UNIVERSITY OF SOUTHAMPTON

THE FOSSIL FORESTS OF THE BASAL PURBECK FORMATION (UPPER JURASSIC) OF DORSET, SOUTHERN ENGLAND

Palaeobotanical and palaeoenvironmental investigations

by

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A thesis submitted for the degree of
Doctor of Philosophy

October 1982

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

GEOLOGY/BIOLOGY

Doctor of Philosophy

THE FOSSIL FORESTS OF THE BASAL PURBECK FORMATION (UPPER JURASSIC) OF DORSET, SOUTHERN ENGLAND: PALAEOBOTANICAL AND PALAEOENVIRONMENTAL INVESTIGATIONS

by Jane Elizabeth Francis

During the Upper Jurassic, coniferous forests grew adjacent to the Purbeck evaporitic basin in Dorset. The palaeobotany of the forests is described for the first time and the Purbeck forest environment reconstructed.

The basal Purbeck Formation of Dorset was deposited during minor transgressive and regressive phases on the borders of a shallow hypersaline basin. The sediments include evaporites, hypersaline intertidal algal stromatolitic sediments and lagoonal pelletoid silts interbedded with supratidal algal mat sediments. The unusual features are brecciated calcrete and calcareous marls representing former forest soils.

The trees which grew in the rendzina-like palaeosols of the Lower and Great Dirt Beds are now preserved *in situ* as silicified tree stumps and branches. They were drowned by rising hypersaline water and preserved within mounds of algal stromatolitic sediment. The wood was rapidly silicified by length-slow chalcedony (quartzine), a type of silica commonly associated with evaporitic environments.

The fossil forests were dominated by one type of conifer belonging to the extinct family Cheirolepidiaceae. The wood of this is designated *Protocupressinoxylon* sp∧nov., the small scale-like leaves are *Cupressinocladus valdensis* (Seward) Seward and the small male cones *Classostrobus* sp. Alvin, Spicer and Watson. The tree is a source of *Classopollis* Pflug pollen so widespread in the Jurassic. A reconstruction of this Purbeck tree, based on evidence from fossil remains, is presented. The trees were monopodial with low branches and shallow spreading roots and formed fairly dense, closed forests. A few other conifer species were also present but much less abundant and cycadophytes (Bennettitales) are also represented by their silicified stems. The miospore assemblage from the palaeosols is dominated by *Classopollis* pollen (70% of samples), but also represents a rather poor flora of filicalean and lycopsid plants.

Comparison with modern tree-ring data from semi-arid regions suggests a Mediterranean-type of climate for the Purbeck with warm, wet winters and hot, dry summers. The markedly seasonal nature of the climate is supported by sedimentary and faunal evidence such as ephemeral lake sediments containing both a freshwater fauna and flora plus evaporites.

Modern analogues to the Purbeck environment have been found in the Mediterranean areas of the southern parts of Australia. The environment of the *Callitris* forests of Rottnest Island, Western Australia, appears remarkably similar to that of the Purbeck forests.

This type of seasonal, semi-arid climate during the Upper Jurassic accounts for the paradoxical association of evaporites with well-developed forest vegetation. It contrasts with the widely held view that the Jurassic climate was warm and equable. The reconstruction of the Purbeck trees and forest environment may serve as a model for other Upper Jurassic and Lower Cretaceous vegetation.

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Acknowledgements

This research was undertaken in the Biology and Geology Departments, Southampton University, during the tenure of a grant from the Natural Environmental Research Council, which is gratefully acknowledged.

I wish to thank Dr P.J.Edwards (Biology) and Dr I.M.West (Geology) for their supervision and guidance during this project and for their critical reading of this thesis.

I am most grateful to the following:-

Dr C.R.Hill (British Natural History Museum) for allowing me to borrow specimens of fossil plants, for instruction in palaeobotanical techniques and much useful discussion.

The many other people who have helped me with palaeobotanical work, both in identifying specimens and reviewing manuscripts, particularly Dr K.L.Alvin(Imperial College).

Dr W.A.Loneragan and Mr M.Williams (University of Western Australia) for supplying me wtih literature and their own tree-ring data.

Dr R.G.Clements (Leicester University) for identification of the fossil branchiopods and permission to use his unpublished data.

Mr E.Jarzembowski (British Natural History Museum) for identifying the dragonfly wing.

Mr R.Coram, Wimbourne, Dorset, for lending specimens of fossil plants.

Staff and technicians in both Geology and Biology Departments for their help in many aspects of this work, particularly Mrs A.Dunkley for help with artwork.

To Mrs Sharpe and Miss F.Bradbury for typing this work.

Finally I wish to thank my mother and father for the constant support and encouragement that only parents can give.

"To find other trees between Pebblebank and Beal, it was necessary to recede a little in time - to dig down to a loose stratum of the underlying stone-beds, where a forest of conifers lay as petrifactions, their heads all in one direction, as blown down by the gale in the Secondary geologic epoch."

Thomas Hardy.

'The Well-Beloved'
1897.

For my Mother and Father

CHAPTER 1

INTRODUCTION

1.1 General

The Purbeck Formation of southern England represents the products of a major regressive phase at the end of the Upper Jurassic, when the shallow marine sediments of the Portland Group were replaced by freshwater, brackish and hypersaline sediments at the margin of a very shallow, very large lagoon (West 1975).

In Dorset the basal beds of this formation consist of intertidal and supratidal deposits formed in an hypersaline environment during the initial minor transgressive and regressive episodes. The sequence consists mainly of algal stromatolitic limestones, called the Hard and Soft Caps (nomenclature derived from quarry terms, Arkell 1945). These Caps were formed as mounds of sediment trapped by blue-green algae on hypersaline tidal flats (Brown 1963; Pugh 1968). Pelletoid and intraclastic limestones surround them. Laminated algal mats also occur in the basal beds, particularly at the top of the Hard Cap where they contain calcitised pseudomorphs after gypsum, desiccation cracks and other evidence of aridity.

Interbedded with the limestones are the dark carbonaceous marls of the Great Dirt Bed and Lower Dirt Bed (Table 1.02). These represent former forest soils formed during periods of subaerial exposure. Within the Great Dirt Bed pebbles and boulders of limestone are found, some of which are blackened.

Silicified tree stumps, trunks, branches and rarer cycadophyte stems, the remains of ancient forests which bordered the lagoon, are preserved in their original growth positions. The conifer trunks of the Great Dirt Bed are encased within "burrs" or domes of the overlying algal limestone of the Soft Cap.

Very little was previously known about the fossil forests and their vegetation, or how they managed to survive in what appeared to be a saline, semi-arid environment.

This research was planned with several objects in mind. The fossil wood was studied in detail in order to establish the anatomy and habit of the trees and the density and composition of the forest. The tree-rings and adjacent limestones and soils were investigated in order to understand the palaeoenvironment, particularly the climate,

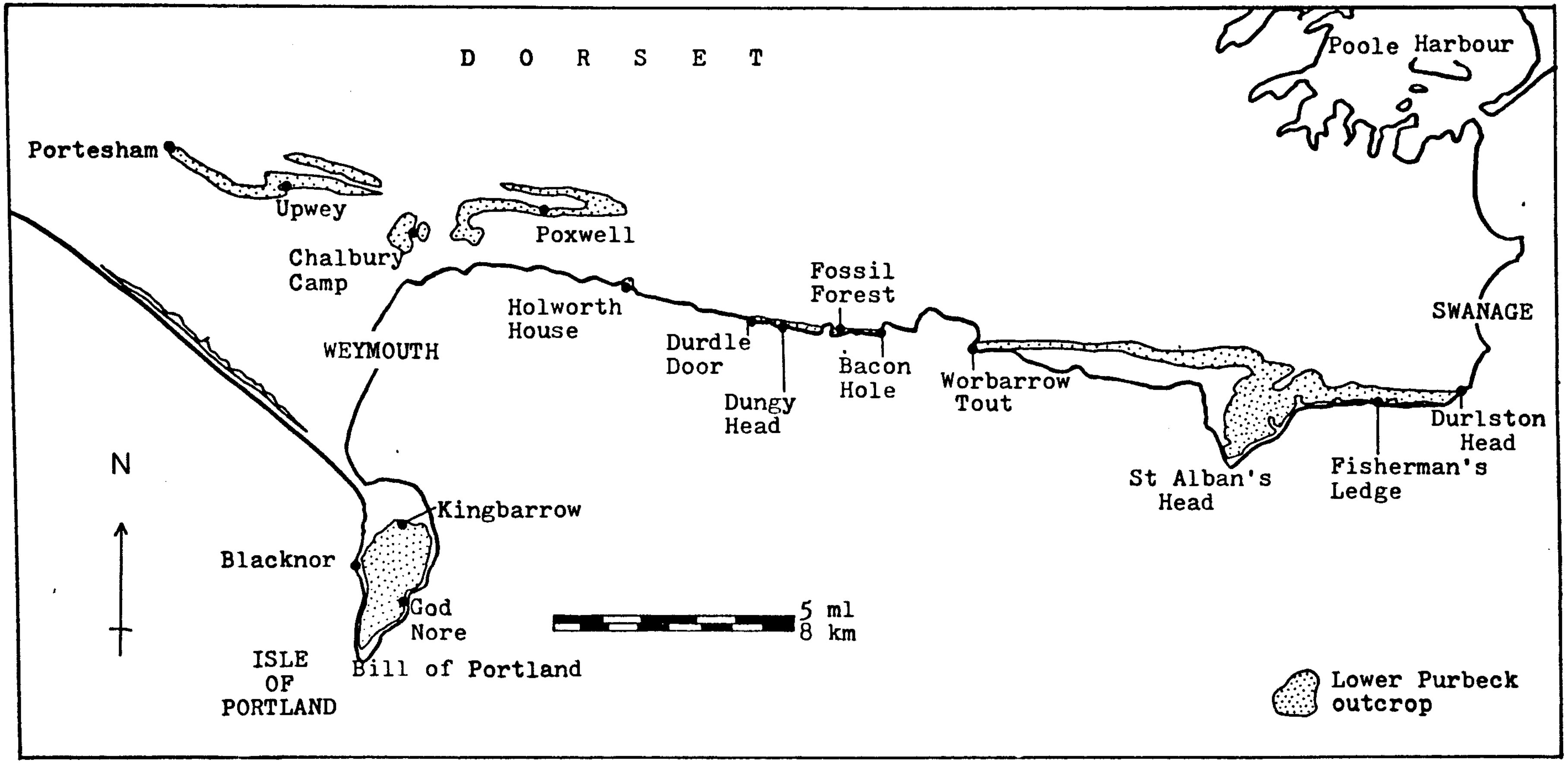

Fig. 1.01. Map showing the Lower Purbeck outcrop in Dorset and locations mentioned in the text.

in which the trees grew. Comparison with modern forests and their soils and growth ring data was attempted in order to establish a modern analogue to the basal Purbeck forests and palaeoenvironment.

1.2 The Purbeck Formation of Dorset - its Age in Relation to the Jurassic/Cretaceous Boundary

During the major Upper Jurassic regression in Dorset, the marginal continental facies of the Purbeck Beds replaced the shallow marine sedimentation of the Portland Group with no obvious break or major unconformity. Freshwater deposits became more common in the Upper Purbeck, which were then conformably overlain by the dominantly freshwater, fluvial sediments of the Wealden Formation.

In the earliest geological studies the Purbeck and Wealden Beds were grouped together because they contain similar freshwater faunas (Webster 1826; Fitton 1836). The discovery of the marine echinoid *Hemicidaris purbeckensis* in the Cinder Bed of the Middle Purbeck Beds (Forbes 1851), however, led to the reclassification of the Purbeck Group with the more marine Jurassic strata rather than the freshwater deposits of the Lower Cretaceous (Fisher 1856). In contrast, Seward (1895) considered the two formations inseparable from the evidence of their similar fossil floras.

In southern England the Jurassic/Cretaceous boundary was traditionally placed at the Purbeck/Wealden junction (Allen 1955), the Purbeckian being regarded as the youngest Jurassic stage at that time (Arkell 1947). However there is little palaeontological evidence to support such an interpretation, since a dominantly non-marine facies was developed. The boundary was proposed by Casey (1963) to lie at the base of the Cinder Bed, considering it to represent a widespread marine incursion which could be traced over a large area of north-west Europe. This division of the Purbeck Formation across the Jurassic/Cretaceous boundary caused the erection of new strata names. Casey (1963) proposed the new terms "Lulworth Beds" and "Durlston Beds" for the parts of the Purbeck Beds below and above the boundary respectively. The British Mesozoic Committee accepted Casey's suggestions, and the Lower Cretaceous was then considered to commence at the base of the Cinder Bed (Ager 1968). In 1973, at the Lyons Colloquium on the Jurassic/Cretaceous boundary, the junction was considered to correspond

	Formations	Informal divisions	Strata in Durlston Bay	Cypridean zones
PURBECK FORMATION	Durlston Formation	Upper	Upper '*Cypris*'Clays and shales	*C.setina*
			Unio Beds	
			Broken Shell Limestone	
		Middle	Chief Beef Beds	*C.g. fasciculata*
			Corbula Beds	
			Scallop Beds	
			Intermarine Beds	
			Cinder Beds	
	Lulworth Formation		Cherty Freshwater Beds	*C.g. granulosa*
			Marly Freshwater Beds	
		Lower	Soft Cockle Beds	
			Hard Cockle Beds	
			'*Cypris*' Freestones	*C.dunkeri*
			Broken Beds	
			Caps and Dirt Beds	

Table 1.01

The stratigraphy of the Purbeck Beds of Dorset and ostracod zones.
(Strata names from Clements 1969;ostracod zones from Anderson 1974).

to the Berriasella jacobi-grandis ammonite zone in marine limestones at the base of the Berriasian stage in southern France (Anon. 1975). In this case the boundary would lie within the lower part of the Lulworth Beds, placing most of the Purbeck Beds within the Lower Cretaceous.

Ostracods have been used to correlate the Purbeck Beds of southern England with similar facies in Europe, reviewed by Anderson (1974). Correlation of the Purbeck Beds in Germany (Anderson 1962; Anderson and Hughes 1964), France (Donze 1958; Oertli 1963), Sweden (Christiensen 1968) and the Jura mountain area (Carozzi 1948; Bartenstein and Burri 1955) has been based mainly on ostracod distribution. Palynological studies which attempted to locate the Jurassic/Cretaceous boundary in southern England were inconclusive (Norris 1969; Dörhöffer and Norris 1975). Hughes and Moody-Stuart (1969) correlated the Lower Fairlight Clay of the Weald with the Upper Middle and Upper Purbeck of Dorset using miospores, suggesting that these beds may thus be Lower Cretaceous in age.

The Jurassic/Cretaceous boundary has still not been internationally defined as there is a trans-facial problem of correlation between the Boreal and Tethyan realms. In Dorset the boundary is provisionally located at the Cinder Bed, and the Purbeck Beds below this are included with the Portland Group in the Portlandian Stage (Wimbledon, in Cope et al. 1980). This boundary is, however, subject to dispute and liable to be changed in the future. It seems likely that the basal Purbeck Beds of Dorset will remain within the Upper Jurassic.

1.3 Divisions of the Purbeck Beds in Dorset

The name "Purbeck Beds" has been used as a lithostratigraphic term, since it was first applied by Thomas Webster in 1812 (in Woodward 1895). The "Purbeckian" was later considered to be a stage (Arkell 1947), but at the Colloquium on the Jurassic System (Ager 1963), the Purbeckian was recommended as a facies term only for the continental and freshwater deposits at the Jurassic/Cretaceous boundary.

Informal divisions of the Purbeck Beds into Upper, Middle and Lower parts have long been recognised. Each division was considered to have distinct faunas (Forbes 1851), although in Dorset the lithologies

TABLE 1.02

Terminology of the basal Purbeck Beds of Dorset

	Arkell 1947	This Study
Basal Purbeck Beds	Slatt Marl	Broken Beds
	Bacon Tier	Soft Cap
	Aish	
	Soft Burr	
	Great Dirt Bed	Great Dirt Bed
	Top Cap	Hard Cap
	Lower Dirt Bed	Lower Dirt Bed
	Skull Cap	Upper Skull Cap
	("dirt")*	Basal Dirt Bed
		Lower Skull Cap
Portland Group	Portland Stone	Portland Stone

* The Basal Dirt Bed is not formally named but recorded as a "dirt resting on Portland Stone".

vary considerably and there are no really significant lithological and palaeontological breaks. Ostracods were used for zonation by Forbes (1851) and Lyell (1855), but Jones (1885) was the first to provide generic descriptions. Strahan (1898) divided the Purbeck Beds into the three divisions based on ostracods. A history of the zonal classification is given by Anderson (1958, 1962), who in 1940 proposed a more detailed sub-division than the original tripartite grouping. This was subsequently revised by Sylvester-Bradley (1949), Anderson (1958) and Anderson and Bazley (1971).

The algal limestones, fossil soils and forests forming the subject of this thesis occur within the lower part of the Lower Purbeck division (Tables 1.01, 1.02), and so will be subsequently referred to as the basal Purbeck Beds.

1.4 The Outcrop of the Purbeck Formation

In southern England the Purbeck Formation is exposed in Dorset, Wiltshire, Buckinghamshire and Sussex (Woodward 1898; Arkell 1933) and known from subsurface boreholes in Kent (Lampugh, Kitchen and Pringle 1923), Hampshire (Taitt and Kent 1958) and the English Channel (Donovan and Stride 1961; Larsonneur et al. 1974). Isopachyte maps of Howitt (1964) indicate the presence of two basins, one in the Weald and one in Dorset, separated by a north-east/south-west trending ridge from Portsdown to Winchester (Fig.1.02). Additional borehole information at Fairlight, near Hastings (Holliday and Shephard Thorn 1974) suggests another basin may be present in the eastern English Channel (Fig.1.02).

In Dorset the Purbeck Beds outcrop from Portesham in the west to Durlston Bay in the east (Fig.1.01), a distance along the strike of about 40 kms. The thickest sequence is seen at Durlston Bay (121m), (see Clements, 1969, for details of the succession); here large masses of gypsum occur in the Soft Cockle Beds, but the basal Caps and Dirt Beds are greatly disrupted by faulting at Durlston Head (Phillips 1964). The sequence thins in the Lulworth area (55m), but thickens in the west at Ridgeway (58m) (Arkell 1933). The main exposures are coastal sections or inland quarries; the extensive quarrying on the Isle of Portland affords good exposure of basal Purbeck Beds and fossil soils with trees.

The thickest sequence of Purbeck Beds is known from borehole data at Penshurst in the Weald (181m). In this eastern basin sedimenta-

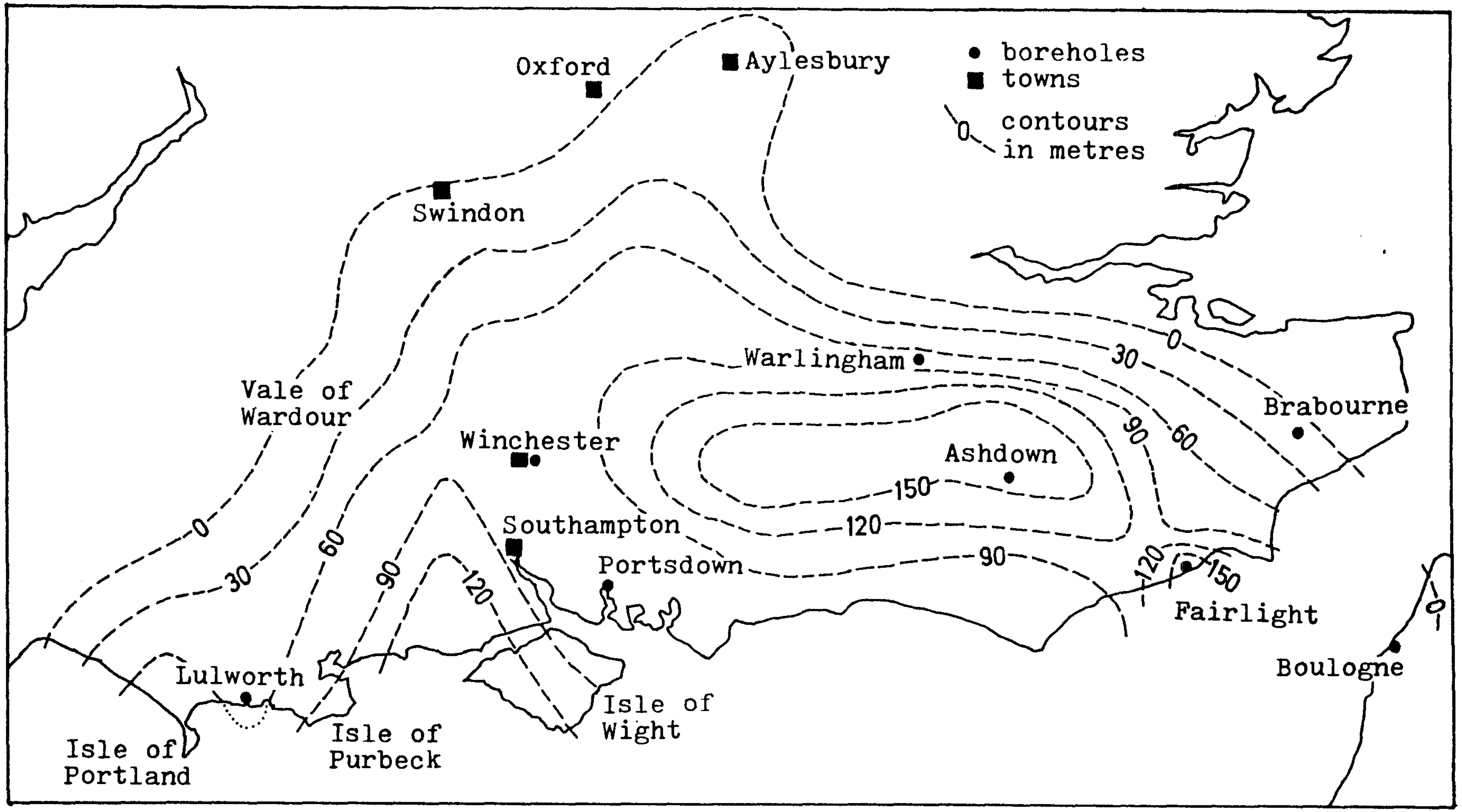

Fig. 1.02. Isopachyte map of the Purbeck Formation in southern England. After Howitt(1964) with emendments from Holliday & Shephard Thorn(1974).

This simplified map does not take into account recent geophysical and borehole data (much unpublished)which suggests substantial unconformities exist. A specific example is the known absence of the Purbeck Beds at Wytch Farm (Colter and Havard 1981) tion differed from that in Dorset and was marked by an hiatus towards the end of the deposition of the Portland limestone. The "Lower" Purbeck of the Weald contains economically important gypsiferous beds associated with pyritic and calcareous mudstones (Howitt 1964). Although sabkha cycles have been recognised (Shearman 1966; Holliday and Shephard Thorn 1974), thick soils with forests are not present as they are in Dorset. There are, however, "Plant and Bone Beds" with some plant remains among the "Middle" Purbeck freshwater deposits in the Weald. The marine episode marked by the Cinder Bed in Dorset is not as readily recognisable in Sussex, but consists of a group of limestones and shales representing a phase of high salinity (Howitt 1964). With additional evidence of varying salinity from carbon isotope ratios (Allen and Keith 1965) and from boron (Walker 1964), this seems to be only one of several major episodes of increased salinity (Bazley, in Anderson and Bazley 1971). Anderson (1971) established cycles of salinity changes based on the alternating occurrence of the ostracod Cypridea Bosquet with other genera and with these proposed a correlation with Dorset. As a result of a palynormorphic investigation of the Purbeck Beds in these two areas Norris (1969) proposed that the lowermost Purbeck of Sussex was in fact equivalent to the Lower and Middle Purbeck of Dorset, the equivalent of the basal Purbeck Beds being absent in the Weald. This contrasts with the normal correlation, that in both areas the Lower, Middle and Upper divisions are equivalent, which has been well established by the detailed ostracod correlation of Anderson (Anderson 1940; Anderson and Bazley 1971), the lithological similarities (Howitt 1964; Lake and Holliday 1978), and lithological correlation with boreholes between the two areas (Taitt and Kent 1958).

The Purbeck outcrops near Swindon and Aylesbury occur on outliers of the Portland Group and are the thinnest recorded sequences (Woodward 1895) (Fig. 1.02). Faunal evidence from the Aylesbury area (Barker 1966) and from Swindon (Sylvester-Bradley 1940) suggests that the brackish-lagoonal conditions became established in this area first, prior to those in Dorset. There appears to have been an alternation of Portland and Purbeck conditions in this area too. In the Vale of Wardour (Fig. 1.02), 29m of Purbeck Beds include an exposure of the Great Dirt Bed containing silicified conifers and cycadophytes, the northern extension of the bed in Dorset. Further north, at Swindon, forest soils are not present but pebble beds and marls with intercalations of the Portland "Roach" are present. Since both marine and freshwater fossils occur together here, the age of these "Swindon Series" has been interpreted as both Middle Purbeck by Arkell, and Lower Purbeck by Arkell and Sylvester-Bradley (1941). However, the discovery of the ostracod Cypridea dunkeri Jones in a marl at Portesham, Dorset, by West (1961) suggested that the Swindon Series, with a similar fauna, corresponded to the Lower Purbeck of Dorset. The sediments and faunas of the Swindon and Aylesbury Purbeck Beds are indicative of sedimentation at the very edge of the Purbeck depositional gulf.

At Bas Boulonnais in north France (Fig. 1.02), Purbeck sediments form part of the south-eastern end of the Weald Pericline (Pruvost and Pringle 1924). Algal stromatolitic mounds, similar to those in the basal Purbeck Beds of Dorset, occur within the 1m thick Calcaire des Oies (Townson and Wimbledon 1979). No fossil soils are recorded although lignite and fossil plants have been observed in earlier Portlandian horizons. Further south in the Pays de Bray silicified wood has been found in the "Trigonia Sand" (late Portlandian) beneath the supposedly Purbeck gravels (Laffite 1939).

Marginal continental facies, similar to the Purbeck of southern England, were also developed in north-west Europe, in north-west Germany, Denmark, Poland and the Paris Basin (see Arkell 1956). In France, sediments equivalent to the Lower Purbeck are recorded from L'Isle d'Oléron (Donze 1958) and from the Paris Basin (Oertli 1963). Evaporitic sediments are found in the Purbecks of the Jura Mountains (Carozzi 1948; Ainardi 1975) and in Germany (Jordan 1971; Kemper 1974; Schonfeld 1979). Shallow lagoonal sediments of Purbeckian facies were also developed in Tunisia (Busson 1967).

1.5 Structure in Dorset

The Portlandian strata in Dorset is affected by the Purbeck and Weymouth anticlines; two eastward-plunging, asymmetrical folds exposed between Weymouth and Durlston Bay (Fig. 1.03) (Phillips 1964). The axial zones of the folds are located within the Corallian Beds on the sea floor 2·4 km south of Lulworth Cove (Donovan and Stride 1961).

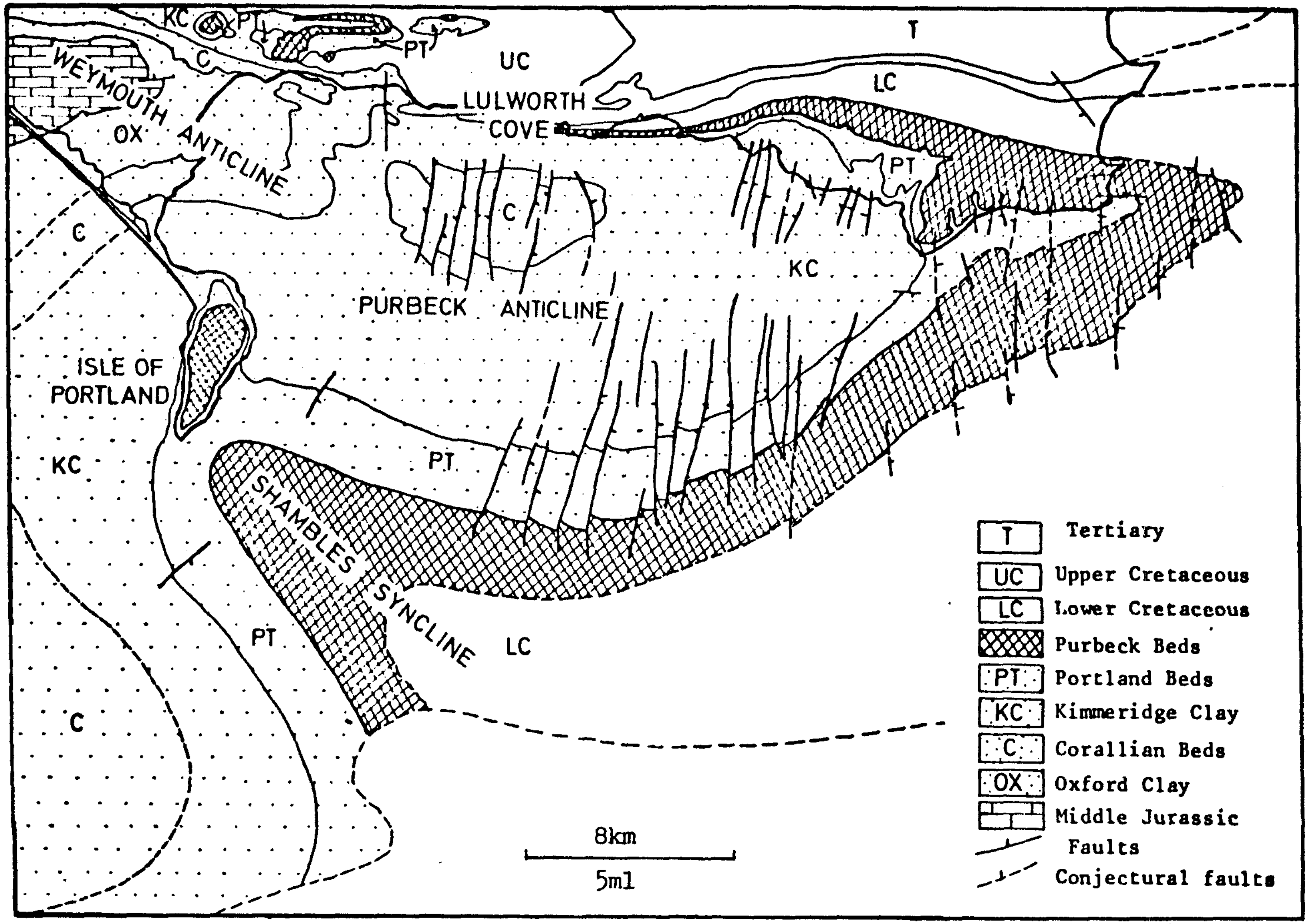

Fig. 1.03. Geological map of the sea floor south of east Dorset.
(Broken lines denote uncertain geological boundaries).
Based on Donovan and Stride 1961.

The southern limb has a shallow dip of only 1° - 3°, exposed only on the Isle of Portland. The island is also involved in the western end of the Shambles Syncline (Fig. 1.03), which trends parallel to the Purbeck anticline. The south-easterly plunge of this syncline causes a progressive swing to the east of the southerly-dipping strata on Portland.

On the northern limbs of the main anticline the dip of the strata ranges from between 20°N on the Isle of Purbeck to 40° near Weymouth. Between Mupe Bay (SY 839797) and Durdle Door (SY 807802) the dip of the Portland Beds increases to 80°N and the overlying Purbeck and Wealden Beds are frequently overturned. Small folds and "crumples" are associated with these high dips, reported by Arkell (1938, 1940) who also discussed the origin of the "Broken Beds" and the attenuation of strata towards Durdle Door. Details of the Weymouth anticline are discussed in House (1961) and Ridd (1973).

An upland swell or barrier appears to have influenced Purbeck sedimentation in Dorset. Townson (1975) postulates a "Mid-Dorset Swell" trending south-west/north-east across the Lulworth area, dividing Dorset into two basins. Local uplift in this region was also proposed by West (1975) to account for thickness variations of the facies of the Lower Purbeck Beds; this would also explain the reduction in the total thickness of the Purbeck Formation near Lulworth (Arkell 1938; Howitt 1964). Drummond (1970) also considered that intermittent movement associated with a north-west/south-east trending swell from central Dorset to the Isle of Purbeck (the Mid-Dorset Swell) was responsible for several unconformities in Upper Cretaceous strata. It is possible that the same swell was active during pre-Cretaceous times and affected Jurassic sedimentation in this area.

A demi-horst structure, step-faulted on its southern side, is preferred by Allen (1981) for his "south Dorset Swell". This may account for the origin of Upper Jurassic sediments, described from Friar Waddon by West and Hooper (1969), though the authors suggested the sediments were the result of erosion on the crest of the Weymouth Anticline to the south. In contrast to Townson, Allen (1981) considered the swell to trend north-west/south-east, parallel to the South Hampshire Swell around Portsdown.

The presence of a swell to the north is also proposed by Colter and Havard (1981) to account for the thinning of Jurassic strata in the Wytch Farm area. The attenuation of strata over this area implies that the Purbeck Beds were also considerably reduced in thickness.

1.6 Summary of Previous Research

Valuable information about the basal Purbeck fossil forests was recorded by geologists in the nineteenth century, particularly from quarries on Portland in which fossil trees and soils were being uncovered during a period of extensive quarrying (Webster 1826; Buckland and De La Beche 1836; Fitton 1835, 1836; Mantell 1854 and others). They discovered erect tree stumps in their original growth positions, often over 1m in height and penetrating the overlying "Soft Burr" and "Aish" limestones (Strahan 1898). Numerous trunks and fallen branches were observed on the fossil soils, some over 10m in length and 1·3m in diameter. The erect stumps were shown to have roots which did not penetrate the underlying limestones but grew horizontally along the base of the soil.

The first sketch of a trunk of one of these trees, by Flewker (1831), illustrates that they were not small and shrub-like but fairly large trees at least 6m tall (though this one was erroneously identified as oak). Fitton (1836) also pictures a very similar fossil trunk from Portland, 7·8m tall. His detailed report documented many basal Purbeck exposures in southern England, with particular reference to fossil wood remains. Fitton (1835, 1836) was especially interested in the fossil forests and recorded detailed measurements and locations of petrified wood and cycadophytes in the Dirt Beds. He noted, for example, that no fossil trees were ever discovered in the Lower Dirt Bed on Portland, although large tree stumps could be seen in the equivalent bed on the mainland.

Damon (1884), Mantell (1854) and Gray (1861), amongst others, agreed that the profusion of fossil wood found on the surface of the Great Dirt Bed indicated that the trees grew as close as those of a modern forest. The trunks appeared to lie in a predominantly north-south direction as if they had been "felled by the swoop of some terrible tornado" (Gray 1861).

Plate 1

The Silicified Purbeck Wood and Algal Stromatolitic Burrs

1. Large silicified tree stump *in situ* at Chalbury Camp. The trunk is encased in algal stromatolitic limestone of the Hard Cap and its roots preserved in the Lower Dirt Bed. A small silicified branch (see Plate 14, Fig. 1), only 44 cm above the top of the palaeosol, is also preserved and still attached to the tree (part is exposed in the cavity on the right).

2. Algal burrs of the Soft Cap at the Fossil Forest, near Lulworth. The long trough-shaped burr once enclosed a fallen tree trunk.

3. A large silicified tree trunk reconstructed in the gardens of the Portland Heights Motel, Isle of Portland. The trunk is approximately 2 metres high and shows the twisted nature of the wood grain near the roots. Numerous knots can be observed on the trunk.

4. and 5. Circular 'open' burrs of algal stromatolitic limestone in the Soft Cap at the Fossil Forest, near Lulworth. The burrs once contained silicified tree trunks which have since been lost. Impressions of the wood grain can often be seen on the inner surface of the burrs.

(Hammer handle length 27 cm. Lens cap diameter 7 cm)


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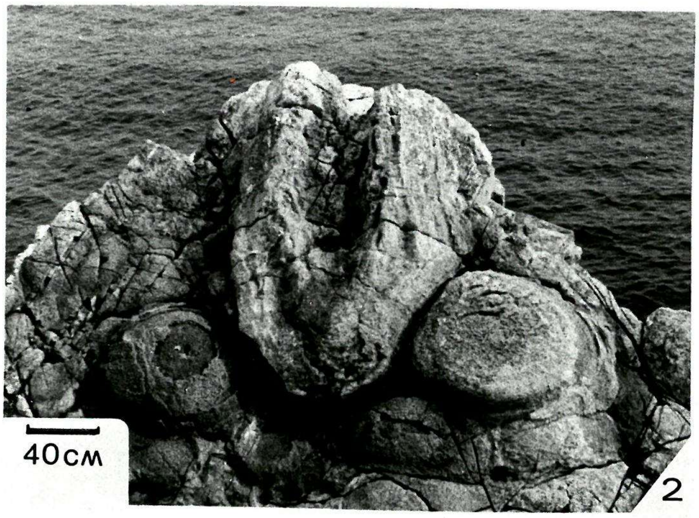

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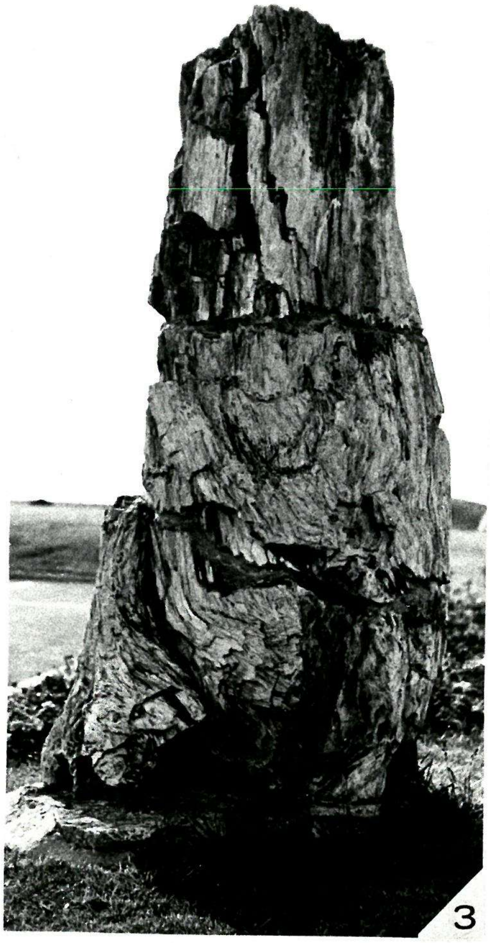
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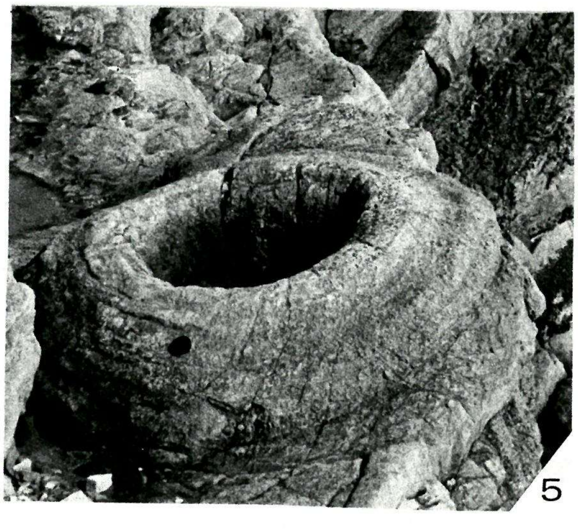
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PLATE 1

The foliage of the trees was noticeably absent from the major exposures of the forests (Buckland and De La Beche 1836), although a single fossil conifer shoot was illustrated by Damon (1884b) from the Top Cap Limestone overlying the Great Dirt Bed on Portland. It was a small shoot with scale-like leaves tentatively identified as Cupressinocladus. Fitton also found a cone on the Portland cliffs which was identified as Araucaria sphaerocarpa by Carruthers (1866). Mantell (1854) considered that this cone, plus the presence of Araucarian wood in the Wealden deposits, suggested that the Purbeck fossil forests were dominated by trees of Araucarian affinity.

The silicified stems of cycadophytes in the fossil soils aroused particular interest since it was due to the presence of such plants that Fitton (1835), Buckland (1829) and Damon (1884) first concluded that a warmer climate than at present prevailed during the Upper Jurassic, comparing them with modern cycads which today occur chiefly in tropical regions. Due to their round, bowl shape, they were believed by quarrymen to be fossil birds' nests which had fallen from the branches of the fossil trees! (Gray 1861). Buckland (1829) classified the cycadophytes into two simple species: Cycadeoidea megalophylla and Cycadeoidea microphylla. Carruthers (1868) proposed six new species from Dorset. These were all considered to be members of the Bennettitales, an extinct group but which resembled extant Cycadales. Cycadophytes from Portland were also described by Mansell-Pleydell (1878) and by Seward (1897). They are rarely found in situ today. The leaves of the Purbeck cycadophytes have never been recorded.

Details of the fossil forests and basal Purbeck strata were included in many other geological reports of the Dorset area, including those of Weston (1848), Forbes (1851), Fisher (1856) and Austen (1852). These records were based essentially on field descriptions, but the rock-types and thicknesses were accurately determined. The Lower Purbeck Beds were originally considered to represent a freshwater facies (Webster 1826, Fitton 1835). However, Forbes (1851), in his study of the organic remains, discovered the marine echinoid Hemicidaris purbeckensis in the Middle Purbeck Cinder Beds and postulated a more marine environment, as did Fisher (1956).

Detailed descriptions of the coastal sections were compiled by Bristow and Fisher (1857) and Bristow and Whittaker (1859). The Geological Survey memoirs of Woodward (1895) and Strahan (1898) provided thorough descriptions of the Purbeck Beds. Anderson contributed details of the westerly exposures of the Purbeck Beds in the Bridport and Yeovil memoir (Wilson et al. 1958). Arkell included the Purbeck Beds in his work on the Jurassic Geology of Great Britain (Arkell 1933) and of the world (Arkell 1956). His latest memoir (Arkell 1947) remains the standard reference to the stratigraphy of the Purbeck Beds in Dorset.

More recent work on the basal Purbeck plants includes that of Barker et al. (1975), who found fragmented plant remains in the Portesham Charophyte Chert. These included fusainised and silicified wood, small foliage fragments, seeds and charophytes. The Middle Purbeck charophytes were studied in great detail by Harris (1939) and by Reid and Groves (1916). Hughes (1975) briefly mentions the Purbeck flora in his study of the plant succession in the Wealden.

Palynological studies have contributed some information on the nature of the vegetation, but have been used mainly for stratigraphic purposes. Examples of the widespread Mesozoic pollen Classopollis Pflug were first illustrated by Erdtman in 1935 (in Erdtman 1956), originating from "a dirt bed, lowest part of the Middle Purbeck, Upper Jurassic, Swanage, Dorset". Couper (1958) obtained pollen from Purbeck limestones and shales for his study of Jurassic miospores and Lantz (1958) identified similar types which were used for stratigraphic sub-division and correlation. Extensive research by Norris (1963, 1969, 1970) produced the most detailed palynological data of the Purbeck Beds, though he was particularly interested in using his results for correlation of the Purbeck Beds in the Weald and Dorset and to locate the Jurassic/Cretaceous boundary.

The sedimentology and diagenesis of basal Purbeck sediments' evaporites in Dorset have been investigated in detail by West (1960, 1961, 1964, 1965, 1973, 1975, 1979), Salter and West (1965), West and Hooper (1969) and Shearman (1966). Pugh (1968) and Brown (1963, 1964) have studied the algal and pelletoid limestones adjacent to the basal Purbeck fossil forests.

CHAPTER 2

FIELD OBSERVATIONS AND PETROGRAPHY OF THE BASAL PURBECK LIMESTONES

2.1 Introduction

Selected exposures of basal Purbeck strata were studied in order to investigate the positions and lateral extent of the fossil soils (the Dirt Beds) and to record the location and preservation of fossil wood and organic material within these sediments. Although published sections already exist for many of the localities recorded here (West *et al.*1969c; Brown 1963; West 1975; Clements 1969) it was found that in most cases inadequate details were recorded, particularly concerning the location of fossil trees. Field and petrographic descriptions are recorded in Figures 2.03-2.12. The field sections at Portesham and at the Fossil Forest have already been recorded in great detail by West (1975, 1979b) and were not repeated. The petrographic classification of the sediments was modified after Folk (1959, 1962) and the particle sizes related to the Wentworth-Udden scale (Pettijohn 1975).

The Dirt Beds and their forests are interbedded with algal and pelletoid sediments of the Skull Cap, Hard Cap and Soft Cap which dominate the basal Purbeck sections. There is great lateral variation across Dorset which has been shown to some extent by West (1975) but is particularly apparent from the distribution of the fossil trees and the nature of the Dirt Beds. The eastern sections, near Durlston Head, are dominated by limestones containing replaced evaporites which have been studied in detail by West (1979b) (and previous references therein). Calcitised pseudomorphs after lenticular gypsum are common in these limestones and for brevity are henceforth referred to simply as gypsum pseudomorphs.

The fauna of the basal Purbeck Beds in Dorset is very limited. The gastropods have been studied by Arkell (1941) and Clements (1973), the ostracods by Jones (1885), Anderson (1939, 1941, 1966) and Clements (1973). Other descriptions are included in Geological Survey memoirs of Strahan (1898) and Arkell (1947). However in the course of this field study two types of faunal remains were discovered which have particularly interesting palaeoecological implications: the impression of a large dragonfly wing and the carapaces of fossil clam shrimps.

These are discussed further in 2.4.

The algal sediment which now forms the Hard and Soft Caps originally covered the forest trees which grew in the Lower and Great Dirt Beds respectively and although most of the trees are now absent, their original positions are still marked by the positions of 'tree-holes' in the Hard Cap and circular hollow burrs in the Soft Cap. Mapping of these features in the field enabled an estimate of the density of the forest to be made, particularly that of the Great Dirt Bed, and the spacing of the trees to be made. The distribution, dimensions and positions of the 'tree-holes', holes once occupied by tree branches, were recorded in order to understand their origin. These results are presented and discussed in 2.6.

2.2 The basal Purbeck limestones

2.2.i The Algal Limestones

The basal Purbeck Limestones are largely of algal origin, having been formed by the action of carbonate-secreting or sediment-binding algae. Two main types of algae and their structures have been described: the Porostromate microstructures consisting of preserved filamentous algal structures, and the Spongiostromate microstructures without recognisable organic structures but identified by their resulting sedimentary characteristics, such as pelletoidal and micritic laminae and fenestral fabrics (Monty 1981) (the 'skeletal' and 'non-skeletal' stromatolites of Riding, 1977).

Pugh (1968) described representative genera of the three main algal phyta forming the Porostromate microstructures in the basal Purbeck limestones (based on the classification of Pia (1927, now disputed). The genera Ortonella, Cayeuxia and Hedströemia ("green" algae) occur as nodules or crustose growth forms composed of branched filaments. All are similar morphologically but show different branching patterns: Ortonella has simple dichotomous branching, Cayeuxia branches at right angles and Hedströemia has groups of branches forming acute angles with each other. Ortonella is the most abundant genus and occurs as clear, branching filaments 30-70 μm in diameter with well-defined micritic walls and drusy calcite infill. The filaments occur in colonies of about 2 cm in diameter in a micrite matrix and appear as pustulose or nodular protruberences on weathered surfaces. Ortonella has been recorded from many localities at the base of the Hard Cap. The genus Cayeuxia occurs less frequently as smaller, rounded colonies (10 mm diameter) in the Hard Cap (at God Nore, Fig.2.03) and at Perryfield and St. Alban's Head (Pugh 1968). The much rarer "green" alga Hëdströemia with its multiple-forked branching filaments was found in the Hard Cap at Stair Hole (Pugh 1968) and the "red" alga Solenopora was recorded by Brown (1963) and Pugh (1968) from the Hard Cap at Worbarrow.

Most of the basal Purbeck Caps are composed of spongiostromata-type stromatolitic limestone, formed into large irregular mounds or layered algal mats. This type lacks any recognisable algal microstructures and has been classified according to the growth form (Logan et al. 1964; Hoffman 1976). Brown (1963) used that of Cloud (1942) and Pugh (1968) used that of Logan et al. (1964) to describe the geometric shapes of the Purbeck stromatolites. Most of the Hard Cap and Soft Cap consists of hemispherical mounds linked by flat-lying algal mat (Type LLH-S of Logan et al., 1964) (Pl. 2 , Fig. 7). The mounds themselves exhibit a coarse concentric banding texture. This is particularly prominent in the circular 'burrs' of the Soft Cap which surround petrified tree stumps (Pl. 1 , Figs. 4,5) and in the large mounds of the Hard Cap, encircling the 'tree-holes', now empty cavities which once contained tree branches (see 2.6). The circular burrs in the Soft Cap not only show concentric banding but also circular ridges, 10-20 cm wide, around the central cavity which appear to be the result of increased growth of algal colonies at these levels. Some circular burrs are completely closed at the top and the cause of doming is unknown, though one such burr in Independent Quarry (Portland) contained a short fossil tree stump and at the Fossil Forest a large boulder of limestone in the Great Dirt Bed caused the algal layers to dome over it (Pl. 5 , Fig.5). Between the areas of doming the same layers of algal limestone are horizontal.

In thin-section this type of algal limestone appears devoid of algal filaments and lamination but consists instead of patches of pelmicrite, pelsparite and micrite, often with a 'mottled' texture. Fish scales and ostracod debris are often incorporated in the large irregular voids between these patches. Some voids are infilled with drusy calcite but most are empty, giving the limestone a coarse, fenestral texture. Some voids contain geopetal infillings of pelletoid sediments (Pl. 2 , Fig. 1). Some micrite nodules with the filamentous algae do

Plate 2

The Algal Stromatolitic Limestones

1. Geopetal sediment infilling cavity in algal micrite within algal stromatolitic limestone of Hard Cap, Dungy Head (Bed E_1). Pelsparite fills the lower part of the cavity while sparry calcite fills the upper part. (Thin-section. PPL).

2. Ripple cross-lamination preserved in oolitic limestone at the top of the Hard Cap, Fossil Forest, near Lulworth.

3. Laminated algal mat of the Hard Cap, Worbarrow. The mats show a crinkled or nodular upper surface with pelletoid limestone draped over them.

4. The 'clotted', pelletoid sediment characteristic of the spongiostromata-type algal limestones. This sediment often grades into pelsparite, pelmicrite or mottled micrite (Soft Cap, Dungy Head, Bed G. Thin-section. PPL).

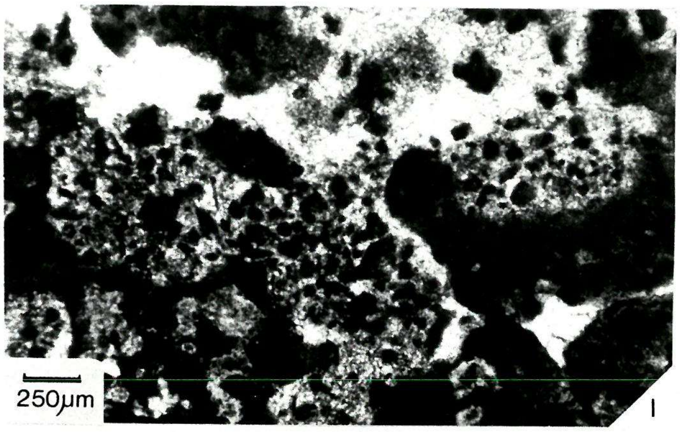
5. Dicotomously branching filaments of the alga *Ortonella* in the Hard Cap at Holworth House (Bed E). The filaments walls are composed of micrite and the centre infilled with drusy calcite. (Thin-section. PPL).

6. Laminae of algal filaments encrusting micrite/microspar nuclei (similar to the *Pycnostroma*-like nodules of Brown, 1963). Hard Cap, Bed C, God Nore, Portland.

7. Banded, algal stromatolitic limestone of the Soft Cap, Fossil Forest. This 'tufaceous' limestone domes up over boulders in the Great Dirt Bed (Plate 5, Fig. 5) and encircles silicified tree stumps (Plate 14, Fig. 3). Between domes the banding is horizontal.

8. Algal mat traversed by large polygonal dessication cracks at the top of the Hard Cap, Fossil Forest, Lulworth. Similar limestone became dessicated and fractured into clasts (or pebbles) which later became incorporated into the Great Dirt Bed palaeosol.

(Hammer handle length 27 cm)



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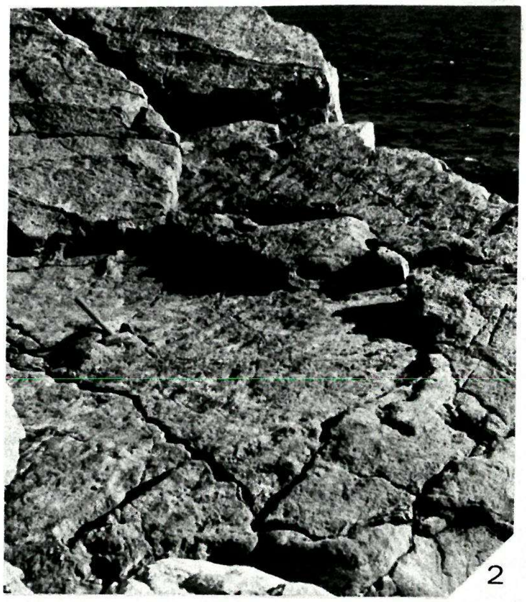

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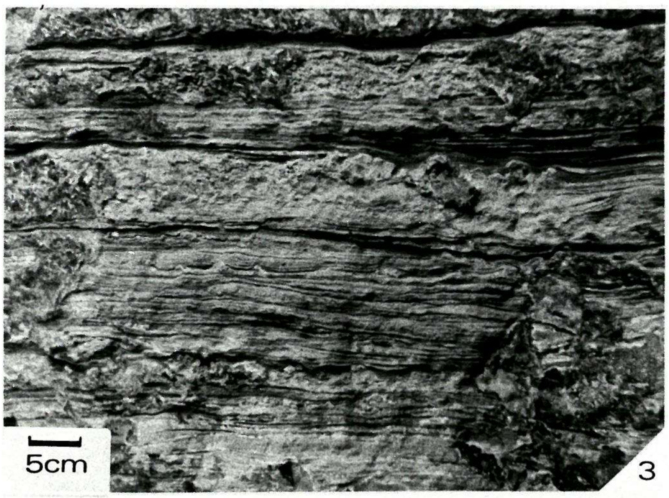

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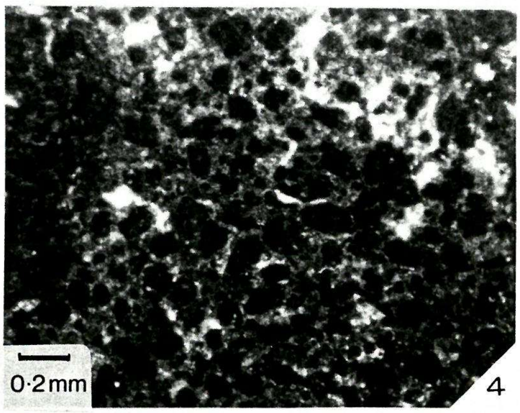

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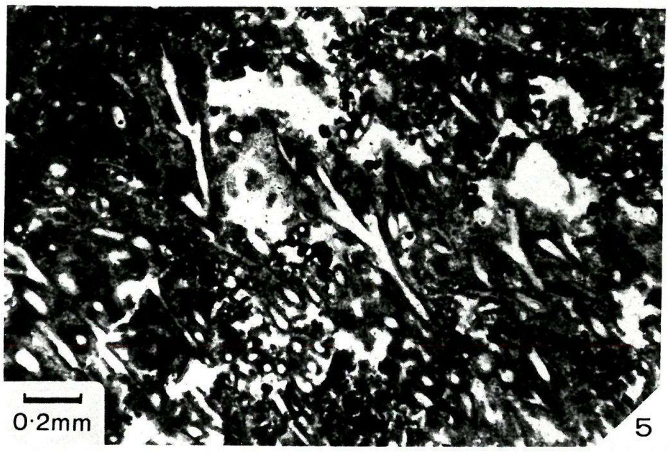

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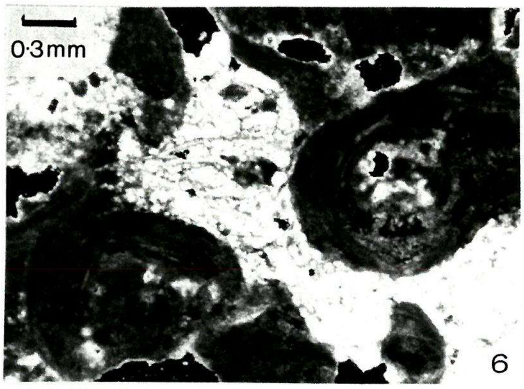

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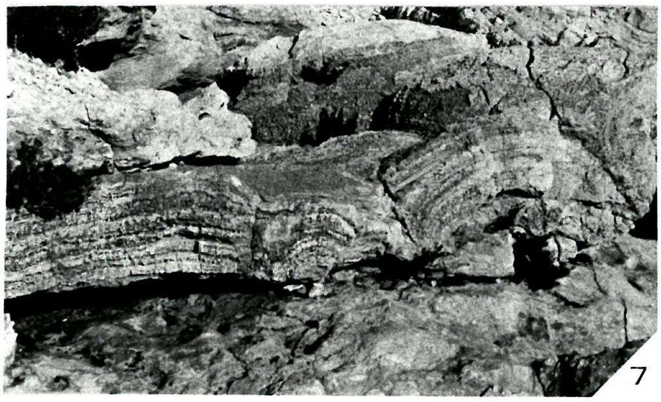

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8

PLATE 2

occur here as do other minor growth forms such as the Gymnosolen and Pycnostroma of Brown (1963) (botryoidal, laminated nodules) (Pl.2, Fig.6).

In contrast to the large mounds of coarse, fenestral algal stromatolite, some of the Hard Cap consists of finely laminated algal mat, particularly well-developed at Worbarrow (Fig.2.10) and Bacon Hole (Fig.2.09). Algal mat also occurs in the Soft Cap at God Nore. The algal laminae, 3-50 mm thick, have a nobbly pustular upper surface (Pl. 2 , Fig. 3) and a coarse texture. Laminae of softer, pelletoid sediments are draped over the surface. Often the laminae exhibit pronounced doming or slump structures. In thin-section the mats consist of inter-laminated pelmicrite and pelsparite layers, some of which are darkened by the inclusion of organic material. Calcitised gypsum pseudomorphs are also present.

Algal limestones with similar growth forms to those of the basal Purbeck occur today in Shark Bay, Western Australia (Hoffman 1976; Playford and Cockbain 1976), in the Coorong Lagoon and Spencer Gulf, South Australia (von der Borch 1976; von der Borch et al. 1977), in the Persian Gulf (Kendall and Skipwith 1968; Kinsman and Park 1976) and in the Great Salt Lake, Utah (Halley 1976) as well as many reports of Proterozoic stromatolites (Walter 1976; Monty 1981). In Shark Bay algal mats are most prominent in the intertidal zone but also extend to the lower supratidal and shallow sublittoral zones. Many different types of algal mat are found (Davies 1970), their distribution dependent upon the amount of desiccation (which obviously increases towards the shoreline), a suitable rate of sediment influx to maintain the mats but not rapid enough to bury the algae, cementation of the sediment and lack of erosion. The form of the stromatolites depends not only on the type of mat but also their position on the shoreline. On the rocky headlands of Shark Bay, where wave and tidal scour are strong, discrete columnar structures form (intertidal to sublittoral zones). They are formed of "colloform" mat (Hoffman 1976) which has a coarse fenestral fabric. The columns may have a relief of up to 1m and often coalesce to form bioherms. Both 'smooth' mat (with finer fenestrate fabric) and unlaminated 'pustular' mat, similar to that in the Purbeck mounds, form columnar structures on the rocky headlands. In the more sheltered bays these mats form shorter columns (0·5m) which tend to become elongate perpendicular to the shoreline (parallel to wave scour). In the protected embayments where wave action is negligible mats form continuous undifferentiated sheets with only minor relief. The supratidal zone may also contain dead and decaying stromatolites which have been stranded by a drop in sea-level (Playford and Cockbain 1976).

In comparison with these modern algal sediments the stromatolites which form most of the Hard Cap probably originated in the intertidal zone where they formed large, often coalescing, mounds. The actual relief of the mounds is hard to determine in the Hard Cap but in the Soft Cap the top of the burrs rises approximately 40-60 cm above the level of horizontal mat between. The algal stromatolites of the Caps do not form such well-defined columnar structures as those of the rocky headlands of Shark Bay but were probably more protected and wave energy not so great. As in Shark Bay (Hoffman 1976) the algal mats in the basal Purbeck were well-preserved because the high salinity deterred destructive, grazing and burrowing molluscs (Garrett 1970). The laminated algal mats at Worbarrow are indicative of the high intertidal or supratidal zone where wave action is very weak and where the mat is intermittently exposed to allow the formation of gypsum. The surface of the algal mat has a surface relief similar to that of the convoluted algal mats of Shark Bay (Davies 1970). At God Nore the relief of the algal mat is greater, suggesting upper intertidal origin.

2.2.ii The pelletoid limestones

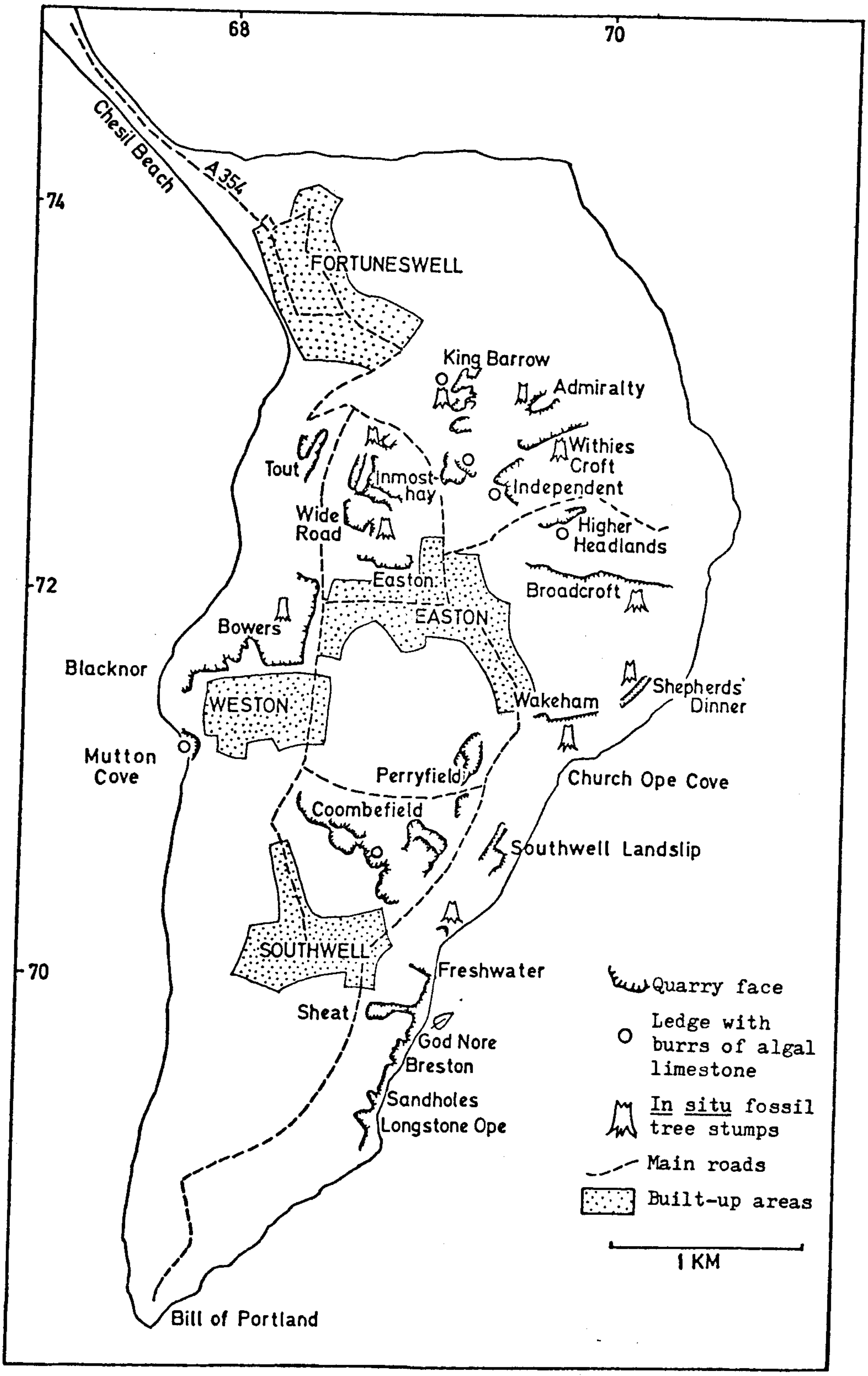
Pelletoid sediments are intimately associated with the algal limestones, either as components of algal mat laminae, as infills in voids between algal colonies or as finely laminated limestones draped over and between the algal mounds. The pellets are small rounded aggregates of microcrystalline calcite devoid of internal structure, and range in size from as small as 30 µm to over 200 µm when they would strictly be classified as intraclasts (Folk 1962). Many of the pelletoid sediments also have an intraclastic texture with micrite and algal micrite interclasts. Although House (1968) and Brown (1964) considered that some of the basal Purbeck Pellets were of faecal origin the wide size range and shape of most of those associated with the algal sediments suggest an inorganic origin. Micrite pellets have been reported to have formed by inorganic precipitation, cementation and recrystallization (Illing 1954; Beales 1965) and particularly from the breakdown of organic material (Wolf 1965).

The pellets and intraclasts occur in a matrix of sparite or micrite. In the algal mats these two types are interlaminated. The pelmicrite often has a very patchy, 'mottled' or 'clotted' texture which appears to have formed by the merging of adjacent pellets and obliteration of their boundaries. The 'clotted' texture resembles the 'structure grumeleuse' of Cayeux (1935) which consists of diffuse clots of micrite in a calcite matrix. The origin of this texture may be due to recrystallization of the micrite matrix to coarser spar leaving clots of original micrite or to the patchy recrystallization of spar to micrite (Cayeux 1935; Beales 1965; Bathurst 1971). Wolf (1965) considers the clotted texture to be of algal origin. The pelletoid sediments which drape between the algal mounds consist of pelmicrite and pelsparite with a high content of algal intraclasts (presumably having broken off from the stromatolite mounds) and many fish scales and ostracod carapaces. At the Fossil Forest these limestones (with ooliths) exhibit ripple-marks (Pl. 2 , Fig. 2) reminiscent of those in the sediment between algal mounds in Shark Bay (Logan et al. 1974).

Within the 'clotted' pelmicrite and algal micrite spherulites of pale brown radially-crystallized calcite occur either singly (about 200 μm in diameter), in patches or replacing all the micrite. The external surface of such beds is very hard and nodular. Filamentous algae do not appear to be present in the micrite clasts with these calcite spherules ('radial calcite') though they have been observed in adjacent clasts, contradictory to Brown (1963) who concluded that the two were mutually exclusive. Identical spherulites were described by Hudson (1970) from the algal limestones of the Great Estuarine Series of Skye and by Buchbinder (1981) in the Dead Sea stromatolites where they consist of microspherules of aragonite crystals.

The pelletoid-intraclastic limestones at the top of the Hard Cap in the Lulworth area contain scattered, oolitically-coated grains. They are predominantly superficial ooliths (Illing 1954), having as few as 1-3 coatings of radially-orientated calcite fibres. They range in size from 50 μm to 0•2 mm, the larger ones being composite and including several generations of oolitically-coated grains. The nuclei consist of pellets, aggregates of calcite spar, ostracods, shell fragments and gypsum pseudomorphs (both single grains and aggregates). The oolitic coats are often incomplete, resembling those formed in the quiet waters of Laguna Madre, Mexico (Rusnak 1960), and have 'perched' inclusions of

FIG.2.01 THE ISLE OF PORTLAND
showing location of quarries mentioned in the text.



micrite between successive layers. At the very top of the Hard Cap oolitically-coated clasts of over 2 mm in diameter (the 'pisolites' of Folk 1962) have concentric alternating laminae of fibrous calcite and micrite with inclusions of organic matter and resemble those associated with calcrete formation (Dunham 1969, Esteban 1976). Their environment of formation is much different from that of marine ooliths (shallow-water shoals) and is discussed in 3.5.ii.

2.3 Lithological Variation of the basal Purbeck Beds across Dorset

2.3.i The Skull Cap

The basal Purbeck beds overlie the Portland Stone without a sharp break but are recognisable in the field by the appearance of finely laminated limestone and the absence of the large marine bivalves characteristic of the Portland Stone. These beds, up to the Lower Dirt Bed, constitute the Skull Cap. The lower part, below the Basal Dirt Bed, is conspicuous in West Dorset and on Portland as fine, porcellaneous limestones with bands of external and internal moulds of small fossils. These beds consist of fossiliferous micrites, biopelmicrites and biopelsparites with ostracods, foraminifera, bivalves and turreted gastropods. This is the Basal Cast Bed of Arkell (1941) in which he identified the gastropods Valvata helicoides, Hydrobia chopardiana and H.forbesi. The ostracods have been identified by Clements (1973) as the saline-tolerant types Fabanella bolonensis, F.ansata and Macrodentina sp. The Basal Cast Bed is present from Portesham (West 1975) to Holworth House and on Portland, where it is less fossiliferous. In general the fossil content decreases upwards as the pelmicrite is replaced by pelsparite but at the top, below the Basal Dirt Bed, a mottled unfossiliferous micrite occurs.

In the Lulworth area the Lower Skull Cap consists of algal stromatolitic limestone of variable thicknesses. At Bacon Hole much of the algal micrite is replaced by radial calcite, giving a nodular, botryoidal exterior. Fish scales are abundant in these beds. At Dungy Head the whole Skull Cap is absent and the Lower Dirt Bed rests directly on Portland Stone. From Worbarrow Tout eastwards the equivalent horizon is indistinguishable since the Basal Dirt Bed is not apparent. West (1975) described a thin bed of laminated limestone with ostracods, foraminifera and gastropods fused to the Portland Stone (the Shrimp Bed) and a similar limestone is visible at Fisherman's Ledge.

The Basal Dirt Bed is a thin (2-5 cm) but fairly persistent bed of laminated or streaked clay, sometimes carbonaceous. It has a sharp top and base with no sign of a weathered profile in the limestone below. It can be traced from Portesham to Worbarrow (but is absent from Durdle Door to Lulworth) but is best developed on Portland where it consists of a top carbonaceous layer, a brown laminated centre and white marl at the base. Silicified wood has not been recorded from this bed and the only conspicuous plant remains are fragments of shiny black fusinite (fusain) in this bed at Bacon Hole.

The upper part of the Skull Cap consists almost everywhere of filamentous algal limestone. On Portland it attains a maximum thickness of about 1m and has a hard, irregular surface characteristic of this limestone. Micrite clasts with the algae Ortonella, Girvanella and Cayeuxia are well preserved at God Nore and Holworth House (Pl. 2 , Fig.5). Fish scales and ostracods are common and at Holworth House pieces of bone are trapped in the micrite. Calcitised gypsum pseudomorphs are found here. This horizon may correspond with Fisher's (1856) record of the fish Histionotus breviceps in a band below a 'dirt bed' at Ridegway. At God Nore a thin bed containing many fish scales amongst algal intraclasts overlies the algal mounds (Pl. 3 , Fig. 6). The upper part of the Skull Cap on the east Dorset cliffs consists of stromatolitic limestone with interlaminated micrite and pelmicrite, but at Bacon Hole and Worbarrow the laminae are slumped and brecciated. Laminae of well-preserved plant material and gypsum pseudomorphs are present.

2.3.ii The Lower Dirt Bed

The Lower Dirt Bed divides the Skull Cap from the Hard Cap and is the lowermost palaeosol which has yielded silicified conifer wood and Cycadophytes. It is a persistant though irregular horizon which can be traced from Portesham to Bacon Hole where it changes into an impersistent shale from Worbarrow to Durlston Head. On Portland it consists of a dark brown, calcareous marl with very thin discontinuous laminae of dark carbonaceous material. Small lenses or streaks (a few mm's long) of white micrite are present throughout. The upper part of the Dirt Bed is a black, carbonaceous layer with small particles of lignite and is particularly conspicuous on Portland, where at Freshwater Quarry (SY69017008) (Fig.2.01) the upper part is black in colour and consists of a large amount of dark, lignitic material.

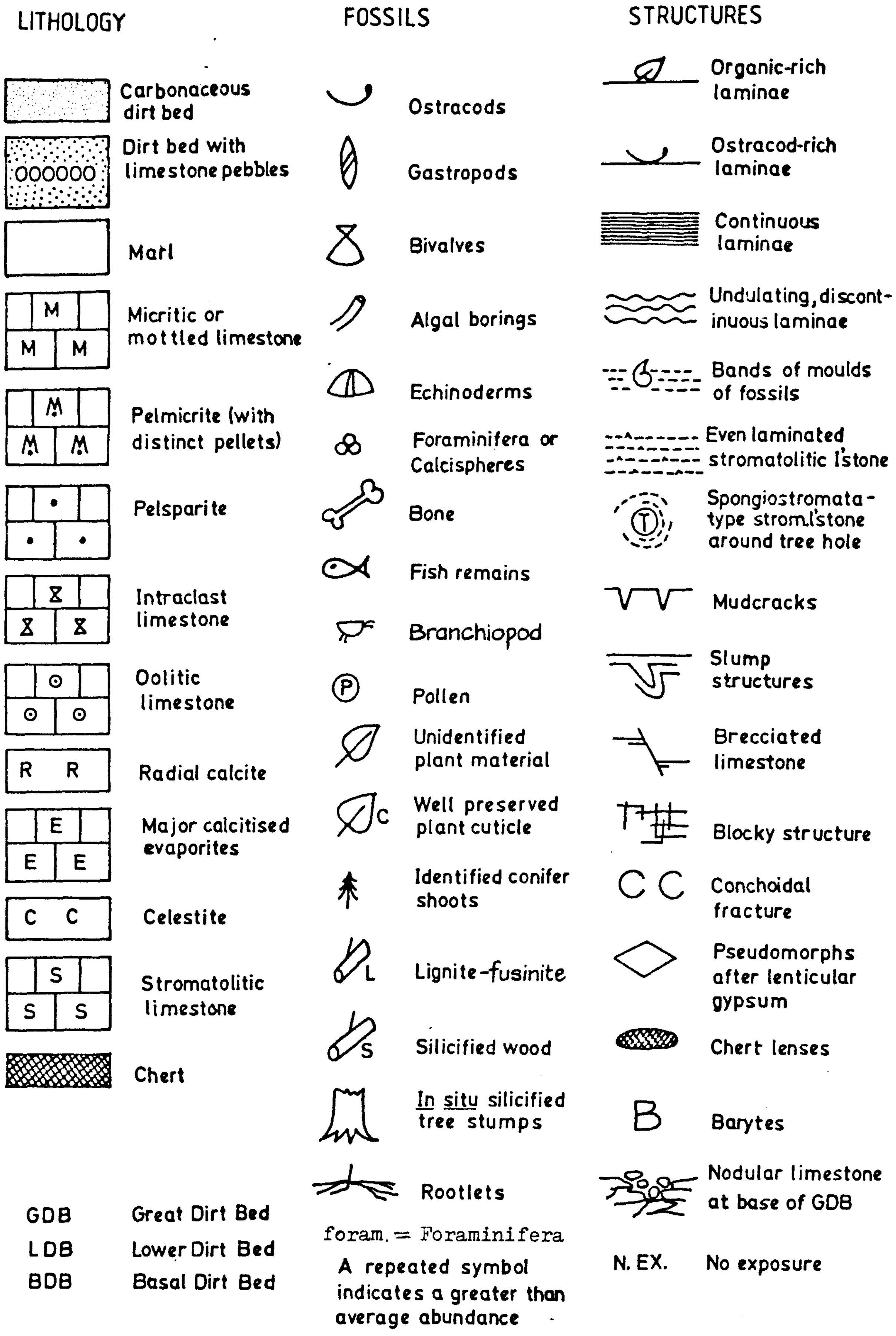


FIG. 2.02 Key to graphic logs.

Locality: GOD NORE QUARRY [Grid Ref: SY690697]

Bed	Field and petrographic description	Thickness
A	Basal Purbeck. Pale cream, porcellaneous limestone with discontinuous laminae exhibiting conchoidal fracture near the base. Lenses and veinlets of calcite near the upper part, fossiliferous pelsparite with unsorted micrite pellets (30-250 µm) in sparite matrix. Fossil content ($<$1%) of gastropods, foraminifera, bivalves and ostracods. Discontinuous laminae of micrite occur near the top.	50 cm
B	Top 1 cm dark brown/black carbonaceous marl with fragments of organic matter. Middle 1 cm light brown, well laminated shale. Basal 1 cm pale cream marl. Small streaks of white micrite throughout. (Basal Dirt Bed)	3 cm
C	Uneven bed of hard, brown, cavernous stromatolitic limestone with vague horizontal banding. Algal biolithite with algal filaments (<u>Cayeuxia</u> and <u>Ortonella</u>) in micrite matrix. Hollows infilled with pelsparite and micrite intraclasts. Fish scales (0·44 x 4 mm) common in the micrite. Bioclastic debris of broken ostracods caught in hollows, in pelsparite. Small spherules of silica replace algal micrite. Upper part of bed composed of intraclastic pelmicrite with intraclasts of algal micrite and pelsparite with fish scales.	33-90 cm
D	Discontinuous band of pale brown granular limestone with conspicuous fish scales, wedging out over stromatolitic mounds below. Intraclasts of algal micrite (extensively replaced by radial calcite) with fish scales orientated parallel to bedding. Large amount of ostracod debris in places. Patches of pelsparite. Plant fragments near top.	4 cm
E	Well laminated dark brown/black calcareous carbonaceous marl draped into hollows of bed below and thinning over mounds of stromatolite. Black lignitic material near the top, grading down to cream marl with lignitic rootlets. Discontinuous white micrite streaks throughout. (Lower Dirt Bed)	0-15 cm
F	Thin bed of soft, cream limestone of constant thickness. Micrite with undulating laminae and patches of pelsparite. Layers of mottled micrite with algal filaments. Scattered ostracods.	6 cm
G	Irregular mounds of hard, brown, porous, cavernous algal stromatolitic limestone, exhibiting horizontal or concentric banding (particularly around cavities left by fossil trees). Algal biolithite with mainly <u>Ortonella</u> filaments in micrite. Some algae binds sediment into circular coated nodules ($\simeq$ 1mm diameter) and undulating films on the edges of cavities. Cavities also have geopetal infills of fine pelmicrite. Much of micrite replaced by radial calcite and small (24 µm diameter) silica spherules. Some cavities filled by large calcite crystals (0·05-0·3 mm).	105 cm
H	Light brown, discontinuously laminated, granular hard limestone with bands of ostracods and brown barites crystals. Fossiliferous intrasparite with fish scales, gastropods, bivalves and many ostracods. Intraclasts of micrite containing crushed ostracods, pelmicrite partially replaced by radial calcite, algal micrite, pelsparite	20-30 cm

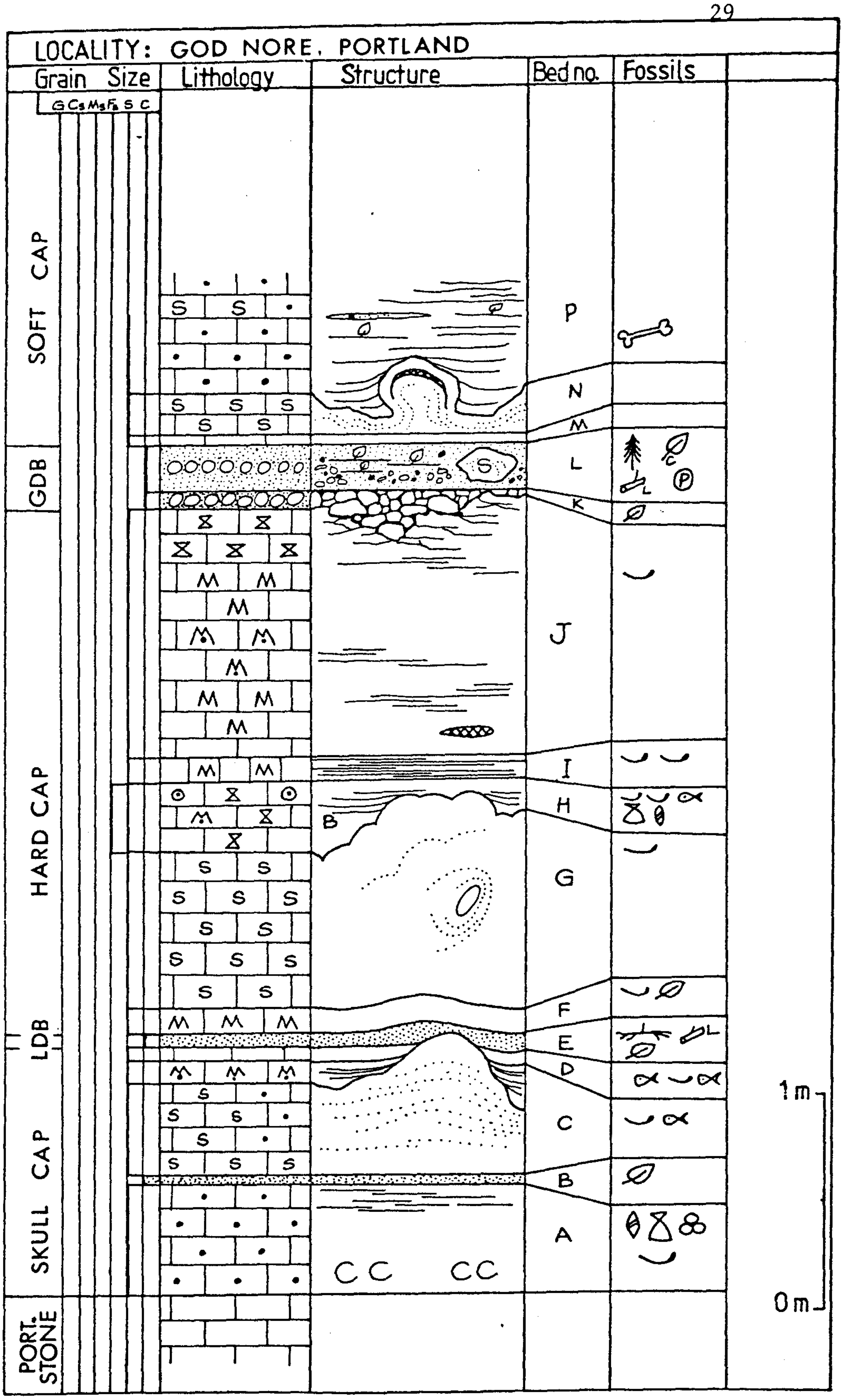


Fig. 2.03. Graphic log of basal Purbeck strata at God Nore quarry on the Isle of Portland.(For location see Fig. 1.01, for key to symbols see Fig.2.02)

God Nore (cont'd).

H contd.	with micrite rim, oolitically-coated composite ooliths. Many clasts, shells etc. have 1-2 oolitic layers which incorporate lot of micrite. Minor silicification of some bivalves or shells of ooliths. Some clasts have irregular coat of algal-bound sediment. Matrix of sparite with barites cement in part (fine sand-sized crystals).	
I	Finely laminated, cream shaly limestone. Biopelmicrite with ostracod debris in pelmicrite or clotted micrite. Patchy replacement of micrite by radial calcite. Few quartz grains (coarse silt sized). Scattered flecks of black organic matter on laminae.	12 cm
J	Basal part of this bed is pale cream, laminated limestone. Sparse biomicrite with few ostracods in a patchy mottled micrite, grading into clear pelmicrite. Upper part becomes nodular and rubbly, without lamination but mottled. Intramicrite. Many irregular intraclasts of dark brown micrite and oomicrite (up to 16 mm long) with smaller round clasts inside them. Large clasts of mottled micrite/pelmicrite. Enveloping matrix of very fine brown mottle micrite (not pelletoid) containing scattered organic matter. Matrix cut by many small veins (0·18 mm wide) filled with banded fibrous calcite.	115 cm
K	Black and white limestone pebbles cemented together, infilling hollows and fissures at top of Hard Cap. The white pebbles appear to be naturally weathered from the limestone at the top of J. Eroded horizontal top. Thin matrix of carbonaceous black marl.	5-20 cm
L	Fairly well laminated light brown, pebbly micrite with horizontal black carbonaceous layers. Contains large boulders (up to 20 cm) of stromatolitic limestone and black and white limestone pebbles ranging from 3-4 cm to pellet-size clasts. These clasts are embedded in fine micrite/microspar matrix, with pollen, megaspores and bone. (Thin section details discussed in later section.) Carbonaceous layers contain identified conifer shoots. (Great Dirt Bed)	20 cm
M	Cream coloured, soft, laminated limestone directly overlying Bed L. Mottled pelmicrite with flecks of organic matter. Impersistent lenses of fine silt-sized calcite grains and scattered fine silt-sized quartz.	5 cm
N	Hard, cavernous stromatolitic limestone with undulating bands and circular domes. The concentric banding in the domes has concentric cavities infilled with chert. Interlaminar pelmicrite and pelsparite with algal micrite patches.	10-20 cm
P	Cream, soft, finely laminated limestone draping over domes and infilling hollows of N. Much organic matter as flecks on laminae. Pelsparite with alternating thin laminae of mottled micrite. Conspicuous bone fragments which clearly exhibit haversian canal systems.	40 cm^{+}

Locality: UPWEY QUARRY [Grid Ref: SY671851]

Bed	Field and petrographic description	Thickness
PS	Portland Stone. Hard, massive cream limestone. No laminations. Thick-walled bivalve debris conspicuous. Intrabiomicrite with micritic intraclasts and bivalve fragments.	-
A	Basal Purbeck junction marked by appearance of finely laminated cream limestone but fused to Portland Stone. Layers of hollow moulds of ostracods, gastropods and bivalves. Biomicrite with sparse ostracods, turreted gastropods and small bivalves in mottled micritic matrix.	31 cm
B	Thin brown clay with white streaks of pure micrite. Slightly carbonaceous. Small chert nodules at base. (Basal Dirt Bed)	2 cm
C	Pale brown, cream granular soft limestone with tufaceous appearance. Micrite and pelmicrite replaced by brown radial calcite. Voids partially infilled with fine silt sized sparite. Abundant fish scales.	2-14 cm
D	2 cm white marl at base. 3 cm dark brown/black carbonaceous marl on top. Covered by thin lamina of micrite with chert nodules and fish scales. (Lower Dirt Bed)	5 cm
E	Massive, rough, hard, cavernous, pale brown algal stromatolitic limestone. Algal filaments in micrite with void infillings of pelmicrite.	140 cm
F	Finely laminated, pale brown soft limestone draping over top of stromatolites. Clotted micrite formed of very diffuse pellets with algal intraclasts. Rare pseudomorphs after lenticular gypsum. Patches of sand-sized sparite. Overlain by thinly laminated cream pelmicrite with dispersed organic material and scattered fine sand-sized sparite grains	50 cm
G	Soft, dark brown marl with white streaks of micrite and fine layers of carbonaceous material. Abundant chert nodules (average size 5x3 cm) with silicified pseudomorphs after gypsum and silicified wood. Pollen and plant material well preserved in chert. (Great Dirt Bed). (Poorly exposed)	8 cm^{+}
H	Finely laminated, soft cream limestone with flecks of organic matter. Interlaminar pelmicrite and micrite bands appear craked and infilled with pelmicrite. - unexposed ≈ 30 cm.	40 cm^{+}
I	Pale cream, blocky limestone. Intrapelmicrite with some algal clasts. Scattered ostracods and calcitised psuedomorphs after gypsum.	20 cm^{+}

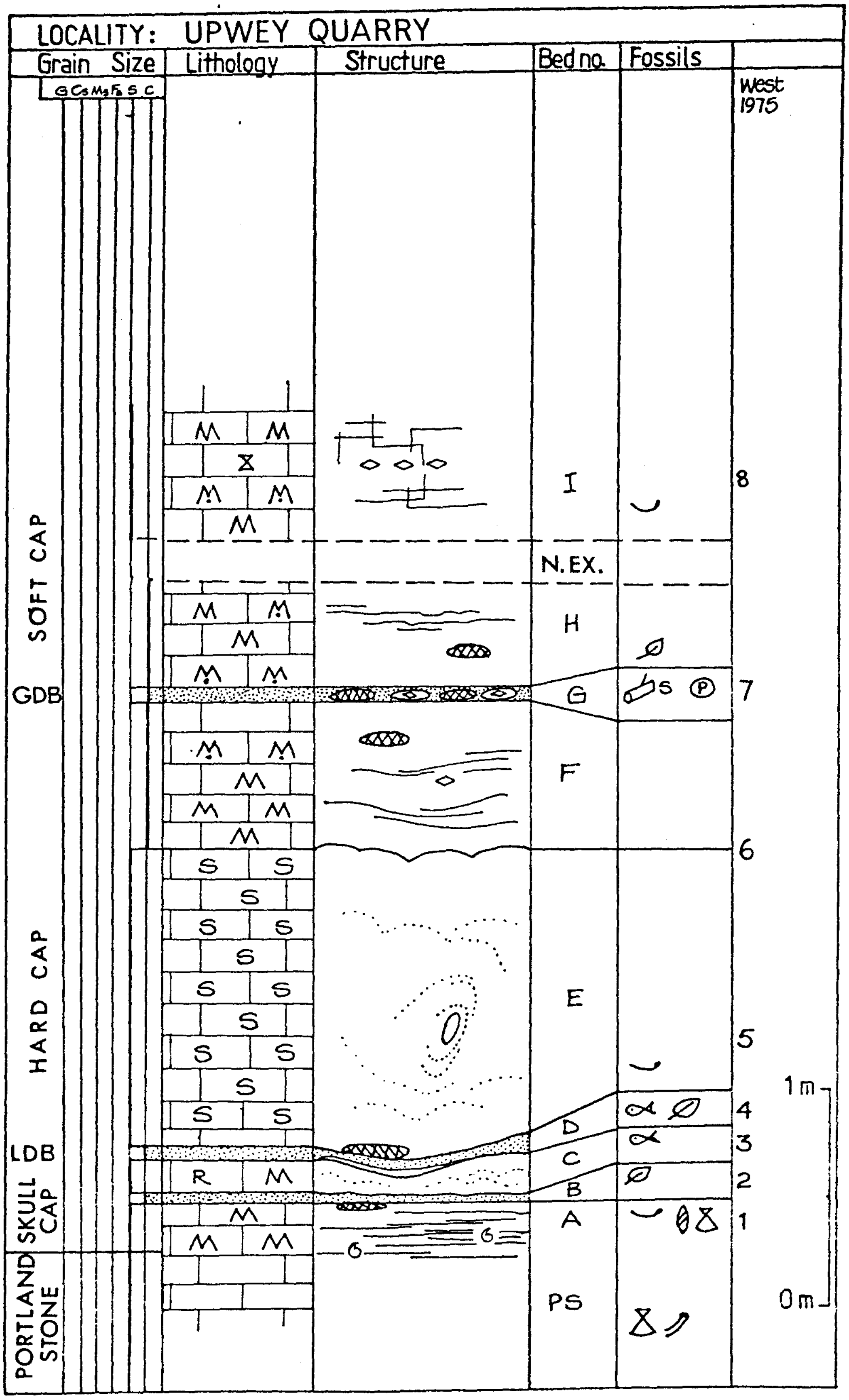


Fig. 2.04. Graphic log of basal Purbeck strata at Upwey(inland quarry).For location see Fig. 1.01,for key see Fig. 2.02.

