The salinity problem was investigated in more detail and faunas and evaporites enabled four major facies to be recognised in the basal Purbecks (West, 1975). A major problem though is the question of whether these strata originated in a lagoon of brine continuously supplied by seawater or whether they were formed in a saline lake completely isolated from the sea. Limited fauna of marine affinities argue for a sea connection. The water in Dorset was not entirely hypersaline, though, as the discovery reported in West (1975) leads to recognition of an ephemeral lake in the Portesham area where a rich silicified fauna has provided many new species of charophytes and land plants described by Barker, et. al. (1975).

The "cockle beds" which form the upper part of the Lower Purbecks have interesting associations of euryhaline bivalves with evaporites. In the Soft Cockle Beds which are predominantly argillaceous, calcium sulphate is still unreplaced and undissolved (West, 1964; West, 1965) and with sabkha cycles (West, awaiting publication). Much of the diagenetic history of the Purbeck evaporites of West (1964; 1965) comes from these deposits which are remarkably similar to the basal Purbeck evaporites of Sussex. The sediments in which they occur have been studied by Brown (1965) and are considered briefly by West (awaiting publication). They are notable for lack of open marine faunas but frequent occurrence of hypersaline lagoonal and tidal-flat deposits. The association of the "cockle" (Protocardia) with gypsum nodules and other evaporitic features can be matched in the sediments of the former lagoon "Lake Mareotis", west of Alexandria, Egypt, where modern gypsum nodules occur above lagoonal sediments of historic date which contain Cardium.

The sabkha origin of much of the Purbeck evaporites was not recognised in the early work. It was the publication of the classic work on the Trucial Coast of the Arabian Gulf (e.g. Shearman, 1966; Butler, 1966) that revealed the importance of the "tidal-flat" deposition. "Intertidal" deposits are particularly well-developed (although true semi-diurnal tides probably did not occur). Nevertheless the writer could not fully accept the Trucial Coast model for the Purbeck. The problem that arose is that evidence of truly desert conditions is limited. With lack of red-bed facies and blown sand but with the presence of forests (West, 1975; West, awaiting publication) it was difficult to ascribe to these rocks such an extremely arid environment.

A similar lack of desert features was noticed in another, rather similar carbonate and evaporite facies that in the Carboniferous of Ireland (West, Brandon and Smith, 1966). Like the Lower Purbecks this is grey-bed facies and contains tree remains (although not in place). The importance of this sequence is that well-defined cycles occur and applying Walther's Law the facies can be placed in their relative lateral positions. This leads to the conclusion that the Carboniferous nodules were developed on sabkhas or tidal flats in spite of the lack of deserts. Here another semi-arid evaporite sequence throws light on the origin of the Purbeck evaporites.

This made sabkha interpretation of the Purbeck nodular horizons more probable in spite of the difficulties. The appropriateness in some respects of Shearman's (1966) sabkha model for the Purbeck evaporites was only fully appreciated by the writer, however, when,with Yehia Ali, he dug into a sabkha in Egypt at a point chosen almost at random and found gypsum nodules (West, Ali and Hilmy, 1979). Nevertheless, detailed comparison shows even this area to be too dry (the palm trees of our Fig.1 exist mainly because of local low salinity water.)

The gypsum or anhydrite origin for the evaporites is an important problem. The argument is put forward in this paper for a primary gypsum origin. Since the paper was written similar but smaller nodules have been found in the second depression which was until recent historic times under the water of a large lagoon.

The environments of deposition of the subdivisions of the Middle and Upper Purbecks are discussed in the contribution to the book on Dorset Mesozoic Environments (West, awaiting publication). El-Shahat (1978) has classified individual beds of the Middle Purbeck into early-cemented and late-cemented types. The early-cemented limestones have been cemented subaerially probably in high intertidal to supratidal environments. In the less arid climate that characterised the time of deposition of the Middle Purbeck strata, these early-cemented shell-hash deposits are the equivalents of the supratidal sabkhas of the Lower Purbecks.

As the climate changed gradually to wetter conditions the clay mineral kaolinite characteristic of more acid soil conditions began to be deposited in the sediments above the Cinder Bed (unpublished work by T. Clayton and the writer). This was followed by increased influx of quartz sand and organic matter. The clastic influx culminates with the introduction of debris from Jurassic strata at the western margin of the basin (West and Hooper, 1969). This probably resulted from uplift which raised the source areas for the coarse Wealden fluviatile and shallow deltaic sediments in Dorset.

Conclusions

Conclusions regarding Purbeck evaporite diagenesis are given in the review of West (in press) and those regarding sedimentary environments in the contribution to the book on Dorset Mesozoic Environments (West, awaiting publication). The large Purbeck lagoon was subjected to a Mediterranean climate, initially, semi-arid, with evaporation exceeding precipitation plus runoff, but later subhumid with precipitation plus runoff exceeding evaporation. Sedimentation took place near mean sea-level and was therefore extremely sensitive to even small environmental changes.

This work represents only a stage in Purbeck investigations and it is hoped that soon a really satisfactory analogue of the Purbeck fossil forests and sabkhas will be found in the Middle East.

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CONTENTS - LIST OF PAPERS

The following published papers were included in the bound thesis, but are not made available due to copyright restrictions. Digital object identifiers (DOI) to the published papers are provided. Pages 16 –105 are removed from the digitised PDF.

West, Ian M (1960) On the occurrence of Celestine in the Caps and Broken Beds at Durlston Head, Dorset. *Proceedings of the Geologists' Association* **71** (4) 391-401 doi:10.1016/S0016-7878(60)80022-3 (complete)

West, Ian M (1961) Lower Purbeck Beds of Swindon Facies in Dorset. *Nature* **190**, 526 http://dx.doi.org/10.1038/190526a0 (complete)

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REVIEW OF EVAPORITE DIAGENESIS IN THE PURBECK FORMATION OF SOUTHERN ENGLAND

by Ian West [1]

ABSTRACT - Evaporites and remains of "vanished evaporites" are widely distributed in the Purbeck Formation of southern England. Associated sediments show that these were formed in semi-arid conditions on the extensive tidal-flats of a shallow hypersaline gulf. The primary sulphate was predominantly gypsum as lenticular crystals. Fabrics developed indicate five major stages of diagenesis. There was early recrystallisation of the initial gypsum mush (stage I) to an anhedral fabric with the small-scale "net-texture" (stage II). Nodular structure and enterolithic veins developed as the sulphate was converted to anhydrite (stage III), a process which commenced penecontemporaneously and was completed before deep burial. The anhydrite was recrystallised, so that several anhydrite fabrics now exist. Hydration, a relatively recent process resulting from contact with meteoric water near the surface, usually proceeded via a stage (IV) of anhydrite with gypsum porphyroblasts. The existing porphyroblastic gypsum represent the final stage (V). Concurrent with sulphate diagenesis there was replacement of the evaporites on an appreciable scale, particularly where they were not enclosed in impermeable clays. Calcitisation has produced peculiar limestones and breccias. Associated replacement products, including celestite, calciostrontianite, lutecite, quartzine and quartz, suggest an inorganic mechanism for the calcitisation. Criteria are listed that may be used for the recognition of similar replaced evaporites elsewhere.

In the "Symposium on Jurassic Sedimentation in Western Europe", Association des Sedimentologistes Francais (1978).

(Erratum - Omit "large" from IIb of Fig. 2 and line II of p.6.
See West, Ali and Hilmy, 1979).

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1. INTRODUCTION

The Purbeck Formation underlies much of southern and southeastern England (see Howitt, 1964, for isopachyte maps) and part of the Channel (Larsonneur *et al.*, 1974). It consists mainly of limestones and clays that originated in shallow waters of various salinities ranging from fresh to hypersaline. These sediments are the products of a widespread regression at the end of the Jurassic Period. Evaporites are common in the lower part of the formation, but, for palaeoclimatic reasons, there are only traces in the middle Purbeck (El-Shahat, 1977) and none in the upper.

The evaporites, attaining about 12m in thickness in some areas, occur most widely at the base of the formation. Anhydrite found in boreholes is associated with pelletal and algal limestones and occasionally dolomite (see Howitt, 1964; Shearman, 1966; Taitt and Kent, 1958; Holliday and Shephard-Thorn, 1974).

In the shallow subsurface at the Mountfield and Brightling gypsum mines in Sussex four "seams" or beds of gypsum occur, the evaporite facies commencing almost exactly at the base of the Purbecks. Some chert and some celestite (James *in* Howitt, 1964) is present. When these basal evaporitic beds are exposed at the surface in Dorset they are extensively calcitised and brecciated (Hollingworth, 1938; Brown, 1964; West, 1964). The main evaporite facies is here interbedded with strata that originated in less hypersaline, intertidal, conditions (West, 1975). Algal limestones are common (Brown, 1963; Pugh, 1969).

At higher horizons in Dorset, in the Soft Cockle Beds, there are evaporites consisting of secondary gypsum. Occurring in a more argillaceous sequence (see Clements, 1969, for details of the succession at Durlston Bay) they are mostly unreplaced. On the Isle of Portland, however, there are celestite, quartz and chalcedony replacements.

2. GENERAL ENVIRONMENT AND CLIMATE

The British Purbeck evaporites have been formed in and around a very large, very shallow, lagoon with extensive tidal-flats. Size and hypersalinity accounts for lack of bioclastic debris.

An important feature of the evaporites is the evidence of semi-arid conditions (West, 1975). They are associated with remains of trees, perhaps of a rather southern (35°N?) type of forest-steppe (Walter, 1973), and with thin, black carbonate-rich soils, once compared to chernozems (Damon, 1884), but probably rendzinas. Occasionally there are thin freshwater beds. There are no blown sands, red beds or beds of halite which could have originated in desert conditions. The evaporites consist predominantly of calcium sulphate and its replacements and occur in a grey mudstone and limestone sequence. They thus resemble other ancient evaporites of semi-arid origin such as the famous Palaeogene gypsum of Paris.

3. SABKHA CYCLES OF SEMI-ARID TYPE

Cycles of sedimentation were reported in the basal Purbecks in the east at Warlingham by Shearman (1966) and later at Fairlight and Brightling by Holliday and Shephard-Thorn (1974). These authors compared the cycles to modern sabkha cycles of sedimentation and diagenesis formed by alternating transgression and progradation on coastal flats bordering deserts. It must be stressed, however, that the semi-arid nature of the Purbeck environment has resulted in some special features.

It is in the basal Purbecks of the Dorset marginal area that cycles with evaporites have, at the top, soils with trees (West, 1975). Such soils would presumably be absent in typical desert sabkha cycles. These cycles and the sabkha cycles of the region to the east are compared in Fig. 1.

Each cycle results from a rapid transgression which submerged a forest. It was followed by a long phase of sedimentation during which evaporites were formed. The soils are best developed where the proportion of carbonates to evaporites in the underlying rock is high and where local

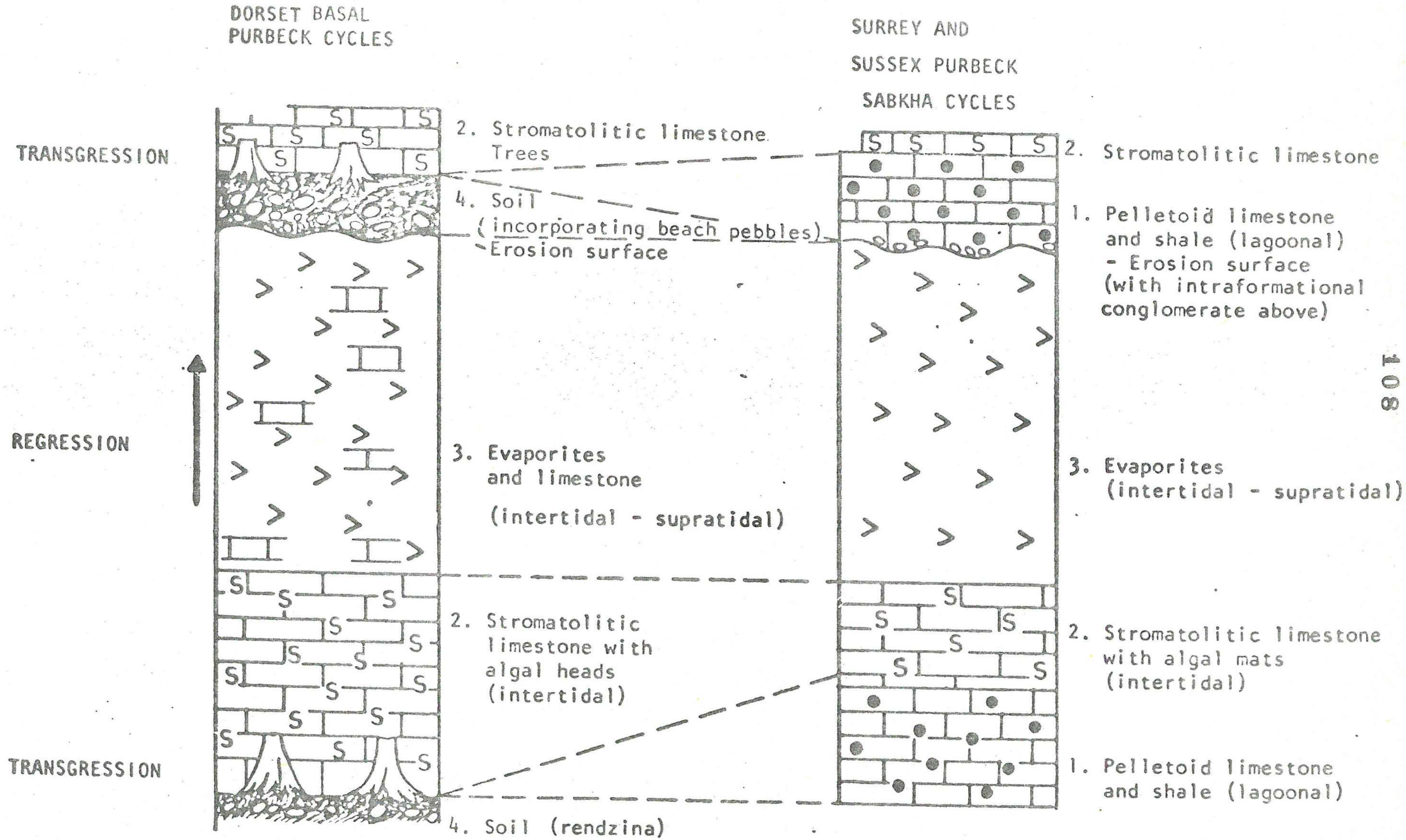

Fig. 1 Probable relationship of Dorset basal Purbeck cycles to sabkha cycles in Surrey and Sussex (Shearman, 1966; Holliday and Shephard-Thorn, 1974). The Dorset sequence is that of the margins of the basin.

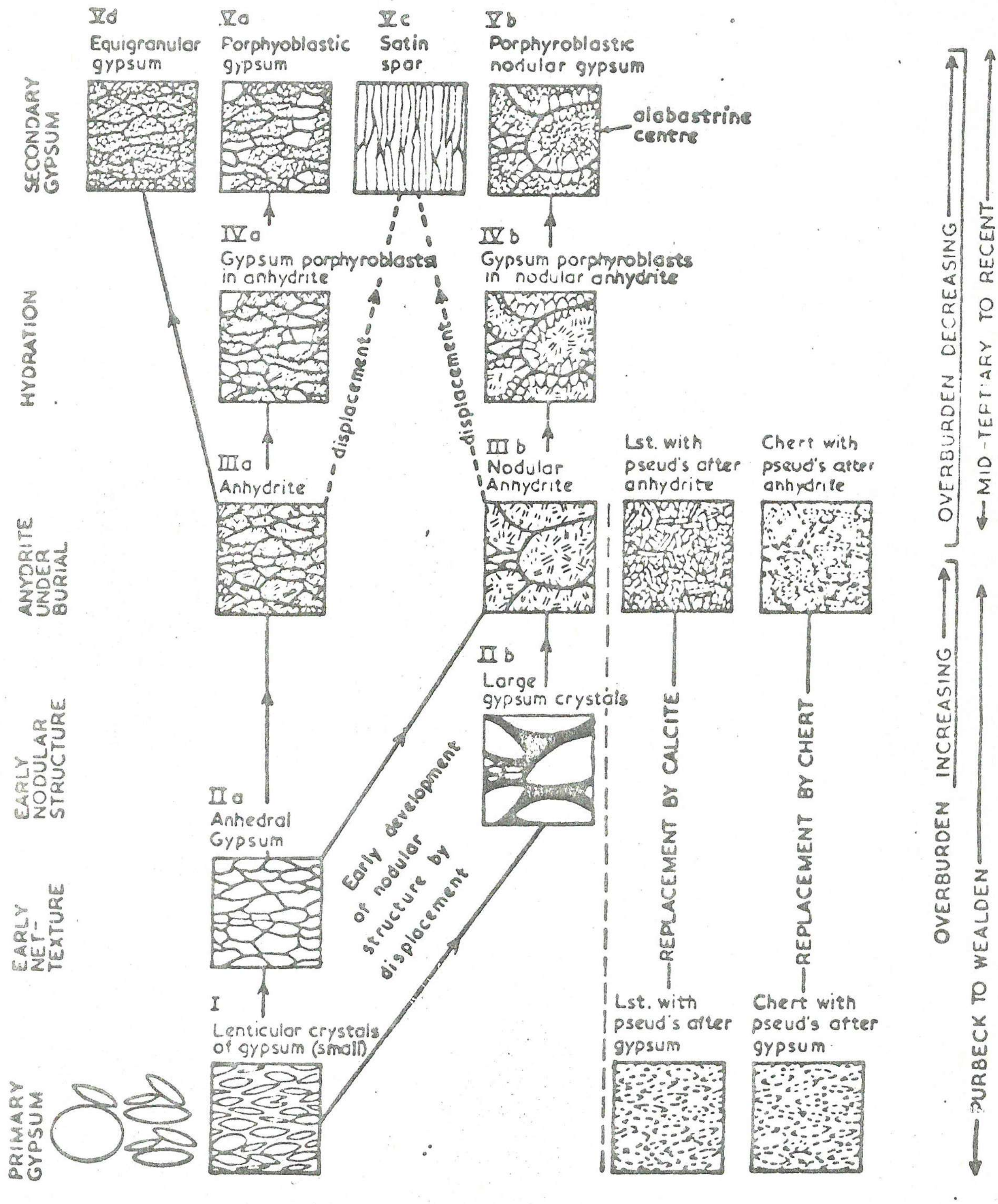

Fig. 2 A general diagenetic classification of British Purbeck calcium sulphate rocks. Comparison with Recent sabkhas suggests that the nodular anhydrite (III b) was formed earlier than the anhydrite with net-texture (III a), although both persisted under conditions of burial. Details of the stages are discussed in the text.

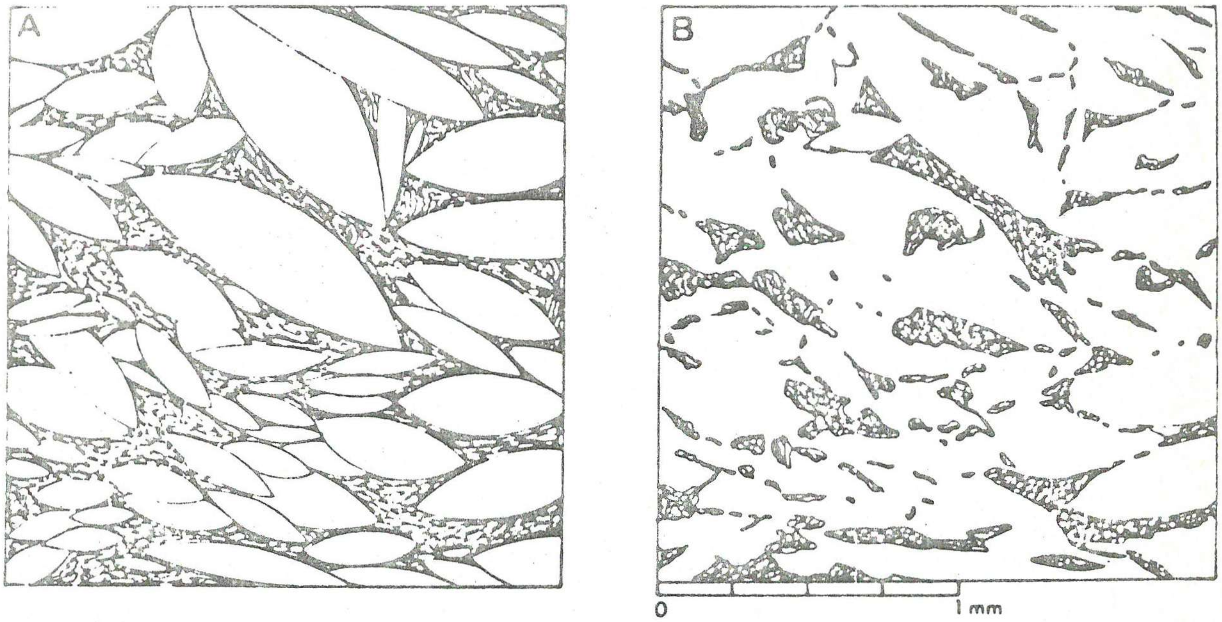

Fig. 3 The conversion of a sediment of lenticular crystals of gypsum (A) into calcium sulphate rock with net-texture (B), shown schematically. Diagram B is based on a photomicrograph of secondary gypsum from Durlston Bay.

uplift has produced well-drained areas favouring growth of numerous conifers and scattered cycadophytes.

