The origin and recognition of laterally continuous carbonate-cemented horizons in the Upper Lias Sands of southern England

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Received 13 August 1987; accepted 31 November 1987

The Upper Lias Sands of southern England contain numerous, laterally extensive, carbonate-cemented horizons. Petrographical analyses of samples from outcrop sections and the Marchwood No. 1 borehole indicate that these horizons result from preferential cementation of bioclast-rich, clay-poor sediments by comparison with interbedded clay-rich, bioclast-poor sediments. The alternation of the two sediment types is attributed to the effects of, respectively, fairweather and storm processes on a submerged marine shoal. Petrographical and ichnological data indicate an early distinction of the strongly and weakly cemented horizons. The widespread extent of the cemented horizons, as indicated by outcrop studies on the Dorset coast, is considered to be a direct consequence of episodic storm activity on the low relief shoal. Sedimentological, palynological and petrophysical criteria are presented to assist in recognition of similar extensive cements in subsurface reservoir horizons that do not outcrop.

Keywords: Shelf sands; sedimentology; diagenesis; ichnology; palynology

Introduction

Several Jurassic oil and gas fields in the North Sea occur within shallow marine sandstones which contain thin tight zones resulting from the precipitation of calcium carbonate cements (Maher, 1981; Olaussen *et al.*, 1984; Kantorowicz *et al.*, 1987). The degree of lateral continuity of these cemented zones has important implications for production from such fields since they may act as extensive barriers, or local baffles, to fluid flow. However, it is often difficult to establish accurately the extent of these cements in the subsurface. The Upper Lias (Bridport) Sands of southern England provide a useful analogue for these North Sea sands since they are also of shallow marine origin, possess similar, thin, carbonate-cemented horizons, form an important hydrocarbon reservoir and may be studied both from subsurface data and at outcrop.

This study integrates new data from investigations of outcrops and the Marchwood No. 1 borehole (*Figure 1*) with published outcrop and borehole data to provide a depositional/diagenetic model to explain the formation and distribution of the carbonate cements within the Sands*. Criteria have been derived for recognition of these cemented horizons in the subsurface and, it is suggested that these criteria may be applicable to the assessment of cement geometries in other reservoirs of similar origin.

*When the word 'Sands' is capitalized it refers to the formation name but then written in lower case it is used as a grain size indicator

Geological setting

Upper Liassic (Lower Jurassic) Sands underlie a large part of southern England (*Figure 2*) and outcrop in a north – south oriented belt from the Cotswolds to the Dorset coast (*Figure 1*). The Sands form a diachronous unit (Buckman, 1910) which rises stratigraphically (youngs) to the south and east (Davies, 1967; Davies, 1969; Colter and Havard, 1981). The Sands were deposited in two basins separated by the shallows of the Mendip axis (*Figure 1b*). In this study only the southern basin is considered, where the Sands are Toarcian to Aalenian (Upper Liassic) in age (Cope, 1980). In this area the Sands have been referred to as the 'Yeovil' and 'Bridport' Sands at outcrop and as the 'Upper Lias Sands' in the subsurface. During the Lower Jurassic the area formed part of a shallow epeiric sea strongly affected by an extensional tectonic regime giving rise to areas of varying subsidence rates ('basins and swells' of Sellwood and Jenkyns, 1975; Hallam and Sellwood, 1976) resulting in the preservation of variable thicknesses of sediment (*Figure 2*).

Over most of the Wessex Basin the Sands overlie the Down Cliff Clay ('Upper Lias Silts and Mudstones'; *Figure 3*) with a gradational contact such that the average grain-size of the Sands decreases downwards, whilst the frequency of sandy and silty laminae in the Down Cliff Clay increases upwards. The Sands are abruptly and/or erosionally overlain by the limestone sequence of the Inferior Oolite (*Figure 3*). In this area the Inferior Oolite is represented by grainstones, ooliths, berthierine pellets, oncolites and other algal

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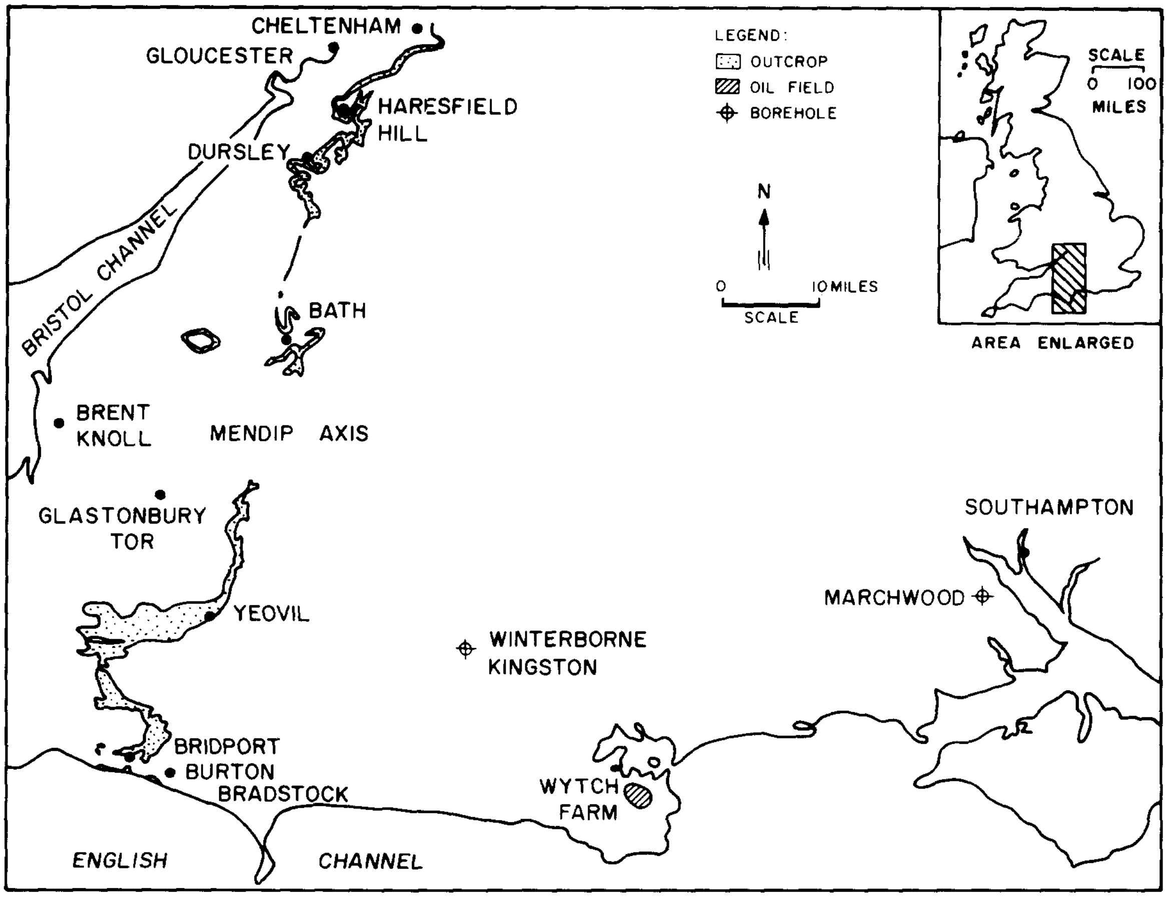
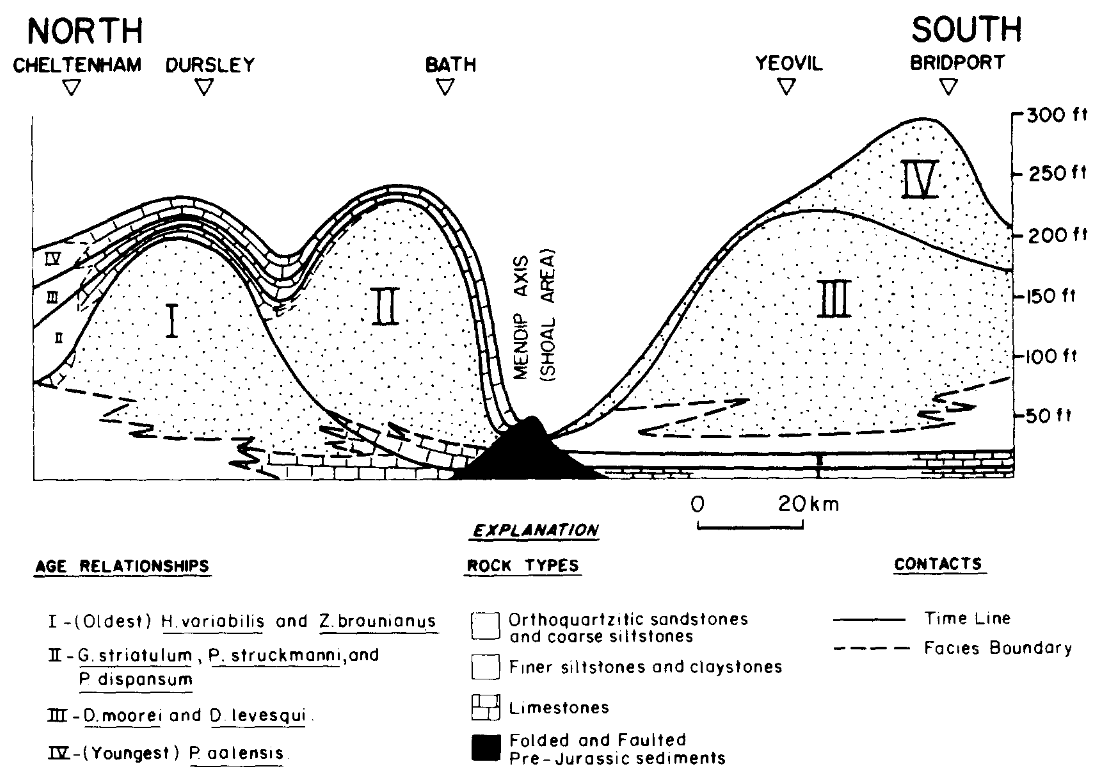


a.



b.

Figure 1 (a) Map to show the outcrop of the Upper Lias in southern England and the location of places mentioned in the text. (b) North-south cross-section through the Liassic Sands to illustrate diachronism (from Davies, 1969)

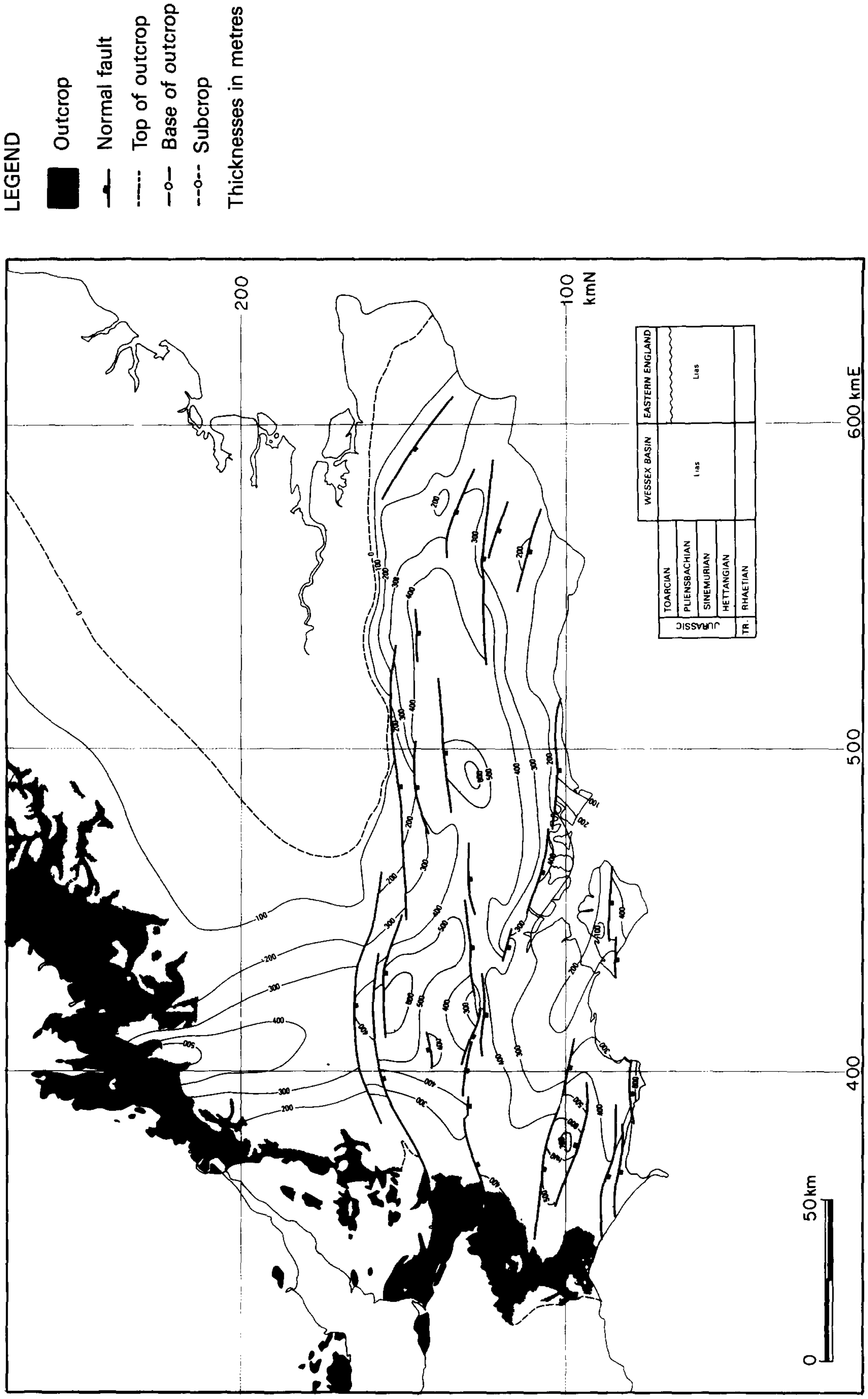


Figure 2 Isppachytes for the Lias (Hettangian to Toarcian) of southern England showing the irregular thickness of sediment as a consequence of spatial variation in subsidence rates. (*From Whittaker*, 1985)