Locality: CHALBURY CAMP [Grid Ref: SY693838]

Bed	Field and petrographic description	Thickness
A	Portland Stone. Biomicrite with large thick-walled bivalves and echinoderm debris. Margin of bivalve shells bored by algae (30μ diameter borings). Small % fine sand-sized quartz grains.	-
B	Light grey/brown porcellaneous limestone with thin calcite veins and 2-3 cm bands of fossil moulds. Biomicrite containing ostracods, bivalves, forams, and turreted gastropods. Faint pellet outlines in micrite.	28 cm
C	Slightly coarser-grained limestone with fewer moulds. Mottled patchy pelmicrite/pelsparite. (Average size of pellets 50μ). Scattered ostracod valves.	9 cm
D	Soft, cream marly limestone with very fine, discontinuous laminae. Mottled micrite. No fossils.	10 cm
E	Finely laminated sticky brown clay, becoming darker towards the top. No conspicuous carbonaceous material. Small streaks of white micrite. (Basal Dirt Bed)	3-4 cm
F	Rough, granular stromatolitic limestone with tufaceous appearance. Algal filaments in micrite with pelmicrite between. (Pellets 0·1-0·2mm diameter). Pelmicrite replaced extensively by radial calcite.	40-50 cm
G	Brown laminated carbonaceous, calcareous clay grading to black, highly carbonaceous clay at top. Infills hollows in limestone below. Streaks of white micrite at the base. Supports *in situ* silicified tree and silicified roots. Lignitic rootlets also. (Lower Dirt Bed)	2-10 cm
H	Thinly bedded, soft granular limestone infilling hollows in clay below; not continuous. Algal biolithite - algal filaments in micrite. Pelmicrite infills hollows and contains crushed ostracods. Conspicuous abundant fish scales (up to 6 mm long) and bone fragments exhibiting clear internal structure.	6 cm
I	Large domes of hard, cavernous, brown algal stromatolitic limestone. Algal colonies of *Ortonella* and *Cayeuxia* in micrite with clotted pelmicrite between. Large voids infilled with fine sand-size sparite. Fish scales abundant.	48 cm
I_2	Very porous, granular limestone with botryoidal surface partially infilling empty tree hole. Silicified intraclasts and fossils in sparite matrix exhibiting geopetal infills and meniscus cement textures. Silicified fossils include conifer wood (Protopinaceous), whole bivalves, ostracods, gastropods (*Valvata* sp. and *Hydrobia* sp.), fish scales and bone (phosphate). Also irregular chert clasts containing pyrite cubes and intraclasts of micrite and algal micrite. Micrite replaced by radial calcite shows botryoidal type coatings of voids and outer surface. Upper coating of algal biolithite to whole deposit.	-
J	Finely laminated pale brown/cream limestone draped over and between stromatolitic mounds. Mainly clotted micrite with some algal colonies. Many undulating layers of crushed ostracods. Fine silt sized sparite infills voids and shells. Conspicuous fish scales and bones.	34-48 cm
K	Thin, harder band of granular stromatolitic limestone. Micrite altered to radial calcite. Many fish scales.	3-6 cm
L	Similar to J.	10 cm
M	Massive, light brown/orange/grey mottled pelsparite and micrite intraclasts. Large voids filled with sparite, particularly cracks in micrite bands. Patches of fine silt sized sparite. Calcitised pseudomorphs after gypsum occur in micrite clasts.	51 cm

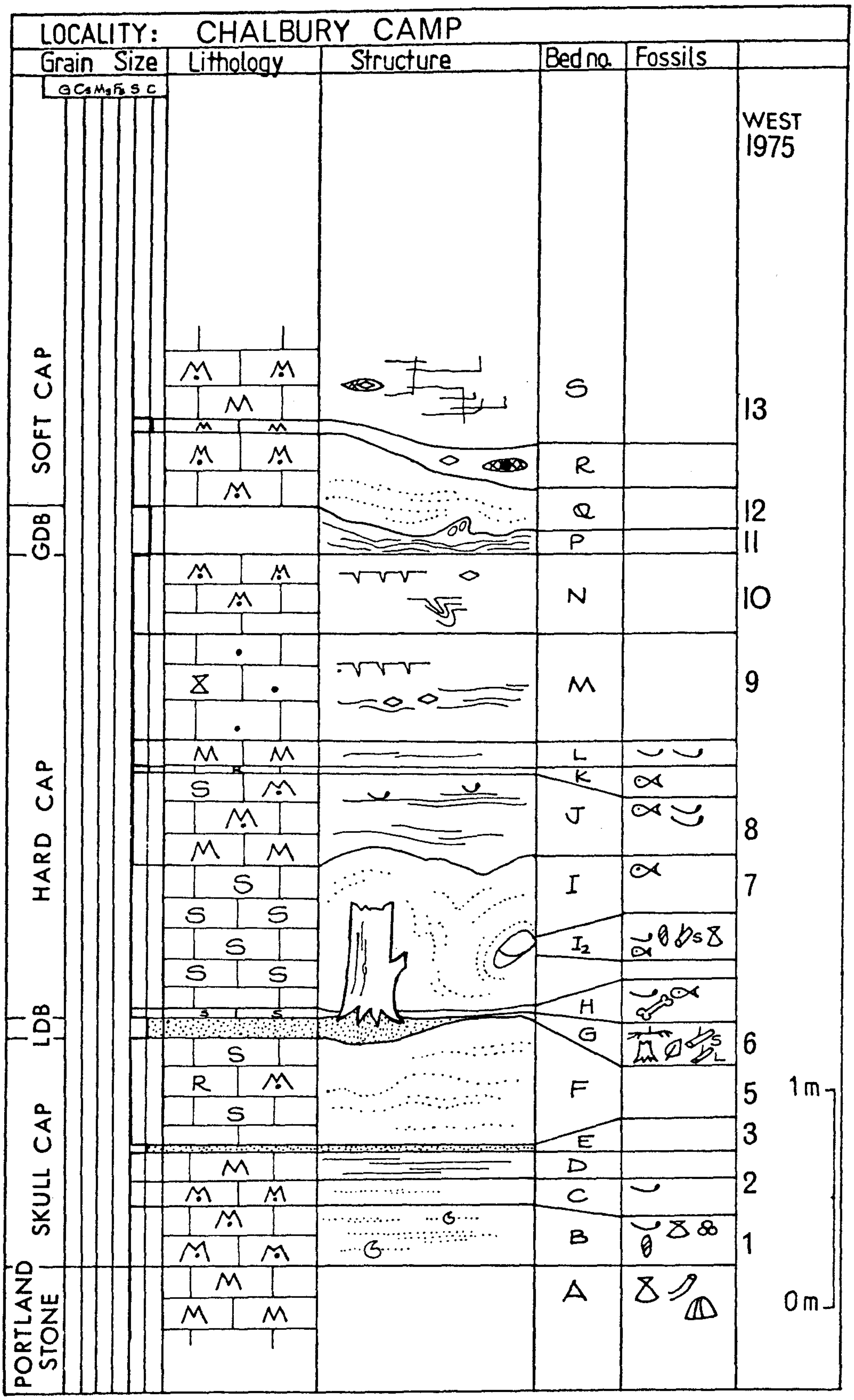


Fig. 2.05. Graphic log of basal Purbeck strata at Chalbury Camp, inland quarry. (For location see Fig.1.01, for key to symbols see Fig.2.02).

Chalbury Camp (cont'd).

N	Fine soft, ·grey limestone with much slumping of faint wavy laminae. Intrapelmicrite with micrite intraclasts, sometimes in pelsparite. Bands of pelmicrite exhibit fracturing and slumping and contain pseudomorphs after gypsum.	34 cm
P	13 cm brown/grey marl at base, overlain by 7 cm orange and white streaked clay and covered with 5 cm brown clay and white marl at top, with nodules of pure carbonate. No fossils or carbonaceous material. (Great Dirt Bed?)	10-25 cm
Q	Irregular bed of porous, granular stromatolitic limestone, evenly laminated. Pelmicrite only. (Pellets 36-66 µm)	29 cm
R	Discontinuous orange/brown porcellaneous limestone infilling hollows of Bed Q. Finely laminated mottled micrite with yellow streaks and darker micrite intraclasts. Incorporates lensoid chert clasts with pyrite. Ostracod and bivalves also silicified and containing pyrite cubes. Scattered calcitised gypsum pseudomorphs and lenses of fine silt sized sparite.	8 cm
S	Fine grey, blocky limestone with chert nodules contained relics of evaporites. Unfossiliferous micrite with sparce blackened pelmicrite intraclasts.	45 cm$^+$

Locality: POXWELL [Grid Ref: SY744836]

Bed	Field and petrographic description	Thickness
A	Portland Stone. Massive, light brown biomicrite with large thick-walled bivalves, echinoderm fragments and ostracods. Fungal borings in bivalve shells and micrite intraclasts. Rare bivalves and gastropods as empty moulds. Chambered forams (250μm diam.).	-
B	Light brown, brittle, laminated limestone with 2 cm wide bands of external and internal moulds of turreted gastropods, bivalves and ostracods. Biopelmicrite with empty moulds or some infilled with micrite pellets. Forams present. Black bituminous matter inside some moulds. Matrix of patchy micrite and pelsparite. (Basal Cast Bed)	13 cm
C	Similar to B but much coarser, granular texture and fewer moulds. Biopelsparite with few micrite intraclasts. Micrite replaced by brown radial calcite.	15 cm
D	Soft, buff-coloured marly limestone with small lenses of fine sand sized sparite. Clotted micrite with algal intraclasts. Scattered ostracods.	8 cm
E	Well laminated black/brown/cream clay with carbonaceous laminae at top. Interbedded with fine, discontinuous white laminae of fine grained sparite. Chert nodules in white clay. Sparse ostracods. (Basal Dirt Bed)	2 cm
F	Massive, rough, porous and cavernous cream stromatolitic limestone. Conspicuous plant material and carbonaceous streaks near top. Micrite replaced by radial calcite obliterating algal filaments. Pelsparite (pellets 60-500 μm) infilling voids. Scattered ostracod shells.	35 cm
G	Dark brown/black carbonaceous, calcareous clay, infilling hollows in limestone below. Layer of black, highly carbonaceous clay on top. Streaked throughout with black organic matter and soft white micrite intraclasts. Ostracods scattered throughout. White chert lenses above and below the clay and silicified wood embedded in centre clay. Large silicified tree rooted <u>in situ</u>. (Lower Dirt Bed)	1-6 cm
H	Large mounds of hard, porous, cavernous brown stromatolitic limestone. Biolithite with algal filaments (<u>Ortonella</u>) in micrite, and cavities filled with sparite and include ostracods.	136 cm
I	Cream, laminated limestone draped over stromatolite mounds. Mottled pelmicrite with moulds of ostracods and algal intraclasts.	36 cm
J	Pale grey limestone with undulating laminae. Interlaminated micrite and pelsparite with algal and micritic intraclasts. Micrite layers contain calcitised pseudomorphs after gypsum (av.size 100μ) orientated with C-axis parallel to bedding. Large cracks in micrite bands infilled with sparite and pelsparite.	40 cm
K	Light brown, soft, marl (not carbonaceous) [overgrown].	3-4 cm
L	Fine-grained grey limestone, unlaminated with ostracod moulds. Micrite, mostly replaced by microspar, with abundant ostracods and some pseudomorphs after gypsum. Brecciated zones infilled with sparite.	41 cm
M	(overgrown). Brown/black calcareous marl, slightly carbonaceous.	15-20 cm
N	Light cream, thinly bedded, finely laminated limestone. Interlaminated pelmicrite and pelsparite with micrite intraclasts. No fossils.	20 cm^{+}

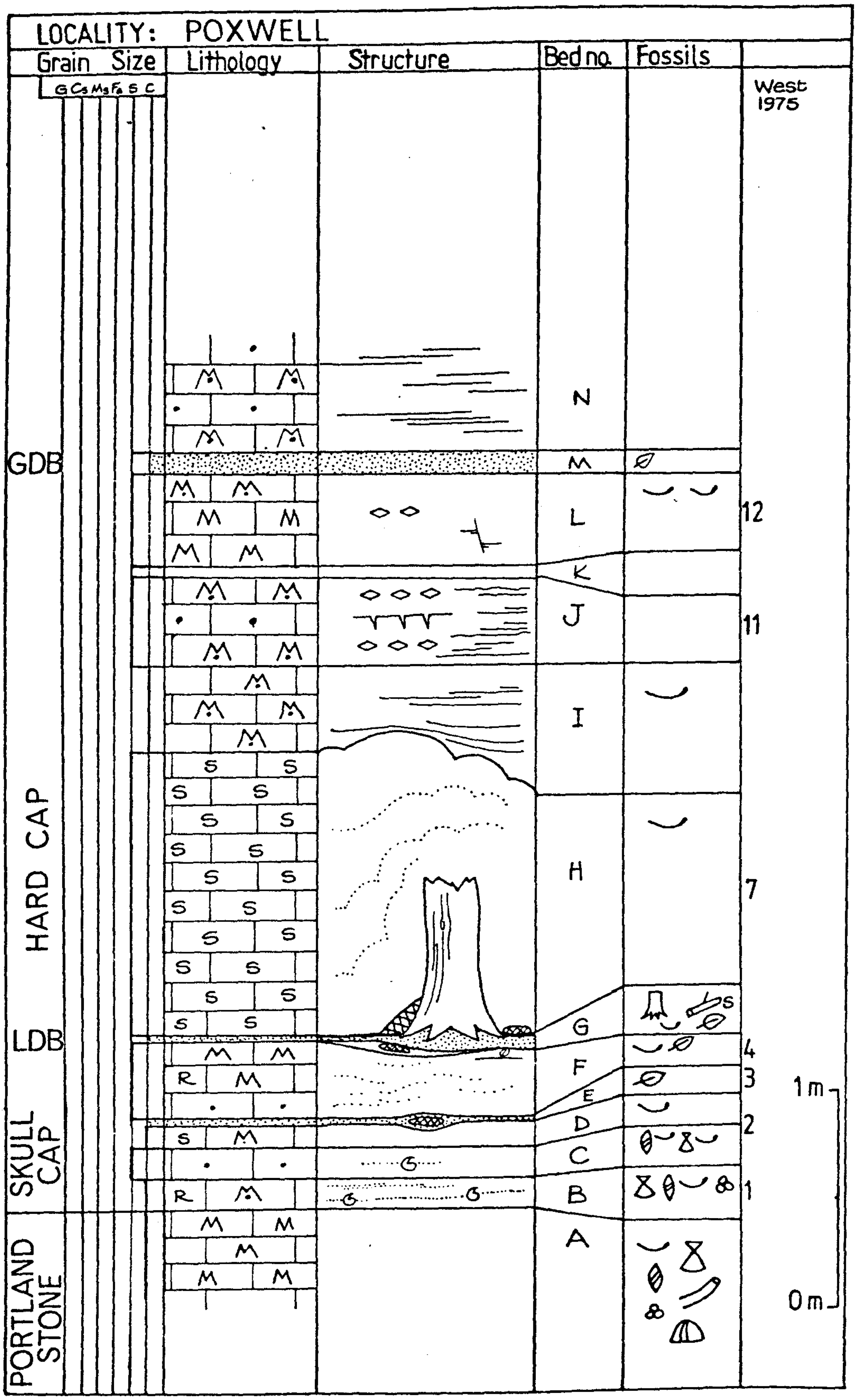


Fig.2.06. Graphic log of basal Purbeck strata at Poxwell Quarry (inland quarry). For location see Fig.1.01, for key to symbols see Fig. 2.02.

Locality: HOLWORTH HOUSE [Grid Ref: SY762816]

Bed	Field and petrographic description	Thickness
A	Portland Stone. Massive, light brown limestone with conspicuous large bivalves. Biomicrite/biopelmicrite with large, thick-walled bivalve fragments, often bored by fungi and partially replaced by chert. Echinoderm fragments common. Upper part oosparite. Ooliths (average diameter 0·3 mm) with up to 4 concentric coats, incorporating micrite and calcite silt. Nuclei of angular quartz grains, micrite pellets and shell fragments.	-
B	Basal Purbeck. Dark, fine-grained limestone with bands of internal and external fossil moulds. Interlaminar biopelmicrite and clotted biomicrite with gastropods, bivalves, forams and ostracods. Pellets of micrite range 0·03 to 0·12 mm diameter. Scattered oolitically-coated shell fragments and few grains of fine sand-sized quartz.	25 cm
C	As bed B but coarser grained (mainly biopelsparite) and with fewer fossils.	10 cm
D	Dark brown, laminated marl with rare white streaks of micrite. Sparse black streaks of carbonaceous matter. (Basal Dirt Bed).	2 cm
E	Cream/light brown, porous, cavernous algal stromatolitic limestone. Lower part hard and brittle but upper part softer and granular. Clear algal filaments (*Cayeuxia* and *Ortonella*) in micrite with pelmicrite infilling spaces between. Some pseudomorphs after lenticular gypsum and bone fragments.	110 cm
F	Top 2 cm of black carbonaceous marl with fusain and plant material. Small white clasts of micrite incorporated. Grades down to cream marl with black rootlets; the junction being mottled with black and white marl. Grades down into algal biolithite at the base. (Lower Dirt Bed)	3-4 cm
G	White, thinly laminated soft limestone of clotted micrite and very rare organic matter.	6 cm
H	Massive, mid-brown limestone with no laminations, just mottled appearance. Mainly mottled micrite with patches of pelmicrite and pelsparite. No fossils. Some micrite patches show vague algal filaments and contain pseudomorphs after gypsum. Small quartz veins (30 μ wide) occur and scattered fine sand-sized quartz grains. Micrite laminae at top containing oolitically coated pellets.	120 cm
I	Conspicuous, dark grey limestone with 'blocky' appearance. Unlaminated. Intramicrite grading to intrasparite in places. Intraclasts of large angular micrite lumps (up to 2 mm diameter), small ostracod fragments, pseudomorphs after gypsum in micrite. Large blackened clasts (3-5 mm diameter) of pelmicrite containing pseudomorphs after gypsum incorporated. Patches of very fine silt-sized calcite and some coarse sand-sized calcite crystals bored by fungal hyphae (3μ diameter). Small pieces of bone (including a vertebra, 150μ wide) and pollen (including the conifer pollen *Cerebropollenites mesozoicus*, 30μ diameter).	50 cm
J	Dark grey/black clay, poorly laminated. Very slightly carbonaceous with identifiable conifer shoots.	2-7 cm
K	Very soft, finely laminated cream/light brown/orange limestone, exhibiting fine algal mat textures. Much slumping and brecciation. Mottled micrite/pelmicrite with scattered oolitically coated pellets.	162 cm
L	Dark clay band, faintly laminated with small micritic patches. No carbonaceous material.	5-7 cm
M	Pale brown, soft, finely laminated limestone. Much slumping. Incorporates stromatolitic bands and layer of chert nodules. Intramicrite - irregular micrite clasts. No fossils but scattered organic material and fine sand-sized calcite crystals.	70 cm

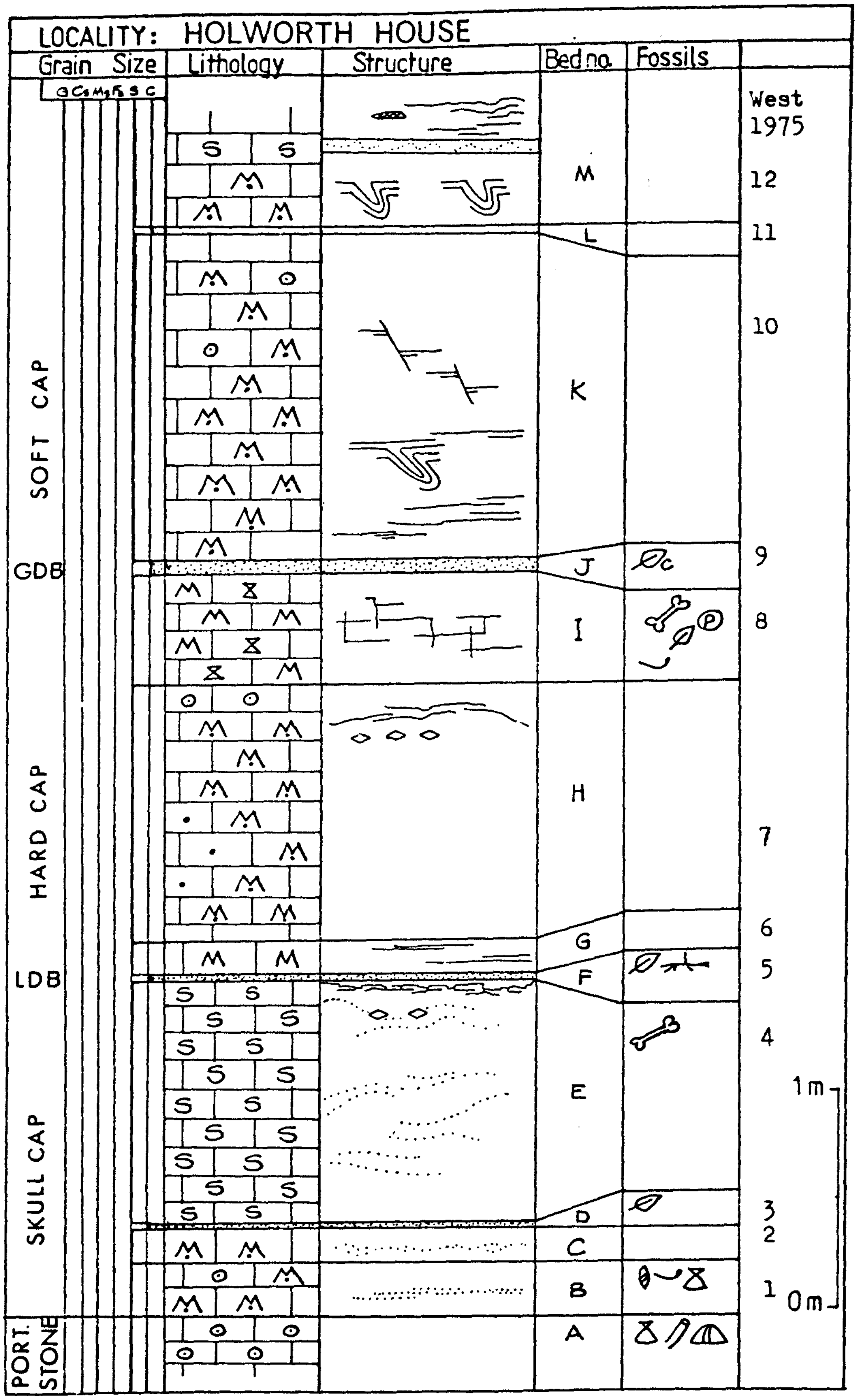


Fig.2.07. Graphic log of basal Purbeck strata at Holworth House(cliff section).(for location see Fig.1.01, for key to symbols see Fig.2.02).

Locality: DUNGY HEAD [Grid Ref: SY815800]

Bed	Field and petrographic description	Thickness
PS	Portland Stone. Cream massive limestone affected by faulting and folding. Oosparite with large bivalves.	-
A	2 cm black carbonaceous marl at top with lignitic bands, grading down to dark brown/mid-brown well laminated marl with lenses of pale micrite. Rootlets in lower horizons. Drapes over hummocks on top of underlying Portland Stone and infills deep hollows. (Lower Dirt Bed)	4-12 cm
B	Soft, white, finely laminated limestone. Micrite. No fossils.	4 cm
C	Cream coloured, shaly limestone, partly granular with discontinuous laminae. Algal mat lamination with pelmicrite and some algal filaments in micrite clasts. Fish scales.	2 cm
D	Hard, cavernous, porous brown stromatolitic limestone. Algal biolithite with algal filaments (primarily <u>Ortonella</u>) in micrite matrix. Surrounding sediment of pelsparite, particularly as geopetal infills of voids. Micrite intraclasts 0·03 to 0·1 mm diameter, often with replacement by radial calcite. Some voids filled with drusy calcite. Few ostracods.	110 cm
E	Pale brown/cream, irregular limestone. Micrite pellets (av. size 20 μm) and intraclasts (irregular shapes up to 3 mm) in sparite matrix. Unlaminated. Scattered ooliths. Mainly consisting of groups of calcite pseudomorphs after gypsum within micrite intraclasts which have 1-2 oolitic layers. Some single pseudomorphs have oolitic coatings, as do ostracod carapaces and micrite pellets.	152 cm
E_1	Top 10-20 cm of E_1 is rubbly and nodular mid-brown limestone; grading up from E but more weathered. Intraclastic oomicrite. Very irregular and varied composition in the patches of mottled pelmicrite, patches of algal micrite intraclasts, and scattered ooliths. Ooliths have nuclei of pellets and pseudomorphs after gypsum with 2-3 oolitic layers. Many composite ooliths (average 0·1 - 0·2 mm diameter).	10-20 cm
F	Black carbonaceous, calcareous marl with dark black plant (lignitic)-rich laminae. No other laminations. Grades down to rubbly limestone at base. Incorporates round blackened limestone pebbles and flatter, platy white limestone pebbles, some with cupped upper surface. White pebbles grade down into weathered limestone below. (Great Dirt Bed)	10-30 cm
G	Pale cream, soft limestone with irregular orange algal mat-type laminae. Wedges of thicker, harder limestone. Interlaminated pelmicrite/micrite and pelsparite layers with undulatory borders. Pellets round and fairly well sorted (40-200 μm diameters). No fossils.	43 cm
H	Dark blue/grey chert band with sharp upper and lower borders. Contains silicified evaporites.	15 cm
I	Prominent bed of pale cream limestone. Pelsparite with some micrite intraclasts. Some blackened micrite intraclasts. <u>Many</u> calcitised pseudomorphs after lenticular gypsum, mainly orientated parallel to each other; size range 0·06 – 1·4 mm. Spherulitic silica replaces centres of larger pseudomorphs.	20 cm

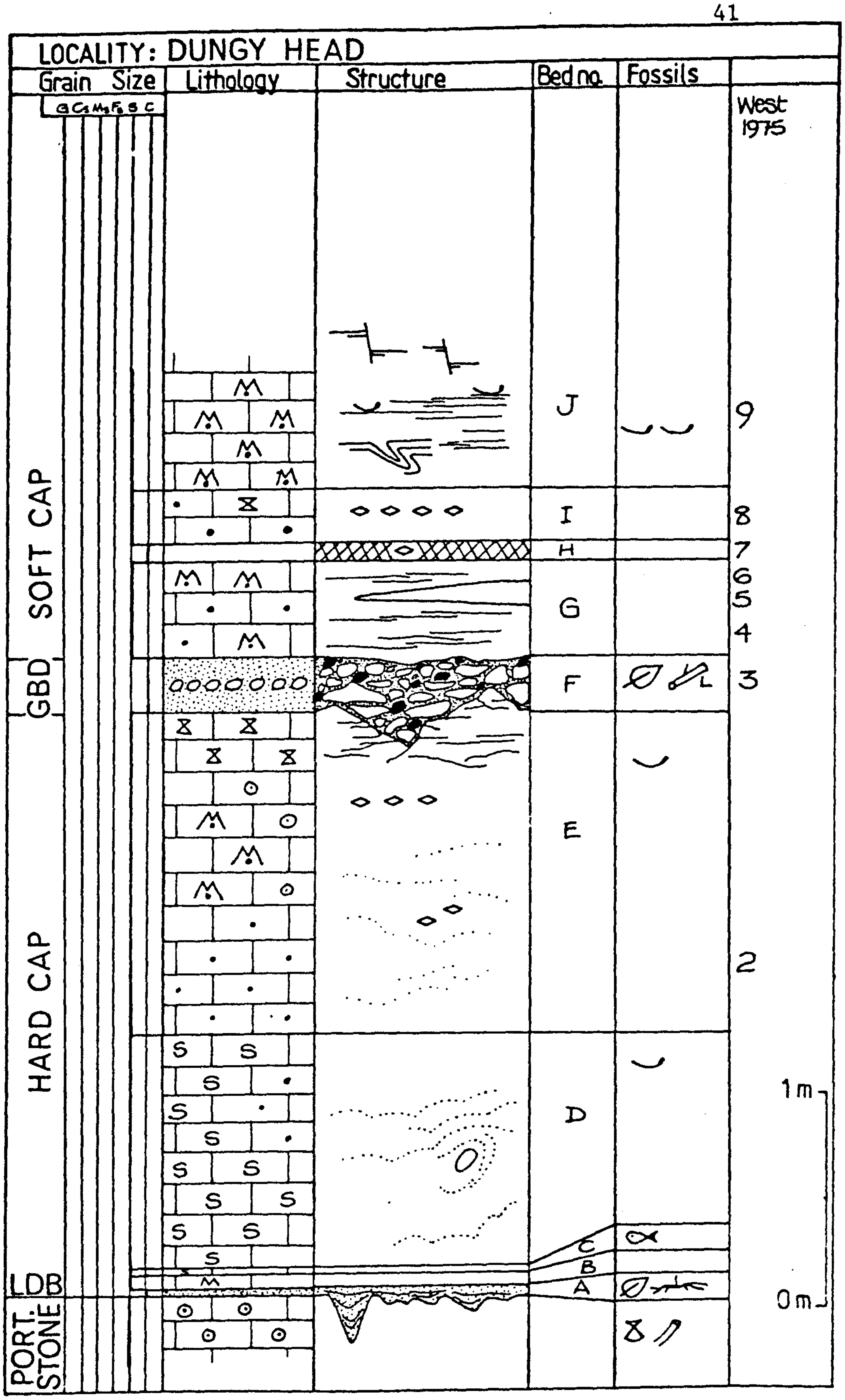


Fig. 2.08. Graphic log of basal Purbeck strata at Dungy Head, (cliff exposure). For location see Fig.1.01. For key see Fig.2.02.

Locality: BACON HOLE [Grid Ref: SY839797]

Bed	Field and petrographic description	Thickness
A	Orange/brown, rough, granular stromatolitic limestone with irregular banding. Upper part is very crumbly and soft. Algal biolithite with much replacement of algal micrite by radial calcite (giving external botryoidal texture). Cavities lined with micritic rind and infilled with drusy calcite (coarse sand-sized grains) or pelsparite. Pellets (0·1 - 0·2 mm) are compacted in places to form mottled micrite. Scattered ostracods and abundant fish scales.	15-20 cm
B	Well laminated, black, highly carbonaceous marl. Upper part contains abundant fragments of shiny fusain (visible wood fibres) and plant cuticle. Grades down into paler brown marl with possible rootlets. (Basal Dirt Bed)	1-2 cm
C	Pale brown, finely laminated soft limestone. Pelmicrite (30-120μ pellets) with some pellets with 1-2 oolitic coats. Lenses of fine silt-sized sparite and few pseudomorphs after gypsum. Fine brown undulating laminae formed of layers of organic material crushed between pellets. [Cuticle well preserved e.g. intact lower and upper cuticle 3μ thick, 1·08 mm long.]	20 cm
D	Fine black and white laminated shaly limestone with many fish scales on laminae surfaces. Basal 3 cm are very black, calcareous shale but not carbonaceous. This grades up into black and white shale; white laminae predominating at top. No vertical disruption of laminae. Basal black laminae have abundant ostracods and carapaces of small (1-2 mm) branchiopods with fine concentric laminae. No conspicuous carbonaceous material but is finely disseminated in the black laminae. (Lower Dirt Bed)	3-5 cm
E	Pale brown limestone with fine horizontal laminae. Basal part has black laminae grading up from bed D below. Scattered small chert lenses at the base. Mottled pelmicrite. Pellets greatly compacted to give mottled or clotted texture. Some have single oolitic coating. Irregular patches of fine silt-sized calcite. Undulating darker laminae formed of finely disseminated organic material - pollen, cuticle, etc.	35 cm
F	Pale brown limestone with algal mat-type lamination. Rubbly, granular surface. Interlaminar pelsparite/pelmicrite and clotted micrite. Pellets range from 0·02 to 0·1 mm and become compacted in part; these areas contain small (60μ) pseudomorphs after gypsum, irregularly orientated.	30 cm
G	Soft, cream limestone with fine laminations. Slumped and contorted near the top. Well sorted pelmicrite/pelsparite. Pellets (0·05-0·2 mm) often packed together to form clotted texture with undulating, brown discontinuous laminae of finely disseminated organic matter. Scattered ostracods.	70 cm
H	Very soft, dark-mid brown, mottled limestone with wavy dark brown laminae. Pelmicrite/pelsparite. Few micrite pellets with single oolitic coating in matrix of very fine silt-sized calcite. The undulating darker laminae formed of fragments of organic material.	33 cm
I	Soft limestone with grey and cream laminae but with much slumping and brecciation. Interlaminated mottled micrite and clotted pelmicrite with many minor cracks and slumps. Patches of very fine silt-sized spar infill cracks. Scattered ostracods.	30 cm
J	Very fine-grained, brown, porcellaneous limestone with conchoidal fracture. Pelsparite with few micrite intraclasts intercalated with thin 0·6 mm bands of micrite.	35 cm

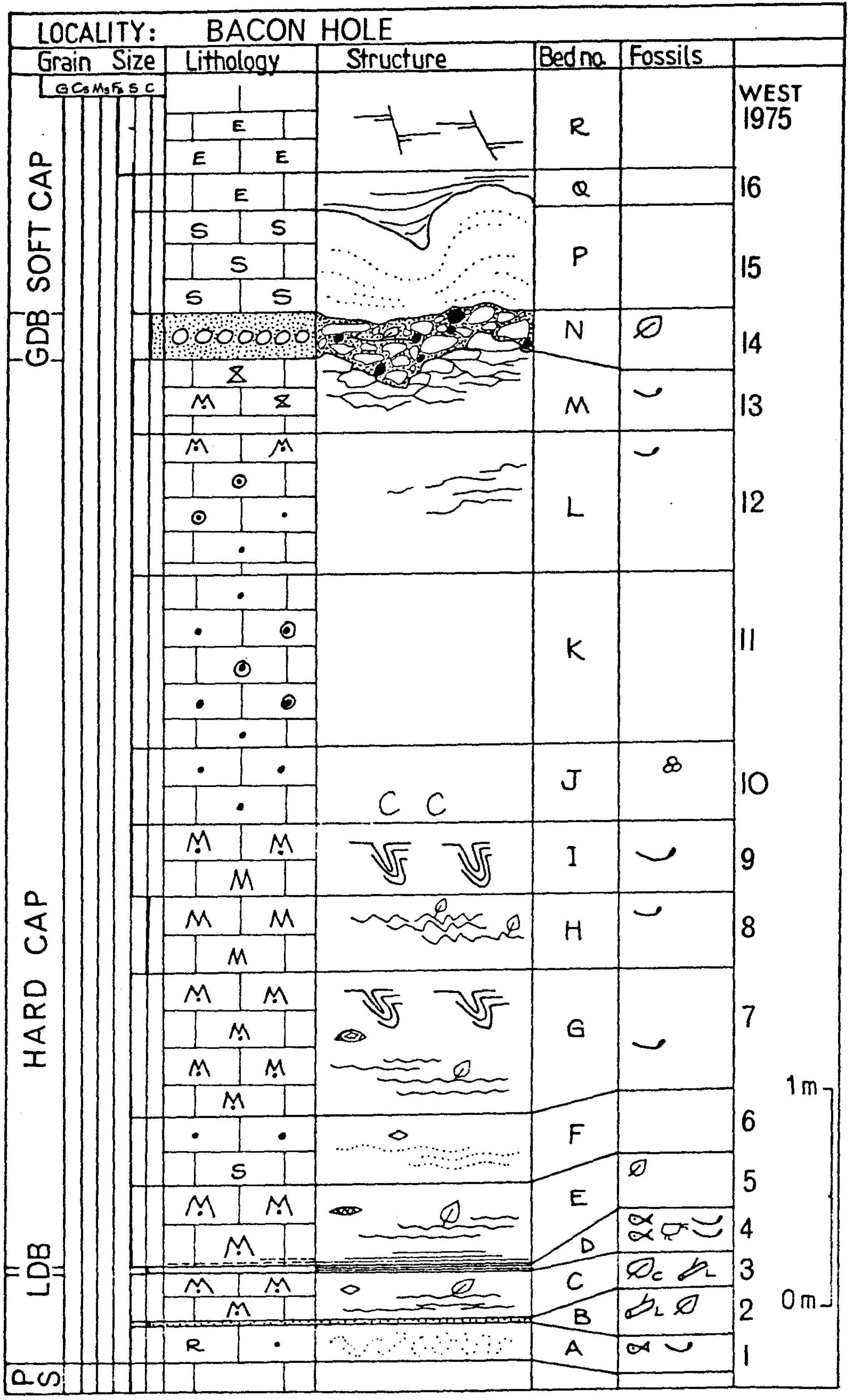


Fig. 2.09. Graphic log of basal Purbeck strata at Bacon Hole (cliff exposure). For location see Fig1.01 , for key see Fig. 2.02.

Bacon Hole (cont'd).

K	Massive, fawn, soft limestone with granular surface. Pelsparite - pellets (0·05-0·2 mm) in fine silt-sized sparite. Some pellets have oolitic coatings.	80 cm
L	Grey/brown blocky limestone, unlaminated. Pelmicrite/ pelsparite. Rounded pellets (0·05-0·126 mm) and micrite intraclasts (up to 0·4 mm). Some pellets have 1-2 oolitic coatings; some ooliths have nuclei of calcite crystals. Matrix incorporates broken oolitic rims.	65 cm
M	Weathered, rubbly nodular limestone grading into the dirt bed above. Upper part is weathered into large blocks and rounded pebbles. Mainly a mottled micrite with patches where pellets can be determined. Layers of organic material encircle 'intraclasts' of mottled micrite. Scattered ostracods and pellets with single oolitic coating. Patchy distribution of very fine paler micrite with voids lined with rinds of fine calcite spar.	35 cm
N	Black, highly carbonaceous, calcareous marl enclosing large pebbles and boulders of black and white limestone. Larger limestone boulders are clearly weathered from mounds in underlying limestone (up to 20 cm long). Large (10 cm), very round black limestone pebbles occur throughout the horizon. 30-40% of the pebbles are blackened. Black lignitic streaks throughout marl. (Great Dirt Bed)	20-25 cm
P	Pale grey/cream, hard, stromatolitic limestones doming over dirt bed below. Shows concentric banding in domes and horizontal banding linking them. Algal biolithite with supplementary pelsparite.	40-50 cm
Q	Pale brown/white finely-laminated granular limestone draping into hollows between P and covers the top. Calcitised evaporites. Becomes brecciated near top.	10-15 cm
R	Pale cream/grey saccharoidal limestone with granular texture and highly brecciated. Calcitised evaporites. Large rectangular crystals (average dimensions 0·4 x 0·1 mm), now calcitised with fine micrite matrix. Scattered crystals of euhedral quartz (0·5 x 0·3 mm).	-

Locality: WORBARROW BAY [Grid Ref: SY868795]

Bed	Field and stratigraphic description	Thickness
A	Pale grey limestone with faint laminae. Pelmicrite/ mottled micrite with forams/calcispheres.	10 cm
B	Pale brown, rubbly; granular stromatolitic limestone without banding. Algal biolithite with pelmicrite/pelsparite.	45 cm
C	Black, soft, poorly laminated marl, only slightly carbonaceous (Basal Dirt Bed)	2-3 cm
D	Pale brown/cream, hard limestone with discontinuous laminae and much slumping. Pelmicrite and micrite layers intercalated. The micrite layers are brecciated and slumped.	8 cm
E	Very finely laminated black and white shale. White laminae consist of micrite with lenses of fine silt-sized spar and few ostracods. Dark laminae consist of accumulations of organic material and includes many fish scales. No vertical disruption of laminae.	8 cm
F	Light grey, fine grained limestone with very fine, continuous laminae. Interlaminated micrite/pelmicrite.	31 cm
G	Pale yellow, light brown limestone with algal mat lamination. 5-10 cm bands of hard granular algal limestone interbedded with soft cream micritic layers and 5 cm bands of algal mat.	90 cm
H	Light brown, mottled structureless limestone with brittle, conchoidal fracture. Top surface is uneven and incorporated into the limestone above. Pelmicrite with patches of calcitised evaporates.	14 cm
I	Dark grey, gravelly textured limestone with small pebbles scattered throughout and pockets of small pebbles along a plane about 5 cm from the base. The upper part has faint undulating laminae. Pelletoid intrasparite with micrite pellets (0·03 → 0·2 mm diameter) and micrite intraclasts (some algal) up to 2 mm across. Scattered ostracods and oolitically coated pellets. Matrix of fine silt-sized sparite or micrite. Intraclasts of blackened limestone. Organic matter (cuticle and pollen) present.	15 cm
J	Dark grey, calcareous shaly clay incorporated into brecciated limestone above. Not carbonaceous. Contains calcitised evaporites and some euhedral quartz grains.	2-9 cm
K	Brecciated finely laminated cream limestone. Pelmicrite with calcitised evaporites.	35 cm
L	Pale grey/cream saccharoidal brecciated limestone. Basal part has brecciated matrix of brown marl which also occurs near top of bed. Calcitised evaporites. Basal and upper parts have cement of fragment of carbonaceous marl with much organic material.	35-50 cm

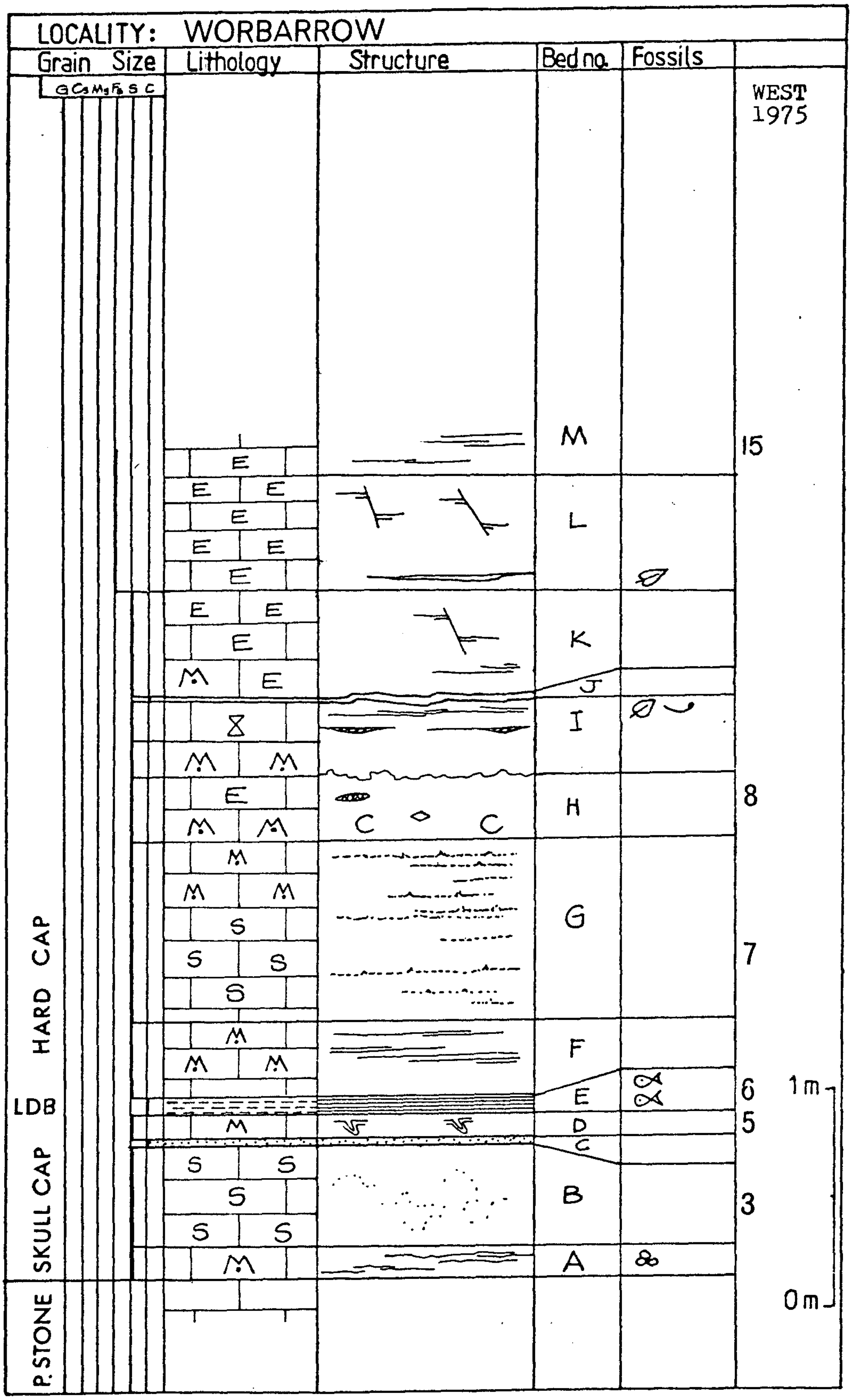


Fig.2.10. Graphic log of basal Purbeck strata at Worbarrow, west side of the Tout.(For location see Fig.1.01, for key see Fig.2.02).

Locality: FISHERMAN'S LEDGE [Grid Ref: SZ01137678]

Bed	Field and petrographic description	Thickness
A	Top of Portland Stone. Light grey, massive limestone with small bivalves (Portland Shrimp Bed). Becomes finely laminated towards the top.	—
B	Very finely laminated black and white, shaly limestone. Few ostracods. Black layers more conspicuous towards the top.	2 cm
C	Light brown, cavernous stromatolitic limestone. Horizontally banded at the base rising to circular, closed burrs at the top. Pelmicrite.	10-25 cm
D	Discontinuous brown shaly band between burrs. Few ostracods.	2 cm
E	Laminated, crystalline limestone; some laminae dark. Coarse saccharoidal texture. Dominantly calcitised evaporites (anhydrite) with micrite crystal outlines.	5-25 cm
F	Light brown, stromatolitic limestone forming closed, circular burrs. Very coarse, vuggy texture.	10-20 cm
G	Finely laminated, saccharoidal limestone draping into hollows over domes. Calcitised evaporites.	10 cm
H	Horizontally layered algal stromatolitic limestone. Very coarse exterior. No domes.	10-15 cm
I	Thin, discontinuous, grey calcareous shale. Some black laminae but not carbonaceous.	0-2 cm
J	Algal stromatolitic limestone; as H.	5-10 cm
K	Even-laminated, crystalline, pale brown limestone. Some laminae dark brown. Very hard limestone. Replaced evaporites.	25-30 cm
L	Mottled yellow and brown sandy clay. Very soft texture. Some harder laminae in places. Calcitised evaporites.	15 cm
M	Dark grey limestone with intermittent shale bands. Partly brecciated and re-cemented. Saccharoidal texture due to calcitised evaporites.	10-15 cm
N	Hard, massive, light grey limestone with chert nodules. Calcitised evaporites.	8 cm
P	Hard, grey, massive limestone with blocky texture.	10 cm
Q	Finely laminated, crystalline limestone with darker laminae at top. Chert lenses. Saccharoidal texture. Calcitised evaporites.	25 cm
R	Impersistent clay. Varies from matt black to brown to orange in colour. No plant material.	0-15 cm
S	Mid-grey, massive, crystalline limestone draping into hollows in clay. Saccharoidal texture andChert lenses.	20-30 cm

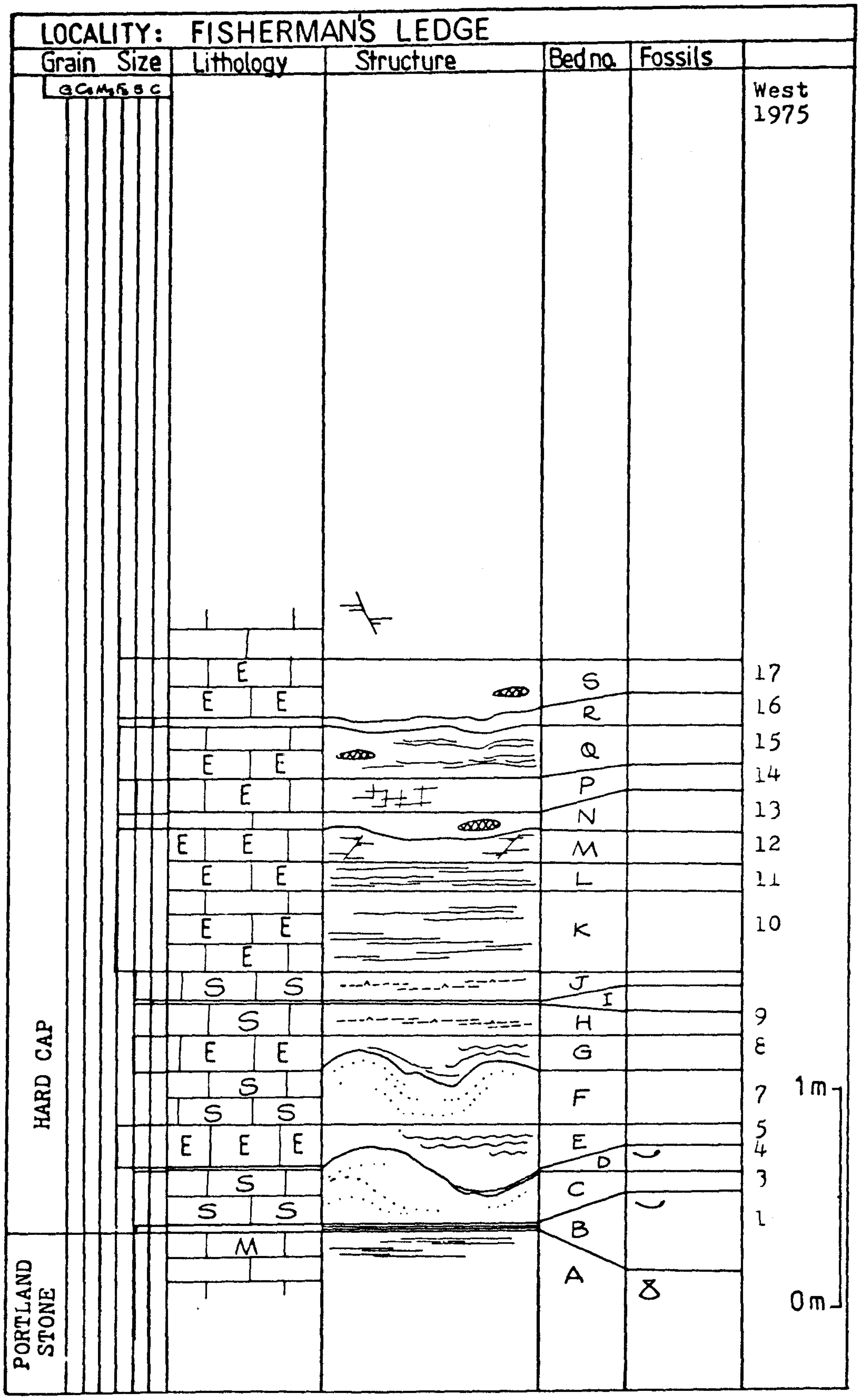


Fig. 2.11. Graphic log of basal Purbeck strata at Fisherman's Ledge, west of Anvil Point. (For location see Fig. 1.01, for key to symbols see Fig. 2.02).

Locality: DURLSTON HEAD [Grid Ref: SZ035773]

Bed	Field and petrographic description	Thickness
A	Fine grained limestone with dark and light laminae draping into folds in underlying Portland Stone. Contains large chert nodules and is partly stromatolitic. Mottled mid-brown micrite with darker bands of organic-rich micrite. Lot of small pieces of lignite and plant material scattered throughout. Few ostracods. Highly brecciated - large cracks infilled with intraclasts of micrite, cemented by fine sand-sized sparite.	48 cm
B	Dark grey limestone with dark brown, fine laminae. Similar to bed A but with sparite matrix. Darker laminae composed of organic matter and micrite intraclasts. Upper part with calcitised evaporites (fine sand-sized grains) and patches of celestite ($< 20\%$) as long bladed crystals up to 0·5 mm long. Small lenses of chert displace organic layers and contain well preserved plant material - pollen, spores and wood.	36 cm
C	Finely laminated black and white limestones with small chert nodules. Calcitised evaporites with $\simeq$ 40-50% celestite (grain size $29\mu \rightarrow 500\mu$). Dark laminae of fine organic material.	4-6 cm
D	Light grey limestone with algal mat lamination. Calcitised evaporites with 50% celestite (up to medium sand-sized grains).	30 cm
E	Fine grained, shaly limestone with orange and grey laminae. Calcitised evaporites and celestite with some alteration to spheres of calciostrontianate.	5 cm
F	Massive limestone with undulating coarse laminae. 60-40% calcitised evaporites and celestite.	37 cm
G	Light grey/brown laminated limestone with chert nodules in upper part. 95% - 5% calcitised evaporites (fine sand-sized) and celestite.	30 cm
H	Light grey, fine grained limestone with lensoid, discontinuous laminae. Unsorted, mottled pelmicrite with small micrite pellets either in microspar/micrite matrix or compacted into mottled micrite. Undulating dark laminae of organic material. Micrite replaced by radial calcite in part. Small (0·1-0·5 mm) pseudomorphs after gypsum. Parts highly brecciated. Cracks (infilled with sparite and celestite) contain wedges of pelmicrite. Celestite crystals up to 3 mm long.	34 cm
I	Massive, poorly laminated cream limestone. Pelmicrite/pelsparite with micrite intraclasts. Micrite layers contain pseudomorphs after gypsum and good plant remains. Upper part of micrite bands have V-shaped cracks in them and a covering of fine silt-sized sparite. Small pseudomorphs after gypsum and irregular patches of chert.	52 cm
J	Soft, orange/cream/grey, finely laminated limestone, brecciated and slumped. Interlaminated pelmicrite and ostracod-rich layers. Ostracod carapaces crushed into laminae forming dark bands. Only few whole ostracods with central cavity infilled with drusy calcite. Scattered fine sand-sized quartz grains ($< 1\%$).	40 cm^{+}

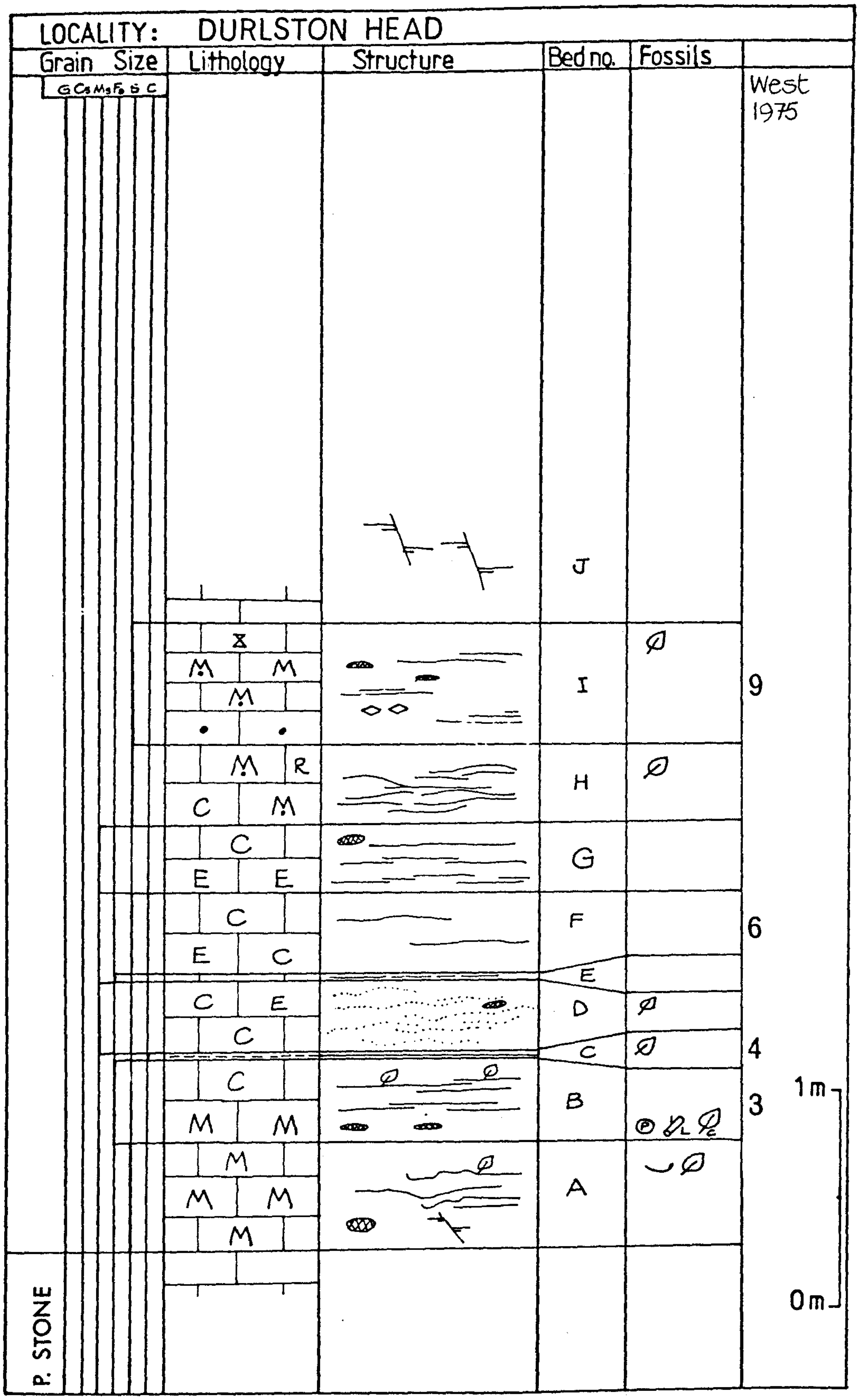


Fig. 2.12. Graphic log of basal Purbeck strata at Durlston Head (cliff exposure). For location see Fig. 1.01, for key see Fig. 2.02.

The base of the Lower Dirt Bed consists of a light brown or cream marl devoid of much carbonaceous matter, apart from fine, lignitic rootlets on the laminae surfaces (Pl.12 , Fig.6). This marl tends to grade into the underlying fine-grained or algal limestone via a zone of mottling, noticeable at Holworth House (Pl. 4 , Fig. 8).

The thickness of the Lower Dirt Bed varies considerably, depending on the underlying relief. It drapes and thickens into hollows and thins over mounds in the Skull Cap in distances of only a few centimetres. The thickest exposure was seen at Sheat Quarry where it infills hollows over 26 cm deep.

This Dirt Bed supported large conifers in the Chalbury and Poxwell area, some of which are now silicified and preserved in their growth positions (Pl. 1 , Fig.1). Their roots are preserved in the palaeosol at Poxwell and Chalbury. Silicified cycadophytes were once found, particularly on Portland (Fitton 1835) though they are rarely found today. A sparse fauna has been observed in this palaeosol; Clements (1973) recorded only gastropods (*Valvata sabaudiensis*, *V.inflatus*, *Loriolina* sp. and *Ceritella* sp.).

From Bacon Hole eastwards the Lower Dirt Bed changes from a carbonaceous palaeosol to a finely laminated, black and white shale (Pl. 4 , Fig. 1). The laminae are 0·4-2 mm thick and are not disturbed by bioturbation or slumping. Black laminae are more frequent near the base and their surfaces are covered with fish scales and vertebrae, white patches of decayed ostracods and the chitinous carapaces of conchostracan branchiopods (fossil clam shrimps) have been discovered (Pl. 4 , Fig.5). The white laminae are coarser-grained and become more frequent towards the top where the shale becomes less fissile and grades into the overlying limestone. Identifiable plant remains are absent and this shale has no features in common with the adjacent palaeosol. This type of 'Dirt Bed' continues along the cliff exposures to the east though tending to contain more carbonate. At Durlston Head celestite and calcitised evaporites predominate in a thin bed of black and white shale which may be equivalent to the Lower Dirt Bed. Small chert nodules at the top contain pollen and fragments of fossil wood. The record of fossil wood presumed to have come from the Lower Dirt Bed at Fisherman's Ledge (West 1975) is contradictory to other evidence that this is not a palaeosol but a river or pond sediment (see 2.4.ii). It seems more likely that either the wood was transported to this area prior to petrifaction or originated in another dirt bed higher in the sequence (as did a cycadophyte stem on Portland, Seward 1897).

2.3.iii The Hard Cap

These beds, between the Lower and Great Dirt Beds, consist mainly of algal stromatolitic limestone in the form of large, irregularly banded mounds up to 2 m high. This is mainly of the spongiostromata-type without well-preserved algal structures but consisting only of clotted micrite, pelmicrite and pelsparite. Some filamentous algae do occur within nodules of algal micrite at the very base of the Hard Cap. Fish scales, ostracod debris and bone fragments are more common in this basal algal limestone than in the pelmicrite.

The spongiostromata-type algal limestone tends to form large mounds with coarse banding which encircles the long cylindrical holes, the 'tree-holes' (see 2.6.i) (or the "chaff-holes" of Woodward 1895). These holes once contained the branches of trees which were never preserved, though silicified wood has been recorded in a few (Strahan 1898). The 'tree-holes' are mainly found on Portland, though one can be seen at Upwey and at Chalbury Camp. On the mainland the silicified remains of trees are preserved in situ with their roots in the Lower Dirt Bed and their trunk bases encased in the Hard Cap (Pl. 1, Fig.1). Most of the tree-holes are empty but one in Perryfield Quarry (Portland) has a "geopetal"-like infilling of brecciated, interlaminated pelmicrite and pelsparite and one at Chalbury Camp has a partial filling of algal micrite containing silicified clasts. The clasts include pieces of chert, silicified conifer wood, ostracods (Fabanella bolonensis) and gastropods (Valvata helicoides and ? Hydrobia sp.). Clasts of pelmicrite and micrite are incorporated and cemented by coarse sparry, meniscus cement. Empty voids remain between the clasts. Algal micrite and radial calcite cap this deposit, which is found only within the tree-hole.

The algal limestone tends to form large mounds, often extending up to the base of the Great Dirt Bed where it encloses tree-holes. Elsewhere it tends to form rather low domes which weather out from the surface as circular "burrs". These can be seen near Portland Bill, Chalbury Camp and along the east Dorset cliffs at, for example, Fisherman's Ledge.

Thinly-laminated intraclastic, pelletoid sediments drape into hollows between the algal mounds and often appear to grade directly into them (see

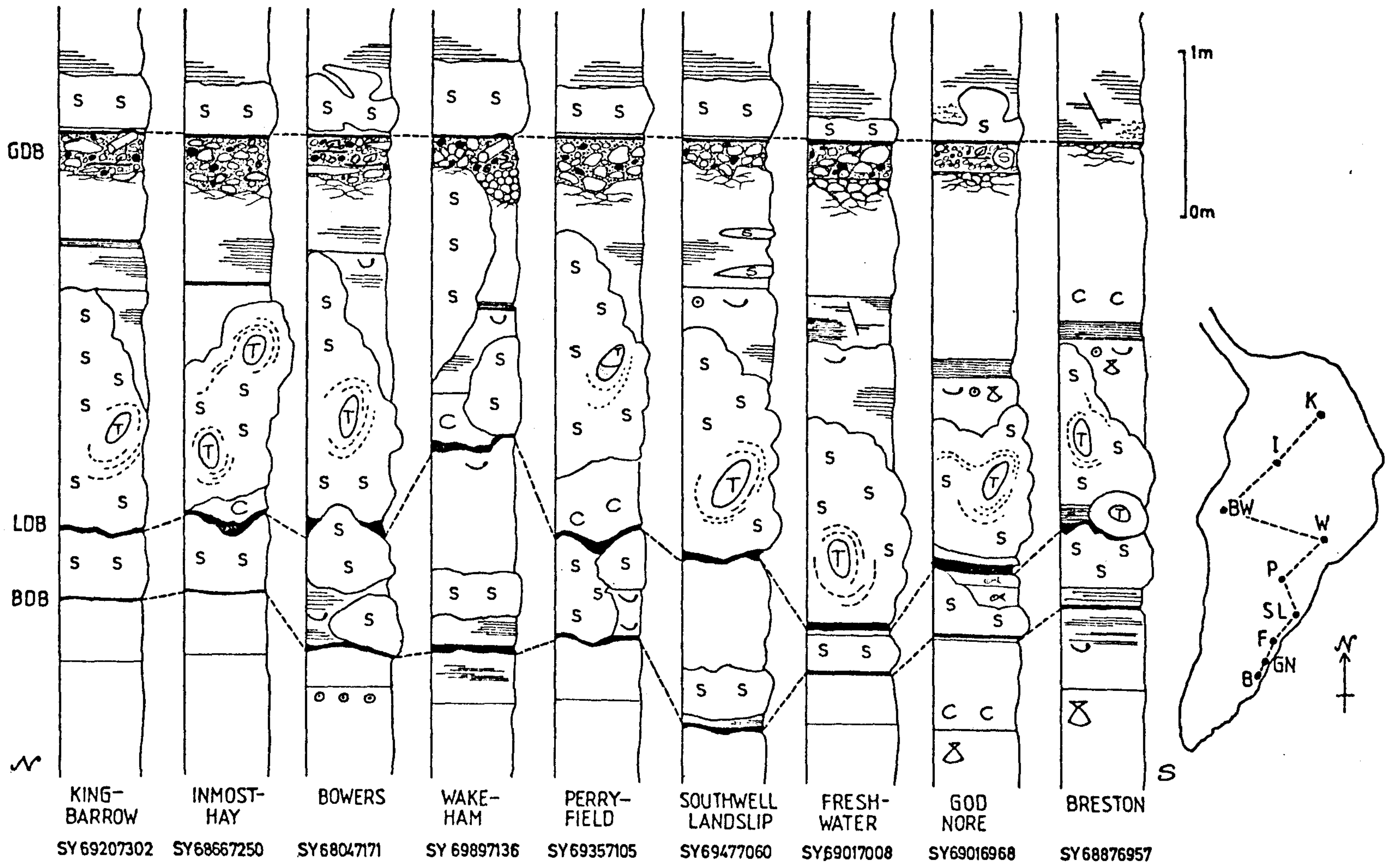


Fig. 2.13 Correlation of basal Purbeck exposures on the Isle of Portland.

Brown 1963). The pelmicrite is often clotted or mottled and encloses many algal intraclasts, presumably eroded from the adjacent algal mounds. Layers of crushed ostracods, fish scales and sparite-filled irregular voids are common. Gypsum pseudomorphs are sometimes present.

On Portland a conspicuous band (2-15 cm) of shaly limestone (Fig.2.13) occurs within the intraclastic beds (but does not affect the algal mounds), consisting of finely laminated pelmicrite with a few ostracods. Immediately below this a coarse, bioclastic limestone occurs which is conspicuous throughout Portland (Fig.2.03 - God Nore, bed H). Brown barytes crystals are visible on the exterior and occur as a patchy coarse-grained cement along with patches of pelsparite and pelmicrite matrix. Sub-rounded clasts of algal micrite, pelmicrite, pelsparite, micrite with gypsum pseudomorphs or with crushed ostracods are present along with gastropods, ostracods, fish-scales and bivalves. Some of the clasts have an oolitic coating of fibrous calcite, many of them are composite. The proportion of micrite matrix increases upwards into the shaly bed. This bioclastic bed has not been observed on the mainland, although it is approximately equivalent to the infilled tree-hole at Chalbury Camp, which contains a similar collection of clasts.(Pl.3,Fig.1).

The limestones change in character towards the top of the Hard Cap, particularly in the Lulworth-Portland area, and have an oolitic texture. The ooliths, both superficial and composite, are scattered throughout intraclastic sediments or in pelmicrites or pelsparites. Their nuclei consist of micrite pellets, ostracods and gypsum pseudomorphs. As the limestone becomes rubbly and nodular beneath the Great Dirt Bed the ooliths become composite, enclosing several clasts, and contain rinds of micrite between the fibrous coats. Irregular intraclasts up to 4 mm in size, of pelmicrite, pelsparite and micrite are enclosed within a mottled micrite matrix in which gypsum pseudomorphs are common. At the Fossil Forest (West 1979b, p.141) ripple cross-lamination can be seen (Pl. 2 , Fig. 2) and the upper beds contain large megapolygons (Pugh 1968) (Pl.2,Fig.8.).

From Holworth House to Portesham the upper limit of the Hard Cap is difficult to define because the Great Dirt Bed is either poorly exposed or unidentifiable. Stromatolitic limestone either spongiostromata-type or even-laminated) occursabove the Lower Dirt Bed, encasing the in situ tree stumps. Towards the top of the Hard Cap finely laminated pelmicrites,

Plate 3

The basal Purbeck Sediments

1. Fossiliferous intrasparite (Bed H), God Nore, Portland. The fauna consists of fish scales, gastropods, bivalves and ostracods. Many intraclasts have oolitic rims and are silicified. (TS, XPL)

2. Silicified pseudomorphs after lenticular gypsum in a chert nodule from the Great Dirt Bed, Upwey. The gypsum has been replaced by lutecite, a form of length-slow chalcedony. (TS, XPL)

3. Oosparite, Dungy Head (E_1). The nuclei include micrite pellets, ostracod fragments and calcitised gypsum pseudomorphs. Many ooliths are composite. (TS, PPL)

4. Traces of fungal hyphae in an organic-rich pebble in the Great Dirt Bed, God Nore, Portland. The fungal hyphae are found only in a few black pebbles and are absent in the matrix. (TS, PPL)

5. A small bone in the Soft Cap, God Nore, Portland. Details of the Hauversian canal system, characteristic of mammal bones, are visible. (TS, PPL)

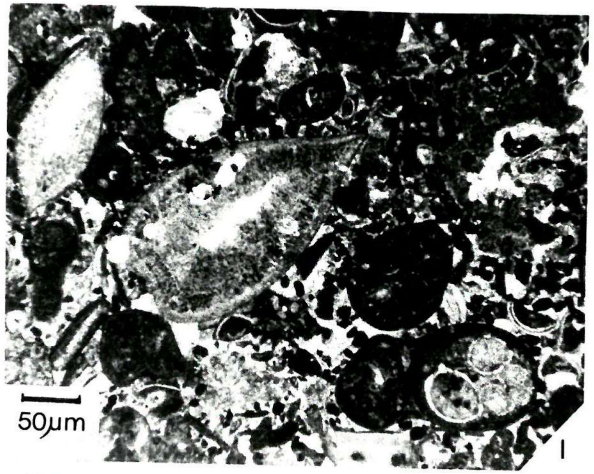
6. Fish scales are abundant in the algal stromatolitic limestones of the Skull Cap and Hard Cap. They are composed of orange phosphate. Bed D, God Nore, Portland (TS, PPL).

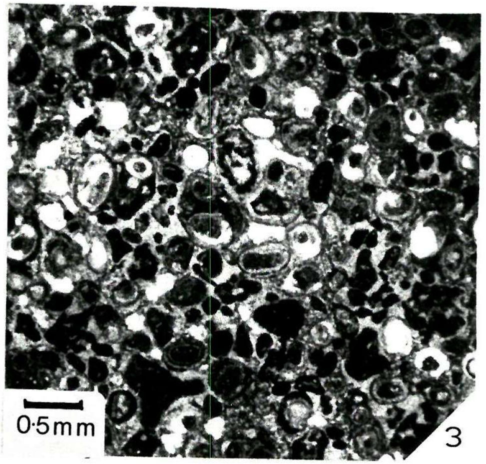
7. Impression of the forewing of a dragonfly. This dragonfly wing is one of the largest insect wings recorded from the Purbeck Beds; it had a total wingspan of about 20 cm.
   Soft Cap, Inmosthay Quarry, Portland.

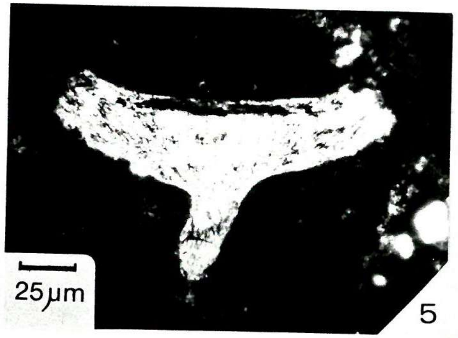
8. Calcitised gypsum pseudomorphs become more frequent at the top of the Hard Cap and in the Soft Cap. Many pseudomorphs are orientated with their C-axes parallel to bedding in pelletoid sediments.
   Dungy Head, Bed I. (TS, PPL).

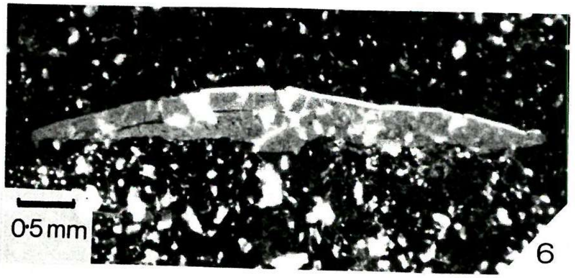
9. Clusters of pollen (Classopollis) preserved within a chert nodule in the Great Dirt Bed at Upwey. The pollen is preserved between silicified gypsum pseudomorphs similar to those in Figure 2. (TS, PPL).

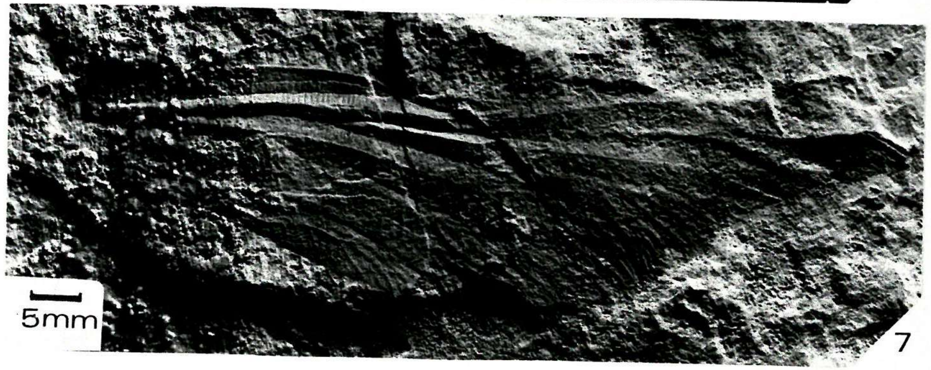
(TS = thin section)

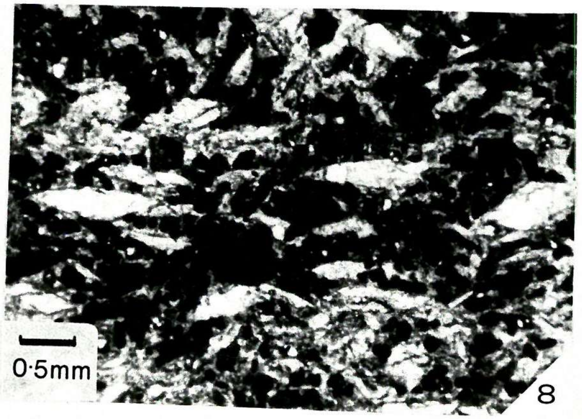












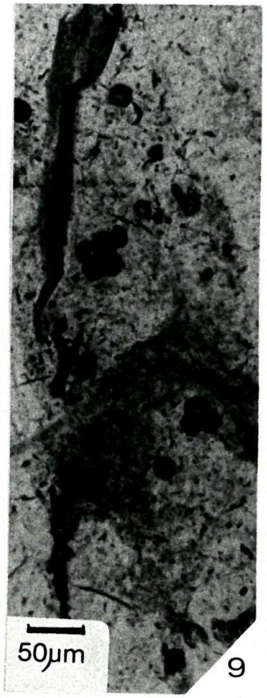


PLATE 3

pelsparites or plain micrite is present, without ooliths but with many gypsum pseudomorphs. These beds tend to have wavy, coloured laminae which often exhibit slump structures or vertical cracks infilled with sparite. Similarly to the east of the Lulworth area at Bacon Hole and Worbarrow Tout, the stromatolitic limestone consists of even-laminated algal mat (Pl. 2 , Fig. 3) with a pustular upper surface, with dark, organic rich laminae and some slumped layers. The top of the Hard Cap at Worbarrow and further west at Holworth House consists of a remarkably similar dark grey limestone (Beds I at each locality) with a 'blocky' texture consisting of intraclasts within a sparite matrix. Blackened clasts of pelmicrite occur at both localities as does fairly well-preserved plant material and bone.

In east Dorset spongiostromata-type limestone occurs along the cliff exposures but is much thinner than that further west. In this region the limestones consist mainly of replaced evaporites (West 1975) and comparison with the westerly exposures is difficult.

2.3.iv The Great Dirt Bed

The Great Dirt Bed is the most conspicuous of the basal Purbeck sediments and represents a fossil soil profile which once supported a large conifer forest. From Dungy Head to Bacon Hole and on Portland it consists of 12-25 cm of calcareous, carbonaceous black marl containing black and white limestone pebbles. This is the palaeosol in which fossil tree stumps and trunks are preserved in situ.

The top of the bed is level and in most cases has a thin band (1-2 cm) of black, highly carbonaceous material underlying a 2-3 cm band of buff-coloured micritic limestone. The main part of the Dirt Bed consists of dark brown/black marl with a granular texture and many streaks of black carbonaceous material. Small carbonate pebbles grading down to pellet size form part of the matrix (see 3.2). Lignitic and silicified tree roots are present and particles of fusinite are common. Large silicified trunks and branches can be found lying horizontally on the top of the palaeosol. The limestone pebbles range in size from those considered part of the matrix (less than 2 mm) to some of 'boulder' size (over 25 cm). The larger pebbles and cobbles (over 64 cm) tend to occur over mounds in the Hard Cap below; some are in fact still attached to the underlying limestone, as seen when the Dirt Bed is excavated. The buff-coloured (white) pebbles are clearly derived from the underlying limestone as they often exhibit interlocking shapes with other pebbles and with the limestone below. There is no obvious size sorting or grading throughout the Dirt Bed profile nor over the Lulworth area as a whole. The blackened pebbles appear much smaller and rounder than the flatter, platy white ones. The largest black pebble observed was only 14 cm in diameter. They are randomly scattered amongst the white pebbles, constituting about 30-40% of the total pebbles.

The base of the Great Dirt Bed merges into the weathered part of the Hard Cap below. Black marl and pebbles infill hollows in the limestone and the marl infills the fissues between the fracturing limestone. At Wakeham East (Portland) large depressions (60 cm deep, 1-2m wide) between algal mounds at the top of the Hard Cap are filled with cemented nodules (about 3-5 cm diameter) of a buff-coloured, intraclastic, oolitic limestone (Pl. 6 , Fig. 1) similar to that at the top of the Hard Cap in the Lulworth area. Many of the nodules have rims of microcrystalline, laminated carbonate (calcrete) and are also identical in composition to pebbles in the palaeosol.

Although the Great Dirt Bed clearly represents a palaeosol over much of Portland, in the south-east part the bed thins and even disappears completely at Breston. From Freshwater to Breston (see Fig. 2.13) the Great Dirt Bed is represented by 20 cm of light brown, indurated, intraclastic limestone or conglomerate composed of black and white carbonate pebbles in a micrite matrix. The composition of the pebbles is identical to those in the black marly Dirt Bed but here they are much smaller and rounder. The organic-rich matrix is replaced by microcrystalline calcite though some plant remains here are much better preserved (conifer shoots and pollen - see 5.2). No silicified plant material has been found here. The top and base of this type of Dirt Bed is very sharp. It overlies the rubbly top of the Hard Cap which has larger black and white pebbles incorporated in a sparse black marly matrix infilling small hollows and fissures. At Breston, the most south-easterly point, the upper Dirt Bed disappears, leaving only a few pebbles in the Hard Cap hollows overlain by limestone of the Soft Cap.

Beyond the Lulworth-Portland area the Great Dirt Bed loses its palaeosol features. To the west this horizon is marked by a brown clay without conspicuous carbonaceous material but with chert nodules. At Portesham this chert (the Portesham Charophyte Chert) contains an anomalous mixture of silicified gypsum pseudomorphs with silicified charophytes, freshwater gastropods, ostracods and land plants (Barker

For map showing localities see Figure 1.01.

For key to the logs see Figure 2.02.

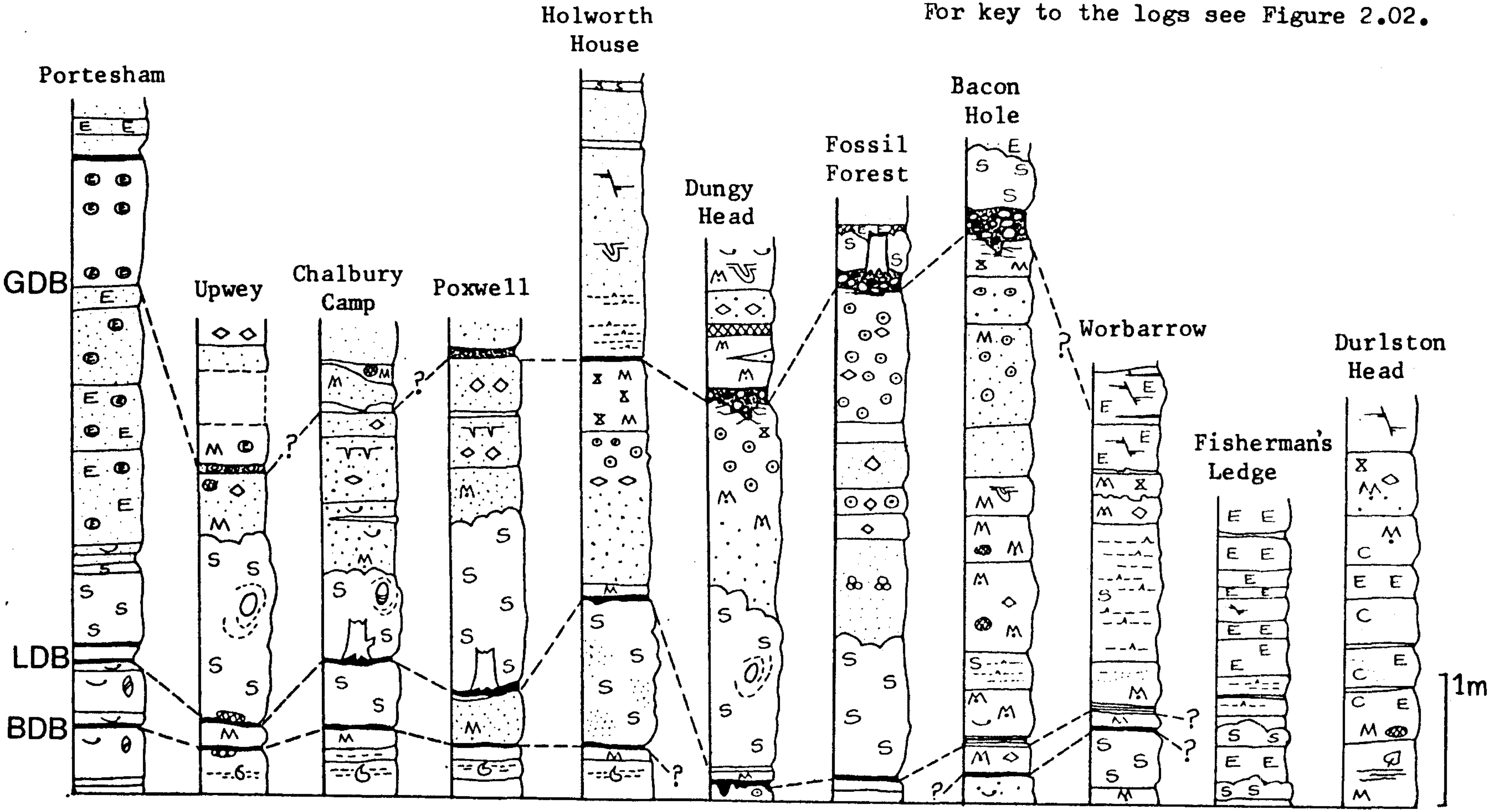


Fig. 2.14. Correlation of the Purbeck Beds across Dorset.

The sections from Portesham and the Fossil Forest are taken from West 1975 and 1979b. Full details of the remaining sections can be found in Figures 2.03 - 2.12.

et al. 1975; West 1975). The equivalent bed at Upwey contains nodules of silicified wood, chert containing pollen and silicified gypsum pseudomorphs (Fig.2.04). This clay band is not easily traced east of Upwey but at Holworth House two clay bands are present, the upper one regarded by West (1975) as the Great Dirt Bed. However, the lower dark grey clay has carbonaceous streaks and yielded well-preserved conifer leaves (Pl. 11, Figs.2 ,3,4.). identical to those from the Great Dirt Bed at God Nore, so is here considered to represent the lateral equivalent of the palaeosol.

To the east of the Lulworth area the Great Dirt Bed is difficult to identify because it is not present as the normal marly palaeosol. At Worbarrow carbonaceous clay is incorporated into a brecciated and slumped horizon of pelletoid limestone, probably equivalent to the Dirt Bed (Arkell 1940). From here to Durlston Head only thin clay bands can be determined amongst the stromatolites and replaced evaporites.

2.3.v The Soft Cap

Algal stromatolitic limestone, forming part of the Soft Cap, overlies the Great Dirt Bed in the Lulworth-Portland area. Large circular 'burrs', 0·72 to 2 m in diameter, which originally formed around the trunks of the forest trees, are conspicuous on exposed areas of the Soft Cap on Portland and the Fossil Forest (see 2.6). Many burrs have a central hollow from which petrified wood was lost (Pl. 1 , Fig. 5) but a few burrs still enclose in situ silicified tree stumps, e.g. at the Fossil Forest, Kingbarrow Quarry, Independent Quarry and Broadcroft Quarry. From the spacing of these burrs the forest density has been estimated (2.6iii).Some burrs are completely covered at the top and their origin is unknown. The algal limestone has a coarse, vuggy texture with a concentric banding pattern around the burrs and horizontal banding in the limestone connecting them.

The stromatolitic limestone (spongiostromata-type) is thickest in the Lulworth area (over 50 cm at Bacon Hole) and north Portland (Fig.2.13). In south-east Portland where the Great Dirt Bed thins, the Soft Cap does the same. At God Nore only flat algal mat with the occasional spherical head is present and at Breston algal limestone is absent, the finely laminated pelletoid limestones of the upper Soft Cap overlying the Hard Cap. These pelletoid limestones with algal intraclasts, bone, and gypsum pseudomorphs are draped between the algal mounds. Finely disseminated plant material and insect remains are preserved on the laminae (see 2.4)

To the west of the Lulworth area the stromatolitic domes are replaced by flat algal mats with interlaminated pelmicrite and clotted micrite and many gypsum pseudomorphs. The fine laminae are often slumped and brecciated. Thin clay bands occur amidst them (e.g. at Poxwell and Upwey) but are not carbonaceous though finely disseminated plant material is present in the limestones.