4. THE DIAGENETIC HISTORY

Pseudomorphs, ghosts and the present sulphate textures have enabled the general diagenesis of Purbeck evaporites to be established (West, 1964; 1965). A broadly similar scheme, but with some changes, particularly subdivision of the anhydrite stage, has been put forward by Holliday and Shephard-Thorn (1974) for the Fairlight Borehole. Shown diagrammatically here (Fig. 2) is a modified, updated, scheme of West (1965). Descriptions of the diagenetic stages follow.

Stage I

Chert in evaporitic rocks of the Purbecks usually contains numerous minute (about 2mm or less) pseudomorphs of chalcedonic silica (usually lutecite) after lens-shaped crystals of gypsum. Sometimes these are quite separate and can be studied in three dimensions. It can then be seen that these crystals had the lenticular habit well-known from the Paris Palaeogene gypsum (Lacroix, 1897). Even more abundant throughout most of the basin, but less perfectly preserved are calcite and secondary gypsum pseudomorphs after early gypsum crystals of this type (West, 1964; Shearman, 1966; Holliday and Shephard-Thorn, 1974).

The modern environments in which mushes of such minute lenticular gypsum crystals are found are those of arid or semi-arid tidal-flats. Examples have been described from the Trucial Coast (Shearman, 1966), Texas (Masson, 1955) and elsewhere.

Stage IIa — Net-texture

Frequently visible in thin-sections of the evaporitic rocks is a small-scale (2mm) network of impurities such as calcite, clay, quartz and celestite (Fig. 3B). A very similar texture in anhydrite of salt-dome cap-rock was named by Brown (1931, Fig. 22) "net-texture". This microscopic feature should not be confused with the large-scale chicken-wire or nodular structure discussed below. Net-texture is found in Purbeck anhydrite and in secondary gypsum. It is common in calcite replacements and occurs in some early chert replacements of evaporites; all this suggests an early origin.

Net-texture was probably fixed in position during the compaction and crystal growth of the initial sediment of small lenticular crystals of gypsum (Fig. 3). This seems to have been converted into anhedral gypsum with reduced porosity; the carbonate and clay films between the crystals form the net-texture. Sometimes it is particularly conspicuous because calcitisation has been initiated on the network of carbonate nuclei.

Stage IIb – Early Nodular Structure

Some nodular structure may have developed from large gypsum crystals, the growth of which preceded conversion to anhydrite (Fig. 2). It is more appropriate to discuss nodular and enterolithic structures in relation to anhydrite. See stage IIIb, below.

Stage III – Anhydrite – General

Anhydrite is the predominant evaporite in deep boreholes through the Purbeck Formation. It can also be found with gypsum in the Sussex mines. There and in Dorset minute relics of anhydrite are preserved in secondary gypsum; gypsum and calcite pseudomorphs after anhydrite are common (Brown, 1964). The origin of much of the anhydrite rock as gypsum is demonstrated by chert nodules with pseudomorphs after gypsum occurring within anhydrite.

Microscopically, the anhydrite from the Fairlight Borehole was found by Holliday (1973; *in* Holliday and Shephard-Thorn, 1974) to occur as three main fabrics. He suggested that aphanitic anhydrite has given rise to anhydrite with felted-lath or fibroradiate texture by local recrystallisation. Lath-shaped anhydrite with cross-cutting relations to earlier fabrics was considered to be the latest fabric.

Conflicting evidence, however, for the texture of the earliest anhydrite comes from Dorset. Here, chert nodules, presumably early since Purbeck chert predates compaction and tectonic fracturing, contain ghosts or pseudomorphs after fibroradiating or lath-shaped anhydrite (West, 1964). The texture of this early anhydrite is remarkably similar to that of the Recent anhydrite of the Trucial Coast (compare plate 36, fig. 3 of West, 1964, with plate 3, fig. 1 of Shearman and Fuller, 1969). Aphanitic anhydrite rather than being the earliest variety, may be, instead, a recrystallisation product of a coarser-grained "anhydrite", now mostly lost.

Stage IIIb – Nodular and Enterolithic Anhydrite

Where net-texture is absent in anhydrite or later replacements, nodular structure ("macrocell structure" of West, 1965) or chicken-wire structure is usually developed. The nodules consist, or consisted of, nearly pure calcium sulphate with displaced sediment occurring as stringers between them. They are often found as anhydrite in boreholes (Shearman, 1966; Holliday and Shephard-Thorn, 1974) or as secondary gypsum at the surface.

Closely associated with nodular structure are enterolithic veins. The most common type shows small, tightly-closed, folds each of which consists of miniature domes and basins, swollen at crests and troughs. In argillaceous limestones there are some non-transgressive gypsum veins with cylindrical folds. A third type of vein is transgressive, cutting the other veins and, therefore, somewhat later (West, 1965).

The nodules of sulphate have displaced the carbonate and clay as they enlarged. The closely related enterolithic veins provide evidence of expansion since the dome and basin structure can only have originated by such means. Crystal growth was presumably the mechanism, although whether initially as anhydrite – (III b) or as gypsum (II b), is a problem that is discussed below. The transgressive veins have been compared to ptygmatic structures formed by buckling as veins inject plastic country rock (West, 1965).

Early origin of the nodules and veins is shown by their occurrence in anhydrite and by evidence of plastic deformation of the containing sediment (West, 1965). Shearman (1966), in a classic paper, pointed out the remarkable similarity of the Purbeck nodular anhydrite to the Recent nodular anhydrite which he described from the sabkhas of the Trucial Coast. Shearman argued convincingly that the Purbeck nodular evaporites developed penencontemporaneously by crystal growth within the sediments of tidal flats.

A further implication was that the Purbeck nodular anhydrite was of primary origin (Shearman, 1966). Evidence has already been put forward, though, for the initial sediment having consisted of gypsum (West, 1964; 1965) and that the nodules developed from this by the growth of gypsum crystals displacing impurities. This view was later to some extent supported by the discovery that the Trucial Coast nodular anhydrite had often developed from gypsum crystals (Kinsman, 1969; Butler, 1970). Nevertheless, Shearman has shown that the Recent nodules and veins have expanded *as anhydrite* and the increment, at least, is "primary anhydrite". There is no reason to doubt that the Purbeck nodules have also expanded as anhydrite, and, indeed, Holliday and Shephard-Thorn (1974) reported "primary" interstitial anhydrite from the Fairlight Borehole.

It is, however, surprising that in this relatively northern semi-arid environment early anhydrite was developed. The climate was marked by great seasonal changes (West, 1975) and, perhaps, the summers were very hot and dry (Holliday, personal communication, 1977).

Stage IIIa – Anhydrite with Net-Texture

In parts of the anhydrite rock, and in later replacements, nodular or enterolithic structures are predominant and these, then, represent the earliest development of anhydrite. The remainder of the evaporites show traces only of net-texture. Thus, after development of anhydrite nodules and veins there was conversion of the original gypsum mush through anhedral gypsum to anhydrite. This was presumably a consequence of both burial and time, since gypsum is rarely found at great depth (below 700m) in boreholes, and since primary gypsum is common in Cainozoic strata but rarely seems to survive in that of Mesozoic age.

Stage IV – Anhydrite with Gypsum Porphyroblasts

Anhydrite with porphyroblasts ("porphyrotopes" of Friedman, 1965) of gypsum occurs in the Sussex mines and elsewhere. The hydration of the anhydrite usually commenced with the growth of such crystals, hence their abundance in the secondary gypsum rock. Both nodular types (IVb) and types with net-texture (IVa) have been developed. The date at which hydration commenced at particular localities depended upon extent of erosion and access of meteoric water.

Stage V – Secondary Gypsum

Four main varieties exist:

Porphyroblastic with net-texture (Va) – This type of gypsum rock formed from the anhydrite without nodular structure (stage IVa). The relict net-texture is seen as a network of small carbonate and clay particles.

Prophyroblastic with nodular structure (Vb) – This variety, of course, results from complete hydration of nodular (or enterolithic) anhydrite with gypsum porphyroblasts (stage IVb). The porphyroblasts have usually developed centripetally from the films of clays and carbonate around the nodules. The central area of each nodule is now occupied by alabastrine secondary gypsum (Holliday, 1970), consisting of small nearly equant gypsum crystals with interlocking boundaries. This is the consequence of the final, probably rapid, hydration.

Equigranular with net-texture (Vd) – Occasionally found is gypsum with relict net-texture but which is non-porphyroblastic. This was presumably formed by the direct hydration of stage IIIa anhydrite.

Satin-spar (Vc) – Fibrous gypsum is always extremely pure and, lacking relict textures, differs from the other types of gypsum by not being a replacement product. Instead it seems to show evidence of displacement; small fragments of limestone and shale have been lifted by the fibrous crystals.

It cuts, and therefore postdates, the enterolithic veins. Even where the strata dip steeply as a result of Tertiary folding the fibres are consistently of vertical orientation suggesting that the formation of satin-spar postdated folding. Although therefore a fairly late sulphate development, satin-spar occurs in anhydrite rock buried to depths of about 400m (Holliday and Shephard-Thorn, 1974). It must represent some of the earliest gypsum formed when anhydrite rock was beginning to undergo hydration.

An origin during hydraulic-jacking was suggested by Shearman *et al* (1972). Evidence against this, however, is firstly the late development of satin-spar in folded strata not far beneath a plane of unconformity, and, secondly, strontium contents for satin-spar (average for 6 samples – 288 p.p.m.) much lower than adjacent gypsum (average for 7 samples – 1159 p.p.m.). This suggests an open system with regard to water during its formation. Furthermore it does not possess the usual columnar impingement texture of open veins (Spry, 1969). If crystal growth alone caused the displacement,much of the overall expansion of the bed of sulphate that results from hydration may be represented by this new pressure-resistant, non-porous fabric of vertically orientated fibres (West, 1965). The evidence above seems to support this origin.

5. CALCITISATION

Extensively developed at the base of the formation in Dorset are peculiar limestones resulting from calcitisation of evaporites (West, 1975). Criteria used for recognising such formerly evaporitic rocks are given below. It is particularly pseudomorphs which demonstrate the origins of these rocks. Some are soft white porous limestones, crumbling like weakly-cemented sandstone; others are hard, laminated and coarsely crystalline; all are completely unfossiliferous.

Calcitisation is often attributed to bacterial action (Holliday and Shephard-Thorn, 1974). Lack of sulphur in the basal Purbecks, however, and the presence of much celestite (Salter and West, 1966; West, 1973) suggests that in this case inorganic calcitisation by bicarbonate-bearing groundwater was responsible. This explains why calcitisation is best developed in the basal beds, where the evaporites were almost in contact with the underlying Portland limestones.

Calcitisation took place both before and after the tectonic brecciation that resulted in the formation of the Broken Beds. Calcitised evaporites occur both as blocks in the breccia and as matrix. Remaining gypsum was removed in solution.

6. SILICIFICATION

Chert is preferentially developed in the evaporitic beds as nodules or as thin beds. It replaces only stages I, II and III. Certain early Purbeck environments probably resembled in water conditions some modern ephemeral lakes in Australia. These display great seasonal fluctuations of salinity and pH causing precipitation of gelatinous silica, a precursor of chert (Peterson and von der Borch, 1965). The selective replacement of Purbeck gypsum is probably consequent on locally lower pH values around the sulphate, when in contact with alkaline water with silica in solution. Photosynthesis by the Purbeck algae was probably a factor in the production of lagoon water of high pH.

7. EVIDENCE FOR FORMER EVAPORITES

Finally, criteria for detection of "vanished evaporites" of semi-arid type in the Purbeck Formation are summarised (West, 1964; West *et al.*, 1968; Folk and Pittman, 1971) since these may be of value in the study of similar facies. Although single criteria are sometimes used elsewhere, this is not a reliable procedure and *an association of several points of evidence should be sought.* The criteria found useful are listed below:

1. Pseudomorphs of calcite, chalcedony or quartz (or moulds or casts) after gypsum, after anhydrite or after halite.

2. Length-slow chalcedony (quartzine).
3. Spherulites of the lutecite variety of chalcedony.
4. Euhedral crystals of authigenic quartz.
5. Celestite, sometimes with calciostrontianite (occasionally barytes)
6. Net-texture, a small-scale relic of early gypsum, in limestone.
7. Chicken-wire, nodular structure or spherical vugs in limestone or dolomite.
8. Coarsely crystalline limestones without skeletal debris (possible calcitised evaporities).
9. Small contortions that are not obviously of subaqueous slumping or other non-evaporitic origin.
10. Minute rectangular relics of anhydrite in quartz or other minerals.
11. Oligomict limestone breccia with a carbonate matrix (possible calcitised evaporite breccia).

Such evidence is likely to be found in other formations without normal marine faunas but with features such as algal-mats, algal stromatolite heads, caliches, abundant hypersaline ostracods or peculiar breccias. Obviously red-bed evaporites of more arid origin can provide additional criteria resulting from desert environments.

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Primary gypsum nodules in a modern sabkha on the Mediterranean coast of Egypt

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ABSTRACT

Nodules of anhydrite in Holocene sabkhas of the Arabian Gulf and Baja California have been used as analogues to interpret calcium sulfate nodules in ancient rocks as of sabkha origins. Nodules and incipient enterolithic veins of gypsum occur in a modern sabkha about halfway between Alexandria and El Alamein, in a depression between a modern and a Pleistocene beach ridge. The displacive gypsum is apparently being precipitated from hypersaline calcium sulfate saturated interstitial water which increases in salinity as it rises by capillarity from the water-table to the surface. Calcium and sulfate ions seem to be derived mainly from dissolution of pre-existing lagoonal gypsum beneath the water table. The nodules occur within a supratidal sand unit of a sabkha sequence capped by a gray, saline soil on which grow clumps of halophytes, separated by salt-encrusted flats. This discovery shows that calcium sulfate nodules can develop (1) within sediments of a region where the climate is almost semi-arid rather than very arid and (2) as primary gypsum rather than as anhydrite and (3) as a consequence of redistribution of calcium sulfate.

INTRODUCTION

Evaporite structures which provide evidence of sabkha environments are of particular importance to the understanding of ancient sediments, including those from deep sea basins. A much used and well-known characteristic is nodular structure in calcium sulfate usually in the form of anhydrite. The use of this structure follows mainly from the description of nodules in Holocene desert deposits of two isolated areas, the Trucial Coast of the Arabian Gulf (Curtis and others, 1963; Shearman, 1966; Butler, 1969) and Baja California (Kinsman, 1966). Supporting the sabkha theory is the discovery by Dronkert (1978) of gypsum nodules and enterolithic veins in near-surface sediments of an artificial salt pan in southern Spain.

It is surprising, however, that many more examples of calcium sulfate nodules have not been found in modern sabkhas and, indeed, the sabkha implication as a necessary condition for the formation of nodular anhydrite has recently been questioned (Dean and others, 1975). It was suggested that nodules are diagenetic alteration products that may develop in calcium sulfate deposits of various origins including those formed in deep water. Nodules from northern Egypt described here, however, provide new evidence for the sabkha theory from a natural environment and they throw light on the mechanism of formation.

The modern anhydrite nodules of sabkhas have been regarded as primary anhydrite (Shearman, 1966). In contrast, however, several authors (e.g. Kerr and Thomson, 1963; Murray, 1964) have regarded ancient anhydrite nodules as replacements of early gypsum either in the form of large crystals or as displacive gypsum nodules (West, 1965). Development of anhydrite by replacement of gypsum crystals has also been suggested for Arabian Gulf sabkhas (Butler, 1969; and other authors). The Egyptian evaporites show that nodules of fine-grained gypsum can, indeed, be the initial displacive forms of calcium sulfate.

THE SABKHA AND ITS SEDIMENTS

The modern nodular gypsum is present in the Mediterranean coastal zone near El Hammam about halfway between Alexandria and El Alamein (Figs.1 ,2)

Here the coast consists of a series of ridges of carbonate beach and dune sands, all but the seaward of which are cemented into hard limestone, and between which are long depressions floored by sandy sabkhas. We found the nodules in the carbonate-rich clastic sabkha of the first and seaward depression, by means of pits and shallow cores on three measured traverses, one example of which is shown in Fig. 1. Landwards, to the south, beyond the Abu Sir limestone ridge (Pleistocene) is the large second depression with halite-encrusted lakes, fringed by algal-mats and with sabkhas with gypsum, as lenticular crystals and, sometimes, as small nodules.

Climatically this area, at 31°N, lies near the northern limit of the northern hemisphere arid zone. Although dry and fairly hot in summer with maximum monthly average air temperature of 30°C (Trucial Coast maximum is 47°C), the annual rainfall is about 18cm (Trucial Coast has about 5 cm) so this area is almost semi-arid rather than typically arid. In ancient historic times conditions were even less arid and there was much more vegetation. Until the 12th century a branch of a Nile Delta lagoon, Lake Mareotis occupied much of the second depression. The sabkha evaporites discussed here presumably postdate the fall in the water-table consequent upon its desiccation, and are apparently still forming.

The floor of the first depression sabkha is at only about one to two meters above means sea-level and is almost flat except for numerous mounds of blown sand and gypsum around small halophytic shrubs (Fig. 1). The northern, seaward boundary of this depression is the modern Coastal Ridge of white oolitic sand. Beneath this there remains, even in summer, a lens of low salinity water which supports a single line of date palms at its foot (Fig. 1). Forming the southern boundary of the depression are alluvial fans of loam with land-snails that flank the Abu Sir Ridge.

The sabkha sediments consist mostly of brown, laminated, very fine quartz and carbonate sand both of windblown and flood origin, with various quantities of gypsum. There are scattered unoxidised glauconite grains but ooids like those of the Coastal Ridge are generally absent, probably partly because this ridge has only recently moved landwards to its present position and partly because the grains are too coarse to be easily blown across the sheltered depression. Detrital corroded dolomite rhombs and some fine-grained calcite is present.

Gypsum, as the usual small lenticular crystals, was the only calcium sulfate mineral found, but celestite also occurs as small elongate crystals occurring around gypsum crystals in the beds with nodules. The strontium sulfate presumably forms by the reaction of gypsum with strontium-rich groundwaters, derived from local strontium-rich carbonates (e.g. 7656 p.p.m. Sr in the Coastal Ridge).

The sediments beneath the sabkha can be divided into a number of lithological units, mostly without sharp boundaries but with either particular evaporites or hypersaline groundwater. The lowest unit, which has only been encountered in a core, (zone I of Fig. 1) is gray sand with fragments of limestone and algal-bored bivalves and with glauconite grains. Echinoid remains suggest an origin in near-marine water and this unit was presumably formed before the depression was completely separated from the sea by the Coastal Ridge.

There follow sands without shelly debris (zone II). They mostly lack evaporites, but on one of the traverses small lenticular crystals of gypsum were found in this unit and these resemble both in size and in morphology gypsum of intertidal origin from the Arabian Gulf (Shearman, 1966). Occurring between lagoonal or marine and supratidal sabkha sediments an "intertidal" or lagoon shoreline origin seems most probable for zone II. Water from these sands (collected in July) ranges in salinity from 31‰ to 61‰ and although with relatively low chloride is saturated for calcium sulfate (according to the solubility curve of Kinsman, 1974, fig. 3).

Zone III is a thick unit of brown sand with gypsum nodules consisting of coarse crystals of gypsum overlain by a thin bed, a few centimeters thick, of brown sand (zone IV) which contains nodules of very fine-grained crystals of gypsum. A laminated bed of gray, often reduced, sand (zone V) forms a sabkha soil or solonchak, with plant roots. This bed differs from those below in containing some halite. It has a firm brown oxidised surface with, in places, a thin crust of halite and gypsum. Coccoliths in this layer have probably been introduced in sea-spray.

SABKHA SEQUENCE

The sabkha sequence of zones (Fig.5) is comparable in many respects to the classic sabkha sequence of the Arabian Gulf described by Shearman (1966) and to the ancient sabkha cycles. Zone I probably represents the shelly lagoonal facies with which such cycles usually commence. Zone II, laminated, unfossiliferous and with small gypsum crystals, is probably, as discussed above, of "intertidal" facies while zones III and IV correspond to the "supratidal" sabkha facies of the Arabian Gulf and possess the nodules of strikingly similar morphology. The soil (zone V) can be matched in ancient sabkha cycles (in the Jurassic of Dorset, U.K.).