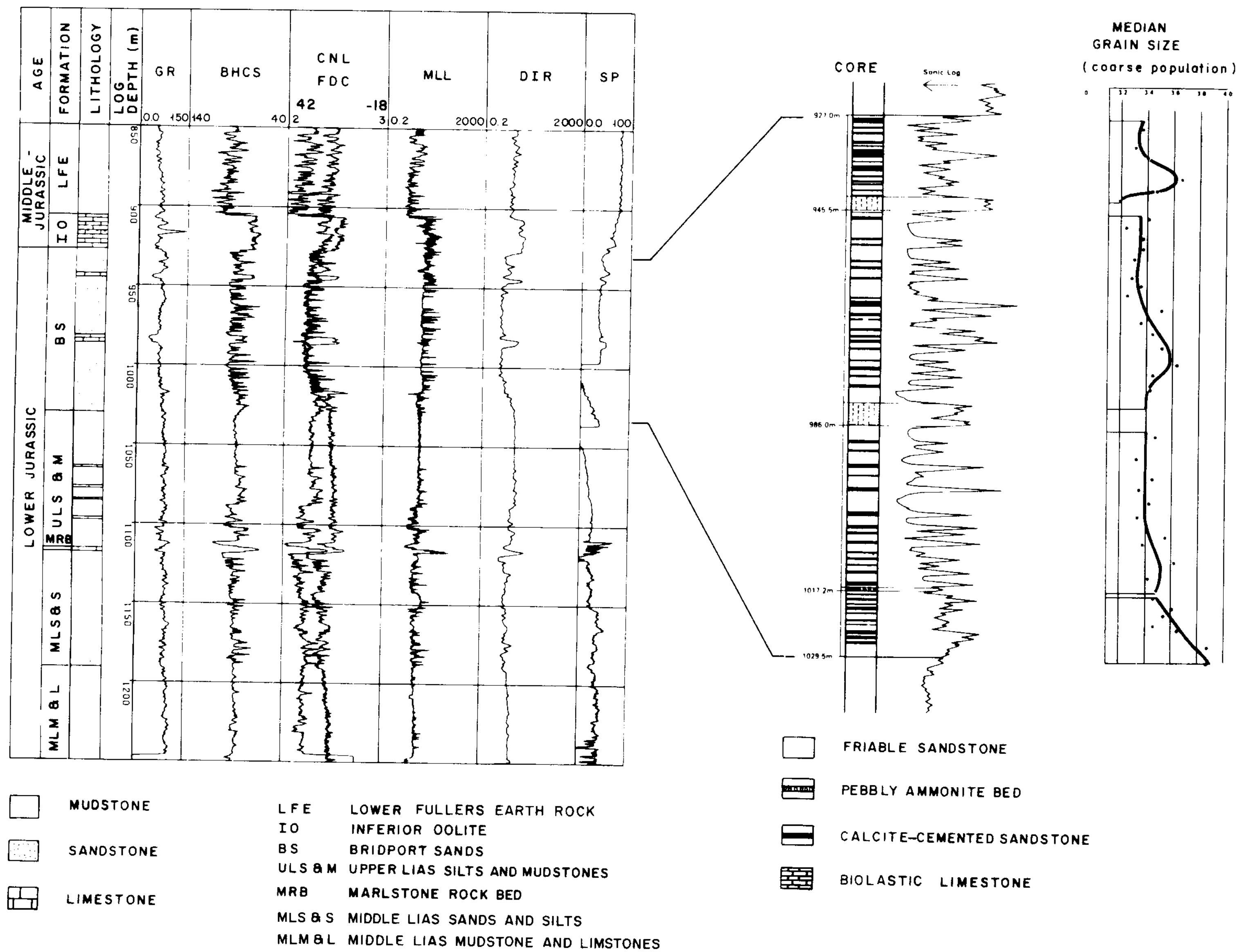


Figure 3 Log and core data from the Winterborne Kingston borehole. Note the correspondence of fast peaks on the sonic log with the tightly cemented horizons recognised in core and the subtle grain size trends in the acid insoluble coarse population (grain size scale in phi units). (Modified from Knox *et al.*, 1982)

structures indicative of a shallow-water origin on a protected marine platform (Davies, 1969). The unit also contains oyster-encrusted and bored phosphatic hardgrounds and omission surfaces and is locally condensed. Fossil fragments within these limestones are themselves often rolled and encrusted with iron precipitates (Kellaway and Welch, 1948). Mapping and palaeontological investigations in the Bridport area have established that locally the lowermost Inferior Oolite is laterally equivalent to the uppermost Liassic Sand (Wilson *et al.*, 1958). Similarly, log correlation in the area of the Wytch Farm oil field suggests that where the Inferior Oolite is particularly thin, the Oolite may be laterally equivalent to the uppermost part of the Upper Lias Sands (Colter and Havard, 1981). In the Yeovil area the Sands are apparently partly eroded and replaced by a lens, over 17 km wide and 30 m thick, of ferruginous, cross-bedded bioclastic limestone known as the Ham Hill Stone. Thinner units of cross-bedded berthierine-rich, bioclastic limestone also occur in the Winterborne Kingston borehole (*Figure 3*) (Knox *et. al.*, 1982 Plates 2 and 3) and the Marchwood borehole (*Figure 4*).

The Upper Lias of the area is thus represented by a shallowing upwards cycle of mudstone – sandstone – limestone. This vertical sequence appears to represent migration of a lateral sequence of facies belts from a muddy shelf in the south, through a sandy bar to a shallow carbonate shelf in the north (Davies, 1969; Hallam, 1975).

Liassic sequences in the Wessex basin show pronounced thickness variations (Arkell, 1933; Sellwood and Jenkyns, 1975; Hallam and Sellwood, 1976; Colter and Havard, 1981; Sellwood *et al.*, 1986) associated with syn-sedimentary growth fault movement (Jenkyns and Senior, 1977; Chadwick *et al.*, 1983) (*Figure 2*). Thus the Winterborne Kingston borehole records an anomalously thick Liassic interval which includes a Middle Liassic sequence of mudstone – sandstone (with carbonate-cemented horizons) – limestone (*Figure 3*) which is similar to the more widespread Upper Liassic cycle. This same Middle Liassic interval is represented in thinner Liassic sections by silty mudstones in boreholes at Marchwood and Cranborne; by limestones at Fordingbridge, and by a similar, but thinner, sequence at Wytch Farm (Colter and Havard, 1981). Such fault-controlled facies variation is unusual however and variations in subsidence are more usually expressed simply as thickness variations (Hallam and Sellwood, 1976), suggesting either frequent and gradual fault movement or high sedimentation rates to maintain a low-gradient submarine topography (Sellwood and Jenkyns, 1975).

Sedimentology and palynology

Sedimentological and palynological features of the Sands were recorded from cores collected from the Marchwood borehole and from outcrops in Dorset and Somerset. These data were supplemented by published descriptions of the Sands from outcrops and from cores collected in the Winterborne Kingston borehole (Knox *et al.*, 1982) and the Wytch Farm oil field (Colter and Havard, 1981; Morris and Sheppard, 1982).

Marchwood cores

The Marchwood cores represent 120 ft (36.6 m) of the upper part of the 238 ft (72.5 m) of Upper Lias Sands proven by the borehole (Whittaker, 1980). The core is illustrated in *Figures 4* and *5* and described in more detail by Bryant and Kantorowicz (in prep.). The interval consists predominantly of bioturbated grey-green fine sands with alternating strongly and weakly cemented horizons. Mollusc shells, ammonites and belemnites occur both dispersed within the sands and concentrated into distinct bands. These bands are tightly cemented by calcite, as are other thin horizons in which macrofaunal remains are not visible. Tight bands tend to be greyer; possess a higher proportion of vertically aligned burrows and have a lower mica and clay content than the intervening more argillaceous beds which are greener and possess a higher proportion of horizontal burrow systems (*Figure 5f*). Many of the tight bands contain thin vertically aligned fractures filled with calcite cement (*Figure 5d*). The fractures are sometimes folded with horizontal axial fold planes (*Figure 5d*). The evidence provided by the folding of the fractures suggests compactional shortening of the tight horizons. However, very little compaction has taken place in these horizons (Davies, 1969), thereby suggesting that the fractures are of very early origin. The high frequency of occurrence of these fractures in the core suggests the existence of a high-density fracture system which is confined to the tight streaks. The tight streaks themselves are thinner and more closely spaced in the lowermost and uppermost parts of the sequence.

Winterborne Kingston cores

The complete thickness of the Upper Lias Sands was cored in the Winterborne Kingston borehole (*Figure 3*) and has been described by Knox *et al.* (1982). The Sands are divided into three coarsening and cleaning upwards cycles, each of which is overlain by a bioclastic limestone (*Figure 3*). The sands are fine-grained, strongly bioturbated and show an alternation of weakly and strongly cemented horizons. The latter show an increase in frequency towards the top of the Sands. The Sands contain variable quantities of admixed kaolinite and chlorite which was originally deposited as fine laminae (*cf. Figure 9*) but which has subsequently been redistributed by burrowing organisms. Scattered bivalve, brachipod and crinoid fragments occur throughout but are more abundant in the tight streaks. Patches of cement also occur in the more argillaceous, less-well-cemented sands where they occur preferrentially in coarser grained burrow-fills. Trace fossils such as *Chondrites, Skolithos* (up to 30 cm long), *Rhizocorallium* and *?Ophiomorpha* are recognizable on core photographs (Knox *et al.*, 1982; Plate 1) and are similar to those seen in the Marchwood cores (Appendix 1 and *Figure 5*). The limestones contain bioclasts, ooliths and pellets and show cross-bedding emphasised by berthierine mud drapes (Knox *et al.*, 1982; Plate 3).