To the east of Lulworth the replaced evaporites occur in the Soft Cap as westerly as Bacon Hole. The stromatolitic beds are not recognisable at all in the east.

2.4 Interesting Faunal Remains

During the course of fieldwork in Dorset the remains of two unusual faunas were discovered within basal Purbeck sediments: an unusually large dragonfly wing and the carapaces of fossil clam shrimps. Their palaeoecological implications are important and merited further discussion.

2.4.i The dragonfly

The impression of a large insect wing was discovered on the bedding surface of a cream-coloured, fine-grained pelletoid limestone at 'Fancy Beach', Inmosthay Quarry on Portland. It was found about 1m above the algal stromatolitic Soft Cap in the thinly-bedded 'Bacon Tier' (Arkell 1947). On the same bedding plane were minute plant fragments and possible smaller insect remains.

The wing is 8·2 cm long and 2·2 cm wide, though the wing tip and lower margin are not preserved on this surface. The wing base is also obscured. However, the impression is well enough preserved in the main part to show very fine ribbing (Pl. 3 , Fig. 7). It was identified by Mr. E. Jarzembowski (Dept.of Entomology, British Museum) as the forewing of a true dragonfly (Order: Odonata, sub-order: Anisoptera) of the family Aeschnidiidae, one which did not survive after the Mesozoic.

This wing is much larger than any other from the Purbeck Beds by a factor of 50-75% (Brodie 1854; Westwood 1854; Barton 1978), and is comparable in size with the dragonfly Urogomphus giganteus from the

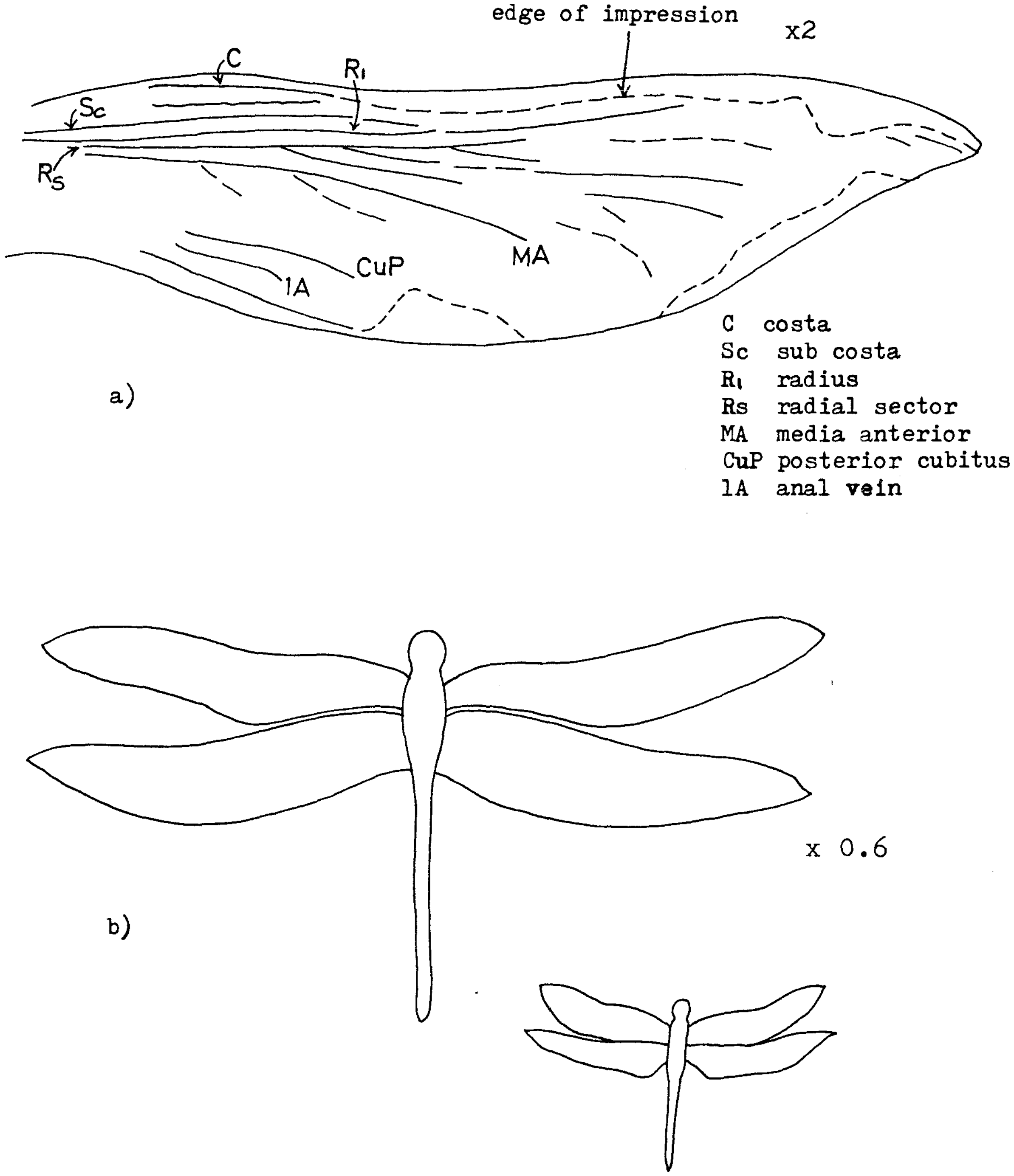


Fig. 2.15. The fossil dragonfly wing from the Soft Cap, Inmosthay Quarry, Portland.

a) Venation pattern of the wing impression (identified by Mr, E. Jarzembowski).

b) Approximate reconstruction of the Purbeck dragonfly to show its size in comparison with a modern one (to the same scale).

Solenhofen Limestone (Kimmeridgian/Portlandian) of Bavaria. Large dragonfly wings have been described from the Lower Purbeck Beds of Durlston Bay by Westwood (1854). These belong to the true dragonfly family, whereas the famous, much larger specimens from the Carboniferous belong to the Protodonata; these have wing spans of over 70 cm (Boule et Piveteau 1935).

Dragonflies today can adapt to many environments. Their larvae require mainly freshwater but they can develop a wide range of salt tolerance to cope with ephemeral pools. The mature dragonflies, which are carniverous, live in many environments, including that of forests, which have a suitable equable climate, abundant food supply and provide a shelter from strong winds (Corbet 1962). The presence of the dragonfly wing in the basal Purbecks on Portland suggests that a source of freshwater such as an ephemeral lake or river, was fairly near although dragonflies can fly up to 15 km to find food. The wing is preserved in limestones indicative of a hypersaline environment which suggests that the dragonfly died and the wing was preserved within the fine-grained sediments but that it did not permanently inhabit this area. Its large size suggests that conditions were not only very suitable for its existence but that it had few enemies, such as the airborne reptiles (Archaeopteryx).

2.4.ii Conchostracan branchiopod crustaceans (clam shrimps)

The Lower Dirt Bed at Bacon Hole and Worbarrow Tout consists of a finely-laminated black and white calcareous shale (Pl. 4 , Fig. 1). Preserved on the black laminae are fish scales (up to 5 mm diameter) and vertebrae, white powdery remains of decayed ostracod carapaces (now unidentifiable) and shiny chitinous carapaces of conchostracan branchiopods (fossil clam shrimps) (identified by Dr. R.G.Clements). The carapaces range in size from small fragments of 0·5 mm diameter to almost complete specimens up to 4 mm. They are reminiscent of bivalve shells in shape but have a conspicuous, very fine concentric ribbing and are composed of shiny, brown chitin. On the more complete specimens 2 or 3 radial ridges can be detected on the outer margin (see Pl.4 , Fig.5) but they become faint towards the umbone. Unfortunately no complete specimens have been found as their lateral margins tend to disappear into the lamina surface. They are best preserved on the very fine-grained laminae, mainly the black ones, though the white laminae are much coarser-grained and the carapaces not preserved.

These fossils, recorded under the generic name *Estheria* (now *Cyzicus* Audouin) were described from the Middle Purbeck Beds in the Vale of Wardour by Jones (1890, 1891). *Estheria subquadrata* (Sowerby) was found in a brown, sandy bed in a quarry at Teffont Evias, along with "fragmentary twigs of Thuia" (possibly *Brachyphyllum* or *Cupressinocladus*) and in a limestone with *Cypridea punctata* below the Cinder Bed, at Lower Chicksgrove. *Estheria andrewsii* Jones was preserved on thin laminae of a dark, shaly clay along with white patches of decomposed *Cyprideae* at a horizon about 1·6m below the previous horizon at Teffont Evias. This clay also contained *Cypridea fasciculata* and *C.punctata*. Both genera are much larger than those from the Lower Purbeck (about 8-11 cm in length as opposed to about 2 cm) and are devoid of radial ribs. Unfortunately the incomplete preservation of the Lower Dirt Bed specimens does not allow an accurate identification since the classification is partially based on the nature of the dorsal margin. However, the possible presence of a few radial ribs which appear to be obsolete at the umbo suggests they belong to the sub-family Monoleiolophinae Novozhilov (Tasch 1969) of the family Estheriellidae Kobayashi.

Conchostracans or clam shrimps, range from the Devonian to the present day. They consist of a short, laterally compressed body enclosed between two lateral valves which constitute the carapace. Only the antennae extend beyond the carapace and are used for swimming and burrowing. The fine concentric growth lines increase in number each time the clam shrimp sheds its skeleton, about once every 3 days (Tasch 1980). Accordingly, by counting the growth bands on a fossil its life span can be estimated. The estimated life span of the largest Lower Dirt Bed fossil is about 150 days (about 5 months).

Fossil conchostracans are very useful index fossils because they occur in very restricted non-marine facies (for example, in the Permian Wellington Formation of Kansas (Tasch & Zimmerman 1960). Assemblages on single laminae represent a single season so the total age of a given thickness of sediment bearing several conchostracan-assemblages can be estimated (Tasch 1980). Each assemblage usually consists of only a single species.

Clam shrimps are found today in fresh or brackish water environments of very limited extent. They often occur in pools of water less than 0•4 ha in extent and even in seasonal puddles or channels of less than 30 cm water depth. The pH of the water has to be between 7 and 9. The clam shrimps are filter-feeders living on plankton, plant material and biogenic debris, and burrow into the bottom sediment (Tasch and Zimmerman 1960). When the pool of water dries out they die, along with fish, ostracods and other fauna. Their eggs however, are particularly resistant to desiccation and are easily distributed by the wind and hatch during the following wet season.

Conchostracans are frequently found in small ponds on coastal flats associated with evaporites. In the Permian Wellington formation they occur in shales with gypsum, fossil wood, charophytes and spores. Insects, particularly dragonflies, are also preserved (Tasch and Zimmerman 1960). In the basal Purbeck in the Worbarrow area the Lower Dirt Bed is clearly not a fossil soil but appears to represent a seasonal, marginal pond in which plant debris was washed from adjacent soils. During the wet winter season (which is estimated to have lasted for at least 5 months) clam shrimps lived in the pond but in the arid summer months when the pond dried out the clam shrimps, ostracods and fish died and their hard parts were preserved.

2.5 Depositional Environments

The depositional environment of the basal Purbeck sediments can be established by comparison with similar modern shallow-water sediments. The salinity tolerance of the limited fauna and flora is particularly useful. The depositional environments are summarised in Figure 2.16.

2.5.i The Skull Cap

The appearance of algal stromatolitic sediments in the Lulworth area and the fauna of the Basal Cast Bed to the west (and on Portland) is indicative of a change from the normal marine conditions during deposition of the Portland Stone (Townson 1975) to hypersaline conditions. The algal stromatolites, similar to those in Shark Bay today (Hoffman 1976), were able to survive because the hypersaline environment deterred grazing, destructive molluscs (Garrett 1970). The ostracod, molluscan and foraminiferal faunas to the west of Lulworth and the absence of gypsum suggest that the salinity was not extremely high, at least in the west.

Plate 4

The Lower Dirt Bed

1. The Lower Dirt Bed at Bacon Hole consists of a thinly-laminated black and white shale, with decayed ostracods, fish scales and vertebrae, and conchostracan branchiopods preserved on the dark laminae.

2. The dark layers are composed mainly of organic material and the light layers of carbonate. The organic-carbon content of this shale is much higher than that of the true palaeosols (section 3.3). A conchostracan branchiopod carapace with its fine concentric growth lines is visible in cross-section.
(Lower Dirt Bed, Bacon Hole. Thin-section. XPL).

3. The Lower Dirt Bed at Worbarrow showing crushed ostracod carapaces within a finely laminated shale. (Thin-section, PPL).

4. The black and white shale representing the Lower Dirt Bed at Worbarrow, west side of the Tout. A similar fauna to that at Bacon Hole has been observed here.

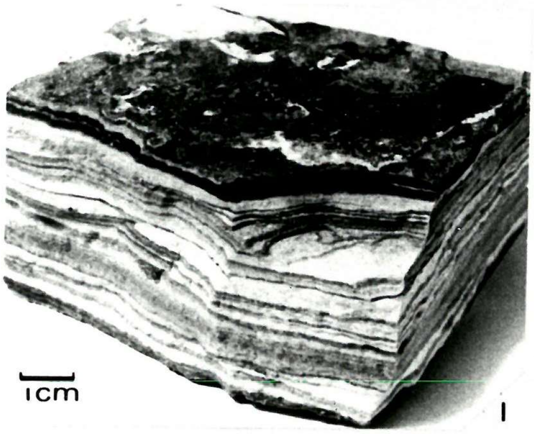
5. The chitinous carapaces of conchostracan branchiopod crustacea from the Lower Dirt Bed, Bacon Hole. Similar crustacea inhabit small, ephemeral ponds in semi-arid regions today. Their concentric growth lines indicate that they were active for at least 5 months.

6. The probable equivalent of the Lower Dirt Bed at Fisherman's Ledge (Bed B) is a finely laminated black and white shale with ostracods. The carbonate content is greater than that at Bacon Hole and the organic carbon content higher than the true palaeosols.

7. The matrix of the Lower Dirt Bed palaeosol (with fossil trees) consists mainly of decayed, amorphous organic material and some microcrystalline carbonate. The amount of organic matter increases towards the top of the bed. Only a poorly laminated or streaked texture is visible.
(Chalbury Camp, Lower Dirt Bed. Araldite impregnated thin-section, PPL).

8. The base of the Lower Dirt Bed at Holworth House. The black, organic-rich matrix grades down into algal stromatolitic limestone of the Skull Cap via a zone of mottling. The mottles consist of microcrystalline calcite outlined by organic material.
(Polished slab).

(Hammer length: 27 cm)



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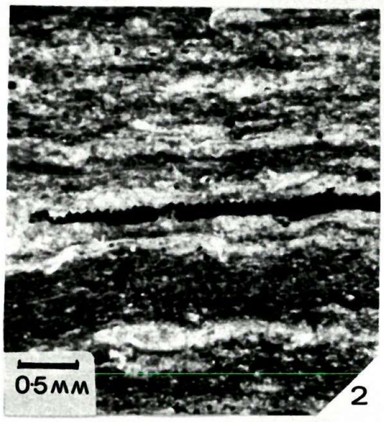

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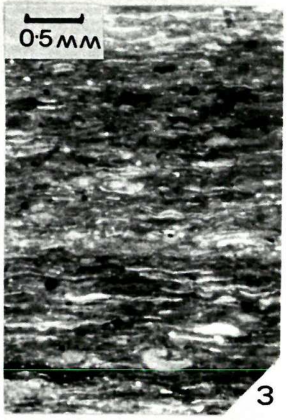

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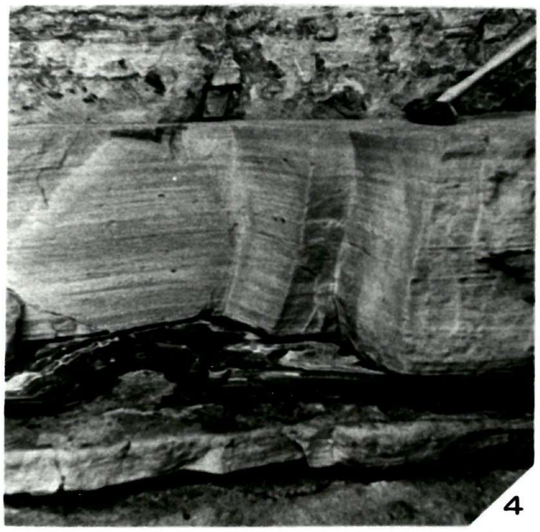

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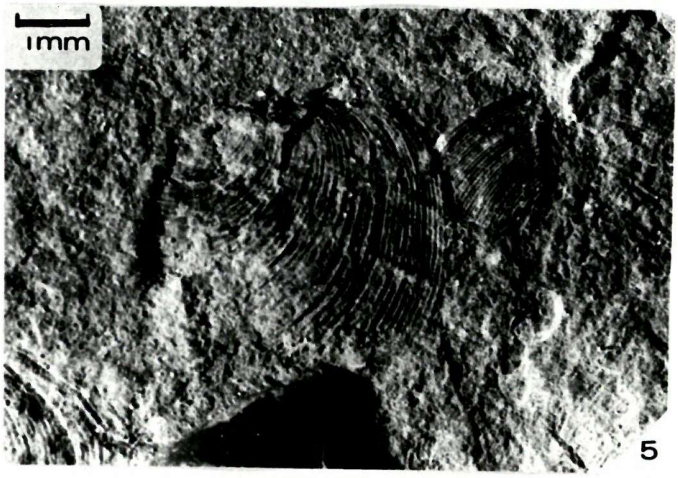

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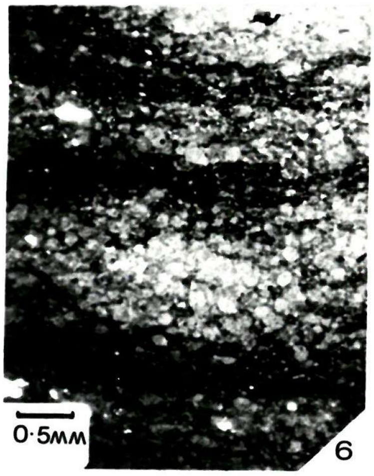

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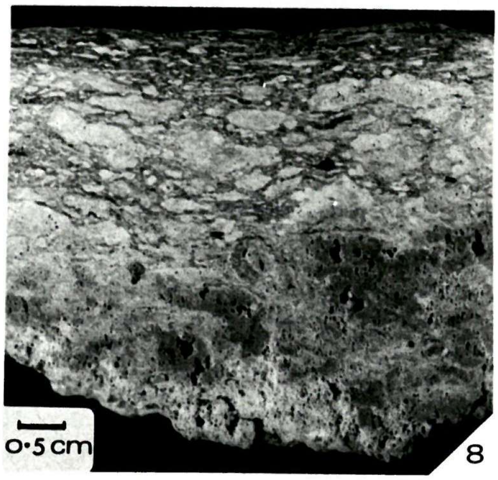

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PLATE 4

Continuation of the regressive phase resulted in sub-aerial exposure of the sediments and the formation of the Basal Dirt Bed palaeosol. The inclusion of small streaks of carbonate in the palaeosol, rather than large pebbles, suggests that the underlying limestone was not fully lithified and the regression fairly rapid. The thin profile and lack of significant plant remains suggest that this was the marginal area to possibly a much denser vegetated area to the north. The Basal Dirt Bed was rapidly covered by hypersaline water and algal stromatolites re-developed over the whole area in the unprotected, intertidal zone.

2.5ii The Lower Dirt Bed.

Another rapid regression left the area sub-aerially exposed and a palaeosol formed, again probably on poorly-lithified limestone. The irregular topography of the underlying algal limestone controlled the initial deposition of the soil. This soil supported Cycadophytes and large trees which would not have tolerated saline water but required a source of freshwater. Around the Worbarrow area the soil was replaced by an alkaline, ephemeral pond or the margins of a saline basin. The laminated nature of the shale and the fauna (fossil clam shrimps) suggest that brackish or saline water existed there for at least 5 months of the year (see 2.4.ii) and organic material from the adjacent soil was washed in. The water periodically dried up but did not become saline enough for the precipitation of evaporites. The presence of many fish remains in this shale supports the evidence that the water was not hypersaline. Further east the Lower Dirt Bed merges into evaporitic sediments which formed in a hypersaline intertidal environment (West 1975), similar to that in modern Persian Gulf lagoons (Shearman 1966). The shaly Lower Dirt Bed in the Worbarrow area may represent the western lateral margin of this evaporitic zone and the transitional area between the forested soil and the evaporites.

2.5.iii The Hard Cap

A rapid transgression of hypersaline water drowned the Lower Dirt Bed forest and intertidal conditions with algal stromatolites were established again. In comparison with those of Shark Bay (Hoffman 1976) the type and growth form suggest that fairly high-energy conditions prevailed over most of the area. The algal sediment encased the tree stumps and formed large mounds. Pelletoid silts with breccia from the algal mounds were deposited between them. The abundance of fish scales near the base of the Hard Cap suggests that at first the lagoon water was only moderately saline. This is supported by the presence of a fauna of ostracods, gastropods and bivalves, similar to that in the Basal Cast Bed, within the algal stromatolitic limestone and in the sediments between the mounds.

To the east of Lulworth even-laminated algal mats were present similar to those today in protected hypersaline, high-intertidal zones of lagoons of the Persian Gulf (Illing et al. 1965; Shearman 1966) and in Shark Bay (Logan et al. 1974). Further east evaporite sediments dominate the sections.

Towards the top of the Hard Cap the stromatolitic limestone is replaced by algal mat (in the west) and pelletoid silts. From Holworth House to Bacon Hole oolitic sediments appear suggesting that this area is one of localised higher energy conditions in shallower water than elsewhere, such as over an uplifted area or bar (the environment in which ooliths are found today, Wilson 1975; Bathurst 1971).

Evidence for more hypersaline conditions is provided by the presence of gypsum at the top of the Hard Cap at several localities (Fig.2.14). In the Lulworth area and on Portland evidence of gradual emergence is presented by micritisation of the sediments and the formation of calcrete textures. At the Fossil Forest large-scale polygonal desiccation cracks in algal mats (Pugh 1968) are also indicative of gradual emergence. It is in this area that the top of the Hard Cap becomes rubbly and nodular and becomes incorporated into the Great Dirt Bed, suggesting that the sediments were gradually exposed, were lithified and subject to erosion and desiccation-fracturing, similar to coastal sediments today on the Yucatan peninsula (Ward et al. 1970). The sediments to the east and west of this region do not show evidence of subaerial exposure but of intertidal conditions with evaporites, particularly in the west.

2.5.iv The Great Dirt Bed

As the Lulworth-Portland area remained subaerially exposed a thick soil developed which supported many large forest trees and into which pebbles of limestone derived from the underlying Hard Cap were incorporated. The presence of such large trees indicates that they

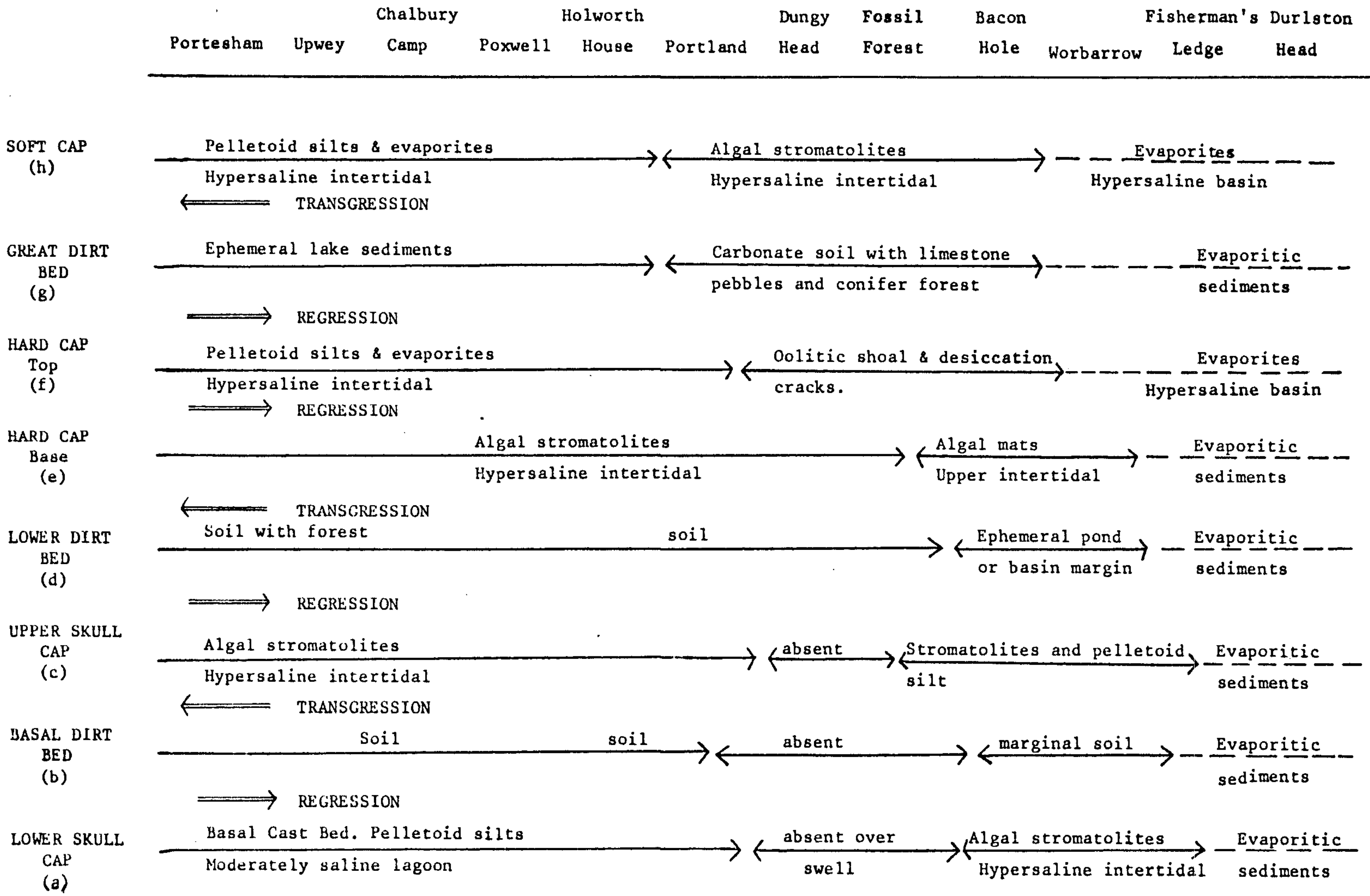

Fig. 2.16. Summary of the depositional environments of the basal Purbeck Formation across Dorset. The effect of a swell in the Lulworth area is apparent from the change in sediments.

received freshwater and were unaffected by saline water. The soil, however, only developed in this localised region.

In the south-east of the Portland area the Great Dirt Bed palaeosol was affected by a minor transgressive phase which resulted in the re-working of the soil. The organic matrix was washed away and replaced by carbonate mud. Into this sediment conifer remains and pollen were deposited (2.3.iv). The re-working of the soil in this isolated region suggests that the basin margin was only a short distance to the south-east.

From Holworth House westwards the equivalent bed is a dark clay, sometimes with plant material (Fig.2.07) and with chert nodules containing silicified wood, a freshwater fauna and land plants, and evaporites (Upwey and Portesham). In comparison with similar environments in coastal lagoons in South Australia (Peterson and von der Borch 1965), West (1975) suggested that this (the Portesham Charophyte Chert) represented a small ephemeral lake which dried out in summer, depositing evaporites.

To the east of Bacon Hole the Great Dirt Bed is also absent as a forest soil. At Worbarrow a soil-like matrix is incorporated into a brecciated horizon, suggested by Arkell (1940) to have originated from the disruption caused by the dissolution of evaporites. Further east evaporite sediments occur indicating that the hypersaline evaporitic basin was transgressing progressively westwards.

2.5. v The Soft Cap

Another rapid transgression of hypersaline water inundated the Great Dirt Bed forest and algal-bound sediment covered the soil and tree stumps. Similar to that of the Hard Cap, the stromatolitic limestone is indicative of low intertidal, fairly high-energy conditions where the algal stromatolites were able to form circular domes over tree stumps in water from 60-100 cm deep. In the south-east of Portland much thinner stromatolitic limestone indicates much shallower intertidal conditions and even high intertidal at Breston (Fig.2.13) where only algal mat occurs. Pelletoid silts were deposited between the algal mounds. To the west the stromatolitic limestone occurs only as laminated algal mat (protected, high intertidal conditions) with pelletoid silts. To the east the margin of the evaporitic basin continued its westward transgression; considerable evaporite deposits occurring in the Soft Cap at Bacon Hole and the Fossil Forest.

2.6 Field Observations of the Fossil Forests

2.6.i Tree-holes in the Hard Cap

Within the algal stromatolitic Hard Cap there are long, cylindrical cavities which extend from the Lower Dirt Bed almost to the top of the Hard Cap (Pl. 5 , Fig. 1). These were known as "chaff-holes" by the quarrymen (Woodward 1895; Strahan 1898 and others) but here are called "tree-holes" since they once contained branches of the Purbeck conifers. Although the wood has long since disappeared, markings of the grain of the wood can often be seen on the inner walls of the cavities. In the field the tree-holes are exposed on old quarry faces as cylindrical holes of various lengths and widths which dip at many angles into the limestone. The cavities range in dimension from about 2·5 cm in diameter to as large as 28 x 36 cm (height x width). Some are round, others are slightly vertically compressed. They were recorded from heights of between 20 cm to over 2 m above the Lower Dirt Bed.

The spongiostromata-type stromatolitic limestone that surrounds the tree-holes has a coarse, vuggy texture and exhibits a concentric banding pattern around each hole. Where several tree-holes are clustered together on a quarry-face the bands tend to coalesce and enclose several holes. In some quarries (e.g. Wakeham East) large mounds of algal limestone are noticeably concentrated around groups of tree-holes and laminated pelletoid limestone occurs between them.

The tree-holes dominate the Hard Cap on the Isle of Portland and can be seen in almost every quarry. They do not now contain silicified wood, though silicified fossil wood was recorded in "chaff-holes" in the Hard Cap in Kingbarrow Quarry by Strahan (1898). There is no evidence of silicification of the limestone around these holes on Portland. There are also no silicified tree stumps associated with the Lower Dirt Bed on Portland, reported originally by Fitton (1835) but this palaeosol has yielded many <u>in situ</u> fossil Cycadophyte stems (Fitton 1835,1836; Buckland 1829).

In contrast, on mainland Dorset only a few tree-holes are visible, e.g. at Chalbury Camp. There are, however, <u>in situ</u> silicified tree stumps

Plate 5

Field Observations of the Fossil Forests

1. "Tree-holes" within the Hard Cap, Breston Quarry, Portland. The long, cylindrical cavities in the Hard Cap stromatolitic limestone once contained tree branches which subsequently rotted away. The algal stromatolitic limestone shows concentric bands around the cavities. In this quarry the Great Dirt Bed is absent and the laminated limestone of the Soft Cap rests directly on top of the Hard Cap.

2. Two circular 'open' burrs of algal limestone in the Soft Cap in Kingbarrow Quarry, Portland (see Fig. 2.23). Fragments of silicified wood were found inside the large burr. From the spacing of such burrs the density of the forest has been estimated (section 2.6 iii).

3. Silicified tree stump preserved in situ with its roots in the Lower Dirt Bed and trunk encased by algal stromatolitic limestone of the Hard Cap. The trunk leans in a direction of 030°. PB.88, Poxwell Quarry.

4. The Fossil Forest, an exposed ledge on the cliffs east of Lulworth Cove. Burrs of the Soft Cap are exposed here along a linear strip about 500 m long, 2 m wide. (For plan see Fig. 2.21)

5. Large boulder of limestone in the Great Dirt Bed at the Fossil Forest which has caused the Soft Cap algal limestone to dome up over it. This is exposed as a 'closed' circular burr on the surface and for this reason the spacing of the 'closed' burrs were not used to estimate the forest density.

6. A partially exposed burr in the Soft Cap in Kingbarrow Quarry, Portland (SY 692731). A short stump of silicified tree which is rooted in the Great Dirt Bed below protrudes in the centre of the burr.

(Hammer handle length 27 cm. Lens cap diameter 7 cm)

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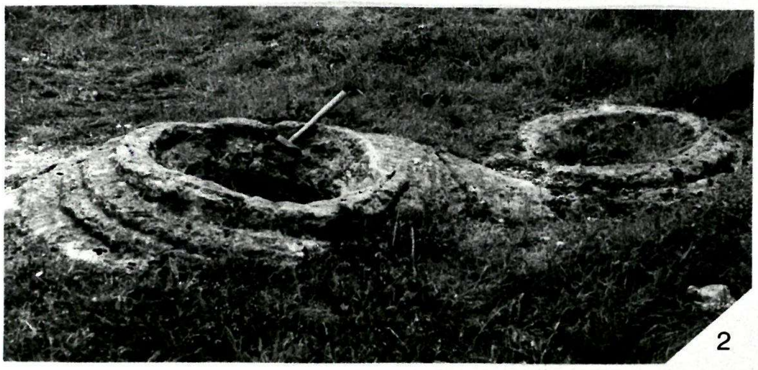

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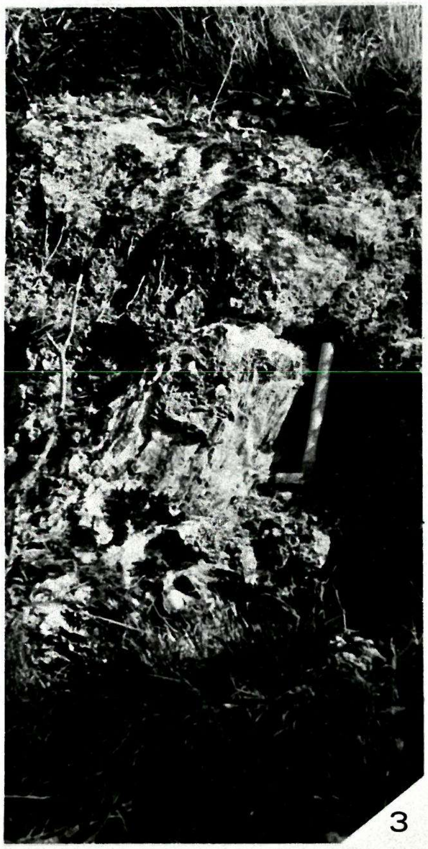

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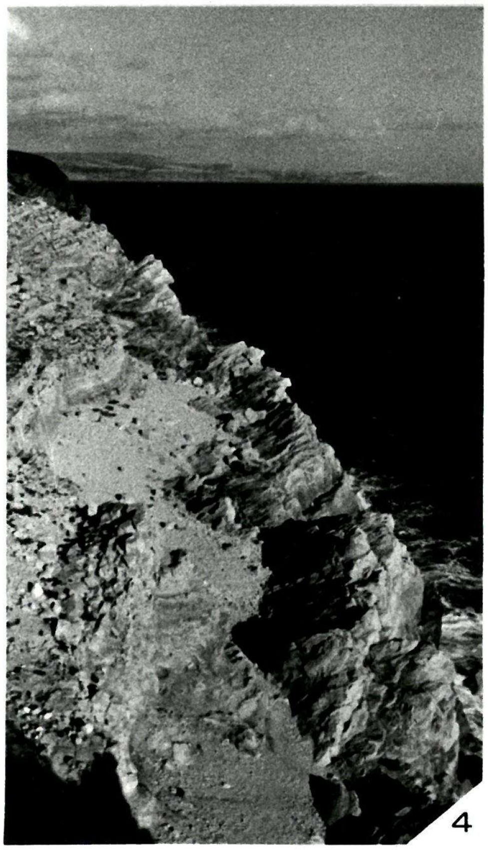

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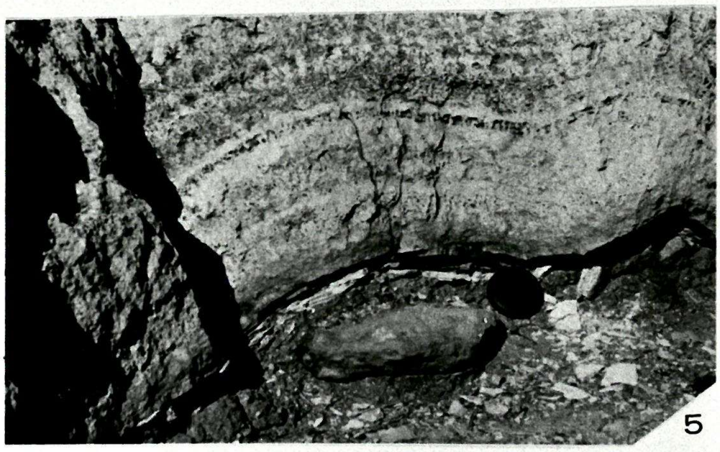

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PLATE 5

in the Lower Dirt Bed at Poxwell and Chalbury Camp and pieces of silicified wood within the palaeosol itself at Chalbury Camp, Poxwell and Upwey. In a quarry at Portisham, Strahan (1898) recorded an erect trunk 2·4m high standing with its base in the Lower Dirt Bed. The trunk was surrounded by a cone-shaped mass of tufa and this by laminated limestone suggesting that the tree remained upright whilst sediment was being deposited around it. In the same quarry there is a large cylindrical tufa case 4·5m long and 1m wide, presumably from the same horizon. Silicified wood was once found inside it (Strahan 1898).

The majority of the tree-holes are completely empty, devoid of fossil wood or contemporaneous or later sediment infill. Only 2 were found with an internal sediment, similar in appearance to a geopetal sediment, infilling the lower part of the hole. In Perryfield Quarry on Portland the infill consists of an intensely brecciated, unfossiliferous pelletoid limestone. At Chalbury Camp the base of the tree-hole is lined with a botryoidal deposit of algal limestone containing silicified bioclasts, including bivalves, ostracods, gastropods and silicified wood (see section 2.3.iii). A zone 20 cm wide around this tree-hole is itself silicified and appears very similar to the same tufa around a silicified branch attached to the nearby _in situ_ tree stump.

The presence of the tree-holes in the Hard Cap suggests possibilities as to the nature of the Lower Dirt Bed fossil forest on Portland: either the trees grew in the Dirt Bed here but for some reason were not silicified and so the tree-holes are thus the only evidence for their presence; or the tree-holes represent the former positions of isolated branches which have been washed or blown into this area from the forested land (now mainland Dorset). Measurements of the dimensions and orientations of many tree-holes were made in an attempt to solve this problem.

Methods of measurement

The length of each hole was measured using a rigid steel tape or, for deep holes, a long cane marked at intervals of 1 cm, which was pushed into the hole as far as it would go. (It is obviously possible that some holes may have been blocked with recent debris.) The angle at which the cane rested was measured to obtain the dip of the tree-hole from the horizontal and the direction of this dip recorded. The height and width of each hole was measured, as was the height of the centre of the hole from the top of the Lower Dirt Bed.

Data

The dimensions of 58 tree-holes were measured, 57 from Portland and 1 from Chalbury Camp. The average length was 53 cm though holes of 10-20 cm were most common (Fig.2.19). The shortest cavity was just 5 cm in length and the longest about 2 m. The average dimensions were 8•8 x 11•4 cm (height x width); the range was 2•5 - 36 cm in diameter. Most tree-holes were circular or very slightly vertically compressed ($<$10%), though a few larger cavities were compressed by up to 40-50%.

Most holes occurred about 80-90 cm above the top of the Lower Dirt Bed; the lowest was 20 cm and the highest at about 2 m, just below the Great Dirt Bed. The level of the hole is, however, related to the dip of the cavity and the position of the quarry face along its length.

The dip directions of all the tree-holes are recorded in a rose diagram (Fig.2.17) and as a contour plot (Fig.2.18). The average dip was 20°, though the most common was less than 5°. The rose diagram illustrates a range of dip directions mainly between the south-west (240°) and south-east (100°). This range is also illustrated on the contour plot but a dominant direction at 190° is stressed.

Discussion

From the evidence of the internal markings of wood grain, the record of fossil wood in the "chaff-holes" and the presence of silicified wood and trunks embedded in the Hard Cap on the mainland, it is apparent that the tree-holes on Portland did originally contain pieces of fresh wood. That all the holes once contained silicified wood is rather unlikely since it is difficult to imagine how it could have been subsequently lost from quite deep holes. Fresh tree-holes revealed by recent quarrying were empty. If the wood was not petrified then the algal-bound sediment around it must have lithified relatively quickly because it did not collapse into the cavities left by the rotting wood.

A possible explanation for the presence of tree-holes in the Hard Cap on Portland is that the trees did not actually grow in the Lower Dirt Bed there but were transported to the area by storms or floods. They may have been broken from trees which grew further north at that time, e.g. at Poxwell and Chalbury. The data suggest that the branches came to rest pointing in a predominantly southerly direction. From their high angle positions in relation to the Lower Dirt Bed it is unlikely that

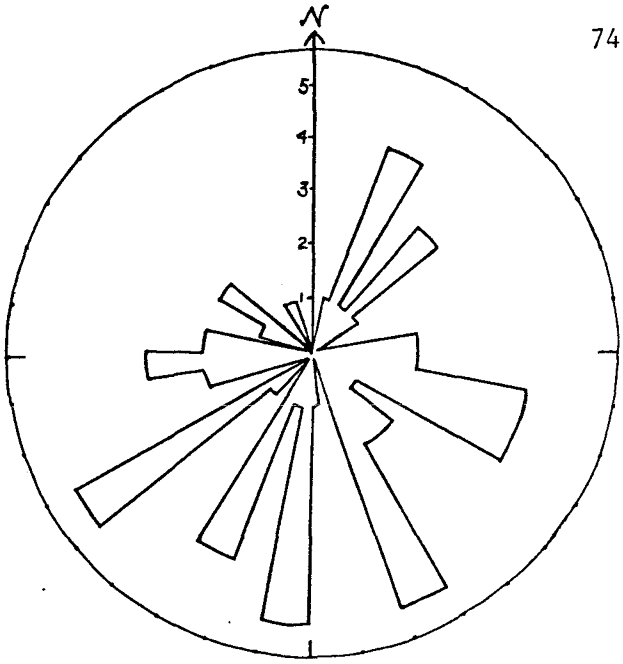


Fig. 2.17 Plot of the dip directions of the tree-holes in the Hard Cap. (58 readings)

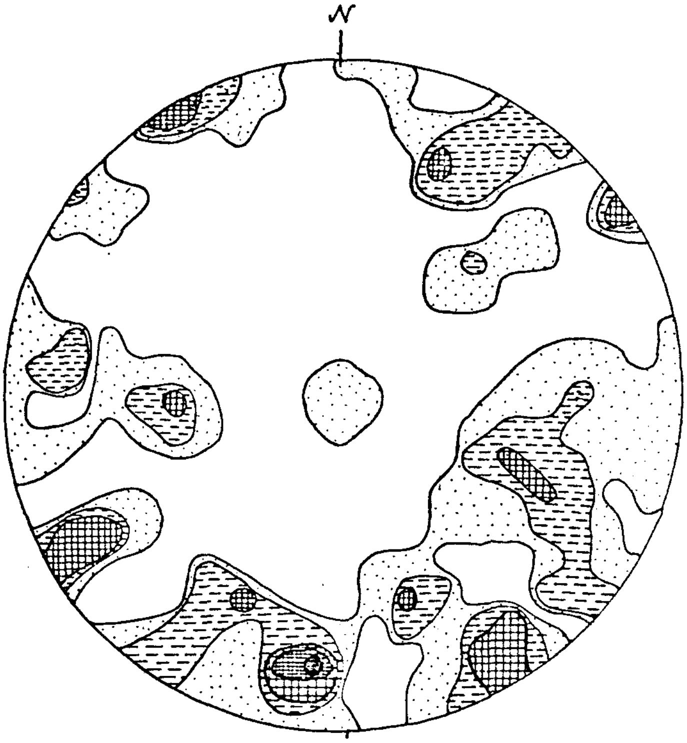


Fig. 2.18 Contour plot of the dip and dip directions of the tree-holes in the Hard Cap. (58 readings)

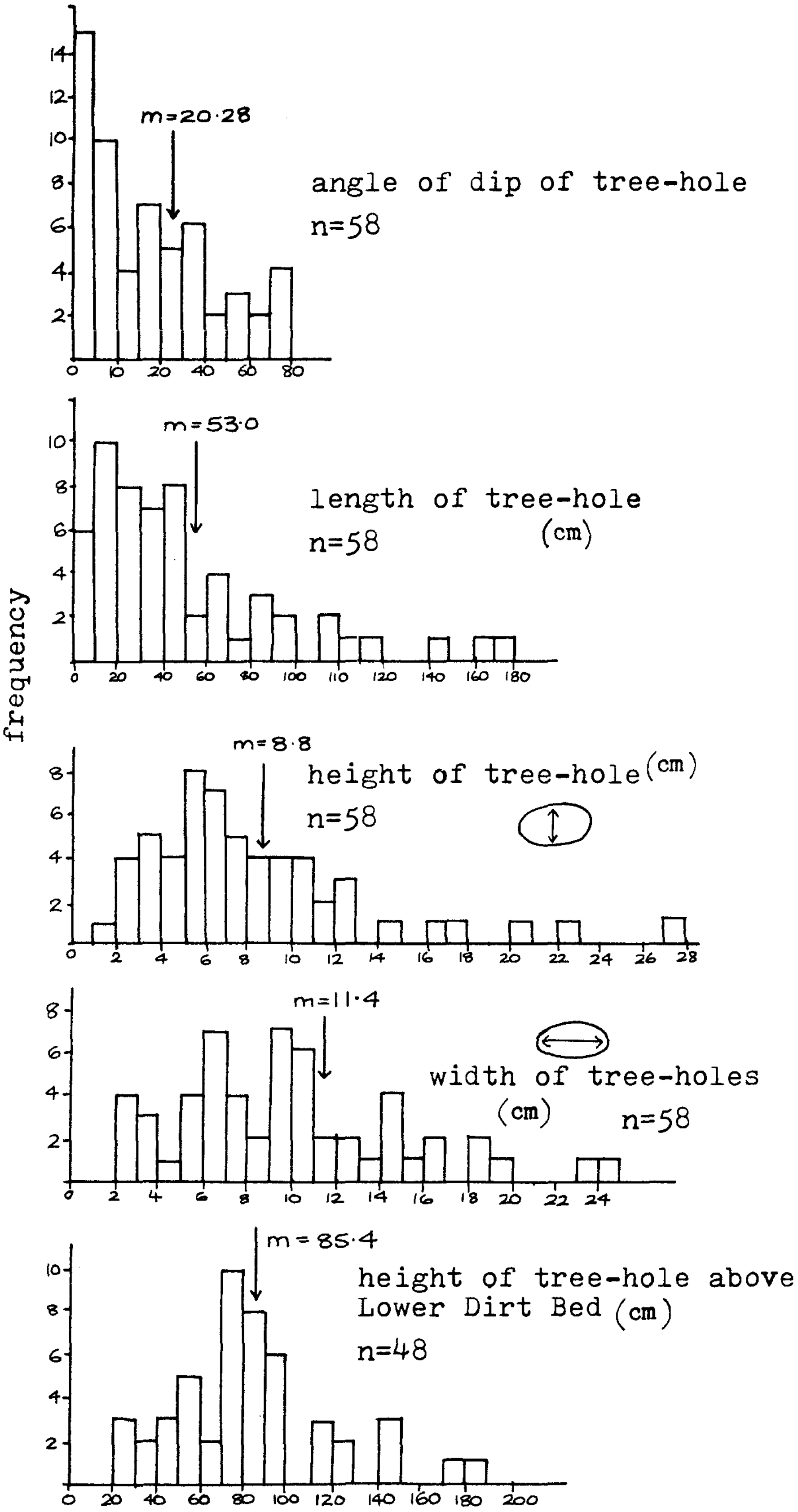
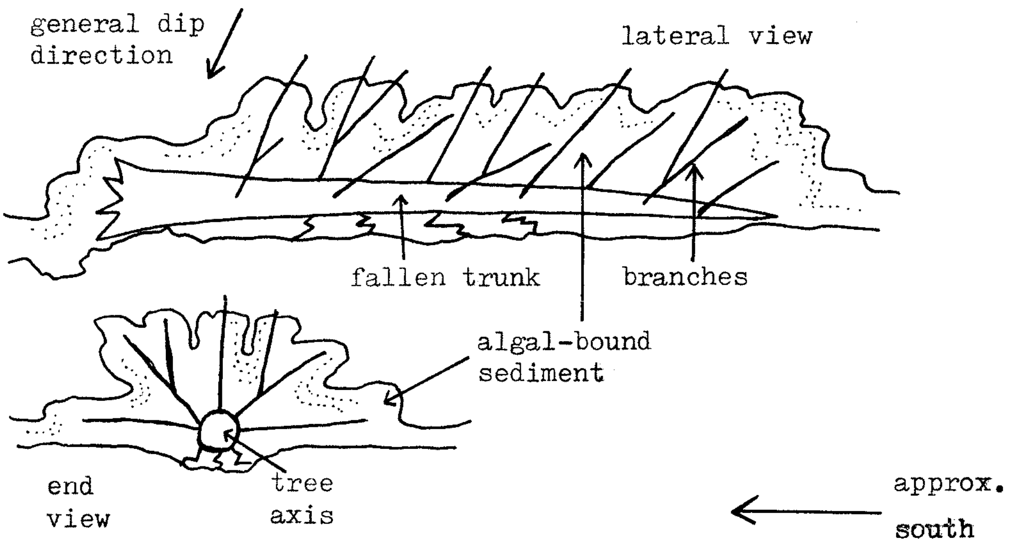


Fig.2.19 Histograms showing the distribution of some values of tree-hole dimensions in the Hard Cap. (n=number of readings)

they were deposited on top of the Dirt Bed itself but at a later time when the level of the lagoon had risen and algal stromatolitic mounds had developed in the intertidal zone similar to those today in Shark Bay (Logan et al. 1970). If the branches had come to rest against the mounds they may well have been propped up at quite high angles and subsequently been coated with algal-bound sediment themselves. The orientation of the branches may have been influenced by the shape of the stromatolite mounds. In Shark Bay stromatolites are developed as elongate flat-topped ridges, 1-3m wide, 0·3m high, separated by sandy areas. They are oriented parallel to the prevailing wind direction (Playford and Cockbain 1976). Although there is no record of large objects such as branches being trapped between these ridges in Shark Bay, it is possible that this may have occurred in the Purbeck. When the in situ trees further north were drowned and their lower boles coated with algal-bound sediment the branches above this level must have rotted and fallen off. They may then have drifted further south to be coated with algae themselves.

Alternatively trees could actually have grown in the Lower Dirt Bed in the Portland area and subsequently be drowned by the rising water and coated with algae, as were those growing further north. If so, it is surprising that no silicified tree stumps have ever been found in the Lower Dirt Bed on Portland, especially since in situ cycadophyte stems were particularly common and conditions thus seemed suitable for silicification. The trees may possibly have been uprooted before petrifaction as it seems most likely that the silica solutions were mobile in the soil and taken up by wood lying on or rooted in the soil (see Chapter 4). In any case if the trees were standing upright their branches (and thus the tree-holes) would presumably dip in all directions but it seems unlikely that anything other than the tree stump would be covered (as seen further north).

If the trees had fallen and were lying on top of the Dirt Bed, with many of the underneath branches broken and the protruding upper branches coated with algal-bound sediment, it is possible that most of the branches (and tree-holes) would dip in a similar direction as shown in the sketch overleaf:



No large, horizontal tree-holes representing the fallen trunks have been found but they would be relatively fewer than the branches. One would expect the branches to be quite large near the trunk and the tree-holes to be of much greater diameter than the common diameter recorded (8 x 11 cm). One would also expect to find branching tree-holes; though obviously this is hindered by lack of exposure. A single branching tree-hole was found at Perryfield Quarry; the angle between the holes was 30°.

The branches of the typical Purbeck conifers rise upward from the trunk, probably at an angle of about 40° (see 5.5.i). If all the branches of a fallen tree dipped in a general southerly direction the main trunk would lie in an approximate north-south direction. Since most of the tree-holes dip in a southerly direction this suggests that, following this idea, most of the trees growing in the Lower Dirt Bed were uprooted and fell in a northerly direction, possibly forced over by a strong wind or storm from the south/south-east.

Both ideas are highly speculative and without further evidence it is difficult to decide which is more likely; there may have even been a combination of both situations. However, the record of silicified wood in tree-holes at Kingbarrow (Woodward 1895) and in the large tufa case at Portisham (Straham 1898) demonstrates that at least some of the trees inside the tree-holes were silicified. Once silicified it would be unlikely that they could be transported far so it seems that some trees probably did grow in the Portland area and a few were silicified. However, the absence of silicified stumps within the Lower Dirt Bed on Portland strongly suggests that much of the material producing the tree-holes must have been imported. Perhaps there were rather few trees in this area and Cycadophytes (widely recorded from the Lower Dirt Bed on Portland) were the dominant element of the vegetation.

Whatever the origin of the tree-holes it is apparent that, by the time the sediment now underlying the Great Dirt Bed was deposited, most of the tree-holes were either still full of wood or were closed at the ends by at least partially lithified limestone, since the tree-holes do not contain Hard Cap limestone or a palaeosol sediment but are now empty.

2.6.ii The orientation of the fossil trees in the Great Dirt Bed

On the Isle of Portland and the Dorset mainland the trees that once grew in the Great Dirt Bed are now silicified and present as in situ tree stumps or fallen trunks and branches lying on top of the palaeosol. The fallen trunks are of more frequent occurrence than the upright tree stumps.

In the field the trunks are found lying horizontally on the Great Dirt Bed with their lower side embedded in the marl for a few centimetres and the top part covered by the algal stromatolitic Soft Cap. In fact the base of the Soft Cap forms a dome over the trees. The size of prostrate logs ranges from about 5 cm in diameter up to 30 cm, though in most cases only part of the original diameter is preserved and often only a small portion of the circumference is preserved. When the centre of the log is present it is clear that there has been vertical compression from between 8-47% (there does not appear to be a correlation between the size of the branch and the degree of compression). The length of the exposed portions of these logs ranges from 7 to 54 cm, though most are between 10-15 cm long. Large logs are invariably fragmented; observations confirmed by early reports when large areas of the Great Dirt Bed and its trees were exposed during quarrying. Gray (1861) reports that "some of the prostrate trunks are from twenty to thirty feet long, but never in one continuous length, being always broken into short pieces about twenty inches long; . . ." Fragmented trunks over 7.6m long were reconstructed (Fitton 1836).

It is possible to distinguish between the fallen trunks and in situ tree roots within the Great Dirt Bed since roots, especially those which are clearly associated with upright tree stumps, do not occur on the surface of the soil but quite near the base; often directly on top of the Hard Cap itself.

It became apparent in the field that many of the prostrate trunks and branches were lying in a similar direction. This phenomenon had been reported long ago when many logs were uncovered over large areas during quarrying and their orientation could immediately be seen. Damon (1884a) reported that the fallen trunks appeared to lie in a north-south direction and Gray (1961) wrote: "there we see the prostrate giants of the forest, as if felled by the swoop of some terrible tornado". Even Hardy (1897, p.100) included in his novel "The Well-Beloved":-

> "To find other trees between Pebble-bank and Beal*
> it was necessary to recede a little in time - to dig
> down to a loose stratum of the underlying stone-beds,
> where a forest of conifers lay as petrifactions, their
> heads all in one direction, as blown down by the gale in
> the Secondary geologic epoch."

To test these observations more rigorously the orientations of the prostrate trunks and branches were measured. Gray (1861) also notes that the fossil tree stumps lean in the same direction as the fallen trunks. Few of the remaining stumps exhibit a significant lean today though the tree at Poxwell leans in a direction of 030^{o} and one in Broadcroft Quarry in a similar direction at 015^{o}. Some of the open "burrs" in the Soft Cap tend to be elongated in this direction (Fig.2.20), presumably caused by the algal-bound sediment collecting around leaning trunks. The directions of elongation of such burrs in the Soft Cap at several locations are added to Fig.2.20, as are the directions of elongation of the clearly trough-shaped burrs in the Soft Cap, which formed around fallen trunks.

Data

The orientations of the silicified prostrate trunks in the Great Dirt Bed range in all directions but with a slight bias towards a north-south orientation. When the directions of elongation of the Soft Cap burrs are added (Fig.2.20) this direction becomes much more pronounced, although the results of a X^2 test were not significant.

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* Chesil-beach and Portland Bill.

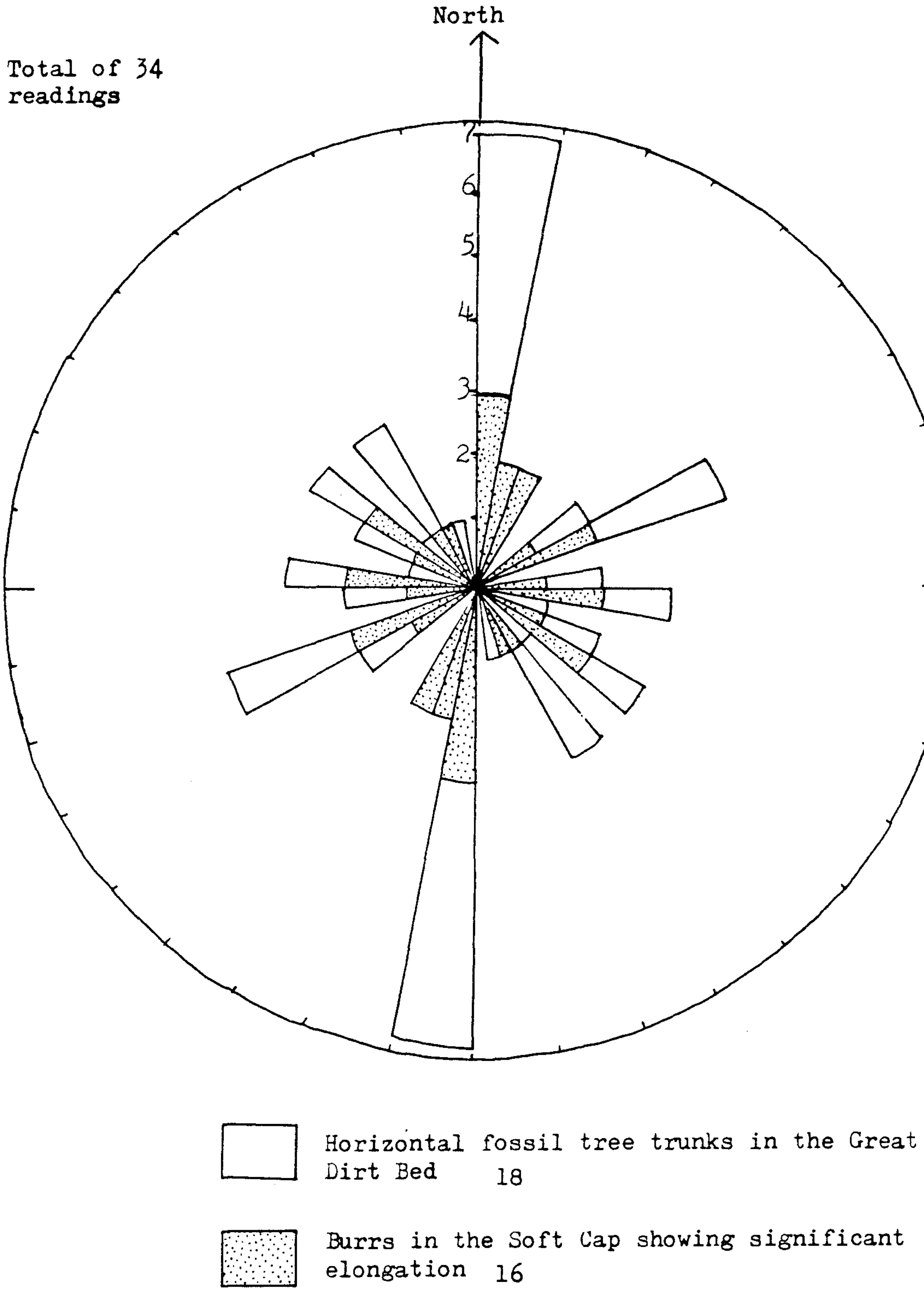


Fig. 2.20. Plot of the directions in which the horizontal fossil tree trunks are lying on the Great Dirt Bed and the directions of elongation of some burrs in the Soft Cap.

Discussion

The orientations of the fossil trunks lying on the Great Dirt Bed (measured here) tentatively agree with the early observations (Gray 1861 and others) that they tend to lie in a north-south direction. Since they are found below the Soft Cap they must have fallen over before the incoming algal sediment could have bound onto them. As originally suggested by Gray (1861) and others, they could have been blown over by strong winds, a relatively common occurrence in hurricanes (Ball et al. 1967). Unfortunately no fallen trunks have been associated with their tree stumps so their direction of fall and hence the direction of the wind is unknown. In contrast, the trunks and branches which were once enclosed within trough-shaped burrs of algal limestone in the Soft Cap must have fallen after the forest was inundated with hypersaline water since the algal tufa encircles or occurs beneath the branch. In this case it seems most likely that the branches and upper parts of the trunks fell from the rotting tree stumps.

The effect of winds from a constant direction on the roots of Stigmaria in Carboniferous coal forests near Sheffield was noted by Sorby (in Stützer and Noé 1940). The roots directed to the west were horizontal whereas those to the east were more inclined. This was considered to represent anchoring of the roots against strong winds blowing from the west to east. In many coal forests, both from the Carboniferous and Tertiary, there are areas where stems are located in a common direction probably due to the effect of wind (Stützer and Noé 1940).

Drowned forests are present today in areas of coastal subsidence, such as the Atlantic coast of America, the Gulf of Mexico and the Ganges estuary (Johnson 1913). Forests also become inundated where barrier islands are breached by storm waves and the water level in the adjacent lagoon rises. The inundation of such forests is usually relatively slow, the wave action gradually removing soil from around the roots of the tree and the salt water then killing it. At Cape Sable on the Florida coast a marine transgression over peat has covered the peat surface with beach deposits (Stach et al. 1975). The trees, which die when in contact with salt water, often remain upright with bare branches for a long period until the wood above the water level begins to rot and the top of the tree falls into the water, often aided by strong winds.

A similar process is envisaged for the Purbeck Dirt Beds, particularly the Great Dirt Bed. The cause of the rise in water level is unknown but it may be related to minor episodes of tectonic activity along the Purbeck - Isle of Wight Disturbance, an east-west trending zone of folding and faulting in this area (Colter and Havard 1981). The incoming water was hypersaline (West 1975) which would have immediately killed the trees. Algae and sediment that was brought in with it collected around the tree stumps. The dead trees presumably began to rot above the level of the water and the upper parts fell into the surrounding sediment. When freshly exposed most of the silicified tree stumps were up to 1 m in height (Fitton 1836; Woodward 1895; Strahan 1898; Arkell 1947 and others), suggesting this was the approximate depth of water during the time when the trees began to disintegrate.

2.6.iii The density of the Great Dirt Bed forest

Part of the algal limestone forming the Soft Cap consists of circular domes of limestone called "burrs" which range in diameter from 0·72 to 3·16m. Some burrs enclose silicified tree stumps though many have a central cylindrical cavity from which the petrified wood has been lost. The fossil tree stumps represent the remains of trees which once grew in the Great Dirt Bed palaeosol and often silicified roots associated with the stumps can be seen in the Dirt Bed (e.g. at the Fossil Forest (SY832796), at Chalbury Camp (SY693838) and Broadcroft Quarry on Portland (SY69847212)). Although few large tree stumps now remain in the burrs many contain small fragments of silicified wood, e.g. burrs in Higher Headlands Quarry (SY69637233), Kingbarrow Quarry (SY69067278) and Coombefield Quarry (SY68917042). Even those with completely empty central cavities (here called "open" burrs) usually have markings of the wood grain on the inner walls, so even though the fossil wood may not be present it is assumed that all "open" burrs originally formed around an *in situ* tree stump. On this assumption an estimate of the spacing of the trees and the density of the forest can be made by studying the positions of the "open" burrs.

Some circular burrs in the Soft Cap are completely covered and the central cavity cannot be detected ("closed" burrs); the formation of the burr is then unknown. However, at the Fossil Forest a "closed" burr which is exposed in cross-section clearly formed over a large

<u>Key to Fig.2.21</u>: Dimensions of Burrs in the Soft Cap at the Fossil Forest

d = diameter of whole burr (m); L = length of troughs (m)
dh = diameter of central hole (m)
1) = Burr number on Figure 2.21.

1) d = 1·96

2) d = 1·76

3) d = 1·34
dh = 0·45

4) d = 1·07

5) d = 0·82
dh = 0·16
L = 1·46

6) d = 1·65

7) d = 1·48
dh = 0·63
L = 1·30

8) d = 1·58
dh = 0·81

9) d = 2·62
dh = 1·08

10) d = 1·80

11) d = 1·68
dh = 0·60

12) d = 1·36

13) d = 1·30
dh = 0·60

14) d = 1·46

15) d = 1·04

16) d = 1·68
dh = 0·48

17) d = 1·40

18) d = 1·20

19) d = 1·40

20) d = 0·80

21) d = 0·99

22) d = 1·21

23) d = 0·91x0·72

24) d = 1·75

25) d = 1·38

26) d = 1·60

27) d = 1·96
L = 1·83

28) d = 1·16
dh = 0·48

29) d = 0·64

30) d = 1·72

31) d = 1·60
dh = 0·78

32) d = 2·36
dh = 0·64

33) d = 1·60
dh = 0·78

34) d = 0·80

35) d = 1·38

36) d = 1·42

37) d = 1·50
dh = 0·92

38) d = 1·56
dh = 1·02

39) d = 2·00

40) d = 1·20

41) d = 1·10

42) d = 0·80

43) d = 2·14
dh = 1·00

44) d = 1·04

45) d = 1·21

46) d = 1·74

47) d = 1·89
dh = 0·88
L = 4·98

48) d = 2·00

49) d = 1·55

50) d = 2·08
dh = 0·78
L = 4·68

51) d = 1·59

52) d = 1·37

53) d = 2·62
dh = 0·72

54) d = 1·58
dh = 0·89

55) d = 1·44

56) d = 2·20
dh = 0·46

57) d = 1·34
dh = 0·76

58) d = 1·84

59) d = 1·52
dh = 0·40

60) d = 0·84x0·48
dh = 0·28x0·13
L = 1.15

61) d = 1·07

62) d = 1·78
dh = 0·31

63) d = 0·80

64) d = 0·72

65) d = 2·18

66) d = 1·94

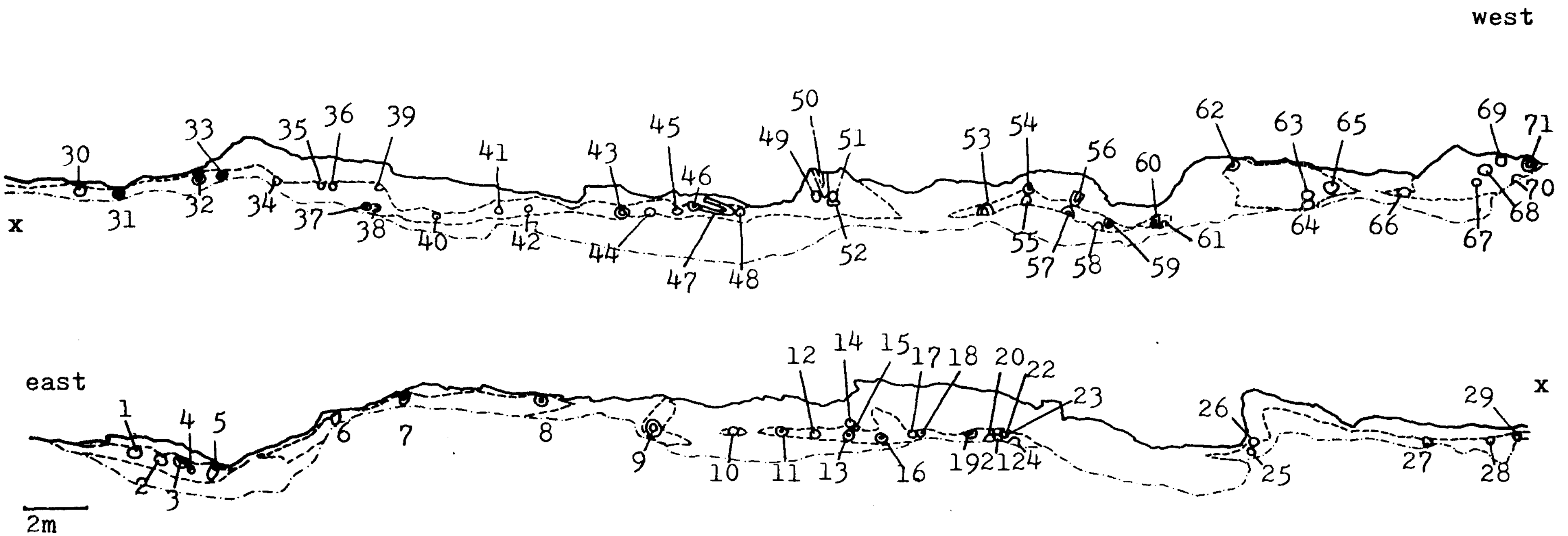
67) d = 1·54

68) d = 1·70

69) d = 1·96

70) d = 1·60

71) d = 1·40
dh = 0·38



Location map

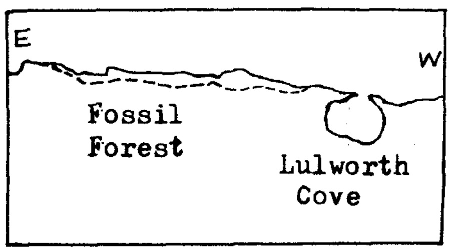


Fig.2.21

THE FOSSIL FOREST

Plan of the exposed ledge of the Soft Cap showing the positions of the algal burrs.

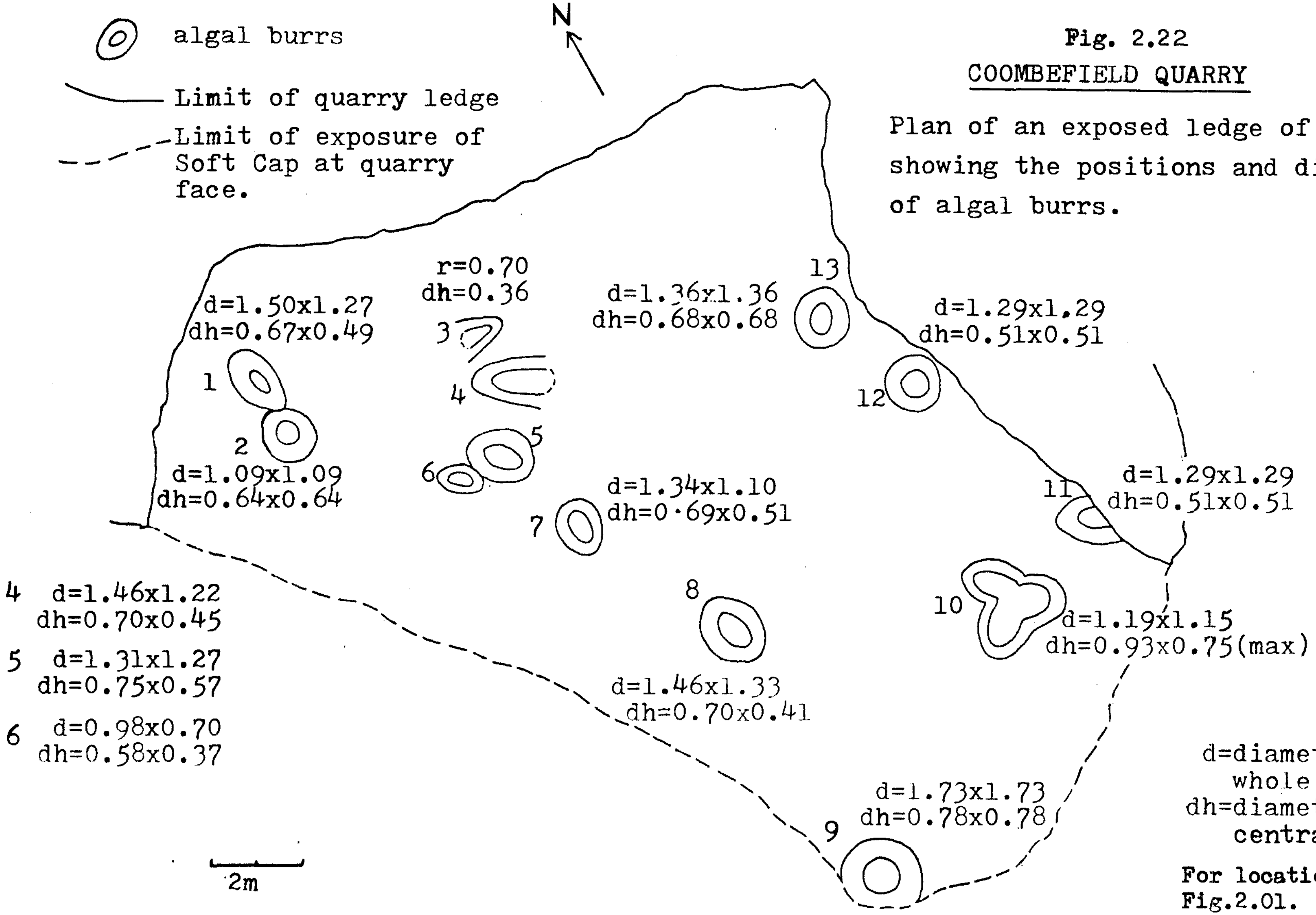
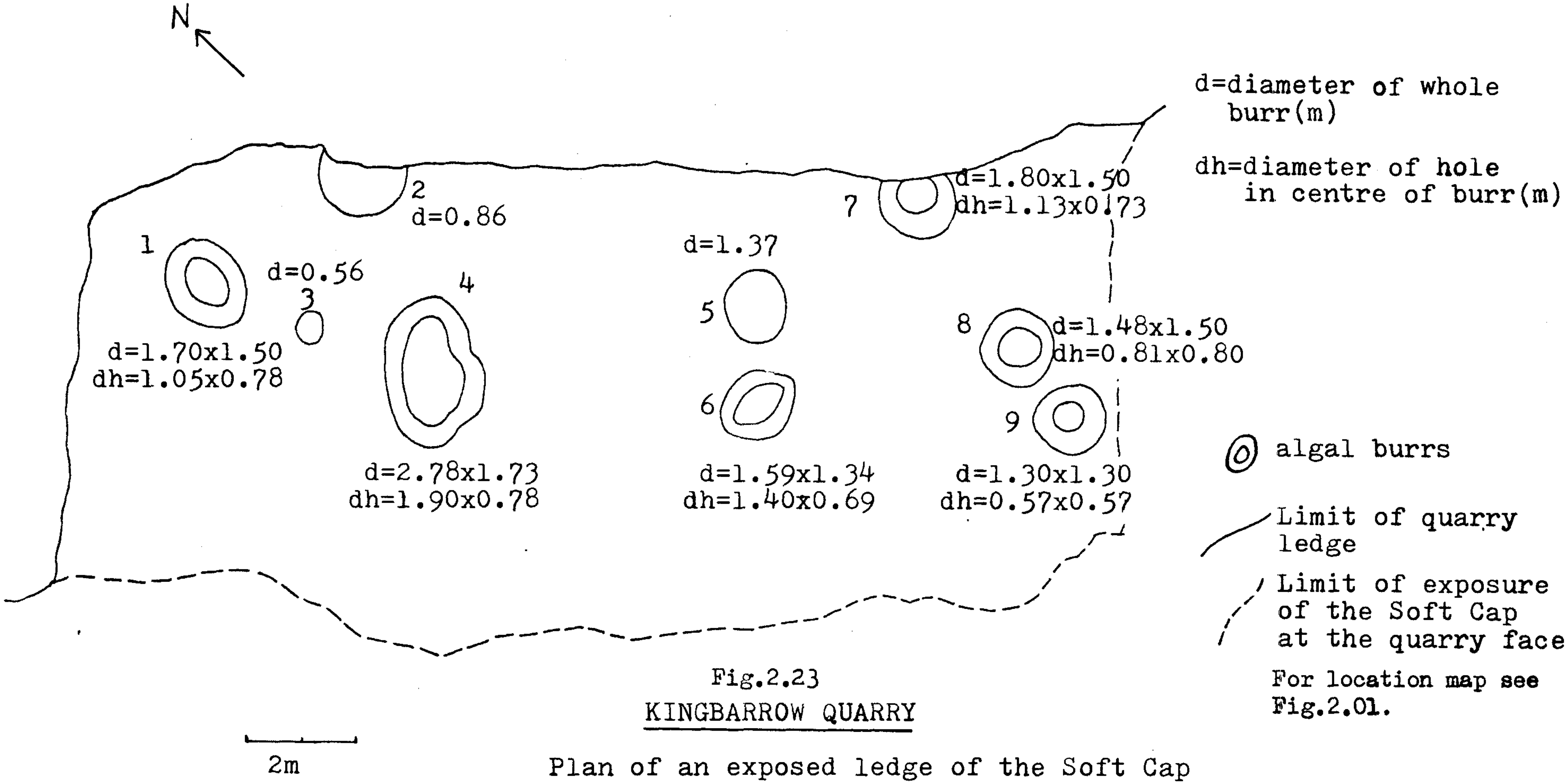


Fig. 2.22
COOMBEFIELD QUARRY

Plan of an exposed ledge of the Soft Cap showing the positions and dimensions of algal burrs.

d=diameter of whole burr
dh=diameter of central hole

For location map see Fig.2.01.



For location map see Fig.2.01.

Fig.2.23

KINGBARROW QUARRY

Plan of an exposed ledge of the Soft Cap limestone showing the positions and dimensions of algal burrs.

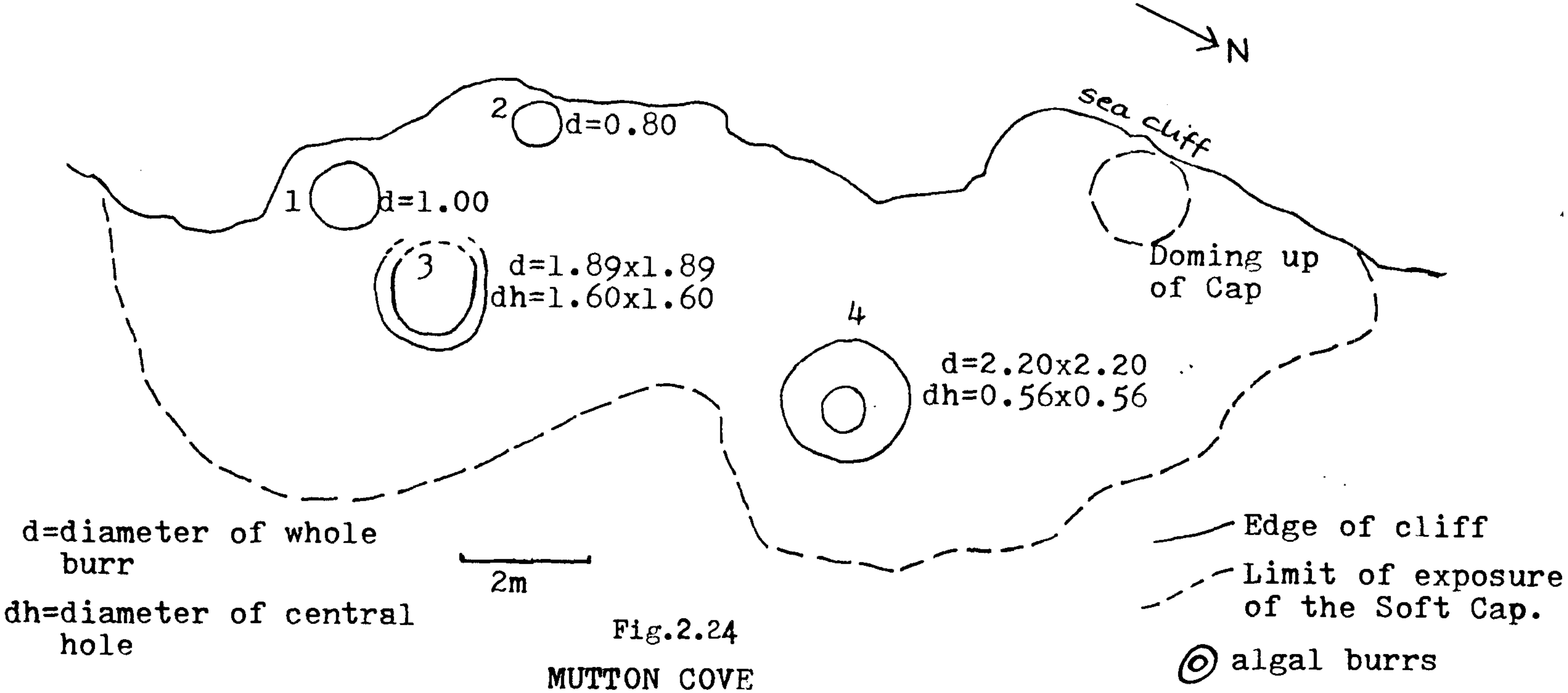


Fig.2.24

MUTTON COVE

Plan of an exposed ledge of the Soft Cap on the west cliffs, showing the positions and dimensions of algal burrs.

For location map see Fig.2.01.

boulder (22 x 15 cm) of limestone in the Great Dirt Bed. In contrast, in Independent Quarry on Portland (SY69477240) a large "closed" burr, 2·4m in diameter, encloses a short, silicified tree stump (25 cm in diameter) and in Broadcroft Quarry (SY69817211) a large fossil root in the Great Dirt Bed is similarly covered with a "closed" burr of algal limestone. Some "closed" burrs thus contain fossil wood but some do not and for the purposes of estimating the tree density in the fossil forest they are not considered to represent the former positions of in situ trees. However, it is noted that the estimate using only "open" burrs is probably slightly low since some in situ tree stumps are undetectable beneath "closed" burrs.

The spacing of the burrs was studied on cliff and quarry ledges where large areas of the algal stromatolitic Soft Cap and burrs were exposed. Suitable exposures were found in Coombefield Quarry (SY689704), Kingbarrow Quarry (SY691728) and Mutton Cove (SY698713) (all on Portland) and at the Fossil Forest (SY832796). Whereas the sites on Portland are relatively rectangular, the Fossil Forest exposure is linear, about 500m long and 2m across (Fig.2.21). At this locality there are also trough-shaped burrs (Pl. 1 , Fig. 2), which originally formed around fallen trunks. These were assumed to have fallen from tree stumps which were already represented by circular "open" burrs and were omitted from the calculations.

At each locality each burr (both "open" and "closed") was assigned a number and the various dimensions recorded. These included the diameter of the whole burr, the diameter of the central cavity (if present) at both the top and base of the hole, the total thickness of limestone from the top of the Great Dirt Bed to the top of the burr if possible (if not, then the thickness of the burr above the general level of the Soft Cap). If the "open" burrs were noticeably elongate the direction of elongation was recorded. The distance and direction between every possible pair of burrs in each area were also measured.

A plan (to scale) of the positions of the burrs at each locality was constructed using the measurements recorded and with the aid of photographs taken as high above the ledges as possible, usually from the top of the cliff or the quarry face.

The area of the Soft Cap exposed on ledges on Portland was deduced by counting the number of centimetre squares covered by the area on the scale map and converting the result to square metres. The area of Soft Cap at the Fossil Forest was estimated by cutting out pieces of card of the same area as the Soft Cap on the scale plan and weighing them. Pieces of card of a known area were also weighed and the area covered by the Soft Cap on the plan and then in the field calculated.

Data

The results of the measurements and calculations are recorded in Table 2.01. A total of 108 burrs were measured from the four localities, 56 of which were "open", having a central cavity which in all but 2 burrs was empty. Burr 3 at the Fossil Forest and Burr 1 in Coombefield Quarry contain a silicified tree stump and fragments of fossil wood respectively. The average radius of all the burrs was 0·78m (overall range 0·36 - 1·08m) and the average area covered by a burr was 2·05m^2. (range 0·41 - 6·07m^2). The area of the Soft Cap taken up by the burrs ranges from 7·33% to 13·60% at Mutton Cove and the Fossil Forest respectively (average 10·98%).

For all "open" burrs the average radius of the hole was 0·46m (range 0·10 - 1·02m). If these burrs were assumed to have formed originally around a tree stump then the cross-sectional area of the hole is equivalent to that of the tree which once occupied it. This measurement is approximately equivalent to the "basal area" of a tree, a statistic used in modern forest inventories and representing the cross-sectional area of 'breast height' (1·3m) (Cailliez 1980). The basal area of the fossil trees estimated from the area of the cavity in the burr may be slightly less than the true value since the outer portions of the fossil trees are not preserved; however the height of the measurement is lower than breast height. The average basal area of the Purbeck trees (i.e. the cross-sectional area of the trunk calculated from the dimensions of the burr hole) is 0·57m^2 (range 0·41 - 0·79m^2). The average portion of Soft Cap which is covered by the basal areas of the fossil trees is 1·50% with a range of 1·37% to 1·71% at the Fossil Forest and Coombefield respectively (this is based on the assumption that all "open" burrs represent the former positions of *in situ* fossil tree stumps).

The density of the forest at each of the four localities was calculated by counting the numbers of trees (i.e. "open" burrs) in the measured area. The density varied from 1 in 17m^2 (650 trees per hectare)

TABLE 2.01: Data on Dimensions and Distribution of Algal Burrs from four Great Dirt Bed sites.

	LOCALITY			
	Fossil Forest	King-barrow	Coombe-field	Mutton Cove
Total Number of Burrs	71	9	15	4
"Open" burrs	33	6	15	2
"Closed" burrs	38	3	0	2
Average radius of burr (cm) (Standard deviation in brackets)	83·3 (7·0)	85·9 (23·1)	68·6 (12·6)	73·8 (34·0)
Average radius of central hole in "open" burrs	36·8 (19·8)	57·3 (23·1)	35·1 (7·2)	54·0 (36·7)
Area of exposed Soft Cap m^2	1026	162	220	108
Average area covered by one burr m^2	2·18 (1·31)	2·46 (1·50)	1·59 (0·59)	1·98 (1·60)
% exposed Soft Cap covered by burrs	13·60	12·16	10·84	7·33
Average area of central hole m^2	0·52 (0·08)	0·41 (0·09)	0·29 (0·10)	1·13 (0·11)
% exposed Soft Cap covered by tree bases	1·37	1·54	1·71	1·39
Estimated basal area of fossil forests m^2 ha^{-1}	137	154	171	139
Estimated density of fossil forests:-				
all burrs	689 ha^{-1} 1 in 14m^2	400 ha^{-1} 1 in 20m^2	650 ha^{-1} 1 in 17m^2	600 ha^{-1} 1 in 18m^2
"open" burrs only	262 ha^{-1} 1 in 38m^2	300 ha^{-1} 1 in 27m^2	650 ha^{-1} 1 in 17m^2	200 ha^{-1} 1 in 54m^2

at Coombefield to 1 in $54m^2$ ($200\ ha^{-1}$) at Mutton Cove, with an average of 1 in $34\ m^2$ ($371\ ha^{-1}$).

The density of all the burrs ranged from 1 in $14m^2$ ($689\ ha^{-1}$) at the Fossil Forest to 1 in $20m^2$ ($400\ ha^{-1}$) in Kingbarrow Quarry, with an average of 1 in $17\ m^2$ ($585\ ha^{-1}$).

The calculation of the average shortest distance between two burrs (the nearest neighbour) was applied to the burrs in Coombefield Quarry. The burrs there are all "open" and spaced in an approximately rectangular area. The shortest diatance between the centre of a burr and its nearest neighbour ranged from 0•99m (where the edges of the burr actually touch) to 6•40m. The average distance was 2•14m. In Kingbarrow Quarry the average nearest neighbour distance for all burrs is 1•81m and for the "open" ones only is 3•20m, and at Mutton Cove the shortest distance between 2 burrs is 2 m. Evaluation of the nearest neighbour distance at the Fossil Forest would be misleading since the site is linear. Some burrs touch each other, others are spaced as far apart as 28m. In an area of limited exposure the value of the 'nearest neighbour' distance will always be an over-estimate since the nearest burr could be just out of the exposed area.

Discussion

From observations of burrs in the field it is apparent that the trees once within them grew in close proximity. This was previously noted by authors who were able to see directly the density of the fossil tree stumps on the undisturbed Great Dirt Bed as the quarrymen removed the overlying limestone. Damon (1884a) recorded 7 tree stumps and 2 cycadophyte stems in an area of a few square metres of the Great Dirt Bed on Portland and suggested that the trees once grew as close together as a modern forest.