GYPSUM NODULES AND BANDS

The nodules are roughly spherical or elliptical, mostly between 1 and 4 cm in length and consist of pure gypsum (Figs. 2 and 3). They are very similar in appearance to Holocene anhydrite nodules from the Trucial Coast. The sediment laminae that have been pushed aside clearly show that, like ancient examples which they resemble (Fig. 4), the nodules are displacive. Sometimes they form upward-bulging, almost diapiric, structures (Fig. 2) which seem to be incipient enterolithic veins. The displacement by the gypsum crystals suggests slow crystal growth (Kastner, 1970).

The most conspicuous nodules are those that are white, soft and friable. These nodules are confined to zone IV (Fig.2). They are composed of minute (usually less than 50μ) lenticular crystals of gypsum and the white appearance results from the small size of individual crystals and the lack of impurities.

Nodules in zone III beneath the zone of white nodules consist of aggregates of cemented crystals about 1 or 2 mm in length (Fig. 2). The larger size of these crystals and relatively large pore spaces causes these to appear a darker, buff color and they are less obvious. The closely packed crystals sometimes lose their lenticular shapes and become subhedral to anhedral and rather blocky.

Ruckled bands of coarse gypsum crystals, each band being about ½ cm thick and about 2 cm apart (Fig.2) are associated with the nodules in zone III. Individual crystals are between 1 and 3 mm in length , sometimes with planes of flattening vertical (i.e. " on edge") and are lenticular to anhedral depending upon the amount of contact. Although sometimes incorporating some quartz and carbonate sand grains they usually displace the enclosing sediments.

ORIGIN OF THE NODULES - GYPSUM OR ANHYDRITE

In view of the Arabian Gulf investigations, referred to above, the possibility of an anhydrite origin has to be considered. Growth of early fine-grained gypsum, displacing sediments has not been previously observed and, indeed, growth of nodules is usually attributed to the growth of constituent anhydrite crystals (Shearman, 1966). Thus the Egyptian gypsum nodules might have formed by hydration of anhydrite nodules, a process recognised in the Arabian Gulf sabkhas (Butler, 1969). The following, however, suggests that they are primary nodules of gypsum and that they are forming at present, and are not secondary replacements of older anhydrite:

1 No trace of anhydrite was found in the area, in spite of a search at almost the hottest and driest time of the year (July) and after a winter with slightly less rainfall than usual. Even within gypsum crystals no minute relics of anhydrite were detected .

2. The uppermost gypsum nodules are soft and very friable and uncemented by diagenesis; all nodules have high porosities.

3. There is some relationship between crystal size and distance from the modern sabkha surface , a relationship unlikely to result from hydration of anhydrite . Nodules of small crystals overlie nodules of coarser crystals .

4 The nodules regularly terminate upwards at the base of the halite zone and yet this halite is presumably seasonal and washed out by the winter rains.

5 No large toothlike gypsum crystals or disturbance of the sabkha surface, features of hydrated anhydrite nodules in the Arabian Gulf (Butler, 1969) were found.

MECHANISM OF NODULE FORMATION

A mechanism is proposed which accounts not only for the position, purity and morphology of the nodules but also for the relative proportions of evaporites in the various zone of the sabkha sediment profile.

Firstly the origin of the groundwater must be considered. There are no channels through the Coastal Ridge to allow seawater to enter directly and the brine is, in any case, not simply of seawater derivation because, although the Na/Mg ratios are close to those of seawater, it is saturated for calcium sulfate yet remaining relatively low in chloride. Winter rain and sea-spray are undoubtedly contributors, but whether sea-water is also supplied through the sands under the Coastal Ridge is not yet known. As the second depression groundwaters are very different in composition (with high sodium and chloride) it is unlikely that water comes from that source. The high proportion of calcium sulfate argues for dissolution of gypsum, a theory supported by its relative rarity below the water table. The most likely gypsum source is the unfossiliferous zone II. The special groundwater composition together with the flushing of the sabkha by winter rains explains the low ratio of halite to gypsum in the sabkha sediments.

Halite occurs above the water-table but only in the uppermost zone(V). Salinity obviously increases upwards to the warm surface where evaporation results in a salt crust (Fig. 5). This presumably results in upward movement of water by capillarity through the permeable sands, the oxidizing water causing oxidation beneath the gray reduced surface layer. The significant thickness of the halite zone is probably due to some downward seepage of heavy brine (Fig. 5) particularly at night when there can be heavy dew.

The position of the gypsum nodules between the water-table and the halite zone (V) is the consequence of the increase in salinity as waters already saturated for calcium sulfate move upwards (Fig. 5). The small size of the crystals in zone IV suggests that these are the most recently formed, and presumably this zone of fine-grained gypsum precipitation rises as the surface of the sabkha rises with clastic sedimentation. The coarser-grained gypsum nodules beneath in zone III probably represent similar gypsum which has been enlarged by crystal growth.

The bands or laminae of relatively large gypsum crystals in zone III also apparently result from crystal growth within the sediments. The evidence is (1) they are large, (2) they poikilotopically incorporate sand grains and (3) they often show preferentially vertical orientation. These rather hummocky laminae resemble the thin horizontal ruckled gypsum layers or bands commonly found in ancient sabkha sequences and which when very contorted form non-transgressive enterolithic veins (West,1965). Such contortions would be the consequence of continued crystal growth.

CONCLUSIONS AND IMPLICATIONS

The existence of these modern gypsum nodules in a supratidal sabkha on the coast of the Mediterranean Sea, provides new evidence supporting theories of supratidal sabkha origins for similar nodules in ancient rocks, such as for example, those in the Miocene beneath the adjacent Mediterranean (Garrison and others, 1978).

The mechanism of nodule formation in northern Egypt is mainly one of sulfate redistribution. Gypsum, probably originally of lagoonal origin is dissolved and transported from a position below the water-table to one above by capillary water, and is there precipitated as nodules which displace the sediment.

The Egyptian nodules demonstrate that extremely arid desert conditions are not essential for the formation of calcium sulfate nodules. Association of nodules in sabkha sequences with halophytic plants and even trees may explain the proximity of evaporite nodules to petrified forests in ancient strata (West, 1975).

The continuing growth and survival of the nodules as gypsum may be because this area, partly vegetated and within a few hundred meters of the Mediterranean Sea, is neither sufficiently arid nor sufficiently hot for development of anhydrite near the surface.

After deep burial the primary gypsum would presumably change to anhydrite. The change, however, may take place near the surface. The sabkha west of Alexandria lies between two of a series of barrier beaches progressively building seaward. If such progradation continues the nodules will eventually be situated inland from the mild coastal fringe and experience the harsh aridity of the Western Desert. High temperatures and high interstitial water salinities could then convert these nodules into anhydrite nodules resembling those of the Arabian Gulf. Preservation of sulfate nodules like those in northern Egypt, whether as gypsum or as anhydrite, inevitably depends on burial under impermeable sediment.

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ACKNOWLEDGMENTS

Reviewed by B. Charlotte Schreiber, G.M.Friedman, R.E.Garrison and J.R.Merefield. We particularly thank Douglas Shearman and D. Kinsman for valuable comments on the typescript. We are obliged to Professor F. Hodson for having made this work possible; help in various respects was given by Dr Adam El-Shahat, Dr.M.E.Cosgrove, Mr.T.Claytòn, Mrs.E.Diaper and Mrs.A.Dunkley. This work forms part of a Ph.D. research program by Y.A.A. supported by Ain Shams University, Cairo. I.M.W. is particularly grateful to the authorities of Ain Shams University for financing his field work in Egypt and providing generous facilities.

CAPTIONS

Figure 1 - Above - Location of the cross-section, shown below, and the general geology of the area (locality B is 2.4 km E.N E of the El Hammam road junction).

Below - One cross-section of the first depression based on measured pits and cores. Zone I - glauconitic shelly sand; II - brown sand without shells, but with gypsum crystals in a nearby traverse. III and IV - brown sand with nodules and bands of gypsum; V - gray, often reduced, sand with some dispersed halite. Alluvial fans of loam with land-snails border the Abu Sir Ridge. Groundwater salinities are given.

Figure 2 - Nodules and incipient enterolithic veins of gypsum displacing brown sand (box sample from pit AD 2). Zone III contains light-coloured nodules and ruckled bands of gypsum, not well-defined because they consist of coarse crystals. In Zone IV are nodules that are conspicuously white because of the small size of the crystals. Zone V has some dispersed halite and gypsum.

Figure 3 - Horizontal section through gypsum nodules forming mosaic structure and incipient enterolithic veins. Zone IV, pit AD2.

Figure 4 - Comparable ancient nodules of gypsum from the Lower Purbeck Formation, Upper Jurassic, Dorset. U.K.

Figure 5 - Typical vertical section through the sediments of the first depression idealized from several pits and boreholes. Salinity (in summer) increases upwards from moderately hypersaline (31‰ - 61‰ measured) beneath the water-table to the zone of halite precipitation (presumed to be greater than 300‰) in the uppermost sediments. Note that the water is saturated for sulfate, even beneath the water-table.

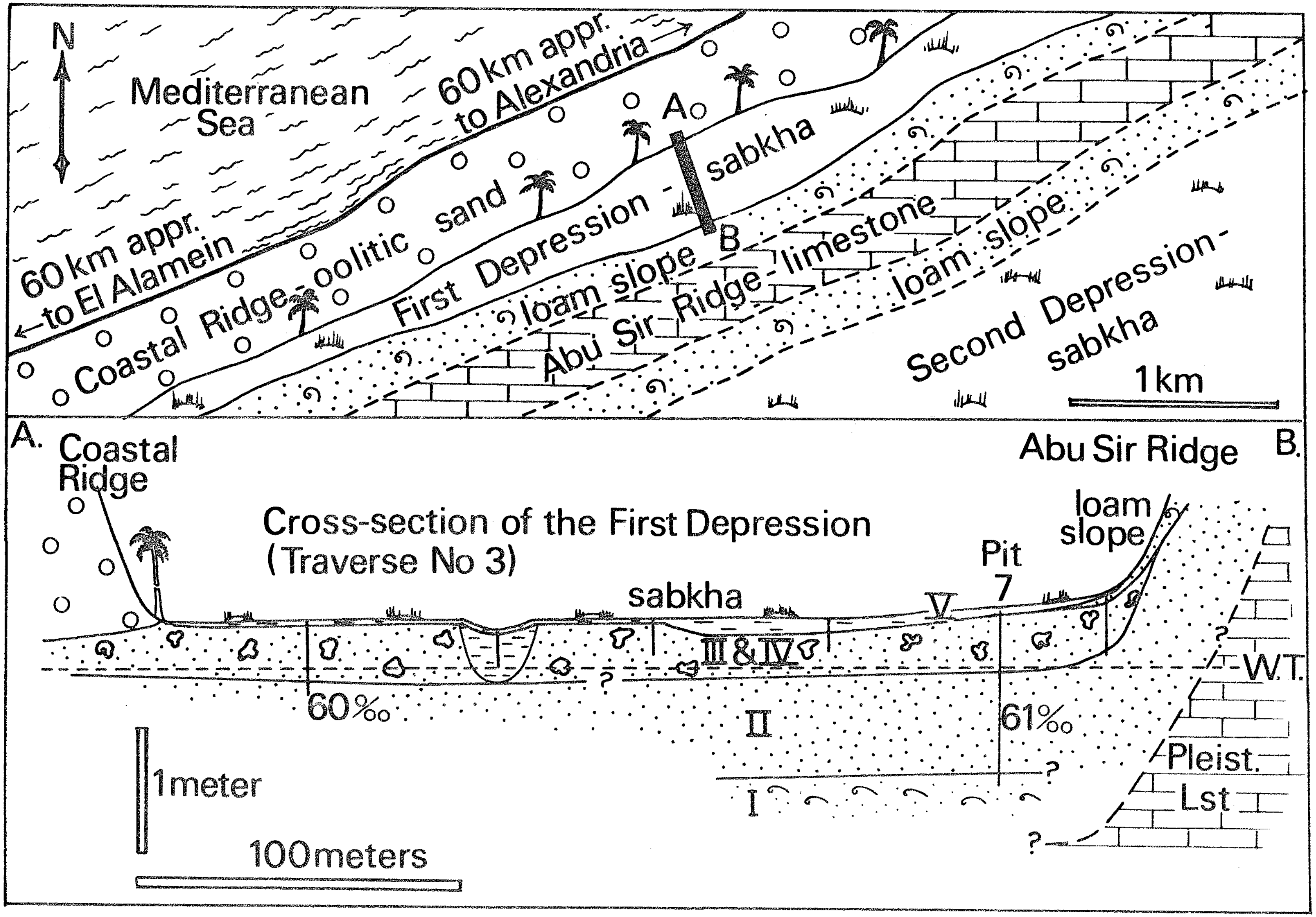

N
Mediterranean Sea
60 km appr. to Alexandria
60 km appr. to El Alamein
Coastal Ridge oolitic sand
First Depression
sabkha
A
B
loam slope
Abu Sir Ridge limestone
loam slope
Second Depression sabkha
1 km
A.
Coastal Ridge
Cross-section of the First Depression
(Traverse No 3)
sabkha
Abu Sir Ridge
B.
loam slope
Pit 7
V
III & IV
W.T.
60‰
61‰
II
I
Pleist. Lst
1 meter
100 meters