Outcrops on the Dorset Coast

The uppermost 37 m of the Upper Lias Sands were logged by tracing the coastal exposure between West Bay, Bridport and Burton Bradstock (*Figure 1*). The section is illustrated by *Figures 6–8*.The cliffs comprise alternations of friable yellow, silty fine sand and grey/brown calcite-cemented calcareous sandstones which form prominent ledges on the weathered cliff face and both decrease in thickness and increase in frequency towards the top of the section (*Figure 8a*) (Davies,

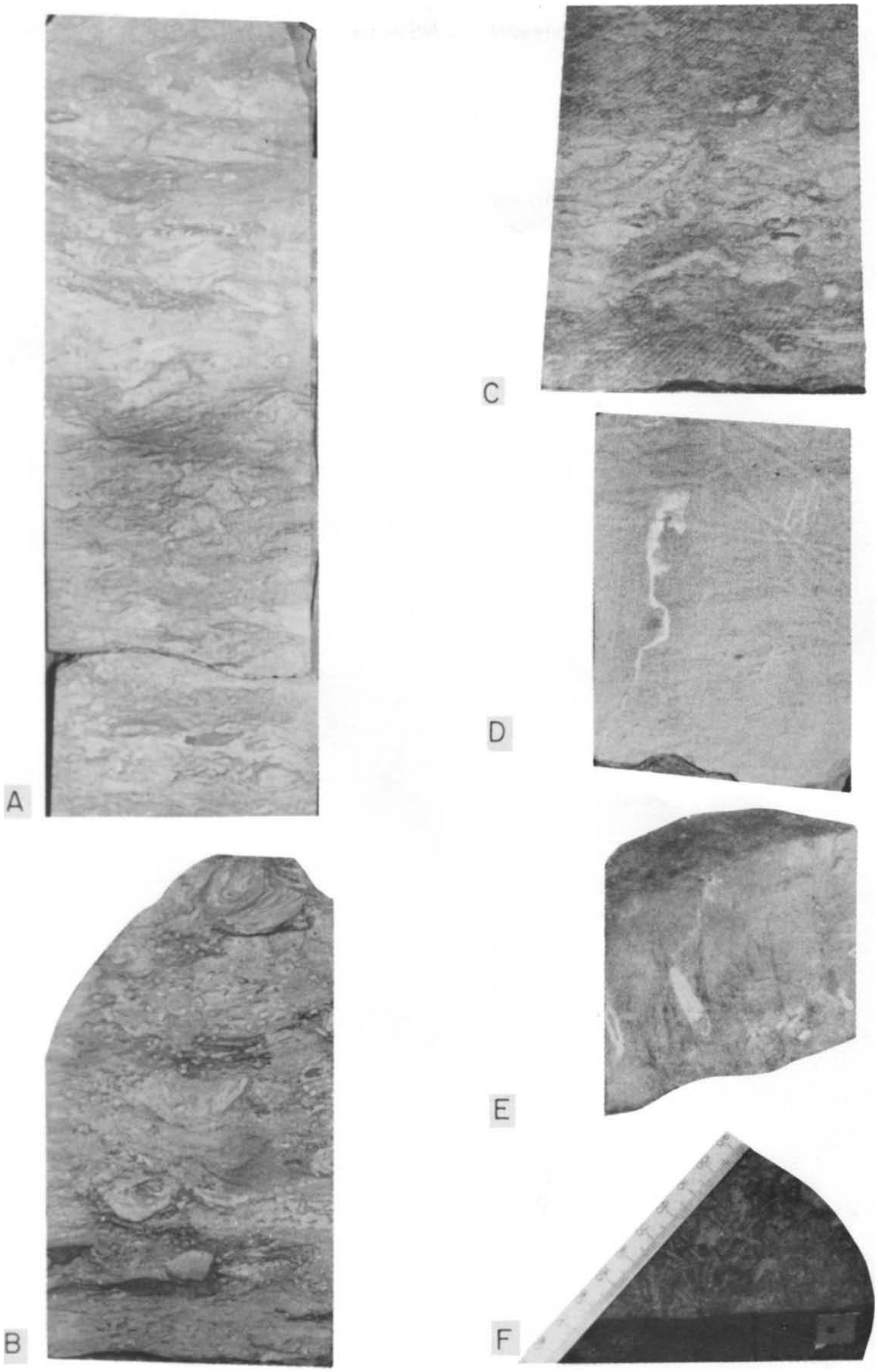


Figure 5 Marchwood No. 1 borehole cores. (a) Depth: 3841′4″–3843′0″. Core slabbed perpendicular to bedding to show *Rhizocorallium, Chondrites, Teichichnus* and *Thalassinoides* burrows in very fine-grained, silty sands. Note compaction of *Thalassinoides*. (BGS specimen BDZ2758). (b) Depth: 3827′5″–3828′3″. Core slabbed perpendicular to bedding to show *Rhizocorallium, Chondrites,* and *Teichichnus* burrows in very fine-grained, silty sands. Note layered back-filling (vertically retrusive) *Rhizocorallium* burrow at the top of the core. Compare sharply defined, circular *Teichichnus* (centre of slab) with compacted *Thalassinoides.* burrows at the base. (BGS specimen BDZ2757). (c) Depth: 3936′0″–3936′6″. Core slabbed perpendicular to bedding showing grey (low silt content) strongly cemented horizon and brown/grey (more argillaceous) weakly cemented horizons in very fine, silty sandstones. (BGS specimen BDZ2762). (d) Depth: 3854′1″–3854′8″. Core slabbed perpendicular to bedding to show a calcite-filled fracture within a well-cemented horizon of very fine-grained sand. (BGS specimen BDZ2759). (e) Depth: 3886′10″–3887′3′. Core slabbed perpendicular to bedding to show a calcite-filled ammonite and an associated cemented fracture. (BGS specimen BDZ2760). (f) Depth: 3890′0″. Core slabbed parallel to bedding to show narrow diameter, cylindrical horizontal (*Planolites*) burrows in sandy silt. (BGS specimen BDZ2761)

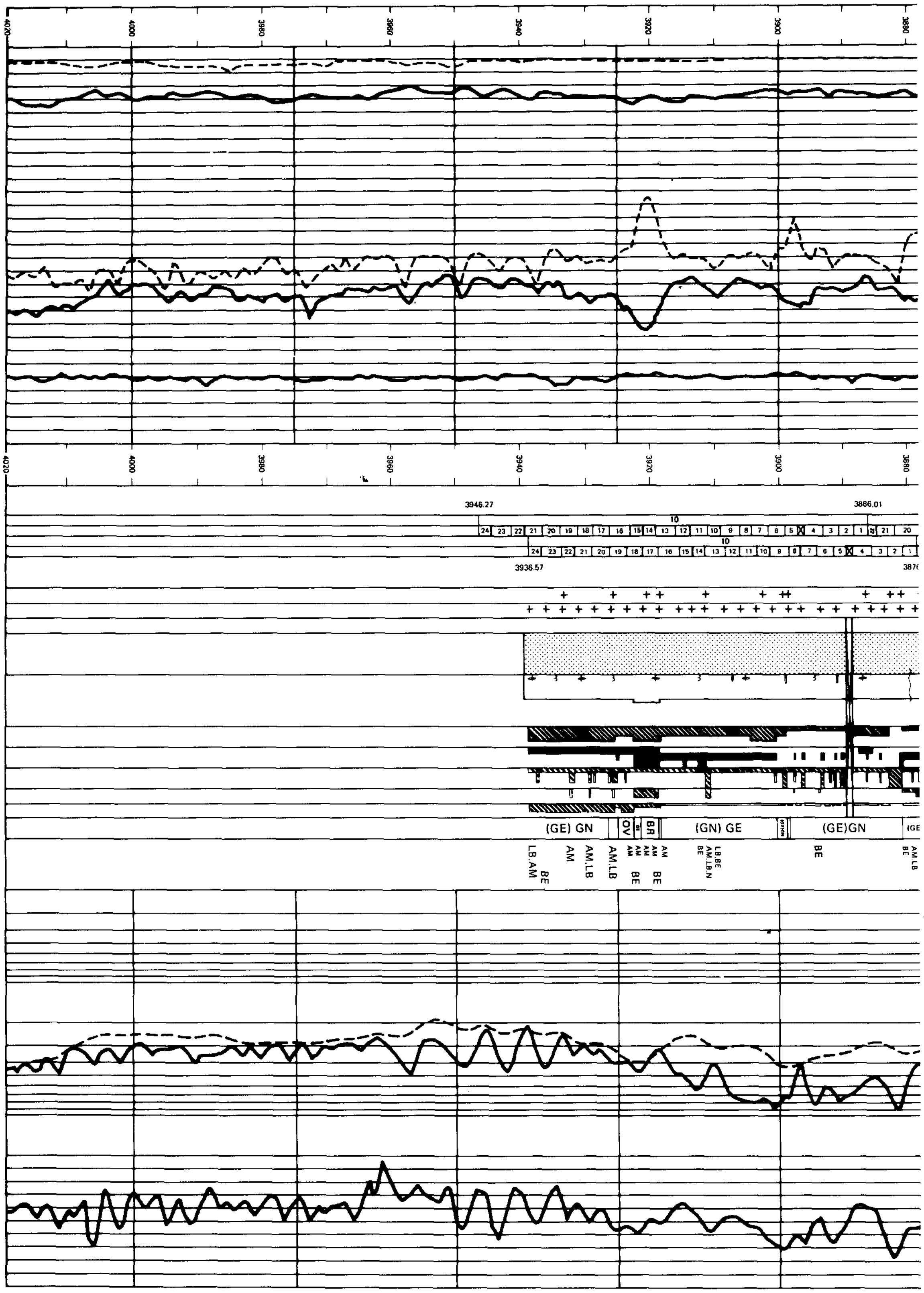
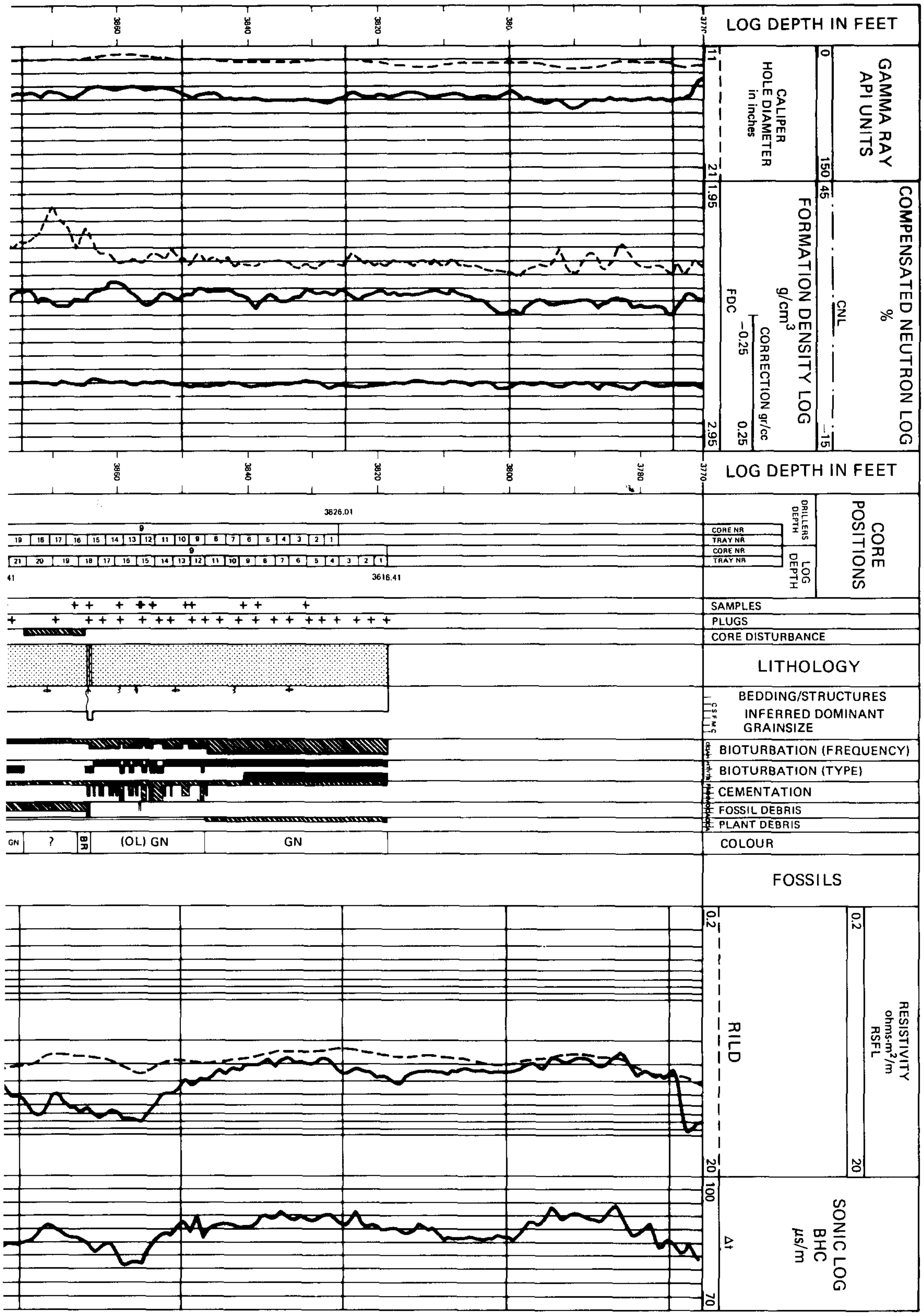