The density of modern forests is recorded as the area of the forest covered by the total area of the trunks of the trees (basal area m^2/Hectare) (Cailliez 1980). For the Purbeck trees the diameters of the trunks were obtained from the diameters of the internal holes of "open" burrs. The measurement was taken near the top of the burr, at an average height of about 1•09m above the top of the Great Dirt Bed. Exposed cross-sections of burrs containing trees showed that this height was sufficient to avoid the thickening due to the roots.

The diameter of the fossil trees was estimated to range from 0•20 to 1•04m; the most common diameter was 0•6-0•8m. This does not account for the outer part of the trunk which was not preserved. This suggests that there was a considerable range in the size and presumably in the age of the trees present. The mean basal area for the four sites is 150 m^2 ha^{-1}. About 1-2% of the exposed Soft Cap is covered by the basal areas of the fossil trees (this does not include the roots which obviously occupy a much greater proportion). Comparable values for modern forests are difficult to find but a comparison can be made with the basal areas of forestry plantations in England; data obtained from forestry management tables (Hamilton and Christie 1971). For mature trees (26m tall) the basal areas range from 28 m^2 ha^{-1} (stands of European Larch) to 63 m^2 ha^{-1} (Red Cedar). The highest values recorded are those for high-yielding stands of Lawson Cypress and Red Cedar where stands of 80-year old trees have a basal area of 75•6 m^2 ha^{-1}.

The spacing of the in situ tree stumps which are uncovered in coal seams often gives some idea of the density of these more tropical swamp-like forests; for example, in the Tertiary brown-coal mines in Germany where fossils of Taxodium distichum and Sequoia langsdorffi are preserved (Stützer and Noé 1940). The trunks are remarkably large, some over 4 m in diameter, and their annual rings indicate that many lived for over 1000 years. The tree stumps are in situ within the seams and the trunks, some 60m in length, are found lying on its surface. A surface of 1000 m^2 is reported to have over 30 tree stumps of 1-3m in diameter on it (a density of about 1 in $33m^2$ or 300 ha^{-1}). From the plan of a coal mine showing the location of tree stumps on two seams (Keilhack in Stützer and Noé 1940, p.150) the basal area of one of the coal forests can be estimated to be about 214 m^2 ha^{-1}. The coal forest was considered to have been "dark and deeply shaded".

The estimated basal area or density of the Purbeck Great Dirt Bed forest is much greater than the managed forests in England but is not unlike that of the Tertiary coal forests. The Purbeck forest was clearly a closed forest with closely spaced trees. They probably had a wide age range and many were of considerable diameter so their basal areas would have been greater than, for example, a stand of trees of all the same age.

An estimate of the density of the Great Dirt Bed forest based on the "open" burr spacing could also be exaggerated if some of the burrs had originally contained cycadophyte stems. These plants were smaller and could grow more closely together. Some of the burrs may have formed around broken tree stumps which were dying when the forest was flooded. Some of the trunks appear to have fallen onto the palaeosol before the water level rose. These broken in situ stumps, although later preserved in burrs, would not be competing for light or soil nutrients so adjacent trees could grow larger or new trees grow nearer.

In conclusion, despite the many problems of estimating tree density from the distribution of burrs, it is clear that the trees in the Great Dirt Bed grew closely together and formed a closed forest with a high basal area. It may seem surprising that a forest of such stature grew in semi-arid conditions, when in modern times similar areas are covered by grassland or rather low scrub vegetation. The explanation for this paradox may lie in the almost total destruction of natural vegetation in semi-arid areas by man (Specht 1969). Forests in their condition are very vulnerable to fire and the wood is in demand for fuel and building material. A combination of fire, felling and grazing has probably eliminated former forests which might have provided useful comparisons with the Purbeck forests. However, it is clear from the data presented here that high forests with large trees covered extensive areas in the early Purbeck.

CHAPTER 3

THE BASAL PURBECK DIRT BEDS

3.1 Introduction

The study of fossil soils and their relationship with the landscape in which they formed (palaeopedology) has been receiving more attention recently as a result of the recognition of their potential as stratigraphic marker horizons and palaeoclimatic indicators (Buurman 1975). Soils in Quaternary sediments have received most attention, whilst only a few older palaeosols have been studied (Ortlam 1971; Terrugi and Andreis 1971; Retallack 1976, 1977; Buurman 1980; Riding and Wright 1981). Little is known about the persistance of soil features over long periods. Diagenetic and lithogenetic changes may have altered the chemistry, mineralogy, even the soil morphology. Even the definition of a soil varies from the sedimentological root or vegetated horizon to the pedological unit with some soil characteristics but not necessarily with plants. Several factors in modern soil descriptions, such as the true thickness, the chemistry and the soil-plant interactions,cannot be compared to fossil soils so only tentative identifications of palaeosols can be made.

The Purbeck Dirt Beds, in particular the Great Dirt Bed, are undoubtedly fossil soil horizons since the remains of fossil trees are preserved in situ within them. Although the Great Dirt Bed has a relatively well-preserved profile, the Basal and Lower Dirt Beds would probably not be regarded as palaeosols if the plant material was absent. Since the morphology of a soil is the most enduring characteristic, the study of the Dirt Beds has been based on field and thin-sections descriptions and comparison with modern soil sections. Complete chemical analysis would be of use for geological interpretation only if accompanied by similar work on adjacent sediments, so this was not attempted, apart from a preliminary study of the trace elements in the palaeosols.

Although palaeosols have been used as stratigraphic marker horizons (Buurman 1975), a feature of modern soil types is their occurrence in areas of limited lateral extent. Change in the lithology of the Dirt Beds was observed over the outcrop area and so this was further examined on a morphological basis.

3.2 Petrographic Descriptions

3.2 i The Great Dirt Bed

The Great Dirt Bed has a thicker (10-25 cm) and better developed profile than the Lower and Basal Dirt Beds. Although it laterally merges into clay horizons, it clearly represents a fossil soil in the Lulworth and Portland area where large silicified conifers are rooted *in situ* within it. Here it consists of a black, carbonaceous, calcareous clay containing black and white limestone pebbles. The top of the Dirt Bed is level and marked in most cases by a 2-3 cm black band consisting almost entirely of organic matter. This is overlain by algal stromatolitic limestone though in places a 1-2 cm band of mottled micrite separates them. There is very little mixing of the top of the Dirt Bed into the limestone above.

The base of the Great Dirt Bed grades down into the rubbly top of the Hard Cap below. The black or dark brown marl has a waxy, granular structure and does not break up into large blocks or peds (Brewer 1964) but crumbles when dry into small aggregates of grains and adheres to pebble exteriors. Horizontal, organic-rich streaks of a black lignitic material (up to 30 cm long, 4-5 cm wide) are common in many sections and appear to represent fossil roots. Silicified tree roots are also found spreading laterally through the marl.

The matrix of the Great Dirt Bed (the marl between the pebbles) has a continuous distribution of grain sizes from clay particles to limestone pebbles. It is convenient to use the pedological terminology of Brewer (1964) and call this the S-matrix, consisting of skeleton grains (e.g. small clasts), voids and plasma (the fine-grained fraction). An upper size limit of 2 mm is taken to separate the pebbles from those considered to be skeleton grains in the S-matrix.

The skeleton grains consist mainly of pellets but also include a few small calcitised gypsum pseudomorphs (most with oolitic coatings) and clasts of microcrystalline calcite containing well-preserved pollen grains. These skeleton grains are included in a plasma of organic material, clay minerals and microcrystalline calcite. The S-matrix tends to 'flow' around the limestone pebbles. Silt and sand-sized sub-angular quartz grains (7-120 μm) are more common in this dirt bed than the others, constituting about 4-5% of the S-matrix. There is, however, no secondary silicification of the S-matrix.

The nature of the primary voids is difficult to determine since the S-matrix is always disturbed during collection and impregnation. Likewise the presence of burrows is not clear. No signs of extensive bioturbation either by roots or animals are evident.

The base of the Great Dirt Bed, infilling hollows in the Hard Cap, is lithified to a much greater extent than the top and aggregates of pebbles can be collected, particularly from the Fossil Forest. The carbonaceous S-matrix is absent and instead the pebbles are cemented together by microcrystalline calcite or pelmicrite. Areas with a "net-texture" (West 1979_a of micrite enclosing calcitised evaporites occur between pebbles, as do rinds of brown fibrous calcite. Many pebbles, which here are in contact, have rims or cutans of concentrically-banded fibrous calcite, clay or organic material (organo-argillans). Many clasts, particularly pellets, have pisolitic-type coatings of irregular layers of fibrous calcite and grey/brown micrite (Pl.7, Fig. 2).

In the south-east of Portland the Great Dirt Bed has an S-matrix of microcrystalline calcite, pelmicrite and microspar. The black organic matrix is absent here. Some organic matter is present only as clean, relatively well-preserved pieces of cuticle and pollen between the pebbles. There are no replaced evaporites in the matrix here, only in the pebbles, nor do any pebbles have cutans of any sort. The range in pebble size is much smaller (2-8 cm only), although large boulders of limestone (up to 28 cm) are present. The pebbles are cemented together and cannot be individually removed as is possible in the black marl.

3.2 ii The Basal and Lower Dirt Beds

These two Dirt Beds are lithologically very similar. Where they are well developed (e.g. the Basal Dirt Bed at God Nore, the Lower Dirt Bed at Sheat Quarry) both consist of an upper black carbonaceous layer, underlain by a dark brown marl which itself grades into a white marl at the base. At many localities only the brown marl is present. Lamination is generally not strongly developed but instead consists of short, horizontal streaks of black organic material, brown clay or white carbonate. Small streaks or lenses, a few millimetres long, of very fine-grained, white carbonate are common in both Dirt Beds.

Plate 6

The Great Dirt Bed

1. The black, marly Great Dirt Bed containing black and white limestone pebbles in Wakeham East Quarry, Portland. Silicified wood has been found lying on the top of this palaeosol. The depression near the hammer is filled with cemented nodules of buff-coloured limestone with laminar rinds and calcrete features similar to those of Plate 7.

2. The black, marly Great Dirt Bed at Dungy Head. This section shows the nodular, rubbly surface of the underlying Hard Cap grading into the palaeosol. Some of the white pebbles have cupped upper surfaces similar to those observed in modern calcrete profiles (see section 3.5 ii). (At this locality the strata have a vertical orientation).

3. The Great Dirt Bed at Broadcroft Quarry, Portland (SY 698721). Several silicified tree stumps are preserved *in situ* in this palaeosol in this quarry.

4. and 7. The matrix of the black, marly Great Dirt Bed. The fine-grained 'plasma' consists mostly of decayed, amorphous organic matter with some clay minerals and microcrystalline carbonate. The 'skeleton' grains consist of small clasts of micrite and quartz silt. (Admiralty Quarry, Portland. XPL. Araldite-impregnated).

5. The Great Dirt Bed at Freshwater Quarry, Portland (2 m north of God Nore). The matrix consists of micrite and patches of microspar with black and white limestone clasts showing calcrete textures.

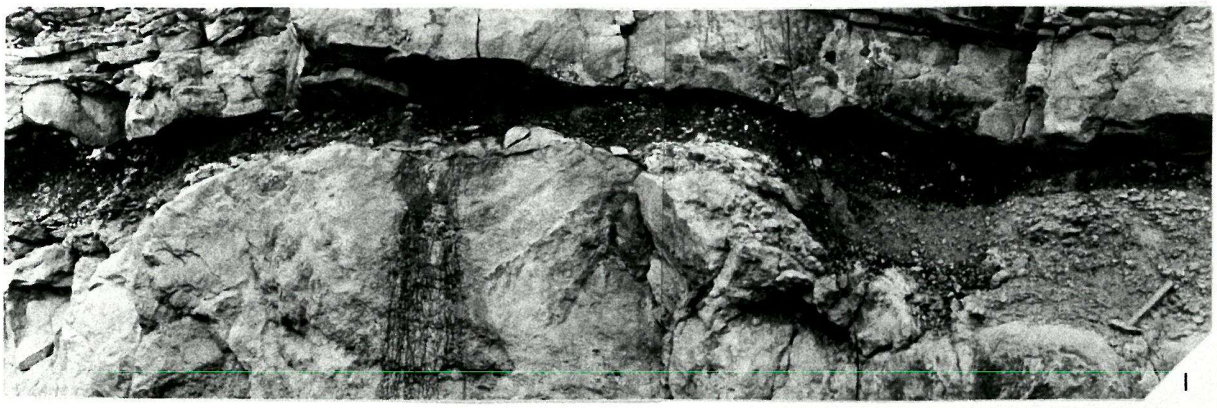
6. The Great Dirt Bed, about 5 m south of God Nore, consists of a 20 cm bed of pebbly, 'reworked' Dirt Bed with a micrite matrix overlying 5 - 20 cm of black and white limestone pebbles with a sparce organic-rich matrix which infill hollows in the top of the Hard Cap.

8. The Great Dirt Bed at God Nore, Portland. As opposed to the large rounded pebbles in the black marly Dirt Bed, the pebbles here are smaller and more angular though of similar composition. The matrix here consists of microcrystalline carbonate. Although organic material is much rarer here, plant cuticle and pollen has been found (Plate 12) which is well preserved. (Polished slab).

9. The top of the Hard Cap at God Nore, Portland, showing black and white limestone pebbles in a mottled micrite matrix. Many of the pebbles have small laminar calcrete rinds. (Polished slab).

10. The Great Dirt Bed and Soft Cap at God Nore, Portland. The top of the Hard Cap becomes nodular and grades into the pebbly Dirt Bed above. Black and white limestone pebbles in a sparse black matrix of organic matter infills hollows below. The finer-grained, micritic limestone overlies this. Laminae with compressed shoots were discovered here (those in Plate 12, Fig. 1). A thin, black organic-rich layer covers the Dirt Bed, underlying the algal-stromatolitic limestone of the Soft Cap.

(Hammer handle length 27 cm. Lens cap diameter 7 cm)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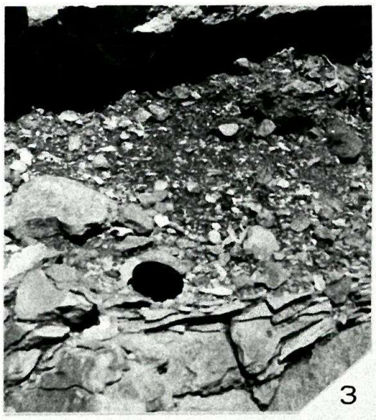
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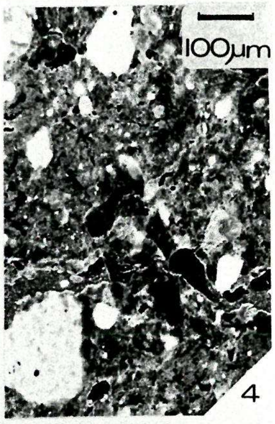

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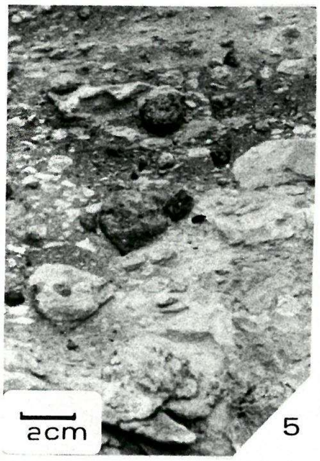

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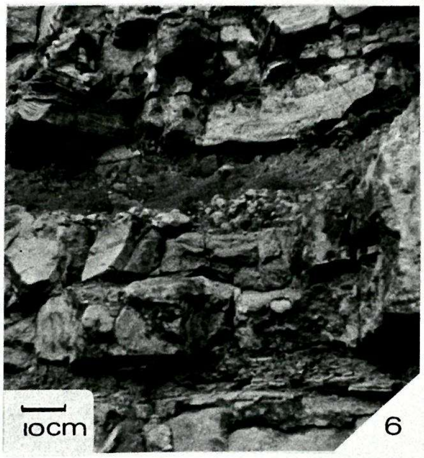

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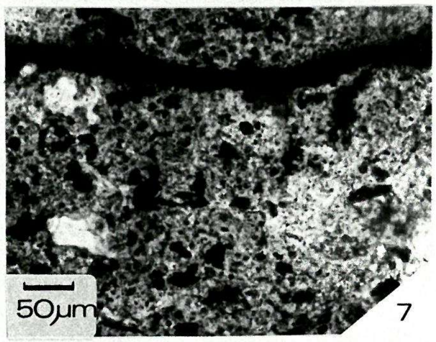

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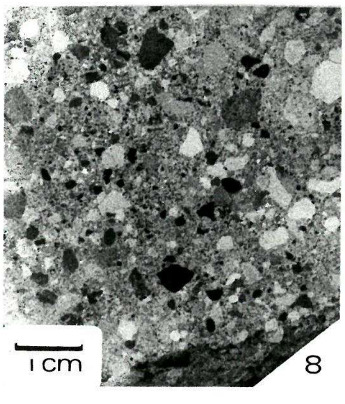

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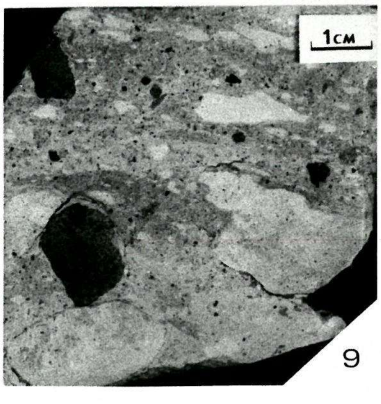

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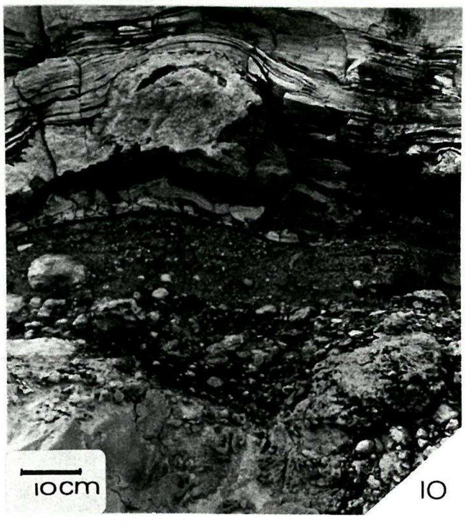

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PLATE 6

The top of each Dirt Bed has a fairly sharp contact with the overlying bed which is usually a thin band of micrite; the organic material from the upper carbonaceous layer has not been reworked into the overlying micrite. The Basal Dirt Bed is generally horizontal, lying on the level top of the Basal Cast Bed below. The Lower Dirt Bed, however, lies over the irregular relief of the algal limestone mounds at the top of the Skull Cap and subsequently thickens where it draped into hollows and thins over the top of mounds; this is particularly conspicuous at Dungy Head and on the south of Portland. The mark increases in thickness around tree roots, e.g. up to 10 cm at Chalbury Camp. There is no rubbly weathered zone at the base of these marls; the basal white marl simply grades into the limestone below. At Holworth House, however, a zone of mottling (Pl.4 , Fig. 8) separates the dark and light layers.

No significant plant remains have ever been found in the Basal Dirt Bed, although at Bacon Hole the upper part of this bed has a black sooty texture and contains many black shiny fusinite fragments with well-preserved wood structure. In contrast the Lower Dirt Bed contains the silicified remains of large conifers which are rooted _in situ_. On Portland silicified cycadophytes were often found in this horizon (Fitton 1836). Silicified and lignitic roots occur, particularly in association with the large tree trunks at Chalbury Camp and Poxwell. The black lignitic roots are difficult to detect in the dark layers of the Dirt Bed but are conspicuous within the basal, paler marl, e.g. at Sheat Quarry (Pl.12 , Fig.6), Dungy Head and Holworth House.

The Basal and Lower Dirt Beds are petrographically very similar and differences in colour are determined by the amount of organic matter present. The dark layers are composed almost entirely of small fragments of organic matter some of which are botanically recognisable (cuticle, pollen, resin etc.), while others are amorphous. The matrix consists of small (1·5 - 8 μm) grains of carbonate with random orientation but in places the organic matter is arranged in small, discontinuous laminae. The white streaks seen in hand specimens consist of lenses of microcrystalline calcite, up to 2-3 mm long, 300 μm wide, often showing a 'pinching' and 'swelling' texture. The edges of these clasts are diffuse and merge into the matrix. Some larger clasts contain flecks of organic material.

At some localities the Lower Dirt Bed is fairly well laminated and larger pieces of plant material occur in horizontal layers. At Sheat Quarry horizontal, elliptical root moulds (about 4 mm long x 0·5 mm high) are common and are filled with opaque black lignite. Pollen grains (of cycadophytes in particular) were found in these layers.

Detrital quartz grains are uncommon in these Dirt Beds though a few silt-sized, sub-angular grains of quartz and irregular chert clasts (90-800 μm) enclosing small (18-24 μm) pyrite clasts are present. Large, single calcite crystals (140 μm) are scattered throughout the Basal Dirt Bed, many of which have been penetrated by fungal hyphae (5 μm in diameter). Small unidentifiable fragments of bone have also been found. As with the Great Dirt Bed there is no clear evidence of bioturbation or disturbance due to soil organisms.

At Worbarrow and Bacon Hole the Lower Dirt Bed becomes a well-laminated black and white shale with horizontal, continuous laminae, 20-500 μm thick. The base is predominantly black at Bacon Hole and many fish scales and crushed ostracod carapaces are preserved on the laminae surfaces. The presence of the fish scales and the carapaces of conchostracan branchiopod crustaceans clearly indicate that this was a fresh or brackish water deposit, not a soil.

3.3 Identification of the Palaeosol Profiles

3.3 i The Great Dirt Bed

Since its formation as a forest soil the Great Dirt Bed has undergone many diagenetic changes. Its mineralogy and geochemistry would have been most susceptible to change, but its morphology appears relatively unchanged, apart from the probable removal of the upper layers by the incoming waters and thinning due to compaction. The part of the Great Dirt Bed considered here as a true palaeosol is that which occurs over the area from Dungy Head to Bacon Hole and on the Isle of Portland.

Using the modern method of soil description (Curtis et al. 1976) the Great Dirt Bed can be characterised as outlined below. This description is an average profile based on several samples.

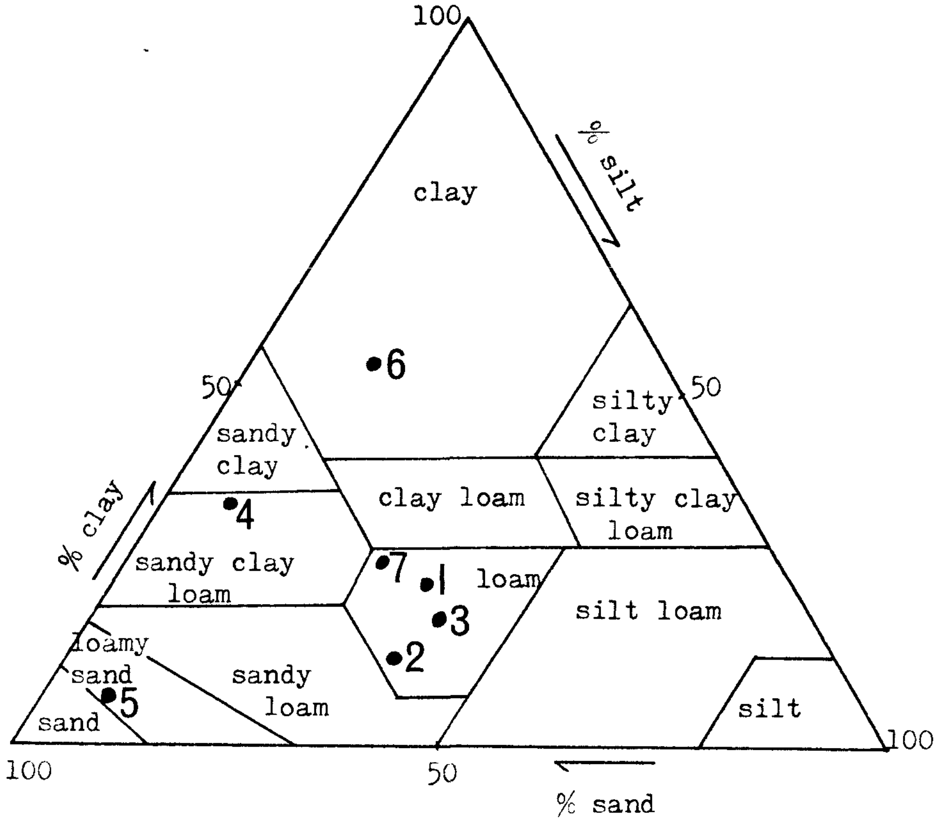


Fig.3.01 Soil texture analysis of the basal Purbeck Dirt Beds compared to some modern rendzinas.

1 Great Dirt Bed: Perryfield Quarry, Portland.
2 Lower Dirt Bed: Perryfield Quarry, Portland.
3 Basal Dirt Bed: Wakeham East, Portland.
4 Modern rendzina, south Australia (Norrish & Rogers 1956)
5 Modern rendzina, Seychelles (Lionnet 1952)
6 Modern rendzina, south Australia (Stace 1956)
7 Calcareous alluvial soils, Iran (Abtahi 1980)

Horizon		Description
A_1	1-2 cm	Black, organic-rich layer without carbonate nodules. (This horizon is sometimes absent)
A/C	10-25 cm	Dark brown/black marl with granular texture incorporating organic-rich, lignitic laminae and black and white limestone pebbles. Lower part contains pebbles with rims and/or cement of secondary carbonate. Pebbles near the base grade into C below.
C	10 cm+	Rubbly, nodular parent rock of pelletoid, partly oolitic limestone.

The profile is simple with one main undifferentiated horizon of variable thickness grading into the parent limestone from which the pebbles are derived. In places the lower pebbles are cemented by secondary carbonate and the boundary (A/C) is much sharper. There are no conspicuous paler leached horizons or red layers of iron accumulation. The upper organic-rich layer is probably a remnant of a much thicker layer.

In a modern soil the proportions of clay, silt and sand determine to a large extent the soil texture and other soil properties. Mechanical analysis of particle sizes was determined for a typical Great Dirt Bed profile at Perryfield Quarry. The particle size classes of Buol et al. (1979) were used (sand 2 mm-50 μm, silt 50-2 μm, clay < 2 μm), and separated by the method described in the appendix. The results are given in Table 3.01. When plotted on a soil-texture diagram the Great Dirt Bed is texturally classified as a loam (Fig.3.01) although it is highly likely that this texture is mainly a result of diagenetic alteration resulting in the decrease of particle sizes.

The diagnostic features of the Great Dirt Bed important for classification include i) the simple A/C profile (or A_1/A-C/C) and lack of well-delineated horizons, ii) the dark, organic-rich calcareous solum, iii) the calcareous parent rock and iv) the incorporation of primary carbonate nodules derived from the underlying bedrock. The identify of the palaeosol profile under various schemes of soil

TABLE 3.01: Analysis of Some Constituents of the basal Purbeck Dirt Beds

	% Sand	% Silt	% Clay	% $CaCO_3$	% Organic Matter
Great Dirt Bed	40·3	36·0	23·7	50·5	2·95
Perryfield Quarry				52·94 o	2·95 o
Lower Dirt Bed	48·9	38·0	13·0	58·9	0·91
Perryfield Quarry				63·0 *	2·26 *
Basal Dirt Bed	41·4	40·6	18·1	88·4	0·34
Wakeham Quarry				70·7 +	1·41 +

o Average value for all samples of Great Dirt Bed.

* Average value for all samples of Lower Dirt Bed.

\+ Average value for all samples of Basal Dirt Bed.

classification is as follows:

i) Original soil classification for England and Wales.
(after Avery, in Curtis *et al.* 1976)

Group IV Soils of the Calcareous Group
(Developed from calcareous parent rock;
containing primary carbonate

Subtype: Rendzina
Gray calcareous soils - dark surface horizon, high organic content. $CaCO_3$ decreases down to parent material. Secondary deposition of $CaCO_3$ may occur.
Red or Brown calcareous soils - on hard limestone, shallow, low in organic matter. Contains fragmentary calcareous rock and secondary $CaCO_3$

ii) New Soil Classification for England and Wales 1973
(Curtis *et al.* 1976)

Major Group	Group
Lithomorphic A/C soils	Rendzina over calcareous, non-alluvial material, fragmented limestone or chalk.

iii) American classification 1949

Order	Suborder	Great Soil Group
Intrazonal	Calcimorphic	Rendzina
(No climatic influence)		(Brown Forest Soil)

iv) 7th Approximation, U.S.Dept. of Agriculture, 1960
(in Hunt 1972; Ragg & Clayden 1973)

Order	Suborder
Mollisol	Rendoll
Calcareous soil, dark A horizon on calcareous parent rock.	

A firm identification of the Great Dirt Bed palaeosol according to modern soil groups is not possible, nor justified, due to its imperfect preservation, diagenetic alteration and different Jurassic vegetational and climatic patterns. Consequently the Great Dirt Bed could possibly be referred to as an entisol or litho sol (young, immature soils) or an aridosol (soils of arid regions) (U.S.7th Approximation, Hunt 1972). However,in comparison with modern soil descriptions the Great Dirt Bed is most similar to modern rendzinas with simple A/C profiles, characterised by an upper dark, organic layer (mollic epipedon) and the material below containing more than 40%$CaCO_3$ with carbonate pebbles

(Ragg and Clayden 1973).

Rendzina soils are said to be intrazonal since they are found in many climatic zones. Their character is determined by the nature of the calcareous parent rock rather than by climate, as are zonal soils. In England rendzina soils are most commonly developed on chalk. A typical profile in Sussex consists of a dark brown, highly calcareous clay with 1-15 cm subround chalk fragments overlying closely packed rubble on top of the parent chalk. This has an A/A - C/C profile. In the tropical climate of the Seychelles (latitude 4-5°S) rendzina soils supporting coconut palms occur on coral limestones along coastal plateaux. A very simple A/C profile of 2-30 cm of black loamy sand overlies white calcareous sand (Lionnet 1952). In this case a hard calcareous layer (80-90% $CaCO_3$) had accumulated at the water table level.

Rendzinas and their iron-rich equivalents, terra rossas, are common in regions with a Mediterranean-type climate. In the Mediterranean region itself terra rossas, with their characteristic red coloration, are dominant (Klappa 1967; Townsend 1973) but in slightly less arid regions the black rendzinas occur. In the semi-arid region of South Australia rendzina soils have formed on dunes on the Eyre Peninsula and near the Coorong (Stace 1956). A typical profile consists of 0·6 - 1·0 m of granular, black loamy clay with carbonate nodules. The carbonate content is often so high that the soil appears pale grey. A hard band of secondary carbonate occurs just above the parent rock. Large clasts of the underlying slates (the Adelaide Series) are often incorporated into the soil matrix (Norrish and Rogers 1956).

Soils have been described from Iran (Abtahi 1980) which have a similar loam texture (Fig. 3.01) but are not strictly rendzinas as they do not have dark organic layers. Developed on calcareous alluvial fan material they range from very immature to highly saline, mature soils with relatively increasing carbonate accumulations (cambic, calcic and petrocalcic layers). They support only a sparse vegetation of shrubs, grasses and halophytes.

Morphologically the Great Dirt Bed palaeosol is very similar to modern rendzinas and this is largely confirmed by more detailed analysis (Table 3.02). The organic matter (or carbon) content is slightly lower than modern rendzinas (1·71% as opposed to 4·2% in a rendzina from Adelaide, Table 3.02). Despite the low value, in thin section the dark

TABLE 3.02: Analysis of Some Rendzina Soils compared to the Great Dirt Bed.

		% Sand	% Silt	% Clay	% Organic carbon	% $CaCO_3$	pH
Great Dirt Bed		40·3	36·0	23·7	1·71	50·5	-
B Seychelles		85·0	2·0	6·0	5·08	80·0	8
C South Australia		59·0	7·0	34·0	-	-	-
D Adelaide	(Top)	36·0	16·0	48·0	4·2	-	8·5
	(Base)	30·0	15·0	55·0	3·8	-	8·7
E South Australia		-	-	-	0·7-15·3	1·5-93	8·5
F England	(Top)	16·0	42·0	14·0	(Org M)9	19·0	8·1
	(Base)	4·0	37·0	12·0	1	46·0	8·3
G Iran	Soil with cambic horizon	46·0	38·0	16·0	1·1	55	8·0
	Soil with calcic horizon	44·0	30·0	26·0	0·38	41	7·9

Source

B	Lionnet (1952) (24/49A): rendzina on calcareous coral sand.
C	Norrish & Rogers (1956): rendzina on calcareous slates.
D	Stace (1956): typical rendzina profile, near Adelaide.
E	Stace (1956): rendzinas on calcareous slates.
F	Townsend (1973): rendzina on chalk.
G	Abtahi (1980): immature calcareous soils on alluvial fans.
_	Data not available.

colouring does appear to be due to the presence of minute plant fragments and amorphous humic material. Modern alkali soils in high temperature regions tend to produce darker, more humic soils than those of humid regions (Robinson 1949). The blackening could also be due in part to the presence of elementary carbon produced by charring of plant material by fire, evidence of which is found in the Great Dirt Bed as fusinite (see 4.3).

The dark colour of the soils may also be related to the clay content. On tropical Barbados the colour of the "Black Association" clayey soils formed on coral limestone (Vernon and Carroll 1965) is probably due to the sorption of organic matter on the montmorillonitic clays. Dark coloured, clay-organic complexes form when organic matter and montmorillonite occur in clay soils, including rendzinas (Singh 1956; Juo and Barber 1970). However this process requires acid, anaerobic conditions and since most dark soils are found in semi-arid climates such conditions would exist during the wet period of seasonal climates.

Modern rendzinas are typically grassland soils (Hunt 1972) and abundant grass roots yield a high organic carbon content. They are an immature form of the thicker chernozem soils, grassland soils of semi-arid and humid climatic regions which have a very thick organic-rich horizon (A) up to 150 cm deep, a zone of carbonate accumulation (Cca) and a parent rock usually consisting of loess (Townsend 1973). Unlike rendzinas they do not specifically require a calcareous parent rock. The Great Dirt Bed was compared to a chernozem by Müller (in Damon 1884a) by virtue of its organic content, but chernozems rarely contain primarily carbonate nodules and they usually have a much thicker profile than the Great Dirt Bed.

Prior to the advent of the angiosperms, the Jurassic vegetation was dominated by gymnosperms (Wesley 1973) thus it must be considered that the relationship between vegetation and soil types today (such as grasslands on rendzinas) are not necessarily applicable to the Jurassic. Likewise the presence of a broad, equable climatic zone spanning the Equator in the Mesozoic (Barnard 1973), rather than the narrower, more variable, climatic regions today, would probably have restricted the range of soil types formed. Therefore, although the Great Dirt Bed palaeosol supported coniferous forests, the soil morphologically resembles an immature soil developed on a calcareous parent rock, a modern rendzina.

3.3 ii The Lower and Basal Dirt Beds

Identification of these two palaeosols is much more difficult since their profiles are not well developed and in some places the beds are only a few millimetres thick.

Where they are reasonably well developed, for example at Sheat Quarry and God Nore respectively, both have a similar profile, described below (an average of several samples).

Horizon (unclear)		Description
? A_1	0-2 cm	Upper dark brown, brown/black carbonaceous layer. No carbonate nodules.
? A/C	1-8 cm	Mid brown clay with horizontal streaks of lignite (roots?), carbonaceous material and small streaks of white carbonate. No mottling of bioturbation.
? C	0-4 cm	Pale brown/cream marl with very little organic matter, grading into limestone below.

At most localities only the central brown layer is visible or the whole bed may be completely absent, especially over mounds in the underlying limestone. The thinness of these Dirt Beds suggests that a great deal of soil was lost before the overlying limestone was deposited or reduced in thickness by compaction. Their interpretation as palaeosols would be dubious if it were not for the occurrence of large conifers rooted _in situ_ in the Lower Dirt Bed, and its similar morphology suggests that the Basal Dirt Bed was also originally a soil.

These Dirt Beds are texturally similar to the Great Dirt Bed (Fig. 3.01, Table 3.01). The organic carbon content decreases and the carbonate content increases from the Great Dirt Bed through to the Basal Dirt Bed, suggesting a significant decrease in the amount of organic matter originally available in the later palaeosol, perhaps due to a much sparser vegetation.

Comparison with modern soils with such thin and poorly preserved palaeosols is difficult but since they are developed on calcareous bedrock and have a high carbonate content they could be an immature form of calcimorphic, rendzina-like soils. The weak lamination and lack of many limestone pebbles suggests an alluvial origin for the original clays.

The equivalent horizons east of Lulworth have previously been regarded as palaeosol horizons (West 1975). The Basal Dirt Bed contains abundant fossil charcoal and plant remains at Bacon Hole and Worbarrow and most probably represents a palaeosol here, though it cannot be traced further east. The Lower Dirt Bed is clearly not a palaeosol at Bacon Hole and Worbarrow since it became a well-laminated black and white shale containing fish-scales, ostracods and branchiopod carapaces. Its organic matter content is noticeably higher than the true palaeosols (10·95% as opposed to 2·26%); in thin section the black laminae appear to consist almost entirely of organic matter. This suggests that the organic matter was less readily oxidised than in the soils, perhaps because of anaerobic conditions and reduced microbiological activity. This is the reason suggested by Hunt (1972) for the higher organic content of bituminous rocks and shales than that of soils. The dark laminations in the Lower Dirt Bed at Bacon Hole thus suggest that periodic anaerobic conditions occurred, preserving incoming organic matter (presumably from the soils in the west) and possibly killing fish and the other fauna, which are now found in abundance on the dark laminae.

Other clays from Fisherman's Ledge (C17) and Durlston Head (C16), though not directly correlatable with the Lower Dirt Bed elsewhere, also have a high organic content (12·7 and 10·7% respectively), suggesting that they are not fossil soils but water-deposited sediments.

3.4 Trace Element Analysis of the Dirt Beds

A complete chemical analysis of the Dirt Beds was beyond the scope of this project. The geochemistry is a feature of palaeosols most susceptible to diagenetic change (Retallack 1976) and comparison with the detailed and complicated chemistry of modern soils would be invalid. Of the few palaeosols described, morphological descriptions are most useful (Yaalon 1971; Retallack 1976, 1977; Burgess 1960; Buurman 1975, 1980; Riding and Wright 1981).

Trace elements in soils are not as mobile as the major elements, and in shales it has been suggested that trace element content is not seriously modified by post-depositional changes (Potter et al. 1963).

Selected elements were analysed for in the Dirt Beds.

In many modern non-alluvial soils the trace element content is dependent to a large extent on the parent rock composition from which the bulk of the soil material is derived (Mitchell 1964). To comprehend the full implications of trace element concentration in the Dirt Beds would necessitate comparison with similar data from other Purbeck shales or palaeosols, and particularly from adjacent basal Purbeck limestones. In isolation, data from the Dirt Beds has limited value and is only discussed briefly here.

The Great Dirt Bed generally has a higher concentration of trace elements (apart from V and Ni) than the thinner Dirt Beds. This may be the result of this soil containing a higher proportion of residues from the parent rock. The three Dirt Beds have little similarity to any particular source, based on comparisons with world average trace element concentrations in limestones, shales and modern soils (Table 3.03). For most elements they tend to have concentrations midway between those of limestones and shales. The range of trace element content of modern soils is vast and dependent upon many factors such as parent rock, vegetation and climate (Bowen 1977), and so similarity between the Purbeck palaeosols and mean values in modern soils is not to be expected.

The trace element content of a typical modern rendzina is given by Oertel (1961):

	CO	Cu	Mn	Mo	Zn
A horizon	6•8	44	335	5•8	71
C horizon	2•7	23	190	7•4	40

Although these values are of the same magnitude as Dirt Bed values, the comparison is no stronger than other values from Table 3.03.

Analysis of the individual data indicates significant correlations between the quantities of the various elements in the non-carbonate fraction (Rb, Ti, Zr, Pb, V, As, Mn, Mo, Ni and Cu); there were also some correlations, though less significant, between these elements and organic carbon. Amounts of Cr, Sr and $CaCO_3$ vary independently of the other elements investigated in all three Dirt Beds.

An interesting result arising is the anomalously high Sr content, 1432 ppm average in the Great Dirt Bed reaching up to over 4000 ppm in

TABLE 3.03: Trace Element Content of the basal Purbeck Dirt Beds compared to world averages for Limestone, Shales and Modern Soils

		A		ppm	B	
Trace Element	Great Dirt Bed	Lower Dirt Bed	Basal Dirt Bed	Limestone	Shale	Soil
Sr	1432	795	843	610	300	250
Rb	113	43	31	52	160	150
Ti	2287	1277	875	300	4600	5000
Zr	112	65	59	20	160	400
Mo	17	14	9	0·16	2·6	1·2
Mn	274	152	129	620	850	1000
Ni	26	39	31	7	68	50
Cu	21	18	19	5·5	39	30
V	67	83	75	45	130	90
Zn	51	39	49	20	120	90
As	21	16	13	1	13	6
Cr	59	55	55	11	90	70
Pb	19	11	11	5·7	23	35

A Average values for basal Purbeck Dirt Beds based on 15, 11 and 6 samples respectively. (Samples consist of all particle sizes less than 2 mm.)
(For individual values see appendix)

B World averages, compilation from many sources in Bowen 1977.

one case. A similar anomaly was observed by El-Shahat (1977) from analyses of Middle Purbeck limestones and shales. Here the high Sr content was the result of rapid burial of the sediments, preventing the loss of Sr^{2+} which was released during the aragonite-calcite transition in mollusc shells.

The loss of Sr from sediments occurs during early diagenesis before major cementation or lithification, when aragonite changes to calcite (Kahle 1965). Sr is primarily incorporated into the aragonitic structure but during the subsequent change to calcite the Sr^{2+} ions cannot be accommodated in the calcite structure and thus are usually flushed out of the sediment. Therefore, although the Sr content of Recent aragonitic sediments is about 10,000 ppm, that of ancient calcitic limestone is only, on average, 610 ppm (Kahle 1965).

Some of the Sr may be reprecipitated as strontianite ($SrCO_3$) or celestite ($SrSO_4$), the secondary mineral common in limestones in east Dorset (West 1964). To check for the presence of celestite, samples of the Dirt Beds, some untreated and some treated with HCl, were reanalysed for Sr by atomic absorption spectroscopy. These results supported the original (XRF) data proving that the Sr was present in the carbonate fraction and therefore not present as celestite. The presence of Sr-carbonates was not detected by X-ray diffraction analysis.

A significant relationship between the Sr content and the amount of insoluble residue was noted in the Upper Jurassic limestones of Germany by Bausch (1968). However, a similar plot for the basal Purbeck Dirt Beds resulted in insignificant correlation coefficient values, showing no such relationship.

The high Sr content does not seem to be related to the clay content or secondary minerals and it therefore seems most likely that it was inherited from the original sediments. Experimental analysis has shown that certain organic components of the soil form insoluble coordination compounds with Sr under favourable, high pH conditions (Juo and Barber 1970). This process is likely to be a permanent fixation rather than mere occlusion of the Sr within the exchange matrix of the soil. When an organic soil was introduced to an alkaline environment a large amount of Sr in the solution was present as Sr complexes rather than free Sr^{2+} ions. A rise in pH caused weakly acidic groups of soil organic matter to disassociate, leaving additional sites for non-exchangeable Sr sorption.

The amount of Sr in these complexes increased with increasing pH. Modern rendzina soils have suitably high pH values of 7-9 (Stace 1956; Norrish & Rogers 1956), but whether the Sr would remain in these complexes even after diagenesis is unknown. It must be noted that there is no significant correlation of Sr and organic matter in the Dirt Beds now (correlation values of -0·2 for each Dirt Bed).

A high input of aragonitic sediment in the palaeosols at the time of their formation would supply a high concentration of Sr to the soil. Aragonitic dust or mud, brought landward by storms, is trapped by vegetation baffles on the hammock 'islands' on the tidal flats of Andros Island in the Bahamas (Gebelein et al.1980; Hardie and Garret 1977), on the shores of Shark Bay (Davies 1970) and in the Coorong region of south Australia (von der Borch et al. 1977). On Andros Island this lime mud mixes with the terrestrial flora and intraclasts to form an incipient sandy soil, supporting Casuarina sp. scrub. The lenses of water below the hammocks are supersaturated with aragonite (and thus has high Sr content) during the dry season. A similar source of aragonitic sediment may have been available in the Dirt Bed palaeosols, supplying such a high quantity that,even after diagenesis, a considerable amount would still remain.

The high content of Sr in the Middle Purbeck biomicrites may have been due to large quantities of Sr with primary calcite which would not have been affected by diagenetic alteration (El-Shahat 1977). This may have been another possible source of Sr in the basal Purbeck Dirt Beds.

One of the most interesting, possible explanations for high Sr is the contribution from fossil teeth and bones, which themselves have very high concentrations of Sr (Wyckoff and Doberence 1968). For example, Cretaceous reptilian bones from America contain 900-2500 ppm; bones of Jurassic dinosaurs from the Purbeck equivalent in America (the Morrison Formation) have 1000-2000 ppm; bones from the Triassic of Arizona 1000-2500 ppm. Notably high values are found in bones and teeth from the Triassic petrified forest in Arizona (2000-5000 ppm). Wyckoff and Doberence (1968) consider that such high values are the result of high Sr concentrations in the vegetation eaten by the animals. Fossil teeth and bones were considered to be the cause of high Sr values (1000 ppm) in the Jurassic limestones of the Alps (Flugel and Wedepohl 1967). They are very common in the basal Purbeck limestones adjacent to the Dirt

Beds and are often present in thin sections of the Dirt Beds. Small fragments of bone could possibly account for samples with particularly high Sr values.

Further analysis is required to completely resolve this problem, particularly of the adjacent limestones, the pebbles in the Great Dirt Bed and the different particle sizes of the palaeosols. The most likely cause of the high Sr value is possibly a very high content of aragonitic sediment within the original soils.

3.5 The Limestone Pebbles in the Great Dirt Bed

3.5 i Petrography

The black and white limestone pebbles within the Great Dirt Bed are similar in composition to the underlying Hard Cap limestone (see 2.3 iii). No evidence was found that suggested that any of the pebbles had been derived from outside this local area or from the beds below the Hard Cap. This contrasts with the report of Webster (1826) which suggested some pebbles were derived from the Portland stone. In the field the "black" (mostly dark grey) and "white" (buff coloured) pebbles are easily distinguishable but in thin section the two types are lithologically identical, apart from the brown staining of the allochems and/or matrix. On the basis of their petrography, pebbles (from both the Lulworth and Portland areas) can be divided into the following groups:

White Pebbles:
- i) Micrite with filamentous algae.
- ii) Plain 'clotted' micrite.
- iii) Micrite with partial replacement by spherulitic quartz or radial calcite.
- iv) Micrite invaded by fungal hyphae.
- v) Micrite with calcitised gypsum pseudomorphs.
- vi) Pelmicrite or pelsparite.
- vii) Pelmicrite with oolitically-coated black pellets in a 'white' matrix.
- viii) Pelmicrite with both black and white pellets in a white micrite matrix.
- ix) Microcrystalline mottled calcite with caliche textures (e.g. micrite rims, pisolites etc).

Black pebbles:

i) Dark brown plain micrite.

ii) Brown micrite with fungal hyphae.

iii) Brown micrite with small, calcitised gypsum pseudomorphs.

iv) Dark brown pellets in a white microspar matrix.(Pellets dominant)

v) Dark brown pelmicrite with oolitically-coated brown pellets.

vi) Dark brown intramicrite. Intraclasts themselves composed of oolitically-coated brown pellets in a dark brown micrite.

viii) Clasts of relict dirt bed (laminated, organic-rich sediment).

There are many variations of these types outlined above such as oolitically coated gypsum pseudomorphs within pelmicrites, pelmicrites replaced by radial calcite etc. Gypsum pseudomorphs are most common within the dark brown pebbles, often clustered together as nodules. These pseudomorphs do not have oolitic coatings whereas those in the white pebbles do, suggesting that the gypsum originated within the original black sediment.

There are many combinations of black and/or white pellets occurring within a black or white matrix. The only combination which has never been observed is the presence of white pellets or lithoclasts within a black matrix, suggesting that the blackened sediment formed before the white. This is supported by the observation that lithoclasts of former blackened pelletoid sediments sometimes occur in the pebbles.

The blackening of the sediment appears to be due to finely disseminated organic matter in the micrite. The insoluble residue consists of a dark brown amorphous material, with rare recognisable plant remains. There are no pyrite cubes or opaque minerals.

Many of the pebbles, both black and white, show secondary accumulation of microcrystalline carbonate. Skeletal grains within these pebbles have thin rinds of finely laminated micrite and radial calcite, 1-5 μm thick, forming rinds up to 2 cm thick. Individual laminae are often stained dark brown and drape from one grain to the next enclosing several pellets (composite ooliths). The nuclei consist

Plate 7

Pebbles from the Great Dirt Bed.

1. Thin-section of the Great Dirt Bed at God Nore, Portland. The black pebbles, darkened by disseminated organic matter, also contain blackened intraclasts. The sediment consists of many small intraclasts in a sparite matrix. (TS, XPL)

2. Part of a black pebble composed mainly of oosparite with a rind of dark, organic-rich micrite and a large band of mottled micrite. Great Dirt Bed, Dungy Head (TS, PPL).

3. White pelsparite pebble with a possible root mould or burrow. The mould has a lining of darker micrite and is infilled with mottled micrite/pelmicrite. Great Dirt Bed, Fossil Forest (TS, XPL).

4. Cemented pebbles from the base of the Great Dirt Bed at the Fossil Forest. Most of the pebbles have a thin rind of irregular laminae of micrite and/or fibrous calcite.

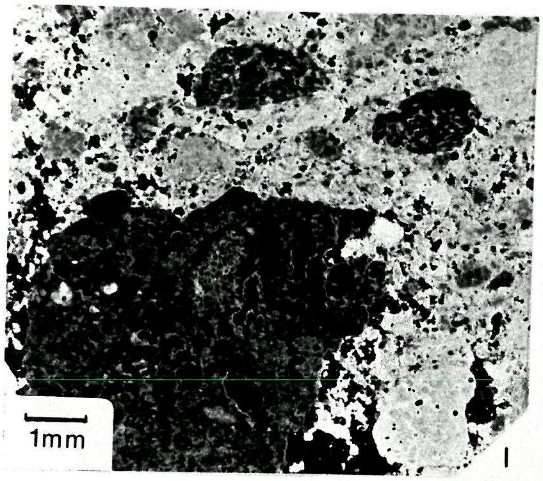
5. Patches of mottled micrite are very common in pebbles, between pebbles or in the top of the Hard Cap. The mottled area is sometimes slightly laminated and stained by organic material. White pebble, Great Dirt Bed, Bacon Hole (TS, PPL).

6. Irregularly laminated calcrete crust bordering a black pebble. The crust encloses calcite grains and organic matter. Fossil Forest, Great Dirt Bed (TS, PPL).

7. Black pebble of oomicrite with nuclei of calcite crystals (once possibly anhydrite) and with irregular rinds of fibrous calcite. Great Dirt Bed, Bacon Hole, (TS, PPL).

8. Pisolitic nodule within oomicrite pebble from Great Dirt Bed, Fossil Forest. The nodule is coated with irregular layers of microcrystalline calcite, noticeably perched on one side. (TS, PPL)

9. Cemented pebbles at the base of the Great Dirt Bed, Fossil Forest. Many pebbles have irregularly laminated calcrete crusts or fibrous calcite rinds. (TS, XPL)



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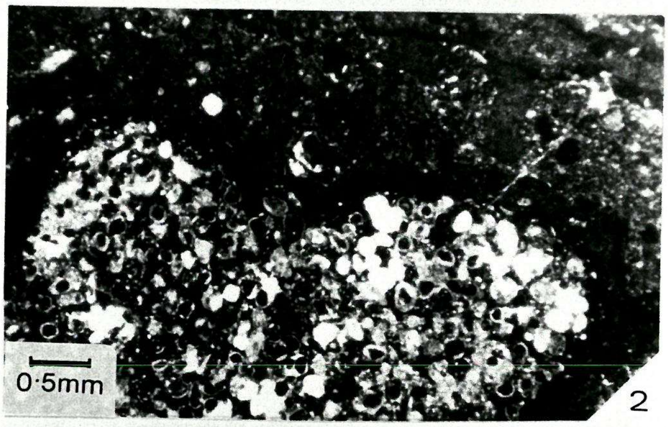

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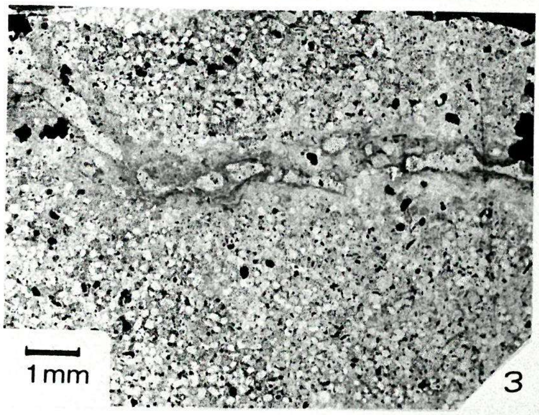

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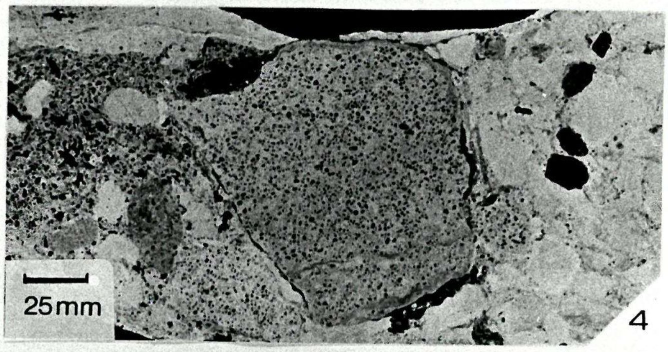

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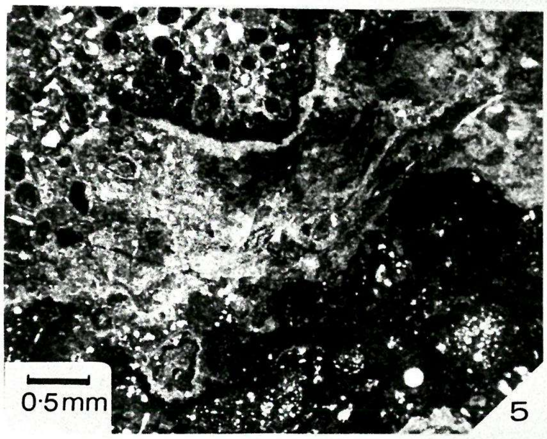

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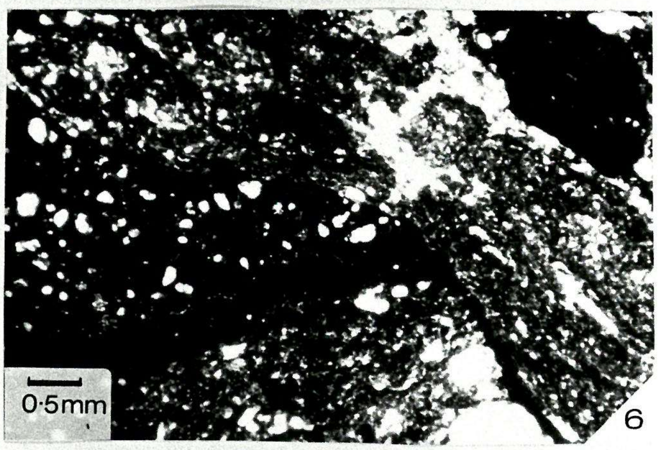

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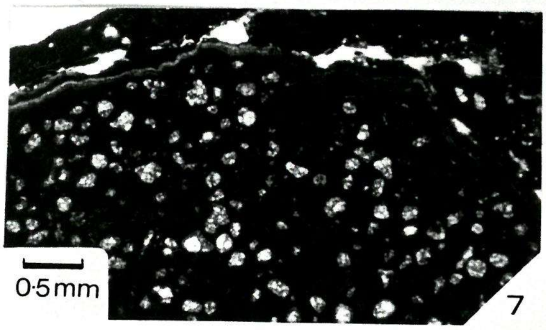

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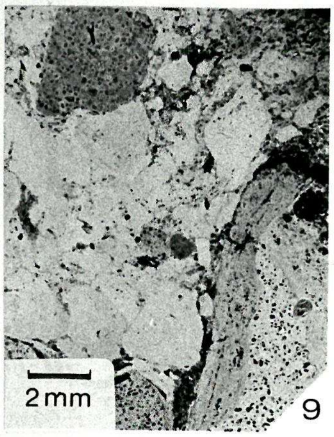


9

PLATE 7

of micrite pellets, intraclasts, sparite and partially micritised bioclasts. Elongate bioclasts have a markedly thicker coating on their long sides than at each end. Whole pebbles sometimes have external coatings of irregular layers of microcrystalline calcite, often truncated by the overlying laminae. These laminae are often concentrated to the upper or lower surface of the pebble, some of which have a cupped, concave upper surface. Many of the flat, platy pebbles are composed entirely of laminated and fenestral micrite and this sediment often cements pebbles together, draping into the hollows. Patches of pisolites and ooliths occur between these layers. In some laminated micrite tiny plant fragments are present, as are small voids (50-100 µm diameter) infilled with spar, some of which may represent former root voids. Although root casts have not been observed in the soil S-matrix, they may be preserved in the micrite layers as small, irregular voids lined with micrite and infilled with spar (Pl.7, Fig. 3).

At the base of the Great Dirt Bed the pebbles are cemented together by microcrystalline calcite which is textureless, mottled or sometimes has a vague pellet texture. Pollen and plant material is well preserved here. This micritic cement extends down into the top of the Hard Cap, which itself has a patchy, mottled texture and partially micritised skeletal grains (Pl.7, Fig. 5). There is no evidence that micritisation is due to the effects of boring algae (Bathurst 1966) or the mottling biogenic (no burrows have been observed) but appears to be the result of inorganic precipitation.

3.5 ii Calcrete textures associated with the pebbles

The microcrystalline laminae, pisolites and fibrous rinds described above are similar to textures found in modern calcrete (caliche) (Bretz and Holberg 1949; Brown 1956; Blank and Tynes 1965; Aristarian 1970; Reeves 1970; James 1972; Read 1974; Harrison 1977; Arakel 1982).

Calcrete is a term broadly applied to the epigenetic accumulation of secondary carbonate formed by the evaporation of carbonate-rich waters. This term is usually applied to carbonate which has been deposited within soil profiles, either as a thin laminar horizon or a strongly indurated, thick horizon, by capillary action of soil waters in semi-arid climates (Aristarian 1970). The initiation and evolution of this pedogenic calcrete is controlled by a) the climate which is typically sub-humid or semi-arid; b) by the soil as a source of carbonate and as a medium regulating the flow of percolating water; and c) the bedrock which may be a source of carbonate and may form an integral part of the calcrete fabric, influencing its thickness. The length of exposure determines the thickness of the calcrete.

The calcrete begins to form as a laminar crust on skeletal grains and pebbles at the base of the soil by the precipitation of microcrystalline calcite from carbonate-rich water. The laminae increase in extent and thickness until these nodules coalesce and eventually an impregnable horizon is formed. This horizon (the K-horizon of Gile et al. 1976) restricts further percolation of carbonate-rich water and so more carbonate is deposited on top of this layer. If the soil processes are still active the K-horizon may be brecciated and incorporated back into the soil, supplying a new source of carbonate (Stuart and Dixon 1973).

Laminated calcareous crusts are forming today on Pleistocene limestone below soils in Florida (Robbin and Stipp 1979; Multer and Hoffmeister 1968). Rainwater which percolates through the acid humic soil dissolves the carbonate in the soil but precipitates it as a laminar crust at the base of the soil as the water evaporates. The high content of organic matter derived from the soil stains the crust dark brown. The crusts also contain limestone breccia weathered from the bedrock below. Carbonate is not only derived from pebbles and shells within the soil but is also added from the sea spray and leached from the bedrock. These crusts are estimated to have formed at a rate of 1 cm per 200 years (Robbin and Stipp 1979).

In the rendzina soils of Spain a layer of immature, laminated calcrete has formed above the micritised bedrock (Klappa 1967, 1980). The soils, very similar in appearance to the Great Dirt Bed, consist of black loam with relict fragments of the underlying limestone and the laminar calcrete, though they often consist only of brecciated limestone and plant litter. The thinly laminated calcrete layers are actively brecciated by plant roots, especially those of the trees Pinus halepensis. These trees have shallow spreading roots, limited to about 40 cm in depth. The living roots not only actively brecciate the calcrete (rhizobrecciation) but chemically alter the soil. As they take in water, carbonate is precipitated around them; calcified roots are a common feature of calcretes. Klappa (1980) also suggests that the calcrete acts as an aquiclude creating a perched water table which allows the vegetation to obtain water. Boulaine (1961) describes similar crusts in the Mediterranean within forested regions with a seasonal rainfall of 350-650 mm. The vegetation (particularly the Alepo pine, the olive trees and species of Thuja) plays an important part in the calcrete formation as proposed by Klappa (1980). A similar situation is found on the Bahaman islands where Pinus carribea grows in shallow soils which have an underlying calcrete crust (Little et al. 1977).

The examples above have a seasonal but fairly high rainfall (350-1500 mm). As the climate becomes more arid the calcrete layers form nearer the surface as the water evaporates more rapidly. On the west coast of Australia Quaternary fossil soils of rendzina type are underlain by concretionary nodules and laminated calcrete (Fairbridge and Teichert 1952; Logan 1972; Read 1974; Arakel 1982). Older fossil calcrete has been described from the Jurassic (Bernoulli & Wagner 1971), Carboniferous (Riding and Wright 1981; Walls et al. 1975) and from the Old Red Sandstone (the Cornstones of Burgess 1960 and Steel 1974). The presence of calcrete is considered an important diagnostic feature of sub-aerial exposure.

The calcretes described above all formed in vadose, pedogenic environments. However, on the Trucial coast of the Persian Gulf aragonitic supratidal crusts are forming in an hypersaline environment. Very thin (50 μm), strontium-rich aragonitic laminae encrust boulders and cliffs within the splash zone (Purser and Loreau 1973). The crusts are formed by the same process as freshwater caliche but with a different pore-water chemistry yielding different mineralogies (aragonite and high-Mg calcite) (Scholle and Kinsman 1974). Gypsum is also present within the crusts. The crusts are readily dissolved by dew further inland. They do not support a soil or any vegetation due to their high salinity. Supratidal aragonitic crusts have been described by Davies (1970) from Shark Bay and by Ward et al. (1970) from the Yucatan peninsula.

The calcrete crusts at the base of the Great Dirt Bed and on the pebbles appear very similar to those developed in soil profiles in Spain, Australia and Florida, described above. The extent of the carbonate accumulation in the Great Dirt Bed is limited to a thin indurated horizon at the base of the soil and coatings on pebbles, which suggests that the caliche profile was immature and formed for only a short time. It seems highly likely that the laminated crust was brecciated by the shallow roots of the Purbeck conifers, similar to the rhizobrecciation caused by pine trees in Spain (Klappa 1980). This is the probable origin for the flat, platy pebbles which consist of fragments of laminated crust. The tree roots also probably help the break-up of the parent limestone below the soil into pebbles.

Aragonitic crusts like those of the Persian Gulf (Purser & Loreau 1973) may well have formed on top of the nodular Hard Cap before the soil formed and when the environment was arid and hypersaline. This may account for the presence of gypsum within some pebbles and for the high Sr^{2+} content of the Dirt Beds (see 3.4). There is no evidence within the Great Dirt Bed itself, or its pebbles of dolomitisation or microstalactitic cement as there is in the aragonitic crusts. These crusts would not survive in a soil environment suitable for tree growth but may have formed near the margins of the Purbeck hypersaline lagoon.

The formation of calcrete requires a semi-arid, seasonal climate with periods of rainfall followed by periods of intense drought (Harrison 1977). This type of climate was prevalent during the growth of the Purbeck forests, as shown by their growth rings (Chapter 6). It may have been suitably arid for the formation of evaporites in the soil during the dry season but they would have dissolved during the wet season unless the rainfall was very low and evaporated before it reached the lower part of the soil. The rainfall was obviously sufficient to allow carbonate-rich water to percolate to the base of the soil where the carbonate was deposited on and between the pebbles; that of the Mediterranean, 350-600 mm (Boulaine 1961) seems appropriate.

3.5 iii The Black Limestone Pebbles

Blackened limestone pebbles have been described from many types of sediment worldwide, particularly from calcretes (Multer and Hoffmeister 1968: Florida; Klappa 1967: Spain; Mr. R.N. Young (pers.comm. 1982): Bahamas) and from algal sediments around hypersaline lagoons (Ward *et al.* 1970; Rose 1972; Wilson 1975).

Some dark particles may be due to iron sulphide staining in anaerobic environments (Illing 1954; Sugden 1966; Maiklem 1967; Davies 1970). Iron and manganese are reduced by bacteria and precipitate as sulphides on the outer surface of organic-rich particles such as pellets, shells and foraminifera tests. However, when brought to the surface by erosion these particles readily oxidise to a pale brown stain only.

The most common cause of blackening is due to the inclusion of finely disseminated organic matter in sediment associated with algal mats. The black colour is derived from decaying organic matter, chiefly filamentous boring algae which thrive in the mats, and organic-rich water which impregnates the underlying sediment (Wilson 1975). On the Yucatan Peninsula, New Mexico, blackened caliche and bedrock clasts cover the shores of hypersaline lakes, particularly on Isla Mujeres (Folk 1967; Ward et al. 1970). The fragments are formed by dissolution and desiccation fracturing of the underlying bedrock and both types of clasts are lithologically identical apart from large quantities of organic matter within the black clasts. Although an obvious black parent limestone does not now exist, Folk (1967) suggested that the black sediment originated from the black, organic-rich, smelly gelatinous mud that occurs just below the salt crust and in the algal mat at the edge of the salt lakes. Tiny gypsum crystals formed on top of this black algal mat when it dried out. Similarly blackened crusts were also found in calcrete in Spain (Klappa 1967), in the laminated crusts on Florida (Multer & Hoffmeister 1968) and on the shores of the Persian Gulf (Kendall and Skipwith 1969).

The presence of blackened pebbles in geological sediments is considered to be a marker of subaerially exposed surfaces in proximity to hypersaline water, locating ancient coastal areas and the landward edge of evaporite deposition (Ward et al. 1970; Wilson 1975). Blackened caliche and biosparrudite pebbles occur within supratidal sediments in the "Black Bed" of the Lower Cretaceous Edwards Group in Texas (Rose 1972). Black pebble breccias and hard grounds marked sites of exposure within the tidal flat sediments of the Vorbourg Beds in the Oxfordian strata in the Swiss Jura mountains (Wilson 1975).

Carozzi (1948), Cotillon (1960) and Bläsi (1981) described black pebbles from the Purbeck Beds in the Swiss and French Jura mountains. In the Swiss Jura the pebbles occur in a limited area around anticlinal highs which were precursors to larger anticlines formed during Tertiary tectonism. Carozzi (1948) proposed that these pebbles originated from a previously existing, organic-rich sediment which was eroded from the crest of the exposed anticline during a regressional phase. Cotillon (1960) proposed that the pebbles testified to the proximity of vegetated land from which organic matter was derived and deposited in shallow basins, later to be re-worked and eroded as pebbles. Bläsi (1980) proposed that the black pebbles were the result of storm activity.

The blackening of the pebbles in the Great Dirt Bed appears to be due to the inclusion of finely disseminated organic matter within the sediment matrix. Organic matter constitutes about 10-20% of the non-carbonate fraction (20-40%) of a black pebble (the remainder are clay minerals). The staining is definitely black, not pale brown in colour and therefore, in an aerobic environment, could not be due to the inclusions of reduced iron or manganese. Also the pebbles are blackened through to the centre, unlike the stained rim usually observed with sulphide-stained clasts (Sugden 1966). The sediment from which the Purbeck black pebbles originated was obviously thoroughly mixed with organic material before the pebbles were formed. Since the hypersaline tidal flat environment in which black pebbles are found today is comparable to that of the basal Purbeck (West 1975) it seems probable that the black pebbles in the Great Dirt Bed originated in a similar manner, from the lithification and brecciation of dark, algal mat which formed on the lake margin. The formation of small gypsum crystals on the algal mat on Isla Mujeres (Ward et al. 1970) suggests a similar origin for gypsum, now calcitised, within the black pebbles. There is no continuous black bed within the basal Purbeck strata which is the obvious origin of the pebbles. The source rock must have been completely brecciated, but in relation to the underlying Hard Cap algal stromatolites and the Great Dirt Bed palaeosol the black sediment would probably have been located at the base of the soil on top of the Hard Cap. However, dark grey limestones containing blackened clasts were recorded from Holworth House (Bed I, Fig.2.07) and Worbarrow (Bed I, Fig. 2.10) at horizons just below the probable position of the Great Dirt Bed, which as a distinct palaeosol is absent. These limestones may represent sediments equivalent to those at the base of the Great Dirt Bed palaeosol into which blackened debris was deposited, in the east into the lagoon margin and to the west into the margins of an ephemeral lake (West 1975). The lateral extent of the black pebbles in the palaeosol (Bacon Hole to Dungy Head and on Portland) probably represents the initial bed of subaerial exposure on which the Great Dirt Bed soil formed.

3.5 iv Analysis of Pebble Shape and Roundness

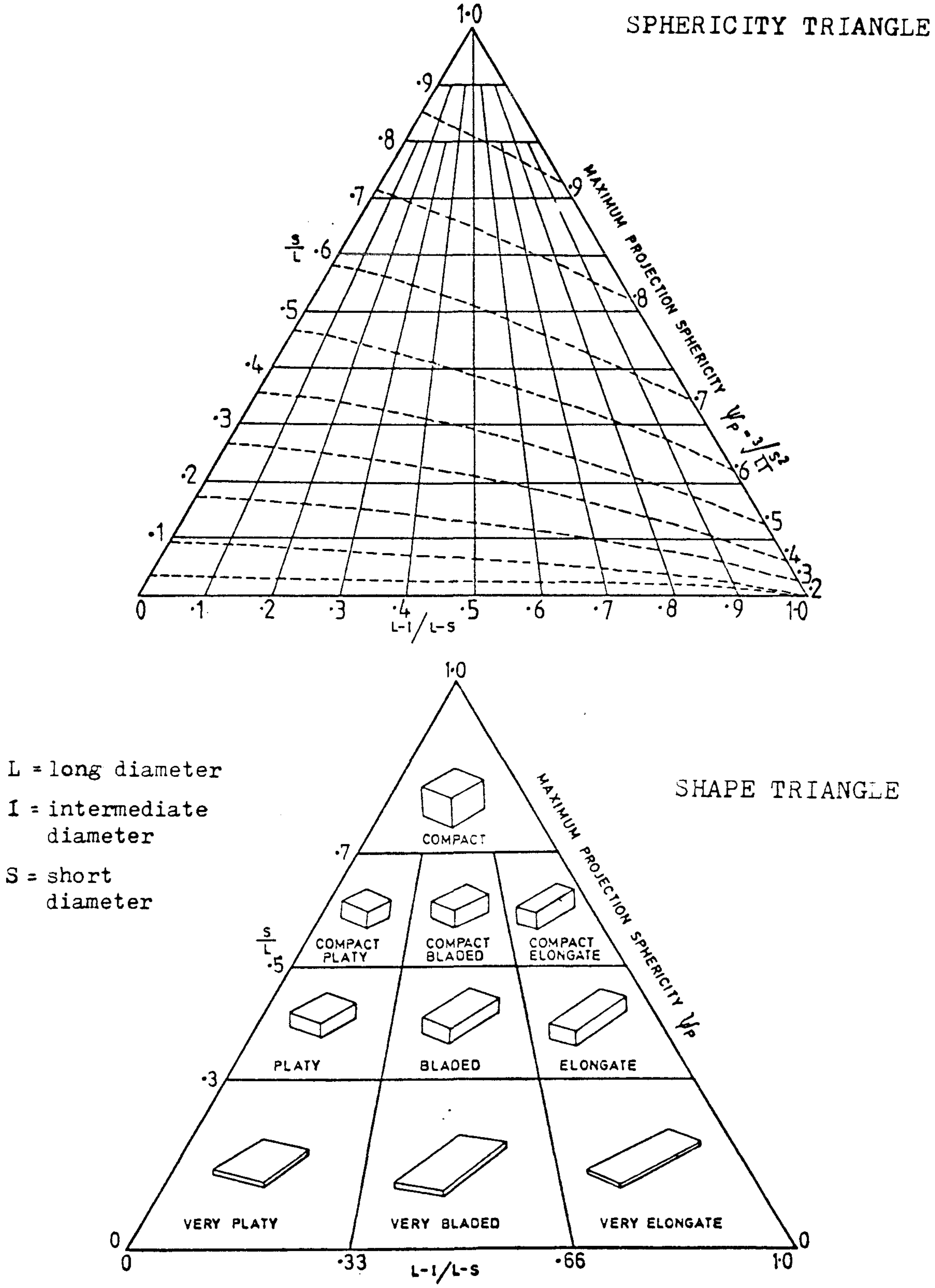
It was apparent from field observations that the black pebbles were smaller and rounder than the larger, platy white ones. Sphericity, shape and roundness analyses (Krumbein 1941; Sneed and Folk 1958) were applied to evaluate statistically the difference between the black and white pebbles and to express quantitatively the frequency distribution of pebble size and shape ranges as a possible basis for interpretation of their mode of formation.

The "shape" of a particle relates to its overall form irrespective of the sharpness of the corners and edges. It is related to "sphericity" which is a measure of the degree of conformity of that shape to a sphere. A formula used to calculate the sphericity of irregular shaped particles was defined by Krumbein (1941) and later re-defined by Sneed and Folk (1958) to take into account the maximum projection area of a sphere of the same volume. This is called the maximum projection sphericity ψ_p and is defined as:

$$\psi_p = \sqrt[3]{\frac{S^2}{LI}}$$

where L, S and I are the long, short and intermediate diameters respectively. These axes are mutually perpendicular though not necessarily intersecting at one point (see Krumbein 1941). The value of ψ_p for each pebble can be read directly from the sphericity graph (Fig. 3.02a) once the values of S/L and (L-I)/(L-S) have been computed. This graph (Fig. 3.02b) also illustrates the 10 shape classes delineated by Sneed and Folk (1958). The shape is dependent on the ratio of L, S and I and although sphericity is a quantitative value illustrating the departure of a body from equidimensionality, pebbles with the same sphericity and volume may have a different shape.

The "roundness" of a particle depends only on the sharpness of the corners and edges and is geometrically distinct from shape or sphericity. A value for roundness can be accurately determined by measuring the radii of all the curves of a pebble surface (Brewer 1964). However, a visual comparison with pictures of pebbles of known roundness is adequate. The chart of Powers (1953) was used in this case and pebbles divided into 6 roundness categories: very angular (VA), sub-angular (SA), angular (A), sub-round (SR), round (R) and very round (VR). Specific values of roundness were not found for the Great Dirt Bed pebbles.



SPHERICITY TRIANGLE

SHAPE TRIANGLE

L = long diameter

I = intermediate diameter

S = short diameter

Fig.3.02 The sphericity and shape classes of Sneed and Folk(1958) used for pebble analysis.

When the values of S/L and (L-I)/(L-S) have been calculated for each pebble the relevant value of sphericity and the shape can be read from the graphs.

Method of Analysis

Limestone pebbles, both black and white, were collected as part of samples of the Great Dirt Bed from 4 localities. They were separated from soil particles of less than 2 mm by wet sieving and were carefully washed and dried to remove adhering soil material. A minimum of 25 pebbles were picked from each sample (as suggested by Krumbein 1941) though more were picked if possible. They were picked at random and to avoid preferential picking of the larger pebbles the whole sample was divided into two groups with size ranges 2-20 mm and above 20 mm. An equal number of pebbles were picked from each. For each pebble the diameters L, I and S were measured and its colour (black or white) recorded. The values were computed to find S/L and (L-I)/(L-S) and plotted onto sphericity shape triangles (Fig. 3.03). The results are recorded in Fig. 3.04.

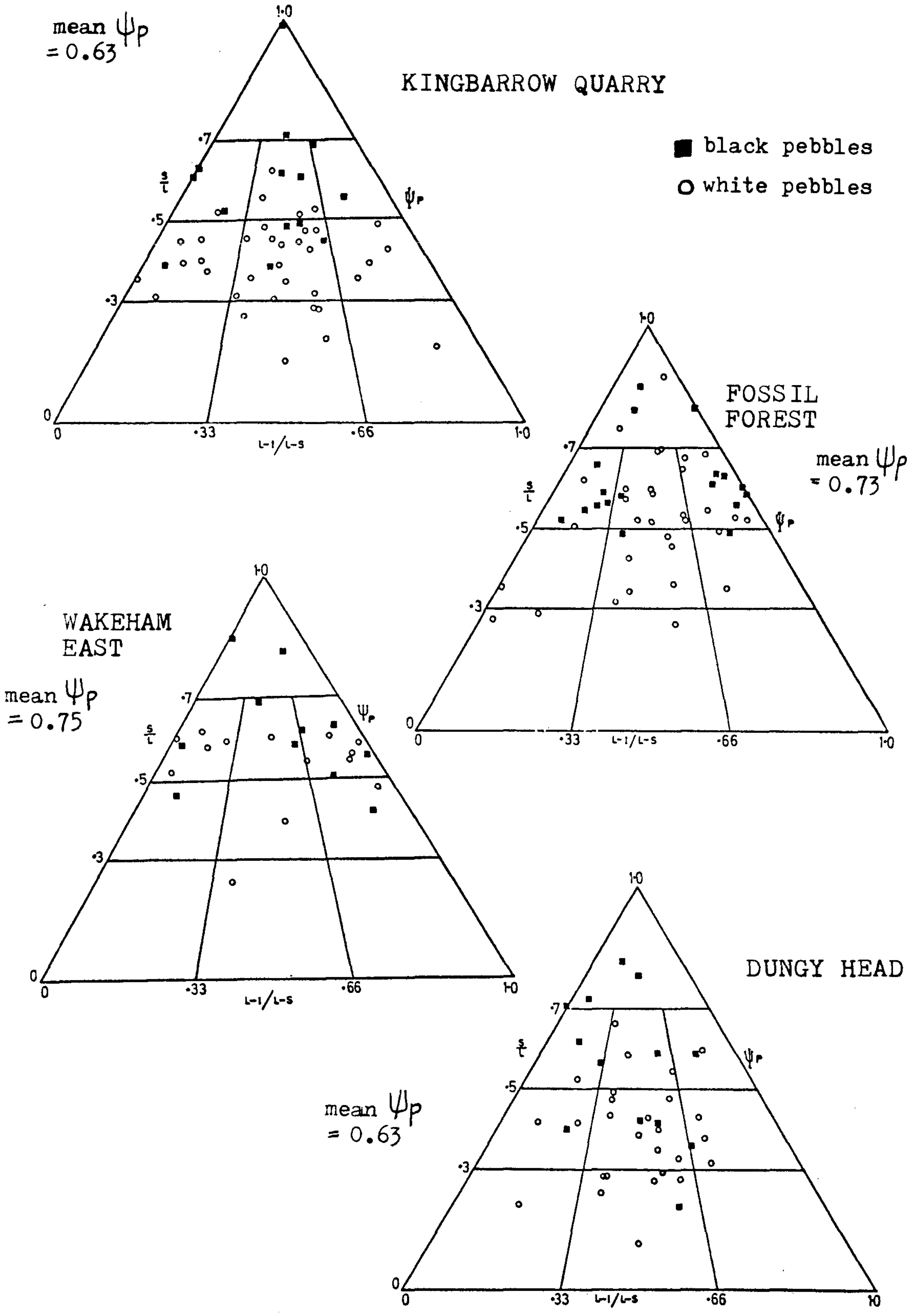
Results

165 pebbles were measured overall. The white pebbles (109) dominated the samples and the field estimate of 30-40% black pebbles was reflected in the randomly picked pebbles (28-44% black). The pebbles ranged in size from 7-89 mm (L values), spanning the "pebble" grade of the Wentworth-Udden particle-size scale (Pettijohn 1975) and including a few of "cobble" size.

Computation of ψ_p values gave an average value of 0·69, ranging from 0.63 at Kingbarrow and Dungy Head, and 0·73 and 0·75 at the Fossil Forest and Wakeham. The readings confirm that the black pebbles are more spherical than the white by a factor of 10-20%.

The distribution of the pebbles throughout the shape categories for each locality is recorded in Figure 3.05 and the total distribution in 3.04. The majority of pebbles are bladed in shape (22%). However, the black pebbles are clearly distributed in the "compact" shape categories, reflecting their higher sphericity values (Fig. 3.04). The black pebbles are mainly compact, compact-platy or compact elongate in shape (a wide range of (L-I)/(L-S) values) whereas the white pebbles are dominantly bladed.

The variation in shape at each lovality reflects the bimodal sphericity values (Fig. 3.05). At Dungy Head and Kingbarrow the pebbles



Fig, 3.03 Distribution of pebble shape at four localities of the Great Dirt Bed.

The position of each pebble plot is determined by the ratios of the short(S), intermediate(I), and long(L) diameters, calculated as S/L and (L-I)/L-S). The shape categories are outlined in Figure 3.02.

are dominantly bladed whereas compact-elongate is the dominant shape at Wakeham and the Fossil Forest, and even though these latter samples have a higher proportion of black pebbles, bladed pebbles are relatively uncommon.

Roundness analysis shows that whereas the majority of pebbles are sub-angular, the black ones are rounder (Figs. 3.04, 3.05). There is no significant variation of roundness over the whole area, though the Portland pebbles may be slightly more angular than those from the mainland.

Discussion

The roundness of a particle is indicative of the maturity of the sediment and its history of abrasion. Sphericity and shape reflect the conditions of deposition at the moment of accumulation (Pettijohn 1975). The shape of a pebble, however, depends initially upon the nature of the parent rock (particularly its structure), its particle size, composition and the agent of erosion. Most pebble analysis is concerned with the modification of pebbles during water transport, both in the field (Grogan 1945; Folk and Ward 1957; Sneed and Folk 1958) and under laboratory conditions (Kuenan 1956).

In the Great Dirt Bed, however, the pebbles appear to be derived directly from the underlying limestone and are not only all lithologically identical but many have interlocking faces. If any of the pebbles have been moved then it could only have been from a very local area. Obviously a lot of the pebble characteristics have been inherited from the parent rock. The white pebbles are platy and angular since they originated from thinly-laminated limestone, at the top of the Hard Cap. The effects of soil-forming processes must have been important but hardly any studies have been made on the modification of sphericity and roundness during soil formation. In a soil a common effect is the progressive reduction in the size of the mineral grains and clasts of parent rock (Brewer 1964). In thin-section and in the field it is apparent that many pebbles are fracturing in situ within the Great Dirt Bed.

An interesting result of this analysis confirms that the black pebbles are rounder and more spherical than the white. This suggests that they either originated from a relatively more massively-bedded sediment or they have undergone slightly more weathering (of whatever

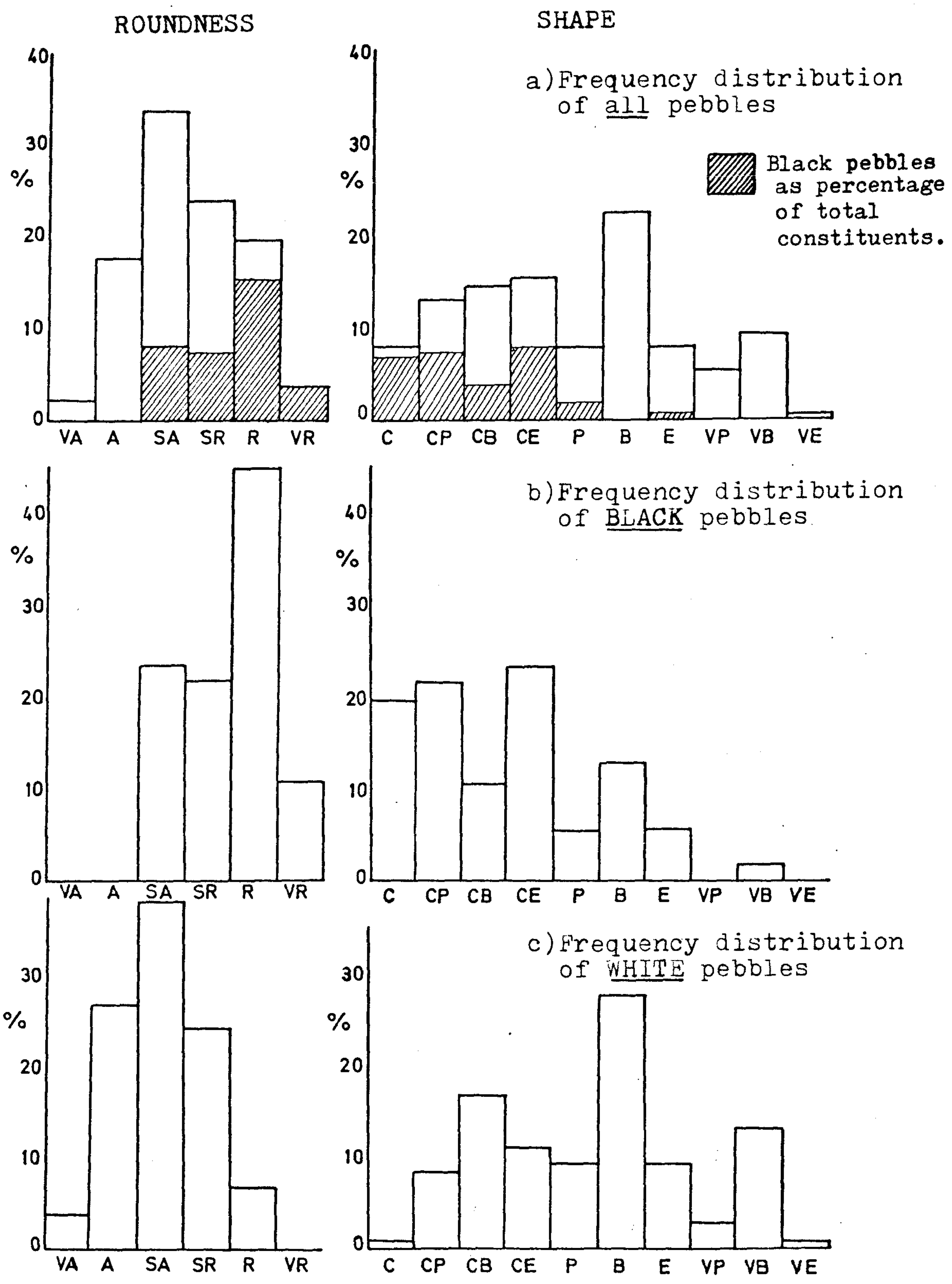


Fig. 3.04 Distribution of shape and roundness of measured pebbles from the Great Dirt Bed.

The shape categories are explained in Figure 3.02 and the roundness categories in Figure 3.05.

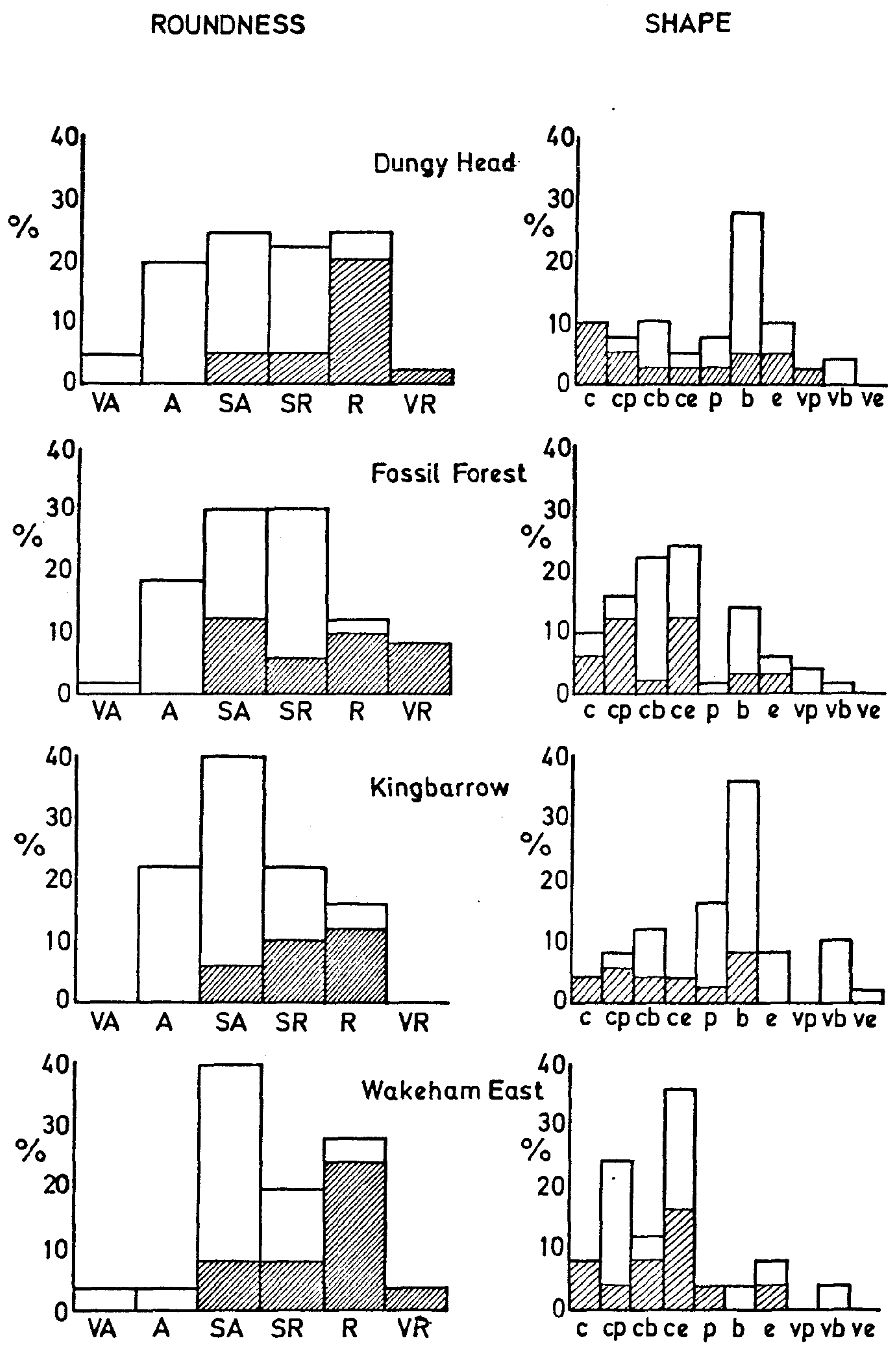


Fig. 3.05 Results of pebble analysis from four exposures of the Great Dirt Bed.