Fig. I

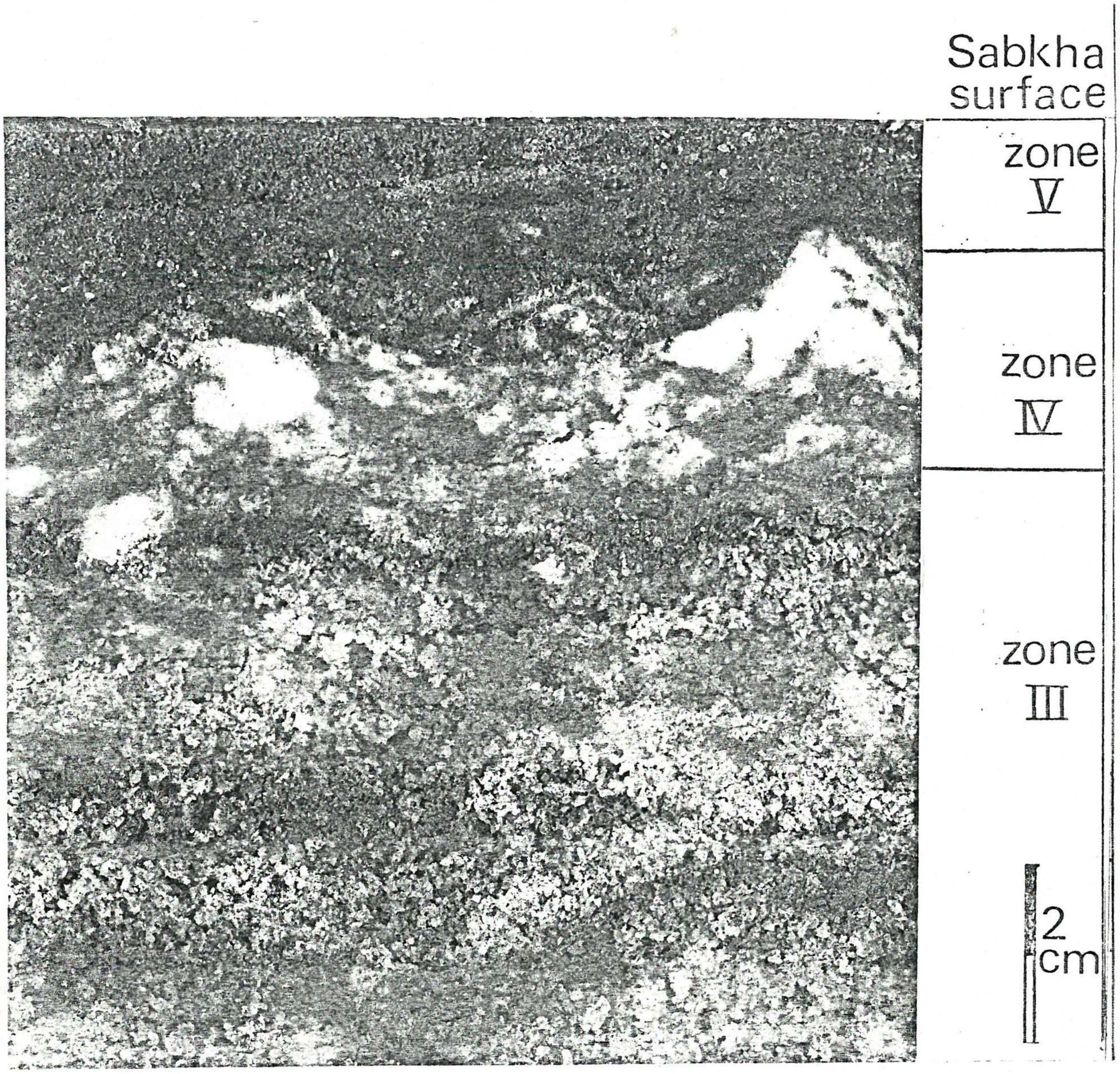


Figure 2

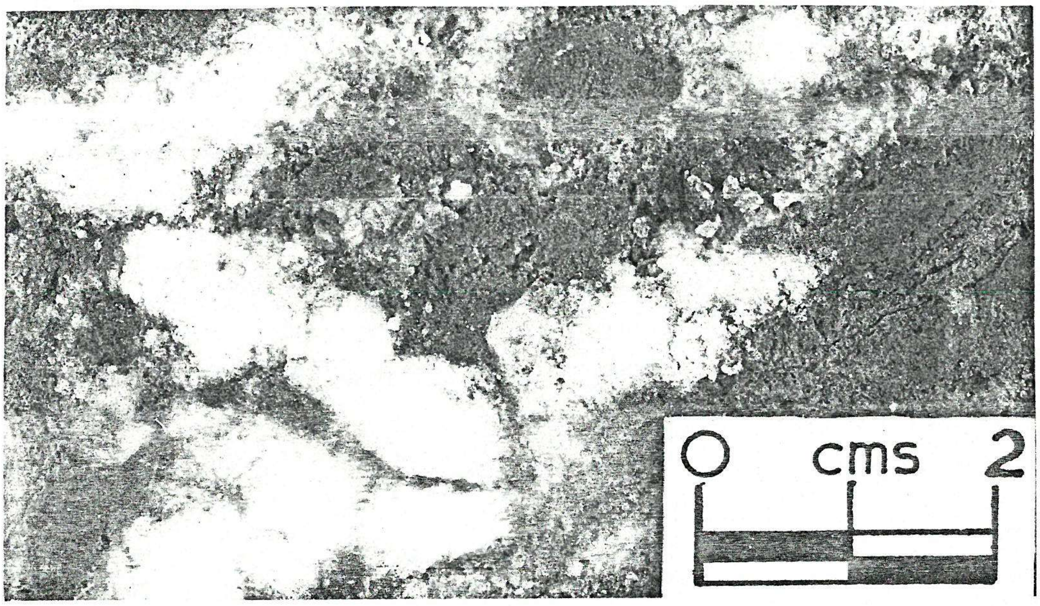


Figure 3

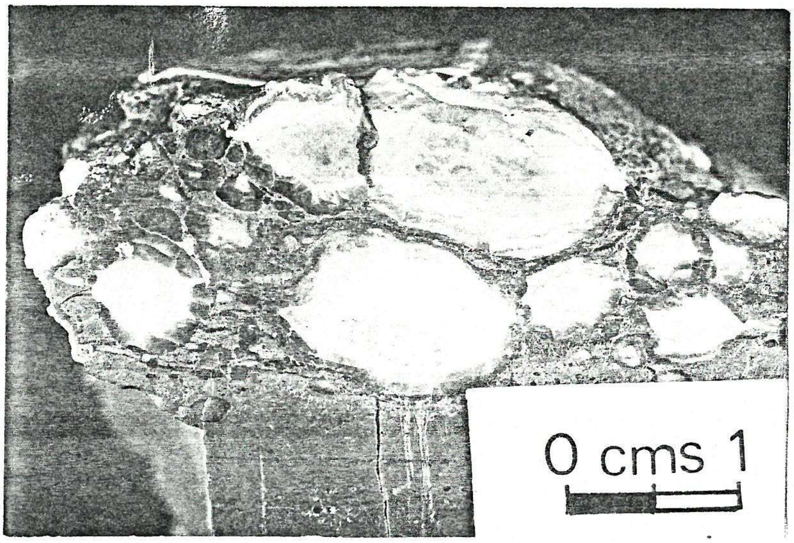


Figure 4

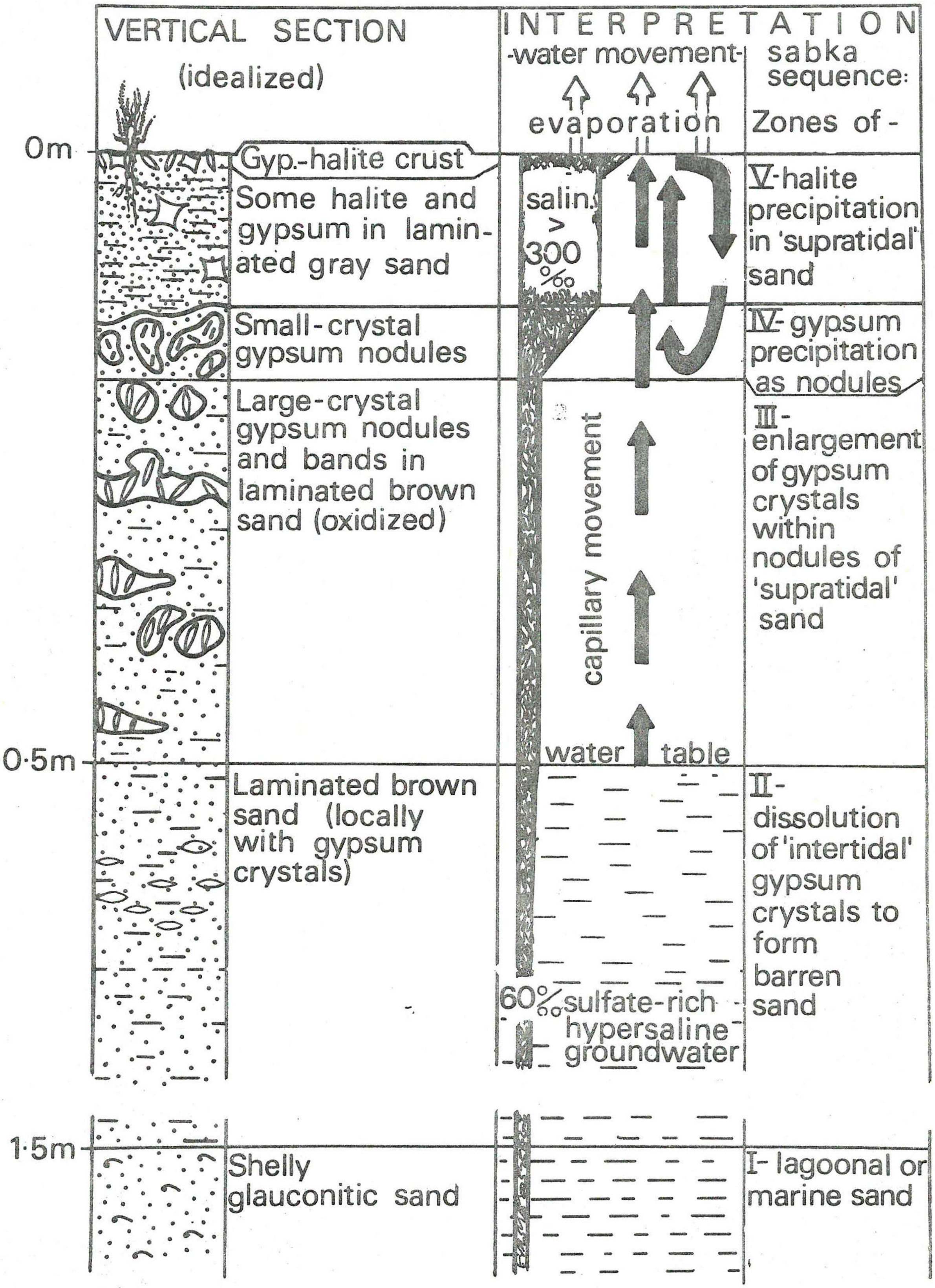

VERTICAL SECTION
(idealized)
INTERPRETATION
-water movement-
evaporation
sabka sequence:
Zones of -
0m
Gyp.-halite crust
Some halite and gypsum in laminated gray sand
salin. > 300 ‰
V-halite precipitation in 'supratidal' sand
Small-crystal gypsum nodules
IV-gypsum precipitation as nodules
Large-crystal gypsum nodules and bands in laminated brown sand (oxidized)
capillary movement
III-enlargement of gypsum crystals within nodules of 'supratidal' sand
water table
0·5m
Laminated brown sand (locally with gypsum crystals)
II-dissolution of 'intertidal' gypsum crystals to form barren sand
60‰ sulfate-rich hypersaline groundwater
1·5m
Shelly glauconitic sand
I-lagoonal or marine sand

Fig. 5

PRODUCTS OF THE FINAL JURASSIC REGRESSION - THE PURBECK STRATA

by Ian West

Part of

Chapter 6 of -

"A FIELD GUIDE TO MESOZOIC ENVIRONMENTS OF THE SOUTH DEVON AND DORSET COAST"

R.C.L. Wilson, B.W. Sellwood and I.M. West

PURBECK FORMATION - DESCRIPTIONS AND INTERPRETATIONS OF MEMBERS

(1) Introduction

Deposition of the unusual Purbeck strata came at the end of the long Jurassic phase of marine sedimentation. These limestones and clays have revealed an exciting variety of fossil remains including mammals, insects, dinosaurs, crocodiles and trees. They are well-exposed in many fine cliff exposures between the Isle of Portland and Swanage and in inland quarries (Fig. 6.01).

These thin-bedded, varied and frequently ostracod-rich strata (Fig. 6.02) originated in a very large, but very shallow gulf or interior sea which from time to time partly dried up. There are no ammonites or brachiopods because the water was usually either of higher or lower salinity than normal seawater. Detailed studies of the ostracod faunas have revealed many short-term fluctuations in salinity (eg. Anderson and Bazley, 1971). Nevertheless, typical salinities for each of the main subdivisions of the Purbecks can be estimated; the evidence is the assemblages of molluscs, charophytes, ostracods and other fossils (Fig. 6.03) and the mineralogical and petrographic characters of the sediments.

The Purbeck Formation is traditionally divided into lower, middle and upper parts (Fig. 6.02), a well-established classification which the author prefers to retain, at least as informal terms. Division into "Durlston Beds", from the base of the Cinder Bed upwards, and "Lulworth Beds" for the strata beneath was proposed by Casey (1963), even though the Cinder Bed does not mark a major lithological change (beds of "Cherty Freshwater" facies occur immediately above). The proposal was made because the Cinder Bed, an oyster limestone, was believed to correspond to the Jurassic-Cretaceous boundary. According to modern codes of stratigraphical nomenclature such correlation should not affect the lithostratigraphical terminology. In any case the position of the boundary has not been internationally fixed at the time of writing with regard to marine sequences of the world and if recent French proposals are accepted (Anon, 1975) most of the Purbeck Formation may be included in the Cretaceous.

The Purbeck is also split into smaller units probably of member status such as the Intermarine Beds and the Corbula Beds. The general features of the subdivisions are summarised diagrammatically in Fig. 6.02. A description is given for each, followed by an interpretation of the environment. The basal Purbeck is discussed in more detail because it has been more studied in relation to environments.

(ii) Occurrence

The basal part of the Purbeck (Caps, Broken Beds and "Cypris" Freestones) is, perhaps, best seen east of Lulworth Cove at the Fossil Forest ledge (SY 832796). Although within a military firing range it is frequently open at weekends and for longer periods at certain times of the year. When closed, Potter's Hole (SY 828797), a small ledge just west of the boundary fence, can be substituted. Although the graphic log (Fig. 6.04) and the descriptions refer specifically to the Fossil Forest they can be used in general for other sections near Lulworth (Durdle Door, Dungy Head, Stair Hole, Lulworth Cove and Bacon Hole).

Details of other exposures of these beds which show lateral facies changes have been given by West (1975). At Worbarrow Bay there is brecciation of the Great Dirt Bed; further east as at Worth Quarry (SY 969784) and at the tectonically and mineralogically interesting section at Durlston Head (SY 035773) breccia (and evaporitic strata) commence near the base of the Purbecks. West of Durdle Door the Broken Beds are thin at Holworth House, Ringstead (SY 762815) and Upwey (SY 671851) and are absent at Portesham where freshwater

Footnote: With regard to these descriptions it should be noted that Folk's terms "biosparrudite" and "biomicrudite" are often used here to describe shell-debris limestones of the Purbecks and they refer to the coarse-grained equivalents of biosparites and biomicrites in which the grains are larger than 1mm (Folk, 1959). Some coarse-grained limestones have been incorrectly described in previous literature as biosparites and biomicrites (eg. Clements, 1969).

faunas and floras are associated with evaporites (West, 1975; Barker et al., 1975). On the Isle of Portland although there are no true Broken Beds, there are numerous good exposures of the Caps with dirt beds, in the quarries. Although a few specimens survive on the mainland, the "island" is by far the best place to see silicified trees.

The sequence from the "Cypris" Freestones to almost the top of the Purbecks (Fig. 6.02) is described with particular reference to the type-section at Durlston Bay, Swanage (SZ 035780) but it can be applied in general to other exposures such as those around Lulworth. Certain features, such as the gypsum in the Soft Cockle Beds, are better exposed in the thinner but otherwise similar section at Worbarrow Tout (SY 869795).

At Durlston Bay the sequence is most easily studied by descending the zigzag path in the centre of the bay and walking northwards. The main subdivisions are easily recognised, the bluish-grey oyster limestone, the Cinder Bed, providing a conspicuous datum (Fig. 6.02). For detailed information on the lithology and fauna of 235 beds at Durlston Bay the excellent graphic log of Clements (1969) should be consulted. Petrographic and geochemical data on each bed of the Middle Purbecks have been given by El-Shahat (1977).

(iii) The Basal Purbecks, (with particular reference to the Fossil Forest exposure)

The Hard Cap and Dirt Beds (Facies A & B) - Description. The lowest bed at the Fossil Forest exposure (Fig. 6.03) and at most other localities which is of Purbeck facies is a thin laminated limestone without any of the large Portland molluscs but sometimes with moulds of Hydrobia and Valvata and small bivalves. It is followed by algal-stromatolitic limestone, easily recognised by its coarse vuggy appearance. A thin bed of carbonaceous marl which overlies it is the Lower Dirt Bed, a remarkable stratum in which at several localities remains of trees are common.

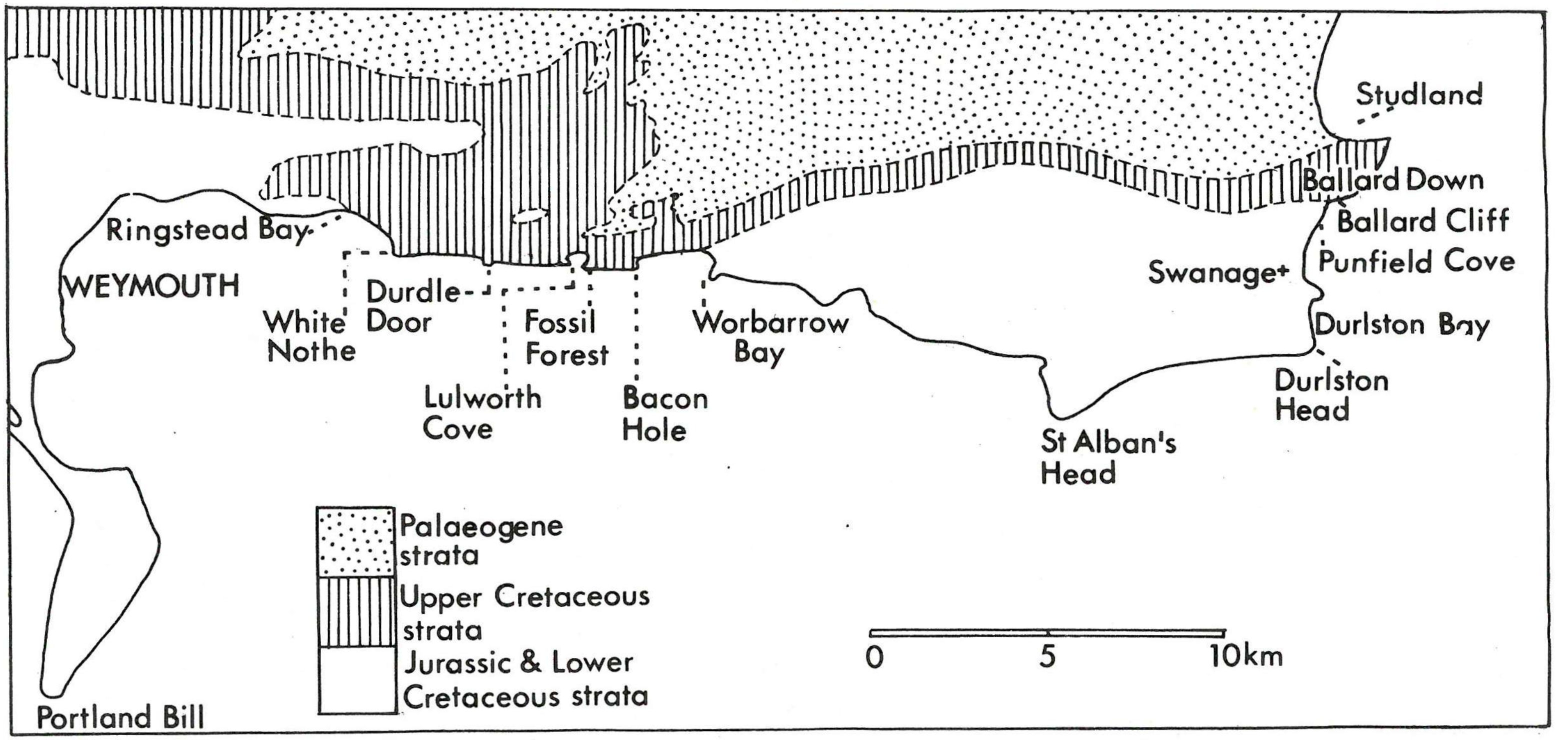


Fig. 6.01. Location map for east Dorset sections described in Chapters 6 and 7.

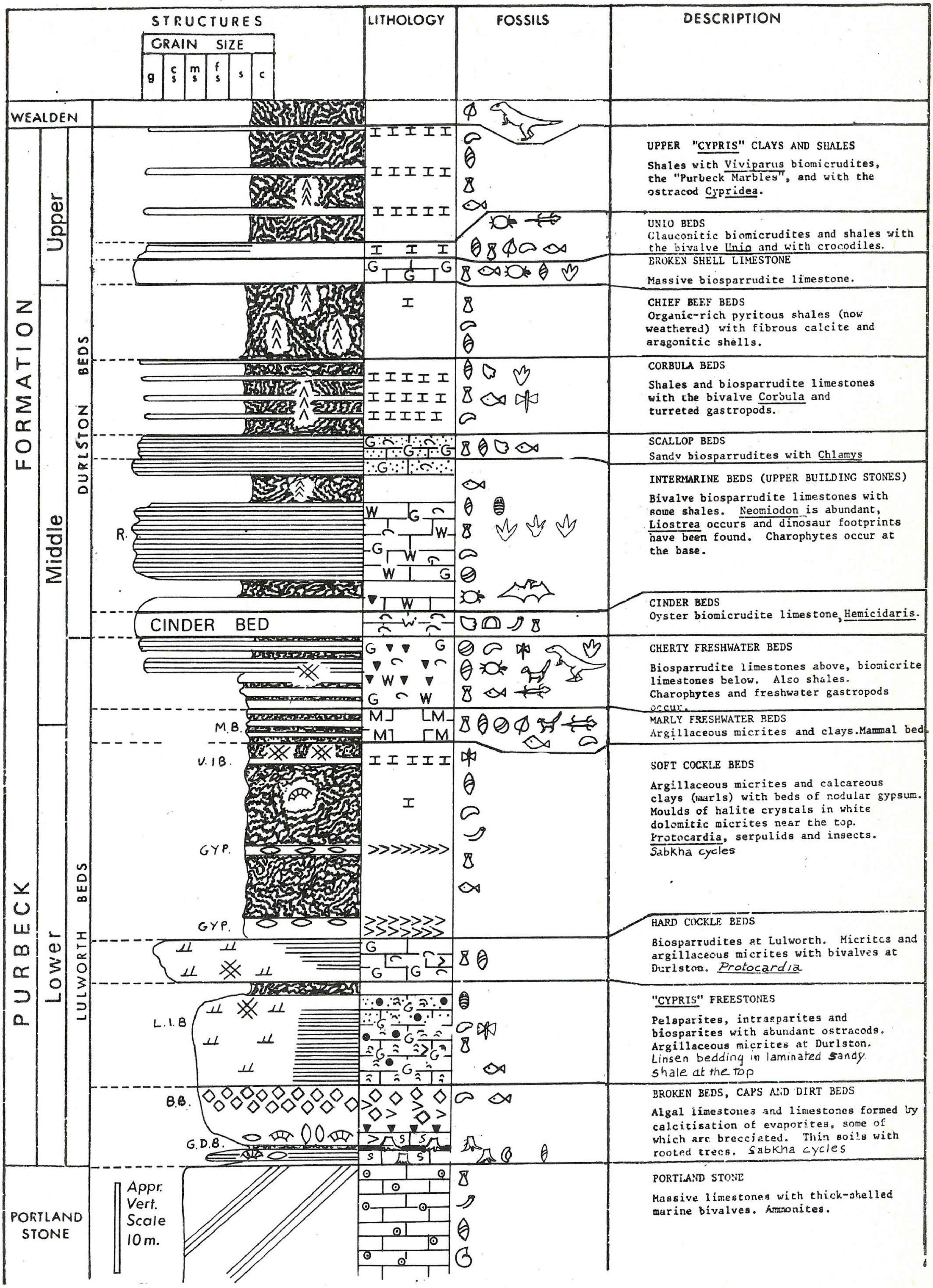


Fig. 6.02. Simplified graphic log of the complete Purbeck succession of east Dorset. It is based mainly on the Durlston Bay section (Fisher, 1856; Bristow and Forbes in Damon, 1884; Clements, 1969; Delair and Lander, 1973; El-Shahat, 1977) but on the Lulworth sections for the lowest three units (West, 1975). B.B. - Broken Beds; G.D.B. - Great Dirt Bed; Gyp. - gypsum; L.I.B. - Lower Insect Bed; M.B. - Mammal Bed; R - Roach; U.I.B. - Upper Insect Bed.

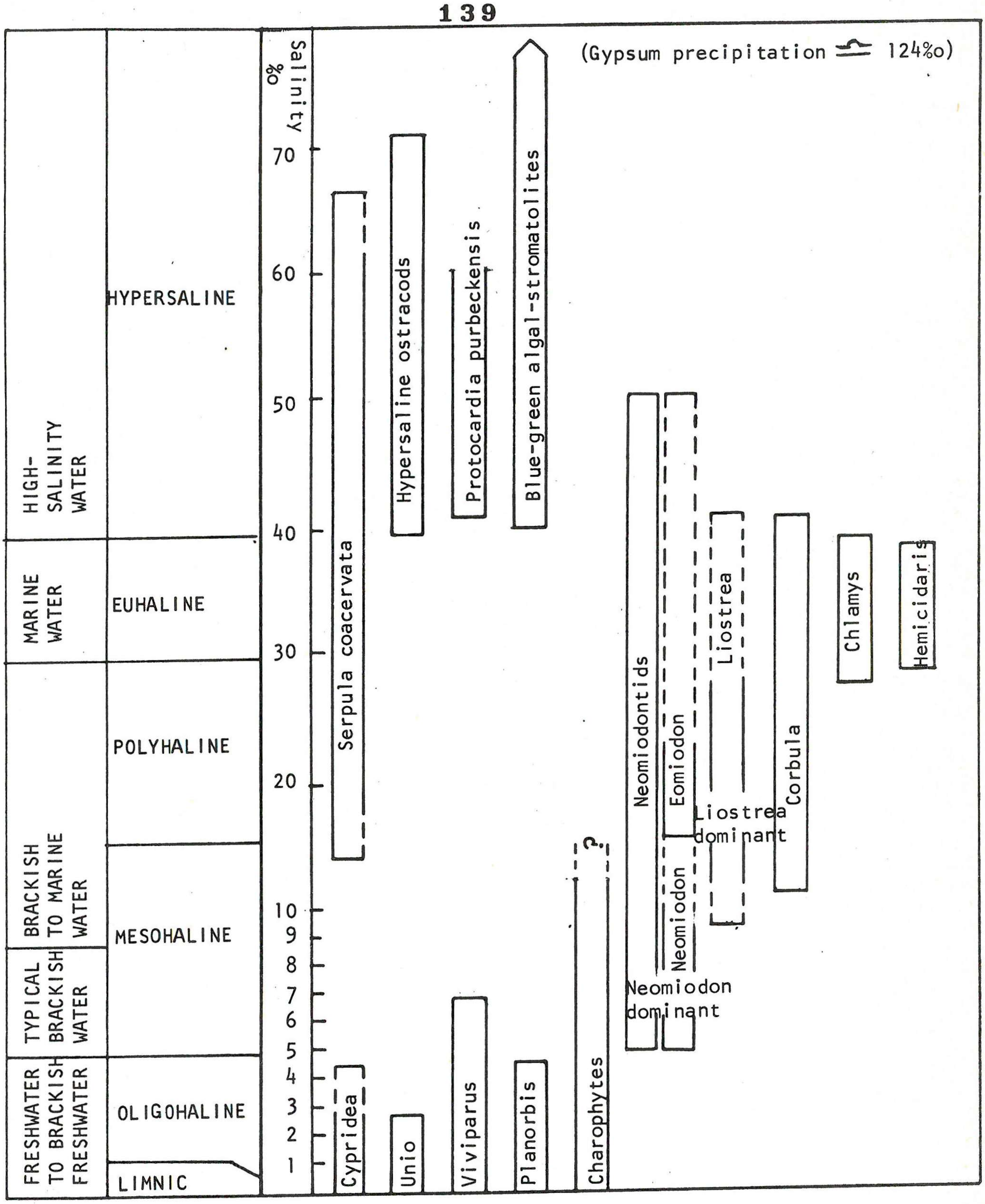


Fig. 6.03. Estimates of usual salinity ranges of some Purbeck faunal and floral elements based on comparisons with certain modern and ancient assemblages and on associations with evaporites, etc. (sources include: Casey, 1955; 1971; Daley, 1972; El-Shahat, 1977; Hallam, 1976; Hudson, 1963; Huckreide, 1967; Kilenyi and Allen, 1968; Parker, 1960; West, 1975).