Figure 4 Core description and selected logs from the Marchwood No. 1 borehole. (Colour codes: BR — brow
OV — Olive. Fossil codes: AM — ammonite; BE — belemnite; LB — lammellibranch)



n; GN — green; GE — grey;

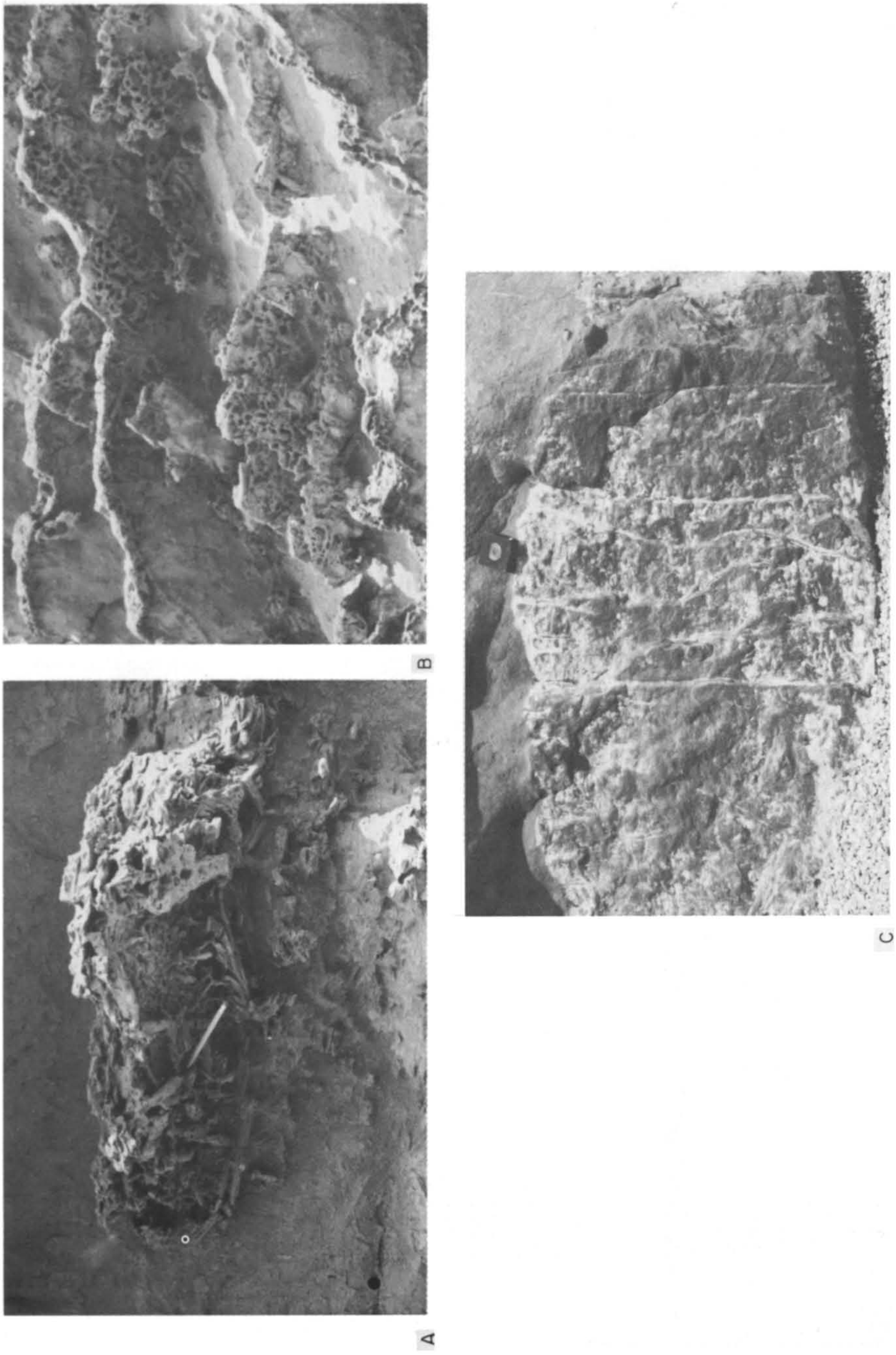


Figure 6 Detail of outcrop sections from the Dorset coast between Bridport and Burton Bradstock. (a) Preferentially cemented burrow systems. Note the horizontal to gently inclined *Thalassinoides* burrow systems intersected by a dense network of sub-vertically oriented burrows. (Pencil length 18 cm). (b) The underside of several cemented horizons, showing the preferential cementation of *Thalassinoides* burrows. (c) A strongly cemented horizon showing long *Skolithos* burrows. (Tape measure 5 cm long)

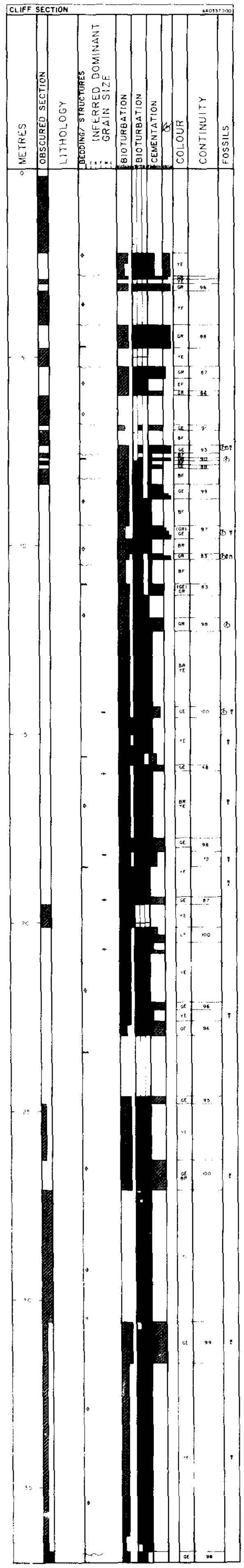


Figure 7 Log of the outcrop section between Bridport and Burton Bradstock. (For explanation of codes see *Figure 4*. Continuity refers to the lateral extent of the cemented horizons as a proportion of the outcrop length)

1967). The tight bands are less obvious at the sites of recent cliff falls, where each section of friable sand apparently consists of several beds of a similar thickness to the adjacent tight horizons, thereby suggesting that the thickness of the tight horizons (6–67 cm) is related to bed thickness. Occasional belemnites occur within the friable sands, whilst many of the tight horizons (particularly towards the top of the section) contain shell fragments, belemnites and partially calcite-filled ammonites. All the sediments are strongly bioturbated (*Thalassinoides, Rhizocorallium, Teichichnus* and *Skolithos*) (Sellwood *et al.*, 1970) with a predominance of long vertical burrows visible in the tight horizons (*Figure 6c*). Cementation is preferentially developed within burrow systems immediately above and below tight horizons (*Figures 6a* and *b*), suggesting either a more favourable chemical micro-environment and/or increased permeability in these burrows. Sedimentary structures are poorly preserved but occasionally low-angle or hummocky lamination is visible (Hounslow, 1987; Figure 4).

The coastal outcrops reveal the presence of four morphological types of cementation:

1. Isolated nodular and concretionary forms generally less than 0.5 m thick and 1 m wide (*Figure 6a*).
2. Interconnected bulbous cements of similar thickness to (1) but linked to form a 'patchy-sheet'.
3. Laterally extensive sheets continuous in three dimensions (*Figure 8a*).
4. Small-scale, vertical fracture-defined cements (*cf. Figure 5d*).

The first three categories form a continuum such that many of the more continuous horizons appear to have developed from linking of concretions. Often this process appears to be controlled by horizontal burrow systems (*cf.* Fürsich, 1973). Most of the cemented horizons are extremely laterally extensive (61% of them extend for over 90% of the 5 km coastal outcrop). The most common causes of discontinuity in these, otherwise laterally extensive, horizons are large-scale, fracture-solution pipes oriented at an angle to the cliff line and occurring at irregular intervals (*Figure 8a*). The origin of these features is uncertain but it may be related to fractures caused by gas escape (Clarke in Lake, 1985). At the western extreme of the outcrop extensional faults offset the cemented horizons (*Figure 8b*).

Small-scale vertical fracture-defined cements are:

- i always confined to the tight horizons;
- ii composite and extensional in character;
- iii infilled by calcite cement; and
- iv preferentially oriented east-west and north-south, thereby imparting a blocky fracture pattern to the cliff (*Figure 8a*).

Their containment within the tight horizons indicates that differential strengths between the weakly and tightly cemented horizons already existed at the time of fracture propagation. These constraints suggest that the most likely origin of the fractures is an extensional hydraulic fractures formed by the release of overpressures developed in the weakly cemented horizons as a result of early restriction of vertical pore-fluid movement by the tight horizons.

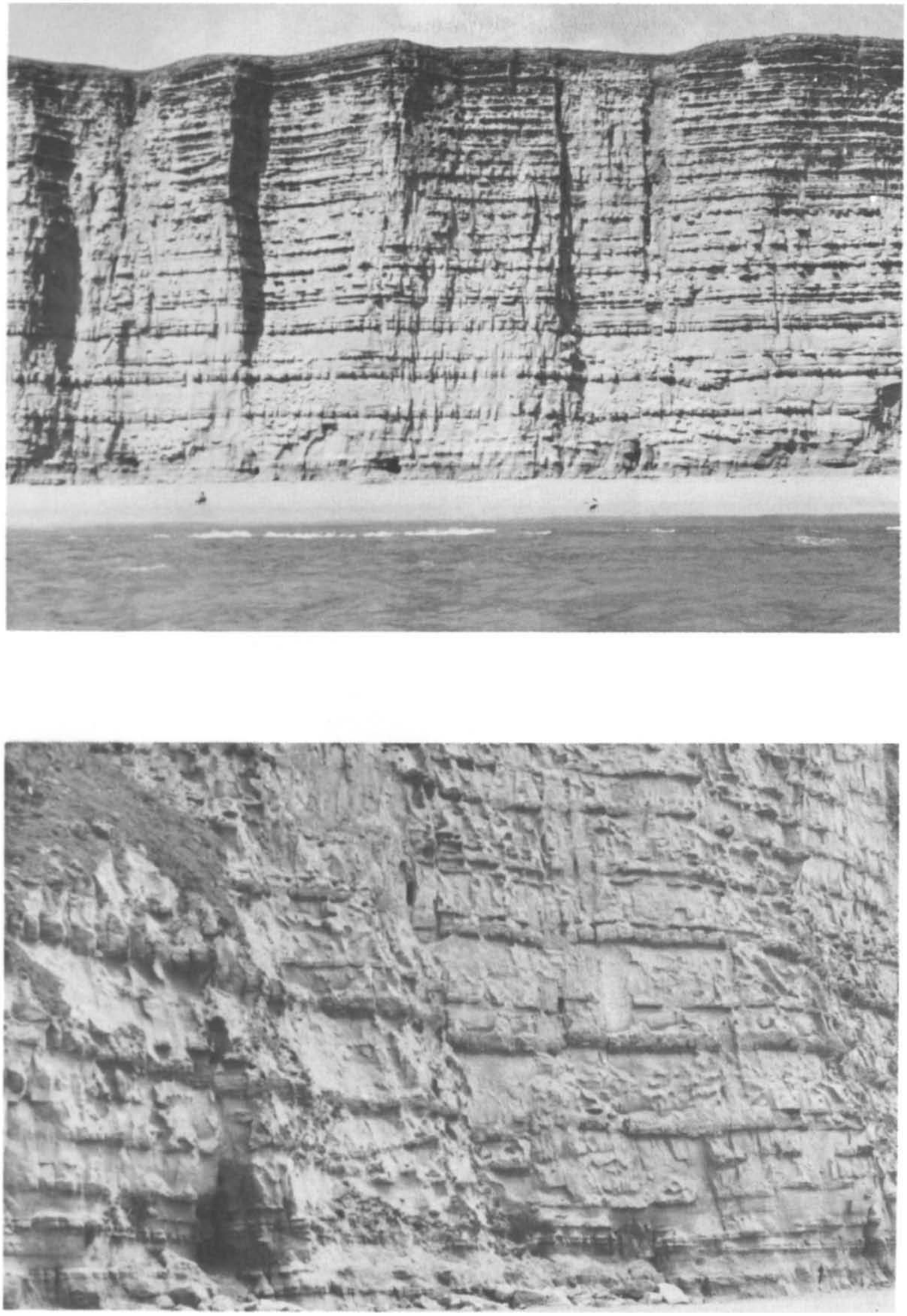


Figure 8 Coastal exposures. (a) Cliff section through the Sands between Bridport and Burton Bradstock. Note the lateral continuity and variable spacing of the cemented horizons. (b) Cliff section at West Bay, Bridport showing small offsets of the cemented horizons associated with extensional fracture systems.