The roundness categories are : VA very angular, A angular, SA sub-angular, SR sub-round, R round, VR very round. The shape categories are explained in Figure 3.02.

sort) than the white ones. The black pebbles may thus have formed slightly earlier than the white, as previously suggested from petrographic evidence (3.5 i) and their origin (3.5 iii). A difference in shape between the smaller, sub-round black pebbles and the larger, more variable, platy white pebbles was noted by Ward et al. (1970) on the Yucatan Peninsula. The difference was attributed to the greater susceptibility of the black rock to desiccation-fracturing.

To summarise, the black and white pebbles in the Great Dirt Bed are lithologically identical to the underlying Hard Cap limestone and there is no evidence that pebbles were derived from older strata or from a different area. The pebbles were originally formed by the desiccation fracturing and brecciation of the limestone below, probably aided by the destructive action of spreading tree roots (rhizobrecciation, Klappa 1980).

Some of the pebbles have a coating of laminated, microcrystalline carbonate (calcrete) formed by the deposition of secondary carbonate by evaporating, carbonate-rich soil waters in the semi-arid environment. Pebbles at the base of the Great Dirt Bed are often cemented together and an indurated horizon developed. Some of the calcrete is itself brecciated and found as platy pebbles.

The white pebbles are more platy and angular than the black. Though they are identical in composition the black pebbles contain more organic matter which is the cause of the blackening. The black pebbles probably originated from black algal mat that formed at the lagoon margin and later desiccated and fractured and became incorporated into the overlying soil as it formed. The presence of these black pebbles in the Great Dirt Bed is consistent with the view that they represent subaerially-exposed surfaces at the margins of hypersaline lakes (Ward et al. 1970).

CHAPTER 4

THE PRESERVATION OF THE BASAL PURBECK FOSSIL WOOD

In the basal Purbeck Dirt Beds fossil wood has been found preserved either in a silicified form or as fusinite ; fusain; fossil charcoal . The large fossil tree stumps and trunks are silicified, whereas the fusain is found as tiny brittle fragments within the soil matrix itself. Although in both cases the cell structure is sufficiently preserved to allow taxonomic identification, the state of preservation of the fusain is far superior. The nature and origin of each type are discussed below.

4.1 The Silicified Wood

4.1.i Introduction

Although fossil wood is reported to have been petrified by many different minerals (St. Johns1927; Mitchell 1967; Buurman 1972) the most common petrifications are siliceous. The silica allows excellent preservation of the original wood structure and since crystalline silica is one of the most durable of minerals, its hardness and lack of cleavage make it particularly resistant to weathering. In consequence, large collections of fossil wood representing whole forests, are usually petrified by silica e.g. the in situ fossil forests at Amethyst Mountain in Yellowstone National Park (Dorf 1964), the silicified drift wood of the Chinle Forest in Arizona and the petrified forest of Cerro Cuadrada, Patagonia (Calder 1953) which was overwhelmed in an outburst of volcanic activity. Even these few examples illustrate that both wood buried in situ and after transport can be silicified.

Tertiary fossil wood is commonly opaline and the structure is usually excellently preserved. This type does not occur in older deposits where silicification by microcrystalline quartz is most common, either as submicroscopic equant grains or radiating fibres of chalcedony.

A number of theories have been forwarded for the mechanism of silicification and the source and nature of the silica. Some have suggested preferential silicification of silica-rich plants (Scurfield et al. 1974a,b) such as grasses, bamboo and Equisetum but this idea is not supported by the common silicification of plants without a great deal of silica, such as conifers (Siever and Scott 1963). Furthermore, fossilisation appears to be related to circumstances of burial rather than the taxonomic status of the wood (Müller-Stoll 1951). Most petrified woods occur in volcanic tuffs which weather rapidly, liberating large amounts of soluble silica (see Hunt 1972). In sediments with no history of volcanic activity the petrificant may be released in silicate-mineral diagenesis (Siever 1972), as biogenic silica evolved from the dissolution of sponge spicules or diatom and radiolarian tests, or the dissolution of detrital quartz grains and inorganic precipitation of the silica under conditions of seasonal fluctuations of pH (Peterson and von der Borch 1965).

In the past the process of silicification was considered to be a "molecule-for-molecule" replacement of the wood cellulose (Storz 1933). Buurman (1972) considered that mineralisation by disordered tridymite, an intermediate stage in some chalcedonic silicifications, occurred by replacement of cell walls. However, the silicification of most fossil wood by quartz and chalcedony is now believed to be fundamentally a process of infiltration and impregnation wherein the wood substance serves as an active template for silica deposition (St. Johns 1927; Arnold 1941; Barghoorn 1952; Muir 1970; Schopf 1975; Leo and Barghoorn 1976; Sigleo 1978a; Scurfield 1979). Many laboratory experiments to petrify wood have been attempted in order to understand the natural mechanism of wood petrifaction (outlined in Leo and Barghoorn 1976; Drum 1968a,b; Buurman 1972). Geochemical analysis of lignin compounds in Triassic wood from Arizona was carried out by Sigleo (1978a,b).

In the Purbeck fossil wood the preservation of the cells and anatomical details are sufficient to enable taxonomic identification of the wood and measurement of the growth rings. The wood was studied in thin-section and by SEM. Some of the features seen with the SEM were casts of original pits and cavities in the wood. In conifers the xylem (the only part preserved in the Purbeck wood) consists mainly of tracheids which function both in water conduction and support. These cells, between 10-80 µm wide, are axially elongated and have no living contents at maturity. The structure of the tracheid wall is important in the permineralisation process. It consists of a thin primary wall and a thick, usually three-layered secondary wall (S_1, S_2 and S_3 layers) of which the middle S_2 layer is thickest (Fig.4.01). Each wall layer is composed of an oriented matrix of cellulose microfibrils forming a strong framework, embedded and bound together in a matrix of lignin and hemicellulose. The orientation of the microfibrils differs in successive

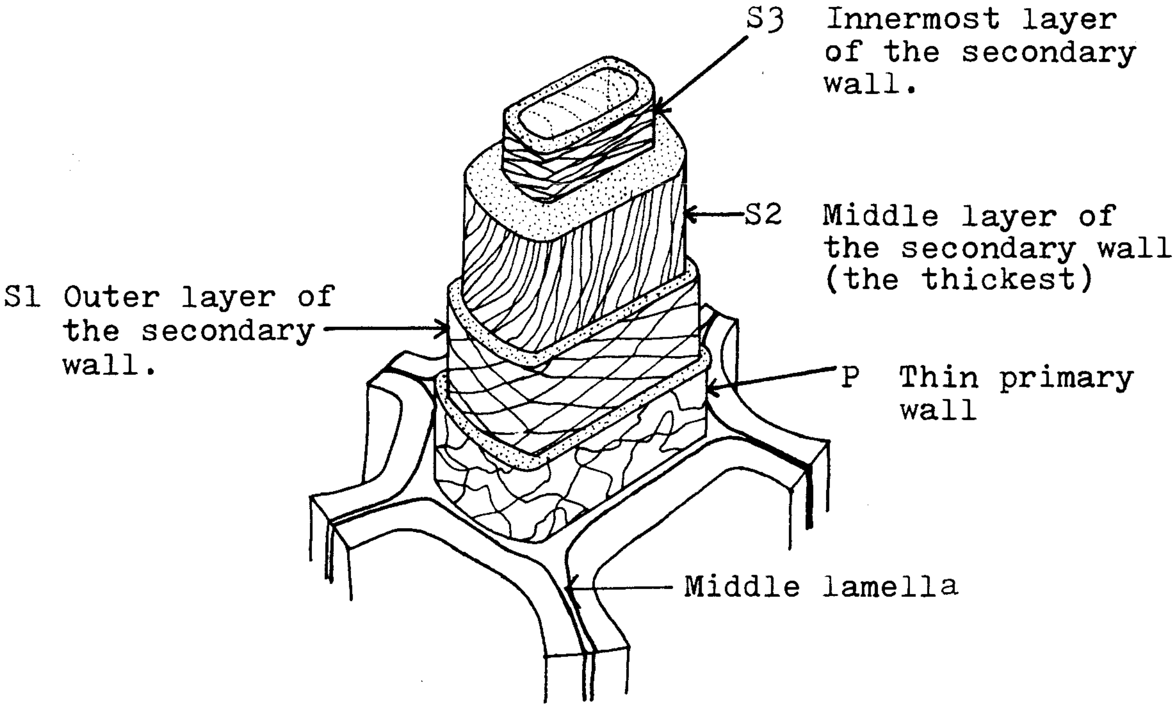


Fig. 4.01

Schematic diagram illustrating the general structure of the cell wall and the dominant helical orientation of the microfibrils in each layer.
(Based on Butterfield and Meylan 1980)

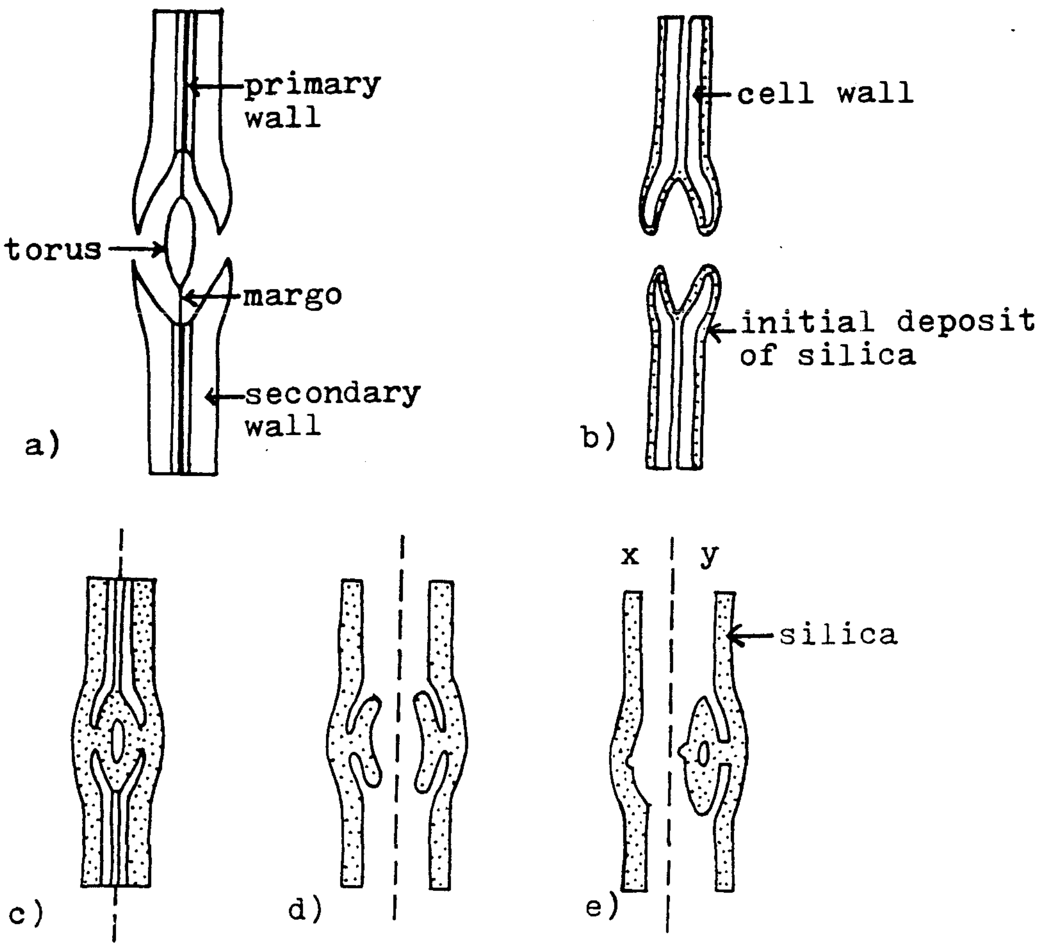


Fig. 4.02.

Mode of silicification of wood schematically relating silica deposition to vascular tissue structure.

a) Diagrammatic representation of a bordered pit between adjacent walls of a conifer.

b) Wood during the early stages of impregnation of silica, the pit membrane having already decayed.

c) Petrified wood. The cell wall rimming the lumen and the pit chamber have been coated with silica.

d) If the pit chamber is only partially filled the tracheid tends to fracture along the line of the middle lamella revealing casts of the pit chamber as small dishes on stalks.

e) If the pit chamber is almost completely filled the break tends to occur at the thinnest point as shown resulting in either a hollow dish(x) or a protruding dome(y).

(Based on Leo and Barghoorn 1976).

wall layers. Either the lignin or the cellulose may be removed during initial decay from the heavily lignified cell walls leaving a structurally intact residue (Siever and Scott 1962). The middle lamella which lies between adjacent cell walls, is an amorphous material rich in lignin, low in cellulose and composed mainly of pectin compounds which are easily dissolved.

The radial walls of the tracheids are pierced by pits which are paired with other pits in adjacent cell walls; their precise arrangement being a useful diagnostic feature for classification. The structure of these pits is shown in Figure 4.02. The pits are "bordered" where the secondary wall overarches the pit membrane leaving an aperture smaller than the membrane itself. Small cross-field pits occur between the tracheids and ray cells. In the Purbeck wood these are of Cupressoid-type with a slit-like aperture enclosed within a circular border.(Pl. 9 , Fig.6).

4.1.ii The nature of the silicification of the Purbeck wood

The state of preservation of the Purbeck wood before petrifaction was usually very good because individual cells are preserved in most trees. Although large portions of some trees have subsequently been replaced by secondary silicification, where cells are visible their walls remain intact. There is some evidence of fungal attack in only 2 samples: a small nodule of wood from within the Great Dirt Bed at Upwey and in a shrinkage crack in PB.11 from Blacknor, Isle of Portland. In these, cell walls have been broken down into tiny fragments in certain areas and distinct cell outlines have been lost resembling the cells of fungal-attacked plants illustrated by Moore (1963; 1964, pl.29,fig.3). The fungal hyphae themselves have not been detected.

Many specimens exhibit localised areas of contortion or compression in which the cell walls are not fractured but are folded and pushed between other cells. In PB.1 some tracheids have been completely twisted and curled into balls, presumably by contortion of the living tree. Several trees also exhibit shrinkage cracks in the wood which occurred either before or contemporaneously with the initial stages of silicification. The cracks tend to be located between tracheid walls, separating the wood cells (but never splitting the individual cells themselves) and are predominantly orientated in a radial direction. The cracks range in width from 0·01 - 0·60 mm wide and are conspicuous because they are filled with silica which has a dark brown coloration (Pl. 8 , Fig. 9). This is due to the inclusion of soil particles, portions of tracheids (separated from the rest of the wood along the middle lamella) and pollen grains. The pollen is exceptionally well-preserved, remaining grouped in tetrads, and its presence confirms that the cracks must have been open prior to silicification. Pollen and soil particles are also included in cracks encircling small knots (Pl. 9 , Fig.7).

In the majority of Purbeck trees each individual cell has been silicified so the cell outline has remained intact. The clarity of the cell outline is related to the amount of brown organic matter remaining along the boundary of the cell wall. In the best preserved specimen, PB.1, the cell walls are outlined by a 2 µm band of organic matter. Between adjacent cells there is a 2-3 µm band of silica which appears to be composed of tiny fibrous crystals oriented perpendicularly to the organic layer. Under SEM (Pl. 8 , Fig. 4) these crystals appear to meet along the line of the middle lamella and to have replaced the whole cell wall. The relative position of the organic matter is now seen as a cavity between the cell wall and lumen. Each lumen is filled individually by a single crystal. This appears to be the case for most Purbeck specimens as the cell walls are normally discernable in thin-section. Many cells have, however, only a very thin impersistent layer of organic matter outlining them and sometimes this is completely absent. It is then difficult to differentiate cell wall and lumen.

Sometimes a spiral, network pattern can be seen on the tracheid walls both in thin section (Pl. 8 , Fig.14) and under SEM (Pl.8 , Fig.13). This distortion of the components of the cell wall tends to affect the bordered pits and they appear slit-like, paralleling the orientation of the wall spiral. Pits of this shape are characteristic of compression wood (Butterfield and Meylan 1980); the strengthening wood found on the lower side of leaning branches. In compression wood the S_3 layer is absent and the microfibrils of S_2 become more prominent. However, in the Purbeck wood these slit-like bordered pits appear to be purely the result of the splitting of the silicified wood along a secondary wall layer as in the adjacent tracheid in Figure 12 (Pl. 8) the pits are clearly circular.

Bordered pits with a silica infilling of the aperture occur in two forms seen under SEM. Most commonly the cell wall surface facing into the lumen is exposed and the pit appears simply as a raised circular disc with a central filling of granular silica marking the pit aperture (see Figure 4.02) (Pl. 8 , Fig. 5). More rarely the wall facing the middle lamella is exposed. The infill of the pit chamber appears as a small disc on a stalk, though usually this is broken off (Fig.4.02)(Pl. 8 , Fig.6).

Cross-field pits are preserved in a similar way but they are rarely visible in the silicified wood due to their small size (about 5 µm). They are also affected by the spiral nature of the microfibrils (Pl. 9 , Fig.11).

An interesting feature of the Purbeck wood is the abundance of resin. In thin-section this appears dark orange and is present as a film on the ray cells and in tracheids (Pl. 9 , Fig.10), though not in specialised resin cells. The resin was not detected in the SEM samples, probably because it dissolved in the acetone in which the wood was cleaned prior to mounting on stubs.

Also observed in the tracheids were small spherical bodies composed of silica, 2-20 µm in diameter,which occur on the tracheid walls (Pl. 10 , Fig. 1 ; Pl. 8 , Fig. 8). These spherules are sometimes coated in dark orange resin. They may have originally been spherical starch grains, commonly found in modern wood (Butterfield and Meylan 1980, fig.49), which were later replaced by silica. Identical spherical structures were noticed in the cells of a piece of modern Cupressus wood though it is unclear whether they were composed of starch or resin.

In the best preserved specimens of Purbeck wood each cell lumen was infilled with a single silica crystal (oligoblastic crystallisation of Storz, 1933). In a few samples each cell was filled with many fibrous crystals and in some cases several cells were replaced by one large crystal (hyperblastic crystallisation) though in this case very little organic matter remained and the cell outlines were hard to determine. Deterioration of the wood structure occurs where a secondary stage of silicification has resulted in the growth of the silica crystals at the expense of the cell outlines. All stages of this process can be traced within a single specimen in thin section. Patches of the wood with well-preserved cells begin to show polygonal shapes (about 0·4 mm diameter, consisting of many cells) outlined by dark lines (a "network" texture). Gradually the silica in the cells at the margins of these areas replaces them and organic matter from the cells is obviously pushed back to the dark line formed by the concentration of this material. This process progresses until nearly all the cells have been replaced by a 'rosette' of large crystals of megaquartz radiating from the centre. Only a few intact cells remain in the centre and even these may be replaced. Organic matter originally present in the cells accumulates at the edge of the 'rosette' as large patches of a dark brown substance. These replacement 'rosettes' occur sometimes singly within patches of well-preserved cells or as groups, progressively replacing cells on the edges of the group. The 'rosettes' in the centre of a specimen are always the largest, often up to 6 mm in diameter (Pl. 8 , Fig. 7).

Nearly every tree specimen exhibits cell replacement of this kind, sometimes in small patches, but often replacing nearly the whole cross-section of the tree. This is the main cause of loss of cellular detail which hindered the measurement of growth rings in some specimens (Chapter 6). In rarer cases the cells are replaced simply by large irregular crystals of quartz, their margins outlined by organic matter as before.

Apart from the infilling of the cellular structures and their subsequent replacement, another type of crystallisation is that which occurs in cracks in the silicified wood. Unlike the early shrinkage cracks these have a very irregular shape and have little relationship to the lines of weaknesses expected in the wood structure. Some cracks are preferentially oriented in a radial or tangential direction, splitting apart files of cells, but most have irregular orientations. The edges of the cracks are often irregular and sometimes individual cells are separated and incorporated into the silica filling the crack. Unlike the shrinkage cracks the silica is clear and unstained. Rarely the primary layer of silica has a dark stain due to minute inclusions of organic matter (but not large soil particles or pollen grains). The crack contains progressively clearer layers of silica which are of fibrous form; towards the centre often the boundaries between each successive layer have a dark stain. Up to 7 successive layers have been observed infilling cracks; each layer consists mainly of fibrous crystals of varying lengths, though layers composed of minute crystals of microquartz sometimes occur. The centres of the cavities are generally infilled with large, irregular-shaped quartz crystals or large radiating megaquartz crystals. Rarely a small cavity remains in the centre.

Plate 8

(TL = transmitted light. SEM = scanning electron microscope)
Silicification of the fossil wood

1. Transverse section showing independent silicification of cell walls and lumen. The cavity between the two is usually infilled with organic material. The silicified wall of a medullary ray cell crosses the picture. PB.1, Fisherman's Ledge. (SEM)

2. Transverse section in transmitted light. The cell walls are darkened by included organic material. Although the individual layers of the cell walls are not apparent the position of the middle lamella is clear. The dark cell contains dark orange resin. PB.1. Fisherman's Ledge. (TS, PPL)

3. Radial section illustrating the silicified cell wall layers. The oblique slits on the right are bordered pits. PB.30, Broadcroft Quarry, Portland. (SEM)

4. Replacement of the cell wall by fibrous, length-slow chalcedony. The individual layers of the wall have been lost but the position of the middle lamella is still apparent. PB.46. Inmosthay Quarry, Portland. (SEM)

5. and 6. Silicification of the bordered pits (see Fig. 4.02). Those in Figure 5 consist only of a low dome with a central granular plug. The pits in Figure 6 has small caps on stalks. Both from PB.24, Portland. (SEM)

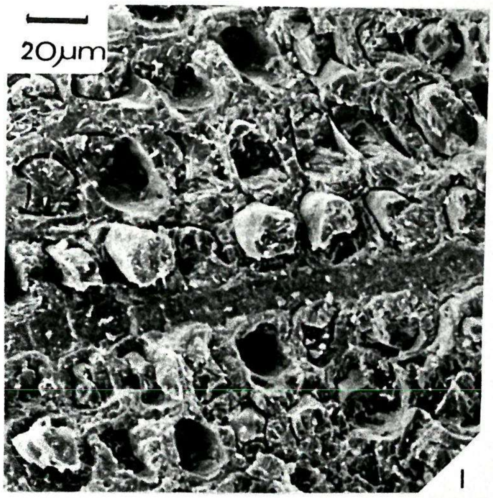
7. The large 'rosettes' of megaquartz which are formed by the secondary replacement of length-slow chalcedony infilling individual cells. Organic matter from the cell walls is pushed to the edge of the 'rosette'. Some cells may still be preser ved in the centre. PB.46. Inmosthay Quarry, Portland. (SEM)

8. Small, smooth spherical bodies lining the walls of tracheids (or possibly parenchyma cells). The rest of the cell is usually infilled with resin.
PB.1, Fisherman's Ledge. (SEM)

9. Shrinkage crack in the wood of PB.11. The silica infilling the crack is stained brown and includes well-preserved pollen, including <u>Classopollis</u>, and soil particles. The wood fibres are bent and ragged. PB.11, Blacknor, Portland (TS, PPL).

10. Large tangential crack infilled with quartzine and containing pollen and soil particles.
PB.54, Fossil Forest. (TS,PPL)

11. Several stages of fracturing and infilling. The large crack infilled with brown-stained silica is the earliest. This crack itself has been fractured and infilled. Fracturing after the wood has been silicified has led to the inclusion of petrified cells, their walls and lumen infilled with silica, within the later vein. Secondary replacement of the cell structures is also visible on the right. PB.11, Blacknor, Portland. (TS, PPL)



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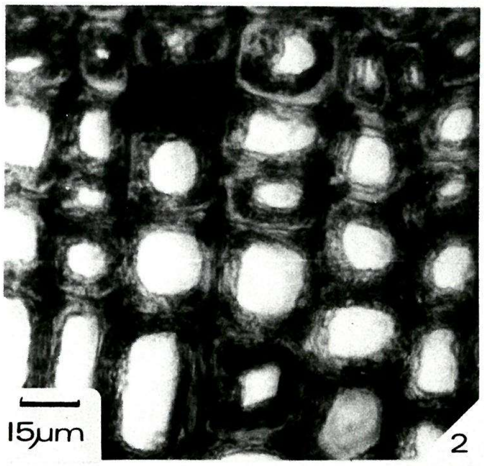

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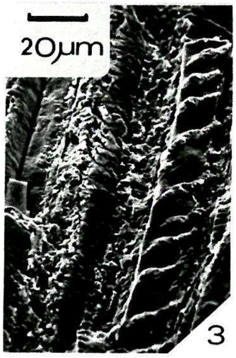

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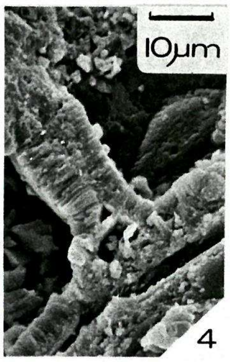

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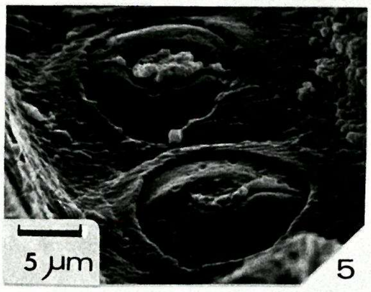

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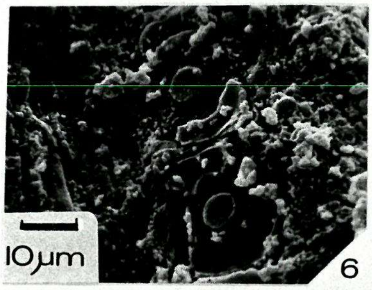

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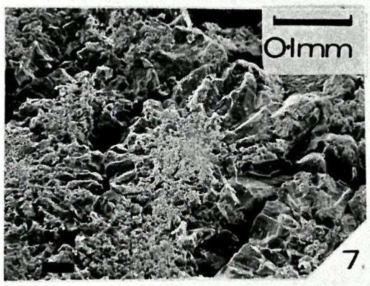

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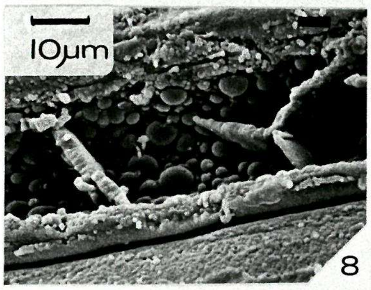

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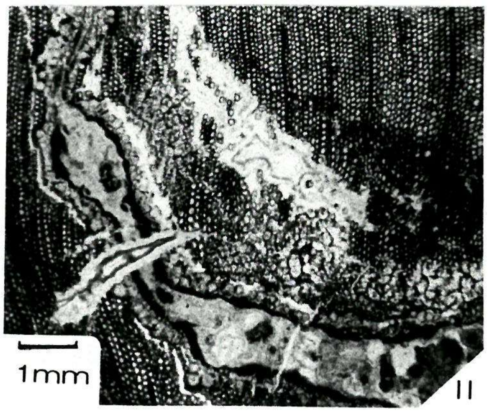

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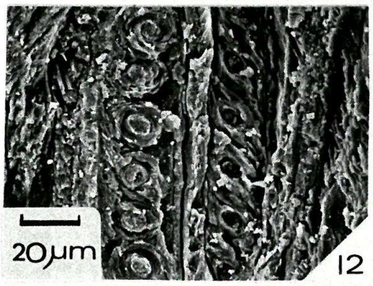

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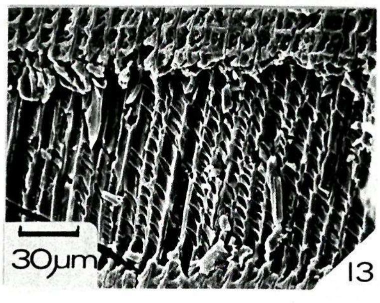

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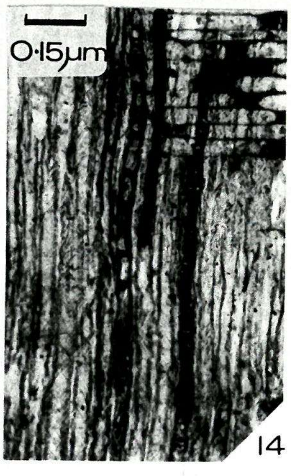

14

PLATE 8

Plate 8 continued

12,13 and 14. Silicified wood and fusain, exhibiting oblique bordered pits and fibrous structures on the tracheid walls. This may be compression wood but could also simply reflect the oblique orientation of the cellulose microfibrills of the original wood, now preserved by the silica (Figures 12 and 14) and in the fusain (Figure 13).
Fig. 12; PB.46, Inmosthay Quarry, Portland (SEM). Fig. 13; Fus/1. God Nore, Portland (SEM). Fig. 14; PB.24, Portland (TS, PPL).

These large cavities are themselves traversed by thin (20 µm wide) cracks, now infilled with fibrous quartz orientated normal to the sides of the cracks. The silica is very clear and does not penetrate beyond the sides of the cracks. The cracks only occur across large infilled cavities and rarely protrude very far into the cellular part of the wood.

4.1.iii The types of silica in the trees

The quartz in the Purbeck trees occurs as two main types: microquartz and megaquartz. The former, formed of crystals less than 20 µm in width, is most common and itself occurs as two forms: microcrystalline quartz and chalcedony. Microcrystalline quartz consists of minute, irregular grains, 3-4 µm in size, with random orientation. This is the typical component of chert (Folk and Weaver 1952). In the Purbeck wood this type infills the shrinkage cracks and sometimes the cell lumina and walls. Because the crystals are so small their optical properties are hard to determine and they tend to exhibit "pin-point" extinction. The most abundant type of quartz is a fibrous chalcedonic form which both replaces cell structures and occurs as a cavity-filling. Cell walls are replaced by small fibres, a few microns wide, oriented normal to the wall and in some trees individual cell lumina are filled with fibrous quartz. Most of this fibrous type in the Purbeck wood is length-slow with the C-axis parallel to the length of the fibres, a variety of chalcedony known as quartzine (Folk and Pittman 1971). It occurs mainly as spherules or rosettes of rather irregular fibres radiating from a central nucleus. They have been observed in groups of 3 or 4 or singly, in the centre of shrinkage cracks, surrounded by microcrystalline quartz. The quartzine tends to have a slighter yellow tinge (PPL) but its refractive index is almost the same as the surrounding quartz. The ends of the fibres tend to grade into the surrounding microquartz but between two adjacent spherules a straight darkened interface-boundary is visible.

The quartzine also occurs as spherules of radiating fibres in the centres of the large rosettes replacing the cells. The ends of the fibres are irregular in length and tend to grade into the terminal fan-shaped crystals of megaquartz.

One tree, PB.8, is composed almost entirely of spherules of quartzine with small patches of microquartz which are the only areas where cells are well preserved. The quartzine spherules range in diameter from 30 µm to 1000 µm and have a very irregular appearance, the fibres being of different lengths and thicknesses. The centres of some of the spherules have a dark orange staining which appears to be similar to the resinous material found in some cells.

In contrast, length-fast chalcedony (with the C-axis normal to the fibre length) is much less common. Only one tree, PB.83 from Chalbury Camp, is dominantly length-fast chalcedony. The cells are replaced by microcrystalline quartz and length-fast chalcedony infills all cavities as layers of radiating fibres and in a few places replaces groups of cells in spherulitic form. Length-fast chalcedony occurs in the fossil wood which is dominantly replaced by quartzine but only as a late-stage infilling of cavities. These radiating fibres are much more regular and neater in appearance since they are all of the same length and width. This chalcedony tends to have fewer inclusions and is clearer than quartzine.

Crystals of megaquartz (length-slow) occur as the final stage of infilling in cavities where they are present as irregularly-shaped interlocking forms. The large replacement rosettes also consist of megaquartz at their terminations and similar crystals line small empty cavities in the wood. Their terminations are not well-shaped but tend to be rather blunt in appearance. The spherules of quartzine gradually grade into megaquartz crystals near cavities.

4.1.iv Discussion

4.1.iv(a) The process of silicification of wood

In most trees the wood structure of the xylem is well preserved and in some trees very fine detail can be seen. The outer part of every tree (the bark and the phloem) do not appear to have been silicified and these parts probably decayed rapidly before permineralisation. In contrast the cells of the inner xylem remained intact before silicification and the apparent absence of much fungal attack or structural decay suggests that either conditions were not suitable for microbiological activity or that permineralisation proceeded soon after the death of the trees. Dead wood normally decomposes beyond recognition within a matter of years, principally effected by lignin-digesting fungi which utilise the holocelluloses and lignins for their metabolic processes.

Microbiological activity and the resulting organic breakdown occurs most rapidly in a warm, moist, highly aerobic environment, in particular the upper levels of soils (Barghoorn 1952). Moist wood is particularly susceptible. Wood fungi can also tolerate a comparatively wide range of pH, from values of about 4 up to 9, though under highly saline conditions fungal activity decreases (Leo and Barghoorn 1976). In very alkaline conditions wood decomposition is accelerated through chemical breakdown and dissolution of wood substances and so unmineralised wood is rarely preserved under such conditions (Browning 1963).

The basal Purbeck Dirt Bed palaeosols are highly calcareous; their modern soil equivalents (rendzinas) have pH values of about 7-8. Although the soils were relatively shallow and the climate was semi-arid (West 1975) there was sufficient moisture in the soil to allow large conifers to grow, albeit slowly. Soil fungi were probably present though rarely visible now (see Chapter 3) and in combination with the high alkalinity suggests that plant material buried in the palaeosols would decompose quite rapidly. This may account for the lack of structurally preserved plant material in the dark, marly Dirt Beds.

The best conditions for the preservation of wood is in an anaerobic environment, since most of the organisms responsible for wood decay require oxygen for respiration. Processes of decomposition are at a minimum in stagnant, poorly drained, shallow basins (Barghoorn 1952). Such an environment would have formed when the Dirt Bed palaeosols and their forests were inundated by incoming hypersaline water, when the soils and tree trunks were coated by algal-bound sediment (Chapter 2). The tree trunks within the algal sediment probably decayed more slowly, although portions remaining above the water level might eventually rot near the surface of the water and break off, to be coated in the sediment below. This is a possible origin of the trough-shaped burrs in the Soft Cap at the Fossil Forest.

The main pre-permineralisation changes in the wood structure appear to be the cracks in the wood into which were incorporated contemporaneous pollen and soil particles, and a minor degree of compaction in logs which were found lying on the Great Dirt Bed surface, illustrated by contorted and crushed cells. Even if decay of the wood was not particularly rapid the excellent preservational state of the cells and lack of much compaction due to burial suggests that silicification occurred soon after the trees died.

Degradation of plant cell walls proceeds in a consistent sequence both with regard to the components of the cell wall and to its lamellar organisation. At first there is a reduction of the original cellulose, leaving the more resistant lignin residue. Then the central layer of the secondary wall breaks down (S_2), followed by the S_3 and S_1 layers and lastly the thin primary wall (Barghoorn 1952). The semi-rigidity of the walls prevents collapse of the internal structure. The silicification process entails the gradual infilling of the spaces left by the decaying layers of the cell wall, thus there is penetration of siliceous solutions into the cell wall without the "replacement" of organic molecules as once thought essential. The silica may even occupy the microfibrillar spaces created by the removal of the original cellulose (Siever and Scott 1963).

In the early stages of silicification deposition occurs primarily upon the more accessible cellular surfaces, particularly on the wall of the cell lumen and the lining of the pit chambers. The cell contents and middle lamella are the first parts to decay and present the first available space (Buurman 1972). With the continual influx of the siliceous solution the lumen and pit chambers gradually become filled. It has been proved by experiment that the wood serves as an active template for silica deposition (Leo and Barghoorn 1976). Gradually the woody parts of the cell begin to deteriorate and the silica solution infills the vacant spaces.

The good preservation of the anatomical structures in some specimens of Purbeck wood illustrates that a gradual infilling of the vacant layers of the cell walls was likely. In some cases (Pl. 8 , Fig.14) even the microfibrillar structures have been fossilised resulting from the infilling of the vacant S_2 layer. The silicification of the wood has not gone to completion since in most trees a good deal of organic matter has been retained within the cell walls. In fact this is also the case with most silicified wood from other sites. For example, the organic matter within silicified wood (Araucarioxylon arizonicum) from the Triassic fossil forest of Arizona has been analysed by Sigleo (1978a,b) and was shown to be the degraded products of the original cell lignin. The amount of organic material retained in the samples of Purbeck wood determined the clarity of the cells and wood structure.

Molecular silicic acid (H_4SiO_4) is the most probable silicifying agent of silicified wood because its hygroscopic particles can penetrate the very fine cellular interstices of wood and it is the only common form of soluble silica found in nature (Siever 1972). An ionic form of silica rarely forms in very alkaline environments (Peterson and von der Borch 1965) and suspended colloidal particles would be too large to penetrate cell walls. It is thought that there is some chemical affinity between soluble silica and the ligno-holocellulosic wood complexes (discussed in Leo and Barghoorn 1976) which may account for the pre-eminence of silica as a wood petrifant and thus explain the presence of silicified wood in an unsilicified matrix, such as the Purbeck Dirt Beds.

The physical state of silica in newly petrified wood is considered to be nearly amorphous. Over a long period of time this converts to an opaline deposit and ultimately to low quartz, though this process requires a period of 10^7 to 10^8 years (Siever 1972).

Buurman (1972) found that some Tertiary wood was mineralised with "disordered tridymite" (wood-opal), an unstable form of silica which gradually changes to finely crystalline quartz. Stable tridymite has mineralised some wood (Mitchell 1967) but only under certain conditions, such as high pressure. Because the wood structure is so well preserved in his tridymite wood specimens Buurman proposed that some well-preserved chalcedonic wood may have recrystallised from an intermediate stage of "disordered tridymite", though in some Tertiary wood chalcedony is clearly the primary phase. However, Buurman considers that the tridymite wood has formed by the replacement of cell walls rather than permineralisation, and so lignified organic matter was not preserved. This suggests that the Purbeck silicified wood, with often a good deal of organic material remnant in it, was primarily permineralised by chalcedony.

4.1.iv(b) The source of silica

The source of the silica for the permineralisation of the Purbeck trees is not immediately obvious. Most silicified fossil wood is found within volcanic sediments from which siliceous solutions were derived by weathering (Siever and Scott 1963; Dorf 1964) but there is no evidence of volcanic deposits within the basal Purbeck beds. Nor were there siliceous hot springs, which in other areas have led to the mineralisation of plants such as the Devonian plants in the Rhynie Chert in Scotland (Kidston and Lang 1921).

Silica-secreting planktonic organisms such as diatomites and radiolarites are potential sources of silica and can form siliceous oozes at the bottom of both oceans and freshwater lakes. These may have been a source of silica for the trees and other Purbeck cherts (House 1968), since diatoms do occur in comparable modern algal-rich sediments (Monty 1976). Their tests have not been observed within the Purbeck cherts, to be expected if they had dissolved completely. (There is no record of diatoms preserved in rocks older than Cretaceous, Lohman 1960.)

Sponge spicules provided the silica for the silicification of the Corallian and Portland Beds of southern England (Raison 1903; Wilson 1966). However, the only record of sponges in the Purbeck Beds is of Spongilla purbeckensis in chert at Stair Hole (Young 1878). A considerable amount of siliceous remains and sponge spicules would be necessary to provide enough silica for permineralisation of the trees (sponge spicules form more than 25% of the Corallian and Portland Beds) and no such source has been found.

During weathering processes silica is released in silicate mineral diagenesis. Some minerals liberate silica when transforming from one type to another with a lower silicic to alumina ratio, particularly montmorillonite to kaolinite (Siever 1972). There is very little kaolinite within the basal Purbeck Beds (T. Clayton, pers.comm.) and too little is known about the clay mineralogy of the Dirt Beds or adjacent limestones to confirm such an origin for the silica.

pH has an important effect on the chemistry of silica. Although its solubility is very slight and independent of pH for values below 9, above 9 it rises markedly (Krauskopf 1959). Conditions of such high alkalinity are found today in the lower levels of some calcareous soils and in ephemeral saline lakes. In the coastal lagoons of South Australia (suggested as a modern analogue for aspects of the Purbeck environment by West 1975), and particularly in the Coorong Lagoon, chert is precipitating inorganically (Peterson and von der Borch 1965). Seasonal photosynthetic activity of the plants raises the pH of the water at times to values sufficiently high for the dissolution of silica, mainly from detrital quartz and silicate clay minerals. The silica-rich brine either dries or sinks down into the sediment. Just below the sediment surface the pH has been lowered by the organic decay of plant material and the liberation of CO_2. During the dry summer season gelatinous opal-cristobalite is deposited at this pH boundary; this will gradually recrystallize to chalcedony (chert).

The chemical transformations of silica in saline lagoons suggest a possible origin for soluble silica in the Purbeck, particularly with respect to the silicified trees. During the dry summer seasons the pH at the base of the calcareous Dirt Bed palaeosols may have risen to a level high enough for the dissolution of quartz and the release of soluble silica. However, no evidence remains today that the Dirt Beds ever had a significant content of detrital quartz. There is only a minute quantity of quartz grains in the Dirt Beds and adjacent limestones, and no evidence, such as pseudomorphs, to suggest there ever was more. Again a large quantity of detrital quartz would be necessary to silicify all the Purbeck trees and such a source is not apparent. Once the forests had been drowned a shallow hypersaline lagoon formed in an environment very similar to that in the coastal lagoons in Australia, and it is conceivable that silica was precipitated in a similar way.

Leo and Barghoorn (1976) suggest that a special bonding potential exists between the soluble silica and the molecular constituents of the wood which allows the silica to be preferentially precipitated in the wood rather than the surrounding matrix, although the reason why the silica solution preferentially permeates the wood and not the matrix is essentially unknown (Siever and Scott 1963).

It was most likely that the Purbeck wood was encased in algal mat during the initiation of silicification. Not only would the algal mat protect the wood against rapid decay and produce very high values of pH but water is also essential in petrifaction as a medium for transport and dispersal of soluble silica in and throughout the specimen, to exclude oxygen and also to keep the wood in a swollen state, thus maintaining maximum permeability (Leo & Barghoorn 1976).

Once the silica solution had permeated the wood the initial decay of the organic matter would have lowered the pH slightly causing the silica to be precipitated on the cell walls (the chemistry of this process is discussed in Leo and Barghoorn, 1976). The pH of the fluid within the wood was probably near neutral since acidic or highly alkaline conditions would have rapidly destroyed the wood materials and the cell structure would not have been well preserved.

4.1.iv(c) Silicification in evaporitic environments

The commonly observed replacement of carbonate rocks by silica is also related to pH (Walker 1964). The highly alkaline environment suitable for the solution of silica (pH > 9) causes precipitation of carbonate, whereas silica precipitates and carbonates dissolve in conditions of low pH. Fluctuations in pH are usually caused by the periodic build-up of CO_2 evolved from the decay of organic matter. The prevailing pH conditions have important implications for the form of silica which preserved the wood.

Most of the Purbeck wood is replaced by a particular type of chalcedony, i.e. length-slow quartzine. Although quartzine has not been observed in the basal Purbeck limestones before, the other form of length-slow chalcedony, lutecite, was recorded by West (1964) in the Caps at Upwey. In contrast to quartzine which has the C-axis parallel to the length of the fibres, in lutecite the C-axis is at approximately 30° to the fibres and a chevron-like intersecting pattern is apparent in thin section. In the Purbeck Beds lutecite pseudomorphs after lenticular crystals of gypsum occur in the Caps (West 1964) and similarly in chert nodules from the Great Dirt Bed at Upwey. However, a nodule of silicified wood from this bed contained quartzine, and lutecite has not been identified in any silicified Purbeck tree.

Length-slow chalcedony has recently been identified in many other evaporitic sediments (West, Brandon and Smith 1968; Folk and Pittman 1971; Siedlecka 1972; Chowns and Elkins 1974; Shreiber 1974; Tucker 1976; Milliken 1979). Folk and Pittman (1971) considered that at high concentrations of silica and high pH, silica would form fibrous crystals due to its rapid rate of crystallisation. In high pH conditions (i.e. evaporitic environments) the silica in solution tends to occur in an ionic form as single tetrahedra which can precipitate easily with the C-axis parallel to the fibres (length-slow chalcedony). In contrast, when the pH is low (non-evaporitic conditions) the silica solution is polymerized and is precipitated as spiralling chains of silica tetrahedra with the C-axis perpendicular to the fibre lengths (length-fast chalcedony). Hence length-slow chalcedony should be the "normal" type formed under evaporitic conditions. The abundance of quartzine in the Purbeck trees therefore supports the idea that the environment was generally alkaline. Lutecite seems to occur only as pseudomorphs of evaporite minerals (West 1964; Folk and Pittman 1971). There is no sign of the original presence of evaporite crystals in the trees, either as pseudomorphs or small inclusions, though they have been reported in Oligocene petrified wood

(Staples 1950). In the Purbeck trees length-fast chalcedony occurs as a late-stage fibrous crust infilling cavities. A similar sequence observed by Folk and Pittman (1971) was considered to represent a late stage infilling when conditions were less alkaline. The anomalous presence of mainly length-fast chalcedony in the fossil tree from the Lower Dirt Bed at Chalbury Camp suggests that the environment was somewhat less alkaline at the time of its petrifaction.

The silicification of the Purbeck Beds occurred in several stages (West 1964). An early period of silicification occurred soon after deposition but prior to lithification, replacing gypsum crystals. This probably occurred at the same time as the trees were being petrified as the preservation of the cell structure indicates that petrifaction occurred quickly. A later phase of silicification replaced the anhydrite crystals of Stage III of West (1964), probably in the period from the Wealden to Mid-Tertiary, though this later stage is not identifiable in the Purbeck wood.

Quartzine has also been recorded from samples which have no primary association with replaced evaporites but which occur in alkaline soils with caliche from semi-arid regions (Folk and Pittman 1971). These soils are either alkaline volcanic soils, soils adjacent to evaporitic sediments or soils in a semi-arid environment suitable for sulphate-rich conditions to occur. The occurrence of length-slow chalcedony is considered by Folk and Pittman (1971) to be a palaeoclimatic indicator, indicative of a semi-arid climate.

4.1.iv(d) Summary of the silicification processes

To summarise, the anatomical preservation of the silicified Purbeck is, in most cases, very good. Not only are the individual cells still visible due to the retention of some organic matter within the walls but even the laminar wall structure and the shape of the border pits are preserved. The nature of the silicification agrees with the widely held view that the permineralisation proceeds by a process of infilling and impregnation with the wood structure acting as a template for deposition, rather than molecular replacement of the wood material (Leo and Barghoorn 1976, and others).

Apart from the initial loss of the external layers of the trunks, the wood decayed very little before permineralisation, there being very little evidence of fungal attack. This was probably due to the inundation of both the Lower Dirt Bed and Great Dirt Bed forests by algal-rich hypersaline water which waterlogged the tree stumps and retarded decay in the resulting anaerobic environment.

The origin of the silica in the Purbeck wood is not clear but was most probably biogenic silica from silica-secreting planktonic organisms such as diatoms, which today abound in algal-rich sediments (Monty 1976). Some contribution from the weathering of detrital quartz is possible. In comparison with a modern chert-precipitating environment (Peterson and von der Borch 1965) it seems likely that the pH was seasonally high enough (pH > 9) for silica to be present in solution, the pH being raised due to the depletion of CO_2 by the photosynthesising activities of the algae. The reason for the preferential localisation of the silica in the wood rather than the surrounding sediment in both the Purbeck Dirt Beds and other fossil forests is unknown, though it has been suggested that the silica solution is preferentially attracted to the molecular constituents of the wood (Leo and Barghoorn 1971). Having once permeated the wood structure, the initial decay of the organic matter would have lowered the pH sufficiently to allow precipitation of the silica, intimately preserving histological details.

The initial state of the silica in the wood was most likely amorphous (Siever and Scott 1963) but over a long period of time crystallized to fibrous chalcedonic quartz, the result of high concentration of silica in an environment of high pH (Folk and Pittman 1971). The most abundant type of silica in the Purbeck wood is quartzine, a particular type of length-slow chalcedony which has recently been identified in many evaporitic sediments and was proposed as an indicator of semi-arid alkaline environments (Folk and Pittman 1971). The presence of this mineral in the fossil trees and lutecite replacing former evaporite crystals in adjacent sediments (West 1964) supports the evidence from the well-preserved cell structure of the trees that silicification occurred soon after the death of the trees before decay of the cells and whilst the environment was semi-arid and seasonally very alkaline.

4.2 Preservation of the Non-Silicified Plant Material

4.2.i Introduction

Fusain occurs as black, opaque, brittle fragments, often with excellently preserved wood structure. Due to its brittle nature it is usually found in sediments as isolated pieces but also occurs within coal measures as whole beds or lenses (Francis 1961). The term 'fusain' has been used for individual fragments (Harris 1958 and others) though 'fusinite' is now widely used (Marshall 1954; Cope 1979, 1981). Due to its small size and opaque nature it has not been studied widely in the past. However, the study of the 'fragmentary plant material' (F.P.M.) of Scott and Collinson (1978) and the 'dispersed organic matter' (D.O.M.) of Cope (1981), in which fusain is a major constituent, has been aided by the use of SEM and the properties of fusain in particular have been revealed in this way (Alvin and Muir 1969; Alvin 1970; Muir 1970; Scott 1977; Scott and Collinson 1978; Cope 1981; Harris 1981).

Two theories as to the origin of fusain have been debated. Its resemblance to modern charcoal supported the now widely-held view that fusain represents the chemically-inert products of natural burning, making it highly resistant to microbiological and chemical degradation (Harris 1958; Komarek 1972; Alvin 1974; Scott 1974, 1977; Batten 1974; Cope and Chaloner 1980; Cope 1979, 1981; Harris 1981). It can withstand the high temperatures of deep burial and can survive for long periods in environments in which other plant material has otherwise been destroyed (Cope 1981).

However, some believe that fusain is formed by wet oxidative decay at an early stage, although the exact mechanism is not reported (Schopf 1975).

4.2.ii Observations of fusain in the Dirt Beds

Small pieces of fusain, most less than 2 mm in size, were recovered from the Lower and Great Dirt Beds after bulk maceration of the palaeosol matrix resulting in the dissolution of the carbonate matrix. Within the black marly Dirt Beds the fusain remained the only structurally preserved plant material, the remainder consisting of amorphous material. In the Great Dirt Bed at God Nore, however, the fusain particles were more abundant and occurred with the recognisable cuticle remains (Chapter 5). The Basal Dirt Bed yielded only a small quantity of fusain in most places, except at Bacon Hole. At this locality this Dirt Bed was exceptionally dark and some layers were composed almost entirely of very small, shiny, sooty fusain fragments. The fusain is not found in association with the silicified wood, either around its exterior circumference or in patches inside the trunk. Nor are pieces of fusain found in the adjacent algal limestones.

The small fragments of fusain are black, opaque and have a striking silky lustre. They are extremely brittle and tend to split along the length of the wood grain, ultimately dissociating into long fibrous pieces. They can rarely be forced to split in a transverse direction but when they do the cell surfaces are very cleanly fractured (Pl. 9 , Fig. 1). In the Dirt Beds the pieces of fusain are very angular, exhibiting no rounding due to transport. Another characteristic feature is its sooty texture, similar to that of modern charcoal.

The preservation of the wood structure is excellent, as seen under the SEM (Pl. 9 , Figs. 1-6) Unlike the silicified wood where original empty cavities were infilled with silica (e.g. pit chambers, cell lumen), in the fusain these are still empty. The laminar structure of the cells has been lost and in some cases two adjacent cell walls appear to have been homogenised. In some specimens the middle lamella is still present as a separate layer (Pl. 9 , Fig.1) though intercellular spaces may be present along this line. The membrane spanning the bordered pit chamber is absent though the pits are still preserved as circular structures with circular apertures. In adjacent tracheids, however, the cell walls show a fine oblique ornamentation, very similar to that observed in the silicified wood. The pit apertures here are also slit-like, paralleling the wall pattern, and probably reflect the micro-fibrillar orientation of the wall structure. The cross-field pits are exceptionally well preserved and are best seen on the inner surface of the ray cell wall (Pl. 9 , Fig. 3). There is no evidence of resin nor of microbiological decay of this wood.

Although there is no evidence of compression, a significant difference in the dimensions of the wood structures was noted in the fusain in comparison with the silicified wood. The measurements are recorded in Table 5.01. A reduction of about 30%, sometimes up to 70%, in wall thickness was noted but the lumen and pit apertures were reduced by only 14-50% from values recorded in the silicified wood. Despite this difference it is clear that the wood species are the same in both types of material.

4.2.iii Preservation of the roots

The silicified roots of some of the fossil trees are preserved within the Lower Dirt Bed at Chalbury Camp and the Great Dirt Bed at the Fossil Forest (Pl.14 , Fig. 5). One silicified root, which has an average diameter of about 10 cm, has a 2-3 cm sheath of black, coal-like material around it. The silicified part becomes narrower towards the end of the root and ultimately disappears, leaving only the black woody part forming the finer rootlets. Even where silicified stumps are no longer present the black rootlets can still be seen in the Dirt Beds. The black material is not similar to the fusain . It has, instead, a duller waxy lustre, is not sooty and tends to break with a conchoidal fracture. In places the bluish-white colour of silica is visible, particularly in the centre (Pl.14 Fig. 5). The cell structure of the black material is visible in places in thin-section where the cell walls are very dark brown and still contain a great deal of organic matter, but even here the cell lumina are infilled with silica, preserving the structure. Where there is no silica the cell structure is not preserved and the 'black' root then consists only of a dark brown/orange, structureless, resinous-looking material.

Not only can the roots be proved to be in situ because they are attached to tree stumps but also in some cases particular roots have obviously grown around large pebbles in the soil (Pl.14 , Fig. 5). These roots are found in the middle or near the base of the Dirt Beds but show no signs of brittle fracture or compaction as if they had fallen onto soil. The end of one root branches up into the Great Dirt Bed, having carefully grown between the limestone pebbles. These black roots have been recorded up to 50 cm long and do not exhibit the fragmental appearance of fusain.

4.2.iv Discussion

The properties and preservation of the fusain within the Dirt Beds is consistent with evidence from other geological sediments (Harris 1958, 1981; Komarek 1972; Alvin 1974; Scott and Collinson 1978; Cope and Chaloner 1980) and from recent experiments (McGinnes et al. 1976) that fusain is, in most cases, fossil charcoal produced by the natural burning of plant material.

Charcoal is formed by the incomplete combustion of woody tissue, retaining the wood structure but making it chemically inert (Cope and Chaloner 1980). Complete burning tends to produce a white powdery ash which is easily dispersed (Harris 1981). One of the initial effects of burning is the homogenisation of the cell wall due to the loss of its laminar structure and the middle lamella. This occurs at a temperature of about 300°C and is associated with the production of carbon monoxide and methane (Cope & Chaloner 1980), which ignite to produce flames above 280°C.

Although the cell structures are exceptionally well preserved, a considerable shrinkage occurs, as was observed in the Purbeck wood. The amount of shrinkage is related to temperature; an overall amount of 28·8% at 400°C rising to 38·4% at 800°C was recorded in an experiment by McGinnes _et al._ (1976). They also found that the amount of shrinkage varied with the wood structure, the cell walls tending to shrink more than the lumina, as observed in the Purbeck wood. Alvin _et al._ (1981) recorded 40-57% shrinkage of the cell walls in fusainised wood of _Pseudofrenelopsis parceramosa_ from the Wealden of the Isle of Wight compared to silicified wood.

The black, coal-like roots within the Dirt Beds do not have properties characteristic of fusain There is no evidence that they have been burnt and it is difficult to imagine how they could have been subject to fire without the exposed tree trunk being burnt as well. The lack of cell structure in the unsilicified part of the roots and their _in situ_ position within the Dirt Beds suggests that the black material is simply the result of incomplete oxidative decay. The permeation of silica into the cells obviously aided cellular preservation and stopped the decay. A similar occurrence of roots (possibly of _Equisetites_) in Middle Jurassic sediments in Yorkshire was discussed by Fisher and Hancock (in Scott and Collinson 1978 and Cope 1981). Although the roots were _in situ_ no cell structure was observable and they concluded that inertinisation of the roots was the result of progressive oxidation, not of burning. The roots were then formed of vitrinite, a once gelified and structurally homogeneous substance.

The presence of fossil charcoal within sediments has been taken as evidence for forest fires occurring as early as the Devonian; sediments of this age are the oldest to contain fusain (Cope and

Chaloner 1980). Forest fires have also been considered to be the origin for fusain in the Carboniferous (Scott 1974, 1977; Komarek 1972), Jurassic (Harris 1958, 1981), from the Cretaceous (Wealden) (Alvin 1974; Batten 1975); Alvin et al. 1981) and the Tertiary (Francis 1961). Harris (1981) suggested that in the Wealden fires occurred during lightning and electrical storms at the very start of the wet season while the vegetation was very dry. The ferns and other herbaceous plants which grew on low banks on the flood-plains were charred in the fire which probably passed by very rapidly, and the burnt fragments soon washed into nearby scour basins by flood waters where they were subsequently preserved. Harris suggests the fires occurred frequently enough to prevent the growth of gymnosperms, which were apparently restricted to the uplands (Batten 1975; Harris 1981) but would have otherwise dominated the flood-plain vegetation. In contrast, the reconstruction of the Wealden fern Weichselia by Alvin (1974) does not appear to be fire-resistant and so to maintain a constant population forest fires must only have occurred periodically to produce the fusain found today.

Fires occur today even in the tropical, swamp forests such as the Everglades and Okefenokee Swamp in Florida (Cypert 1972; Komarek 1972). During dry periods the peat and vegetation dries out sufficiently for parts of the forest to be intensely burned. Indeed some plant communities exist because of frequent fires which destroy competing vegetation. Plants which are more resistant to fire then flourish. For example, in the Everglades National Park Zamia floridana, a modern representative of the ancient group Cycadales, flourishes because competing series are regularly destroyed by fire to which Zamia is resistant. Also in the Everglades, swamp cypress trees (Taxodium distichum) not only have a thick, fire-resistant bark but are able to recover from fire-damage very quickly by the rapid growth of adventitious buds.

The most common natural source of ignition of forest fires today is lightning (Komarek 1972) though some are considered to be due to volcanic activity or the spontaneous combustion of decaying vegetable matter. Lightning seems to be the most usual cause of forest fires in the past though evidence of this would be hard to find (such as trees showing the scars of lightning strikes,Komarek 1972).

Forest fires vary in their effects (Harris 1958). In some the heat is so intense that the soil is burnt and the only plant remains are the charred stumps of large trees. At the other extreme the fire may pass very quickly through the undergrowth, scorching the plant material which may be saved from complete combustion by falling onto cool ground. Large trees may not be affected at all.

The small quantity of fusain in the Purbeck Dirt Beds suggests that forest fires did occur but not frequently, and they were clearly not frequent or intense enough to hinder the growth of the conifers, particularly in the Great Dirt Bed. The absence of silicified trees in the Basal Dirt Bed and the Lower Dirt Bed on Portland may be due to their destruction by fire, but the large amounts of fossil charcoal (which would support this idea) have not been found. None of the silicified trees shows any evidence of lightning scars or partial charring, nor are there large deposits of fusain within the Dirt Beds to suggest that whole branches or trunks had been burnt. Since fusinite is highly resistant to decay it is reasonable to assume that any large-scale burning would still be detectable in the palaeosols. In a few places within the Dirt Beds thin laminae of fusain may represent charred vegetation but not whole trunks.

All the fusain examined from the Dirt Beds was conifer wood of the same type as the silicified trees; these fragments probably represent small charred twigs. No evidence of a burnt herbaceous undergrowth has been found.

The conditions within the Purbeck forests would probably have been very suitable for fires, in particular the arid environment, the close proximity of the trees and their abundant resin. It is possible that lightning occurred at a time when the vegetation was very sparse and conditions unsuitable for spreading fire, such as the beginning of the wet season. The fires in the Purbeck forests perhaps passed very quickly, charring dead twigs and dried foliage near the ground but not necessarily destroying the trees.

CHAPTER 5

PALAEOBOTANY OF THE FOSSIL FORESTS

5.1 Introduction

Although the basal Purbeck forests have often been quoted as fine examples of in situ fossil forests (Seward 1919, 1931), it is surprising that very little palaeobotanical identification has been made. Detailed field observations were made on the positions and dimensions of the silicified trunks, tree stumps and cycadophytes at a time when they were being regularly uncovered by quarrying in the nineteenth century (Fitton 1835, 1836; Gray 1861; Damon 1884 and others). These records have proved to be of great value for the reconstruction of the trees now that the fossils are less frequently exposed. Conifer foliage was occasionally found in the basal Purbeck sediments but was placed in museums (e.g. in the Brodie Collection or Damon Collection in the British Museum, Natural History) with little or no identification. None was recorded from the Dirt Beds. Damon (1884b) illustrated a specimen of Cupressinocladus Seward from the "Top Cap" limestone of Portland, and Carruthers (1866) described the cone Araucarites sphaerocarpa from the Portland cliffs. The latter obviously led Mantell (1854) to suggest that the Purbeck fossil forests were composed of Araucarian conifers.

In order to obtain more information about the fossil trees and their relationship with the basal Purbeck sediments, samples of silicified fossil wood were collected from museums and quarry specimens found in their original positions within the Dirt Beds, most valuable since they enabled estimates of the forest densities to be made (see 2.6). The dimensions of each piece and features such as knots, cracks and the position of the centres of growth, were recorded. Each sample of silicified wood was studied in thin-section or by SEM (see appendix for details of preparation) and the wood type identified. Small pieces of fusain were also found within the Dirt Beds which had excellently preserved structures (see 4.2).

The systematic descriptions of the wood are recorded in 5.2. The classification of fossil wood has been reviewed several times (Seward 1919; Eckhold 1922; Krausel 1949), becoming more complicated each time. However Bailey et al. (1934) have shown that the fine details upon which some classifications are based can vary within a single specimen of modern wood. To avoid this taxonomic problem Creber (1972), in describing gymnosperm wood from the Kimmeridgian, used the biorecord system of Hughes and Moody-Stuart (1969) mainly for the purpose of stratigraphic correlation. Although useful for this purpose the biorecord system does not require the detailed taxonomic description necessary for the accurate comparison with previously described species, which was particularly important for the palaeobotanical reconstruction of the Purbeck tree. A further review of the classification of gymnosperm wood is desirable, but is beyond the scope of this project and so that of Krausel (1949) has been used.

The foliage of the conifers was introduced to this study with the discovery of conifer shoots within the Great Dirt Bed itself. They consisted of single, compressed branchlets scattered on organic-rich laminae. The laminae, of about 10 cm^2 in area, were discovered within the Great Dirt Bed at God Nore, a locality at which the nature of the Dirt Bed changed from the usual black, marly palaeosol to a re-sedimented, pebbly deposit (see 2.3 iv) where plant remains were preferentially preserved. Small, highly compressed male cones were also preserved amongst the branchlets. The leaf cuticle was rather poorly preserved and at first proved unidentifiable, although the overall leaf arrangement could be discerned. Better preserved conifer shoots with the same leaf arrangement but on limestone, were studied (from museums) and the cuticle characteristics described. The cuticle from God Nore was compared to these better samples and found to be identical in important details; thus the shoots were identified. Well-preserved cuticle was also found within the Great Dirt Bed at Holworth House (Fig.2.07).

The male cones were too compressed to obtain information on the arrangement of the microsporophylls though some cuticle was obtained and identified. The pollen sacs were absent but isolated pollen grains were found associated with the cuticle and these were also described. Unfortunately female cones were absent.

During maceration of samples from the God Nore Dirt Bed for cuticle, it became apparent that a variety of spores were also present. Conspicuous lycopod megaspores were obtained and some miospores identified. Several studies of Purbeck miospores had previously been published (Couper 1958; Lantz 1958; Norris 1969) so a detailed investigation was not repeated, although it was interesting to note that pollen was preserved within the Dirt Bed at God Nore when previous reports (e.g. Norris 1969) had found none in the Great Dirt Bed. A few samples of the black, marly Dirt Bed were macerated to obtain pollen but none was found, suggesting the conditions in the palaeosols were generally unsuitable for its preservation (3.2). Details of the preparatory techniques of the Dirt Beds, cuticle and miospores are listed in the appendix.

Information from the silicified tree stumps and branches and from the leaves, cone and pollen enabled a reconstruction of the typical Purbeck conifer to be made, illustrated in Francis (~~in press~~ 1983) and in 5.5. Other plant fossils from the basal Purbeck Fossil forests are sparse, poorly preserved and their origin poorly recorded (5.4) so were not included in this study. The silicified cycadophytes, once found frequently in the Dirt Beds (Fitton 1836), are rare today and provided no further information on the forest density or the environment. They were identified by Buckland (1929) and Carruthers (1869) and are discussed briefly in 5.4.

5.2 Systematic Descriptions

WOOD

Order CONIFERALES

Form-genus PROTOCUPRESSINOXYLON Eckhold 1922

Protocupressinoxylon sp.A.nov. [1]

(Pl. 9 , Figs. 1-11)

Diagnosis

Growth rings fairly well defined, with a relatively wide zone of early wood and a narrow zone (3-4 cells) of late wood; false rings often present within the growth rings. Files of tracheids of uniform appearance; tracheids polygonal or rounded in cross-section; average lumen diameter 29·4 μm in early wood, 6·2 μm in late wood; wall thickness constant throughout, 9 μm.

Bordered pits on the radial walls of tracheids mainly uniseriate (Pl. 9 , Fig. 11), biseriate opposite arrangement rare; biseriate alternate pitting absent. Pit border and aperture circular (mean diameters 17·2 μm and 6·0 μm respectively); pitting both spaced and contiguous. Contiguously

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Footnote 1. Holotype: PB·11 from Great Dirt Bed, Blacknor, Portland (deposited in B.M.N.H.)
This species has been designated P. purbeckensis sp.nov. See Francis (1982).

Plate 9

(TL = transmitted light. SEM = scanning electron microscope)

Protocupressinoxylon sp. A. nov.

Figs. 1-3, 5, 6. Fusain from the Great Dirt Bed, God Nore, Portland (SEM)

1. Transverse section showing empty cell lumen and preservation of cell walls. The wall layers have been homogenised though the position of the middle lamella is still visible.

2. Radial longitudinal section showing tracheids crossed by medullary ray cells.

3. Enlargement from Figure 2 showing the shape and oblique orientation of the cross-field pits.

5. Tangential longitudinal section illustrating the depth of medullary rays.

6. The cross-field pits are of cupressoid-type with slit-like apertures inclined at 45° and included within a circular border.

4. Silicified wood showing contiguous bordered pits on the radial walls of the tracheids. (PB.24, Great Dirt Bed, Blacknor, Portland. SEM).

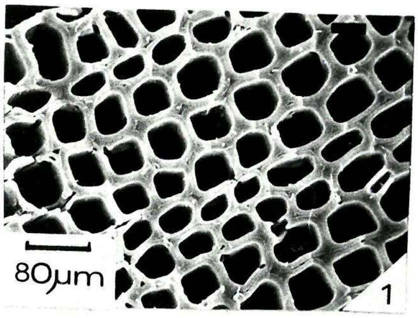
7. Small knot preserved in silicified wood. The crack around the knot has been infilled with silica and contains pollen and soil particles.
(PB.53, Great Dirt Bed, Inmosthay Quarry, Portland. TL)

8. Tangential longitudinal section showing medullary rays 2-8 cells deep.
(PB.24, Blacknor, Portland. TL)

9. Transverse section showing the highly variable growth ring widths. The cells are well preserved in this specimen though parts of the wood have been replaced by secondary silica.
(PB.24, Blacknor, Portland. TL)

10. Radial longitudinal section showing the medullary rays crossing the tracheids. The rays cells are infilled with dark orange resin, as are some tracheids.
(PB.24, Blacknor, Portland. TL)

11. Radial longitudinal section showing bordered pits in both contiguous and separate, uniseriate arrangement on the radial walls of the tracheids. The slit-like cross-field pits have been influenced by the oblique orientation of the cell wall layers.
(PB.24, Blacknor, Portland. TL)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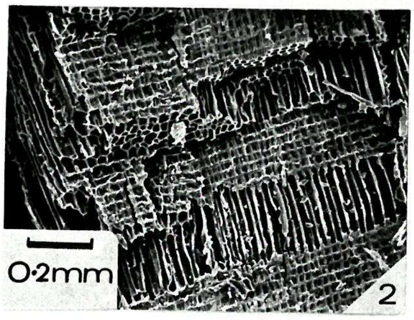
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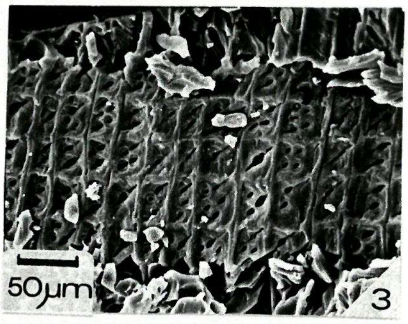
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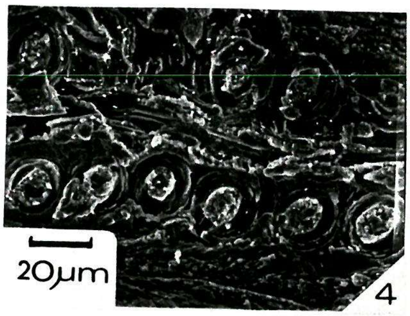
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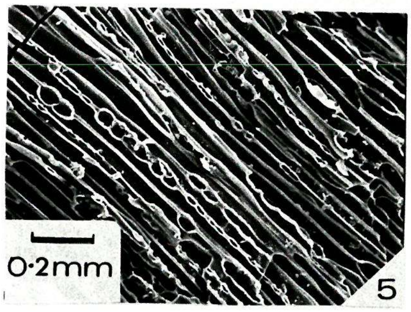
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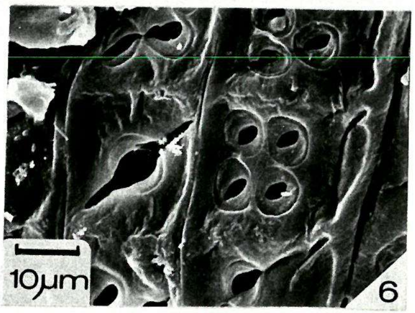
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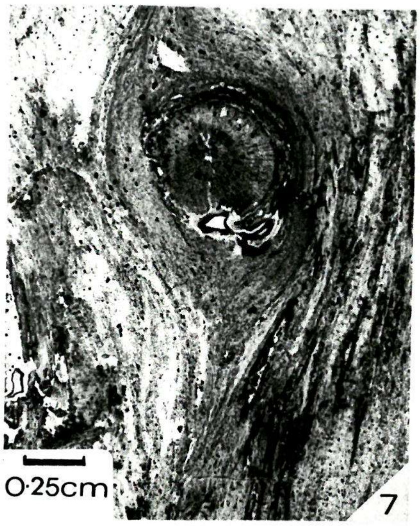
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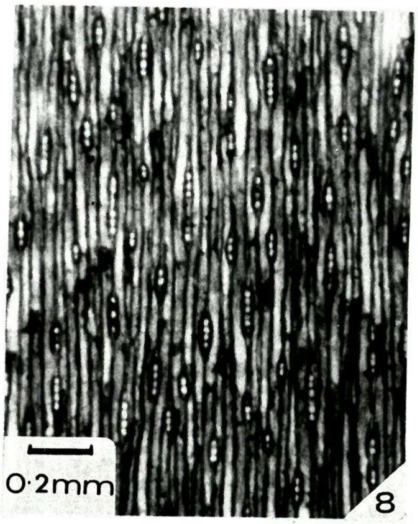
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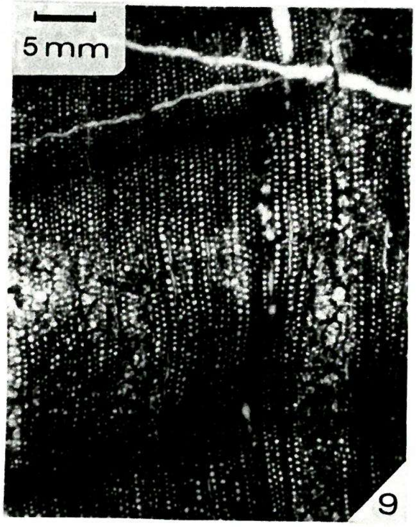
5 mm
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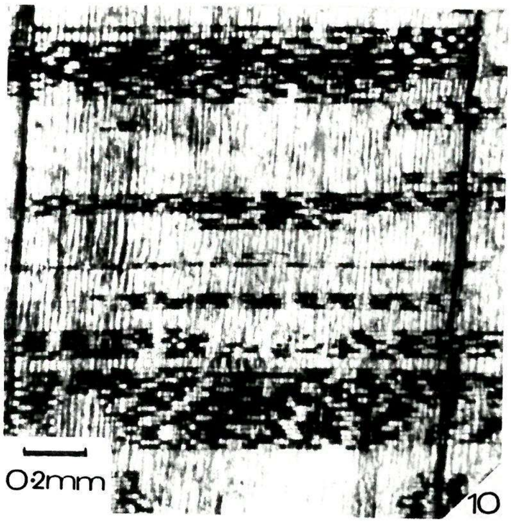
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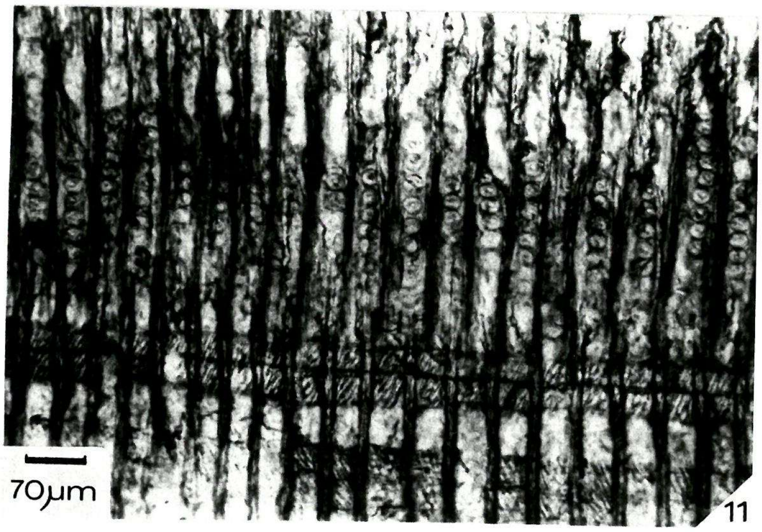

70µm
11

PLATE 9

arranged pits have adjacent borders touching and slightly compressed with vertical thickenings.

Rays, seen in tangential longitudinal section (Pl.9 , Fig.8), numerous, often separated by only 3-4 tracheids, 2-9 cells deep, mostly 3. Ray cells seen in radial longitudinal section, rectangular with 2-7 small pits per crossfield; pits cupressoid with a slit-like aperture within a well-developed, round border; aperture inclined at about 45° (Pl.9 , Fig.6), mean diameter 7-8 µm. Horizontal and tangential walls of the ray cells thin, unpitted. Wood parenchyma absent. Resin canals absent, but tracheids containing a dark resinous deposit throughout the growth ring and ray cells.

Description

Fossil wood with this structure is most common in the Dirt Beds and constitutes over 90% of all identified silicified and fusainised wood samples examined. Although the state of preservation is extremely variable in the silicified wood the most easily recognisable and distinguishing character is the arrangement of bordered pits on the radial tracheid walls. This is of semi-araucaroid or "mixed" type, with series of both contiguous and separate pits on the same tracheid (Pl.9 , Fig.11), though the contiguous type is the most common. In this case the pit borders always touch, sometimes retaining a circular outline, often vertically compressed but never to the extent of acquiring a polygonal outline like the pits of araucarian wood. (The separate pits are more circular in outline.) Pit diameters range from mean values of 12·5 - 17·6 µm, the overall mean for all specimens being 14·3 µm. Bars of Sanio (cellulose thickenings across the tracheids) are not visible, perhaps because most of the pits are closely packed. Biseriate rows are more common in some samples than others; where they occur the pit arrangement is always opposite. No pitting was observed on the tangential tracheid walls.

The crossfield pits are visible in the silicified wood but are most well preserved in the fusain (Pl. 9 , Fig. 6). They are of typical cupressoid type with slit-like aperture enclosed within the circular border (Butterfield and Meylan 1981). The pit aperture maintains a constant orientation close to 45° throughout the whole ray and even the whole specimen (Pl. 9 , Fig.3); horizontal or vertical apertures have never been observed. A maximum of 7 pits have been observed per crossfield,

Sample No: / Structural details	PB· 11	PB· 46	PB· 47	PB· 40	PB· 54	PB· 27	PB· 26	PB· 24	PB· 22	* F	PB· 8	FF· R/2	PB· 1
Earlywood wall thickness µm	9.4	4.7	6.3	10.9	3.9	18.0	4.7	3.1	9.4	1.7	-	8.0	4.7
Earlywood lumen diameter µm	32.0	20.8	32.6	30.0	23.3	44.8	25.6	16.0	28.1	12.0	-	32.2	29.6
Latewood wall thickness µm	9.4	4.7	6.2	4.7	5.9	12.5	10.0	3.1	4.8	-	3.1	8.0	7.8
Latewood lumen diameter µm	6.3	6.2	6.3	10.9	7.9	6.2	12.0	4.7	9.6	-	24.0	18.0	7.9
No. of cells in latewood.	5-6	6-7	4-5	-	3-4	4	3-4	2-3	3-4	3-4	-	1-2	3-5
No. of trachieds between rays.	2-20	2-7	2-5	-	1-10	-	2-8	1-5	-	2-11	2-5	-	2-8
Bordered pit arrangement	semi-araucaroid mixed separate and contiguous										biseriate alternate		uniseriate
Bordered pit diameter µm	17.6	12.5	16.1	13.9	14.0	13.9	13.9	15.0	-	12.5	°10.9x 23.0	°9.0x 12.1	17.0
Pit aperture diameter µm	6.0	3.1	4.7	4.0	3.1	3.4	4.6	4.5	-	2.9	-	-	6.0
Depth of ray cells	2-8	2-5	2-8	-	2-10	3-15	2-5	2-20	2-6	2-9	30+	2-20	3-6
Ray cell width (vert)	24.1	17.2	24.2	23.5	18.9	28.8	20.2	19.2	-	15.4	25.0	28.1	25.0
No. of pits per crossfield	3-8	-	2-7	3-5	2-4	1-6	-	4-5	-	1-7	19+	10+	1-2
Diameter of cross-field pits µm	8.0	-	7.5	6.0	6.9	-	-	7.8	7.5	4.2	5.0	4.0	9.0

Protocupressinoxylon — Araucarioxylon — Circoporoxylon

*F Fusain

° Heightxwidth.

Table 5.01
Measurements of some specimens of Purbeck wood.

though 2 or 4 are most common. They tend to be arranged in 1 or 2 vertical columns in opposite or alternate positions. The medullary rays themselves are relatively short, consisting of mainly 3-4 cells but sometimes up to 9. No biseriate rays have been observed.

The dark orange resin infilling rays and tracheids is a conspicuous feature of this wood. (although resin is even more abundant in the sample of Circoporoxylon Krausel from Fisherman's Ledge). The resin is present in these cells (but not in true resin canals or in parenchyma cells) as small round spherules about 8 µm in diameter or as a smooth coating on tracheid or ray cell walls. Sometimes a complete ray cell may be infilled (PI. 9 , Fig.10).

The specimens of fusain (fossil charcoal) of this same species show far better preserved structural details than do the silicified samples (Pl. 9 , Figs.I ,2,3). There are, however, considerable differences in cell dimensions (Table 5.01); a reduction of about 30-70% in wall thickness and 14 to 50% reduction in lumen and pit apertures in the fusain .This is probably attributable to shrinkage by charring, which has also been reported by Harris (1958) and Alvin et al. (1981). The walls tend to shrink more than the cell luman and pits and the amount of shrinkage also tends to increase with temperature (McGinnes et al. 1976).

Form-genus ARAUCARIOXYLON Krausel 1872

Araucarioxylon sp.A

Description

Two specimens of this genus have been identified from the basal Purbeck beds: PB.8, a silicified branch from Blacknor, Portland, and FF/2, a small coalified root from the Great Dirt Bed at the Fossil Forest, Lulworth. Unfortunately not all their structural details were visible but they are clearly differentiated from Protocupressinoxylon Eckhold by the diagnostic araucaroid pitting of the tracheids. The bordered pits are polygonal in outline, closely packed in an alternate arrangement in biseriate or triseriate rows. Uniseriate rows are rare but where present the pits retain their characteristic compressed, polygonal shape, being much broader than high (Table 5.01). The medullary rays are frequent and noticeably deep, consisting of 3 to over 30 cells; they appear to be always uniseriate. The crossfield pits consist of numerous, small (5 μm) simple pits (sometimes over 10 per field). The tangential and horizontal walls of both the tracheids and ray cells appear unpitted.

A few distorted growth rings are visible but in both specimens the cells are highly compressed. Dark orange resin is occasionally present in some tracheids but not as profusely as in Protocupressinoxylon Eckhold. True resin canals are absent and wood parenchyma has not been observed.

Due to the poor preservation of these samples and indistinct features they have not been classified to species level.

Form-genus CIRCOPOROXYLON Krausel

Circoporoxylon sp.A

(Pl.10 , Figs.1-6.)

Description

Only one specimen, PB.1 from Fisherman's Ledge near Swanage (Fig.1.01), is attributed to this genus. It is distinguishable from Protocupressinoxylon Eckhold by the presence of circular bordered pits in uniseriate rows on the radial walls of the tracheids. The pits are scattered and separate within each row, their borders never touching and never appearing compressed. Bars of Sanio (cellulose thickenings) are clearly visible spanning the tracheids between pits. Biseriate rows of pits are rare; the pits are then arranged in opposite pairs. Crowding of pits at the end of the tracheids is common. In this tree the tangential walls of the tracheids also have small pits (Pl.10 , Fig. 4).

The medullary rays are 3-16 cells deep and dominantly uniseriate. Each crossfield has usually 1 but sometimes 2 or 3 large oval pits, 9 μm (longest diameter). The horizontal and tangential ray walls are unpitted.

The tracheids are isodiametric in cross-section and the growth rings are well preserved. Many tracheids are filled with dark orange resin; these infilled cells occur throughout the rings but tend to be concentrated along the ring and false ring boundaries. Many of the cells containing resin are short and thin-walled and may well be parenchyma cells. True or traumatic resin canals are absent.

Plate 10

(TL = transmitted light. SEM = scanning electron microscope)

Figs. 1-6 Circoporoxylon Krausel. PB.1 from Fisherman's Ledge near Swanage. (Horizon unknown)

1. Circular, separate bordered pits on the radial walls of the tracheids. The dark tracheid contains resin and spherules of silica. (Radial longitudinal section. TL)

2. Transverse section illustrating narrow growth rings and very narrow latewood zone consisting of only 3 or 4 cells. Cells filled with dark resin tend to be concentrated along the latewood. (TL)

3. Cross-fields of ray cells with one or two oval pits per field. The horizontal and vertical ray cell walls are unpitted. (Radial longitudinal section. TL)

4. Small, simple pits irregularly arranged on the tangential walls of the tracheids. This feature in particular distinguishes this genus from Protocupressinoxylon in which the tangential walls are unpitted. (Tangential longitudinal section. SEM)

5. Radial longitudinal section showing the characteristic spaced arrangement of the bordered pits. (SEM)

6. The cross-field pits contain only 1 or 2 large oval pits. (Radial longitudinal section. SEM)

7-11 Specimens of Cupressinocladus valdensis from the Purbeck Beds. (The sample numbers are those of the British Natural History Museum).

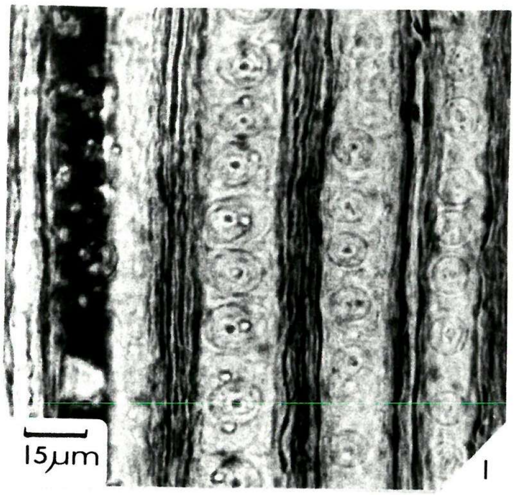
7. V.4025. Specimen figured by Damon (1884 b). The cuticle is absent but the impression shows the opposite-decussate arrangement of the leaves, particularly on the main stem. The leaves on this specimen have more prominent free tips. Locality: "Top Cap. Purbeck, Portland".

8. V.2933. Impression with good cuticle from "Portland".

9. V.4029. From the "West Cliffs, Portland". This specimen consists of a very deep impression without cuticle. In places a large, extended free tip can be observed.

10. V.4033. Specimen from "Top Slate Bed, 30ft above Portland Beds" showing very long leaf bases on the main shoot. The suture between adjacent leaf margins is particularly clear. Branching appears to be alternate.

11. Specimen from the Day collection, Southampton University Geology Museum. Small shoot with poorly preserved cuticle but illustrating alternate branching.