The unfossiliferous limestones between the Lower and the Great Dirt Bed contain large ovoid stromatolites or mounds of algal limestone with a characteristic vuggy or fenestrate fabric and often a pustular surface (Brown, 1963; Pugh, 1969). They are enclosed in pelsparite and very fine-grained oosparite. The generally laminated appearance of these finely granular limestone results from small-scale cross-laminations formed by ripple-marks, including interference types. In the upper part of these limestones, just beneath the Great Dirt Bed, there are bedding planes on which the remains of algal-mats show large-scale polygonal ruckles (Pugh, 1969, plate 14a) beneath which there are cracks containing caliche-type pisolites. Locally, carbonate mud-flakes occur at this horizon.

The Great Dirt Bed is a dark carbonaceous marl (bed 9 of Fig. 6.04) lying on an erosion surface. There are numerous pebbles within it consisting of Purbeck limestone like that beneath (not of Portland Stone as stated by Perkins, 1977). A large proportion are quite different in appearance because they have been blackened penecontemporaneously.

The famous trees of the Fossil Forest and of the Isle of Portland, were mostly rooted in the Great Dirt Bed. Some were silicified so perfectly as to preserve annual rings and cellular structure while others rotted leaving only hollow moulds in limestone. No silicified specimens have been visible in the main Fossil Forest exposure since before 1880 (Damon, 1884) but silicified wood is common in the quarry spoil of Portland and specimens in situ can still be seen at Kingbarrow and Inmosthay Quarries (please do not damage them!). Good specimens are on display in the grounds of the Portland Heights Hotel. Broken prostrate trunks between 10m and 13m long have been found (Mantell, 1854) and show some limited compaction prior to silification. Between them grew occasional beehive-shaped cycad-like trees (cycadophytes) up to a metre in diameter (mainly on Portland).

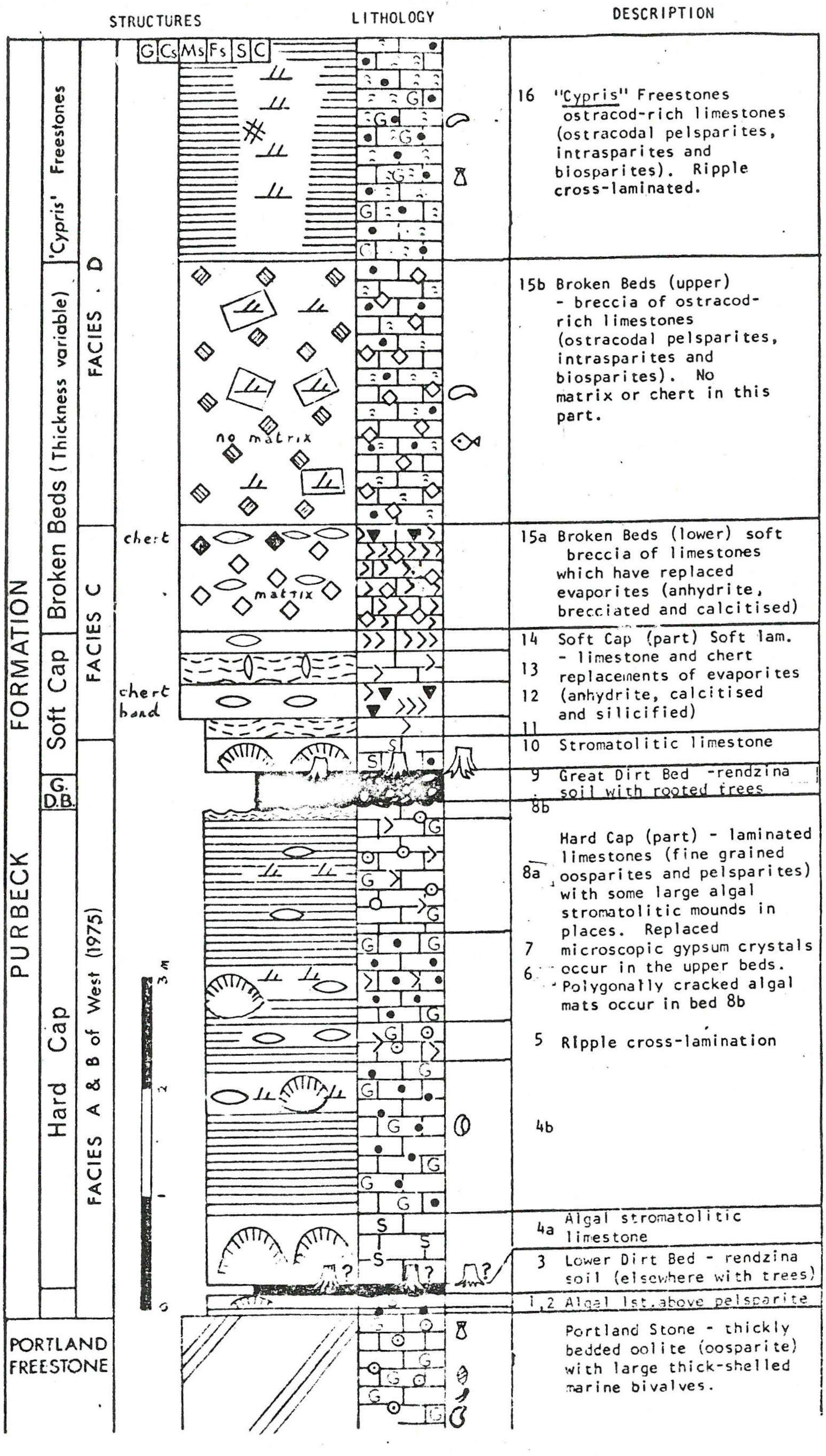


Fig. 6.04 Basal Purbeck strata at the Fossil Forest exposure, near Lulworth Cove. Note the replaced evaporites at the base of the Broken Beds. Other sections in the Lulworth area are similar but thicknesses vary, particularly those of algal limestones and of the breccia. Based on West (1975). Note that the particle size shown for the Great Dirt Bed is only for its matrix.

Mounds of algal stromatolitic limestone developed around and over the tree-stumps. These form the lower part of the Soft Cap and were formed by blue-green (spongiostromata) algae which, as in the case of some Holocene stromatolites, did not usually leave very well-defined tubules (Pugh, 1969). A remarkable stromatolite 4.6m long seems to have coated a standing tree-trunk and is still visible in Portesham Quarry (SY 609858) even though it was figured as long ago as 1898 by Strahan (fig. 130). Limestone with continuous crenulate algal-mat lamination occurs in the Soft Cap sometimes with calcite pseudomorphs and moulds of lenticular gypsum crystal "on edge" (with c-axes horizontal).

Hard Cap and Dirt Beds (Facies A & B) - Interpretation. The lower part of the Hard Cap lies between marine and evaporitic strata and contains a limited fauna of foraminifera and ostracods with the algae *Girvanella* and *Ortonella* (Brown, 1963; West 1975). Moderately hypersaline conditions, with salinities of about 50‰ to 70‰ are suggested by comparison with lagoon sediments of the Persian Gulf and of Shark Bay, Western Australia (Logan and Cebulski, 1970; Hughes-Clarke and Keij, 1973; West, 1975).

The Lower Dirt Bed is a thin but very widespread calcareous forest soil. While the forest was growing there was rapid transgression which at Portesham attained a depth of about 3 or 4 metres so as to form the long stromatolite (West, 1975). The tree stumps provided attachment for blue-green algal filaments and initiated the development of the stromatolitic mounds. These resemble modern pustular or mammilated algal-stromatolites of the intertidal zone of a Shark Bay lagoon (Hoffman, 1976; Playford and Cockbain, 1976). In the ancient, as in the comparable modern semi-arid environment, relatively high salinities kept away browsing molluscs which would otherwise have destroyed these algal-bound hummocks of lime-sand (Garrett, 1970).

The pellets and unusually small ooids of the Hard Cap resemble those of modern hypersaline lagoons bordering the

Persian Gulf (Evans and Bush, 1969; Loreau and Purser, 1973). The shallow floor and beaches were ripple-marked by wave action. Comparison with modern algal mats suggests that the algal mats with small gypsum crystals, at the top of the Hard Cap originated on high "intertidal"[1] flats bordering the hypersaline lagoon. The megapolygons are not simply cracks or ruckles in the mats as in many Recent examples (Rusnak, 1960; Shearman, 1966; Pugh, 1969; von der Borch et al., 1977) but also involve cracking of the early lithified limestone beneath during development of a limited caliche soil profile.

The Great Dirt Bed above is similar to the Lower Dirt Bed, a thin forest soil of black calcareous clay and, since it overlaid newly-formed limestone, is probably a type of rendzina. Leaching within the soil was limited, removing aragonitic but not calcitic debris. Its pebbles show that the limestones beneath had already been lithified. They are probably lagoon storm beach pebbles resulting from wave-erosion during emergence prior to the formation of the soil (Fig. 6.06). The blackening of some pebbles probably took place in the marginal hypersaline water, an environment where sulphate-reducing bacteria undoubtedly thrived (cf. Ward, Folk and Wilson, 1970).

The forest apparently developed on a peninsula or island extending from Lulworth to Portland (Fig. 6.06). The only identified cones and twig fragments from the dirt beds (Mantell, 1854; Barker et al., 1975) seem to indicate the presence of Araucaria trees related to the Norfolk Island Pine and the Chile Pine ("Monkey Puzzle"). The silicified trees, however, lack the regular pattern of knots of these strikingly symmetrical conifers and sometimes fork at the top of a long straight trunk (see Fitton, 1836). Furthermore, in microscopic structure they resemble wood not of the Araucaraceae

Footnote 1: Because of the large size and shallowness of the lagoon it is unlikely that true semi-diurnal tides were of significance, but wind-driven floods were likely.

but instead of the Cupressaceae family (J. Francis - personal communication 1979).

In spite of the aridity suggested by the proximity of evaporites the large conifer trees were not obviously stunted or shrub-like. The close-spacing of the annual rings, though, indicate that they were slow-growing and this may be the result of aridity (P. Edwards - personal communication 1978). The cycadophytes of this area seem to have been short and stumpy like modern cycads, even though tall species were in existence long before and common in the, perhaps less arid, Middle Jurassics environments of Yorkshire.

In present-day Florida, tall conifers together with cycads grow on sandy calcareous soil at about 5m above sea-level (Oldham, 1976). The Purbeck forests were like these "pine flatwoods" but with a rather drier climate. The growth of the forests in a semi-arid environment is an important problem that is discussed below. The dryness of the forest made it occasionally prone to forest fires the relics of which are fragments of fusain (fossil charcoal) in the Portesham Charophyte Chert (Barker et al., 1975; Harris, 1958).

The mounds of stromatolitic limestone above the trees probably originated mainly in "intertidal" conditions. As in the case of the stromatolites above the Lower Dirt Bed the water was probably too hypersaline for gastropods which would have destroyed the algae.

Sabkha Cycles

The basal Purbeck sequence at the Lulworth Fossil Forest can be interpreted in terms of "sabkha cycles" or sedimentary cycles with evaporites (Fig. 6.05). The best-developed cycle commenced with the limestone overlying the Lower Dirt Bed and ends with the Great Dirt Bed. These cycles are related to cycles of limestones and evaporites first described in a classic paper by Shearman (1966) from a borehole through the Purbecks at Warlingham, Surrey. He compared them to

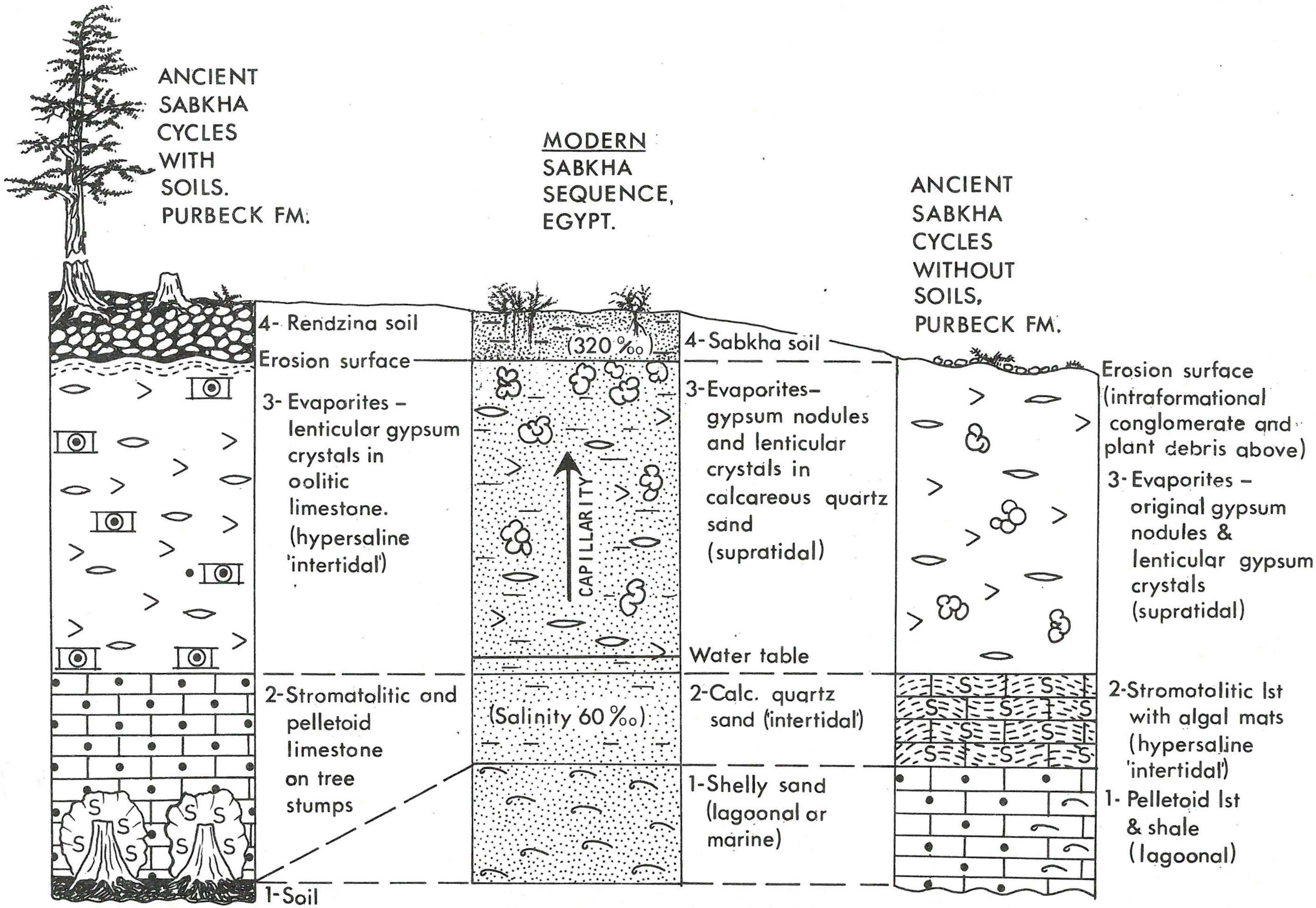


Fig. 6.05 Sabkha cycles in the basal Purbeck of Dorset (West, 1965; in press) shown in comparison to the sabkha cycles of the southeast England Purbecks, first described by Shearman (1966) and later by Holliday and Shephard-Thorn (1974), and to modern sabkha sequences in northern Egypt (West, Ali and Hilmy, in press).

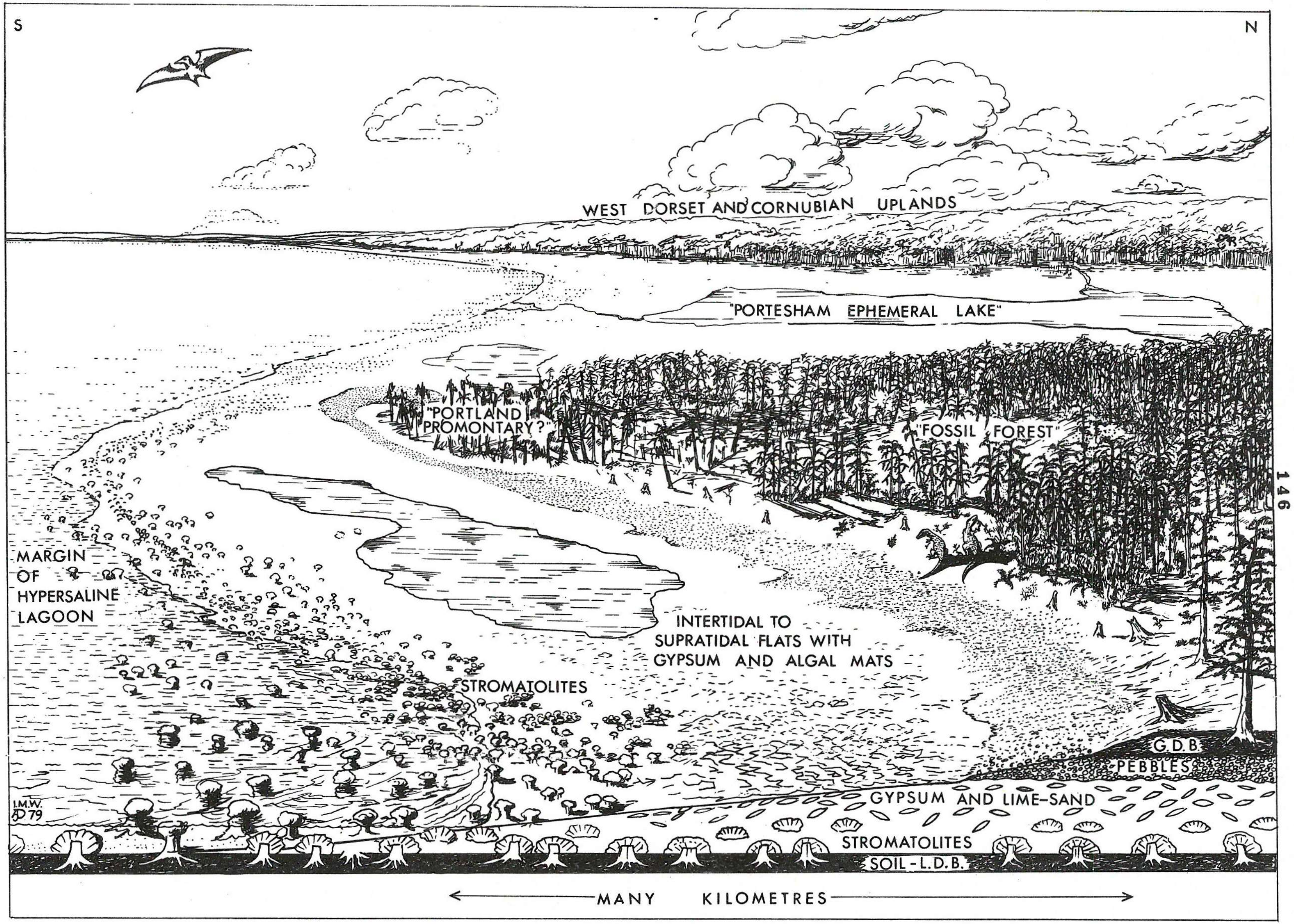


Fig. 6.06. Schematic model of early Purbeck environments in Dorset showing the origin of the lithological units. Note the great foreshortening. Following rapid flooding of the Lower Dirt Bed slow progradation of tidal-flat sediments took place. The Great Dirt Bed (shown forest-covered) was formed on an area of temporary and local uplift from Lulworth to Portland; it incorporated limestone beach pebbles. Based partly on West (1975).

sabkha cycles of sedimentation and diagenesis in Recent sediments of the Trucial coast of the Arabian Gulf.