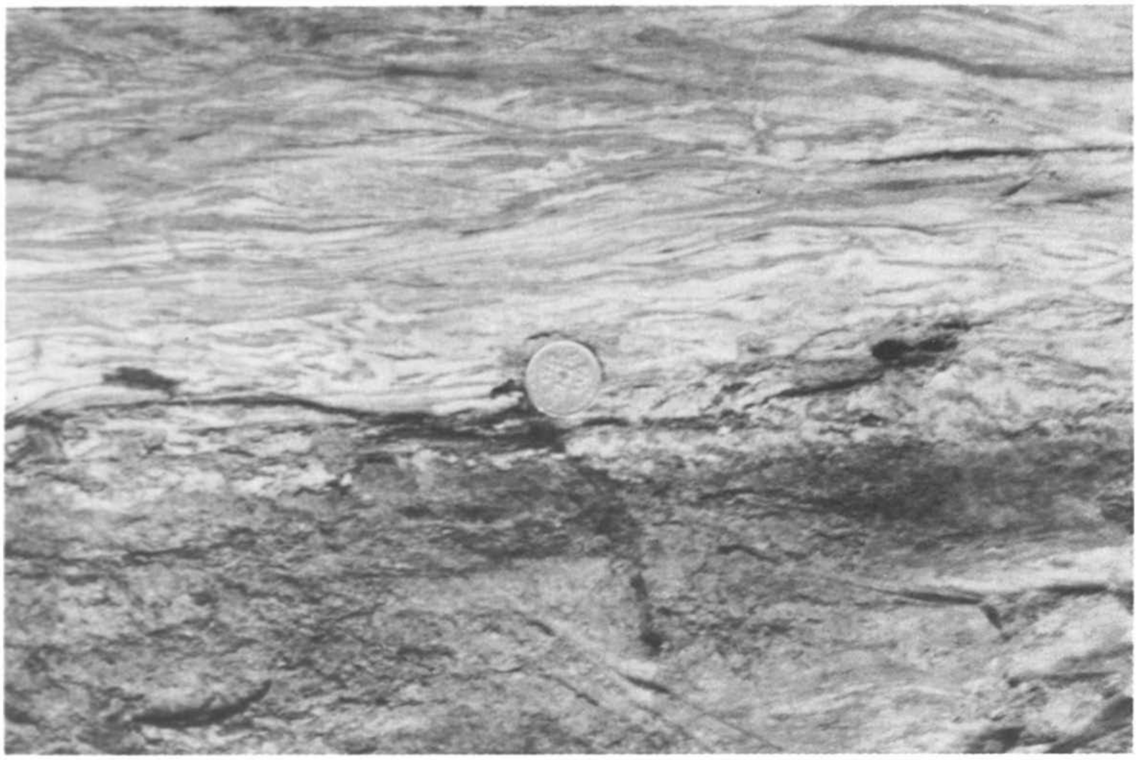


Figure 9 Inland outcrop at Bradford Hollow, east of Yeovil (Grid. Ref. ST580160) showing flaser ripple-laminated sands. (Coin 24 mm diameter)

Inland exposures in Dorset and Somerset

Exposures inland are less aggressively weathered than those on the coast and show less evidence for distinct alternations of tight and friable sands. Carbonate-cemented sands occur most commonly as discontinuous lines of concretions, often centred on burrows (*cf.* Fürsich, 1973). In the area around Yeovil (*Figure 1*) bioturbation is generally less intense than that observed on the coast and in the Marchwood cores, so that ripple, climbing ripple, flaser ripple (*Figure 9b*) and low-angle lamination are observable (Hounslow, 1987; Figure 6). Coarsening-upwards cycles of metre to decimetre scale are also seen in the area around Yeovil. These Sands contain a higher proportion of silty material and are finer grained than those exposed on the coast, leading to the suggestion that they were deposited in a quieter water, protected environment (Davies, 1969).

Palynology

Palynological (palynofacies) analysis was carried out on 18 samples from the Marchwood borehole and on 4 samples from the coastal outcrop. The three samples collected from the Burton Bradstock outcrop (*Figure 1*) were taken from within 0.23 m of each other in one cemented block to test within-bed variability.

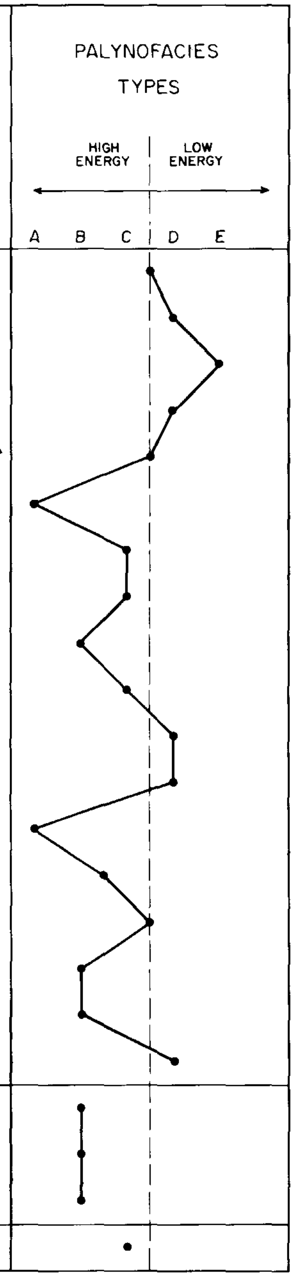
The samples were prepared using standard palynological techniques and sieved at 15 μm prior to slide mounting. Each slide was systematically examined using transmitted normal and incident ultra-violet light. The palynomacerals/palynomorphs present were recorded semi-quantitatively and the data are reproduced in *Figure 10*. The classification of palynomacerals used is an adaptation of that summarily described by Whitaker (1984). A brief description of the palynomacerals 1–4, and of the other palynological constituents, is provided by the captions accompanying *Figure 11*).

Five palynofacies types, which can be described as the global microscopical characteristics of a palynological assemblage after palynological preparation, have been identified and are assigned to the informal types A–E (*Figure 11*). The principles of palynofacies analysis have been discussed in several papers, notably by Combaz (1964), Hancock and Fisher (1981), Batten (1982a; 1982b) and Whitaker (1984). However, most of these publications refer to non-marine and deltaic deposits and the palynofacies of fully marine sediments are less well documented. The palynomaceral/palynomorph content and main physical characteristics of the palynofacies types are shown in *Figure 10* and are also described in the captions for *Figure 11*.

The presence of common or frequent dinoflagellate cysts, including *Nannoceratopsis* spp., *Eyachia prisca* (Gocht, 1979) and *Mancodinium semitabulatum* (Morgenroth, 1970) in all the palynofloras would indicate a marine depositional environment. However, acritarchs, tasmanitids and 'leiospheres' are also present in the assemblages, especially in the samples towards the top of the Marchwood borehole. These microplankton groups are found in ecologically more pressurised environments, perhaps with more restricted water circulation conditions (Tappan, 1980). The presence of these morphotypes may reflect the influence of material derived from a protected shallow marine platform to the north.

In this study the main controlling factor on the variations in palynological constituents is considered to be depositional energy. The five palynofacies types therefore form a gradational series which reflects deposition in relatively high (A) and low (E) energy conditions. There is no indication of post-depositional oxidation which would alter the palynomaceral proportions and appearance. The effects of bioturbation, seen

SAMPLE ORIGIN	DEPTH/ SAMPLE NO.	ORGANIC CONTENT	PALYNOMACERAL SORTING	PALYNOMACERALS: PALYNOMACERAL 1	PALYNOMACERAL 2	PALYNOMACERAL 3	PALYNOMACERAL 4 EQUIDIMENSIONAL	PALYNOMACERAL 4 BLADE	SOM	ALGAL MATTER	PALYNOMORPHS: DINOFLAGELLATES	SPOROMORPHS	ACRITARCHS	TASMANITES / LEIOSPHERES	LARGE LEIOSPHERES	PALYNOFACIES TYPE	CARBONATE CEMENT *
MARCHWOOD NO. 1 BOREHOLE	3838'0"	G/M	M/P	•	/	/	●	●	/	•	/	○	/	●	●	C/D	P
	3846'3"	G	P	/	/	●	●	■	•	•	/	○	○	/	○	D	P
	3856'0"	G/M	P	○	●	○	●	●	○	/	•	/	/	○	○	E	P
	3857'0"	G/M	P	/	○	/	●	●	/	•	/	●	/	/		D	P
	3862'3"	G/M	M/P	•	○	/	●	●	•	○	/	○	○	/		C/D	R▲
	3863'11"	P	G,M		•		/	/		•	/	•	•			A	R
	3864'1"	M	M/P	•	/	•	●	○		○	/	○	○	•		C	R
	3866'9"	M	M	•	/	•	/	○		•	○	•	/	•		C	R
	3888'3"	M/P	M	•	•	•	/	/		•	○	•	/	•		B	R
	3890'3"	M	M	•	•	•	●	○	/	•	○	•	/	•		C	R
	3894'1"	M	P	•	○	•	■	■	•	/	○	○	•	•		D	P
	3898'3"	M	M/P	/	○	•	■	○	/	●	•	•	•	•		D	P
	3898'11"	P	M	•	•	•	/	/		●	/	•	•	•		A	R
	3905'11"	M	M	•	•	•	○	/			○	•	/	•		B/C	R
	3909'9"	M	M/P	•	/	/	●	○			/	/	•	/		C/D	P
	3918'9"	M	M	•	•	•	●	/			○	•	/	•		B	R
	3928'0"	M/P	M	•	•	•	○	/			○	•	/	•		B	R
	3933'2"	G	P	•	○	•	●	○	•		/	●	•	•		D	P
BURTON BRADSTOCK	BB9	M/P	M	•	•	•	■	○		/	/	/	○	•		B	R
	BB 9A	M	M	•	•	/	●	○		•	○	•	/	•		B	R
	BB 9B	M/P	M	•	•	•	●	/		•	/	•	/	•		B	R
WEST BAY	WB 4	G/M	M/P	•	/	•	●	○		/	/	/	○	/		C	R



L E G E N D

PALYNOMACERAL / PALYNOMORPH FREQUENCY :

- • RARE
- / FREQUENT
- ○ COMMON
- ● ABUNDANT
- ■ VERY ABUNDANT

SORTING / ORGANIC CONTENT

- P POOR
- M MODERATE
- G GOOD

* CARBONATE CEMENT DETERMINED BY PETROGRAPHY :

- R RICH
- P POOR

▲ SEE TEXT

PALYNOMACERAL / PALYNOMORPH DISTRIBUTION CHART

Figure 10 Palynofacies characteristics of samples of Upper Lias Sands collected from the Marchwood No. 1 borehole and from outcrops on the Dorset coast. (BB — Burton Bradstock (Grid. Ref. SY483892) and WB — West Bay (Grid. Ref. SY465903))