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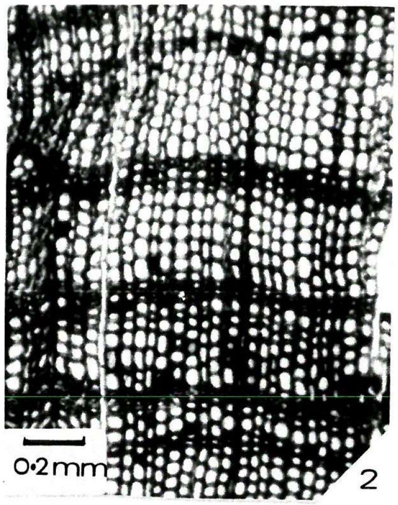

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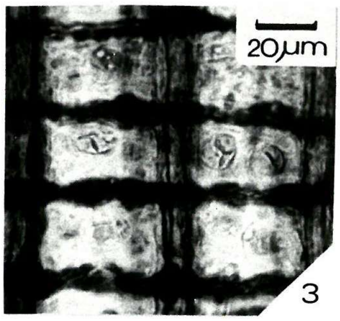

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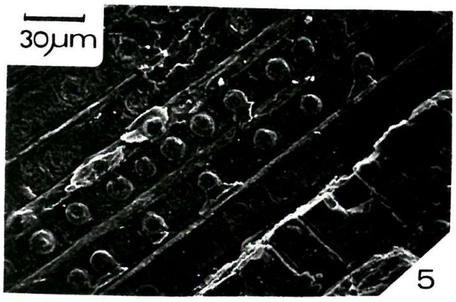

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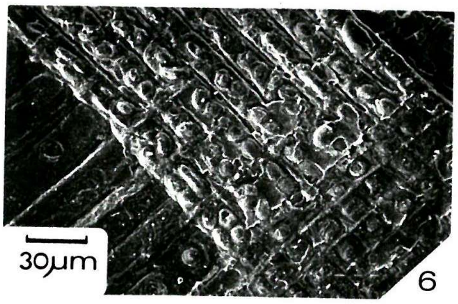

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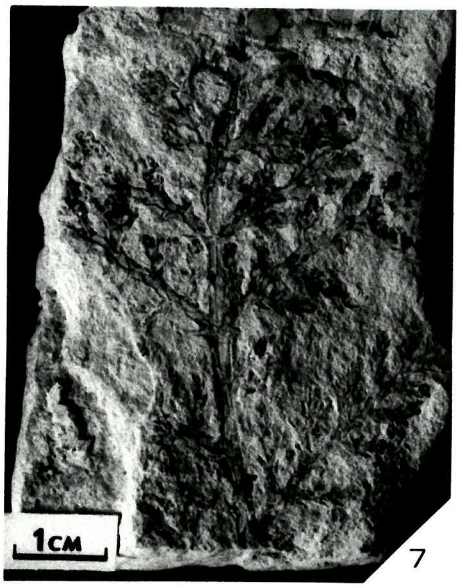

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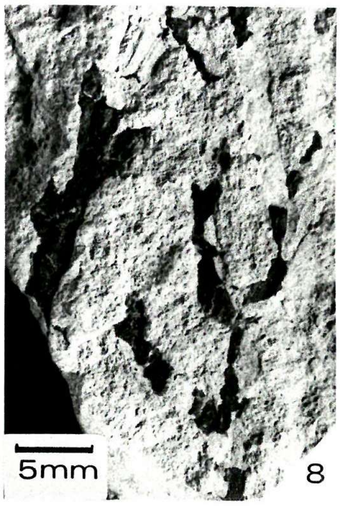

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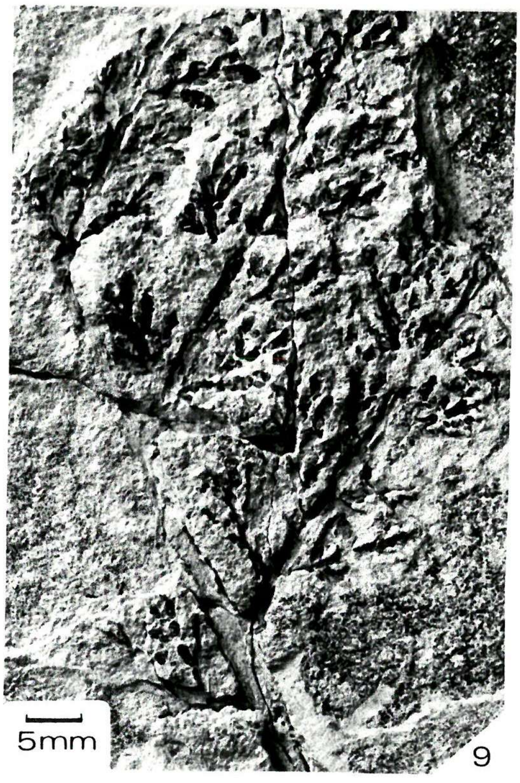

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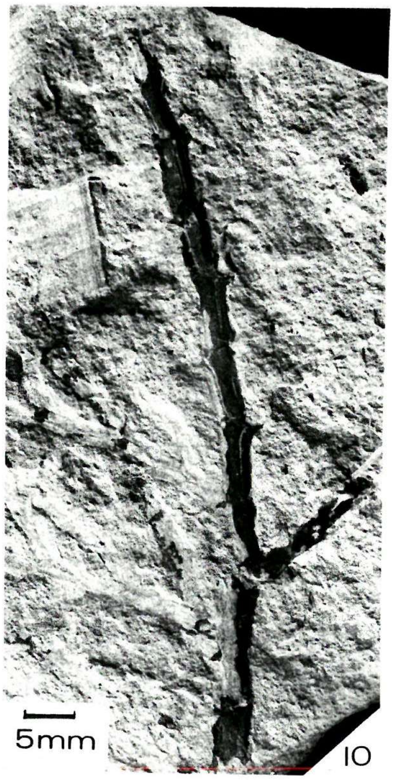

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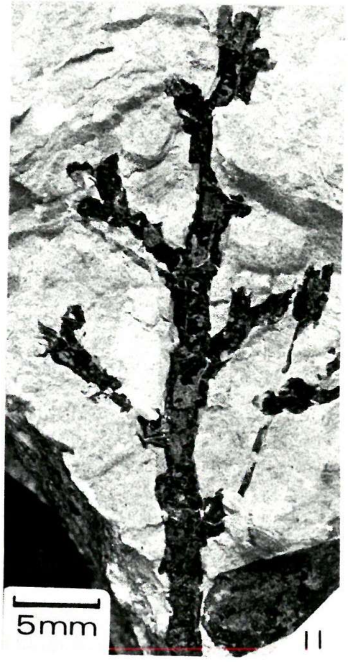


11

PLATE 10

This sample has not been assigned to a species since it is the only specimen found and not referable to a specific horizon within the basal Purbeck Beds. No foliage has been found with it and it is a minor constituent of the Purbeck wood samples.

FOLIAGE

Form-genus CUPRESSINOCLADUS Seward 1919

Cupressinocladus valdensis (Seward) Seward

(Pl. 11, Figs.1-13)

1895 Thuites valdensis Seward, 209, pl.20, fig.6.
1919 Cupressinocladus valdensis (Seward) Seward, 309
1960 Cupressinocladus valdensis (Seward), Chaloner and Lorch, 236
1977 Cupressinocladus valdensis (Seward), Watson, 742, pl.97, figs.6-11.

Holotype: British Museum (Natural History), V.2138 from the Wealden of Ecclesbourne near Hastings.

Purbeck material

Many conifer shoots and cuticle from the Purbeck Beds belong to this genus and most are identifiable to this species. Single shoots and dispersed cuticle fragments were discovered in the Great Dirt Bed itself at God Nore, Portland (SY690697) (Fig.2.03) and at Holworth House (SY762816) (Fig.2.07). More complete shoots from adjacent limestones were studied to discover leaf and branch arrangement. These specimens, mainly from museum collections, include:

PB: Conf.1	"Purbeck Beds, near Southwell" Portland Museum.
PB: Conf.2	"Purbeck Beds, Lulworth Cove" Southampton University Geology Museum, Day Collection.
PB: Conf.3	"Middle Purbeck Beds, Durlston Bay" Private Collection of Mr. R. Coram, Wimborne Road, Colehill, Wimborne, Dorset.

Specimens from the British Museum (Natural History) include:

V.2933	"Portland"
V.4029	"West Cliffs, Portland"

V.4033	"Top Slate Bed. 30 ft. above Portland Beds West Cliff, Portland"
V.2545	"Top Cap. Purbeck. Portland". Figured by Damon 1884b.

(The localities given in quotation marks are the original museum labels.)

Description

The most complete shoot, PB:Conf.1 (Pl.11 ,Fig.11) is 9·6 cm long and exhibits up to 4 orders of branching with branches arising in one plane to produce a frond-like shoot. Branches arise alternately at every node on the main stem and minor branchlets but appear to be arranged in opposition on the ultimate shoots. Alternate branchlets are straight or slightly curved. The main laterals subtend an angle of about 45° to the main stem and subsequent branches subtend an angle of about 55°. The whole shoot is now strongly compressed and bears small leaves in an opposite and decussate arrangement, reminiscent of modern Cupressaceae such as, for example, Thuja plicata.

The main axis of this specimen has elongate rectangular leaves 10 mm long, 6 mm wide and pressed close to the stem. Secondary and tertiary branchlets have shorter and narrow leaves which ultimately become square in shape, with a length and breadth of 1 mm on the youngest shoots. The range in leaf sizes of all specimens is 1-10 mm in length, 1-6 mm in width (Table 5.02). Each leaf on the main shoot was a short, triangular free part and a long decurrent cushion with clear grooves separating it from adjacent cushions (Fig.5.01).

The abaxial cuticle ranges from 15-20 µm thick. Both the abaxial and adaxial cuticle are covered with short, blunt papillae about 10 µm in height, though on some specimens these are less well-defined and appear merely as a slightly raised area of the cuticle (Pl.11 , Fig.6). In the cuticle from the abaxial surface of the free leaf and cushion stomata are arranged in fairly well-defined files and extend over the whole leaf base, including the marginal area. Stomata are, however, absent from a small area at the leaf tip (Pl.11 , Fig.3). The stomata rows are separated by 2-3 epidermal cells and there are 6-8 rows per mm laterally. The stomatal density along each file ranges from 6-9 per mm, giving a mean density of 44 per mm^2.

Plate 11

Cupressinocladus valdensis (Seward) Seward.

1. Well-preserved shoot from the Middle Purbeck Beds, Durlston Bay. The opposite-decussate arrangement of the leaves is well illustrated and the lateral suture between adjacent leaf margins prominent. (PB:conf 3).

2. Single leaf from the Great Dirt Bed, Holworth House, showing its broadly rectangular shape and longitudinal rows of stomata. (H.H./conf 1) (TL)

3. Triangular leaf tip showing the absence of stomata near the tip. (H.H./conf 2) (TL)

4. and 7. Marginal, unicellular hairs of the leaf sheath. The hairs have blunt ends and are joined laterally. Note the small papillae on the cuticle surface (4:SEM, 7:TL).

5. Single stoma surrounded by 6 subsidiary cells each bearing a large, blunt papilla which extends over pit aperture.(TL)

6. Outer surface of abaxial cuticle showing arrangement of stomata in fairly well-defined rows and the slightly papillate surface. (SEM)

8. and 12. Stomata from the cuticle in Figure 6 showing both level and rimmed stomatal apertures. Note also the variation in aperture shape from markedly stellate (Fig. 8) to round (Fig. 12) on the same cuticle.(SEM)

9. Inner surface of abaxial cuticle showing the arrangement of stomata and the shape of the epidermal cells between stomata and between the stomatal rows.(SEM)

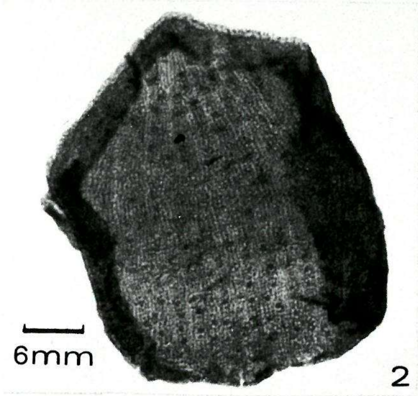
10. A single stoma on inner surface of abaxial cuticle showing the thick epidermal walls and arrangement of subsidiary cells. The subsidiary cells appear to show an opening to the hollow papillae. Poorly preserved guard cells block the aperture. (SEM)

11. Large shoot of C. valdensis showing alternate branching on main axis and opposite branching on the smaller shoots. Specimen from Portland Museum. (PB:conf 1)

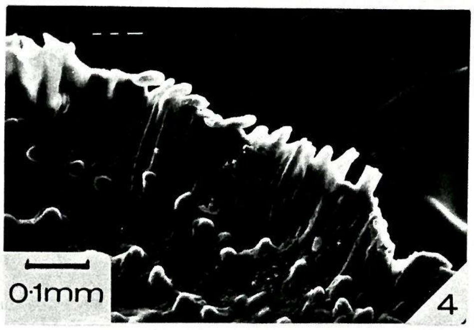
13. Vertical section through a stoma showing the position of the broad, round papillae inside the stomatal pit.(H.H./conf 1) (SEM)

(TL = transmitted light. SEM = Scanning Electron Microscope)


2 mm
1


6mm
2


20µm
3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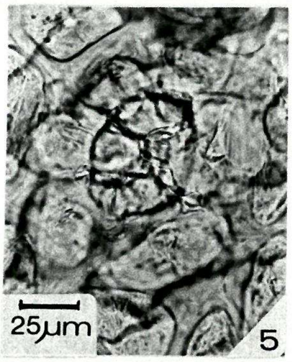
25µm
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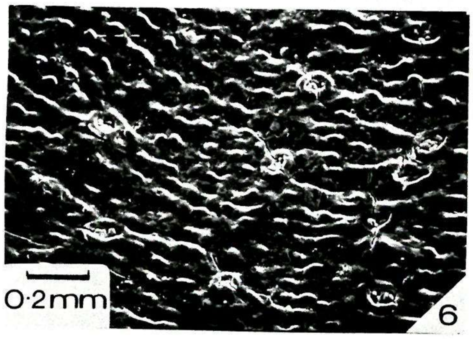
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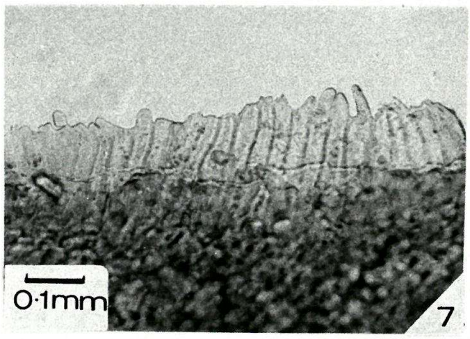
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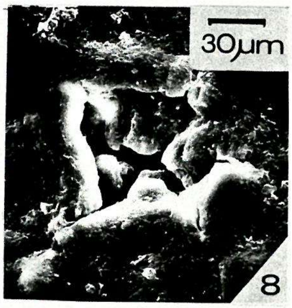
30µm
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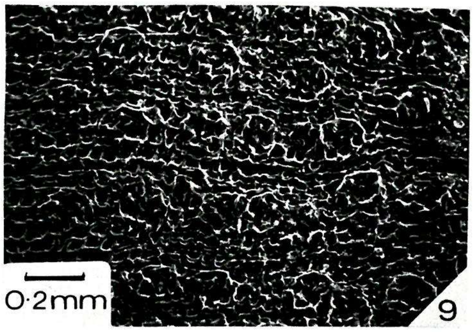
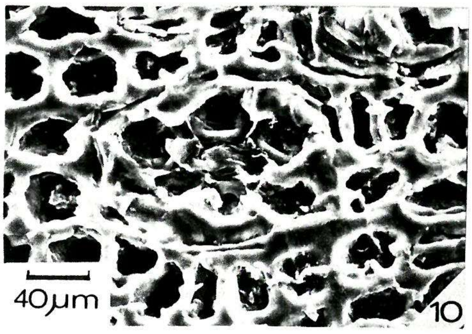
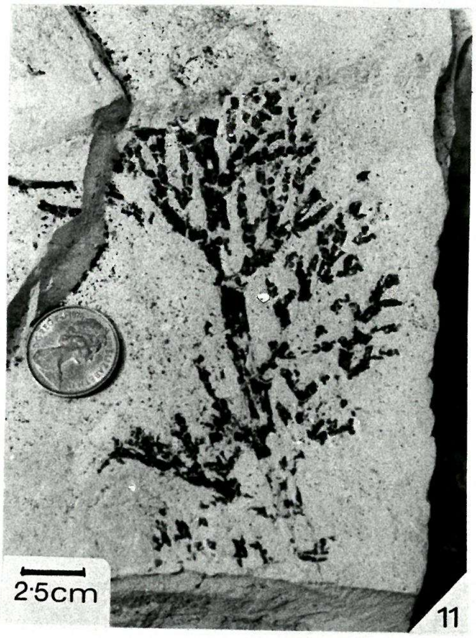
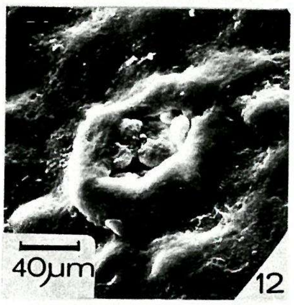

0·2mm
9


40µm
10


2·5cm
11


40µm
12


35µm
13

PLATE II

Specimen Structural details	HB 1	PB· conf 1	PB· conf 2	V 2933	V 4029	PB· conf 3	V 2545	GN1-18	V 4033	C.* vald.
Maximum internode length mm	4.0	10.0	4.0	8.0	4.0	3.1	6.0	9.0	8.0	→ 10
Maximum internode width mm	3.2	6.0	2.0	2.5	2.1	2.2	2.0	3.5	2.0	→ 2
Suture present between leaves?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Leaf number per node	2	2	2	2	2	2	2(?3)	2	2	2
Leaf arrangement	OD	OD	OD	OD	OD	OD	OD	OD	OD	OD
Leaf margin	hairs	-	curled	-	-	thick	-	thick	thick	-
Cuticle thickness µm	28.0	-	18.0	-	19.2	28.0	-	30.0	22.4	20.0
Stomatal arrangement	neat rows	-	neat rows	-	neat rows	poor rows	-	fair rows	-	neat rows
Number of rows per mm	6	-	7-8	-	6-7	6-7	-	7-9	6-7	9-10
Diameter stomatal apparatus µm	60-105	-	65-72	-	70-90	-	-	70-100	80-90	65-85
Diameter stomatal Pit µm	-	-	30	-	32	42	-	25	35	-
Number of subsidiary cells	5	-	4-6	-	5	4-6	-	4-6	4-5	4-6
Papillae present in pit?	✓	-	✓	-	✓	✓	-	✓	✓	✓
Aperture shape	stellate	-	polygonal	-	stellate	stellate	-	polygonal	polygonal	stellate
Cell wall thickness (anticlinal) µm	6.0	-	6.4	-	4.8	-	-	11.0	15.0	-
Papillae on surface?	✓	-	✓	-	✓	-	-	✓	✓	-
Guard cell orientation	random	-	-	-	random	-	-	random	random	-
Preservation	excellent. cuticle only.	impression. No cuticle.	Fair	Impression.	Good sample. Poor cuticle.	Good sample. Fair cuticle.	Impression.	Varied.	Good.	Good sample. Poor cuticle

- Data not available   OD: opposite-decussate

* Description from Watson 1977; holotype Cupressinocladus valdensis

Table 5.02

Measurements of some specimens of Purbeck conifer foliage compared to Cupressinocladus valdensis.

Each stoma is surrounded by 4-6, but typically 5 subsidiary cells and the whole stomatal apparatus has a diameter of 70-100 µm. Each subsidiary cell bears one broad round papilla which extends into the stomatal pit so that its aperture is nearly filled by the papillae (Pl. 11 , Figs. 5,8,12). The mouth of the pit is commonly polygonal but varies from more or less round to markedly stellate. Some stomata have their openings at surface level though adjacent ones on the same cuticle have a prominent rim (Pl.11 Figs. 8,12). The guard cells are sometimes present but are thinly cutinised and often do not survive maceration.

The epidermal cells lying between stomata of the same file are isodiametric, 20-35 µm in diameter. However, between stomatal rows the cells are usually elongate (on average 48 µm long) and arranged in longitudinal files 2-3 cells wide. The anticlinal walls are 8-10 µm thick. The larger elongate hypodermis cells (mean of 64 µm in length, 37 µm wide) can sometimes be seen between stomatal rows.

The free tip of the leaf is always short; for example one leaf on the main shoot had a tip 2·6 mm long and a decurrent cushion 7·8 mm long. The adaxial leaf cuticle is like the abaxial but has less regularly arranged stomata and epidermal cells of a more varied shape.

The margin of the free tip consists of a sharp border of unicellular hairs, 90-100 µm long, 20 µm wide. These hairs are fused laterally for about three-quarters of their length, leaving only their rounded tips free (Pl.11 Figs. 4,7).

The above description is a compilation of characteristics from all the specimens studied. Individual measurements and details for each specimen are recorded in Table 5.02.

MALE CONE

Genus CLASSOSTROBUS. Alvin, Spicer and Watson 1978

Classostrobus sp.A

(Pl. 12 , Figs. 1, 2 and 4)

Description

Three compressed cones were found amongst the foliage at God Nore. They are oval, 7·5-12 mm long and 6-6·5 mm broad. The microsporophyll heads are rhomboidal, up to 1·5 mm wide and 2·0 mm long, and

Plate 12

Plant Remains from the basal Purbeck Dirt Beds

1. Single shoots of Cupressinocladus valdensis on organic-rich laminae from the Great Dirt Bed, God Nore, Portland (GN/GDB 1).

2. Cuticle from male cone in Figure 4. Outer cuticles of several rhomboidal microsporophyll heads. The cuticle structure is very similar to that from the leaves in Figure 1. The microsporophyll stalks are not preserved. (TL)

4. The male cone Classostrobus (sp. indet), preserved amongst the shoots in Figure 1. The female cones were not found. (PB:cone 1, counterpart).

3,5 and 7. Classopollis pollen showing its characteristic equatorial belt of striations and subequatorial furrow. Several grains (including that in Figure 7) were attached to the male cone cuticle (but not in pollen sacs). The clusters (Figs. 3 and 5) were obtained from residue of cuticle maceration. (3, SEM; 5 and 7, TL).

6. Small rootlets on laminae of marly limestone at the base of the Lower Dirt Bed in Sheat Quarry, Portland. The small nodules at the ends of the rootlets are probably mycorrhizae.

(TL = transmitted light. SEM = Scanning Electron Microscope)

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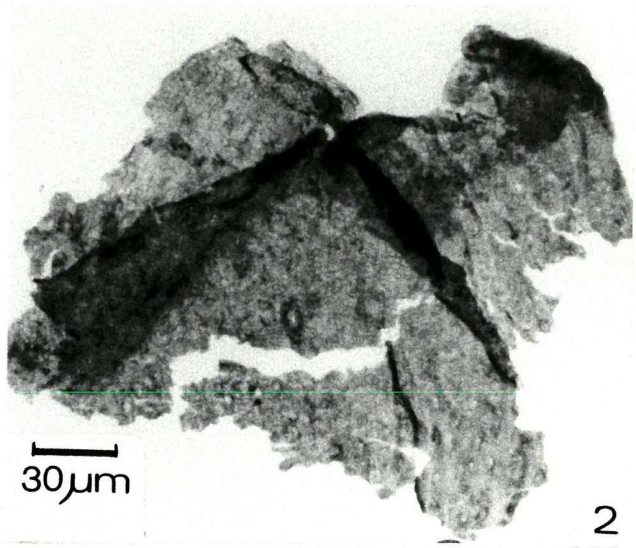

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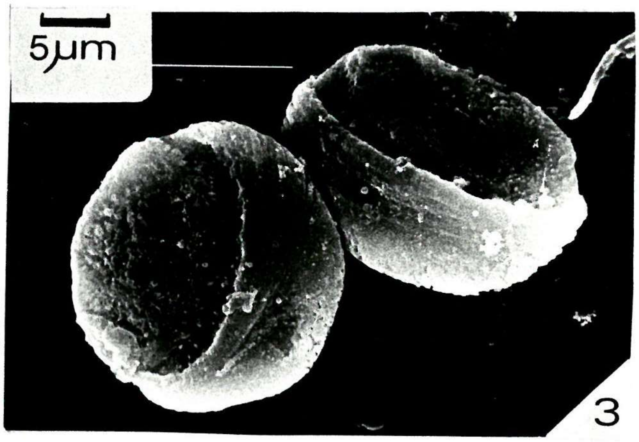

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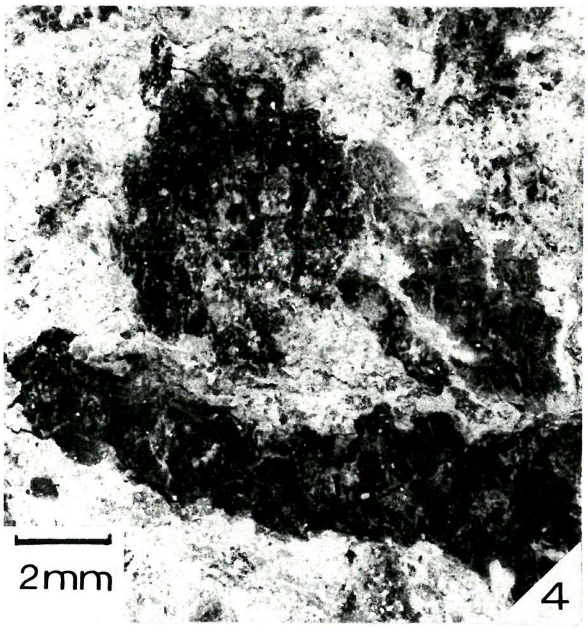

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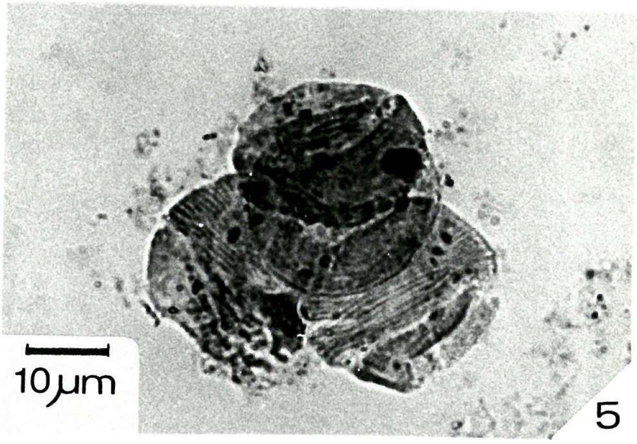

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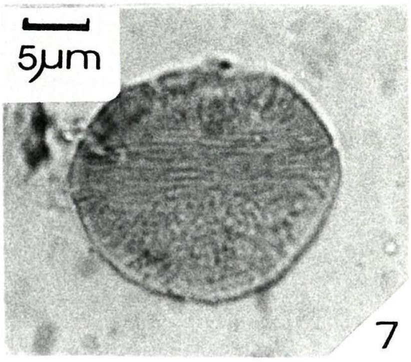

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PLATE 12

appear to be spirally arranged. They are poorly preserved and neither microsporophyll stalks nor pollen sacs were seen (Pl.12 , Fig.4). Fragments of microsporophyll cuticle (Pl.12 Fig.2) resemble C.valdensis (Seward) Seward leaf cuticle, but the stomata are less regularly arranged in files and fewer in number, e.g. 4 per mm. As on the leaves, each stoma is surrounded by 5 subsidiary cells surrounding a stellate pit which is filled with 5 broad round papillae. The epidermal cells between adjacent stomata are isodiametric, with a mean width of 47 µm. However, the cells are somewhat elongate in 2-3 longitudinal rows between the rows with stomata. Anticlinal walls are about 9 µm thick. Small blunt papillae are irregularly scattered across the cuticle surface.

Although the pollen sacs are missing, isolated pollen grains were found adhering to the cone cuticle. These pollen grains are spheroidal and slightly flattened at the poles, an equatorial diameter of 25-30 µm being reduced to 20-22 µm in this polar direction. A thickened belt, 6-8 µm wide and about 2 µm thick, encircles the equatorial region of the grain and bears 8-12 striations. Elsewhere the external surface is covered with small irregular granules. The internal structure is vermiculate. A small groove (the rimula) encircles the grain adjacent to the equatorial band on the distal side. A pore marks the distal pole and is opposed by a triangular or trilete mark at the proximal pole.

MEGASPORES

PTERIDOPHYTA

LYCOPODIALES

Form-genus TRILETES (Reinsch) Dettman

Triletes russus Harris 1961

(Pl. 13 , Figs. 1-6).

1961 Triletes russus Harris p.55, text fig.17, F-J

Holotype: V.32816 (BM(N.H)). Deltaic Series, Middle Jurassic, Yorkshire.

Description

11 megaspores of this species were recovered from the Great Dirt Bed at God Nore, Portland. Although they were in no way organically connected, they were all localised in one small specimen of Dirt Bed and not found elsewhere. Their preservational state is excellent (Pl.13 , Figs. 1-6).

The body of the spore is rounded but the contact facets around the area of the triradiate mark are slightly sunken or flattened. The diameters of the spores range from 380-500 µm, mean value 420 µm.

The triradiate lamellae are not prominent, consisting of thickened ridges about 20 µm high. These lamellae are straight, not curved and extend for approximately two-thirds of the total spore radius. The spore surface is covered with short conical appendages, of mean length 12 µm and mean width 5 µm, which are straight or slightly curved (Pl. 13, Fig.5). These spines occur singly or in groups of 2 or 3 joined along their lateral margins. They are irregularly dispersed over the surface of the spore, though slightly sparser over the contact facets. A denser ring of spines tends to encircle the triradiate lamellae and spines also occur on these lamella themselves. Arcuate lamellae are absent.

The surface of the appendages and spore wall is finely granular, which appears to form concentric striations on the appendages themselves. The spore wall is about 8 µm thick, coarsely granular and tending to split into two layers. The spore is a characteristic dark red colour, hence the specific name "russus".

The megaspores are found as isolated bodies, and never attached to sporangia. The preservation is so good that the appendages have not been damaged or broken. The spore bodies are compressed in one of two main directions: either flattened along the equatorial plane so that the triradiate mark appears centrally on the face, or compressed along the polar plane so that the triradiate mark occurs along the folded margin.

MIOSPORES

Anteturma	SPORITES
Turma	TRILETES
Suprasubturma	ACAVATITRILETES
Subturme	AZONOTRILETES
Infraturma	MURORNATI

Cicatricosisporites sp. Potonié and Gelletich.

(Pl. 13 Fig. 11)

Description

Radiosymmetric spore. Trilete marking on distal face, marked

Plate 13

Figs. 1-6 *Triletes russus* Harris from the Great Dirt Bed, God Nore, Portland.

1. Large isolated megaspore showing one arm of triradiate lamellae at top and the surface ornamentation (TL) (TR1)

2. Detail of the megaspore surface. The exine between the appendages is granular. Very few of the appendages are broken. Many are joined laterally. (SEM) (TR2)

3. Cross-section through the megaspore, devoid of internal contents. (TR3) (SEM)

4. Detail of the spore wall in Figure 2. The wall consists of 2 layers. (TR2) (SEM)

5. Details of the appendages. The surface is finely granular and appears to form concentric striations.(SEM) (TR2)

6. Whole megaspore flattened along the polar plane so that the triradiate mark occurs along the folded margin. (SEM) (TR4)

7 -14. Miospores from the Great Dirt Bed, God Nore, Portland.

7. *Podocarpites* sp. Saccate pollen with spherical central body. Diameter of central body 48μm. (TL)

8. *Inaperturopollenites* sp. Small, simple spore with arcuate folds. Diameter 16μm. (TL)

11. *Cicatricosisporites* sp. Radiosymmetric spore with thick ribs on three contact facets. Diameter 43μm. (TL)

14. *Cerebropollenites mesozoicus*. Large spherical spore with 'brain-like' appearance. Diameter 56μm. (SEM)

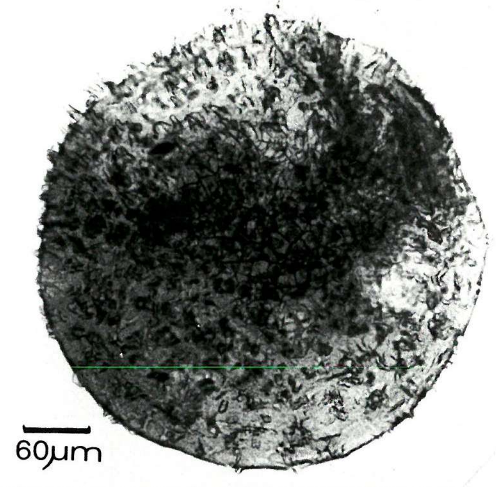
Figs. 9, 10, 12, 13. *Classopollis* pollen from the Great Dirt Bed, God Nore.

9. Cluster of *Classopollis* grains illustrating granular surface ornamentation and equatorial band of striations. The sub-equatorial furrow is smooth. (SEM)

10. Clusters of *Classopollis* pollen were common in the Great Dirt Bed residues. Often up to 20-30 grains were incorporated in a group. (TL)

12. The proximal pole of *Classopollis* is marked by a triangular or triradiate mark. (TL)

13. A small pore can sometimes be seen at the distal pole. (TL)



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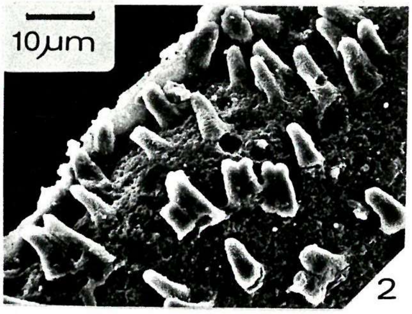

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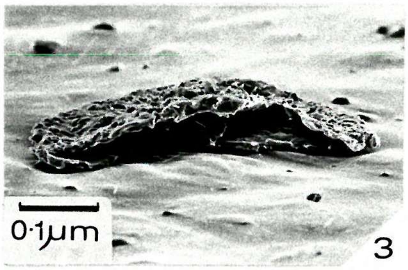

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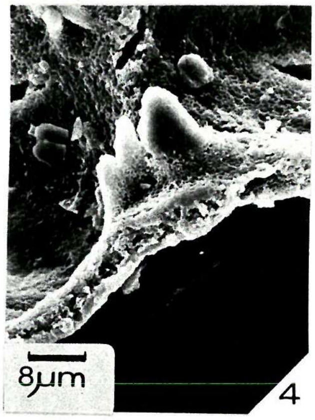

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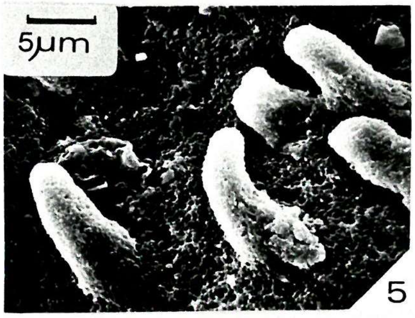

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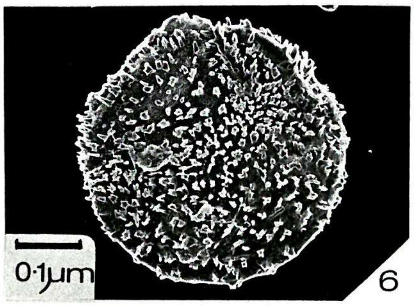

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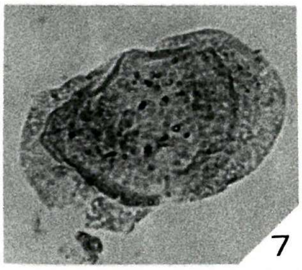

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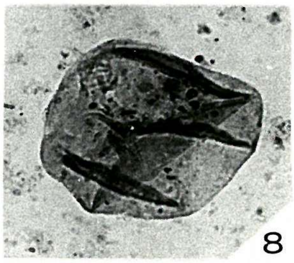

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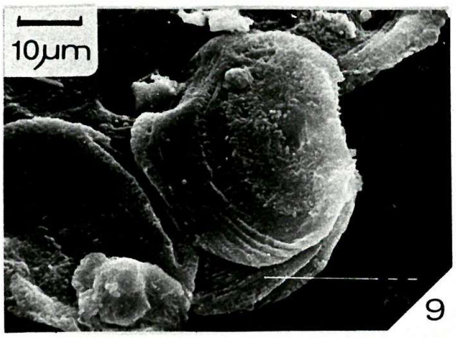

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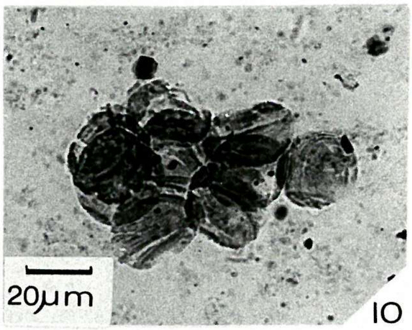

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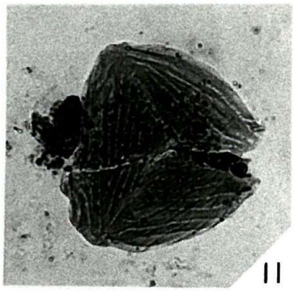

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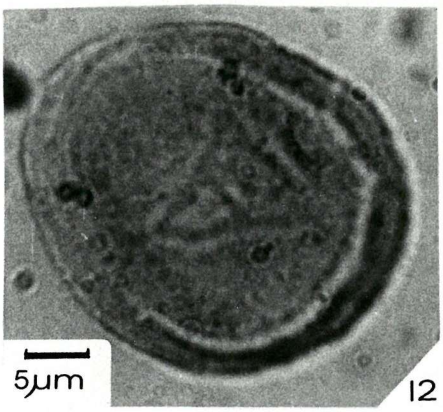

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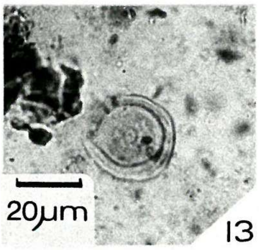

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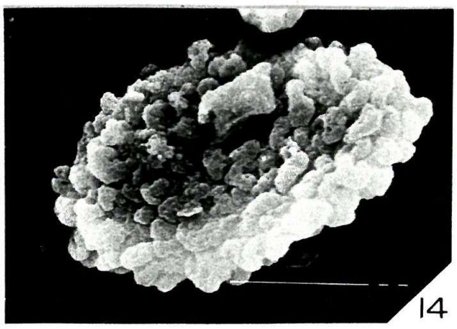

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PLATE 13

by slight groove. Thick ribs (about 4 µm wide) parallel the equator between each contact facet. Ribs generally concave to centre. Average diameter 43 µm. Abundance in identified samples from God Nore, Great Dirt Bed. < 1% (usually as fragments).

Anteturma	POLLENITES
Turma	ALETES
Infraturma	GRANULONAPITI

Araucarites australis Cookson

Description

Large radiosymmetric spore with smooth or granular exine. Characterised by many large arcuate folds over body. Inaperturate. Smooth margin. No central body. Average diameter 50 µm. Abundance in total assemblage studied: approx. 10%.

Infraturma PSILONAPITI

Inaperturopollenites sp. (Pflug x Thomson and Pflug) Potonié

(Pl. 13, Fig. 8).

Description

Small, spherical inaperturate spore. Small arcuate folds. No exine markings. Smooth margin. Average diameter 10-20 µm. Abundance: < 5%.

Infraturma SPINONAPITI

Peltandripites sp. Wodehouse

Description

Large spherical spore, usually compressed and folded into an ovoid. Inaperturate. No central body but many arcuate folds. Marked granular spiny surface. Distinguished from Araucarites by its greater surface relief. Often occurs in groups. Average diameter 52 µm. Abundance < 1%.

Turma SACCITES
Subturma MONOSACCITES
Infraturma SACCIZONATI

Cerebropollenites mesozoicus (Couper) Nilsson
(Pl.13 , Fig.14

Description

Large spherical spore, slightly flattened along polar line. Body covered with short, round appendages to give "brain-like" appearance. Margin undulatory. Average diameter 56 µm (equatorial). Abundance 1-2%.

Subturma POLYSACCITES

Callialasporites sp. (Sukh Dev) Potonié.

Description

Radiosymmetric spore. Thin central body surrounded by slightly frilled membraneous margin. Indistinct trilete mark in central area, arms probably extending to outer edge of margin. Average diameter 56 µm. Abundance $<$ 1%.

Subturma DISACCITES

Podocarpites sp. (Cookson) ex Couper.
(Pl. 13 , Fig. 7).

Description

Saccate pollen with smooth, spherical central body. Slightly frilled margin. 2 sacs attached to main body. Sacs smaller than central body; not folded. Slightly granular exine. Diameter: central body 48 µm. Sacs 23 µm. Abundance $<$ 1%.

Turma PLICATES
Subturma MONOCOLPATES

Cycadopites sp. (Wodehouse) ex Wilson and Webster.

Description

Small ovoid spore with smooth or slightly granular exine. Inaperturate. Smooth margin. 1 or 2 large folds predominate maximum diameter. Average diameter (Polar) 30 µm, (Equatorial) 15 µm. Abundance $<$ 1%.

Family Cheirolepidiaceae

Classopollis Pflug

(Pl.12 , Figs.3,5,7 ; Pl.13 , Figs.9,10,12,13).

Description

The Classopollis pollen found dispersed in the Great Dirt Bed at God Nore was identical to that found attached to the cuticle of the male cone (see 5.3 iv). Individual grains were easily identified by their conspicuous equatorial band of 10-12 striations, sub-parallel in arrangement. The equatorial band averaged 6 μm in width and 4 μm in thickness. On the distal side of this band a distinct furrow encircles the equator (Pl. 12 Fig. 3). On some grains a single pore is visible at the distal end and a triangular mark (each side 6 μm long) at the proximal end. The surface ornamentation is granular.

In the Great Dirt Bed at God Nore this pollen was recovered as individual grains and frequently in tetrads. Clusters of up to 30 grains were also recovered. Average diameter: (equatorial) 25-30 μm, (polar) 20-22 μm. Abundance >75% total miospore assemblage observed.

5.3 Discussion

5.3.i WOOD

The majority of fossil wood specimens from the Dirt Beds are characterised by a "mixed" type of tracheid pitting (dominantly contiguous pits with some separate), cross-field pits of cupressoid type, numbering 2-4 but up to 7, arranged mainly in 2 vertical columns, uniseriate rays and the absence of resin canals and wood parenchyma. On the basis of these features this type of wood is assigned to the form-genus Protocupressinoxylon Eckhold. This type of tracheid pitting intermediate in character between Araucaroid and Pinoid is common to many form-genera of Mesozoic wood constituting the Protopinaceae (Krausel 1949). In fact many of the form-genera defined by Eckhold (1922) and Krausel (1949) are very similar, distinguishable only by minor details. Protocupressinoxylon Eckhold is very similar to Protopodocarpoxylon Eckhold. Examples of this latter form-genus have been described by Lauverjat and Pons (1978) (P.aveiroense) from the Lower Cretaceous of Portugal, and wood from the Wealden of the Isle of Wight was described by Alvin et al. (1981) as being of Protopodocarpoxylon type. Both of their woods are very similar to the Purbeck wood of *Protocupressinoxylon* type apart from the cross-field pitting, which in *Protopodocarpoxylon* Eckhold is of more Araucaroid type. The pits are more numerous (up to 13 in *P.aveiroense* Lauverjat and Pons, up to 17 in the Wealden wood), their apertures tend to be more vertically orientated and the pits are more randomly arranged; these cross-field pits are "podocarpoid" in a narrower sense, as opposed to the cross-field pits of the Purbeck wood, which clearly are typically "cupressoid" with fewer pits with more horizontal apertures more regularly arranged. The Purbeck wood is thus called *Protocupressinoxylon* Eckhold.

Previously described species of *Protocupressinoxylon* Eckhold have been listed by Attims and Crémier (1969). Several species resemble the Purbeck wood with similar tracheid pitting and abundance of resin, especially *P.vectense* (Barber) Eckhold and *P.luccombense* (Stopes) Eckhold (both from the Lower Greensand of the Isle of Wight) but differ in the possession of vertical parenchyma, absent in the Purbeck wood. Species without vertical parenchyma include *P.dockumense* (Torrey) Krausel, *P.koettlitz* (Seward) Eckhold and *P.malayense* Roggeveen, but although the tracheid and ray pitting is similar the rays are far too deep and there are fewer pits per cross-field. *P.chouberti* Attims and *P.aff. chouberti* Attims and Crémier are most similar to the Purbeck wood: vertical parenchyma is absent, growth rings are present, the tracheid pitting is a mixed arrangement of contiguous and separate pits, and the cross-field pits are of similar shape and number. In contrast, tangential pitting is present in *P.chouberti* Attims but absent in the Purbeck wood, and the rays of these 2 species are 1-13 and 1-24 cells deep respectively, whereas the maximum number observed in the Purbeck wood is only 9. The abundance of resin found in the Purbeck wood was not noted in *P.chouberti* Attims.

Although the formation of yet another species of fossil wood is undesirable, the Purbeck wood does not correspond to any previously described species of *Protocupressinoxylon*. Since it so markedly dominates the fossil wood from the basal Purbeck Dirt Beds and because it is an important part of the reconstructed Purbeck conifer (Fig.5.03), this Purbeck wood is thus assigned to the new species *Protocupressinoxylon* sp. A. nov.

The few Purbeck trees which did not belong to the above genus were attributed to the genera *Araucarioxylon* Krausel and *Circoporoxylon* Krausel, easily distinguishable mainly by their individually characteristic tracheid pitting.

5.3 ii FOLIAGE

All the intact shoots from the Purbeck limestones mentioned above and the dispersed cuticle from the Great Dirt Bed have identical leaf arrangement in decussate pairs and similar cuticle structure.

Many Mesozoic conifers have small, scale-like leaves and very similar cuticles. However, the opposite decussate arrangement of the leaves of the Purbeck conifer shoots distinguishes them from those of other form-genera such as Brachyphyllum Lindley and Hutton and Pagiophyllum Heer with spirally-arranged leaves, Frenelopsis Schenk with leaves arranged in a whorl, and from Pseudofrenelopsis Nathorst with each leaf completely encircling the stem. The arrangement of leaves in opposite - decussate pairs is a diagnostic feature of the form-genus Cupressinocladus, originally erected by Seward in 1919 for vegetative shoots resembling those of modern Cupressaceae, and later emended by Chaloner and Lorch (1960) and Harris (1969). More recently Barnard and Miller (1976) emended it so as to exclude frenelopsid foliage where there are typically no suture lines between adjacent leaf bases. Shoots belonging to this form-genus have been described from the Jurassic and Cretaceous worldwide, but the Purbeck specimens appear identical to Cupressinocladus valdensis (Seward) Seward from the English Wealden. No single Purbeck shoot has both good cuticle and well-preserved branching pattern but the complete description in 5.2 incorporated details from all specimens and this agrees with that of the holotype, re-described by Watson (1977). The cuticles sometimes differ slightly from the holotype in the presence of papillae on the epidermal cells which are absent on the holotype but intermittently present on the Purbeck cuticle. The cuticle surface of the holotype is featureless, the stomatal pits lying level with the surface, but in the Purbeck material stomata with both level apertures and encircling rims occur together in the same specimen.

Cupressinocladus ramonensis Chaloner and Lorch (1960) from the Lower Jurassic of Israel is very similar in appearance to Cupressinocladus valdensis (Seward) Seward, but was considered distinct by the authors in having thinner cuticle, papillate epidermal cells and an even surface (they found that the stomata had rims on their preparation of Cupressinocladus valdensis cuticle). The leaf shape also differs from those of the

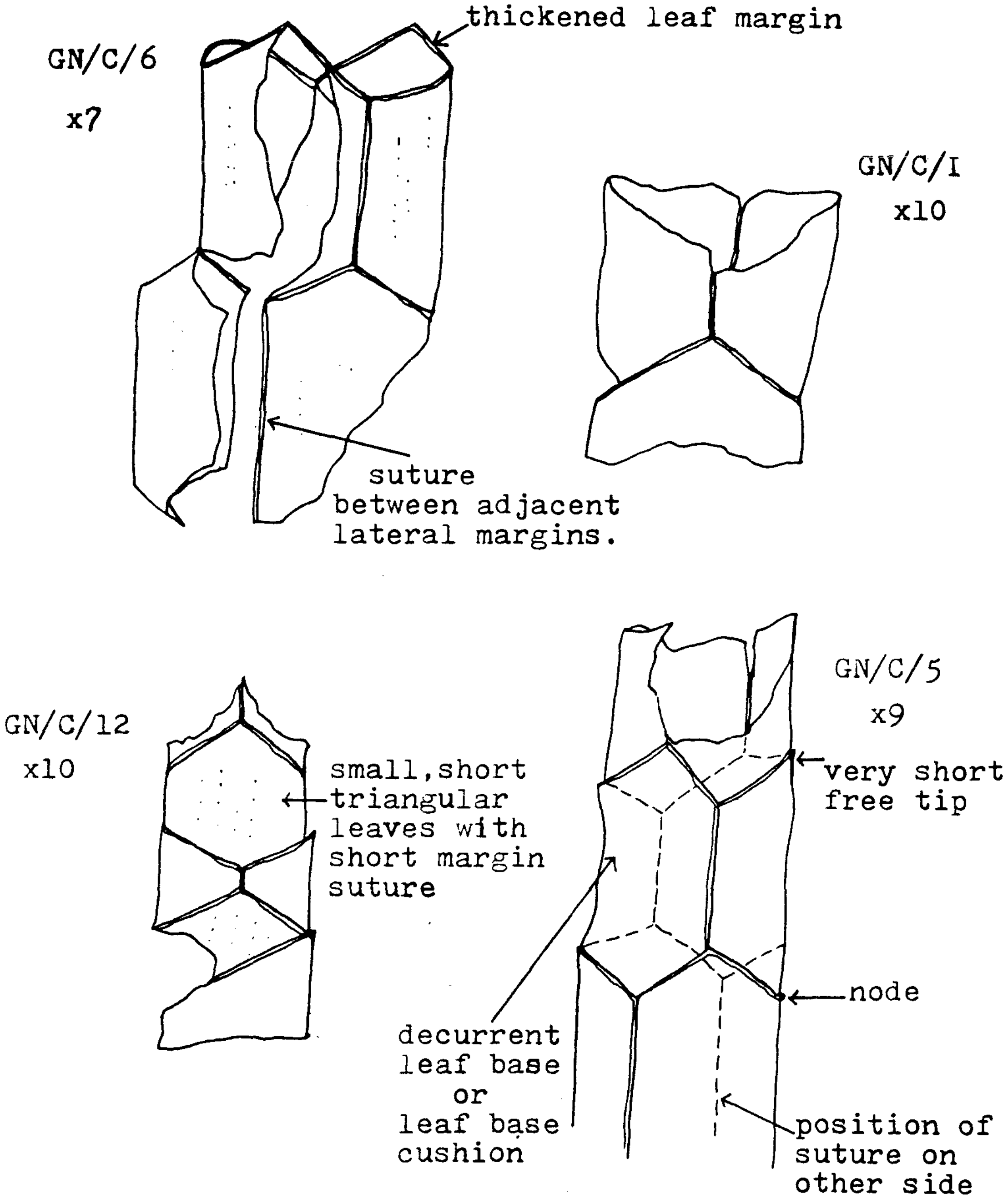


Fig. 5.01. Fragments of conifer shoots from the Great Dirt Bed at God Nore showing the positions of leaves in opposite-decussate arrangement.

Purbeck shoots in having a longer and more conspicuous free tip.

Two Lower Cretaceous conifers from Malaya, Cupressinocladus malaiana (Kon'no) Barnard and Miller (1976) and Cupressinocladus acuminifolia Kon'no (1968) look very similar but since their cuticles are unknown there is no strong evidence for identifying them with Cupressinocladus valdensis (Seward) Seward.

Oldham (1976) found Cupressus-like foliage in the Wealden marls at Swanage. His specimen, 33 CuprCuA is attributed to Cupressinocladus Seward but is most unlike other published species, including the Purbeck shoots, for although the leaves are arranged in pairs, they have shorter decurrent bases so there is no conspicuous suture. The free tips are also much larger and rounder than on other species.

Two specimens of the Purbeck Foliage, V.2933 and V.2545, differ slightly in appearance from the others in having a spray-like appearance due to more profuse branching. The free tips of some of the leaves are also somewhat more extended than usual (Pl.10 , Fig.7) though the leaves on these specimens are small, comparable in size to the ultimate leaves of PB:Conf.1. In appearance these 2 specimens resemble that of Cupressinocladus pseudoexpansum Barnard and Miller (1976) from Iran. This species has an opposite-decussate leaf arrangement on the ultimate shoots (as has V.2933 and V.2545), but has leaves in whorls of 3 on the main stem. The leaf arrangement of V.2933 is not discernable and, despite its very similar appearance to C.pseudoexpansum Barnard and Miller, V.2545 has opposite-decussate leaves on its main stem. It appears that this profuse branching and the large free tips of these 2 specimens are simply variations of C.valdensis (Seward) Seward. (Their cuticles are not well preserved.)

5.3.iii MALE CONES

The close association of the male cones and Cupressinocladus Seward foliage in the Great Dirt Bed at God Nore, supported by similarities in the cuticle of the microsporophyll and leaves, strongly suggests that, though not specifically in organ contact, they are part of the same plant. Several species of male cones associated with Classopollis-producing conifers have been described and Alvin et al. (1978) erected a new genus Classostrobus for male cones containing Classopollis pollen, and thus attributable to the family Cheirolepidiaceae, but which were not specifically in organ contact with the shoots. Two male cones have been associated with *Cupressinocladus* foliage: *Classostrobus rishra* (Barnard) Alvin *et al*. with *Cupressinocladus pseudoexpansum* Barnard and Miller, and *Masculostrobus harrisianus* Lorch with *Cupressinocladus ramonensis* Chaloner and Lorch (Lorch 1968). The Great Dirt Bed cones are similar in shape and appearance to both of these cones, though slightly smaller in size, but lack of internal structure prevents any further comparison.

5.3.iv POLLEN

The pollen associated with the male cones from the Great Dirt Bed is clearly *Classopollis* Pflug. In some cases the grains have not collapsed and exhibit remarkably distinct equatorial striations. Although detailed S.E.M. observations have not been made, it seems that the exine is very thin and the internal structure, including the striations, is more prominent. Hence, of the many species described and illustrated by Reyre (1970) none is particularly comparable. Collapsed grains exhibit a surface structure of small granules, quite similar to that of *Classopollis noeli* (Reyre) from the Upper Jurassic of Algeria, in the Sahara. Couper (1958) found that the Purbeck miospore assemblages were dominated by *Classopollis torosus* (Reissinger) Balme,and Norris (1969) identified 3 species: *C.torosus* (Reissinger) Balme, *C.echinatus* Burger and *C.hammenii* Burger; the pollen grains from the cone are most similar to *C.torosus*.

5.3.v MEGASPORES

Megaspores do not appear to be a common constituent of the megascopic plant remains in the Great Dirt Bed. They tend to be arranged in clusters, being found in only one sample of the Great Dirt Bed. *Triletes russus* Harris represents the only megaspore type found so far and they have not been previously reported from elsewhere in the Purbeck Beds.

Triletes russus was originally described by Harris (1961) from the Middle Jurassic of Yorkshire, where it occurs throughout the Deltaic Series. It is not a common species there, only 40 specimens occurring in a total of 22 localities. No foliage was associated with Harris' *T.russus* and at that time no similar species was known from the Rhaeto-Lias or Wealden.

Harris suggested that these megaspores represent terrestrial or epiphytic lycopods which, in Yorkshire, grew at some distance from swamps or pools and were washed in only by occasional floods. In the basal Purbeck fossil forests the lycopods were probably part of the undergrowth. Their leaves are not known from the Purbeck Beds.

5.3.vi MIOSPORES

The few miospores described here were the most commonly occurring and well preserved of those obtained from the Great Dirt Bed at God Nore. A complete palynological study was not attempted since miospores within the Lower Purbeck Beds have previously been described by Couper (1958), Lantz (1958) and in most detail by Norris (1969). It is interesting to note that Norris (1969) was unable to find miospores in the Great Dirt Bed or the basal Purbeck limestones west of Lulworth Cove, which was unfortunate since these beds were of importance to his correlation with the Purbeck Beds in Sussex. It is now apparent that plant material probably decayed quite rapidly within the black, marly Dirt Beds, hence the absence of pollen. At God Nore the Great Dirt Bed was re-worked and perhaps for this reason the plant material is well preserved. A complete investigation of the miospores here would be most useful for stratigraphic purposes.

The miospore collection from God Nore was dominated by the conifer pollen Classopollis Pflug, often constituting at least 70-80% of a sample. A similar abundance was found by Couper (1958), Lantz (1958) and Norris (1969); the samples of Norris were dominated by either Classopollis torosus (Reissinger) Balme or Inaperturopollenites dubius (Potonié and Venitz) Thomson and Pflug. The other species found at God Nore were also the most frequent types found in the previous studies. Norris (1969) identified two groups of miospores: the "persistent" types which dominated all his samples (which include all those found at God Nore) and "spasmodic" types which occurred very rarely. On this he based his tripartite division into suites A, B and C, each containing the same "persistent" species but a different set of "spasmodic" species. The Lower Purbeck Beds of Dorset contained mainly the "persistent" miospore species (Suite A) but throughout the Purbeck Norris (1969) recorded a progressive diversification of the "spasmodic" species. Assigning the miospores to their natural plant orders (Norris 1969), it seems that the Lower Purbeck vegetation was dominated by gymnosperms and pteridophytes, particularly by the Classopollis-producing conifers and a few of araucarian affinity. A few filicalean and lycopsid types occurred, probably as part of the undergrowth. Cycadophyte pollen was relatively rare although the macrofossils suggest that they were fairly abundant at least in some areas. Throughout the rest of the Purbeck the pteridophytes begin to diversify though conifers remain important (Suites B and C). Although the Upper Jurassic vegetation was considered to be very like that which followed in the Lower Cretaceous (Seward 1895) Classopollis pollen is far less abundant in the Wealden sediments (Couper 1958; Batten 1974; Hughes 1975), suggesting that the Purbeck vegetation had diversified markedly by the Cretaceous.

The palynological work of Lantz (1958) and Norris (1969) was used particularly for stratigraphic sub-division and correlation. Using his three miospore suites Norris proposed that the "Lower" Purbeck Beds of Sussex were equivalent to the top of the Lower Purbeck and base of the Middle Purbeck Beds in Dorset, the equivalent of the basal Caps and Dirt Beds in Dorset being absent in Sussex. This contradicted all former correlations forwarded by detailed ostracod work (Anderson in Anderson and Bazley 1971) and the lithological similarities between Dorset and Sussex and intermediate boreholes (Howitt 1964; Anderson & Bazley 1971; Holliday & Shephard-Thorn 1974; Lake & Holliday 1978). The interpretation of palynological assemblages must, however, take into account many other factors such as preservation, transport, geography and sedimentary environment (Chaloner 1968; Muller 1959). The correlation of Norris was based upon the assumption that the miospore suites were time concordant. If, however, the normal correlation of Howitt (1964) is considered then Norris' results suggest that the more diverse flora with more pteridophyte species (Suite B) was established in Sussex, whilst in Dorset a dominantly coniferous vegetation was found along with evidence of a nearby marine influence (Suite A). Thus a local palaeoecologic control, such as soil type, may have been influencing the vegetation as admitted by Norris (1969, p.606). This situation is reminiscent of the Neves' Effect, discussed by Chaloner and Muir (1968), which proposed that a diversification of some miospore types whilst others remained persistent represented gradual withdrawal of the sea margin. The persistent miospores represented an 'upland' flora (above maximum sea level) which always contributed a constant level of pollen to the depositional area, while the impersistent miospores represented a flora which grew on the "lowland" between the upland and the sea when the sea level dropped. The Lower Purbeck Beds of Dorset contain only a "persistent" miospore assemblage of dominantly conifer pollen associated with some marine dinoflagellates (Norris 1969). The Classopollis-producing conifers would therefore be considered as an "upland" flora. Their proximity to the shoreline is evident from the dinoflagellates, from the adjacent algal stromatolitic limestones and particularly from evidence that the fossil forests themselves were drowned by the rising water. In Sussex conifers from the uplands continued to supply pollen but added to this were "spasmodic" miospores from the lowland area. This vegetational distribution, based on the Neves' effect, suggests that the sea margin was further from the Sussex area than Dorset. This is fully supported by sedimentological evidence such as the presence of high energy stromatolite types in Dorset as opposed to low-energy smooth algal mats in Sussex, and evidence of several short periods of emergence of the Sussex area, one of which may be equivalent to the Great Dirt Bed (Holliday and Lake 1978). These relatively short sub-aerial exposures in Sussex were presumably long enough for a sparse pteridophyte vegetation to develop but not for large conifers.

It seems therefore that there is an alternative explanation to Norris' proposal (1969) for the distribution of miospores in the Dorset and Sussex Purbeck beds which suggests that his miospores suites are not time-concordant and his correlation of the two areas invalid. Sedimentological evidence suggests that during early Purbeck the Dorset area was nearer the forested Purbeck basin margin but closer to normal marine waters, whilst the Sussex area was more arid, was further from the basin margin and the intervening "lowland" area was vegetated by a diversifying pteridophyte flora. The results of Norris (1969) suggest that similar conditions developed in Dorset during the deposition of Middle Purbeck sediments.

5.4 Other Fossil Plants from the basal Purbeck Beds

The Purbeck flora is relatively sparse and poorly described. Apart from early reports of the cycadophytes and descriptions of some land plants from Portesham by Barker et al. (1975), little other palaeobotanical work has been published. Although a complete study of the Purbeck flora is beyond the scope of this project, the list below of the Purbeck specimens in the British Museum (Natural History) gives some indication of other constituents of the forest vegetation. Most are poor plant impressions and have no cuticle suitable to study.(Descriptions in brackets are comments by J. Francis, others are the original labels.)

Specimen Number	Description	Locality and Horizon
V.3403	*Sphenopteris minutifolia*	Purbecks. Hartwell, Bucks.
V.3360	(Rootlet in fine-grained limestone) Brodie Collection	Purbeck. Durlston Bay.
V.7534	*Equisetites*	Purbeck. Perch Hill, Brightling, Sussex.
V.44928	*Equisetum mobergi* (Halle ex Möller) Barker *et al*. 1975	Purbeck Beds. Portisham
V.3411	(Rootlets in fine-grained limestone) Brodie Collection	Purbeck. Dorset.
V.55687	Fern	Lulworth Cove. Portlandian
V.3404	*Trichoptys*, one of the Ginkgoes. Brodie Collection	Dinton, Wiltshire.
V.10384	(Cast of small wood fragment in ? Insect Bed) Rev. Fisher Collection	Purbeck. Swanage.
V.3405	(*Brachyphyllum*?) Brodie Collection	Purbeck. Dinton, Wiltshire.
V.3373	*Palaeocyparis* Brodie Collection	Purbeck. Teffont, Wiltshire.
V.3374	(small cone, 4 mm diameter) Brodie Collection	Purbeck. Swanage
V.4035	(Poor, round cone on stalk. No cuticle. 1·5 cm diameter)	West Cliff, Portland.
V.3440	*Echinostrobus* (*Cupressinocladus*?)	Purbeck. Dashlet, Wiltshire.
V.52615	(*Brachyphyllum*?)	Purbeck. Aylesbury, Bucks.
V.1071	(*Brachyphyllum*? Spirally arranged leaves)	Lower Purbeck. Teffont, Vale of Wardour.
V.4030	(*Cupressinocladus*?) Damon Collection	West Cliff, Portland.
V.4028	Conifer Damon Collection	Purbeck. West Cliff, Portland.

Specimen Number	Description	Locality and Horizon
V.3376	Palaeocyparis or Brachyphyllum May be Echinostrobus	Middle Purbeck. Teffont Lime kiln
V.4027	Conifer Damon Collection	Purbeck. West Cliff, Portland.
V.3376	Palaeocyparis (counterpart) Brodie Collection	Teffont.
V.3383	Plant Brodie Collection	Hartwell, Bucks.
V.60225	Pagiophyllum	Purbeck. Swanage
V.2116	(? Cupressinocladus. Large specimen without cuticle. Straight stem, alternate branching, long internodes)	Portlandian. Portland.
V.3451	(?Cupressinocladus. As above. No cuticle) Damon Collection	Portlandian. Portland.
V.60225	Brachyphyllum	Dorset.

The Purbeck Cycadophytes

Silicified cycadophyte stems were often found *in situ* in the Dirt Beds in the past (Fitton 1835, 1836; Damon 1884a) and many are now in museums (e.g. Portland Museum). However, despite the number of petrified tree stumps which can be found *in situ* in the field today, no cycadophytes have been observed *in situ*. Due to their smaller size they did not protrude very far into the algal limestone above (Fitton 1836) and were thus probably easier to remove from the Dirt Beds. They have been recorded from both the Great Dirt Bed and Lower Dirt Bed (Buckland 1829) where they were found amongst the fossil trees although they were particularly common in the Lower Dirt Bed on Portland where fossil trees were absent (Fitton 1835).

The cycadophytes remains are short, circular stumps, about 30 cm in diameter and 25 cm high. Some are vertically extended to a height of about 60 cm. The largest recorded was *Cycadeoidea gigantea* Seward which was 1·19 m in height and 1·7 m in diameter, described by Seward (1897) from Bowers Quarry on Portland. Most have a circular depression on the top representing the former position of the growing tip which is only represented now by a lining of petrified cellular tissue. This gave the stems a nest or bowl shape which led quarrymen to believe that they were fossil crows' nests which had fallen from the branches of the fossil trees (Gray 1861; Damon 1884a).

Covering the surface of the silicified stems are rhomboidal, helically-arranged leaf bases and tongue-shaped, scale-like hairs. Although mature leaves have never been found attached to the stems, reconstructions show a crown of helically-arranged pinnate leaves extending from the distal end of the stem (Taylor 1981, fig.14.10). The reproductive organs consisted of bisporangiate cones embedded in the trunk among the leaf bases. They were borne on short lateral branches extending from the central vascular cylinder but did not extend beyond the level of the stem surface. These cones had a flower-like appearance due to an encircling mesh of hairy scales, and in some species many appeared on the stem at one time (Thomas 1981). No cones have been reported on the Purbeck cycadophyte stems.

The basal Purbeck cycadophytes were identified as the members of the Bennettitales (Cycadeoidales), which were a conspicuous portion of the flora from the Triassic to the Cretaceous. Buckland (1929) identified them as Cycadeoidea megalophylla, the largest and most abundant type, and Cycadeoidea microphylla, a smaller type with more numerous leaf bases. Carruthers (1868) distinguished the types with the small, squat stems from those with a much taller, slender, branching trunk belonging to the family Williamsoniaceae. The Purbeck Cycadeoidea were re-identified as Bennettites portlandicus, Mantellia nidiformis, M.intermedia and M.microphylla, the distinction of the species based mainly on the size of the stumps and the nature of the leaf-base scars.

Very little cycadophyte pollen was found in the basal Purbeck Beds by Couper (1958), Lantz (1958) or Norris (1969) and only a few grains of Cycadopites were found in the Great Dirt Bed at God Nore in this study. This is consistent with many other Jurassic miospore assemblages where, by comparison with the distribution of petrified stems and foliage, cycadophyte pollen is noticeably scarce (Frederikson 1979).

The living cycads today (Cycadales) are restricted to tropical and sub-tropical regions; some, such as Zamia, live in Florida, Mexico and the West Indies, whilst Cycas is found in Australia, India, China and other tropical zones (Foster and Gifford 1959). For this reason

Fitton (1836), Damon (1884a) and others first concluded that the Jurassic climate was much warmer than that of today. However, since the identification of the Cycadophytes with the modern group Cycadales was erroneous, this conclusion can have no validity.

5.5. Reconstruction of the typical conifer in the basal Purbeck fossil forests.

By virtue of the frequent occurrence of individual parts and their close association within the fossil soils, particularly the Great Dirt Bed, the wood (*Protocupressinoxylon* sp. A. nov), *shoots* (*Cupressinocladus valdensis*), male cone (*Classostrobus* sp.) and pollen (*Classopollis*), described here, are considered to represent parts of one conifer which dominated the basal Purbeck forests. Although these individual parts have not been found specifically in organ contact, this conclusion is strengthened by the apparent scarcity of other types of foliage and wood in these strata and agreement in cuticular structure between the male cone and leaves.

The presence of the *Classostrobus* cone associated with *Classopollis* pollen attributes the Purbeck tree to the family Cheirolepidiaceae. Fossil wood of similar type to that from the Purbeck was once assigned to the Protopinaceae (Krausel 1949), a family specifically for secondary wood which was abundant in the Jurassic and Lower Cretaceous. This family is now regarded as artificial (Alvin *et al*. 1967) and a few form-genera of fossil wood of this type have now been attributed to the Cheirolepidiaceae on the basis of their association with cheirolepidiaceous foliage. In particular, wood of *Protocupressinoxylon*-type was considered by Harris (1979) to represent the wood of *Hirmeriella muensteri* (Schenk) Jung. Wood of *Protopodocarpoxylon*-type was associated with *Pseudofrenelopsis parceramosa* (Fontaine) Watson from the Wealden of the Isle of Wight by Alvin *et al*. (1981). Alvin *et al*. (1981) summarised the wood types attributed to the Cheirolepidiaceae. Their common features (contiguous and separate tracheid pitting, cupressoid cross-field pits and resinous tracheids and ray cells) are consistent with the characteristic features of the Purbeck wood. Although the foliage has been classified as Cupressaceae in the past (e.g. Chaloner and Lorch 1960) due to its similar appearance to modern species, *Cupressinocladus valdensis* (Seward) Seward was classified by Watson (1977) as Cheirolepidiaceae.

Thus, as shown in Figure 5.03, the Purbeck conifer is considered

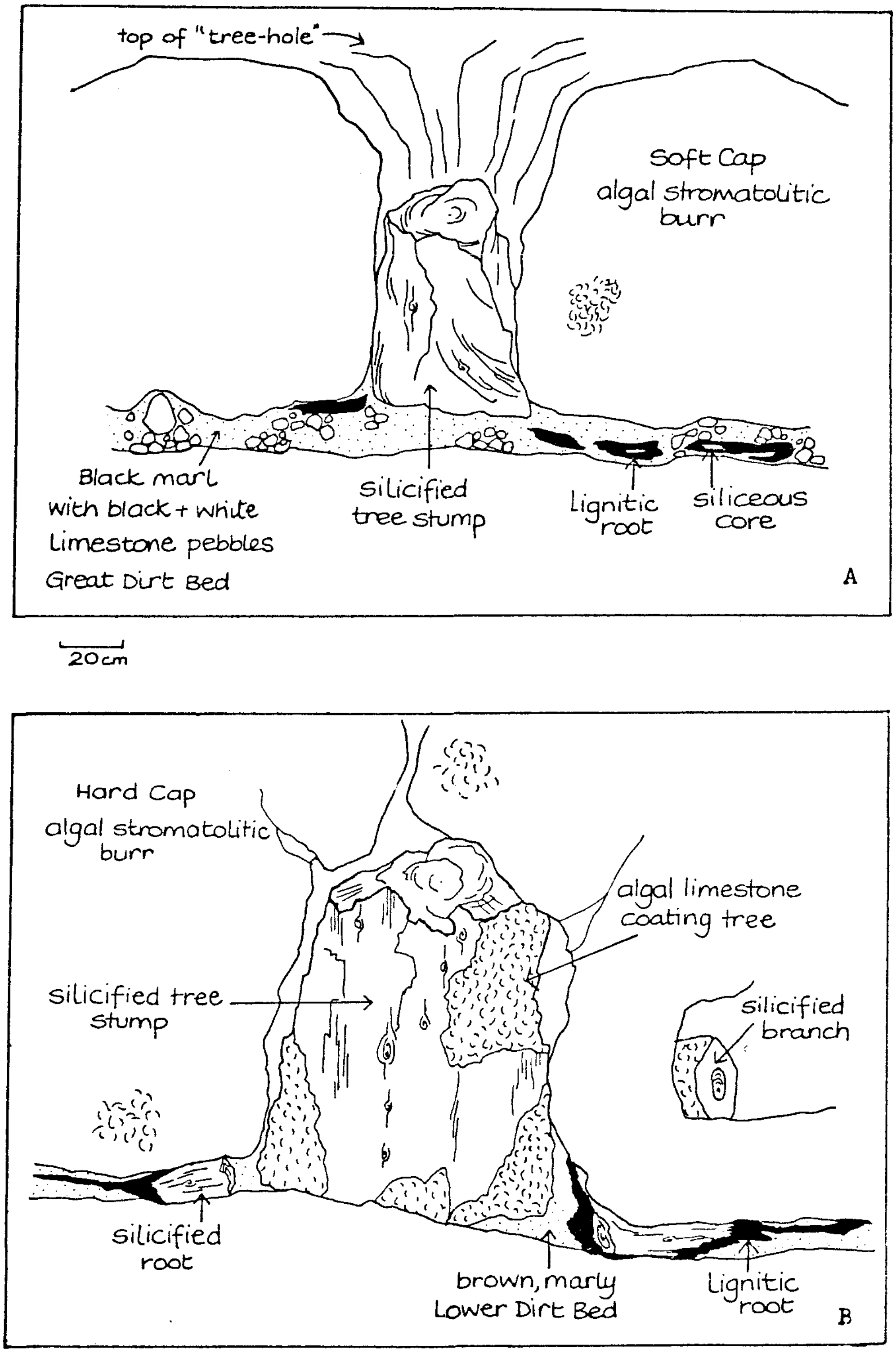


Fig. 5.02. Sketches of <u>in situ</u> tree stumps and roots preserved within:
A) the Great Dirt Bed at the Fossil Forest
B) the Lower Dirt Bed at Chalbury Camp.
(to scale)

to have wood of *Protocupressinoxylon* sp.A. nov., foliage belonging to the species *Cupressinocladus* *valdensis* (Seward) Seward and male cones (*Classostrobus* sp.A) yielding *Classopollis* Pflug pollen.

Additional information regarding the shape, size and structure of these trees can be deduced from silicified tree stumps, branches and trunks found in the Dirt Beds. Branches are seldom found attached to fallen trunks, even very long portions, presumably having broken off on impact with the ground or rotted away. Fitton (1836) recorded a trunk 8 m long which bifurcates at the top into two smaller branches but most trunks found have been monopodial. However, at Chalbury Camp a small silicified branch which seems to be attached to the main tree stump, is preserved within the same mound of stromatolitic limestone as the rest of the tree (Pl.1 , Fig.1). Just over 1m of the main upright trunk remains rooted in the Lower Dirt Bed and attaining a diameter of 92 cm at the base of the trunk. The branch, 8 cm in diameter and 42 cm long, extends upward from the trunk at an angle of 40^{o} from the vertical at a height of only 44 cm from the top of the soil. On the main trunk of this tree, as on many trunk bases, the original positions of branches are indicated by the presence of numerous knots, both large and small. Although not all may have penetrated through the sapwood which has now vanished, some certainly did. The knots range in size from about 0·5 cm in diameter to about 15 cm, though the most common size is about 4 cm. Knots of all sizes occur together on an exposed surface of a trunk but they do not form an obvious pattern such as a whorled or spiral arrangement. The branches appear to have arisen irregularly from the trunk. Nevertheless the evidence suggests that even in a full grown tree several branches arose from near the base of the tree which probably had a more or less monopodial growth form. Radial sections cut across knots in samples of silicified wood verify that the branches subtend an angle of between $30\text{-}50^{o}$ with the main axis.

Several knots seen in thin section are encircled by cracks which contain soil particles and *Classopollis* pollen embedded in silica, similar to other cracks in the trunk wood (4.1). These cracks around the knots must have been open before silicification either when the tree was alive or shortly afterwards, and probably represent 'dead knots' formed when a trunk expands over a dead branch.

Although only pieces of trunk are preserved, some idea of the

Plate 14

Fossil Wood in the Dirt Beds

1. Transverse section through a small silicified branch attached to tree stump in Figure 1, Plate 1. A 7 cm zone of silicified algal stromatolitic limestone surrounds the branch. The branch and tree stump are encased in the algal stromatolitic limestone of the Hard Cap, Chalbury Camp (PB.83).

2. Transverse section through a similar silicified branch also encased by silicified limestone. Location unknown. Specimen from Portland Museum.

3. Cross-section through algal stromatolitic burr in the Soft Cap, Fossil Forest. The algal layers and marks on the limestone indicate that this burr once enclosed a silicified tree.

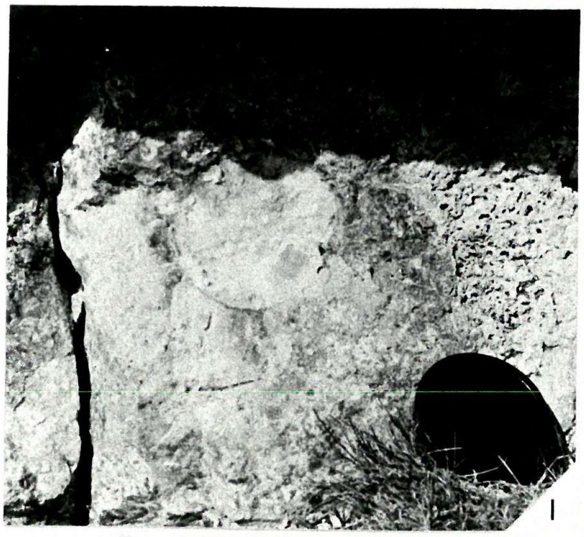
4. Silicified trunk or branch (PB.61) lying on top of the Great Dirt Bed in a north-south direction. Admiralty Quarry, Portland.

5. Black, carbonised root within the Great Dirt Bed, Fossil Forest. The pale core of the root is silicified and the cell structure preserved, enabling identification of the wood as Araucarioxylon. The cell structure in the black exterior has been lost (see 4.2 iii).

6. Small, silicified cycadophyte stem, showing compressed rhomboidal leaf base scars and central cylinder of petrified cellular tissue. Location unknown. Southampton University Geology Museum.

7. Trunks or branches of silicified wood lying in the Great Dirt Bed, Silent Quarry, Portland (SY 688727). The branches lie in a north-south direction and are covered by algal stromatolitic limestone of the Soft Cap.

(Hammer handle length 27 cm. Lens cap diameter 7 cm)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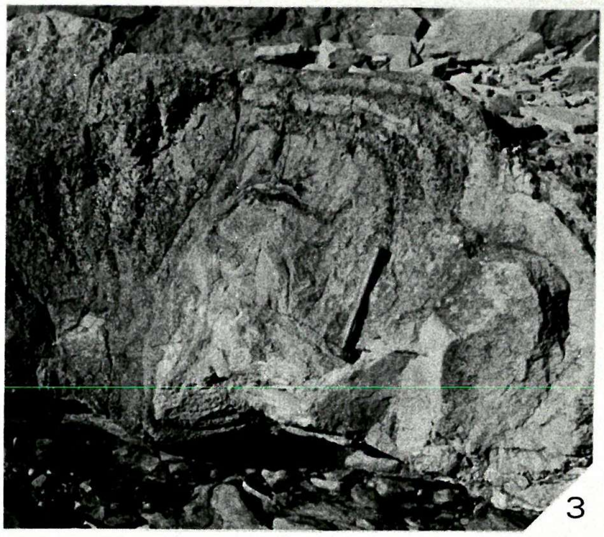
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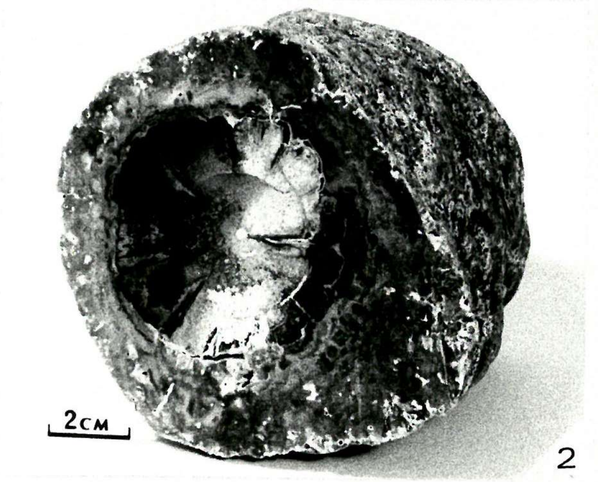

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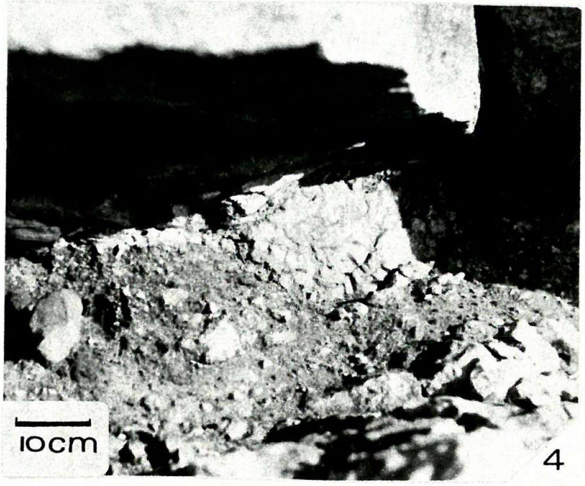

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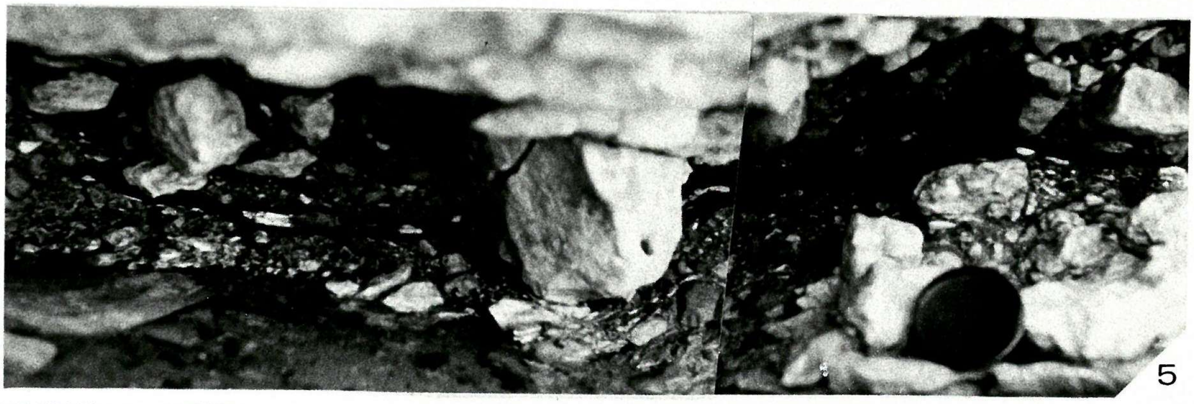
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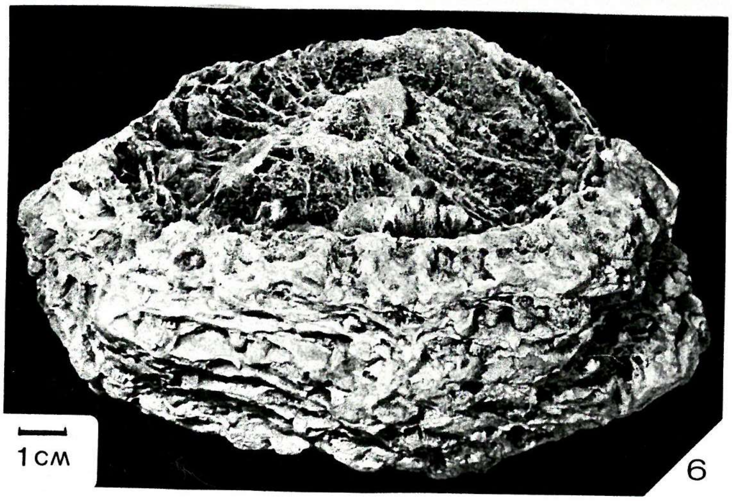

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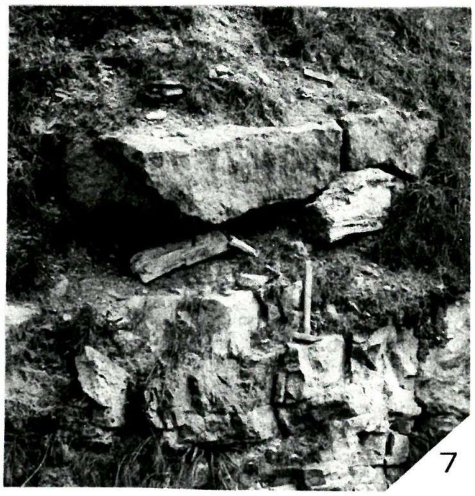
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PLATE 14

height of the Purbeck conifers can be obtained from the dimensions of the remaining silicified parts. Many straight trunks of about 6m in length, some over 13m long, have been observed (e.g. Fitton 1836; Mantell 1854) lying on the dirt beds. Dimensions of a tree trunk recorded by Fitton show that it tapers by only 9·5 cm from a diameter of 47·8 cm at the base to a diameter of 38·3 cm at a height of 5·51m. With monopodial axes of this length, trees of over 20m can be envisaged. The widths of the trunks and tree stumps also suggest that they were large trees; the mean trunk diameter of the sections measured being about 55 cm and the maximum 1·3m. The diameters of some large in situ tree stumps are 45 cm (Fossil Forest); 92 cm (Chalbury Camp); and 60 cm at Poxwell. Because of the nature of the preservation these values represent only part of the heartwood since the outer layers of the tree are always lost. Nonetheless the bases of the tree stumps are often over 1 m in diameter.

The roots of the conifers are also preserved within the Dirt Beds. The bases of the erect tree stumps become thickened (but certainly not to the extent of being buttressed) and often slightly twisted (Pl. 1 , Fig.3) and then divide into roots spreading laterally through the soil in all directions. Silicified roots up to 10 cm in diameter extend from the base of the large tree into the Lower Dirt Bed at Chalbury Camp (Fig.5.02). The silicified parts are broken up into lengths of 10-15 cm but remain within a continuous lignitic sheath about 3 cm wide. Where the roots taper to less than 3 or 4 cm in width, the siliceous core is lost and the roots occur only as "lignite" (Pl. 14 , Fig. 5).

The root system here can be detected extending radially from the trunk for about 1 m, though certainly the finer roots have been lost (Pl. 1 Fig.1).

It was noticed long ago (Fitton 1836) that the tree roots could not penetrate the underlying hard limestone but were diverted laterally through the soil. The fossil roots appear to have grown down vertically as far as they could go but on meeting the limestone doubled back, before finally extending horizontally through the base of the soil. Similarly a small lignitic root associated with the fossil tree at the Fossil Forest appears to have grown back on itself, having been restricted by a large limestone pebble in the palaeosol.

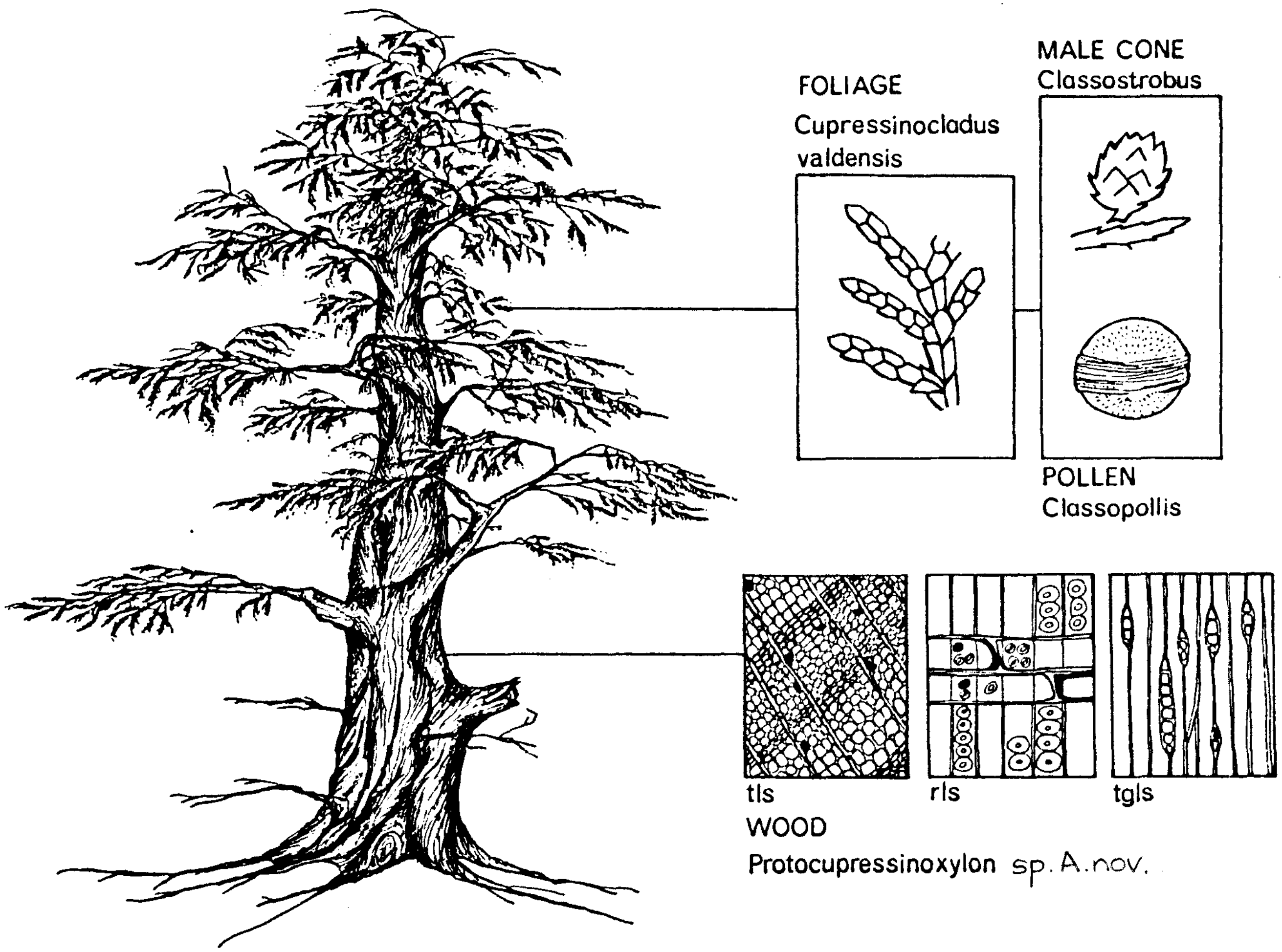

Fig. 5.03. Reconstruction of the typical conifer in the basal Purbeck forests. The height of this tree is estimated to be about 20m.