The cycles in the basal Purbecks of Dorset contain ancient soils (Fig. 6.05) and in this respect differ from those in the gypsum and anhydrite of the basal beds of southeast England and those in the Soft Cockle Beds of Dorset. The normal Purbeck sabkha cycles without soils commence with (1) a lagoonal unit sometimes with Protocardia which is followed by (2) a unit with algal mats and this in turn by (3) nodular gypsum or anhydrite. Shearman (1966) has recognised an erosion surface at the top of such cycles and there, in addition, some plant debris is sometimes present (Fig. 6.05). Cycles of this type closely resemble those of the Trucial Coast and examples can be seen in the gypsum of the Soft Cockle Beds at Worbarrow Tout, discussed below.

The cycles with soils (Fig. 6.05) possess stromatolitic mounds rather than algal mats, probably as a result of higher energy conditions, and have calcium sulphate present as a minor constituent (since calcitised) rather than as the main sediment. Shearman (1966) has shown how cycles can develop by progradation of sabkha sediments over "intertidal" algal mats; a similar mechanism is suggested for the development of the Purbeck sabkha cycles with soils, the soils representing the environment landwards of the sabkha or salt-flats. Modern soil-capped sabkha sequences exist in the northern Egypt coastal zone and show some similar features (Fig. 6.05). The Purbeck climate was less arid, however, and with better-developed soils and forests on the hinterland. Nevertheless, the presence of well-vegetated ground landward of a sabkha with gypsum is a common feature of semi-arid regions and occurs not only in Egypt but also adjacent to a coastal lagoon, the Laguna Madre, of the Gulf of Mexico (Kerr and Thomson, 1963, fig. 7) and elsewhere. Essential for good soil development is good drainage and lack of this may be the reason for lack of soils above the sabkha cycles of southeast England and of the Dorset Soft Cockle Beds. The gypsum in these cases occurs in argillaceous sequences whereas the limestone with gypsum under the Dorset soils is very permeable. The Purbeck cycles are products of an environment like that of the Trucial Coast sabkhas but much less arid. A good modern analogue has yet to be found.

Upper Soft Cap and Lower Broken Beds (Facies C) - Description.

Stromatolitic limestone which forms the lower part of the Soft Cap has been discussed. The upper part consists of peculiar soft and very porous limestones of special interest, similar to those in the lower part of the Broken Beds. There are rare pseudomorphs after halite in the Soft Cap.

The Broken Beds is the conspicuous limestone breccia which lies above. Theories of the origin which have been proposed include collapse after washing out of underlying clay, (Webster in Englefield, 1816), collapse after dissolution of underlying limestone or collapse after decomposition of accumulated vegetable debris, (see Arkell, 1938; 1947). There is very little evidence in favour of these.

The breccia can be divided into two distinct parts. The lower portion comprises blocks of very porous limestone in a soft matrix often of sandy appearance but which in fact consists almost entirely of calcite. It contains fragmented chert. The upper portion consists mainly of joint-bounded blocks of laminated, ostracod-bearing limestone without matrix.

Substantial evidence for the origin comes from the limestone blocks and limestone matrix of the lower part. Both are completely unfossiliferous, coarsely crystalline, saccharoidal and very porous. They are usually laminated and the matrix sometimes shows evidence of plastic flow. When certain of the limestones, or almost any of the chert (preferably etched with hydrofluoric acid), is examined in thin-section numerous lanceolate shapes become visible (Plate 6.01). They can sometimes be seen with a hand lens in whitish parts of the chert, particularly that at the base of the Broken Beds. These are pseudomorphs after lenticular crystals of gypsum (cf. Masson, 1955) or "seed gypsum" (Von der Borch, et al., 1977). At the western end of the Fossil Forest exposure there is an interesting algal-laminated limestone within the Soft Cap which contains pseudomorphs and moulds after lenticular crystals of gypsum large enough (several millimetres) to be easily seen in the field. The crystal moulds are orientated "on edge" or with planes of flattening nearly vertical. Pseudomorphs after anhydrite also occur in this part of the Purbecks particularly in the Swanage district but they are entirely microscopic.

Nodules originally of calcium sulphate, but now partly replaced by calcite from the periphery and dissolved away in the centre, are features of a conspicuously porous bed of saccharoidal calcitised anhydrite beneath the Broken Beds at Worbarrow Tout (warning - it is unwise to approach the bed closely because of overhanging rock; loose blocks of the bed, however, can sometimes be found on the beach).

At Durlston Head (SZ 035773) the Broken Beds are thicker than at Lulworth and show a close relationship to a major fault (West, 1960). Celestite and calciostrontianite are present, occurring in an interesting sequence of saccharoidal calcitised anhydrite beds (Salter and West, 1965).

Upper Soft Cap and Lower Broken Beds (Facies C) - Environmental Interpretation.

The peculiar porous limestones of the Soft Cap and of the breccia can be shown by petrographic evidence, particularly of pseudomorphs of relict minerals and distinctive varieties of chalcedony, to be calcium carbonate replacements of calcium sulphate evaporites (West, 1964). The crumbly porous character results from incomplete replacement. Plastic flow structures and relict sulphate such as celestite (strontium sulphate) are most obvious at Durlston Head, where calcitised evaporites are best developed, (West, 1960, 1975) but can be seen in the Lulworth area.

The chert, which like most such forms of silica is of early (precompaction) origin, reveals by its ghost fabrics that lenticular crystals of gypsum formed the primary sulphate. These resemble the small gypsum crystals of the intertidal zones of hypersaline lagoons of the Persian Gulf (Shearman, 1966) and Texas coastal lagoons (Masson, 1955) and marginal sand-flats of salt lakes in northern Egypt and like these modern examples, are associated with algal mats. Euryhaline gastropods in the chert bed at the base of the sequence record a brief seasonal phase of lower salinity. These herbivores may have lived on aquatic vegetation which by photosynthesis abstracted CO_2 and raised the pH of the water to a level ($>$ 9.4) at which silica is easily mobilised (see West, 1975 regarding the Portesham Charophyte Chert).

The temporary aquatic phase was followed by desiccation during which the gypsum crystals of this chert were formed. The thin bed with pseudomorphs oriented "on edge" originated on a sabkha like those of the Persian Gulf (Shearman, 1966). The main basal Purbeck phase of evaporite deposition followed. Lack of skeletal debris in these strata suggest that the lagoon waters which periodically flooded the tidal flats and brought fresh supplies of calcium sulphate were mostly too hypersaline for molluscan or ostracod life. The presence of algal mats makes sulphate supply entirely by groundwater unlikely. Nevertheless where there were nodules developed,as in the Soft Cap at Worbarrow Tout, and particularly in Sussex, upward capillary movement of sulphate-supersaturated water probably took place within the sediments with precipitation above the water-table (cf. West, Ali and Hilmy, in press).

Upper Broken Beds and "Cypris" Freestones (Facies D) - Description.

The blocks of laminated limestone which form the upper part of the breccia are similar to the "Cypris" Freestones above. These are brittle pelsparites, intrasparites and biosparites with numerous ostracods (visible with a lens). Casts of bivalves are common near the top of these limestones and the gastropod Hydrobia and Valvata, the isopod Archaeoniscus, and fish have been found.

Ripple-marks are abundant in this division and include symmetrical and interfering types. Occasionally symmetrical current ripples are visible. At the Fossil Forest ripple marks are mostly seen in vertical section as small scale cross-lamination. On the east side of the Durdle Door promontory (SY 807802), however, they are very clearly seen on the surfaces of nearly vertical slabs of "Cypris" Freestones. Natural casts of concave-faced halite crystals can be found in these beds. Only small quantities of gypsum replaced by calcite are found in this facies, but these include gypsum sand crystals. Some small cavities probably result from the dissolution of anhydrite nodules. Large algal stromatolites are not developed in these beds but oncolites, with the alga Girvanella, can be found (Brown, 1964).

Small folds are visible at the top of the Broken Beds. Striations or slickensides can sometimes be seen on the limestone blocks in this part of the Broken Beds at the Fossil Forest.

Upper Broken Beds and "Cypris" Freestones (Facies D) - Interpretation.

Ostracods usually thrive in very shallow water. This is compatible with the evidence of the ripple-marks, salt-cubes, gypsum sand crystals and dinosaur footprints. Tidal-flats of carbonate silt and fine sand which sometimes dried out as supratidal flats are implied. Lack of algal-mats, the abundance of ripple-marks and small-scale cross-bedding and the occurrence of oncolites suggests that wave and current-action was more vigorous than during the formation of the underlying beds.

Comparison of the faunas and sediments with those of modern lagoons (e.g. Logan and Cebulski, 1970) suggests moderate hypersalinity. The absence of normal marine faunas, the abundance of ostracods and the presence of only limited quantities of evaporites indicate that the salinity often lay in the range 50-70‰.

Origin of the Broken Beds - Interpretation.

Clearly the association of brecciation and calcitised evaporites throughout east Dorset is not a coincidence (West, 1975). The former presence of evaporites in the Broken Beds seems to suggest that the brecciation is mainly due to collapse. The upper part of the breccia and the overlying limestones can be seen, however, to be folded with axes trending east-west, almost parallel to the cliffs at the Fossil Forest (Arkell, 1938; 1947). At Durlston Head the northward squeezing of the brecciated strata is particularly obvious (West, 1960). Furthermore there is the appreciable fragmentation of chert nodules in the Broken Beds at most exposures and there are the striations on the limestone blocks. All this shows that brecciation was due to tectonic action and the folds suggest northward movement of the overlying strata. Petrographic evidence reveals that it took place when this was a structurally weak bed of anhydrite before calcitisation was completed. This explains the evidence of plastic flow. Thus, the evaporites provided a plane of weakness at which movement occurred and the overlying brittle limestones also became involved in the brecciation.

(iv) The Main Part of the Purbeck Formation (with particular reference to Durlston Bay)

The succession now described continues upwards with the Hard Cockle Beds seen just north of the foot of the zigzag path. If the sequence is instead examined at Lulworth then the thicknesses will be found to be less than shown in Fig. 6.02. Attention is drawn below, to some differences between the Lulworth and Durlston sections.

Hard Cockle Beds - Description.

These relatively hard limestones and marls with the "cockle" Protocardia purbeckensis are easily recognised by their position beneath the soft marls with gypsum of the Soft Cockle Beds. At Durlston Bay they consist of calcareous clays and argillaceous micrites and pelmicrites. Westwards, in the Lulworth area they are conspicuous yellowish-weathering limestones, mainly biosparrudites and biomicrites (or biomicrudites). Mud-flakes are frequently present particularly at Worbarrow Tout. The skeletal material consists of bivalves and ostracods with some gastropods and serpulids.

Ripple-marks and small-scale cross-bedding, sometimes bipolar, is common. Casts of halite crystals filled with sediment project downwards and sometimes upwards. Examples can be seen at Worbarrow Tout and at the Fossil Forest, where the bed is 8m above the top of the Broken Beds (House, 1966). Numerous small spherical cavities in a limestone at Durlston Bay probably result from dissolution of gypsum nodules.

Hard Cockle Beds - Interpretation.

The low diversity faunas which lack most normal marine molluscs and most freshwater molluscs suggest either brackish water or hypersaline water. Halite crystals point to high rather than low salinities. The increase in shelly material in these beds towards the west is puzzling because that was apparently the direction of the land. In that region even higher salinities, and consequently less fauna, would have been expected, but the shelly debris may represent lagoon beach sediments.

Ripple-marks, mud-flakes and the moulds of halite crystals suggest that the sediment was sometimes exposed as carbonate sand-flats. Lithification of the marl matrix and the dissolution of halite crystals developed within it probably took place during exposure. The gypsum nodules certainly suggest by comparison with modern nodules that the water-table was below the sediment surface at times (Shearman, 1966; West, Ali and Hilmy, in press).

Soft Cockle Beds - Description.

This is a sequence of marls and mudstones with beds of gypsum and pseudomorphs after halite. Protocardia purbeckensis is quite common, sometimes associated with algae and serpulids.

Large masses of gypsum with both nodular structure and veins of satin-spar can be seen in the cliff and fallen blocks on the beach in Durlston Bay. At Worbarrow Bay the gypsum also contains superb examples of enterolithic veins (West, 1965) and, as mentioned above, splendid examples of sabkha cycles. Displaced sediment around the nodules shows that they have developed at an early date before the carbonate-rich matrix was fully lithified.

Near the top of the Soft Cockle Beds some beds of white argillaceous dolomitic micrite (beds 59, 64, 66 and 68 of Clements' 1969 Durlston Bay log) contain hollow cubes that were once halite crystals. Thin barytes crystals can be found within them. Elytra of small beetles and wings of various flies, are also found in these "upper insect beds". Dolomite is relatively uncommon elsewhere in the Dorset Purbeck strata.

Soft Cockle Beds - Interpretation.

The presence of evaporites at certain levels and the very limited nature of the faunas throughout indicate that the Soft Cockle Beds were formed in hypersaline conditions. Well-developed isolated pustular stromatolites at Perryfield Quarry and other localities on the Isle of Portland and on the main-land (House, 1968) and the association of serpulids with the algal structures suggest comparison with modern hypersaline shallow and tidal-flat environments (Playford and Cockbain, 1976). The cockle Protocardia purbeckensis probably lived in hypersaline water just as modern cockles (Cardium edule) can tolerate up to 60‰ salinity in some French lagoons (Dr. A.P. Lockwood, personal communication, 1978). West of Alexandria, Egypt, gypsum is currently being deposited on beds of Cardium shells in a desiccated coastal lagoon.

The nodular structure of the secondary gypsum (a replacement of anhydrite which had originally replaced primary gypsum) closely resembles nodular structure found in early anhydrite of the Arabian Gulf sabkhas (Shearman, 1966) and primary nodule of gypsum in supratidal sabkhas of the Mediterranean coast of Egypt (West, Ali and Hilmy, 1979). A tidal-flat origin for the evaporites is thus indicated and is confirmed by the occurrence of algal lamination like that of Arabian Gulf tidal-flats.

The insect remains in the upper part of these beds were probably washed into a shallow saltlake on the shores of which the halite crystals forms as the lake dried out in the summer. Insect remains are numerous in modern salt lake sediments in northern Egypt. The dolomite is attributed to a high Mg/Ca ratio following precipitation of calcium carbonate and gypsum from the lake waters.

Marly Freshwater Beds - Description.

This is a sequence of argillaceous micrites and calcareous clays containing gastropods which include Hydrobia, Valvata, Physa and Planorbis. The ostracods Cypridea and Darwinula are present and evidence of water-weeds is shown by the stems and oogonia of charophytes ("stoneworts").

Within this sequence in Durlston Bay is the celebrated Mammal Bed, a thin bed of dark grey carbonaceous marl lying on an eroded surface of limestone. Although freshwater gastropod shells are common and crocodile bones can be found, the mammal remains are extremely rare, and consist mainly of isolated jaws and teeth. Most were discovered during the last century in a fossiliferous 'pocket' in Beckle's Mammal Pit, once the world's largest scientific excavation, at the top of the cliff near the zigzag path (Kingsley, 1857).

The Marly Freshwater Beds - Interpretation.

These fine-grained sediments were deposited in quiet lake environments which the gastropods show to be usually of very low salinity. The Physa and Planorbis are part of the first known abundant fauna of air-breathing pondsnails. As yet, however, no land snails had evolved to climb the trees of the surrounding land. The charophytes necessarily grew in the photic zone of the lake which was therefore fairly shallow.

The abundant Hydrobia probably browsed, as they do today, on algal-covered shallows and mud-flats.

The Mammal Bed is the most important stratum within this unit. Of the mammals some were probably insectivorous, whilst others with rodent-like adaptions perhaps fed on the fruit and bark of cycadophytes and conifers and had skeletal structures indicating arboreal habits. The mammals, all small and most only about the size of a mole or a squirrel may have avoided direct competition with the dinosaurs by nocturnal habits (Savage, 1977).

The Mammal Bed superficially resembles the basal Purbeck dirt beds in being a thin carbonaceous marl lying on an eroded surface of limestone. Obvious differences, however, are the remains of the pondsnails and the crocodiles (of marsh-dwelling types) and absence of pebbles and of tree remains. The environment was probably a waterlogged marsh or swamp with freshwater pools here and there. There is no evidence that the margin of the mammal bed swamp was within many kilometres of Swanage. It is puzzling that the mammal remains are found so far from the forests which undoubtedly covered the well-drained ground. They might have been carried eastwards by a flood, or even by crocodiles (see Owen, 1879). Another possibility is that the creatures perished after having travelled to a water-hole during drought.

Cherty Freshwater Beds - Description.

These are white, rather argillaceous limestones with chert, particularly in the "Flint Bed". The pondsnails Planorbis, Physa and Ptychostylus are common in these beds but are not easily recognised except where the rock is suitably weathered. Cypridea is numerous. Particularly abundant are charophytes and something of their calcitic structures (Plate 6.02) can sometimes be seen in the field with a lens (particularly in Stair Hole, Lulworth).

Fish remains and fragments of turtle carapace are occasionally found and equally interesting are bones of dinosaurs, turtles and crocodiles including the unusually small short-snouted crocodiles Nannosuchus and Theriosuchus. It is the Feather Bed and Under Feather Bed in which many of the vertebrate remains have been found (Owen, 1871; 1872-1889), although in some cases (Owen, 1879; Mansel-Pleydell, 1888) the Mammal Bed seems to have been wrongly referred to as the "Feather Bed". Surprising, considering the faunas, is the occurrence of scattered chalcedony pseudomorphs after halite in the Cherty Freshwater Beds. These increase in size from Durlston Bay to the Fossil Forest where they are conspicuous in fallen blocks of material from this bed, lying on the ledge.

Cherty Freshwater Beds - Interpretation.

The faunas and floras of at least the lower beds testify to waters of low salinities (Fig. 6.08). Conditions need not necessarily have been completely freshwater, however (Fig. 6.07). Even charophytes commonly flourish at the present day at up to about 11‰ salinity and exceptionally at higher values. The pseudomorphs after halite show that occasionally some salt remained in the sediments and was concentrated when they dried during subaerial exposure.

The low salinity lake was extensive as is shown by the distribution of these beds over southeast England and their occurrence in the English Channel. The charophytes, like those at present, probably flourished in warm, shallow, carbonate-rich, slightly brackish, water and the associated gastropods probably lived on the rich aquatic vegetation. In contrast the bivalve biosparrudites were probably formed when conditions were rather more saline (compare faunas in Fig. 6.07 with ranges in Fig. 6.03), when wave action was greater and the environment less suitable for aquatic vegetation. The lake margin was probably some distance from the margin of the basin ("non-coincident lake margin" in the terminology of Tucker, 1978) so that the mud-flats were wide and coarse non-carbonate clastics are absent even when shoreline sediments such as mud-flake conglomerates occur.

The white limestones with chert nodules are much more conspicuous than the calcareous shales in this unit. The limestones of the upper part are mainly shell-debris beds or biosparrudites while the lower beds are mainly biomicrites, originally carbonate muds with shells (Fig. 6.06). Desiccation cracks occur and there are two beds of micrite mud-flake and algal-flake conglomerate in the Lulworth area (Brown, 1964).

The dinosaur remains were probably washed from the nearby land. Iguanodon was herbivorous, living in herds, while Nuthetes destructor was a small vicious carnivore. "Dwarf" crocodiles present fascinating problems. Owen (1879) suggested that these really are dwarf species but recently it has been suggested (Joffe, 1967) that Nannosuchus was a juvenile of the large rather alligator-like Goniopholis. Theriosuchus, though, seems to have been a genus of unusually small crocodiles. Owen (1879) suggested that the crocodiles' food was the contemporary small mammals. At the present day, however, young crocodiles eat mostly fish and invertebrates and an exclusively mammal diet for these small forms seems unlikely (Joffe, 1967; Freeman, 1975). In the Wealden deposits, evidence of relative abundance of remains has suggested that they were at the head of a food-chain. Predatory fish fed on the mollusc-eating fish and these in turn were probably devoured by crocodiles (Freeman, 1975). Birds have more recently taken over much of the role of the crocodiles.

To produce the lower salinities the ratio of inflowing freshwater to seawater must have been fairly high. Since there is little coarse clastic material it is more likely that the influx of seawater was low rather than that the influx of freshwater was high. Faulting on the south side of the English Channel may have closed the southern connection to the sea at this time (Fig. 6.08C).