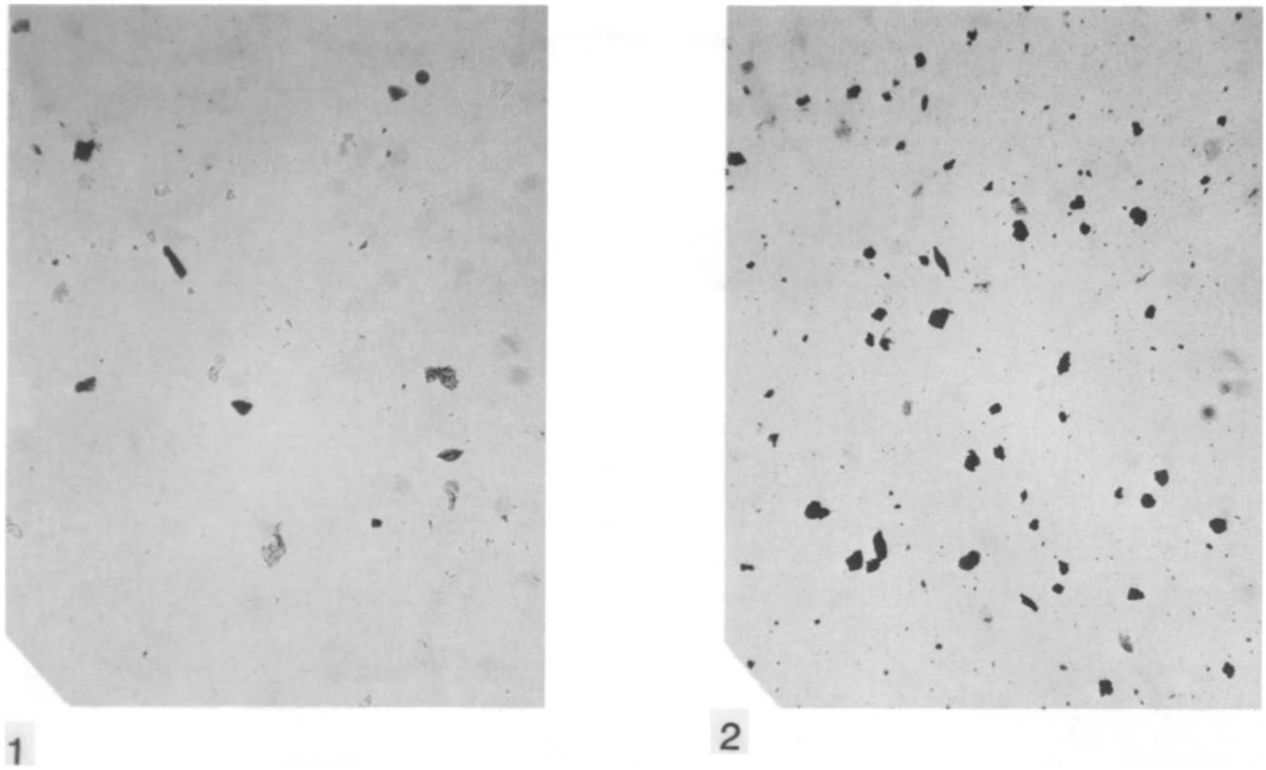
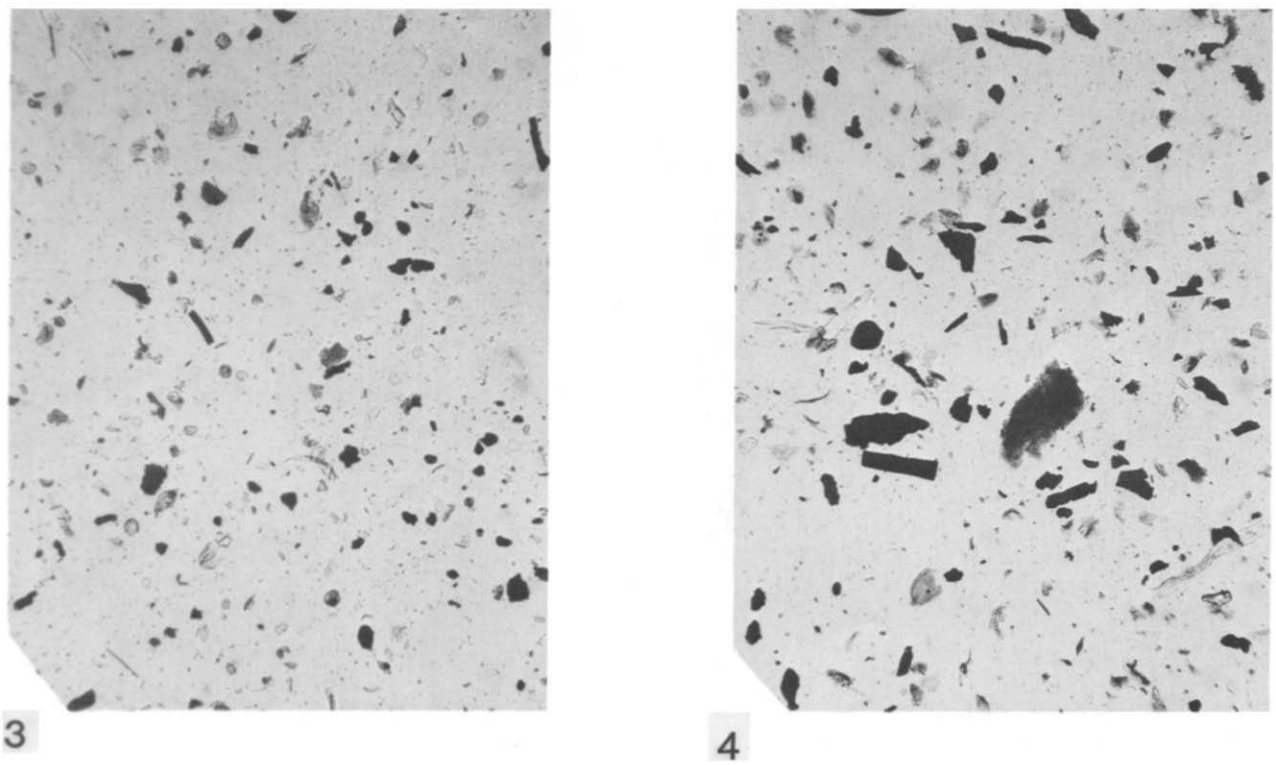


Figure 11a Palynofacies descriptions (photomicrographs at x80)
(1) *Palynofacies A (Marchwood borehole 3863' 11"):* The palynofacies is characterized by the very low quantity of organic material present. The palynomacerals are totally dominated by small, well-sorted palynomaceral 4 with very few other palynomacerals present. Although dinocysts may occur in moderate amounts, sporomorphs and the other palynomorph groups are rare. (2) *Palynofacies B (Marchwood borehole 3918' 9"):* The organic residues recovered are usually moderate to poor. Both equidimensional and blade palynomaceral 4 are common, although the equidimensional variety is slightly more frequent. Palynomacerals 1–3 are rare or absent and SOM is not normally present. The palynomacerals are usually well- or moderately sorted and the palynomaceral 4 constituents may show rounding due to abrasion. Dinocysts may be common and other types of microplankton may occur; sporomorph assemblages, however, are usually poor



(3) *Palynofacies C (Marchwood borehole 3866' 9"):* This palynofacies is similar in many respects to A. However the organic residues are richer and the palynomacerals are not as well-sorted. The palynomacerals are still dominated by palynomaceral 4 with both equidimensional and blade forms equally well represented. Palynomacerals 1–3 may be frequent in this palynofacies and SOM may rarely occur. Microplankton and sporomorphs are normally present and may be frequent. (4) *Palynofacies D (Marchwood borehole 3894' 1"):* The organic content of this palynofacies is normally moderate or good, with the sorting of the constituents often poor. Although the palynomaceral assemblage is still dominated by palynomaceral 4, palynomacerals 1–3 can be frequent or common. A form of SOM may often be found which appears to be bacterially degraded palynomaceral 1. Dinocysts and other types of microplankton, such as acritachs, may be common in the assemblages but sporomorphs tend to dominate the palynomorph fraction

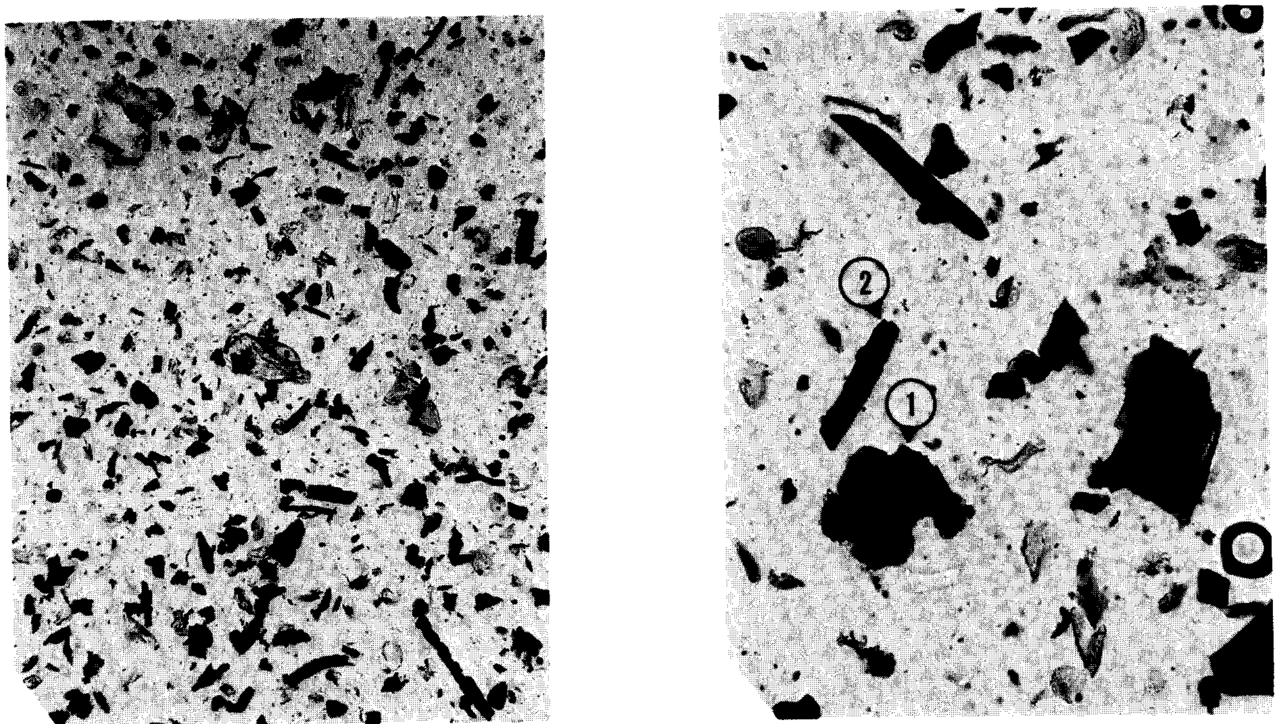


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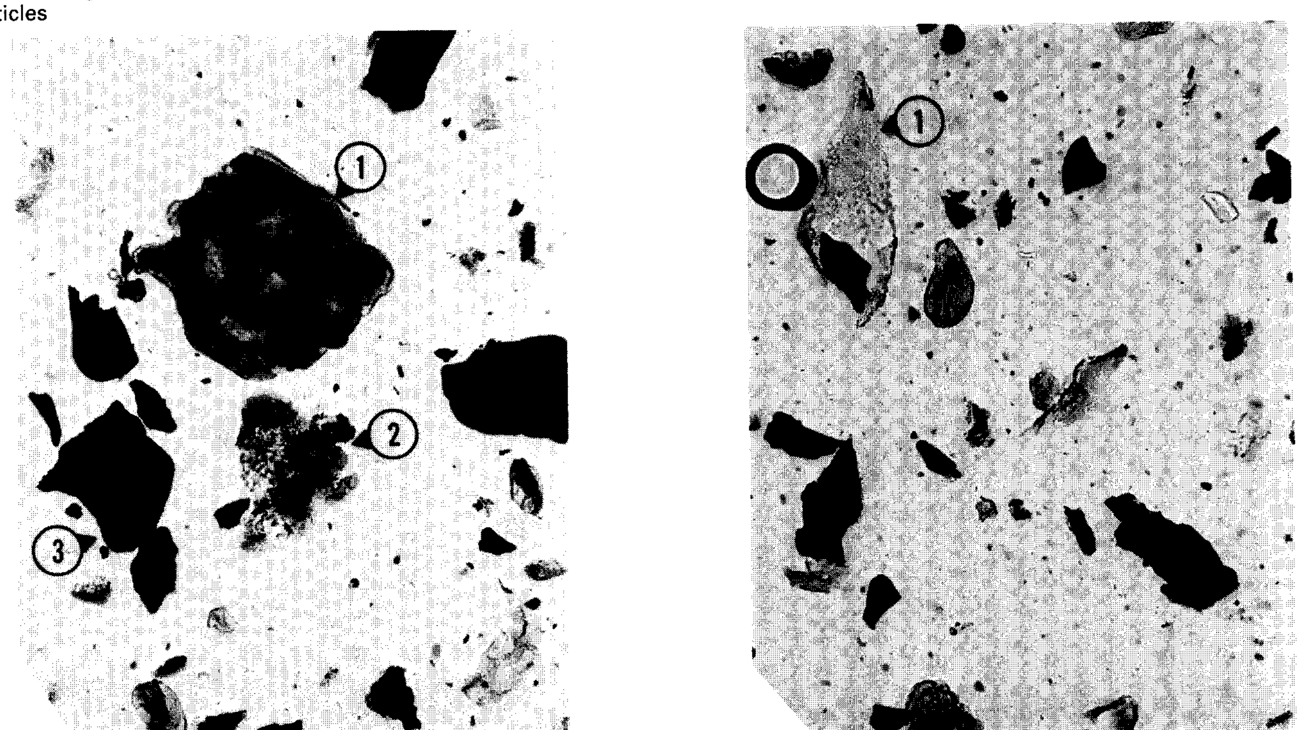
Figure 11b Palynofacies descriptions (photomicrographs at x80) (1) *Palynofacies E (Marchwood borehole 3856′0″):* The palynofacies is organically rich and poorly sorted. It is dominated again by palynomaceral 4 though it contains a high proportion of palynomaceral 1 and significant occurrences of palynomacerals 2 and 3. Low buoyancy sporomorphs are the dominant palynomorph group but dinocysts may occur. Facies controlled species such as the freshwater algae Botryococcus and leiospheres, a form of microplankton associated with brackish/marginal marine waters, may be frequent. **Palynomaceral Descriptions (photomicrographs at x200)** (2) *(1) Palynomaceral 1:* Orange/dark-brown structured or structureless humic matter of irregular shape. It is of heterogenic origin but much consists of 'humic gels' which may contain inclusions of plant material. *(2) Palynomaceral 4 (Blade):* Black or almost black typically blade shaped matter; which is usually uniformly opaque but may occasionally show cellular structure. The constituent is basically charcoal or geothermally fusinized humic material. It has a tendency to break along the elongate structure producing blade shaped particles