Compressions of rootlets are present on the surfaces of pale, marly laminae within the Lower Dirt Bed at Sheat Quarry, Portland (SY 689698) (Pl.12, Fig.6). The ultimate branches of these roots are not particularly fine (0·7 mm diameter) and often terminate in small, nodule-like swellings (0·6 mm diameter). By comparison with roots of modern trees it seems probable that they were mycorrhizae, formed by association with symbiotic fungi (Toumey and Korstian 1947). They are common on roots of forest trees today and sometimes take the form of small nodules, e.g. in Podocarpus spp.

A reconstruction of the most common Purbeck conifer is presented in Figure 5.03, based on evidence outlined above including data on trunk diameters, frequency of knots, branching angle etc. Clearly such a diagram is an imaginative interpretation of the data and where direct evidence is not available comparisons have been made with modern conifers from semi-arid regions such as Juniperus oxycedrus Linnaeus and Cupressus macrocarpa Hartweg.

5.6 Comparison of the Purbeck tree with Other Members of the Cheirolepidiaceae

Many different habits and environments have been proposed for the Cheirolepidiacean plants. The world-wide importance of this family in the Mesozoic is reflected in the distribution of Classopollis pollen (Srivastava 1976). Classopollis has been found in sediments from the Upper Triassic to the Turonian (Upper Cretaceous) after which the Cheirolepidiaceae apparently became extinct. At times the Classopollis-producing plants dominated the vegetation and its pollen constitutes up to 100% of some miospore collections; it was particularly abundant in the Liassic and Upper Jurassic sediments (Chaloner 1962) and in the Toarcian and Oxfordian of Russia (Vachrameev 1970). Its widespread occurrence suggests a cosmopolitan distribution of these plants, perhaps due to the proximity of the continents and a relatively uniform world climate during the Jurassic (Frakes 1979).

Many palynologists suggested that the Classopollis-producing plants grew in coastal areas and marginal swamps because the pollen was found in abundance in marine sediments (Pocock and Jansonius 1961; Wall 1965; Hughes 1973). However, this may simply be a factor of preservation since anaerobic marine sediments have a greater potential for the preservation of plant material than aerobic soils. This is clearly illustrated in the case of the basal Purbeck pollen which is absent, presumably decayed, in the true palaeosols but can be found in the re-worked Dirt Bed at God Nore. The Classopollis-producing Purbeck trees did grow close to the basin margin in Dorset but also grew inland in the Vale of Wardour (Woodward 1895).

An alternative environment suggested by Vachrameev (1970) is that the Cheirolepidiaceae were "upland" plants in the sense that they grew above the coastal plain. This would account for the increase in Classopollis in transgressive sediments when obviously the shoreline became nearer the upland source. The recovery of this pollen from sandy and calcareous sediments, as opposed to alluvial deposits, was also considered indicative of an upland habitat (Kendall 1949; Chaloner 1962; Médus and Pons 1967). Batten (1974) envisaged that Classopollis-producers occurred in the Wealden in a range of habitats; some were upland plants while others occupied sand bars and barrier islands and some were mangrove plants (also suggested by Oldham 1976).

Evidence from the sediments in which Classopollis has been found suggests that some Cheirolepidiaceae were well-adapted to an arid or semi-arid environment. Classopollis was found in evaporite sediments in Soviet territory (Vachrameev 1970) and occurred in more northerly deposits as the climate became warmer in the Upper Jurassic (Srivastava 1976). The domination of miospore assemblages by Classopollis suggests that the Cheirolepidiaceae grew in these conditions at the expense of more mesophytic plants such as ferns. The foliage also exhibits anatomical adaptations to an arid environment such as thick cuticle with sunken papillate stomata to reduce moisture loss. Watson (1977) considered their thick cuticle was reminiscent of succulent halophytic plants. The Purbeck conifers also have a thick cuticle (15-20 µm) and the stomata are sunken with their apertures almost entirely covered by large papillae.

Some idea of the main structural features of the Cheirolepidiacean conifers has been obtained from associations of foliage, cones, pollen and secondary wood preserved together, such as parts of Cheirolepis (Hirmeriella) muensteri (Harris 1957) and Pseudofrenelopsis parceramosa (Alvin et al. 1981). However, their overall habit had not been verified due to the paucity of petrified wood representing their trunks and branches. Vachrameev (1970) envisaged them as low-growing, thermophilous trees or shrubs, not unlike modern junipers in semi-arid areas, though due to their widespread occurrence over a long period it seems probable that the Cheirolepidiacean plants had several forms related to the local environment. A reconstruction of *Cheirolepsis* (*Hirmeriella*) *muensteri* by Jung (1968) pictures a 6m tall tree with a tall, straight trunk and secondary branches at least 22 cm in diameter. The conifer from the Wealden of the Isle of Wight with *Pseudofrenelopsis parceramosa* foliage but with wood structure very similar to that of *Protocupressinoxylon* sp. A. nov. in the Purbeck tree, is now considered to be a more massive tree, often with a trunk diameter greater than 70 cm, forming a forest rather than scrub vegetation (Alvin *et al.* 1981). Although these trees grew on river margins in a climate considered to be fairly warm and wet (Allen 1975) they suffered from water stress during periods of aridity, shown by the irregularity of their growth rings. The foliage also has the features of a rather xerophytic tree (Watson 1977). The occurrence of forest fires in the Wealden has also been considered as evidence for dry periods (Harris 1958, 1981; Alvin 1974; Alvin *et al.* 1981) though natural fires frequently occur today in humid, swamp environments such as the Florida Everglades (Cypert 1972) which was the environment chosen by Oldham (1976) as a modern analogue for the Wealden.

5.7 The Purbeck Fossil Forests and Jurassic Vegetation

The basal Purbeck forests, particularly that of the Great Dirt Bed, were thus dominated by one species of conifer belonging to the Cheirolepidiaceae, as outlined above. Its abundance in the macrofossil remains is reflected in the dominance of its *Classopollis* pollen in the miospore assemblage. A few rarer conifer types were associated with it, particularly members of the Araucariaceae which are represented in the Dirt Beds by pollen and trunk wood. Other evidence of araucarian trees is suggested by the discovery of part of a cone *Araucarites sizerae*, in the lateral equivalent of the Great Dirt Bed, the Portesham Charophyte Chert (Barker *et al.* 1975), and the cone *Araucarites sphaerocarpa* on the Portland cliffs (Carruthers 1866). One specimen of one other type of wood, *Circoporoxylon*, was identified but its foliage and botanical affinity is unknown. Cycadophytes occurred between the trees and probably dominated the seaward margins of the forests as suggested by their more frequent occurrence on Portland as opposed to the mainland. Evidence of other botanical components of the forests is sparse. A small fragment of the foliage of the conifer *Brachyphyllum* was found by Barker *et al.* (1975)

and others have been found in the Purbeck Beds in Wiltshire. On the basis of Classopollis pollen within the male cones, some species of Brachyphyllum have been assigned to the Cheirolepidiaceae (e.g. by van Cittert 1971). Alvin et al. (1981) suggested that in the Wealden Brachyphyllum represented small shrubs which grew beneath the forest canopy. Other plant remains found within the Dirt Bed at Portesham include silicified charalean fragments, stems of Equisetum morbergi and silicified seeds (species of Carpolithus) (Barker et al. 1975). None of these has been found further east in the marly Dirt Beds, possibly due to the poor preservation potential, but these fossils may represent the flora of the western ephemeral lakes (West 1975). The miospores from the basal Purbeck beds (Couper 1958; Lantz 1958; Norris 1969; this study) suggest that a limited herbaceous vegetation of ferns and some lycopods grew on the forest floor or on the coastal margins,though their foliage is not represented.

The association of a few trees of araucarian affinity with the Purbeck conifers supports similar observations from nearly all the miospore assemblages described which include Classopollis pollen (Vachrameev1970: Srivastava 1976). The Araucariaceae dominated the low latitude vegetation (15°-20°N) in the Mesozoic, and thus probably represented the most thermophilous vegetation (Krassilov 1978). They occurred less frequently at higher latitudes (up to about 50°N in the Jurassic) in vegetation with, and subordinate to, Elatides and Classopollis plants. They were also present in the Southern Hemisphere where the two modern genera Araucaria and Agathis are confined today (Taylor 1981). Where they dominated the vegetation they have sometimes been preserved as spectacular fossil forests, such as the Triassic Petrified Forest in Arizona and the Upper(?) Jurassic Cerra Cuadrado Petrified Forest of Patagonia, though they declined in number and geographical distribution from the Cretaceous. Some Brachyphyllum shoots (B.mamillare from the Middle Jurassic of Yorkshire, Harris 1979) have been associated with the seed-cones Araucarites phillipsi and probably represent their foliage.

The similarity of the Purbeck and Wealden vegetation is also supported by the occurrence of Circoporoxylon-type wood, from Fisherman's Ledge (near Swanage) and Shippard's Chine (Isle of Wight) respectively, though the foliage or tree habit is unknown.

The Jurassic vegetation was once regarded as being fairly uniform in nature in response to a warm and equable climate and the proximity of the continents (Wesley 1973; Hallam 1975). Plants were recorded as far south as Graham Land (63°S, contemporary latitude) and Alexander Island (70°S) (Jefferson 1980) and north to the New Siberian Islands (75°N). Some differences existed between the two hemispheres in the Jurassic since the conifer families Taxodiaceae, Cupressaceae and Pinaceae were absent from the Southern Hemisphere and the Podocarparceae confined to this region. The Araucariaceae (and probably the Cheirolepidiaceae) were apparently the only families distributed north and south of the Equator (Florin 1963; Hughes 1973). Evidence for a general widespread warm climate is also given by the distribution of Jurassic vertebrate remains as far apart as Patagonia in the south to Greenland in the north (Colbert 1964).

With an increase in information on fossil plants and the relevant palaeolatitudes from palaeomagnetic evidence, it became apparent that there were latitudinal and/or climatic controls on the Jurassic vegetation. Vachrameev (1964, 1978) summarised the evidence of many Mesozoic floras distributed over the Eurasian continent, ranging in age from early Jurassic to Middle Cretaceous. By plotting the locations of several floras he distinguished two broad vegetational zones: a northern "Siberian Palaeofloristic Province" and a southern "Indo-European Palaeofloristic Province". The zone boundaries illustrate a progressive northward displacement throughout the Jurassic as the climate becomes warmer. The similarity of floral sequences and climatic trends in North America was shown by Smiley (1967). Barnard (1973) plotted the distribution of several fern genera to test the Russian zonation and the reconstructions of the continents. From the Triassic to the early Cretaceous three main floristic regions existed: the Angara or Siberian zone at the northern pole down to about 34°N, the Gondwanan zone to the south and a broad Eurasian equatorial zone lying between them. From about 60°N to 60°S the climate was warm and equable overall. During the Jurassic the Eurasian belt (or the European-Central Asian belt), in which Dorset lay, outlined by floras containing Sagenopteris (Caytoniales) and the fern Klukia, coincided with the evaporite belt of Lotze (1964, fig.11) and the Jurassic terrestrial tetrapod faunas of Colbert (1964) providing ample evidence for a warm and equable climate. This area of semi-arid/arid environment with evaporites corresponds to that in which Classopollis pollen was most abundant (Vachrameev 1970). However at the transition from Jurassic to Cretaceous the northern boundary of the arid zone shifted appreciably southward (Lotze 1964) corresponding to the decline of *Classopollis* in the north (Hughes 1973; Srivastava 1976) and the increased occurrence of Cheirolepidiaceae further south. The Eurasian floristic zone to the north, of Barnard (1973), is denoted by the occurrence of the fern *Weichselia* which is common in the Wealden (Alvin 1974) and probably indicative of the onset of more humid conditions. The boundary between the humid and arid zones did not undergo any appreciable southward shift within Asia (Vachrameev 1964 , 1978) which may account for the occurrence of the cycad genus *Nilssonia* in this region, which Barnard (1973) considered questioned his zones.

Apart from the rather vague deductions about the climate made from the study of floristic zones and possibly some interpretation of the climatic requirements of the fossil plants from comparisons with possible modern relations, individual plant genera or families have not been useful for determining the exact nature of the past climate. Some idea of seasonality or aridity can be obtained from sedimentary evidence with which the plants are associated, such as evidence of forest fires, evaporite formation, storm deposition and desiccation cracks. One of the most accurate records of climate is in the growth patterns of plants particularly trees, so to discover more detailed information about the exact nature of the Jurassic climate the growth rings in the Purbeck trees were examined (Chapter 6).

CHAPTER 6

GROWTH RINGS IN THE WOOD OF THE BASAL PURBECK FOSSIL TREES

6.1 Introduction

The advance in the study of modern growth rings in trees, outlined in Fritts (1976), has thrown light on understanding the environmental controls of the growth of trees, which can be applied to the interpretation of fossil growth rings. Although the past climates may not have been identical to those of today and the vegetation then consisted of now extinct species of trees, we may assume that the same responses of plants to environmental conditions were broadly similar in the past as in the present. Therefore by studying the relationship between variations in tree growth with those of the present climate, one can infer from fossil rings the nature of the past climate. The presence of growth rings in the basal Purbeck fossil wood was formerly noted by Fitton (1835) and Damon (1884), but not related to the Jurassic climate.

Modern growth ring analysis is used to assess climatic influence and is known as dendroclimatology. This is the correlation of growth ring patterns in trees to contemporaneous meteorological data, such as rainfall and temperature, in order to evaluate the environmental factors affecting tree growth (Dobbs 1953; Fritts et al. 1965; Fritts 1976). This approach can also involve extrapolation to reconstruct long term climatic patterns (Douglass 1919, 1928, 1936; Schulman 1956; LaMarche and Fritts 1972; LaMarche 1974). When studying fossil growth rings, direct climatic records are obviously not available, but the data from rings can be interpreted in the light of modern conclusions; this is called interpretative dendroclimatology. A broad picture of the past climate can be deduced from such factors as the presence or absence of growth rings as indicators of temperature or tropical palaeo-latitudes, the absolute ring widths as indicators of the growing conditions and the presence of false rings marking the early onset of adverse conditions. In addition, variation in cell dimensions throughout a single ring also provides some record of growing conditions, though this source of information is rather poorly understood (Creber 1975).

Dendrochronology, the study of chronological sequences of rings for dating purposes, is of no great value to the study of fossil wood. The technique is used for the relative and absolute dating of modern wood and archaeological timber by extrapolation from datable rings and the cross-matching of characteristic patterns of growth rings from tree to tree (Stokes and Smiley 1968; Fritts 1972). In this way chronologies for the past 4000 years have been established using the ancient Bristlecone pines of America (Schulman 1958).

There is a general paucity of tree-ring studies of fossil wood. In the past, palaeobotanists have tentatively explored the possibility of climatic interpretation of fossil growth rings (reviewed in Chaloner and Creber 1973). With further understanding of the biological processes affecting ring formation and with more evidence of palaeolatitudinal control from geophysical studies, Chaloner and Creber (1973) and Creber (1975, 1977) have applied modern analytic methods to growth rings in fossil woods from the Devonian, Carboniferous, Permian and Jurassic. Growth rings in trees from the lower Cretaceous fossil forests of Antarctica have been investigated by Jefferson (1981).

6.2 The Formation of Growth Rings in Trees

The growth of a tree is the result of an increase in its height due to cell activity in the meristem tissue at the apices of stems and branches, and in girth through cambial activity leading to radial thickening. The secondary xylem forming the bulk of the "woody" stem is formed by the division of the vascular cambium (derived from the lateral meristem) just beneath the bark. The cells cut off to the inside of the cambium differentiate as xylem, while those to the outside form the phloem, and associated cells as the innermost part of the bark. The increase in xylem thus occurs on the outermost edge of the woody part. In some climates seasonal variation in growth is reflected in the formation of distinct rings in the xylem. Thus, over the whole tree, this increase in growth may be thought of as stacked layers of progressively larger cones, but in cross-section the growth increments appear as concentric rings. In the Purbeck fossil wood only the xylem is preserved and the bark, including the phloem, is completely lost.

In conifers each ring is formed of a series of long, thin tracheid cells which appear rounded or polygonal in transverse section. Their dimensions vary throughout the ring, depending on internal and external factors. The cells formed at the beginning of a growing season are typically large and thin-walled, being formed during a period of rapid growth. This zone is termed the earlywood, and lies at the inner side of the ring. It grades more or less gradually into the latewood zone of smaller, denser cells with successively smaller radial diameters formed at the end of the growing season under less favourable conditions when cambial activity slows down. The sequence of early and latewood forms one growth increment. The boundary of one growth ring and the next is thus differentiated by the presence of small, dense cells of the previous latewood in abrupt contact with large cells of the following earlywood. In temperate latitudes each growth increment usually represents one year of growth, hence the term "annual ring". There are, however, cases where rings are not annual; for instance, if factors for growth are highly limiting (e.g. drought) growth may not begin at all and no ring is formed (Fritts 1976). False (double or interannular) rings may be formed within a growth layer with the early onset of adverse growing conditions, such as a double wet season or drought (Glerum 1970). Some species of modern trees, such as Cupressus arizonica and some species of Juniperus, are more prone to the formation of false rings than are others (Fritts 1976).

Wood entirely lacking in rings is generally confined to tropical areas with a relatively seasonless climate (Richards 1952; Creber 1977).

6.3 Factors Affecting Ring Formation

The formation of growth rings in trees is affected by many factors which, overall, tend to limit the optimum growth. These include both internal constraints such as food supply, growth regulators, enzymes, etc., and external environmental factors such as topography, soil type and thickness, light intensity as well as the general aspects of climate. Localised constraints such as fire, insect attack and other causes of tree damage may affect the growth of individual trees.

Throughout the life of a tree one or more of these factors may become particularly limiting to its growth. When the tree is young it grows rapidly to fill the space available for its crown. As the tree gets bigger the amount of wood produced annually has to be spread over a larger cross-sectional area, so the ring-width (the thickness of the added layer) declines, rapidly at first then more slowly as the tree ages. The various aspects of the tree's environment are superimposed on this general decline. The decline will be hastened if, for instance, a neighbouring tree grows faster and overshadows it. On the other hand, if the adjacent tree is killed by lightning or disease, the tree will show a release cycle and grow quickly into the available space. The tree itself may be damaged by insects, disease or fire (damage cycle) and its growth rate will drop suddenly, until it eventually recovers its normal growth pattern. The year to year variations due mainly to the effects of the weather produce the growth ring patterns which are important for climatic interpretation,

Characteristic ring-width series with recognisable patterns for dating and cross-matching will only form if one or more environmental factors becomes critically limiting to a large number of trees over a wide area, thus affecting the character of the secondary wood in a large number of trees. If conditions are optimum for tree growth, with insufficient variation to produce recognisable ring patterns, the resulting growth increments will be uniformly wide or narrow. Such sequences are unsuitable for cross-dating or correlation with climate and are termed "complacent". However, the more a tree has been limited by environmental factors, the more likely it is to exhibit variation in width from one ring to the next (Fritts 1976). This variability is referred to as "sensitivity". For modern tree-ring studies "sensitive" trees are deliberately picked for analysis, since they provide the most recognisable sequences most correlatable with climate. Such trees are usually found near the margin of the species' natural geographical range where they are most susceptible to environmental conditions. Those on the arid borders of forests are mainly limited by drought, whereas trees from the upper altitudinal limits and from high latitudes are predominantly limited by temperature. There is often a clear relationship between growth ring characteristics and the environmental gradient through a forest (Fritts *et al*. 1965).

6.4 Problems Associated with the Analysis of Growth Rings in Fossil Wood from the basal Purbeck

In some silicified wood from the Purbeck, clear sequences of growth rings can be easily measured. The rings are visible when the individual cells are well preserved and the cell walls are retained. The measurable sequences vary considerably in length, depending on the state of preservation and the size of the wood sample. For this reason, the sequences are non-random with respect to the position within the radius of the tree, since whatever is available is measured.

Several factors must be kept in mind when measuring and interpreting these fossil growth rings, including both developmental changes in tree growth and problems associated with preservation.

i) Throughout the life of the tree the rate of cell formation, which is rapid for the first 30 years or so, decreases slowly with increasing age. This growth trend is eliminated from modern tree-ring analysis by the process of standardisation, which reduces all ring widths to indices with similar statistical properties (see 6.6 vii). This ontogenetic trend must therefore be considered when working with a sample of fossil wood in which the central part is absent and the location of the rings along the trunk radius is unknown. In most cases the central rings are highly compacted, crushed or replaced in the fossil wood.

ii) Local site factors such as exposure to wind, shading by large trees, soil conditions, etc. may affect individual trees and be reflected in ring sequences. The actual cause cannot be directly related to such anomalies in fossil growth ring sequences, although these effects must be kept in mind. Similarly, random events such as forest fires and storm damage, etc. may affect the production of growth rings and may be superimposed on the overall climatic response. These may be identifiable in fossil wood by comparison with modern examples, but the direct cause will probably remain unknown.

iii) Due to the nature of the preservation, many wood samples consist of only part of the circumference and radius of the trunk. Therefore it is not possible to establish whether the dimensions of the rings have been significantly altered by compaction. Sometimes this problem can be overcome by observing the shape of the cells under a microscope. Replication of ring widths from other trees also emphasises anomalous sections.

Ring width measurements may vary slightly depending upon the part of the tree from which they came (Fritts 1976). The samples of fossil wood collected from the Dirt Beds may represent roots, branches or trunks, but their precise origin is unknown.

iv) The sequence of measurable rings from fossil wood samples is often short, depending on the size of the wood specimen and poor cell preservation. In the present study ring-width series of 9 to 104 rings have been measured, 30-40 being the most frequent. Specimens with longer series (the large trunks) have most often been replaced by secondary silica, so that the rings are undetectable. Furthermore, large pieces of silicified wood proved difficult to cut and measure.

v) The conclusive identification of false or double rings in the Purbeck wood is difficult. Often they can be detected immediately by eye, as they are less dense and less clearly defined than 'true' latewood zones. More doubtful false rings must be checked with a microscope by studying cell dimensions throughout the false ring. The gradation of cell dimensions from the narrow cells of the false ring back to the large cells of the earlywood is much less abrupt than the change from the small, dense latewood cells to the large, earlywood cells at the boundary of a real ring. Sometimes the existence of a false ring is suggested if the ring width measurement is markedly smaller than average. Unfortunately, neither false rings nor partial or absent rings can be checked by cross-matching as they can be in modern tree-ring analyses.

vi) Wood can be compacted upon burial in sediment before being petrified by infiltrating mineral solutions. The rings may have been primarily obscured by microbiological activity or rotting which encouraged compaction. Compaction produces series of crush zones which often simulate growth rings and can only be identified as simply crushed cells under the microscope. Often the areas affected most by compaction in the Purbeck wood are the very first few earlywood cells, producing a crush zone along the ring boundary, making the location of the ring boundary for measurement uncertain. Often, however, the crush zones do not extend around the whole circumference of a ring and the measurement can sometimes be relocated to an uncrushed zone.

vii) Compaction of the fossil wood after petrifaction in the silicified Purbeck wood produces cracks and shear zones, which displace and obscure the rings. Cracks are common in a radial direction between files of cells and in tangential directions between cell walls. Infilling quartz forces the cells apart or removes cells completely. Tangential, clean cracks can be taken into account when measuring ring widths, but if cells are lost these measurements may be inaccurate. Again, this problem is often solved by moving to a different radius without cracks. Large zones of brecciated petrified wood recemented in veins of silica are common in the large wood specimens and destroy all possibility of ring measurement. The central portion of wood samples is, in most cases, brecciated after petrifaction. Cracks formed after petrifaction can be distinguished from those formed by the early splitting of the rotted, dried wood, since the latter are filled with impure, stained silica containing pollen grains and soil particles.

viii) The most common cause for the lack of recognisable rings in some of the Purbeck wood is secondary silicification. If the cells are individually silicified the rings are generally well preserved. In many cases a second stage of silicification has replaced whole groups of cells or even the whole tree. Cell walls were broken apart and pushed aside by the growing quartz crystals (see Chapter 4). The rings are then lost completely, either from small patches along a radius or from the whole tree.

An important feature of the basal Purbeck trees is that the forest is actually preserved _in situ_. Features such as the nature of the soil, the topography and the forest density, which are generally unknown for many deposits of fossil wood, can be used here when interpreting the Purbeck tree-rings. The importance of this for the study of the growth rings is:-

a) The forest is preserved _in situ_ within the Dirt Bed palaeosols in which they grew, and thus the climatic signals interpreted from their growth rings directly relate to this area. In addition, some idea of non-climatic environmental factors which may have influenced tree growth, such as topography, soil type and thickness, forest density and salinity, may be gained.

Most of the Purbeck wood samples come from the Great Dirt Bed palaeosol. In the geologic time-scale this represents a very short period, probably in the order of several 100,000 years. Although this is a long time compared to the life span of the trees, it appears that many of the trees died suddenly with the incoming saline water bringing the algae and sediment which accumulated around the tree trunks, and which later lithified to form the Soft Cap. It therefore seems reasonable to presume that the trees preserved in one area were contemporaneous and affected by precisely the same climatic conditions.

b) Despite the problems of obtaining long series of fossil tree-rings, samples from 20 trees may be expected to provide a coherent picture, since they were all probably influenced by the same type of climate and grew under similar conditions in close proximity to each other. Any sample deviating from the norm may thus be considered to represent adverse local conditions or a local event such as the death of an adjacent tree.

c) Additional information from the adjacent sediments, palaeosols, fauna and flora can be used to reinforce or contradict climatic interpretation of the fossil growth rings. Of particular value in this case is the knowledge of the anatomy and habit of the trees (see Chapter 5) for the understanding of its overall growth response to the climate, its natural requirements for growth and its interactions with the environment.

6.5 Measurement of Growth Rings in the Basal Purbeck Wood

Samples of basal Purbeck silicified wood used for growth ring analysis were collected from their original positions within the Great Dirt Bed, from quarry tips, from museums and private collections. Thus for only a few specimens an exact location in a dirt bed is known. However, most specimens were collected on the Isle of Portland where fossil wood is only found in the Great Dirt Bed; therefore it is assumed that all the fossil wood from Portland came originally from this horizon. Only one tree from the mainland, PB.1 from Fisherman's Ledge near Swanage, was useful for ring analysis; samples from Poxwell, Chalbury Camp, Upwey and the Fossil Forest proved to be of little value. Unfortunately the Fisherman's Ledge tree was found ex situ (by Dr. I. West), so its exact origin is unknown; it is assumed to have come from the Lower Dirt Bed since above this bed the sequence is dominated by replaced evaporitic limestones.

From each fossil sample a transverse section was cut. If possible a slab 2-3 cm thick was obtained. One transverse surface was ground smooth with carborundum powder and the other was labelled with its sample number and location.

With experience it became possible to tell immediately whether suitable growth ring data could be obtained from a sample. If the rings were visible with the naked eye or a hand lens, they were usually measurable with reasonable accuracy. Very little further preparation of the wood was necessary; some smoothed surfaces were covered with Canada Balsam and a glass coverslip, some with clove oil or simply a temporary layer of water under a coverslip. This tended to enhance the dark rings very slightly.

In several specimens the cell walls are indistinguishable from the cell contents because the organic matter has been completely lost and both cell walls and lumen are replaced by homogeneously coloured silica. Attempts to selectively stain the cell walls only with primarily HF etching, then staining with temporary stains and dyes such as Safranin O or ink, or with permanent strong silica stains such as Malachite green or Bismarck Brown Y (Bartholomew _et al_. 1970) were mainly unsuccessful. Etching the wood with HF was useful in only two cases where the wood had a dark stain of bituminous matter which was successfully lightened to reveal good growth rings. In other cases the acid etched both cell walls and lumen equally, rendering the specimen useless.

Altogether over 100 samples of silicified Purbeck wood were sectioned for the growth ring data but only 20 samples yielded measurable ring sequences. Ring data was also obtained from samples of modern wood (see Table 6.02) for comparison with the Purbeck data.

The growth rings were measured with a Zeiss binocular microscope which was specially fitted with Vernier measurers and a large, robust travelling stage that was movable in two perpendicular horizontal directions and could hold large, heavy pieces of silicified wood for long radial measurements.

For each ring sequence measurements began as near to the centre as possible and worked towards the outer edge along a radius. If the centre was absent, the ring of the smallest radius was chosen as the starting point. Each ring was measured (in millimetres) from the beginning of the earlywood (the very edge of the previous latewood) to the end of the latewood. The clearest radial trace for measurement was always chosen although, due to crush zones, secondary silicification etc, it was often necessary to relocate a conspicuous ring along another radius to continue the series.

Apart from the widths of the true growth rings, the locations of false rings were also recorded. In a few samples where individual cell walls were particularly clear the radial widths of files of cells within single rings were also measured in order to study the growth patterns within a single growth increment.

6.6 Statistical Techniques

The general characteristics of a ring-width time series can be described by a number of standard statistical parameters. Although some have been developed particularly for analysis of modern tree-rings (explained in Matalas 1962 and Fritts 1976), they can be applied to fossil growth ring analysis. The statistics used in the analysis of the Purbeck wood include:-

i) The absolute widths of the rings provide an indication of growing conditions. The variance or standard deviation may be used as simple measures of variation.

ii) One of the most important statistics is the relative difference in width from one ring to the next, referred to as the mean sensitivity (Douglass 1928). This is calculated by using the following formula:

$$\text{mean sensitivity (M.S.)} = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(X_{t+1} - X_t)}{X_{t+1} + X_t} \right|$$

where X is the ring width, t is the year number of the ring and n is the number of rings in the sequence. For every possible pair of consecutive rings the difference in ring width is divided by the average of those ring widths. The mean of these values is then calculated. This represents the mean change from each measured yearly ring value to the next. The individual components of mean sensitivity (i.e. AS = $\left| \frac{2(X_{t+1} - X_t)}{X_{t+1} + X_t} \right|$) have been termed "annual sensitivity" by Creber (1977) and will be referred to here as AS. The values of mean sensitivity may theoretically range from 0, where there is no difference, to 2 where zero values alternate with non-zero values throughout the sequence. Most values fall between 0 and 0•6. Those below 0•3 (an arbitrary but convenient value) are termed "compacent" whilst those above are "sensitive" (Creber 1977). Mean sensitivity is a measure of high frequency variation such as might be produced by short term climatic cycles.

iii) A more detailed picture of patterns of variation may be obtained from plotting the data obtained from individual pairs of rings (A.S) as histograms (Creber 1977). This technique may reveal that trees with the same mean sensitivities have different patterns of annual sensitivities.

iv) Another method suggested by Creber (1977) is a graph of the cumulative sum of the ring widths for each tree. This illustrates how the radius of the tree increases from year to year and may reveal a change in circumstance, such as the effect of increased competition from a nearby tree which modifies the normal pattern of growth.

v) Low frequency cycles in a ring width series can be identified by the process of autocorrelation (Fritts 1976), in which correlation coefficients are calculated between increments of a single series which are lagged in time. For example, the ring width for year t can be correlated with the ring width of the following year (t+1) or a ring of L years further on (t+L).

The value of the autocorrelation coefficient can range from an upper value of +1 indicating direct agreement, to -1 perfect but inverse agreement. If the items in a series are completely random with respect to their position within the ring series, the coefficients will be very small and vary in a random fashion about zero. In contrast, high autocorrelation coefficients between ring widths at certain lags indicate that the ring widths are of comparable size throughout the series and are evidence for a cyclical pattern of growth.

A programme to calculate the autocorrelation coefficients for each Purbeck ring width series was written by Mr. T. Clayton (included in Appendix).

vi) The cross-matching of ring sequences is of little value to fossil growth ring studies except to prove that matching tree samples were affected by the same climate at the same time. Cross-dating programmes require accurately measured sequences in which there is no doubt about false or partial rings (Baillie and Pilcher 1973) and are thus not suitable for the Purbeck trees. Simple visual comparison was tried but with little success, mainly because the Purbeck ring sequences were so short.

vii) In addition to variation with environmental conditions, tree-rings also reflect the inherent pattern of growth of the tree. Two factors are involved: one is the changing productivity of the tree as it grows larger, and the other is the fact that new wood is laid down over a progressively increasing radius. The result is that rings tend to become narrower, at first rapidly and then more slowly (e.g. Elm, Fig. 6.02). To enhance the climatic effects on tree growth, the ontogenetic variation can be estimated and removed from the measurements. This process is known as standardisation and is a critical initial procedure in modern tree-ring analysis. The growth of the tree is estimated by fitting a trend line, usually an exponential curve, to the "raw" ring data. The measured ring widths are then converted to ring-width indices by dividing each width per year by the expected growth for that year (obtained from the fitted curve). These standardised ring indices all now have similar statistical properties, since they have no linear trend, and the values have been adjusted so that the mean is unity. The greater variability in the ring widths of the young, fast-growing portions of the trees are then comparable to the lesser variability of the ring widths in the older, slower-growing parts (Fritts 1976).

The effects of the standardisation process upon the Purbeck tree-ring data was investigated on a few selected series. Exponential curves were fitted to the trend and the ring indices calculated. However, there was very little difference between the relative values of the ring widths and indices, probably because the lengths of the ring series are too short to reflect growth trends. In

TABLE 6.01

Growth Ring Data for 20 Basal Purbeck Trees

Sample No.	Location	No.of Rings	Mean Ring Width (mm)	Standard Deviation	Mean Sensitivity
48	Inmosthay Quarry	26	1·18	0·74	0·543
47	Inmosthay Quarry	24	1·32	0·74	0·588
52	Inmosthay Quarry	31	1·15	0·48	0·436
46	Inmosthay Quarry	21	1·08	0·57	0·503
45	Blacknor	12	2·28	0·91	0·437
24	Portland	54	0·92	0·59	0·656
27	Freshwater Quarry	17	2·01	1·23	0·540
22	Blacknor	10	1·46	0·17	0·424
11	Blacknor	31	1·57	0·19	0·290
75	Inmosthay Quarry	23	1·03	0·65	0·788
49	Inmosthay Quarry	9	1·32	0·58	0·340
58	Wide Road Quarry	34	0·85	0·56	0·561
61	Admiralty Quarry	50	0·89	0·59	0·664
57	Easton Quarry	37	0·85	0·41	0·453
60	Admiralty	37	1·39	0·73	0·674
1	Fisherman's Ledge	104	0·56	0·53	0·642
56	Wide Road Quarry	16	0·91	0·32	0·419
94	Kingbarrow Quarry	15	0·52	0·18	0·361
97	Southwell	10	0·59	0·36	0·769
96	Portland	14	0·75	0·40	0·447
	Mean		1·13	0·46	0·527
	Standard deviation		0·46	-	0·14

N.B. 1. All trees come from Portland except 1, which comes from the cliffs near Swanage.

2. Trees from "Portland" are museum specimens without specific locations.

TABLE 6.02

Tree-ring Characteristics of Some Modern Trees used for Comparison with the Purbeck Tree-Ring Data

Sample	Location	Number of Rings	Mean Ring Width (mm)	Mean Sensitivity
Pinus halepensis	North-east Spain Cap de Creuse 42°N Open pine forest on coastal lowland	46	1·86	0·423
Juniperus oxycedrus	Morocco (Exact location unknown)	35	1·23	0·380
Ulmus procera	Hampshire, England. 51°N Arable lowland	56	1·33	0·231
Pinus sylvestris	England, 51°N New Forest	50	3·83	0·170
*Actinostrobus pyramidalis**	West Australia Garden Island and Perth. 32°S.	100	0·33	0·429

* Data supplied by Dr. W.A. Loneragan and Mr. M. Williams, University of Western Australia.

addition, most of the ring series do not involve the rings formed primarily around the centre, the rings which show most increase in growth and provide the least reliable climatic information (Fritts 1976). In fact, for the fossil wood standardised indices are probably most useful for the calculation of autocorrelation, when low frequency variation due to trend is removed. The most important statistic with regard to the fossil wood, that is the mean sensitivity, is not affected by the standardisation process because all growth trends are eradicated in its calculation anyway. After some experimentation it was decided that the standardisation process was unnecessary and growth ring measurements from the Purbeck trees are therefore given as true ring widths, not indices.

6 .7 Data

6.7i Ring widths and cumulative growth increments

The average ring width for all 20 Purbeck trees was 1·13 mm. It is interesting to note from the data in Table 2.01 that the average ring width for all samples with over 20 rings is 1·07 mm, and for samples of over 30 rings 0.91 mm, whereas the mean for samples of less than 20 rings is as high as 1·23 mm. Similarly there is variation in the mean sensitivity associated with the size of the sample (0·567 for samples of over 20 rings; 0·467 for samples with less than 20 rings). Obviously the larger samples yield more accurate statistics; this suggests that for the Purbeck trees the actual mean ring width is probably lower than 1·13 mm and the mean sensitivity even higher than 0·527. The histogram (Fig. 6.01a) shows that the most common mean ring widths were 0·5–0·6 mm, 0·8–0·9 mm and 1·3–1·4 mm equally. Individual mean values are recorded in Table 6.01. The minimum and maximum mean ring widths recorded were 0·52 and 2·28 mm respectively, though the absolute minimum value of all ring widths was 0·05 mm (PB.1) and the maximum 4·44 mm (PB.27).

Plots of the ring width series for the longer sequences measured in Purbeck trees are shown in Figure 6.02. It is apparent that the growth increments for an individual tree are extremely variable, not only through the series in general but also from one year to the next. None of the ring width plots shows an obvious ontogenetic trend, which might be expected in a complete sequence from the centre (cf. Elm tree),

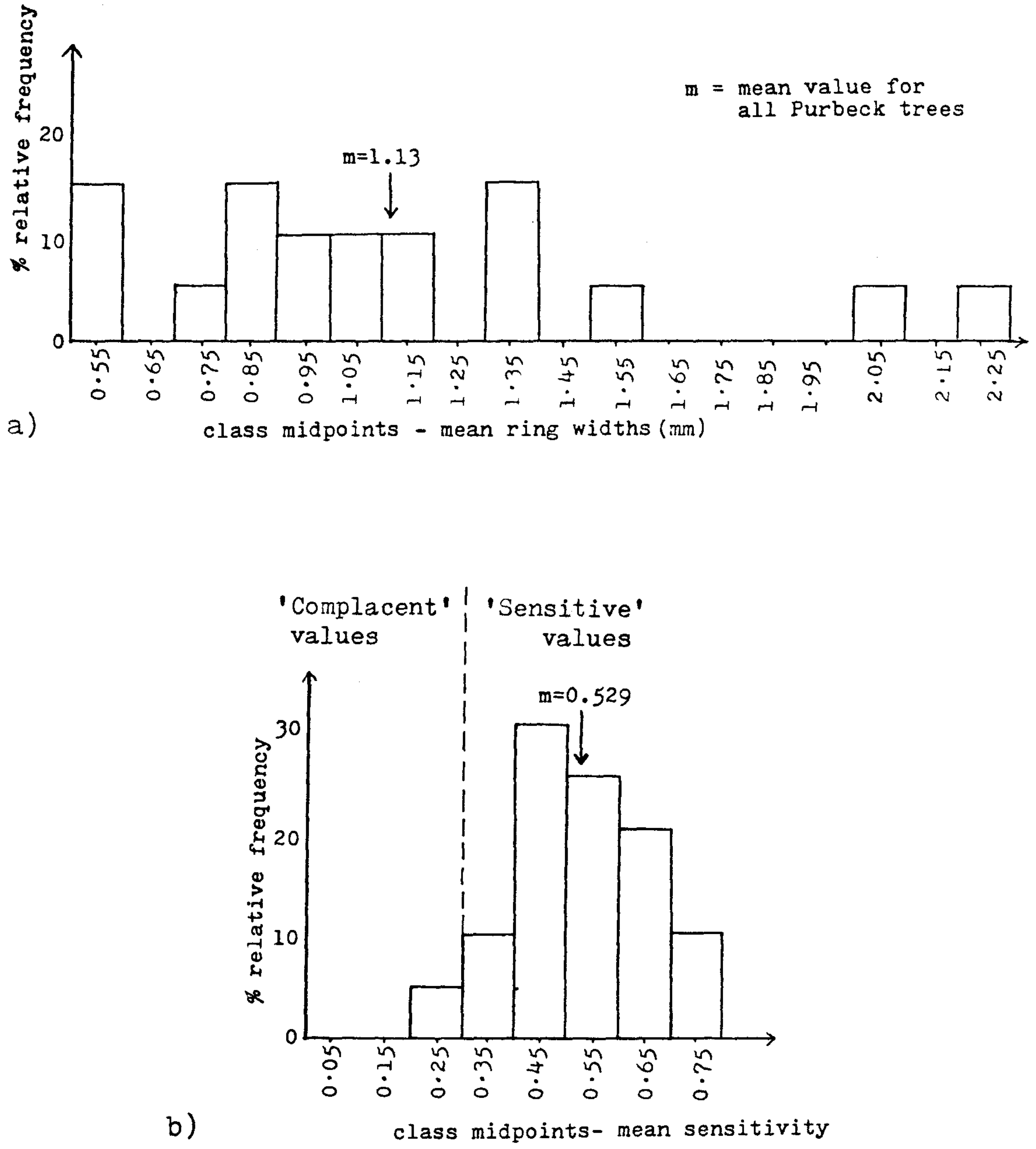

Fig. 6.01 Distribution of a) mean ring width values
b) mean sensitivity values
for 20 basal Purbeck fossil trees.

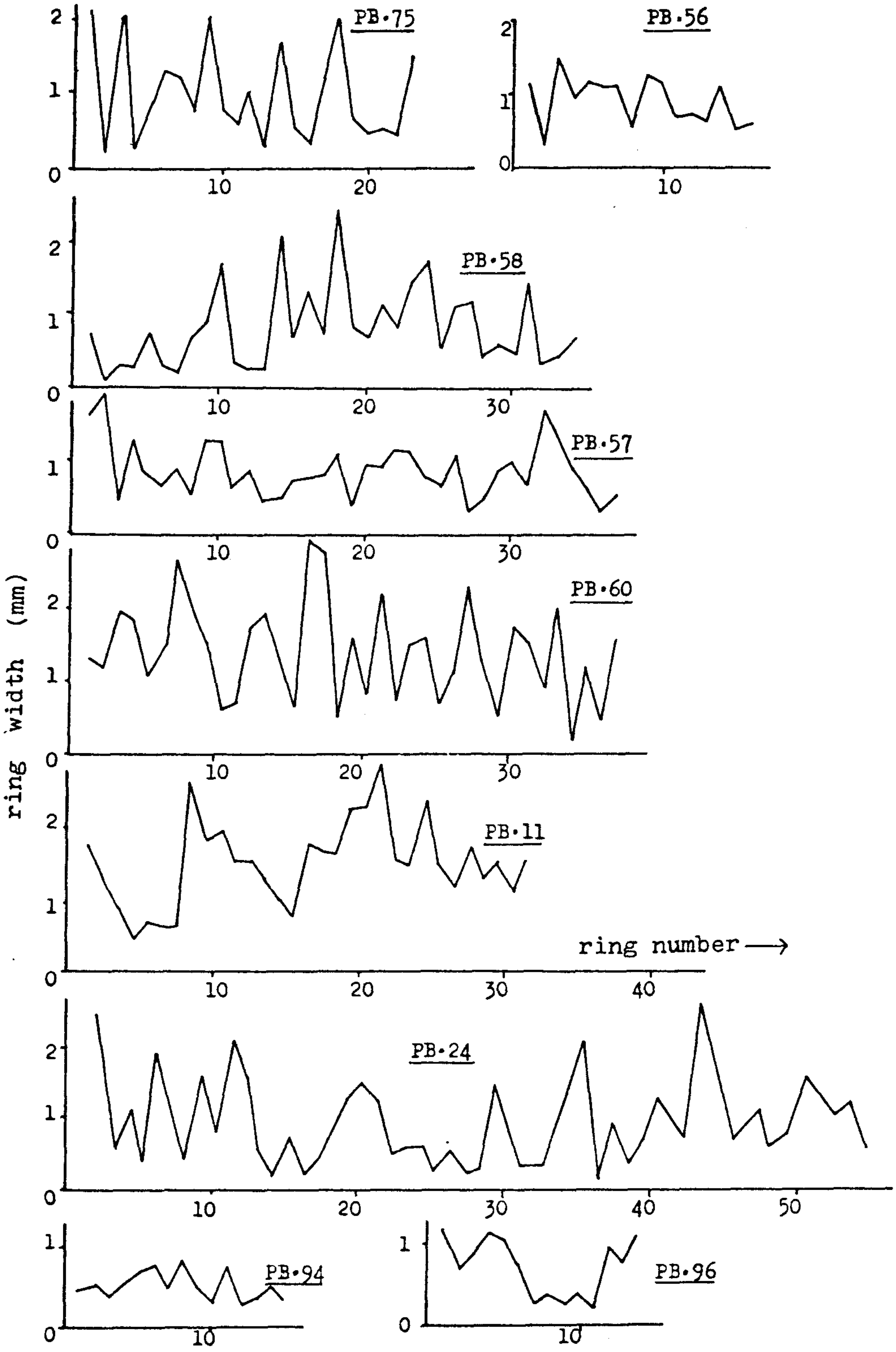

Fig.6.02. Ring width series for 20 basal Purbeck fossil trees and some modern trees.

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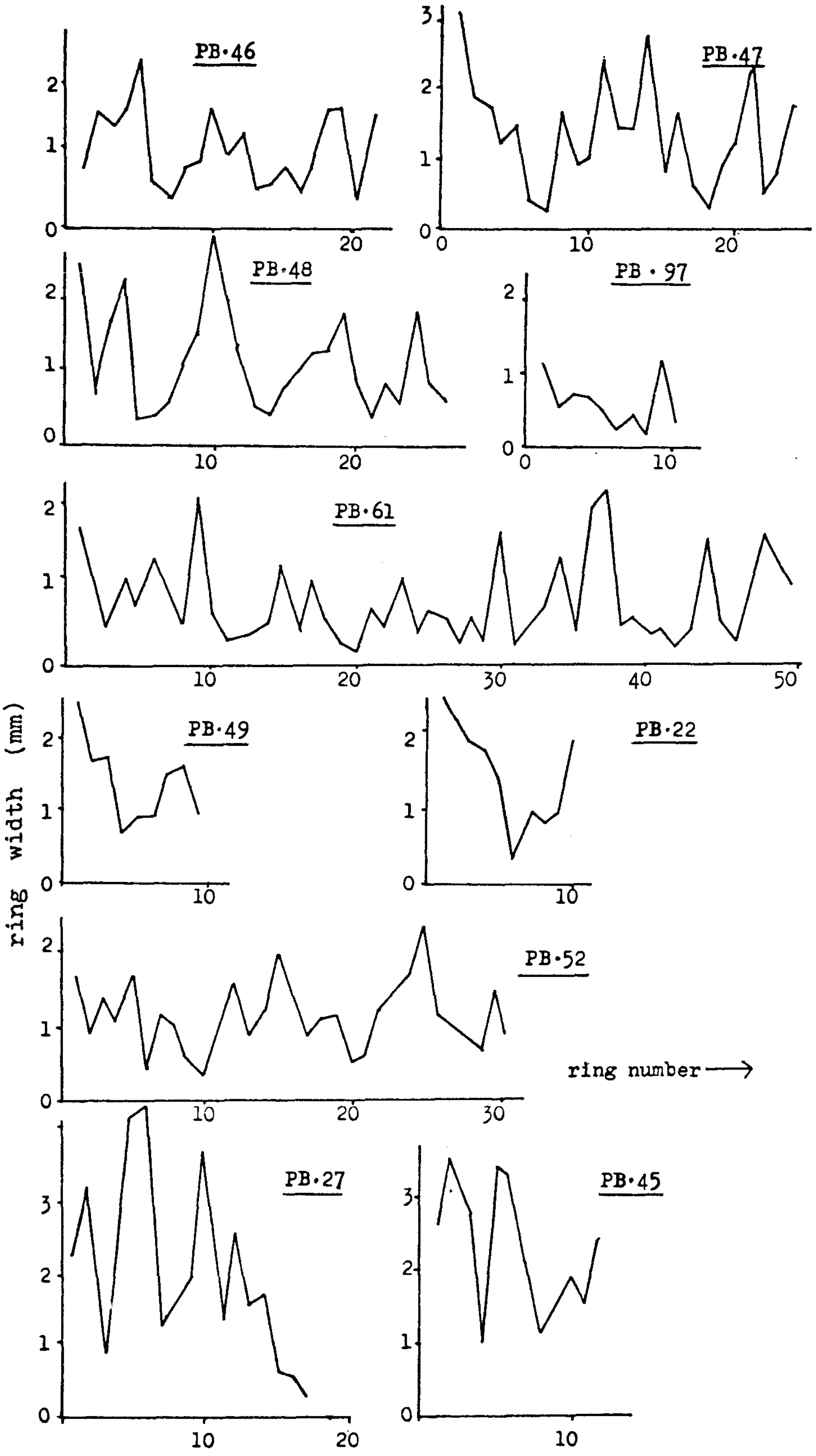

Fig. 6.02. Ring width series for 20 basal Purbeck fossil trees and some modern trees.

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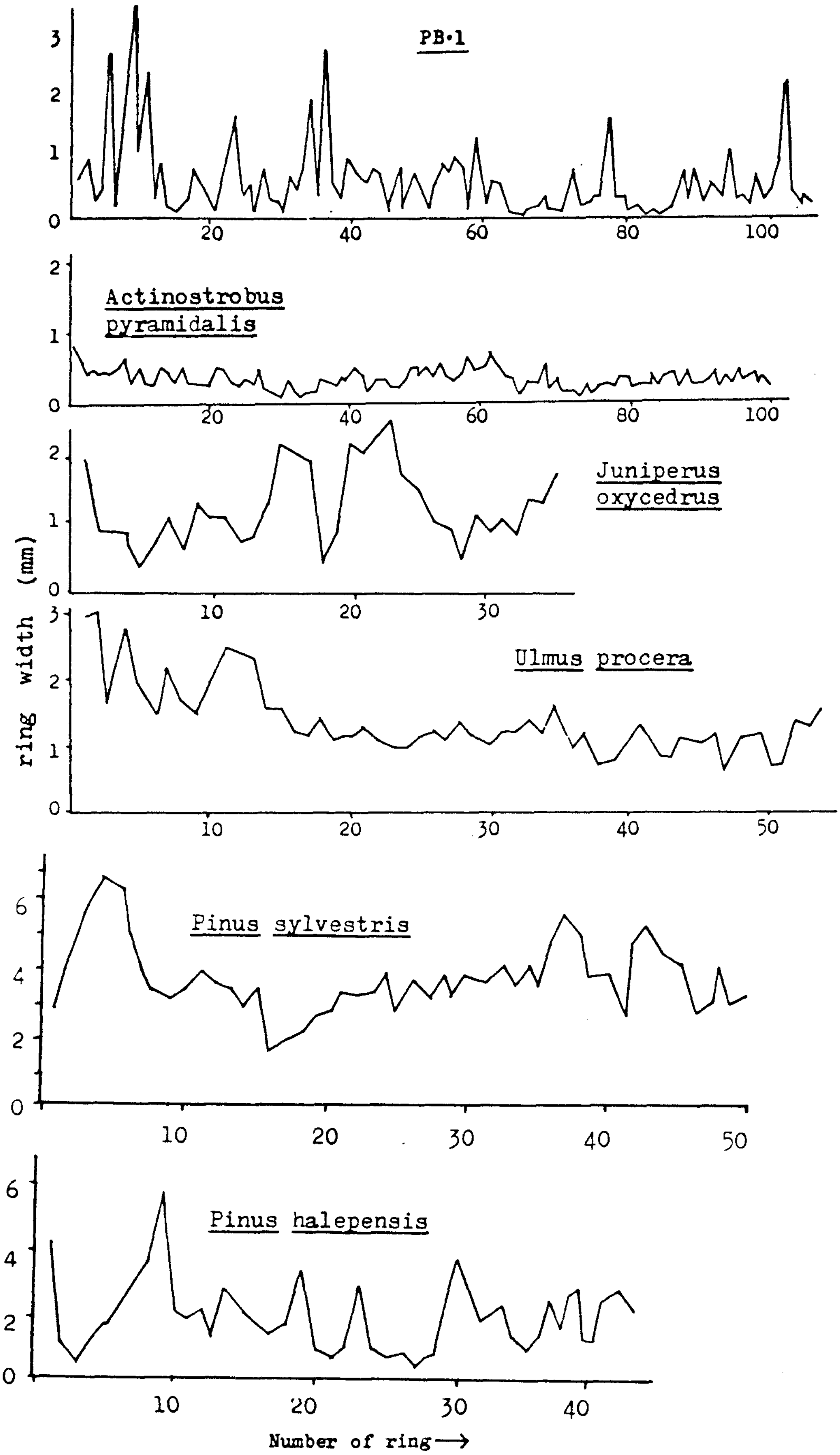

Fig. 6.02 Ring width series for 20 basal Purbeck fossil trees and some modern trees.

nor is there a particularly clear decreasing trend in ring widths throughout a series, probably because most of the ring sequences are quite short.

A graph of the cumulative sum of the ring widths was plotted for each tree (selected examples in Fig.6.03). A curve with a steady gradient (cf. Actinostrobus) would indicate a gradual increase in radius from year to year without any abrupt changes in growth rate. A useful comparison is the plot of the Elm (Fig.6.03), which shows a smooth curve reflecting relatively uniform growth. In contrast, the Purbeck trees had very erratic growth rates shown by the many changes of gradient, well shown by PB.48, 47, 61 and 52. Several of these fluctuations appear to last from 5 to 7 years and others from 2 to over 15 years. These cycles are elucidated by autocorrelation analysis.

6.7ii Mean sensitivity and annual sensitivities (A.S)

Values of mean sensitivity for the Purbeck trees ranged from 0·290 to 0·769, with an average of 0·527. 19 out of the 20 trees sampled have a mean sensitivity greater than 0·3, that is, most trees were "sensitive" to climatic variation. The most common mean sensitivity class was 0·4 - 0·5, followed by 0·5 - 0·6 (Fig.6.1b).

The modern trees from areas of Mediterranean climate (Pinus halepensis, Actinostrobus pyramidalis and Juniperus oxycedrus) have mean sensitivities comparable to those from the Purbeck (Table 6.02). In contrast, Ulmus procera and Pinus sylvestris from England show no significant growth variation but a complacent response with mean sensitivities of 0·231 and 0·170 respectively.

The individual A.S. values of some of the specimens are arranged into histograms (Fig. 6.05). Individual annual sensitivities range from 0 to 1·8, reflecting no variation to extreme variation in yearly growth. In most of the Purbeck wood there is a fairly even distribution of A.S. values throughout all the sensitivity classes from 0 to about 1·8. The mean sensitivity therefore tends to represent the real average of this spread and is not influenced by a dominant class. The large range in A.S. values (i.e. a wide distribution along the X-axis) illustrates that the pattern of variation from year to year was itself variable. There did not appear to be a recurring condition causing a constant variation from year to year. The histogram for the total data from all

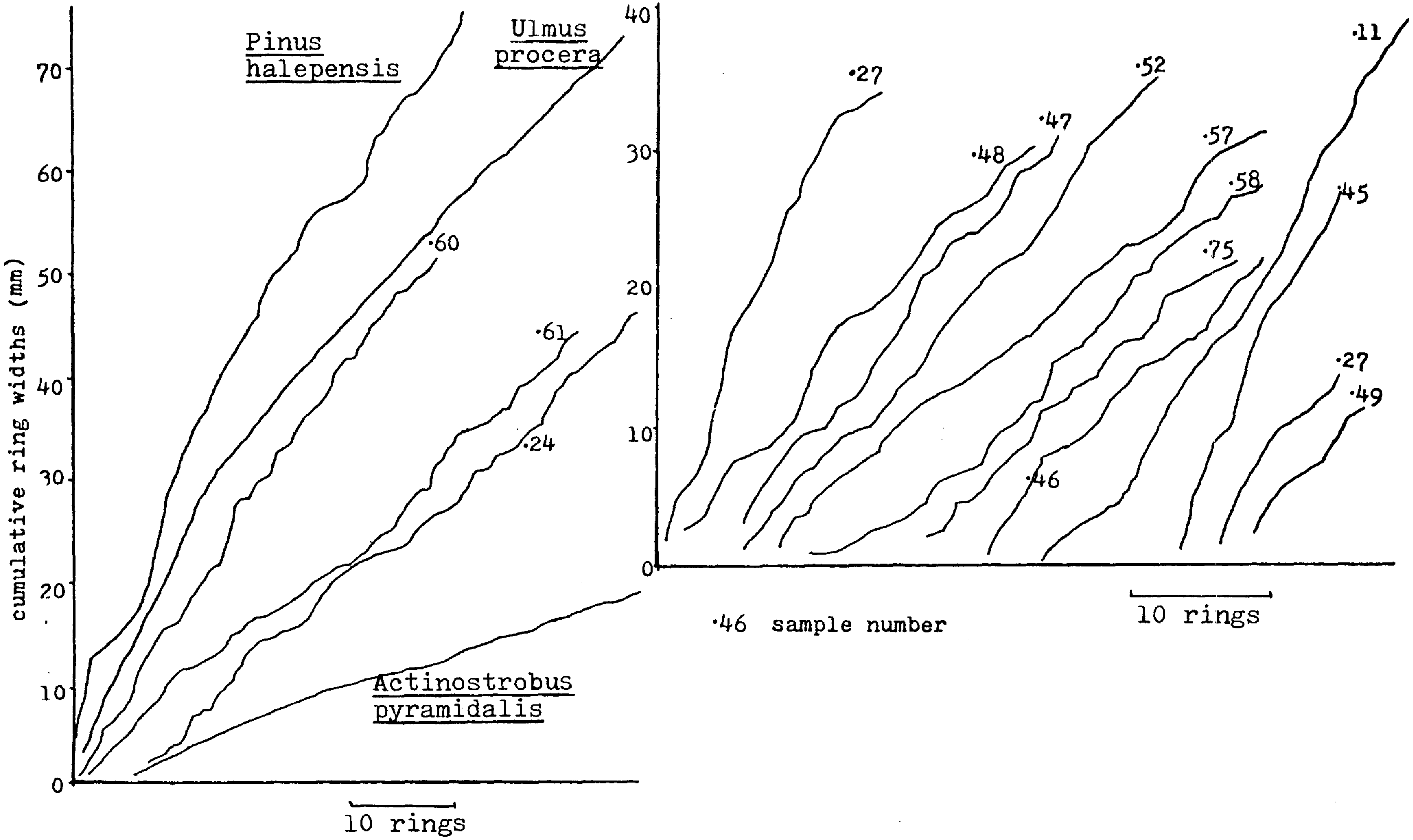

Fig. 6.03 Graphs of the cumulative growth rates of the basal Purbeck fossil trees and some modern trees. The position along the X-axis has no significance since the ring number (from the centre) is unknown in most fossil trees.

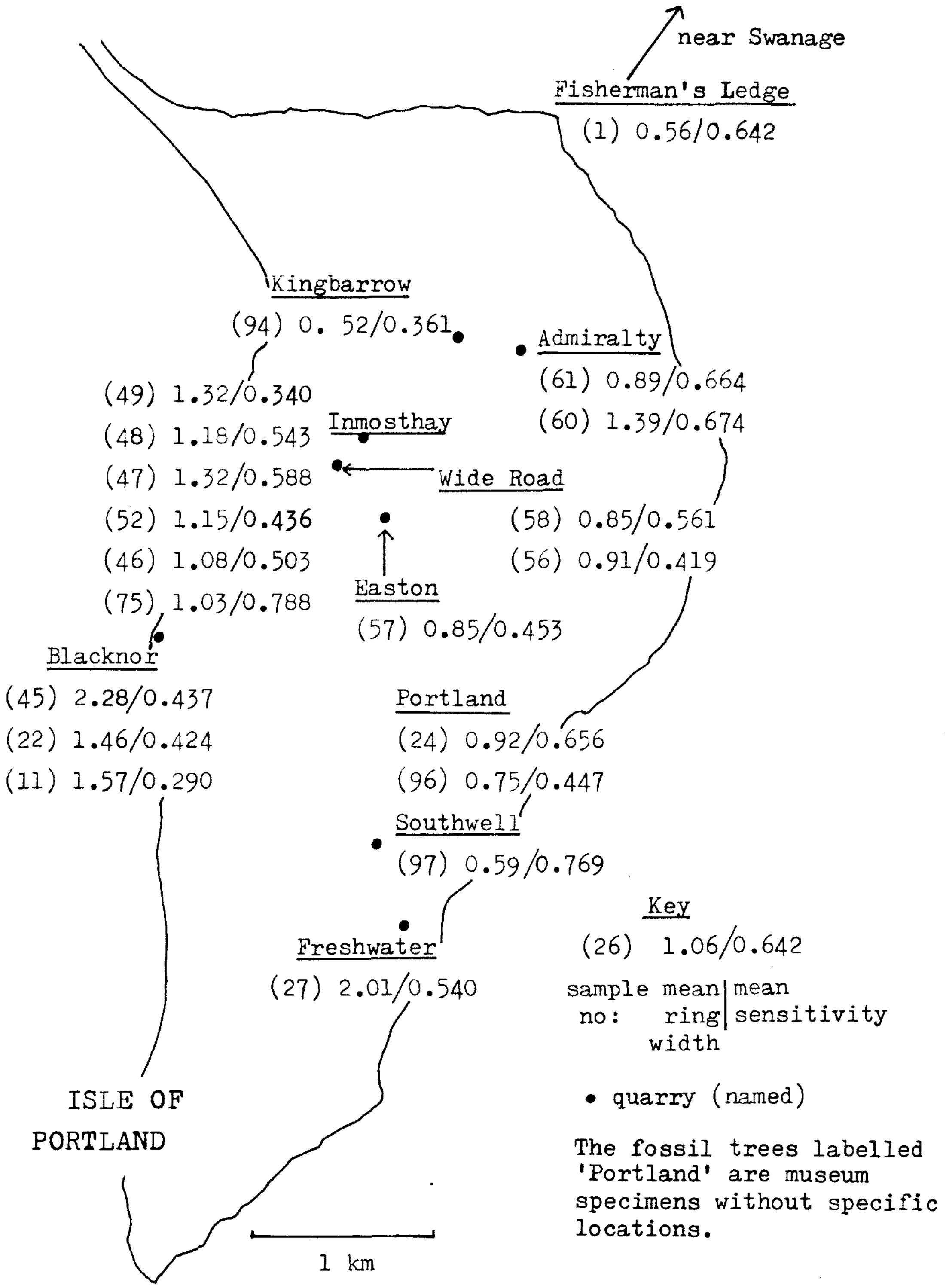

Fig. 6.04 Map showing the location and a summary of growth ring data of the basal Purbeck trees on the Isle of Portland (plus the ring data from the fossil tree from Fisherman's Ledge)

20 Purbeck trees (Fig. 6.06) shows an overall dominance of "complacent" values, but a much wider spread of "sensitive" values of A.S.

An interesting relationship is notable between the percentage of "complacent" ($<$ 0·3) and "sensitive" ($>$ 0·3) values of A.S. of each tree (Table 6.03). One would assume that a compacent tree with a mean sensitivity of less than 0·3 would always have a greater number of complacent, rather than sensitive values of A.S., and likewise with "sensitive" trees. This is not always the case. For example, one Purbeck tree (PB.22) with a mean sensitivity of 0·424 had 66% of its A.S. values less than 0·3. However, there are also some high A.S. values thus raising the mean value. This suggests that its growth was relatively uniform for much of the time but occasional adverse growing conditions caused marked fluctuations in growth. There is a clear correlation between the mean sensitivity and the proportion of individual sensitive A.S. values but even so, the scatter is rather wide (Fig. 6 .07). Computing the data from Table 6.03 into Figure 6.07, it is estimated that with an overall mean sensitivity of 0·527 for the Purbeck trees, an average of 63·9% of the individual A.S. values are "sensitive"; there was considerable variation in growth from one year to the next through the life of the trees.

It is reasonable to expect a negative relationship between mean ring width and sensitivity, since trees growing under marginal conditions would show a low growth rate and extreme sensitivity to climate. However, Figure 6.08 shows that the relationship, although negative, is not significant.

6.7iii Autocorrelation

The coefficients of autocorrelation γ r and the lag L for some Purbeck trees are plotted on correlograms in Figure 6.09. The intervals at which the ring widths of a series are generally similar are represented by high correlation coefficients or peaks on the graphs, and illustrate the nature of the non-randomness in each ring width series. Part of the correlogram pattern is a tendency for the peaks to increase in height as the lags become larger and fewer rings are correlated. The autocorrelation coefficients then become progressively less reliable. For accuracy only the first 20% of the total observations should be considered (Fritts 1976), but obviously for the limited fossil

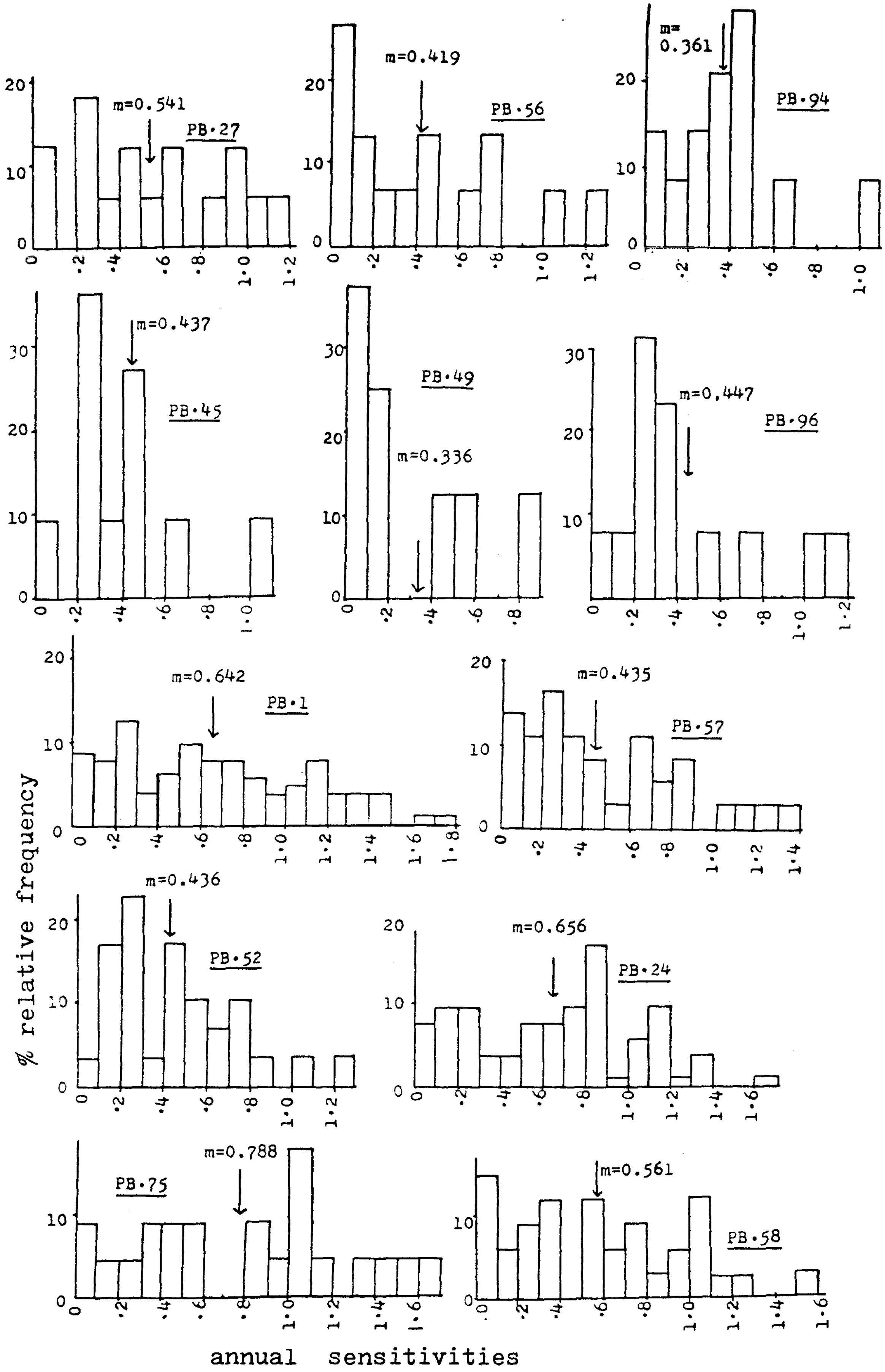

Fig.6.05 The distribution of annual sensitivity (A.S)values for each basal Purbeck tree and for specimens of modern Pinus halepensis,Juniperus oxycedrus, Ulmus procera,Pinus sylvestris.

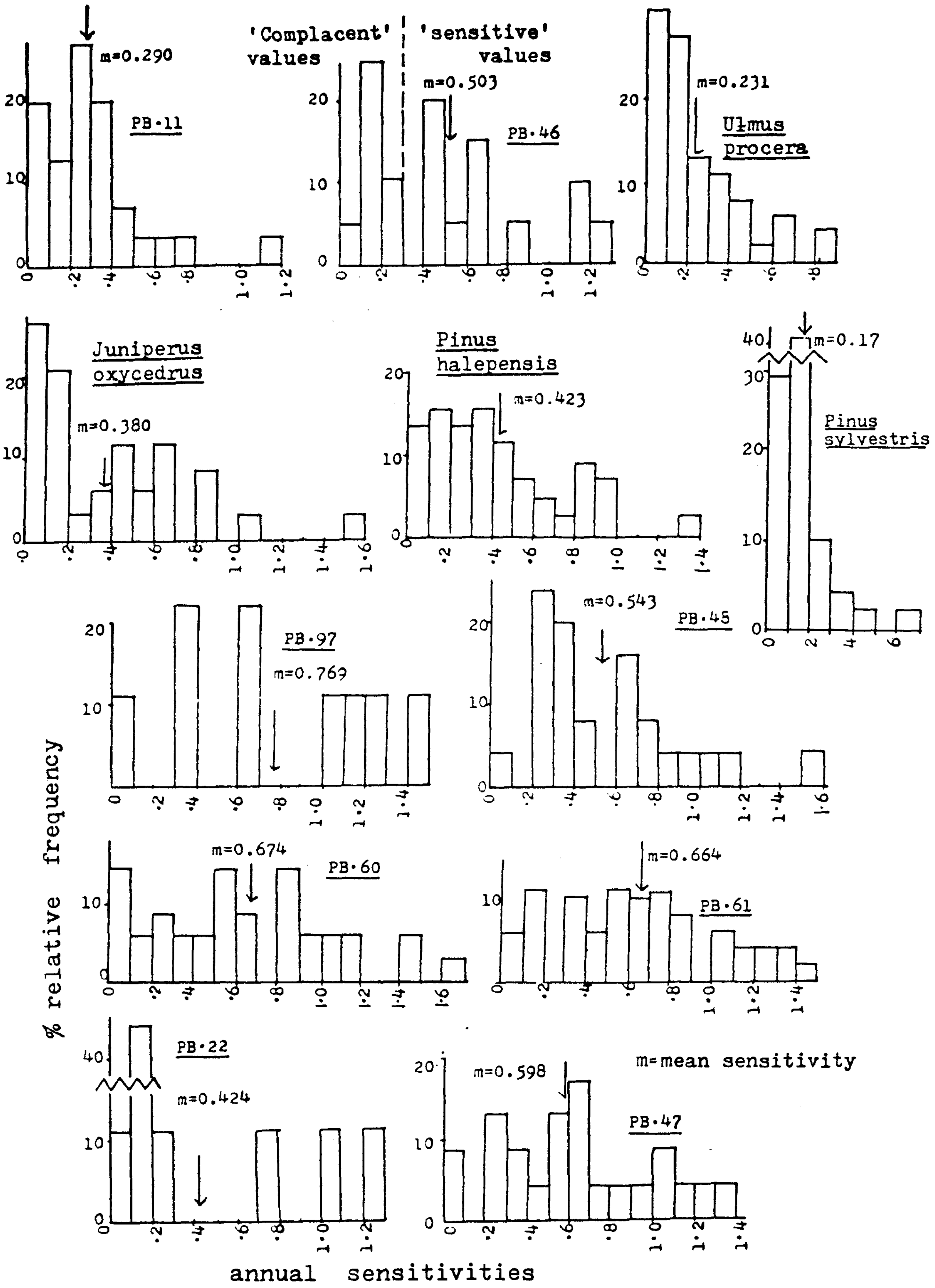

Fig.6.05 (cont'd).

The first column(0-0.1) represents all consecutive pairs of years in which there was minimum variation in ring width;the columns to the right represent increasing variations between consecutive pairs of years.

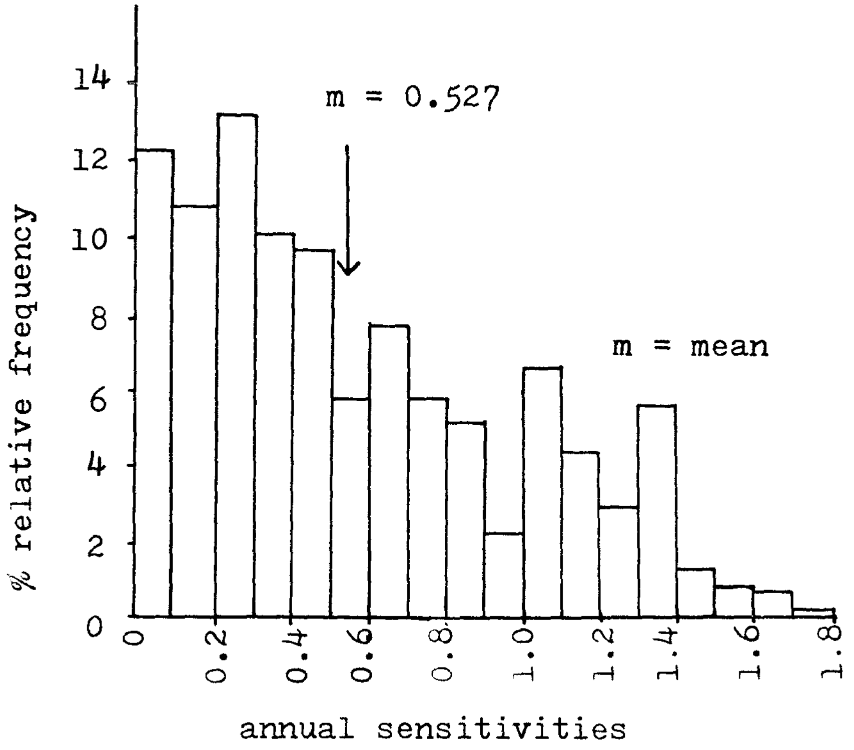

Fig. 6.06 Distribution of annual sensitivities(A.S) for all 20 basal Purbeck fossil trees.

TABLE 6.03

The percentage of Complacent (< 0·3) and Sensitive (> 0·3) Annual Sensitivities for Each Purbeck and Modern Tree Sample

Sample Number	% Complacent	% Sensitive	Mean Sensitivity
22	66·0	33·0	0·424
49	62·5	37·5	0·336
11	60·0	40·0	0·290
56	46·6	53·4	0·419
96	46·2	53·8	0·447
45	45·5	54·5	0·437
52	43·5	56·5	0·436
57	40·5	59·5	0·453
46	40·0	60·0	0·503
94	35·7	64·3	0·361
58	30·0	70·0	0·561
27	29·5	70·5	0·541
1	28·6	71·4	0·642
48	28·0	72·0	0·543
60	27·8	72·2	0·674
24	26·3	73·7	0·656
47	21·6	78·4	0·598
61	18·0	82·0	0·664
75	18·0	82·0	0·788
97	11·0	89·0	0·769

N.B. Data listed in order of decreasing "% complacent".

Modern trees:

Juniperus oxycedrus	51·0	49·0	0·380
Pinus halepensis	42·0	58·0	0·423
Ulmus procera	71·8	28·7	0·231

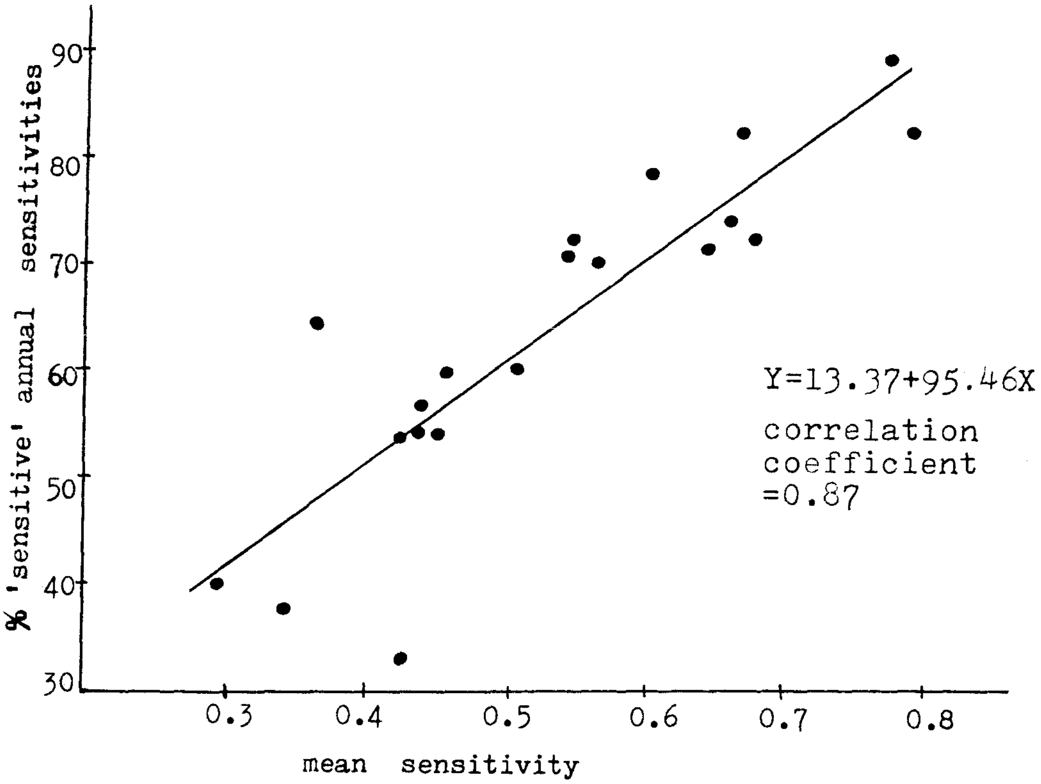

Fig. 6.07 Plot of mean sensitivity v. %'sensitive' annual sensitivities of 20 basal Purbeck trees.

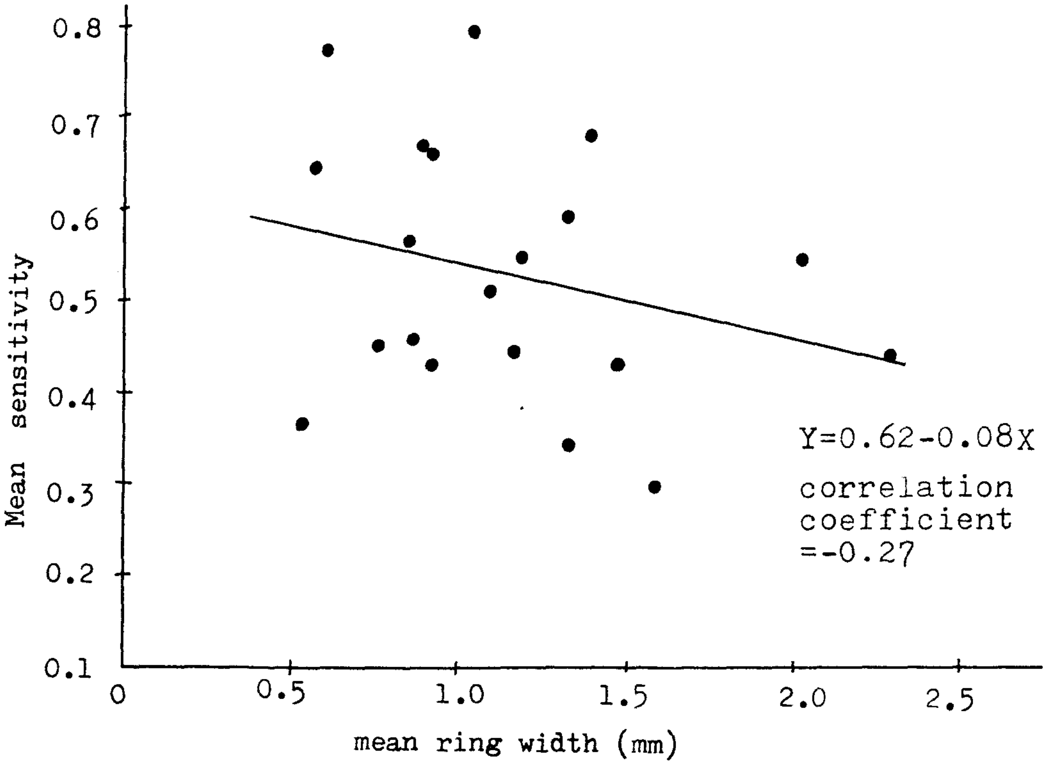

Fig. 6.08 Plot of mean ring width v. mean sensitivity of the growth rings of 20 basal Purbeck trees.

data this is too restrictive. To test the significance of the peaks the 5% and 10% significance levels have been plotted on each graph.

The correlograms of the Purbeck ring series show extremely variable autocorrelation coefficients with both positive and negative values. A value of +1 is always found at L=0 where the series is correlated with itself. The γr value then oscillates from values of 0 up to +0·8. The Elm and English Pine from a more equable climate show a markedly different trend with a clear sequence of decreasing values of γr with increasing lag. This trend is most likely due to low frequency variance related to the overall growth trend (see Fritts 1976, p.262, Fig.6.4), which could be removed by the standardising process. Interestingly the modern Pinus halepensis and Juniperus oxycedrus do not show this trend but have correlograms similar to those of the Purbeck trees (Fig.6.09b).

Only low-frequency cycles are detected here because the series are so short. Ring sequences with less than 20 rings are the most inaccurate and are therefore of little value. There are many well-defined peaks but most of these lie outside the 5 or 10% significance levels. Furthermore, the periodicity of many of these peaks is restricted to single samples. For example, PB.58 shows a 4-year cycle; PB.60 shows a 10-year cycle; PB.75 possibly a 9-year cycle; PB.46 a 7-year cycle; PB.48 an 8-year cycle and PB.61 a 6-year cycle. There are no particularly outstanding peaks which show a significant periodicity in all the Purbeck trees.

The values of the lag L which have autocorrelation coefficients significant at the 10% level are shown in Table 6.04 and as an histogram in Figure 6.10. Cycles which appear most often are 11-years (with its corresponding 22- and 33-year cycle) in PB.11, 52, 47, 48; a 7-year cycle (PB.46, 48, 75); a short 4-year cycle (PB.58, 27, 45) and a corresponding 4-year cycle which is a half-cycle of the 8-9 year cycle (PB.46, 57, 48) and finally a 26-year cycle (PB.1, 57, 58).

6.7iv Variation of cell size throughout the rings

The diameters of individual cells in a growth ring were measured along selected radial files. The radial dimension between the middle lamellae was recorded. In the silicified wood the cell walls were often

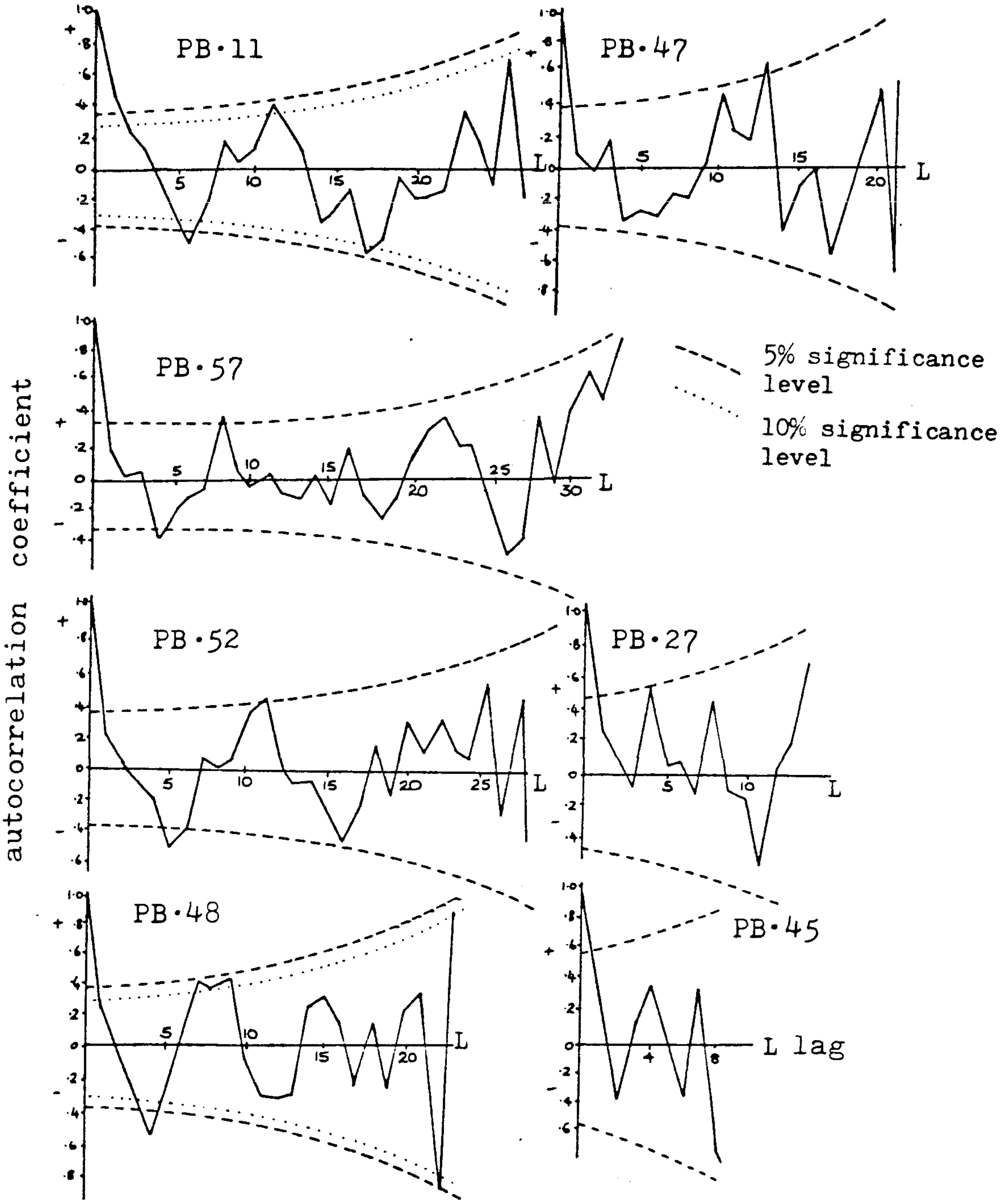

Fig. 6.09 Autocorrelations for the ring width series of the basal Purbeck fossil trees.

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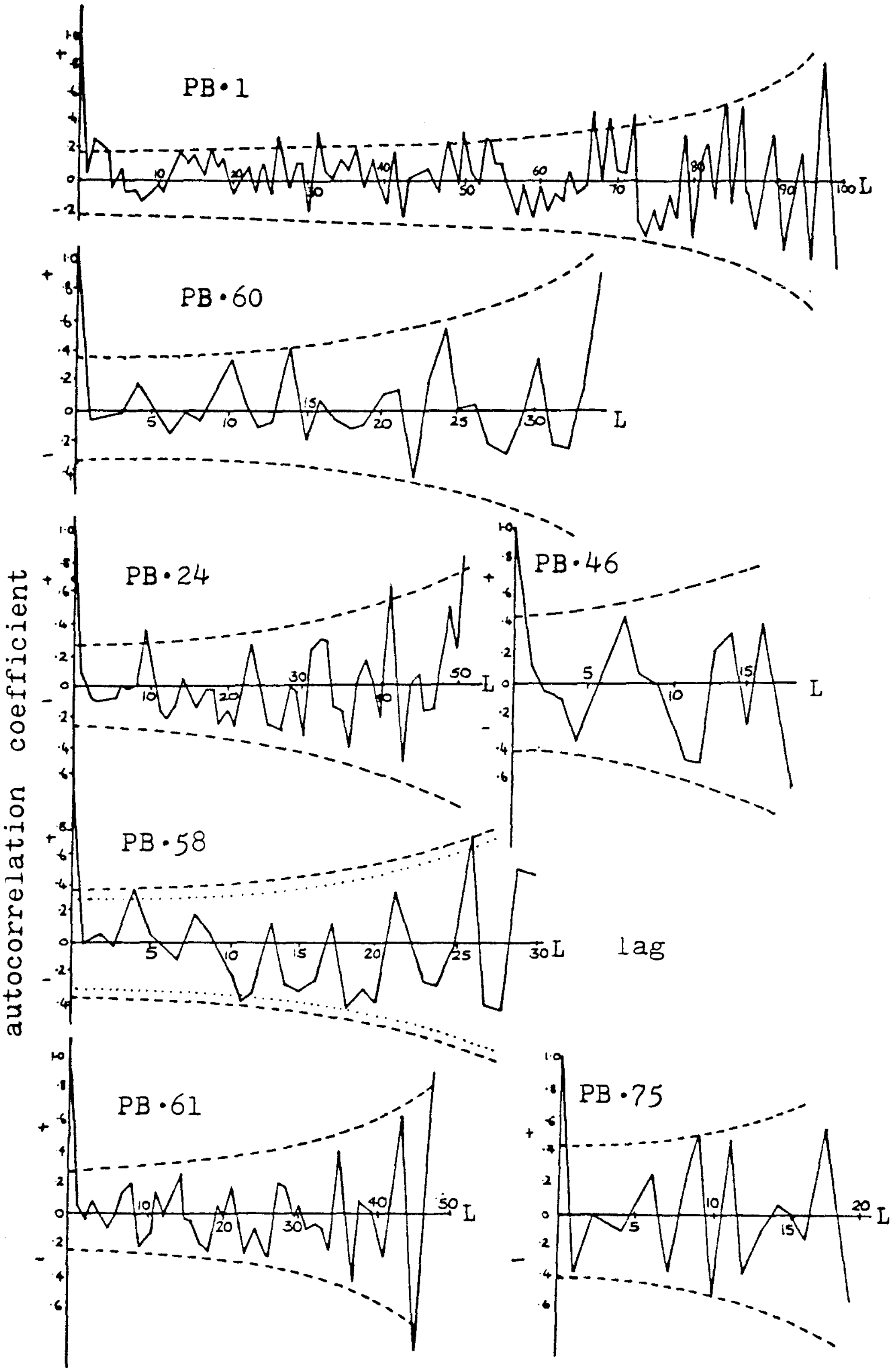

Fig. 6.09 Autocorrelations for the ring width series of the basal Purbeck fossil trees.