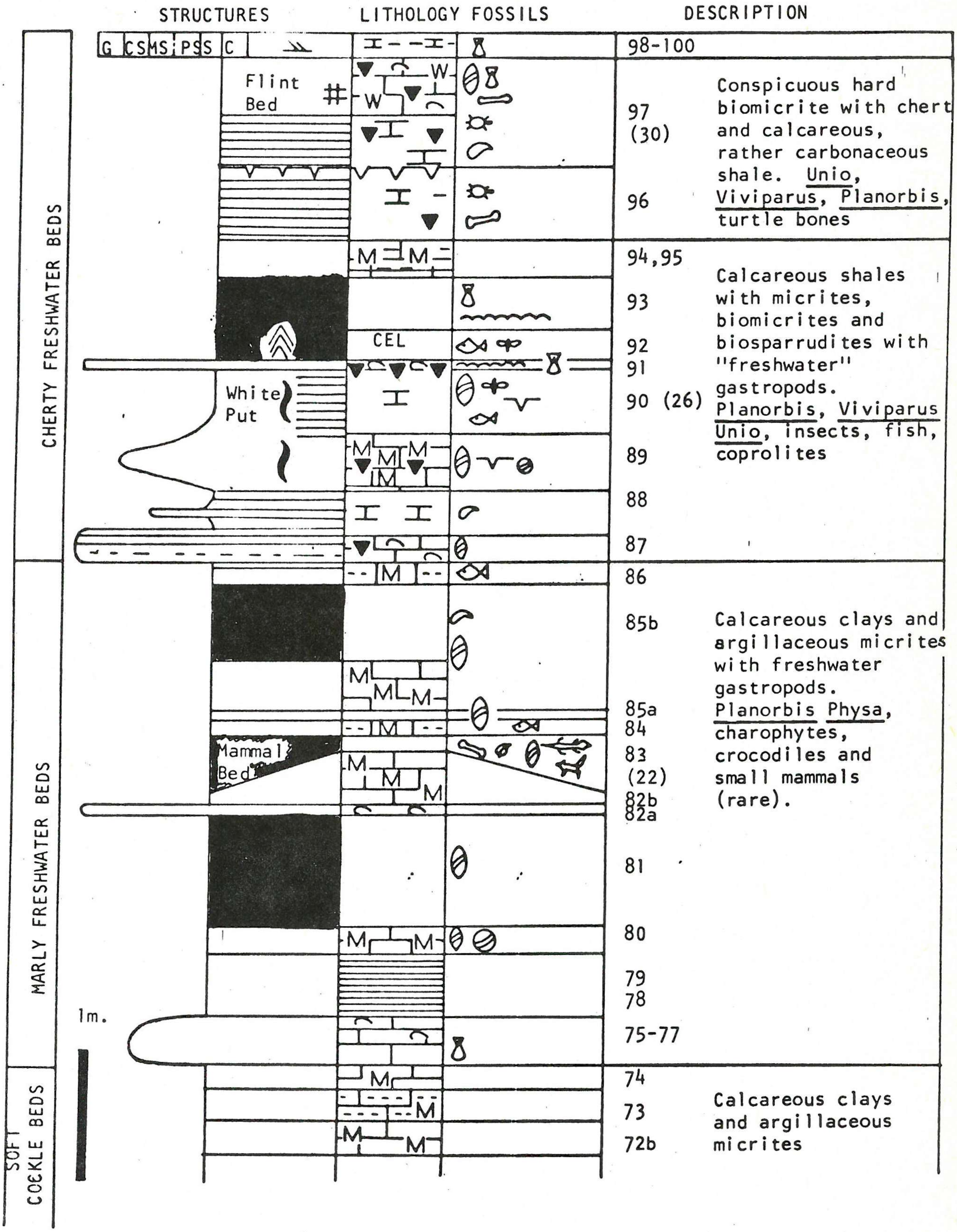


Fig. 6.07. Part of the middle Purbecks of Durlston Bay, Based on Clements (1969), with additional data from Bristow and Forbes (in Damon, 1884), El-Shahat, (1977), Fisher (1856), Owen (1872), and other sources. Bed numbers are of Clements with those of Bristow and Forbes in brackets. For ease of recognition only the darker clays are shown black in the structure column.

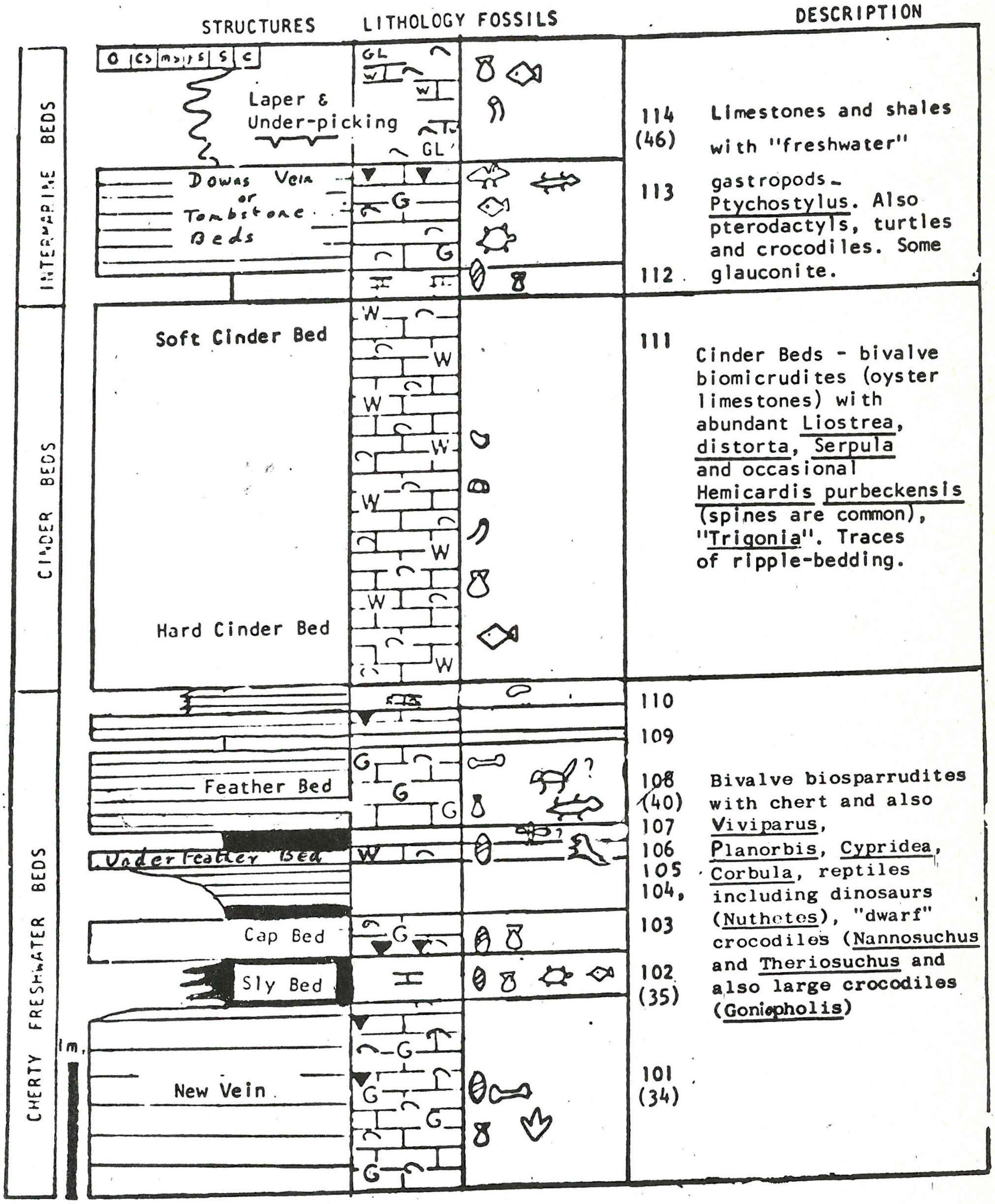
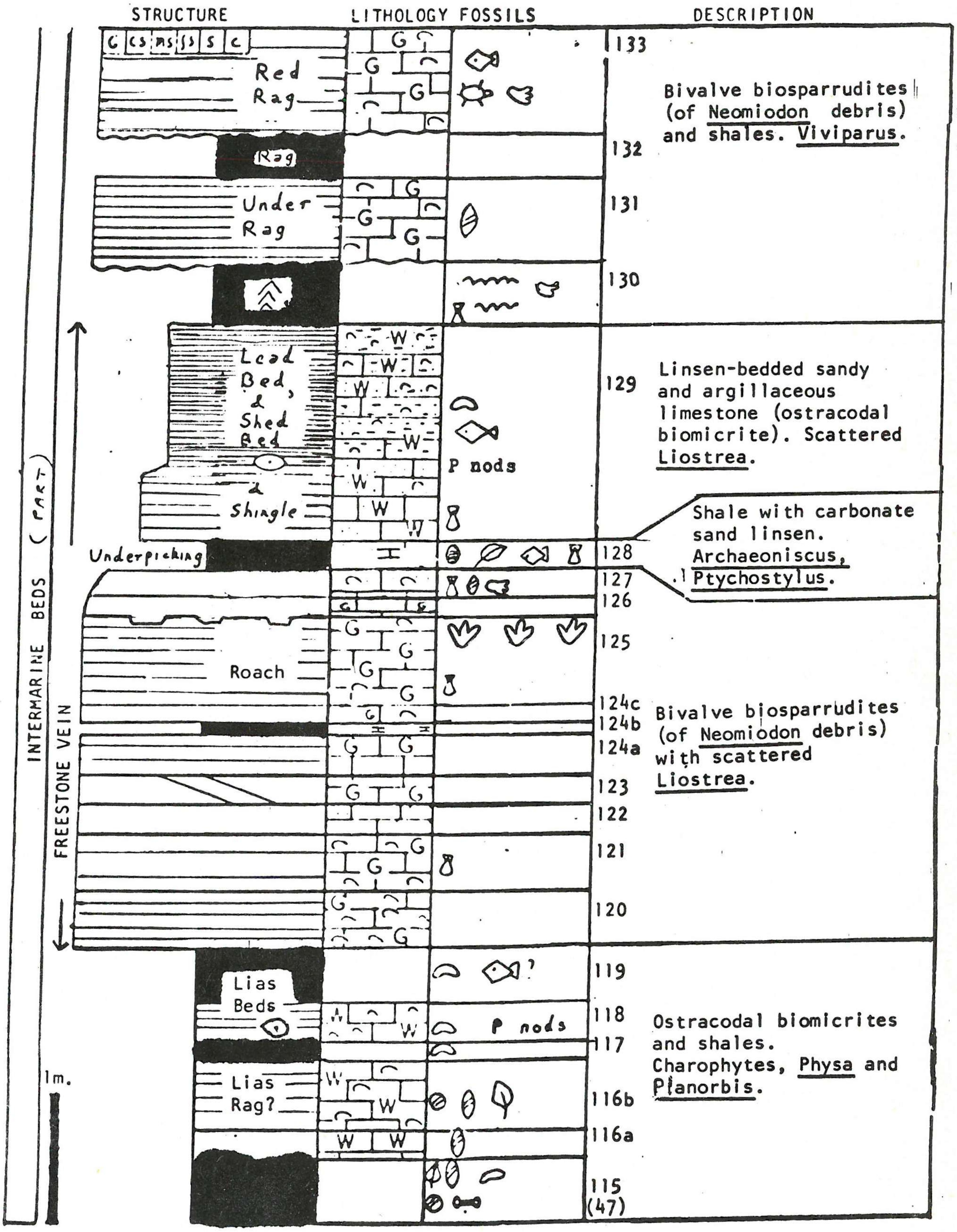


Fig. 6.07 contin.



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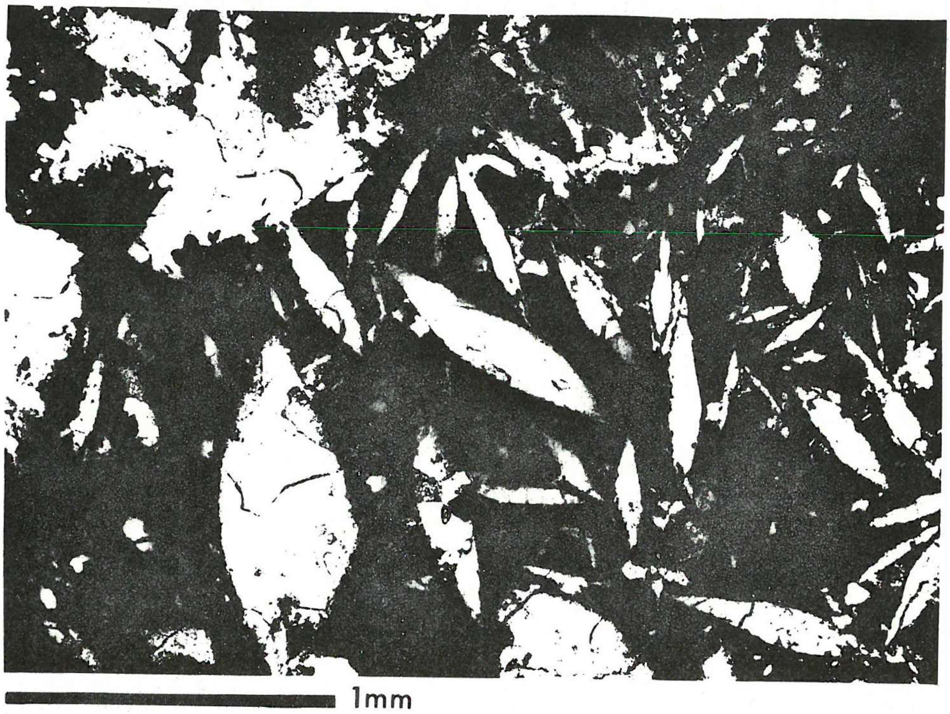

Plate 6.01. Calcite pseudomorphs after lenticular crystals of gypsum. These are abundant in the basal Purbeck Beds of Dorset. L.P. 351, Portesham.

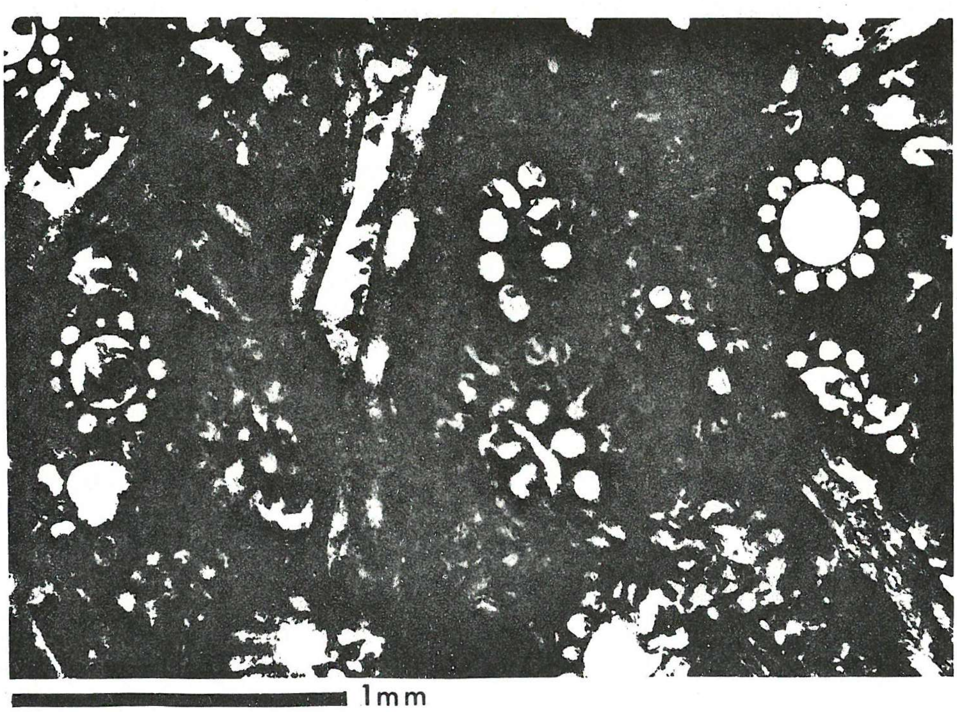

Plate 6.02. Silicified charophyte stems from the Cherty Freshwater Beds of the Middle Purbecks (bed D.B.89) From El-Shahat, 1977.

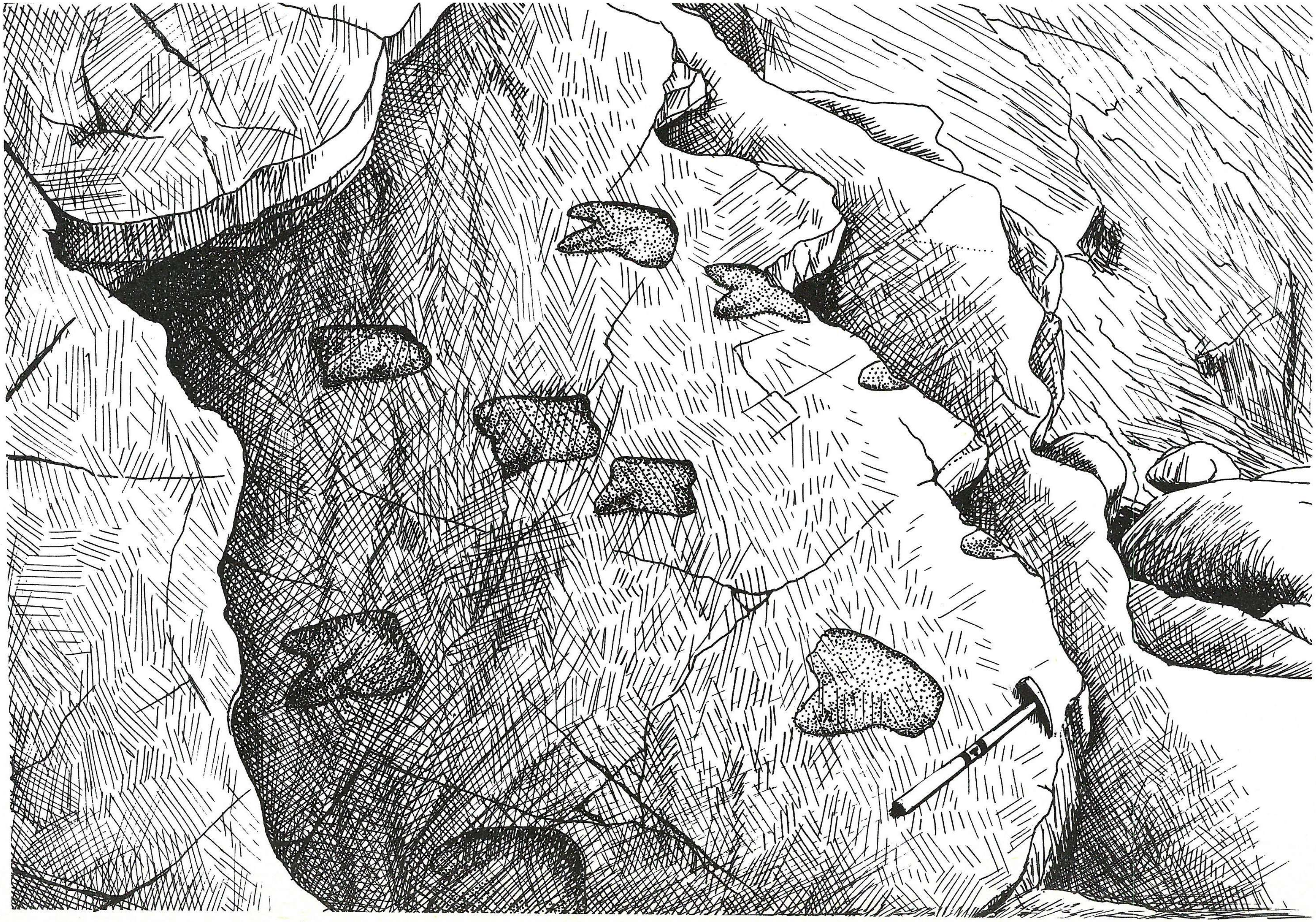

Fig. 6.08. Dinosaur footprints in the Intermarine Beds at Worbarrow Bay.

Cinder Beds - Description.

These oyster limestones are coloured bluish-grey by the small separated valves of Liostrea distorta. Because of the presence of fairly fine-grained matrices they are classified as biomicrudites. Other bivalves are numerous but most are less obvious because of diagenetic changes. Tubes of the worm Serpula coacervata are, however, conspicuous.

In the middle of the unit spines, and occasionally tests, of the echinoid Hemicidaris purbeckensis can be found. With them are bivalves of genera which usually occur in marine strata. Strata apparently the lateral equivalent of this horizon contain mollusca of increasingly marine aspect as they are traced northward into Buckinghamshire (Casey, 1971).

Cinder Beds - Interpretation.

The disarticulated oyster valves form a death assemblage, a thanatocoenose. Nevertheless, as the shells are not greatly damaged they have not been transported far and probably reflect local conditions.

Since echinoids cannot tolerate low salinities, seawater approaching normal marine salinity must have covered the area for part of the time during which Liostrea distorta flourished. Much of the seawater probably came from the north as suggested by Casey (1971 and earlier papers) (Fig. 6.08D). In the overlying limestones, however, Liostrea is accompanied by brackish-water faunas. Being euryhaline it probably occupied the ecological niche of the modern oyster Crassostrea which thrives in brackish lagoons in salinities as low as 17.5‰ (Hudson and Palmer, 1975). Parts of the Cinder Beds without stenohaline organisms are therefore likely to have originated in brackish rather than marine water.

Intermarine and Scallop Beds - Description.