3 4

(3) *(1) Palynomaceral 2:* Brown-orange structured matter. This basically consists of humic material in which the cellular structure is easily visible. *(2) SOM:* Structureless organic material (SOM) is as its name suggests composed of an amorphous mass of organic debris. There are several origins of SOM but much is a result of bacterial degradation of plant matter. Many of the other palynomaceral constituents can be seen to have suffered bacterial attack and may in some cases be transititional to SOM. SOM is rapidly destroyed by oxidation and requires anaerobic or anoxic conditions for preservation. *(3) Palynomaceral 4 (Equidimensional):* This palynomaceral is basically composed of hardened humic gelified material. In normal transmitted light it may resemble palynomaceral 4 (blade) appearing black or dark brown. However, unlike palynomaceral 4 (blade), being structureless, it has a tendency to form equidimensional particles. (4) *(1) Palynomaceral 3:* This palynomaceral appears as thin, normally transparent sheets which may sometimes show structure. The palynomaceral is primarily formed from leaf cuticle

in many of the samples, have also apparently had little effect on the palynomaceral constituents. Although in other sequences studied by the author (CFL), bioturbation has been recognised to have had a significant effect on palynomaceral preservation.

Palynofacies types D and E are generally characterised by organically rich palynomaceral assemblages which are poorly sorted. The palynomacerals are dominated by palynomaceral 4 but they also contain significant quantitites of palynomacerals 1–3 and may include structureless organic matter (SOM).

Sporomorphs are typically the most frequently occurring palynomorph element, but dinoflagellates are also frequently found. These palynofacies types are interpreted as being deposited in relatively low energy conditions. The occurrence of SOM in the samples is significant since it is readily destroyed in highly oxidizing environments. This would suggest that, although energy levels and sedimentation rates were low enough to allow an active bottom fauna, the sedimentation rate was high enough to allow the preservation of SOM.

Palynofacies types A, B and C are in general organically lean and relatively well sorted. The palynofacies are dominated by small fragments of palynomaceral 4 and other palynomaceral groups are rare or absent. Dinoflagellates tend to be the dominant palynomorph group with sporomorphs being rare. These palynofacies types are interpreted as having been deposited in relatively higher energy conditions.

Figure 10 shows the relationship of the palynofacies types to the cement rich/poor horizons determined by the petrographic studies. It shows clearly that the palynofacies types A, B and C correspond to sediments that are strongly carbonate-cemented and clay-poor, whilst the palynofacies types D and E relate to clay-rich, weakly cemented sediments. The correlation of the palynofacies with lithology is highlighted by a 'boundary line' (*Figure 10*). The sample MWD 3826' 6" appears, from petrography, to be carbonate-rich, whilst its palynofacies is more typical of the carbonate-poor samples. In fact the sample was taken at the junction of two horizons and the organic content of the clay-rich fraction of the sample dominates the palynological residue. The three samples taken from the single cemented block collected at Burton Bradstock all contained the same palynofacies type B. This suggests that the palynofacies from a lithologically uniform sample are also uniform. This characteristic is important to the industrial palynologist who frequently works with limited sample material.

Other data

The fauna and palynofloras they contain indicate a marine origin for the Sands, although the precise environment of deposition is difficult to determine in the absence of diagnostic sequences of lithologies or sedimentary structures. This problem may be partly overcome by regional considerations which constrain the possible depositional model.

The petrology of the Sands was analysed by Boswell (1924) who proposed a provenance of the sand from the Armorican massif to the south-west on the basis of detrital heavy minerals. However, palaeocurrent analyses reported by Davies (1969) suggest transport of the sand in southwesterly and northeasterly directions (i.e. slightly oblique to the direction of younging within the Sands) but with a dominant mode *towards* the south-west. However, examination of the details of these measurements (Davies, 1966) suggest that many of the smaller structures measured are unlikely to give reliable palaeocurrent indications. More recent data suggest that a northeasterly source is also possible (Morton, 1982; Knox *et al.*, 1982) although the thickening of the Sands toward the west (*Figure 2*) is more consistent with a westerly source. Palaeomagnetic fabric measurements are unable to resolve this uncertainty since they suggest deposition by either northeasterly or southwesterly directed, wave-generated currents (Hounslow, 1987). These measurements are also difficult to interpret as a consequence of a diagenetic origin for much of the iron-bearing clay.

The intense bioturbation of the Sands suggests slow rates of accumulation, whilst the predominance of small-scale ripple lamination in some areas suggests deposition from low-energy currents. Relatively thick intervals of high-energy beach lamination are not observed in the Sands and this suggests either that the Sands were deposited on a non-emergent shoal (Davies, 1969; p.1349) or that the sequence is truncated. Large-scale cross-bedding is observed only in association with the bioclastic limestone facies and has a dominant orientation almost normal to the palaeocurrents recorded from the sands (Davies, 1969). The low degree of bioturbation within these limestone units suggests relatively rapid emplacement by high-energy currents and is interpreted by Davies to represent deposition in tidal inlets cut into the sands (Davies, 1969). Davies (1969) and Davis *et al.* (1971) interpreted these features with reference to the 'barrier bar' model developed from studies of the modern Gulf Coast of Texas (Bernard *et al.*, 1962). However, there are clear deficiencies in this interpretation:

a there is no evidence of the sands ever having been emergent;
b the 'back barrier' environment is characterised by open marine limestones; and
c trace fossil and palynofacies investigations suggest shelf, rather than shoreline, deposition.

These deficiencies have been further emphasized by later workers. Knox *et al.* (1982) favour deposition of the sands in a shallow sea dominated by wave activity and ascribe shoaling-upwards cycles in the Sands to shifts in the balance between sedimentation and subsidence rather than to progradation of a barrier. On the basis of trace fossils, sedimentary structures, grain size and regional correlation Colter and Havard (1981) consider the Sands to have formed as a storm-dominated sand sheet deposited between the 'transition zone and lower, rarely middle, shoreface environments of Reineck and Singh (1980)'. Hounslow (1987) also attributes the Sands to deposition on a wave-dominated, storm-influenced shelf, below fairweather wave base.

Depositional model

Since cementation appears to be strongly controlled by depositional features of the Sands, the formulation of an appropriate depositional model is an important pre-requisite for the understanding the distribution of the carbonate cements. The studies outlined above define several features that are relevant to the construc-

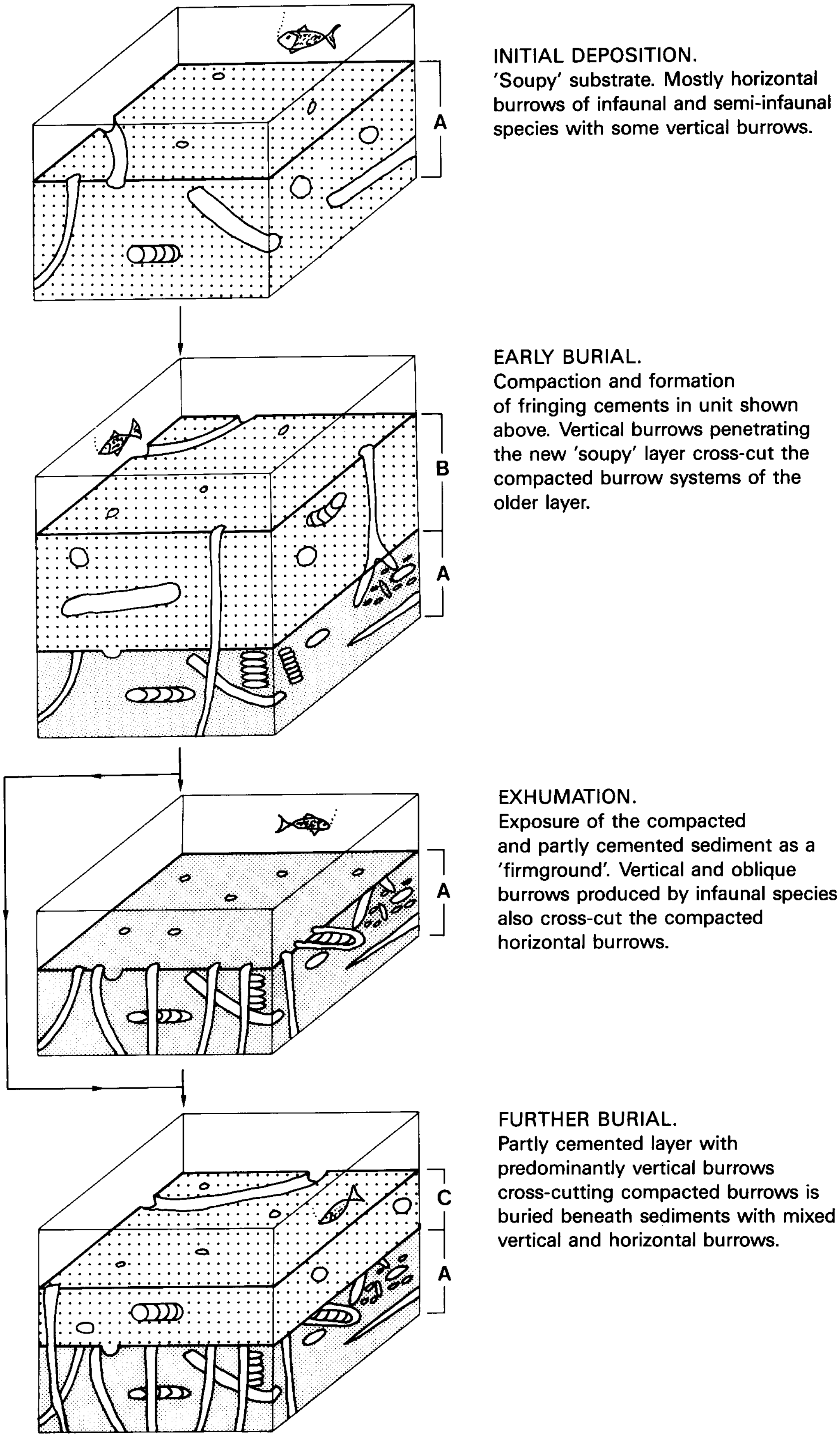


Figure 12 Model to explain the alternation of horizons with mostly vertical burrows and those with mixed, vertical and horizontal burrows

tion of such a depositional model:

a The high degree of bioturbation and fine-grained nature of the sands indicates slow and/or intermittent deposition of sediment.
b The occurrence of bioclastic grainstones and packstones indicates intermittent winnowing of the sand or intermittent introduction of carbonate sediment into an area dominated by clastic deposition.
c Trace fossils and palynofloras indicate an offshore setting.
d Tightly cemented horizons are coarser grained (owing to enrichment of bioclasts and ooids and depletion of clays and mica) with respect to intervening, less-well-cemented beds.
e Trace fossils are predominantly vertical (*Skolithos*) in tight horizons and mixed vertical (*Skolithos, Chondrites* and *Teichichnus*) and horizontal burrow systems (*Rhizocorallium* and *Thalassinoides*) in less-well-cemented horizons.
f Trace fossils are tiered (cf. Bromley and Ekdale, 1986) such that younger, predominantly vertical burrows (*Teichichnus, Chondrites* and *Skolithos*) cut older, predominantly horizontal burrows (*Rhizocorallium* and *Thalassinoides*) (*Figures 5a, 6a* and *12*).
g Evidence for channelling is confined to bioclast-rich horizons of the Ham Hill Stone. In most of the Sands, where bedding is visible, deposition appears to have been by vertical aggradation of a low relief bed giving rise to essentially horizontal bedding.