TABLE 6.04

Values of Lag L which have Autocorrelation Coefficients Significant at the 10% Level

Purbeck Tree Number	Lag L
1	+2, +3, +13, +17, +26, +31, +48, +50, +53, +67, +69, +72, +84, -74
22	-5
96	-6
49	-3
24	+9, +41, +51
75	+9, +11, -1, -10, -7
46	-4, +7
48	-4, +9, +7, +8, -22
11	+11, -6, -17
60	+10, +14, +24, -22
57	+8, +33, +31, -4, -26
58	+4, +26, -11, -18
27	+4
52	+11, -5, -16
47	+10, +13
56	-11

N.B. The sign before each value of L indicates the +ve or -ve value of the autocorrelation coefficient.

indistinguishable, having been crushed or replaced, and so accurate measurements could only be taken in a limited number of cases.

The results for selected radial files are graphically recorded in Figure 6.12.

In some modern trees there is a more or less gradual decline in cell size from the first, large, thin-walled earlywood cells formed at the beginning of the growing season, to the small, dense latewood cells. The size of the cells diminish and the walls thicken as physiological conditions change within the tree towards the end of the growing season.

The Purbeck trees do not show a simple, continuous diminution in cell size. A decreasing trend is apparent in some cases, but superimposed on this is a very irregular pattern. Some rings (e.g. Fig.6.12, PB.57) exhibit so much variation that no overall trend is visible apart from an abrupt decrease in cell size marking the end of the growing season. This variation was analysed using the autocorrelation coefficient, but significant cycles were not revealed.

Amongst this great variation, the end of the latewood is fairly conspicuous (Fig.6 .12, PB.48) and the beginning of the new ring is signified by a marked increase in cell size. Sometimes the largest cell in the earlywood is located at the start of the new ring but it can also be found at any position within the earlywood, or even repeated several times. The remainder of the cells are very variable in size. At the transition with the latewood, cell size gradually decreases, though the first cell of the latewood cannot be accurately located due to preservation problems. The end of the ring is marked by 1-3 cells of the smallest diameter which are in fact much easier to distinguish under the microscope than on the graphs, due to their darker colour. In a few cases (e.g. Fig.6. 12, PB.91a) the variation in cell size is so erratic that it is almost impossible to identify the ring boundary.

The number of cells per ring also varies greatly, obviously reflecting the great variation in ring width. Amongst those measured the cell widths ranged from 8•8 µm to 89•8 µm, the smaller ones in the latewood and the larger in the earlywood. The most common cell size is between 30 and 40 µm, closely followed by 20-30 µm (Fig.6.11). The number of cells per ring varies from as few as 8 to over 90.

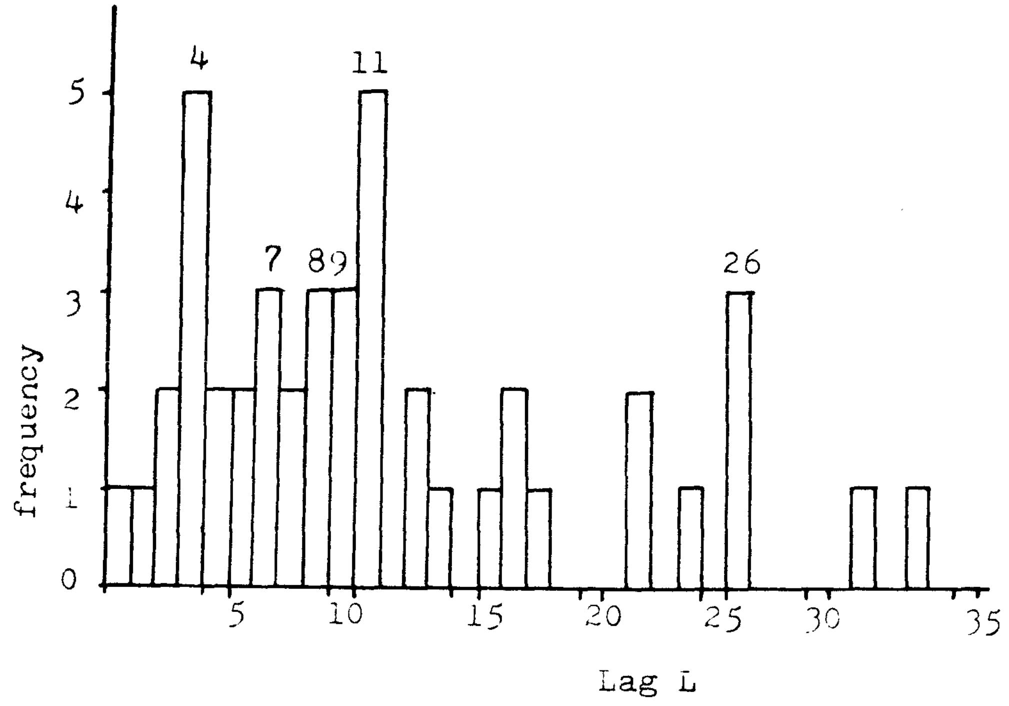

Fig.6.10 Histogram of the values of lag L which are significant at the 10% level.The paucity of data beyond L=25 is due to the preponderance of short ring series.

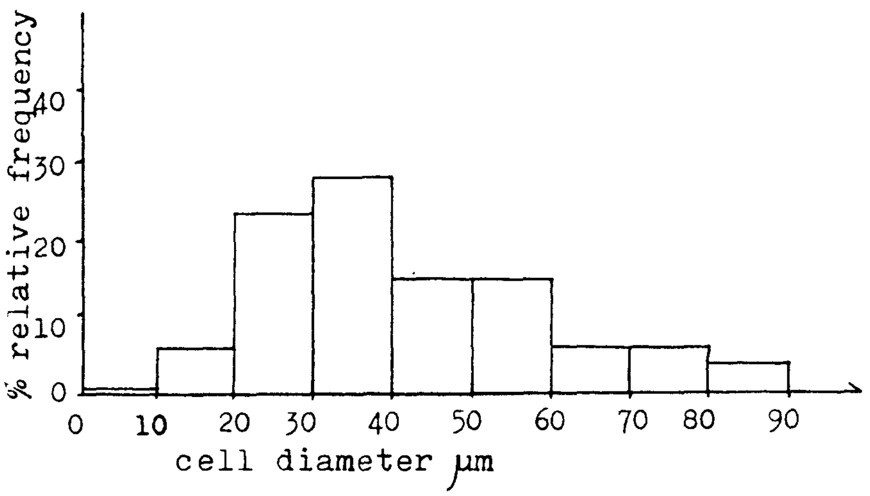

Fig. 6.11 Distribution of cell sizes in the growth rings in Fig. 6.12 based on 370 cells.

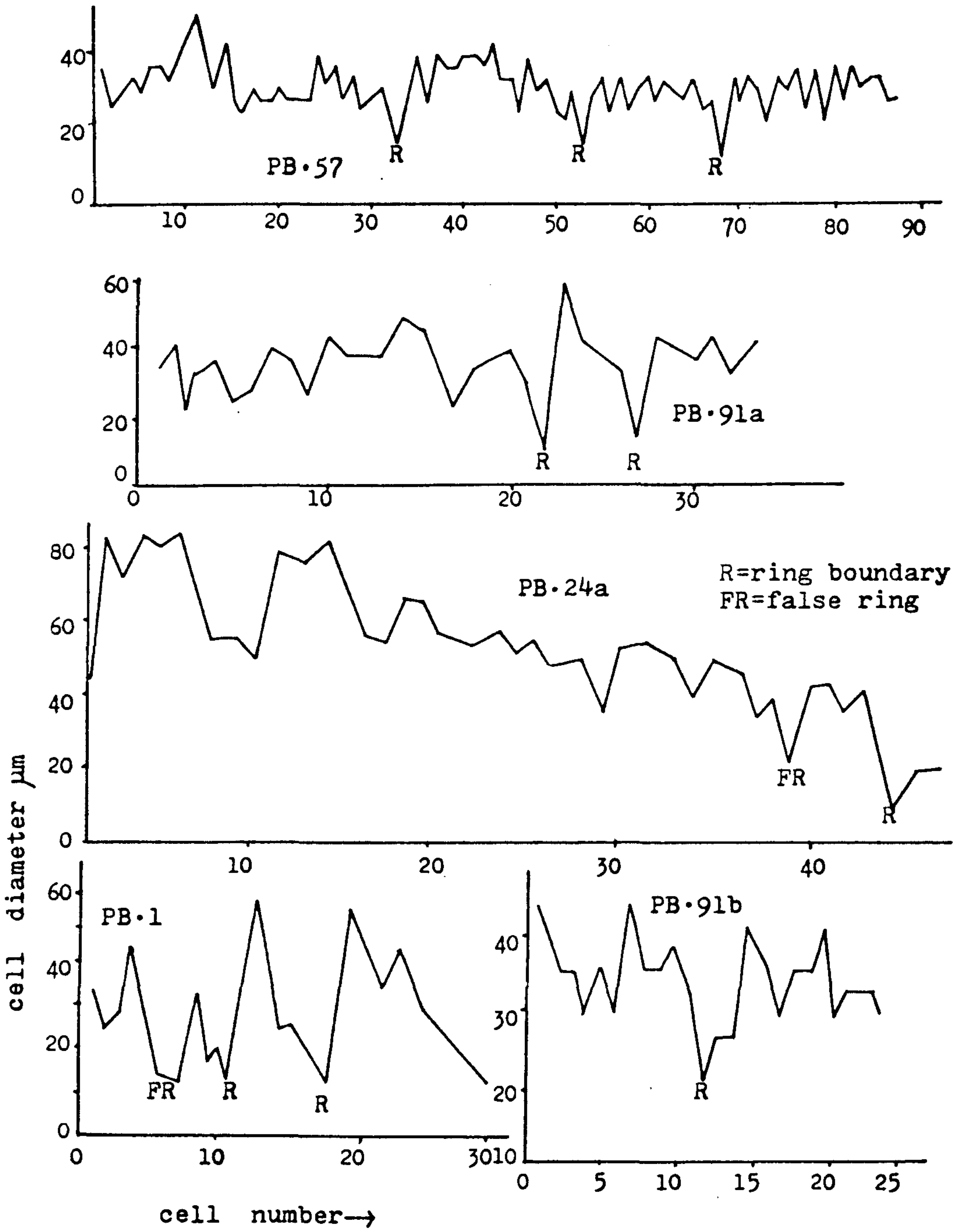

Fig. 6.12 Cell size variation throughout selected growth rings.

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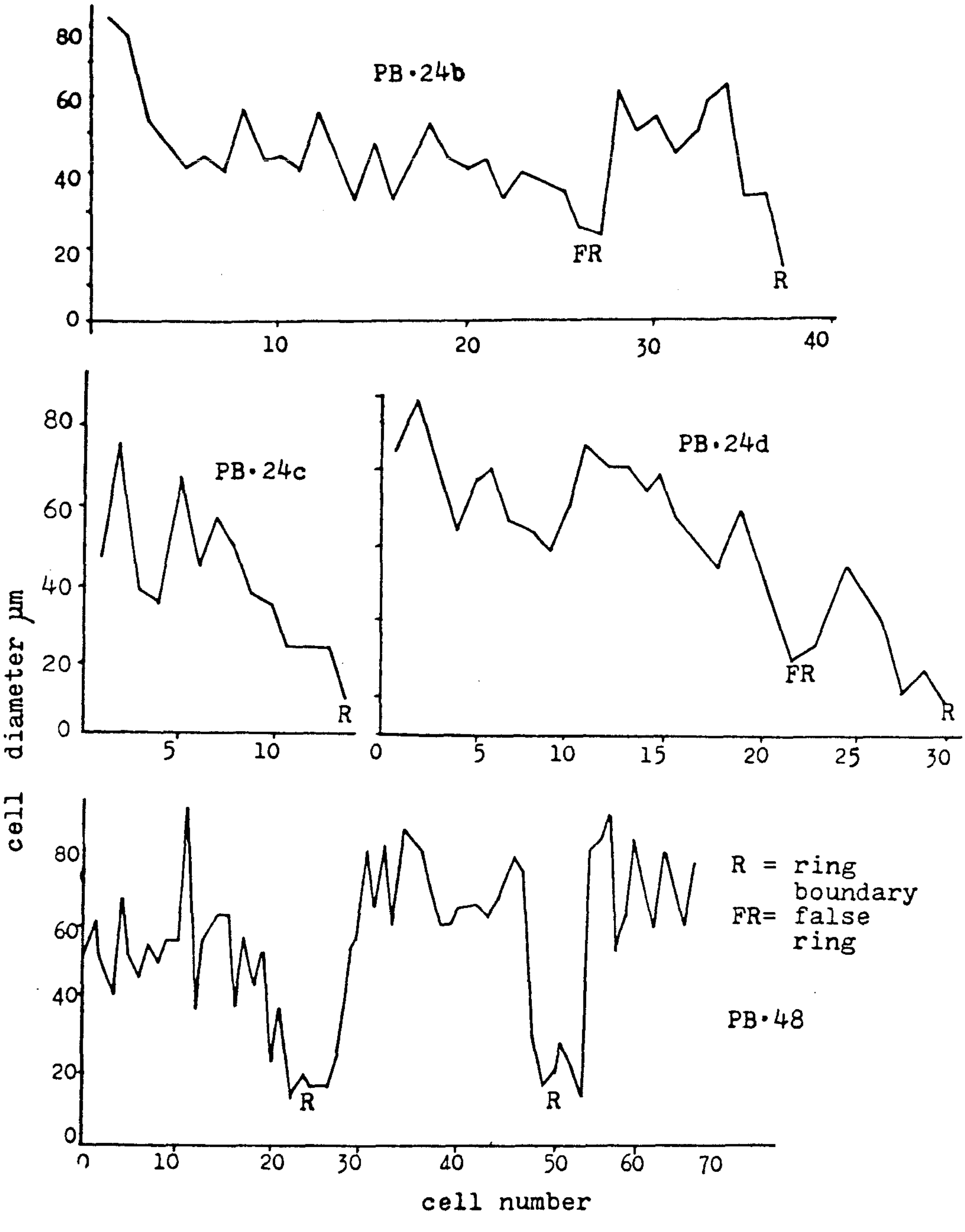

Fig. 6.12 Cell size variation throughout selected growth rings.

Within the earlywood zone of the Purbeck rings there are sometimes abrupt decreases in cell size, with some cells being almost as narrow as those of the latewood. In many cases just a single cell is noticeably small, but if 2 or 3 consecutive cells are narrow they appear as a false ring or "interannular" ring. In most cases these are easily distinguishable from true rings since there is a more gradual increase in cell size, as opposed to the sharp change to the maximum size after a true ring (see Fig. 6.11, PB.48).

Most of the Purbeck trees had only an irregular scattering of false rings, some consisting of only 1 or 2 cells. One tree, PB.1 from near Swanage, had very frequent false rings, on average 1 per "true" ring, whereas the Portland trees had a false ring about every 3-7 rings - sometimes none at all. The position of the false boundary in PB.1 was on average 0·3 mm from the start of the earlywood as opposed to the average true ring width of 0·5 mm. This difference in size enabled some distinction to be made between true and false rings but, even so, in this particular tree the two types of ring were often hard to distinguish. The greater abundance of false rings in this tree, together with its very narrow mean annual increment, suggests that it either grew in an area even more limiting to tree growth or that it originated from a later dirt bed when conditions were perhaps more arid. Unfortunately the exact horizon from which it originated is unknown.

6.8 Discussion

6.8i Patterns of tree growth as revealed in the growth rings

The initial observation that growth rings were produced in the Purbeck trees implies that the Jurassic climate was seasonal and tree growth was restricted to periods favourable for growth. From this we can infer that the trees did not grow in a relatively seasonless equatorial climate in which trees do not generally produce rings (Antevs 1925; Chaloner and Creber 1973).

The growth rings in modern trees are often referred to as annual rings, since in most cases one growth increment is added to the tree each year. This is a fundamental consideration in dendrochronological studies where each ring is taken to represent one year for dating purposes. There are, however, cases where certain species of tree may produce more or fewer than one ring each year; such species are obviously of little use for dating purposes. Whilst it is most likely that the Purbeck rings are in fact annual, this is an assumption which cannot be tested as it is in modern tree samples by cross-matching ring sequences. It is sufficient to relate the Purbeck growth rings to the relevant growing seasons. If, however, the Purbeck rings are considered to be annual, it is interesting to estimate the lifespan of the trees. The tree with the longest ring series measured (PB.1) was thus at least 104 years of age; even this is an underestimate since the outer portions of the tree are lost. One of the largest trunks measured, from Inmosthay Quarry, had a radius of about 50 cm; considering the average ring width for the Purbeck trees is 1·13 mm, this tree was about 400 years in age. A very large stump on Portland over 70 cm in radius probably lived for at least 620 years.

The absolute ring widths are fairly narrow, suggesting that the growing season was short and not particularly favourable for plant growth. An overall ring width of 1·13 mm for the Purbeck trees is comparable to growth data for modern conifers growing in restrictive environments, such as the semi-arid forests of the San Francisco Mountains (0·68-1·50 mm) (Fritts _et al_. 1965), and conifers from semi-arid sites in America studied by Schulman (1956).

The modern trees also measured in this study from Mediterranean-type climatic zones, have narrow growth rings (Table 6.02), though those of _Actinostrobus_ from Garden Island, Western Australia, are particularly narrow (0·1-0·8 mm). Trees from such areas are usually subject to water stress during dry summer months.

The measure of variability in ring-width, the mean sensitivity, is a more significant statistic since it assesses climatic influence on tree growth. The mean sensitivity value for the Purbeck trees of 0·527 (range 0·290-0·788) is high and well within the "sensitive" range, implying that the trees were very responsive to climatic variation which caused growth to fluctuate markedly from year to year. Mean sensitivity values of this magnitude have been recorded today from areas where conifers are growing at the limits of their natural range. Values of

0·20→ 0·58 were recorded by Fritts et al. (1965) from mountainous forest borders; values of 0.429, 0·423 and 0·380 were calculated for Actinostrobus pyramidalis, for Pinus halepensis from Spain and Juniperus oxycedrus from Morocco respectively. The English Elm and Scots Pine both show little growth variation (m.s = 0·231 and 0·17 respectively), and clearly grew quite steadily in the equable English climate. Creber (1977) measured ring widths of fossil wood (Cedroxylon sp.) from the Upper Jurassic of Helmsdale, East Sutherland; some specimens have fairly low mean sensitivities (0·176), whilst others are quite high (0·453, 0·578).

The histograms of the individual annual sensitivites of the Purbeck trees (Fig.6 .05) reflect the pattern of variation in growth; most trees suffered marked variations in growing conditions from year to year. A few trees though (PB.49, 22 and 11: Table6..03), which have "sensitive" mean sensitivities but a greater proportion of "complacent" annual sensitivites, appear to have grown more regularly than the others, but were occasionally subject to very marked fluctuations in growth. These trees may possibly have had deeper roots giving access to more water, or may have been nearer to a local source of freshwater.

Again this fluctuating growth of the Purbeck trees is exhibited in their cumulative growth curves. Their growth rates were irregular, often faster than average for a few years then markedly slower, and there is some evidence for cyclical patterns of growth (Fig. 6 .03). This trend contrasts strongly with the growth patterns of Actinostrobus pyramidalis from Australia and the Spanish Pinus halepensis, for although their high mean sensitivities indicate variable yearly growth rates, the cumulative sums of their ring widths show the same gradients throughout their lives. In these cases, short-term variations in climate apparently oscillate about a constant mean.

When interpreting cell variation, it must be taken into account that cell formation is not only influenced by climate but by many other physiological and environmental conditions. The rate of the growth processes (the basic processes of cell division, cell enlargement and differentiation) are affected by many external and internal factors. Individual parts of the tree respond separately (see Fritts 1976, Fig. 2.8); growth may vary diurnally, seasonally or throughout the whole life of the tree. Cell size and cell wall thickness are also influenced by factors such as age, structure of the tree, limitations of the site and particularly by the conditions of growth in former years. These are discussed fully in Fritts (1976). Creber (1975) also concluded from plots of cell sizes of an Upper Jurassic gymnosperm that the growth variations are strongly related to internal factors.

No one factor can operate independently of prior conditions or other factors occurring at the same time. Thus the interpretation of cell characteristics cannot be related to direct climatic influence, a factor which must be taken into account when considering cell variation in the Purbeck wood. However, a common occurrence within the Purbeck wood is the formation of false rings or very small cells within the earlywood.

The formation of small cells in modern wood marks the onset of adverse conditions during the growing season (Fritts 1976; Glerum 1970). In extreme cases complete cessation of growth may occur before the onset of further favourable conditions. Growing in a semi-arid climate (Arkell 1947; West 1975), the Purbeck trees were probably subject to unfavourable periods of drought or water-stress which caused the formation of small cells. Resurgence of growth marked the onset of more favourable conditions, most likely due to the replenishment of soil moisture and alleviation of water-stress. The great variation in cell size within a growth ring suggests that the Purbeck trees were subject to frequent periods of water-stress, even during the growing season. The latewood consists of only 3-4 cells in every case, suggesting the abrupt onset of harsh conditions at the end of the growing season.

6.8.ii Palaeoenvironmental interpretation

Modern trees with high mean sensitivity which grow on the margins of their ranges, are specially picked for dendroclimatological analysis since their rings accurately record climatic variation (Schulman 1956). The tree-ring characteristics of conifers growing along vegetational gradients have been studied by Fritts *et al.* (1965) as a tool for evaluation site selection in modern tree-ring analysis, and their results (Fig. 6.13) suggest an interesting interpretation of the Purbeck data. In Figure 6.13 the Purbeck trees, with their high mean sensitivites would obviously lie to the right of 'K' and probably

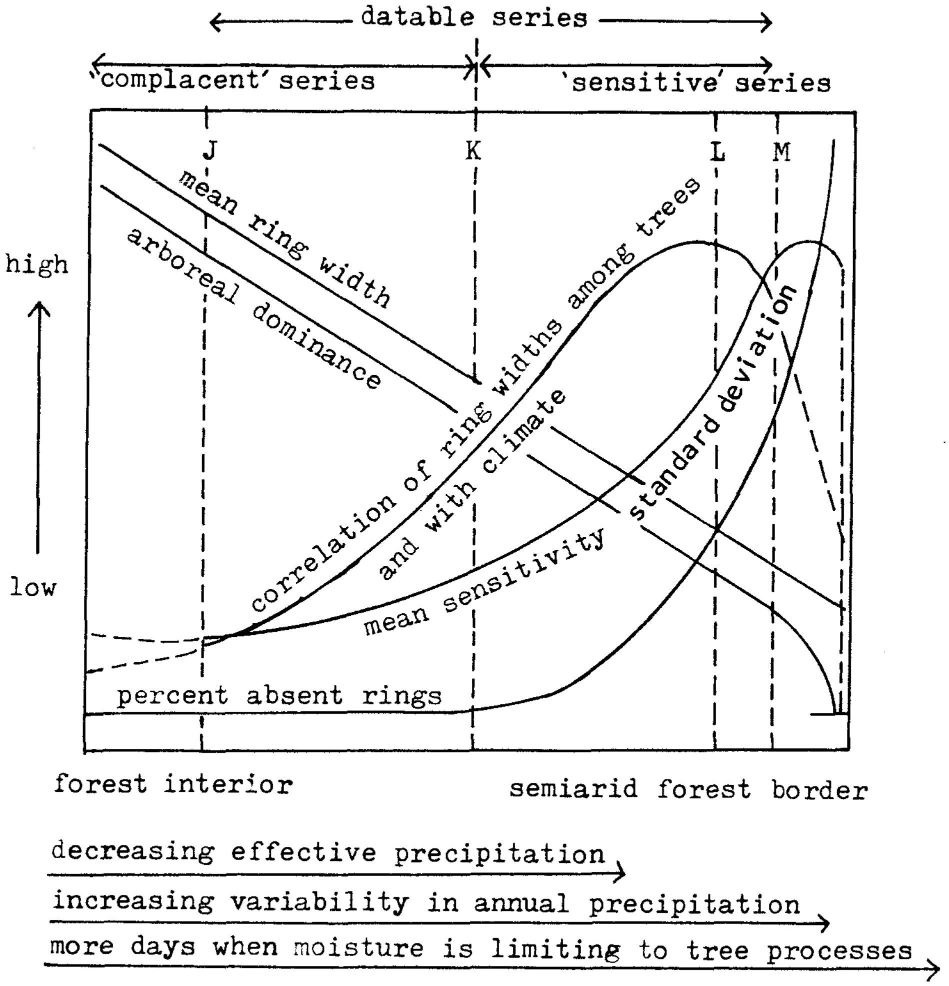

Fig. 6.13. Growth ring characteristics along a vegetational gradient from the forest interior to the semi-arid forest border. (Based on Fritts et al. 1965)

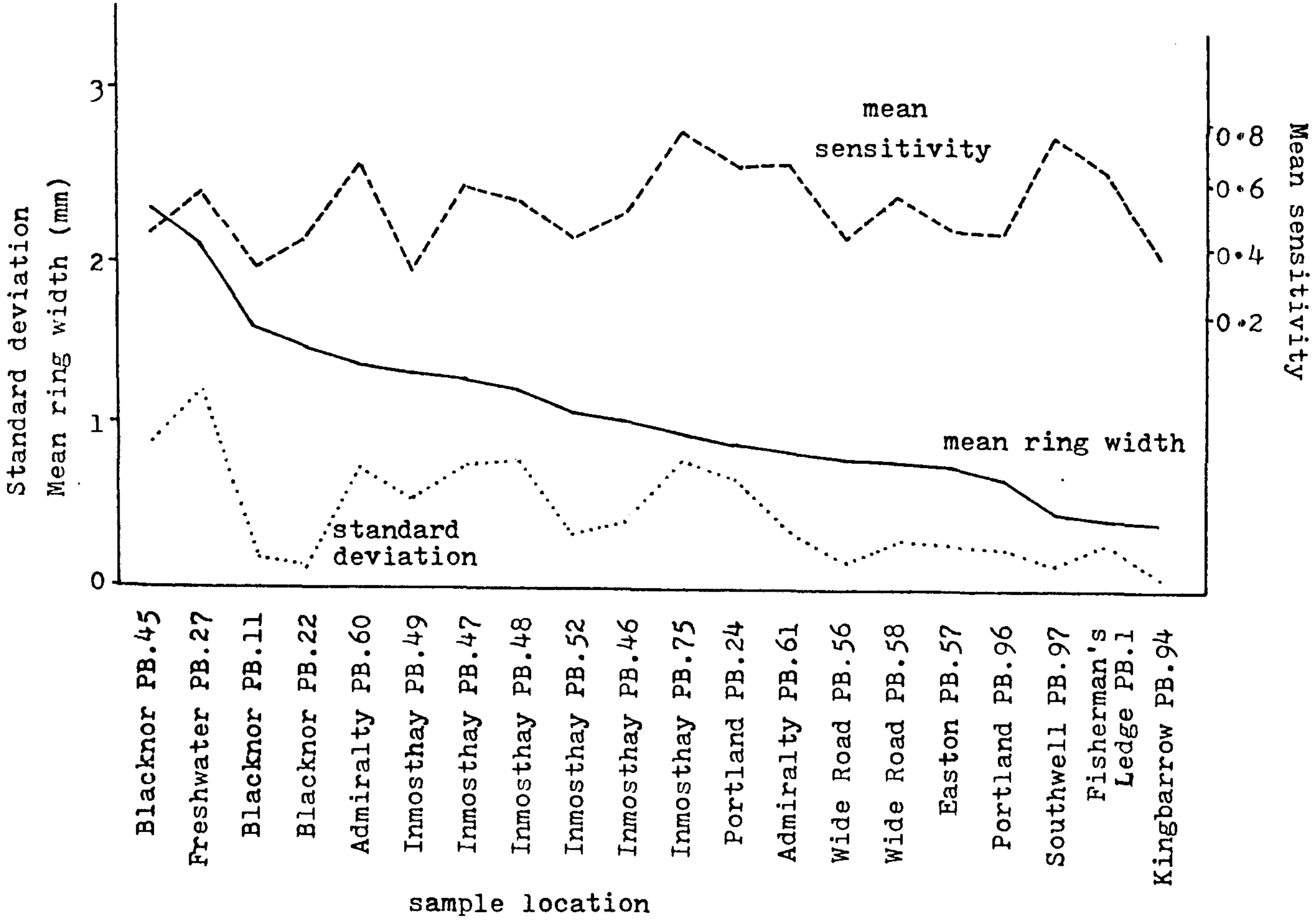

FIG.6.14 Growth ring characteristics of the basal Purbeck trees plotted in order of decreasing mean ring width. According to Fritts et al. (1965) the trend of decreasing ring width indicates the direction of the semiarid forest border (Fig. 6.13) .

close to 'L'. This immediately implies that the Purbeck trees grew on the semi-arid forest border and were subject to water-stress. In an attempt to locate this ecological gradient within the Purbeck forest, the mean ring width for each Purbeck tree was arranged in descending order, as shown in Figure 6.13, but also with its corresponding location (Fig.6.14). Remarkably, the graph shows that in nearly every case trees from the same location have been grouped together, even though there may be quite a variation in actual ring width size. For example, trees from Inmosthay Quarry have mean ring widths ranging from 1·32 - 1·03 mm, yet are still grouped together on this graph. By comparison with the diagram of Fritts <u>et</u> <u>al</u>. (Fig.6.13), the range in locations in Figure 6.14 may indicate a gradient towards the forest border. Obviously such a trend may not be very clear when it is only represented across such a short distance as the Isle of Portland, but yet a slight gradient does emerge. The trees with the highest ring width, on the left of the diagram, are from quarries on the west cliffs of Portland (and tipped over the cliffs at Blacknor, from where they were recovered). The trees in the centre of the graph come from Inmosthay Quarry in the centre of Portland, and those on the right from Kingbarrow and Southwell (and Fisherman's Ledge) are found further east (Fig. 6.04). A few trees (e.g. from Freshwater and Admiralty quarries) do not fit into this trend. However, there does appear to be a general transition from west to east across Portland which, by comparison with Figure 6.13, suggests that the edge of the forest is to the east. It is unlikely that this is a purely climatic change over such a short distance but it could reflect an environmental change such as topography, soil change or salinity increase. As Figure 6.08 and Figure 6.14 show, the relationship between mean ring width and mean sensitivity is very slight. This may possibly represent the point in Figure 6.13 to the right of 'M' where ring variation is so high that the statistical measurements become unreliable due to the presence of many false rings. The proximity of the edge of the forest in the east agrees with sedimentological evidence from the Dirt Beds (see Chapter 3).

The interpretation of the various cycles which appear to be present in the Purbeck growth ring sequences is inevitably speculative in the absence of direct climatic correlation, as is done today. Many cycles can be attributed to climatic phenomena such as temperature and precipitation, and have been recorded in glacial varves and shales

(Richter-Bernburg 1963; Lamb 1972; Gribbin 1978; Pearson 1978). In the Purbeck tree ring sequences possible short-term cycles, revealed by autocorrelation, are also visible in some cases in the graphs of the cumulative ring widths (Fig.6.03). For example, PB.48 appears to relate to a 7-9 year cycle (Fig. 6.08) also visible on Figure 6.03 as periods of increasing then decreasing growth rates; a cycle of 7 years growth for PB.46 and a 10-11 year cycle affects the growth of PB.47. These patterns of growth suggest that these cycles represent a general improvement or decrease in conditions over a period of time, rather than specific events every few years, although any lag effect of a tree's response to environmental conditions may tend to mask a specific effect. These short cycles possibly represent fluctuations in climate although the lack of replication throughout all the trees suggests that they might be of a local nature, such as cyclical changes in population of plant-feeding insects.

The most significant cycles (detected in about 7 trees) are 11-year cycles. Cycles of 11 and 22 years may reflect the well-known sunspot cycles. The 22-year cycle is known as the Hale cycle, which is caused by the reversal of the magnetic polarity of the spots from one 11-year period to the next. There tends to be a climatic response between an increase in sunspot numbers associated with cooler, wetter weather and a decrease in number with warm, dry weather (Gribbin 1978). Sunspot periodicities (5½, 10-12, 22-23 years) have been observed in tree-ring series, confirmed by extensive tree-ring research by Douglass (1919), with convincing evidence that solar cycles affected tree growth. Cycles in solar activity with an 11-year cycle affected Xenoxylon wood from Japan during the Early Cretaceous according to Masuda and Watanabe (1979). Recent work by Bryson and Dutton (1961) and LaMarche and Fritts (1972) did not, however, produce significant correlation between sunspot periodicity and tree growth.

To conclude, in the Purbeck trees there is some evidence for cyclical growth and for an 11-year cycle in particular, but more data for long ring sequences is necessary to demonstrate this convincingly.

The palaeoclimatic interpretation of the Purbeck tree-rings is based on comparison with modern growth ring sequences with known climatic influence. The pattern of cell variation within a ring indicates that the climate was not only very variable but also markedly seasonal, as shown by the transition from the larger thickness of the earlywood to the very abrupt narrow zone of the latewood. Rainfall was probably concentrated in the winter or early spring because if it fell any later, during the summer, the Purbeck evaporites (West 1964) would not survive. The formation of such evaporites requires periods of aridity with low precipitation, and periods of intense evaporation (Braitsch 1963); conditions far from suitable for plant growth. The modern climate with winter rainfall and dry, hot summers is of Mediterranean type. A particular feature of this type of climate in semi-arid areas is not specifically the amount of rainfall, which is between 200-400 mm, but its erratic occurrence and great intensity for short durations (Nir 1974). The summer drought may last for up to 5 months, and dry spells can interrupt the rainy season for days or even weeks. When the rain does fall it tends to fall with greatest intensity at the beginning and end of the wet season; up to 40-50 mm per hour have been recorded (Nir 1974).

The great variability of the ring characteristics of the Pinus sample from this area reflects this type of climate, as do the rings of the trees from Morocco and western Australia. The climate of western Australia, in particular Rottnest Island and Garden Island (at 32°S) from where the sample of Actinostrobus originated, is of extreme Mediterranean type, with hot, dry summers and cool, wet winters. The rainfall, about 600-700 mm per year, is extremely seasonal; 82% of the total rain falls in the winter months of May to September (a total of 83 wet days), but as little as 6 mm can fall per month during the summer (McArthur and Bartle 1981). The average maximum temperature in the summer is 26°C and conditions of evaporation and precipitation are often suitable for gypsum and halite to form (Playford and Leech 1977) but not as extensively as the Purbeck deposits, suggesting that the rainfall was slightly higher than that of the Purbeck. This is supported by the graph of the cumulative growth increments of Actinostrobus pyramidalis (Fig. 6.03) where, although the growth rate is slow, the overall variability is less than in the Purbeck trees. Taking the geological and botanical evidence together, an annual rainfall of about 300-400 mm seems most likely for the Mediterranean climate in which the Purbeck trees grew.

CHAPTER 7

CONCLUSIONS

7.1 The Sedimentary Environment

For much of the Upper Jurassic the Dorset area was situated on the border of an extensive shallow basin (the Purbeck basin) which extended eastwards across southern England (Howitt 1964) (Fig.1.02). The deposition of the marginal continental sediments of the basal Purbeck Beds in Dorset was related to a series of regressive and transgressive phases, ranging from supratidal and terrestrial conditions with forested soils to low intertidal conditions within shallow hypersaline lagoons. The pattern of deposition appears to have been influenced by a relatively low barrier or swell which trended north-east/south-west across the Lulworth area to Portland and separated a very shallow lagoonal area in the north-west from a larger basin to the south-east.

The limits of this barrier were at times well-defined as sedimentary characteristics varied across the area reflecting different degrees of exposure and depths of water (Chapter 2). This is particularly evident during formation of the Great Dirt Bed palaeosol and its forest. During the early Purbeck water depth over the barrier was relatively shallow in the Lulworth area only. Conditions on the Isle of Portland were very similar to those in the west (Fig.7.02a), with alternating lagoons of only moderate salinity (indicated by the presence of a brackish or slightly saline-tolerant fauna of molluscs, bivalves, ostracods and foraminifera in the Basal Cast Bed, 2.3.i) and thin terrestrial soils. During deposition of the Skull Cap and Basal Dirt Bed (Fig.7.01,a-c) the swell was sub-aerially exposed and subject to erosion in the Lulworth region, and so these strata are absent. At Dungy Head in particular the Lower Dirt Bed rests on the very irregular relief of the Portland Stone below.

The Lower Dirt Bed palaeosol (Fig.7.01d) marks a period of emergence of a duration sufficient for the establishment of forest vegetation. The palaeosol is shallow and appears to have a relatively immature profile (Chapter 3). Its laminated appearance and the inclusion of streaks of carbonate (as opposed to lithified pebbles) suggests that it formed quickly upon underlying partially lithified limestone which

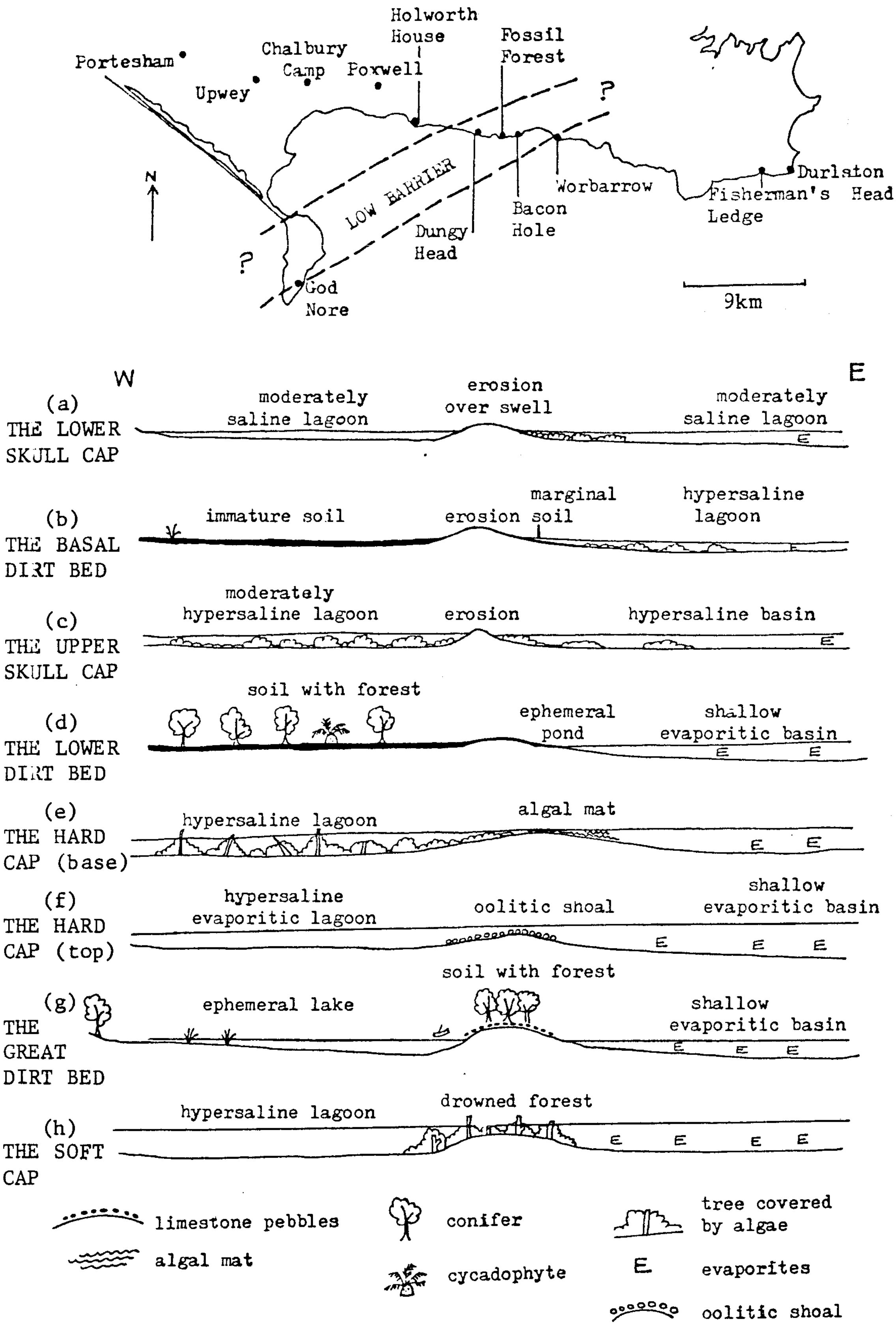

Fig. 7.01. Reconstruction of the depositional environments across Dorset at particular times during the early Purbeck.

itself was relatively rapidly exposed. The soil material may have had an alluvial origin (Chapter 3).

In the east in the Bacon Hole and Worbarrow area, the forest soil merged laterally into an ephemeral alkaline pond or lake margin; its seasonality is demonstrated by the laminated, varve-like lithology and its characteristic seasonal fauna, particularly conchostracan branchiopods (Chapter 2.4).Clay bands occur further east which are probably equivalent to this horizon; these deposits have geochemical properties (particularly high organic carbon content) characteristic of marine shales but not of palaeosols (Chapter 3). This area may be the margin of the Purbeck basin to the east, the borders of which dried out seasonally. However, a different interpretation was proposed by West (1975) who considered that the palaeosols extended further east. The exact nature of the sedimentation to the east of Dorset is as yet unknown due to lack of exposure and paucity of borehole data.

Hypersaline, intertidal conditions became established as rising sea level drowned the Lower Dirt Bed forest (Fig.7.01e). The decreasing depth across the swell is illustrated by the transition from large mounds of algal stromatolitic sediment in the western lagoon to flat-laminated, algal mat at Bacon Hole and Worbarrow where the water was shallower. An oolitic shoal formed over the swell in shallow, more energetic, hypersaline water. Intermittent exposure of the lagoonal pelletoid silts in the west allowed small quantities of evaporites (lenticular gypsum) to form, indicating that the environment was becoming progressively more saline. The eastern basin appears to be another area of evaporite formation at this time.

As the water level dropped with respect to the level of the swell algal mat formed over it (Fig.7.01e). This material was probably dark and highly organic and when exposed in the supratidal zone became desiccated as it lithified and fractured into large polygons (Pugh 1968), resembling those in the supratidal zone of the Persian Gulf today (Shearman 1966). The desiccation and fracture of the black algal mat produced black clasts or pebbles, similar to those found on the shoreline of hypersaline lakes in semi-arid regions today (Folk 1967, Ward et al. 1970; Klappa 1967). At Holworth House and Worbarrow a bed of dark grey, organic-rich limestone probably marks the marine equivalent of the black algal mat each side of the barrier.

For locality names see Figure 1.01

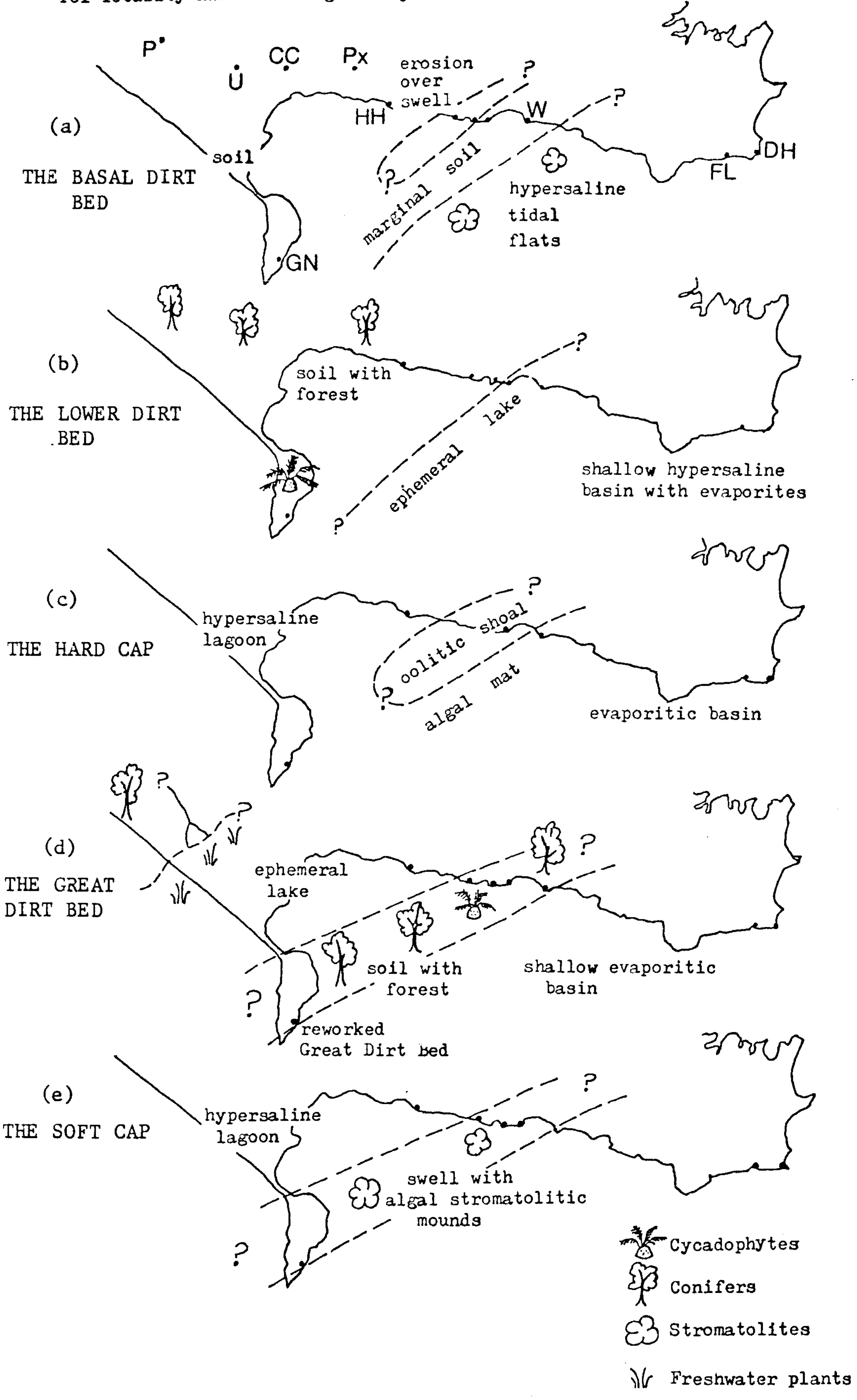

Fig. 7.02. Schematic palaeogeographic reconstructions at particular times during formation of the basal Purbeck Beds in Dorset.

At this stage the swell was about 5 km wide and extended further to the south-west to include the Isle of Portland. In Dorset the Great Dirt Bed forest was confined to the top of the swell which must have been exposed for a relatively long period to allow the thicker, rendzina-like soil to form and large trees to grow. Within this area pebbles derived from the underlying limestone became incorporated into the black, carbonaceous marl of the palaeosol. The eastern edge of the swell appears to be defined by the disruption of the Great Dirt Bed at Worbarrow and its re-working at God Nore, on Portland (Fig.7.02d). To the east there was a shallow evaporitic basin and to the west an ephemeral lake developed instead which was seasonally fresh, presumably fed by rain and freshwater streams from land to the west. Charophytes, Equisetum and a freshwater fauna flourished (Barker et al. 1975; West 1975) and wood and conifer shoots were transported from adjacent forests. During intermittent arid seasons evaporites were able to form.

The Great Dirt Bed forest, as was the forest of the Lower Dirt Bed, was rapidly killed by rising saline water and quickly covered by algal-bound sediment as intertidal conditions became established once more (Fig.7.01h). The highly saline environment was particularly suitable for the prevention of decay of the wood and its petrifaction by silica (Chapter 4).

The distribution of sediments emphasises the importance of a low swell on patterns of deposition during the Purbeck. A barrier across this area, the Mid-Dorset Swell, was considered by Townson (1975) to have influenced most Upper Jurassic sedimentation. He recorded lithological changes across the swell throughout the deposition of the Portland Limestone. The swell was located around the Lulworth area and plunged southwards (indicated by thicker sediments on the Isle of Portland) corresponding to the extension of the swell indicated by the basal Purbeck sediments (Fig.7.02). West (1975) suggested the Lulworth area was subject to small oscillations during sedimentation which caused slumping and disturbance of unlithified sediment (e.g. slump structures at Bacon Hole and Worbarrow, Figs. 2.09 and 2.10). It is possible that this barrier also extended in a north-easterly direction across the Wytch Farm area and would thus account for the thinning of Upper Jurassic sediments in this area (Colter and Havard 1981)(Fig.7.01). Drummond (1970) suggested that an area of uplift divided Dorset into two

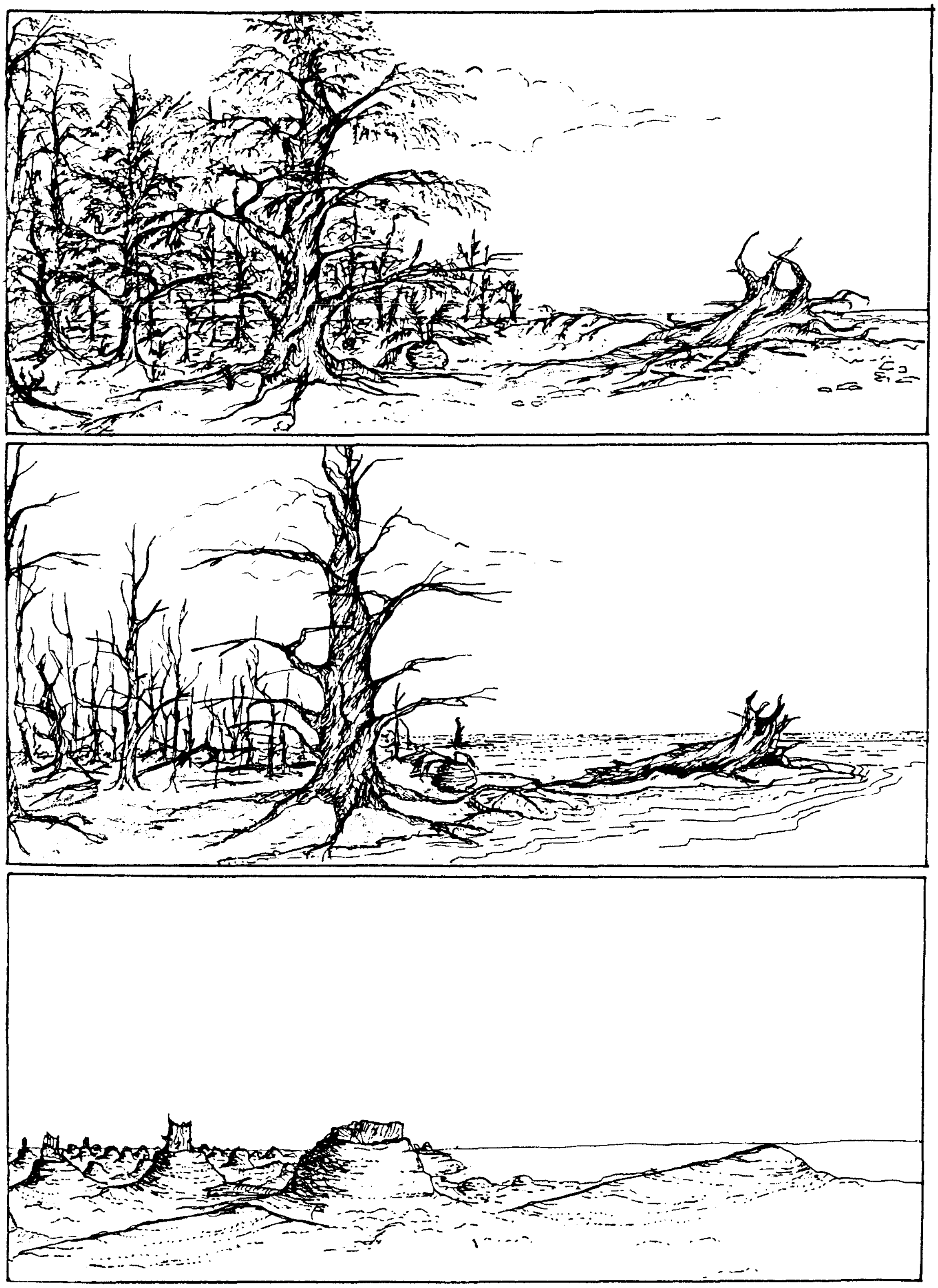

FIG. 7.03. Representation of the sequence of events affecting the basal Purbeck forests.

Top: The conifers formed a closed forest on the borders of a shallow evaporitic basin.

Middle: Rising saline water drowned the forest and killed the trees.

Base: Algal-bound sediment covered the tree stumps and fallen trunks.

basins during the Upper Cretaceous: a shallow shelf to the west and a deeper basin (the Wessex Trough) to the east. This structure, however, trended north-west/south-east, the same direction as that proposed by Allen(1981) for demi-horst structure influencing Wealden deposition.

7.2 Modern Analogues for the Purbeck Sedimentary Environment

There are few large, modern saline basins comparable in size to the Purbeck basin of southern England, with similar evaporitic deposits and coastal sediments. The sediments of the Persian Gulf have been considered analogous to those of the Purbeck (Shearman 1966). The large hypersaline sabkhas of Tunisia, such as Chott el Djerid about 100 km long, 60 km wide, are subject to seasonal changes of partial submergence in winter and to the formation of evaporites as the water level drops due to high evaporation in summer (Coque and Jauzein 1967). Shark Bay, western Australia, is a large hypersaline gulf with algal stromatolites, algal mats and calcrete comparable to that of the Purbeck (Logan et al. 1970). However, barrier islands affecting coastal sedimentation,in a manner similar to that in which the Mid-Dorset Swell influenced Purbeck deposition, are very common along aggrading coastlines today (King 1972). Most modern barriers are composed of emergent bars or submerged coastal dunes, the result of Holocene sea level changes (Hoyt 1967), but few are of tectonic origin. In the Persian Gulf the Trucial coast has numerous islands separating a hypersaline lagoon, the Khor am Bazam, from the main gulf (Kendall and Skipwith 1969; Kinsman 1969). The sequence of lagoonal silts, oolitic shoals, and evaporitic deposits on supratidal sabkhas across the lagoon has been compared with the Purbeck Beds (Shearman 1966). The Mediterranean coast of northern Egypt was studied as an analogue to the Purbeck environment by West et al. 1979. Here evaporites form in supratidal sabkhas between ridges of lithified dune sand. The hypersaline lagoon in California, Oja de Liebre, is restricted by a barrier of dunes and has wide intertidal flats with algal mats, salt flats and evaporites (Phleger and Ewing 1962; Phleger 1969). Padre Island is a linear strip which separates Laguna Madre from the Gulf of Mexico (Rusnak 1960; Kerr and Thomson 1963). A typical sequence of lagoonal muds and silts in the metre deep lagoon, with oolitic shoals, algal mats and salt pans, is similar to that represented by the basal Purbeck Beds.

However, although these areas are good analogues for the Purbeck sediments and evaporites, their climate is generally too arid to allow vegetation like the Purbeck forests to grow. In most cases a salt flat or sabkha is developed rather than a freshwater marsh (Kinsman 1969). Thus the vegetation in these arid areas (with annual rainfall of 50 mm in the Persian Gulf, 180 mm in Egypt, 66 mm in California) consists mainly of small halophytic shrubs, predominantly members of the Chenopodiaceae. In Egypt palms can grow at the base of coastal ridges where a lens of freshwater collects (West et al. 1979). In the semi-arid regions such as the Laguna Madre palms and cacti grow on lagoon shores (Kerr and Thomson 1963; annual rainfall 600 mm). Unfortunately the natural vegetation of these areas has been greatly affected by man (Specht 1969) and together with the domination of modern vegetation by angiosperms, suitable analogues for the fossil forests in the correct sedimentary setting are hard to find.

7.3 The Purbeck Forest Vegetation

The coniferous forests of the basal Purbeck Dirt Beds clearly survived in an environment also suitable for the formation of evaporites. The flora was rather species poor. Most trees belonged to one species of the family Cheirolepidiaceae (a family which dominated world vegetation in the Upper Jurassic). A fairly complete reconstruction of this dominant species has been possible based on fossils of foliage, trunks, roots and male cones (Fig.5.03). These trees had monopodial trunks, low branches and shallow spreading roots. Their foliage consisted of small, scale-like leaves and small male cones yielding Classopollis pollen. Few other types of tree were present, including an araucarian conifer (though represented only by petrified wood). Small cycadophytes were also present in the forests, particularly in that of the Lower Dirt Bed. Lycopods and ferns are represented by their spores and pollen (Chapter 5).

The Purbeck forests are particularly important since the trees are preserved in their original growth positions and details of the habit of the trees, the density of the forest and its response to the semi-arid environment can be established. An important factor governing the preservation of the forests was their rapid drowning by hypersaline water and envelopment of the trees in algal sediment. The high salinity probably inhibited the decay of the wood and deterred wood-digesting fungi. pH conditions were also suitable for silicification which proceeded rapidly before deterioration of the wood structure (Chapter 4). However, as a consequence of the inundation of the forest by water, several aspects of the forest would have been lost immediately. Loose, dried conifer shoots forming the layer of undecomposed plant litter at the top of the soil would have been washed away; small, shallow-rooted plants on top of the soil would have been uprooted. The bark of the trees had probably dried and fallen from the trunks soon after the trees were killed by the salt water and this also would have floated away and decayed rapidly. Small branches and twigs lying on the forest floor would have been lost, the smaller branches probably decomposed before the onset of silicification.

The remaining petrified wood provides a great deal of evidence for reconstruction of the vegetation and the trees. The spacing of the in situ tree stumps and their encasing burrs indicates that the trees grew in close proximity, forming extensive tracts of closed forest (Chapter 2). The mature trees were large and trunk bases over a metre in diameter have been recorded. Their heights are difficult to determine but were probably about 20m, based on comparison with conifers from modern semi-arid regions, such as the Mediterranean coast. Thus from their remains a picture of the forest structure can be obtained at the time when it was killed by rising saline water. Evidence from the direction in which the trunks lie suggests that previous damage may have been caused by a storm or strong winds from a southerly direction. There is some evidence that periodic fires also affected the forest but did not totally destroy the vegetation (Chapter 4).

This reconstruction of the forest may serve as a model for other vegetation in the Upper Jurassic and Lower Cretaceous, particularly for those where fossils are not preserved in situ. In particular the forests of the Wealden Formation appear to have been very similar. The large trunks are preserved only as drifted 'rafts' (the Pine Raft at Brook Chine, Isle of Wight) but their scale-like foliage and wood are very similar to those of the Purbeck trees (Watson 1977; Alvin et al. 1978, 1981). Preliminary evidence from their growth rings suggests a markedly seasonal climate with periods of drought and forest fires (Harris 1958, 1981; Alvin et al. 1981) but wet at other times to account for the large volume of fluvial sediments (Allen 1981).

The abundance of Classopollis pollen produced by the Purbeck conifers,which dominates miospore assemblages, suggests that these forests are the most likely source of the high Classopollis content of sediments in England in the Upper Jurassic (Chaloner 1962).

7.4 The Purbeck Environment and Some Modern Analogues

The Purbeck trees have many features characteristic of xerophytes such as small, scale-like leaves and thick cuticle with sunken, papillate stomata to reduce moisture loss. It seems likely that whole shoots were shed during dry seasons in order to preserve moisture (Harris 1976). Further evidence for a semi-arid climate is the growth pattern of the trees as reflected in their growth rings (Chapter 6). The trees grew very slowly and erratically in response to a variable and restrictive climate which was marginal for tree growth (mean ring width 1•13 mm). There is evidence for a seasonal climate with warm wet winters suitable for tree growth but summers with long periods of drought (Mediterranean-type climate). By comparison with modern Mediterranean weather patterns it is likely that the winter rainfall, between 200 and 500 mm, was variable, often falling in intense downpours, and perhaps interrupted by significant dry spells. The only source of water must have been that held within the soil since the root systems were shallow and unable to penetrate the hard limestone below to reach any water stored at a lower level. However, in rendzina soils in Spain today a layer of indurated calcrete at the base of the soil acts as an aquiclude, retaining a lens of freshwater above it which is taken up by the shallow, spreading roots of Pine trees (Pinus halepensis, Klappa 1980). Possibly the calcrete in the Great Dirt Bed palaeosol acted in a similar way, retaining a limited supply of water for the tree roots. When this supply was depleted the tree would rapidly experience the effect of drought which would cause the abrupt cessation of growth. The presence of false rings in the wood and the very narrow zone of late wood is consistent with such an interpretation (Chapter 6).

The existence of a markedly seasonal, semi-arid climate during the Purbeck is also supported by faunal and sedimentological evidence. The association of evaporites with freshwater plants and molluscs in the Great Dirt Bed at Upwey and Portesham (the Portesham Charophyte Chert of West, 1975) is similar to that observed in seasonal lakes today in areas with a Mediterranean climate in South Australia. In the Coorong coastal lagoons charophytes and a non-marine fauna are associated with evaporites (Burne et al. 1980). The charophytes grow in ephemeral waters, either on lake margins or in adjacent freshwater marshes during the winter period when rain and low evaporation rates allow the lake margins to become fresh. In summer the plants can survive in salinities up to 70‰ but in a dormant state. During the summer drought evaporites are deposited from the hypersaline water caused by high evaporation. The surrounding land supports insects which may drown in the saline lakes (cf. Purbeck dragonfly) and is thinly forested, mainly by Eucalyptus scrubland (Specht 1972). The annual rainfall is about 450 mm with a marked winter maximum from April to October.

Similarly the Lower Dirt Bed at Worbarrow and Bacon Hole also represents an ephemeral deposit on the margins of a seasonal lake or pond (Chapter 2). The branchiopod crustaceans preserved within the finely laminated shale are comparable to those found today in very shallow, small alkaline ponds in semi-arid areas (Tasch and Zimmerman 1960). They require freshwater and are active only during the winter months, being unable to survive except as eggs during the summer months when the ponds dry out. From an estimate of the life-span of the Purbeck branchiopods, based upon the number of growth bands on their carapaces (see 2.4) the ephemeral pond in the Bacon Hole area existed for at least 5 months of the year, presumably throughout the winter.

It has already been shown that the sedimentary evidence strongly indicates an arid or semi-arid climate in which evaporites formed. In addition, a seasonal, semi-arid climate would have been necessary for the formation of calcrete in the Great Dirt Bed palaeosol (James 1972; Harrison 1974; Read 1974). Seasonal variations in pH within the hypersaline waters also provided a suitable environment for the dissolution and precipitation of silica which petrified the Purbeck trees, particularly the types of silica associated with evaporitic sediments. A modern analogue is again found in the Coorong lagoon (Peterson and von der Bosch 1965).

Modern coniferous forests growing on coastal lowlands comparable to the basal Purbeck forests are hard to find due to the effects of man and the dominance of modern vegetation by angiosperms, as mentioned previously (Chapter 5). In the Mediterranean area Pinus halepensis and Juniperus oxycedrus grow under similar climatic conditions to the Purbeck trees, as illustrated by their similar growth ring statistics (see 6.8). However, the sedimentary environments of the particular specimens studied are much different, the Junipers growing in a mountainous region and the Pine trees on a coastal lowland without evaporites. On the Bahaman Islands *Pinus carribea* grows on thin rubbly soils over limestone (Little *et al.* 1977). Although hypersaline lakes bordered by algal mats and calcrete deposits occur on the more arid, southern islands the vegetation consists here of only halophytes and scrub vegetation. The Pine trees grow in areas of sub-tropical climate with an annual rainfall of about 800-900 mm and are greatly affected by forestry practices.

The Mediterranean-type climatic zones of Australia have been shown to have sedimentary environments very similar to those of the basal Purbeck, especially in the Coorong region. The vegetation here is dominated by *Eucalyptus* (Specht 1972). However, off the coasts of Perth, Western Australia, small islands have natural stands of the conifer *Callitris preisii* (Cupressaceae) (McArthur and Bartle 1981). On Rottnest Island the Rottnest Island Pine (*C.preisii*) grows in shallow soils on limestone, its roots spreading laterally across the surface of the underlying limestone. Adjacent ephemeral lakes become hypersaline in summer and evaporites are precipitated (Playford and Leech 1977). Gypsum crusts form on the lake shores where algae also encrust dead branches. In these saline lakes, some of which dry out during the summer, charophytes grow and brackish water molluscs and ostracods live in marginal areas with a freshwater influx (Hodgkin 1959). Smaller freshwater swamps exist only during the winter and dry out in summer. Dragonfly larvae colonise these ponds in winter as do crustacea with aestivating eggs (Edward and Watson 1959), similar to those in the Lower Dirt Bed ephemeral pond at Bacon Hole.

Communities of *Callitris* conifers are found on the coastal islands and the coastal plain of the mainland of western Australia (Speck 1952). *C.preissi* is a small conifer which when young develops a monopodial conical habit with branches reaching ground level, though these lower branches are lost as the tree increases in height. It has a straight bole, and a thin layer of foliage forming a closed canopy. When mature a very irregular habit is developed (McArthur and Bartle 1981). The *Callitris* stands are subject to frequent fires; they are fire-sensitive to the extent that trees cannot withstand foliage scorch but regeneration is favoured by the ash layer on the soil. The habit and environment of these Callitris conifers is very similar to the Purbeck conifers.

Preliminary analysis of the growth rings of Callitris from western Australia indicated that tree growth was slow and irregular (Lange 1965; Pearman 1971). More detailed data obtained from the growth rings of a specimen of Actinostrobus pyramidalis, a conifer commonly found with C.preissi (see Chapter 6) showed that growth was very similar to that of the Purbeck trees, particularly with respect to the great variability in the annual rings. The climate of this part of Western Australia is of extreme Mediterranean-type, with wet winters and extremely dry summers. The mean annual rainfall is 745 mm (McArthur and Bartle 1981) nearly 75% of which falls during the winter (82% in the 5 months from May to September). This is accompanied by strong winter gales and cyclonic storms in late summer which have a very destructive effect on the vegetation. Perhaps similar conditions affected the Purbeck forests and were responsible for the trend of the fallen Purbeck trees to lie in a north-south direction.

7.5 Concluding Remarks

Within the Mediterranean-type climatic zone of South Australia excellent analogues for the Purbeck forests, climate and sedimentary environment have been found. The rainfall in the early Purbeck was probably between 450 and 700 mm, mostly falling during the winter months and then probably intermittently with periods of intense storms and dry intervals. The temperatures probably ranged from about a mean maximum of 26°C in summer to a mean minimum of 14°C in winter (those of Rottnest Island, McArthur and Bartle 1981, and of the Coorong region, von der Borch et al. 1977). The palaeolatitude of Dorset during the Upper Jurassic was approximately 34°N (Smith et al. 1973) which is comparable to the present day latitude of Rottnest Island (32°S) and the Coorong (37°S).

The markedly seasonal climate which prevailed at this latitude (34°N) during the Upper Jurassic conflicts with the widely held belief that the Jurassic climate was uniformly warm and equable (Schwarzbach 1963; Hallam 1975; Frakes 1979). This broad conclusion has been based on broad latitudinal zonation of Upper Jurassic floras, the lack of polar ice caps, the widespread occurrence of corals and the spread of evaporites delineating broad arid belts (Lotze 1974; Hallam 1975; Frakes 1979). These are mainly related to temperature controls. Only brief mention has been made of the occurrence of fossil wood with growth rings, indicating seasonal patterns and possibly other controls such as rainfall (Frakes 1979). Evidence from the basal Purbeck trees, strongly supported by many faunal and sedimentological examples, shows that within the equable Jurassic climate marked seasonal variations affected the whole environment. This type of seasonal, semi-arid climate during the Upper Jurassic accounts for the paradoxical association of evaporites with well-developed forest vegetation in Dorset.The reconstruction of the Purbeck forests and the relationship of these forests and adjacent sediments to this type of climate may serve as a model for other Upper Jurassic and Lower Cretaceous vegetation.

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Appendices

Contents

Preparation of fossil materials and procedures for chemical analysis

A. Preparation of the fossil wood

a) Thin-section

Three thin sections of each sample of silicified wood (transverse, tangential longitudinal, radial longitudinal) were made to fully illustrate the wood structure. The thin-sections were made in the usual way and mounted in Canada Balsam. The thickness to which the section was ground was determined by the maximum clarity of the wood structure; this was often greater than 30μm. Staining of the silica to enhance the structures was attempted but was unsuccessful (see Chapter 6).

b) Scanning electron microscopy (SEM)

Small fragments of silicified wood (cleanly fractured) and pieces of fusinite (obtained from the residue of the bulk maceration of the soil) were studied by SEM. The samples were washed in acetone prior to mounting to remove dust and debris. They were mounted on stubs on clear, double-sided Sellotape and coated with gold or gold-palladium. A Jeol JSM P15 and IS1 60A scanning electron microscopes were used.

B. Bulk maceration of the Great Dirt Bed from God Nore

This palaeosol contained well-preserved dispersed plant remains. To obtain the cuticle and pollen the carbonate matrix and silica were removed by the following procedure:

1. Coarsely crushed pieces of the palaeosol (about 0.5-5 cm) were covered with 30% HCL and gently agitated. The mixture was left to stand until all the carbonate had dissolved. More HCL was added if necessary.
2. The non-carbonate residue was washed repeatedly with distilled water. The residue was allowed to settle slowly (usually left for 24 hours). At no stage was it centrifuged or stirred violently in case the cuticle was damaged or leaves separated.
3. Dilute HF (about 10%) was added to the cuticle in a plastic container. The mixture was allowed to stand (for about 24 hours), stirring occasionally, until the silica had dissolved.
4. The residue was washed very thoroughly until all HF had been removed.

5. Dilute HCL (about 15%) was added and gently warmed until accessory minerals had been dissolved. These minerals were finely crystalline or partly colloidal gelatinous white precipitates mixed with the organic residue (see Norem 1953).
6. The residue, which then consisted only of organic material, was carefully washed. It was stored in air-tight bottles in distilled water with a few crystals of thymol to prevent bacterial growth.

C. Maceration of the cuticle and pollen

Conifer cuticle was obtained either directly from well-preserved shoots on limestone or as dispersed fragments in the residue from bulk maceration of the soil. The cuticle was macerated following the procedure below.

1. The cuticle was placed in distilled water in a small glass dish.
2. A few drops of concentrated nitric acid were added and the cuticle was agitated very gently until it appeared orange and translucent instead of opaque.
3. The acid solution was replaced by clean distilled water and the cuticle thoroughly washed.
4. A few drops of dilute ammonium hydroxide were added to dissolve the oxidised cell contents. The cuticle was gently agitated.
5. The cuticle was thoroughly washed.
6. If the cuticle was not fully macerated at this stage the process was repeated. The length of time required for maceration varied considerably for each piece of cuticle. Maceration with Schultz' solution (nitric acid and potassium chlorate) was unsuccessful since the solution tended to destroy the cuticle completely.

Miospores were obtained from the Great Dirt Bed at God Nore after bulk maceration of the palaeosol matrix. Extra care was necessary to prevent loss of miospores during washing procedures, and in some cases the residue was centrifuged to retain the pollen.

1. The organic residue (from bulk maceration of the soil, step 6) was sieved through 120μm mesh to separate the larger megaspores and pieces of cuticle from the miospores.
2. The clay minerals were removed by placing the fine residue in suspension and decanting the clay minerals of 5μm having calculated their setting time according to Stoke's law (Jackson 1975)

3. The remaining residue was then macerated with fuming nitric acid and ammonium hydroxide (steps C1-6). However the residue was centrifuged during the washing procedures.

D. Mounting

Both cuticle and pollen were mounted in glycerine jelly for study in transmitted light. The glycerine jelly was made from 30 gm pure gelatine crystals dissolved in 180 ml distilled water on a warm hotplate, then allowed to cool. This mixture was then warmed again and 210 ml analar glycerol and 1 gm pure thymol stirred in. The jelly was kept in several small bottles and warmed in a water bath prior to use. All glass bottles, slides, coverslips and instruments were thoroughly cleaned in absolute alcohol before use.

1. A small drop of liquid glycerine jelly was placed on a glass slide.
2. A piece of cuticle or drop of miospore-rich solution was placed in the centre of the jelly.
3. A clean coverslip was placed gently on top.
4. The slide was placed on a warm hotplate for a few seconds until the glycerine (now beginning to set) remelted and flowed to the edge of the coverslip.
5. The slide was removed from the heat. Air bubbles were removed by quickly replacing the slide on the hotplate and pressing the coverslip gently.
6. When the cuticle or pollen was mounted the edge of the coverslip was sealed with a rim of Glyceel.
7. When necessary samples of cuticle and pollen were stained with safranin O, a red stain which sometimes enhanced cell structure. A few grains of this powder were mixed with the cuticle or pollen in distilled water.

Cuticle and pollen were also examined by SEM. Pieces of wet cuticle or drops of miospore solution were placed on stubs coated with double-sided Sellotape and allowed to dry before coating.

E. Preparation of the Dirt Beds for mechanical analysis

1. Weighed samples (approx. 200 gm) of the marly Dirt Beds were disaggregated in distilled water (often with the aid of ultrasonic treatment).

2. The material was separated into size fractions of $>$2 mm (considered as pebbles), 2 mm-50µm (sand), $<$ 50µm (silt + clay) Buol et al. 1979) by wet sieving. The clay fraction $<$ 2µm was separated from the silt using the suspension method based upon Stoke's Law (Jackson 1975).
3. Each grade was dried and weighed.
4. The percentage of sand, silt and clay in each Dirt Bed sample was calculated.

F. Determination of Organic Carbon and $CaCO_3$ in the Dirt Beds.

CO_2 and organic C were analysed using an infra-red gas analyser as follows:-

1. Samples of each Dirt Bed ($<$ 2 mm fraction) were ground to a fine powder.
2. 0.1 gm of sample was heated in oxygen at 85^{o}C in a glass boat in an air-tight pyrex tube. The CO_2 evolved was measured by infra-red detector, the output read on a chart recorder. Chemically pure $CaCO_3$ (0.1 gm) was used as a standard and run between 3 samples. This determines the total CO_2 (carbonate CO_2 + organic carbon as CO_2).
3. Carbonate CO_2 was then determined. A pipette was attached to the pyrex glass tube and orthophosphoric acid (1 ml) was dropped into the silica sample boat. The pyrex tube was preheated to a temperature of 150^{o}C. When all carbonate CO_2 gas was evolved it filled the volume meter, passed through the infra-red detector and was recorded on the chart. The equipment was calibrated at intervals using pure $CaCO_3$ (1 gm).
4. The organic carbon content was then computed from the organic carbon CO_2 content, obtained by subtracting the carbonate CO_2 content from the combined CO_2 content. Organic matter was obtained by multiplying organic carbon by 1.724 (Jackson 1975).

G. X-ray fluorescence spectrometry

The trace elements (Rb, Sr, Zr, V, Cr, Mn, Ni, Cu, Zn, Mo, P, As, Ti, Pb) of the bulk samples ($<$ 2 mm fraction) of the Dirt Beds were determined using an automatic Philips PW 1212 X-ray spectrometer. Analysis was based on established procedures as outlined by El-Shahat (1977), using pelleted samples.

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H. Computer program

The following program was used to calculate autocorrelation coefficients of tree-ring data. The program was written by Mr. T. Clayton, Geology Dept., Southampton University for use on a Hewlett Packard 9825A Calculator.

```
 0: dim X(100)
 1: sPc
 2: enp "NO.of rings",N
 3: for I=1 to N
 4: fmt 2,f3.0,f10.3
 5: ent X(I);wrt 16.2,I,X(I)
 6: next I
 7: sPc
 8: for J=0 to N
 9: N-J→O
10: if O<3; gto "END"
11: 0→A; 0→B; 0→C; 0→D; 0→E;
12: for I=1 to O
13: X(J+I)→Y; X(I)→Z
14: Y+A→A
15: Y×Y+B→B
16: Z+C→C
17: Z×Z+D→D
18: Y×Z+E→E
19: next I
20: B-A×A/O→F
21: D-C×C/O→G
22: E-A×C/O→H
23: if F<=0 or G<=0;
    0→R; gto "PRINT"
24: H/√(F×G)→R
25: "PRINT"
26: fmt 1,f3.0,f10.3
27: wrt 16.1;J,R
28: next J
29: "END":
```

	Sample	Location	%Org.C	%Org.M	%CaC03
Great Dirt Bed	SI	Wakeham East	2.II	3.64	46.8
	S2	Bowers Quarry	I.5I	2.60	40.5
	S3	Admiralty Quarry	0.99	2.7I	6I.6
	S4	Southwell Landslip	1.7I	2.95	53.1
	S5	Easton Quarry	0.I8	0.3I	66.8
	S6	Perryfield Quarry	I.7I	2.95	50.5
	S7	Wide Road Quarry	2.78	4.79	33.9
	S8	Breston	3.29	5.73	I9.9
	S9	Little Perryfield Quarry	I.3I	2.26	53.8
	SI0	Sandholes	I.38	2.38	68.2
	SII	Inmosthay Quarry	0.77	I.33	65.6
	S12	Fossil Forest	2.30	3.97	37.2
	SI3	Upwey Quarry	I.63	2.8I	74.4
	SI4	Bacon Hole	2.05	3.53	56.4
	SI5	Kingbarrow	I.3I	2.26	65.6
Lower Dirt Bed	LI	Wakeham East	I.36	2.35	78.I
	L3	Freshwater Quarry	4.68	8.07	48.6
	L4	Kingbarrow Quarry	2.35	4.05	62.6
	L5	Breston	3.67	6.22	56.6
	L6	Southwell Landslip	3.44	6.03	6I.9
	L7	Bowers Quarry	I.I6	2.0I	69.3
	L8	Perryfield Quarry	0.9I	I.65	58.9
	L9	Inmosthay Quarry	I.55	2.67	72.7
	LI0	Chalbury Camp	I.47	I.53	62.9
	LII	Poxwell	I.96	3.38	6I.9
	LI2	Worbarrow Tout	I0.95	I9.88	59.3
Basal Dirt Bed	BI	Southwell Landslip	I.65	2.85	6I.2
	B2	Kingbarrow Quarry	0.38	0,66	92.I
	B3	WakehamEast Quarry	0.34	0.59	88.4
	B4	Chalbury Camp	2.25	3.88	57.5
	B5	Poxwell	I.67	2.88	76.6
	B6	Perryfield Quarry	0.82	I.42	86.9
	B7	Breston	0.66	I.I4	78.7
	B8	Worbarrow Tout	3.54	6.I0	24.3
	C16	Durlston Head	6.I9	I0.67	43.7
	C17	Fisherman's Ledge	7.39	I2.74	2I.4
	L2t	Freshwater Quarry (Top)	22.II	38.I2	I0.0
	L2b	Freshwater Quarry (Base)	4.39	7.57	40.5

Table A_1 Dirt Bed sample locations and content of organic carbon, organic matter & carbonate.

	Sr	Rb	Ti	Zr	Mo	Mn	Ni
S1	945.6	129.4	2275.7	114.6	20.2	340.6	35.2
S2	2104.8	174.4	3203.7	149.8	5.0	280.8	31.5
S3	1011.8	94.3	1843.2	105.0	19.4	234.2	21.2
S4	1163.8	130.2	2555.5	122.2	19.5	290.6	24.8
S5	1145.9	82.8	1455.9	67.2	7.9	235.5	18.6
S6	1003.0	107.4	2560.2	116.3	33.8	302.0	29.6
S7	1361.8	156.3	3120.6	175.4	19.8	289.1	36.9
S8	356.1	195.1	4038.4	245.9	48.5	377.1	51.0
S9	1803.5	100.2	2267.1	98.1	9.7	250.7	23.8
S10	1164.6	79.2	1339.4	63.7	11.1	239.5	14.8
S11	1172.4	102.1	1917.4	87.9	11.2	181.9	12.7
S12	857.6	123.1	3460.2	146.5	19.1	435.2	32.5
S13	4521.9	30.3	676.5	23.3	12.9	129.0	15.7
S14	980.0	90.7	1713.1	86.9	9.0	284.4	14.1
S15	1882.8	93.6	1882.5	76.7	7.6	245.0	27.3
L1	606.4	17.0	800.4	40.9	7.4	119.0	18.9
L3	394.1	57.9	1891.6	81.0	16.7	155.0	137.0
L4	991.4	43.5	966.0	61.8	7.7	165.0	7.6
L5	1055.1	57.2	1307.3	95.2	34.9	141.0	71.8
L6	825.8	32.7	1249.7	65.8	8.9	117.0	64.5
L7	870.5	32.8	1166.7	54.9	---	129.2	26.2
L8	861.5	49.6	1866.9	81.1	8.7	200.3	8.9
L9	947.6	37.8	904.3	48.4	8.9	176.2	11.4
L10	638.4	55.5	1422.2	60.2	15.4	204.0	19.5
L11	761.4	49.7	1193.2	63.5	---	114.0	26.5
B1	853.2	64.9	1405.9	96.7	10.7	114.0	32.4
B2	581.6	10.4	235.2	11.8	5.3	116.2	---
B3	1049.6	13.4	483.4	22.3	4.9	135.2	15.1
B4	787.3	57.9	2038.9	157.9	16.6	180.3	57.4
B5	772.1	17.1	471.1	23.0	5.3	103.0	11.8
B7	1015.1	22.2	615.4	40.4	12.9	125.0	38.5
C16	592.5	63.5	1500.9	62.4	19.5	233.0	39.8
C17	186.8	102.0	2386.3	67.8	36.8	322.6	99.0
L2t	2627.6	89.6	2568.8	163.9	33.3	225.2	345.2
L2b	804.9	75.6	2329.9	113.1	30.3	213.3	105.0

Table A_2 Trace element content of the Dirt Beds.

	Cu	V	Zn	As	Cr	Pb
SI	I6.3	47.2	6I.5	25.2	68.4	2I.2
S2	25.5	69.2	47.6	I6.8	60.4	I4.6
S3	I7.3	89.I	7I.8	I4.4	42.0	23.4
S4	23.0	66.5	6I.2	I8.7	92.6	I7.9
S5	I6.9	40.8	6I.9	I8.8	3I.9	II.0
S6	I6.0	67.4	58.0	26.3	46.8	I9.I
S7	3I.9	I08.9	62.9	25.2	63.2	26.0
S8	I0.4	205.I	75.I	55.0	78.5	35.6
S9	20.7	34.8	24.9	---	88.I	I8.2
SI0	I5.6	39.8	46.0	I8.6	32.8	20.8
SII	6.5	48.0	29.0	9.5	4I.3	I0.7
SI2	---	6I.I	35.3	29.9	62.6	32.3
SI3	6I.7	49.5	36.5	8.7	94.9	8.2
SI4	I0.2	32.6	24.5	I2.4	39.6	I9.0
SI5	2I.I	43.0	47.9	I4.2	40.6	8.6
LI	I4.7	46.5	30.6	---	80.5	8.8
L3	II.5	I50.0	37.7	35.0	45.7	8.3
L4	I6.6	40.0	3I.8	---	20.5	I2.4
L5	66.8	I69.2	67.4	24.7	45.3	I2.9
L6	I0.9	I05.0	28.I	---	50.0	I2.6
L7	8.8	63.5	26.0	7.2	97.I	8.0
L8	I0.5	55.6	43.3	7.3	56.I	I2.5
L9	I0.2	43.5	2I.8	I0.I	84.5	8.0
LI0	8.8	68.0	45.5	8.5	35.2	I3.5
LII	25.7	84.2	54.6	I8.5	3I.5	II.I
B1	29.4	96.0	49.8	20.7	I7.0	I2.5
B2	8.8	I3.3	20.8	6.3	83.4	5.3
B3	I0.0	35.2	20.5	---	I3.5	I0.I
B4	32.8	222.0	II5.0	I4.2	34.3	I4.3
B5	I5.0	20.6	46.3	I6.5	88.6	8.2
B6	I8.8	---	38.9	I0.2	92.3	II.4
B7	2I.I	62.5	50.3	I2.4	92.3	I2.0
C16	23.3	69.9	82.0	I2.5	43.7	I2.7
C17	26.4	I33.0	I7I.5	5I.4	64.7	23.7

Table A_3 Trace element content of the Dirt Beds.

List of fossils quoted in the text and their authors.

FOSSIL PLANTS

Wood:- *Protopodocarpoxylon* Eckhold
P. aveiroense Lauverjat and Pons
Protocupressinoxylon Eckhold
P. purbeckensis sp. nov.
P. vectense (Barber) Eckhold
P. luccombense (Stopes) Eckhold
P. dockumense (Torrey) Krausel
P. koettlitz (Seward) Eckhold
P. malayense Roggeveen
P. chouberti Attims
P. aff. chouberti Attims and Crémiér
Araucarioxylon Krausel
Circoporoxylon Krausel
Xenoxylon Gothan
Cedroxylon Krausel
Foliage:- *Cupressinocladus* Seward
C. valdensis (Seward) Seward
C. ramonensis Chaloner and Lorch
C. malaiana (Kon'no) Barnard and Miller
C. acuminifolia Kon'no
C. pseudoexpansum Barnard and Miller
Frenelopsis Schenk
Pseudofrenelopsis Nathorst
P. parceramosa (Fontaine) Watson
Pagiophyllum Heer
Brachyphyllum Lindley and Hutton ex. Brongniart
B. mamillare Lindley and Hutton
Elatides Heer
Sagenopteris Presl.
Cheirolepis (*Hirmeriella*) *muensteri* (Schenk) Jung
Classostrobus Alvin, Spicer and Watson
C. rishra (Barnard) Alvin, Spicer and Watson
Masculostrobus harrisianus Lorch
Araucarites sphaerocarpa
A. phillipsi Carruthers
Triletes russus Harris
Classopollis Pflug
C. torosus (Reissinger) Balme
C. echinatus Burger
C. hammenii Burger
C. noeli Reyre
Cicatricosisporites Potonié and Gelletich
Araucarites australis Cookson
Inaperturopollenites (Pflug ex Thomson + Pflug) Potonie
Peltandripites Wodehouse
Cerebropollenites mesozoicus (Couper) Nilsson
Callialasporites (Sukh Dev) Potonié
Podocarpites (Cookson) ex Couper
Cycadopites Wodehouse ex Wibon and Webster
Nilssonia Brongniart
Cycadeoidea gigantea Seward
C. megalophylla Buckland
C. microphylla Buckland
Bennettites portlandicus Carruthers
Mantellia nidiformis Brongniart

M. intermedia Carruthers
M. microphylla Miquel
Equisetum morbergi (Hallé ex Moller)
Carpolithus Schlotheim
Klukia Raciborski

ALGAE

Ortonella Garwood
Cayeuxia Frollo
Hedströmia Rothpletz
Solenopora Dybowski

MODERN PLANTS

Thuja plicata D. Don
Juniperus oxycedrus Linnaeus
Zamia Linnaeus
Cycas Linnaeus
Cupressus macrocarpa Hartweg
C. arizonica Greene
Actinostrobus pyramidalis Miquel
Ulmus procera Salisbury
Pinus halepensis Miller
Pinus carribaea Morelet
P. sylvestris Linnaeus
Casuarina sp. Linnaeus ex Adanson
Callitris preissii Miquel
Eucalyptus sp. L'iteritier

FOSSIL FAUNA

Valvata helicoides Forbes
V. sabaudiensis (Mallard) Arkell
Hydrobia forbesi Arkell
H. chopardiana (de Loriol)
Fabanella ansata (Jones)
F. boloniensis (Jones)
Macrodentina sp. Martin
Cypridea punctata (Forbes)
Cypridea sp. Bosquet
Estheria
E. subquadrata (Sowerby) Jones
E. andrewsii Jones