These thin-bedded shelly limestones constitute the Upper Building Stones which are extensively worked in the quarries near Swanage. The Intermarine Beds (Fig. 6.06) form the greater part of these strata. The Scallop Beds are thin sandy limestones at the top.

Much of the Intermarine Beds is biosparrudite (Plate 6.03) largely consisting of the shells of Neomiodon usually referred to in early publications as Cyrena or Cyclas (e.g. Fisher, 1856). Some of the beds contain scattered dark-coloured Liostrea shells.

The finer grained limestones are mainly biomicrites with ostracods. In these and in the shales and marls there are often gastropods such as Viviparus, Physa and Hydrobia (Clements, 1969) and sometimes charophytes (El-Shahat, 1977).

Near the base of the Intermarine Beds fragments of turtle carapace occur and crocodile and pterodactyl remains have been found (Bristow and Forbes, in Damon, 1884). Good fish remains have also been obtained, particularly from the "Downs Vein" in the quarries (Fisher, 1856). Fish remains and turtle bones are common near the top of the Intermarine Beds. In the Upper and Lower Building Stones at least twenty-four species of fish have been encountered, these being mainly holostean types with thick rhombic scales. Sometimes scales, teeth, vertebrae, fin spines ("ichthyodorulites") can be seen in the blocks on the shore. Some of the Intermarine Beds contain plant debris and the isopod Archaeoniscus occurs in the "Underpicking", a softer stratum in the middle of the Intermarine Beds (probably Clements' bed 128).

Footprints of dinosaurs, often in parallel tracks made by several animals, are commonly found on the beds of shelly limestone, particularly the Roach Bed, in quarries west of Swanage (Delair and Lander, 1973). The discovery of long tracks, extending for up to 140 metres, has caused much excitement in the local region (e.g. Evening Echo, Bournemouth, June 25, 1963). A series of footprints has been cut out and are on display at the British Museum (Natural History). On the coast good examples (Fig. 6.08) can be seen at about the Roach horizon at Worbarrow Bay (not in the Cypris Freestones as stated by Delair and Brown, 1975). Please avoid damaging these fine specimens.

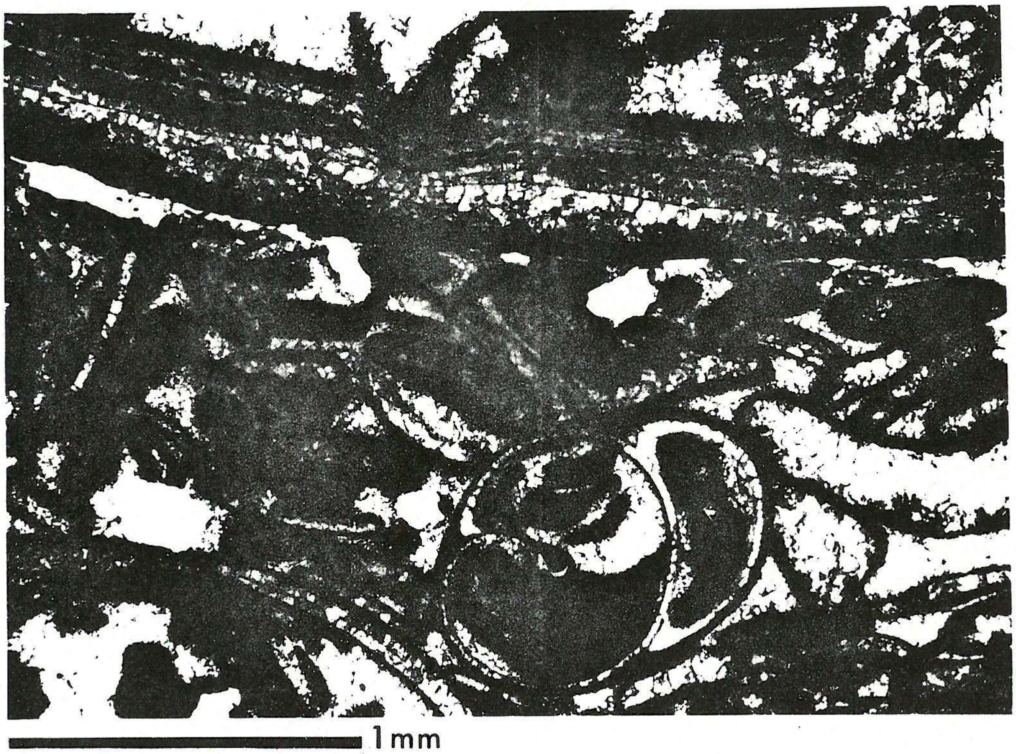

Plate 6.03. A middle Purbeck biosparrudite of early-cemented type, consisting of partly rounded bivalve fragments with gastropods, Bed D.B.186, (from El-Shahat, 1977).

The Scallop Beds are inconspicuous sandy limestones and shales, about 1.5m thick, at about 15m above the top of the Cinder Bed at Durlston Bay (see Clements, 1969). They lie between a conspicuous massive biosparrudite, (the Laneing Vein) about 1.25m thick and the more argillaceous Corbula Beds. Their identity can be confirmed by the shells of the scallop "Chlamys". Other bivalves include Liostrea and Modiolus.

Intermarine and Scallop Beds - Interpretation.

The Intermarine Beds are appropriately named because of their strange mixture of near-marine and of low-salinity faunas and are obviously mainly of brackish water origin. Near the base, however, beds with charophytes originated in water of low-salinity, (Fig. 6.03) and indicates a return to Cherty Freshwater Beds conditions. The crocodiles and turtles lived in the lake and surrounding marshes.

The origins of the Neomiodontid debris beds above is an interesting problem. Neomiodontids occur with various brackish faunal and flora elements from charophytes (of low-salinity origins) to Liostrea (of higher-salinity origins). Studies of similar facies in the Middle Jurassic (Hudson, 1963) has suggested that Neomiodon was euryhaline and dominant at salinities of about 5‰ to 9‰ (Fig. 6.07). Eomiodon seems to have lived in brackish water of salinities above about 16‰ (Casey, 1971; Hallam, 1976). Perhaps its occurrence in the Portland Upper Building Stones of the Vale of Wardour (Casey, 1971), strata which contain stromatolites (Wimbledon, 1976), suggests tolerance of some hypersalinity (cf. Ager, 1976). The disarticulated and often broken valves suggests the effects of wave action. Perhaps the debris was concentrated in this western marginal area of the Purbeck sea (Fig. 6.09) by easterly winds (cf. southeasterly Wealden winds of Allen, 1976).

The footprints, mainly of Iguanodon and Megalosaurus, are, of course, records of subaerial exposure. The shell-hash which was to form the Roach behaved like snow, absorbing the load by the crushing of the shells. The footprints show that the dinosaurs walked in a "pigeon-toed" manner with a stride of rather more than a metre and mainly travelled parallel to the distant margins of the basin, either southwest or northeast (Walkden and Oppé, 1969). Why though, did herds of dinosaurs, such as the herbivorous Iguanodon, wander over the carbonate sand flats? Perhaps they were searching for water during a temporary drought. An unusually hot dry summer would explain the desiccation cracks and the red, early-lithified, crust of the Roach Bed (El-Shahat, 1977).

Important, although relatively short-lived changes in the environment are shown by the Scallop Beds. The faunal evidence (Fig. 6.07) shows that nearly normal marine (euhaline) salinities existed. The inflow of seawater brought in quartz sand, perhaps transported to the area by longshore drift. Probably scallops are common because they were tolerant of a mobile sand substrate.

The Corbula Beds - Description.

Although the limestones in this unit are conspicuous they are thin, and the percentage of clay is fairly high. The limestones are mostly sandy biosparrudites with the small bivalve Corbula conspicuous. Hemicorbicula and other bivalves are present (Casey, 1955) and are accompanied by gastropods such as Hydrobia, Procerithium and Promathilda. Dinosaur footprints have been found (Mansel-Pleydell, 1896).

Corbula Beds - Interpretation.

The faunas suggest that the beds originated in more saline waters than those of the Intermarine Beds, though still much less saline than normal seawater. At the present day Corbula occurs in the restricted Sea of Azov, as well as many other places, at salinities of about 11‰ where the water is shallow and it is also associated with Hydrobia. A slightly sandy estuarine environment is implied for the Purbeck analogue.

Chief Beef Beds - Description.

Shales, sometimes richly organic are the predominant rock types but thin beds of Neomiodontid biosparrudite occur at intervals. A common feature of other units, but best developed here, is the preservation of layers of shells as aragonite, in chalky condition. They have been referred to in previous literature as "perished bivalves" or "rotten lamellibranchs" (Fisher, 1856). Associated with these is the "beef", fibrous calcite, which has developed by diagenesis during or after compaction. Viviparus and even Planorbis have been found in these beds and species of the ostracod genus Cypridea are common (Clements, 1969).

Chief Beef Beds - Interpretation.

These shales, like most strata which contain beef, seem to have relatively high organic contents which accounts for the preservation of the aragonitic bivalve shells. The organic content seems to result from more humid climatic conditions as Wealden times approached; more luxuriant land vegetation contributed more vegetable detritus by rivers. Large quantities of bedload clastics, however, had yet to arrive.

The gastropod faunas suggest fairly low salinities (see Fig. 6.07) perhaps less than about 5‰ (oligohaline) and the greater influx of river water probably accounts for this.

Broken Shell Limestone - Description.

This is a thick biosparrudite probably made up of fragmented Neomiodontid shells but also containing remains of Unio, Viviparus, fish and turtles. Unexplained circular depressions occur on its upper surface.

Broken Shell Limestone - Interpretation.

The fauna and lack of oysters again indicates low-salinity origins, usually below about 8‰. Like the biosparrudites of the Intermarine Beds this mass of shell fragments raises the problem of how it was concentrated. Wave action on extensive gently shelving, intertidal flats of the brackish gulf or lake would account for breakage and sorting, and this bed may also have been accumulated by easterly winds.

Unio Beds - Description.

These are shales and limestones, mainly biosparrudites which are more sandy in the west and everywhere contain the large freshwater mussel Unio and the pondsnail Viviparus. Plant debris and crocodile and turtle bones occur and the teeth and scales of fish are numerous. Pyrite and siderite are present but the abundant glauconite, much of it clearly authigenic, in these apparently non-marine beds is puzzling.

Unio Beds - Interpretation.

The faunas show that the beds originated in very low-salinity, probably oligohaline, conditions (Fig. 6.07). At the present day Unio inhabits rivers and lakes, the larval form being parasitic on fish, and it is interesting to note the evidence of such hosts in the Unio Beds.

The lateral extent of these beds and lack of obvious channels suggests deposition in a lagoon or lake rather than a river. Shallow, almost fresh, water and probably plenty of food, meant that this lake swarmed with pond-turtles and crocodiles. Increase in Upper Purbeck clastics westwards suggests that rivers were not very far away and these presumably brought in the iron for the formation of much siderite and pyrite and, perhaps, for the iron-bearing clay glauconite. Undoubtedly more humid climatic conditions leading up to the even wetter Wealden environments, favoured chemical weathering in the well-vegetated upland areas.

Upper "Cypris" Clays and Shales - Description.

These shales with numerous Cypridea contain three beds of "Purbeck Marble" (Viviparus biomicrudites). They are coloured either green by disseminated glauconite or are reddish where this mineral has been oxidised.

Unio is also common, being most abundant in a thin sandy limestone rich in glauconite, both at Durlston and in the Lulworth area. North of Weymouth, at Friar Waddon (SY 644857) there is a very interesting "Unio Bed" equivalent either of this stratum or of some part of the underlying Unio Beds. It is important because, in addition to many teeth of sharks such as *Hybodus* it contains pebbles of Portland chert and limestone and derived phosphatic ammonites, probably from the Kimmeridge Clay (West and Hooper, 1969).

Upper "Cypris" Clays and Shales - Interpretation.

These clearly originated in lacustrine conditions much like those in which the underlying strata formed. Ostracod, gastropod and bivalve faunas again suggest oligohaline conditions (Fig. 6.03); the sharks were of genera (*Hybodus*, *Lonchidion*) that, surprisingly, had taken over almost freshwater habitats (Patterson, 1966). The *Viviparus* limestones have obviously been formed from the remains of numerous pondsnails; these animals probably thrived on luxuriant aquatic vegetation which has completely disappeared.

The Friar Waddon "*Unio* Bed" is significant because it provides evidence about the adjacent land bordering the basin. The clastics show that by late Purbeck times erosion of much of the Upper Jurassic had taken place in the west and uplift was taking place of the western areas that were soon to provide the Wealden clastics.

CONCLUSIONS-DEPOSITIONAL ENVIRONMENTS OF THE PURBECK FORMATION

The Dorset strata originated in the western part of a very shallow, large lagoon and its bordering sand and mud-flats, covering most of the present site of southwest England and the English Channel. At first salinities were above that of normal seawater; later they fluctuated between marine and freshwater.

The relative aridity of the early Purbeck climate was a change from previous Jurassic conditions. Apart from traces in the Middle Jurassic, evaporites are not known in other British Jurassic strata. The cycadophytes, modern relatives of which grow in relatively warm environments, appear in the dirt beds as a result of the first northward migration in the late Mesozoic (Ager, 1975). Tree rings and evidence of seasonal lakes show the climate was not only warmer and drier than previously but was characterised by well-defined seasons (West, 1975). It must be emphasised, however, that desert conditions did not exist in Dorset. The evaporites and associated sediments, which lack red-beds or blown-sands, and the character of the faunas and the presence of forests suggests merely a semi-arid climate (West, 1975).

In size and shape the lagoon may have resembled the famous Kara Bogaz gulf, a barred basin of hypersaline water with a continuous inflow from the Caspian Sea. The stromatolites were like those today in shallow and intertidal hypersaline water at Shark Bay, the calcium sulphate evaporites like those developed in lagoons and sabkhas which border them as in the Trucial Coast of the Arabian Gulf and more particularly like those of the Mediterranean coastal zone of Egypt (West <u>et al</u>., in press). Sediment associated with the Purbeck evaporites conspicuously lacks blown quartz sand and oxidised iron, but instead contains the well-developed carbonaceous soils. This points to environments appreciably less arid than those of the Trucial Coast and rather less arid than northern Egypt. An ideal modern analogue would lie further north but no large, shallow lagoon of Purbeck size lies near the western

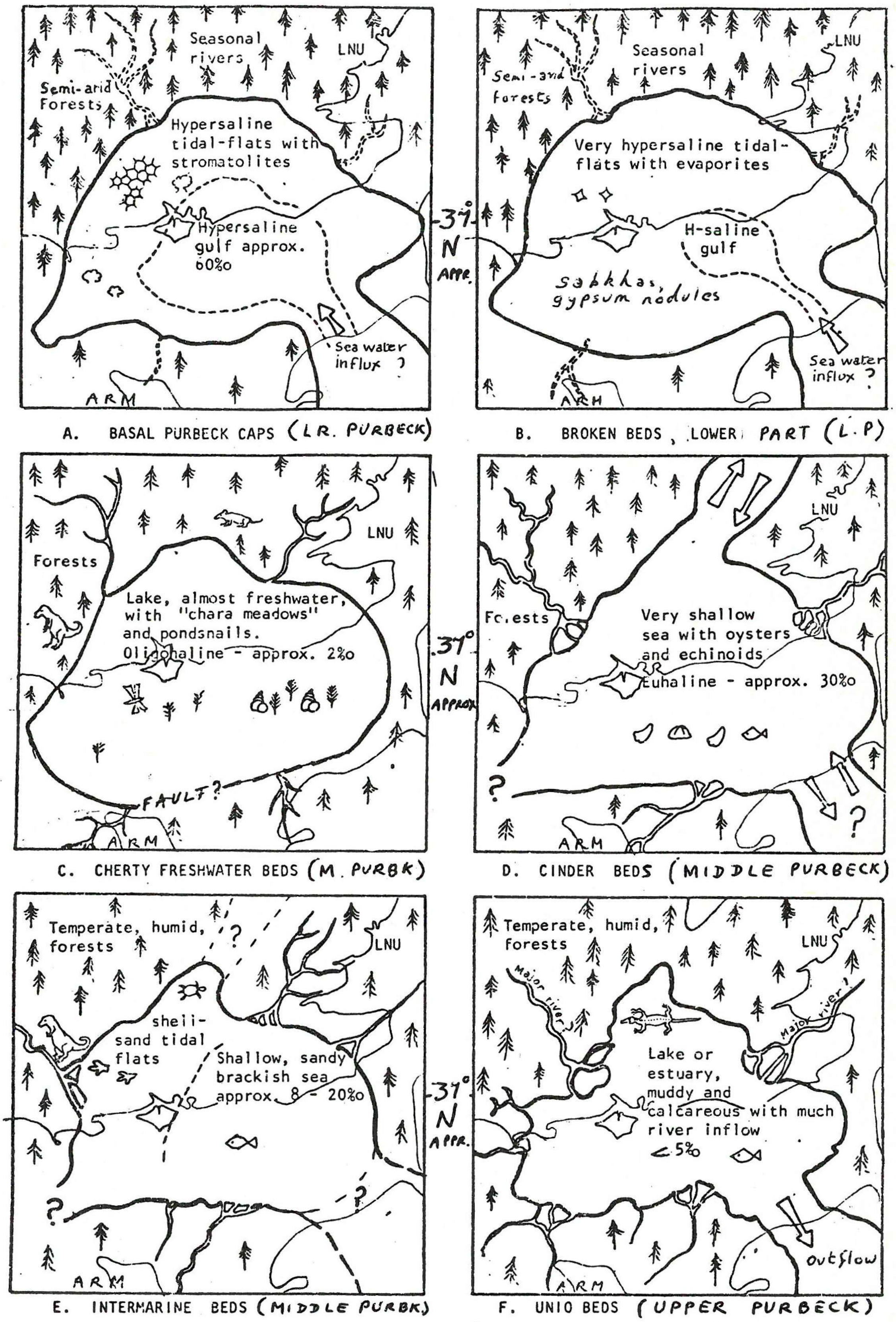

Fig. 6.09. Schematic palaeographic reconstructions for Purbeck subdivisions suggesting salinity control of the restricted shallow sea or gulf by varying influxes of river water and seawater. The basin shown covered part of southern England and the English Channel. ARM - Armorica, LNU - London - North Sea Uplands (London - Brabant Ridge). Based on Howitt (1964), Casey (1963; 1971) and other sources.

margin of a continent (as did the Purbeck lagoon) at the right latitude at the present day.

The ancient forest seems to have flourished adjacent to the huge Purbeck lagoon and its extensive "tidal" flats and presumably received sufficient rain. At the present day most major forests seem to require an annual rainfall of at least 400mm per annum. Nevertheless the climate had to be dry enough for evaporites and warm enough and sufficiently free from winter frosts for cycadophytes, crocodiles and turtles. Regions near the southern limit of temperate forests and the northern limit of evaporites are parts of Syria, Lebanon or Israel and Jordan which agrees surprisingly[1] well with the palaeolatitude of about 37°N (Smith and Briden, 1977). It is of interest that a good analogue of the salt-pickled trees of the Fossil Forest is that of a submerged forest in a salt-lake of that region, the Dead Sea (Neev and Emery, 1966).

On the low flat land around the Purbeck lagoon were the broad calcareous sabkhas and ephemeral lakes and behind them the dark green, conifer-scented forests which with occasional herds of herbivorous dinosaurs and the small inconspicuous nocturnal mammals. Peculiar in comparison with modern lagoons would have been the absence or rarity of water-fowl on the (probably) pinkish algal-rich, very saline waters.

Without human interference, without competition from grass (Walter, 1973) and without large browsing mammals, climatic regions like those today that are occupied by semi-arid steppe or grassland were then probably forested. This explains why it is difficult to find a modern analogue for coniferous forests existing in proximity to major sites of evaporite deposition.

Footnote 1: surprising since there are polar icecaps at present but no evidence that such existed in Purbeck times.

The Middle Purbeck lagoon with brackish faunas and no evaporites but with some kaolinite and more quartz sand indicates wetter conditions. It can be compared to somewhere just north of the northern hemisphere arid zone such as parts of Turkey or Spain. In size, in invertebrate faunas, lack of evaporites and proximity to forests (forest-steppes) it resembled the modern Sea of Azov but the Purbeck crocodile-infested region was obviously warmer, at least in winter. The low-salinity Caspian Sea is similar in some respects but suffers too continental a climate. If a very large shallow lagoon existed in northern Syria it might provide an effective model.

Thus the major trend of Purbeck sedimentation was a progressive change from deposition of evaporites at the base to deposition of brackish and freshwater beds in the middle and upper parts (Fig. 6.09 A-F). Lake deposits at the top were formed near the mouth of a river and are almost fluviatile (Fig. 6.09 F). With evidence of salinity changes there is an increase upwards in quantity of coarse clastics and of plant debris. A trend towards progressively more humid conditions explains this. Thus it would seem that the boundary between the northern arid zone and the northern temperate humid zone moved southwards away from southern England during later Purbeck times, perhaps due to the progressive development of the North Atlantic Ocean.

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