The most common sedimentary structures in the Sands are mud-draped ripple laminae (*Figure 9*; Hounslow, 1987; Figure 3) and low-angle or hummocky lamination (Hounslow, 1987; Figure 4). In some areas (e.g. around Yeovil) the rate of deposition appears to have been such that these laminated sediments are only weakly bioturbated (*Figure 9*). In other areas (e.g. the Bridport coast) almost complete homogenization of the Sands by bioturbation suggests either slower or more sporadic deposition. The only evidence of depositional events in these sands is provided by the type and sequence of bioturbation structures (*Figure 12*).

In contrast to these laminated and bioturbated, weakly cemented sands, the relative coarseness of the bioclast-rich horizons appears to indicate deposition by stronger currents. Current strength on the marine shelves is frequently related to depth, such that coarser sediments occur at shallower depths. Consequently, similar cyclic alternations of fine clastic sediment and coarse bioclastic sediment from the Lias of Britain (Sellwood, 1970) and Germany (Bayer *et al.*, 1985) have been interpreted in terms of shallowing-upwards cycles. Shallowing may be related to both eustatic sea-level movements or variations in subsidence rate relative to the rate of deposition, and a combination of these processes seems likely to account for the large-scale cycles (e.g. Upper Lias Silts and Mudstones – Upper Lias Sands – Inferior Oolite of *Figure 3*) observed in the Lias of southern England. Similar mechanisms probably also account for the medium-scale coarsening-upwards cycles, seen in the Sands (*Figures 3, 4* and *7*).

The smaller scale, cyclic alternation of bioclast-rich, clay-poor and bioclast-poor, clay-rich sediments might be explained by two alternative models.

The first model is essentially similar to that proposed above, to account for the medium-scale cycles. In this model variations in global sea-level and the balance between growth fault movement and rate of sediment supply cause periodic lowering of wave base with respect to the sea-floor, resulting in winnowing of sea-floor sediments (*cf.* Einsele, 1985). Thus previously compacted and/or cemented sediments are exposed to form 'firm grounds' which are then burrowed predominantly by vertical trace-making organisms (*Glossifungites* ichnofacies of Frey and Seilacher, 1980). Shelly material and dispersed ferruginous ooids are also concentrated on the sea-floor to form a winnowed-lag (*cf.* Sellwood, 1972). Concomitant exposure of shallower carbonate sediments to the north could then lead to their erosion and transport southwards in channels incised through the Sands or as shell-rich sandwaves, as possibly represented by the Ham Hill Stone (Knox *et al.*, 1982). Palaeocurrent patterns apparently contradictory to this transport direction (Davies, 1969) might be explained by reversing tidal current systems thereby giving rise to areas of separated ebb- and flood-dominated flows. A tidal origin for much of the cross-bedded limestone is supported by the presence of mud drapes between bundles of foresets, burrowing of some foresets and occasional, apparently paired, mud drapes (Knox *et al.*, 1982; Plate 3).

However, an investigation of the basal Lias by Weedon (1986) suggests that sea-level changes are unlikely to have occurred quickly enough to have produced the observed cyclicity, and an alternative depositional model for the Sands may be postulated in which small-scale apparently 'shallowing–deepening cycles' in fact represent periodic lowering of wave base with respect to the sea-floor during extreme storms (*Figure 13*). In this second model, storm waves may once again erode material from the sea-floor to expose compacted sediments as 'firm grounds' (*Figure 12*) but, additionally, basinward-directed currents created by the storm might also transport material eroded from the shallower carbonate area to the north into the area of sand deposition as sheets, in channels or as migrating shell-rich sandwaves. The palynofacies data are compatible with these interpretations such that palynofacies types D and E may be interpreted as being deposited under fairweather conditions where the sedimentation rates were high enough to allow the preservation of relatively rich palynomaceral assemblages. In contrast, the palynofacies types A, B and C may be considered to have been deposited under high-energy, storm conditions, where the sediments would have been aggressively reworked, winnowed and oxidized, thereby producing the organically lean, better sorted palynomaceral associations. Palynofacies similar to the types described here are discussed by Whitaker (1984) for the Jurassic sands of the Troll field, Norwegian North Sea where organically lean palynofacies dominated by small fragments of palynomaceral 4 are likewise associated with storm-deposited sediments.

If the carbonates were deposited as sheets (*cf.* 'tempestites' of Aigner and Reineck, 1982; 'graded skeletal sheets' of Aigner, 1985) they might be expected to have a widespread geometry. For example Goldring and Stephenson (1972) describe a storm-deposited sand sheet from the Middle Lias of Dorset which has an

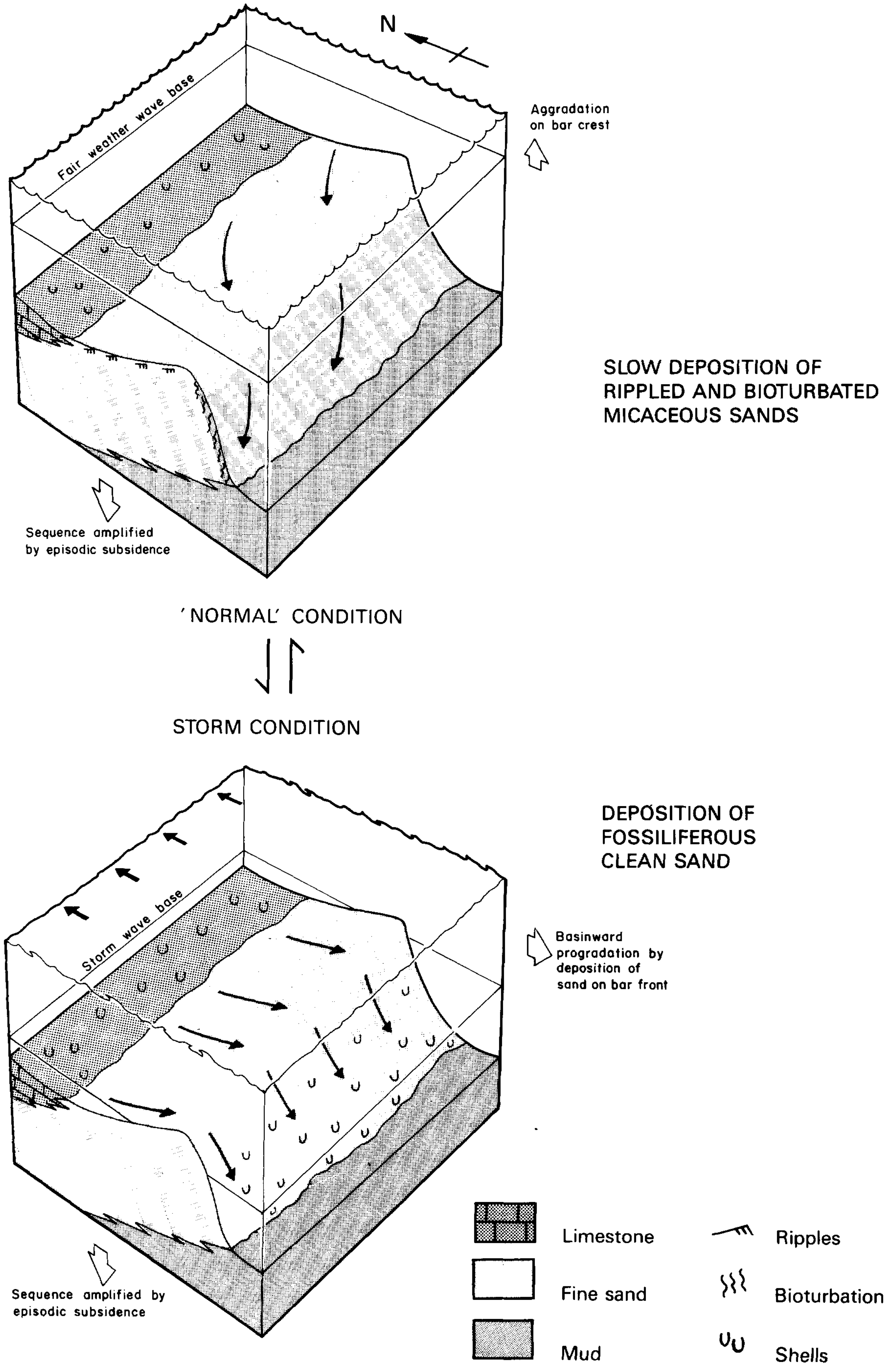


Figure 13 Depositional model for the Upper Lias Sands. Note the large vertical exaggeration such that the true dip of the bar front was probably less than 1°. Our studies cannot resolve the question of the large scale geometry of the ridge but a lateral extent of more than 5 km is suggested by the continuity of beds at the coastal outcrop

areal extent of over 70 km^2, whilst Hayes (1967) describes storm sand deposition of a thin sheet covering more than 500 km^2 associated with hurricanes off the Gulf Coast, USA.

In more proximal settings such sheets may be replaced by storm surge channels (*cf.* James, 1980). The cross-bedded bioclastic limestones recorded at the top of coarsening-upwards cycles seen in the cores may represent such channel-fills. Alternatively, similar limestones within coarsening-upwards Jurassic sand bodies of North America have been interpreted as the deposits of shell-rich sand waves which migrated over shelf sand ridges (Brenner *et al.*, 1985). The Upper Liassic Sands of southern England have several aspects in common with such ridges:

a they show no evidence of emergence;
b they are obliquely orientated with respect to palaeocurrent trends;
c they coarsen upwards; and
d they possess disconformities/erosion surfaces associated with bioclastic limestones.

If the Lias Sands are interpreted as representing a sand ridge, then the cross-bedded limestones may also have a similar origin to those described by Brenner *et al.* (1985) as suggested by Knox *et al.* (1982). However, the palaeocurrent data from the Ham Hill Stone are at variance with this interpretation.

These two models are, of course, not mutually exclusive but complementary (during periods of low sea-level stand storms still rework sediment onto the shelf). The sediments do not contain a uniform distribution of bioclastic material in either model, but rather this biogenic carbonate is concentrated in storm-deposited sheets or lags due to winnowing at low sea-level stands. In both instances, these carbonate-rich horizons will be of widespread lateral extent. Compaction and exhumation and/or early cementation of these layers would result in firmgrounds which are principally burrowed by vertical or oblique burrows (*cf.* Sellwood, 1970; Wincierz, 1973). The upward increase in the frequency, and decrease in the thickness, of the cemented horizons, as observed in cores and at outcrop, might then be explained by decreasing rates of sediment supply prior to deposition of the Inferior Oolite.

Comparison with other models

Although modern shelf environments provide poor analogues for sedimentation in the shallow, widespread epeiric seas of the Jurassic (Hallam, 1975), sediments very closely analogous to the Upper Lias Sands have been described from the modern shelf off Mauritania (Einsele *et al.*, 1977). Between the surf zone and the distal shelf (6–120 m water depth) sea-floor sediments are composed of strongly bioturbated medium- to fine-grained sands, passing basinwards into sandy silts with thin shell beds. The shallower sands contain frequent interbeds of comminuted and bored bioclastic material derived from *in situ* communities and bioclasts eroded and transported from nearshore environments during storms. The storm beds are coarser grained than the intervening beds when the bioclasts are considered but show little difference in the mean grain size of the quartz component. At least three laterally continuous, carbonate-cemented sand layers occur within the recent sediments and are attributed to cementation during low sea-level stands. Trace fossils visible in box cores are similar to those within the Liassic Sands and are likewise interpreted to represent the activities of deposit and suspension feeding organisms (Appendix 1). The frequency of storm layers within vibrocores are of a similar magnitude to the frequency of bioclastic-rich units within the Liassic Sands. Additionally, the similarity of estimates of sedimentation rates in the two environments (Liassic Sands: c. 1 m per 10000 years (Davies, 1969); Mauritanian shelf: c. 1.5 m per 10000 years (Einsele *et al.*, 1977)) suggests that depositional processes in the two environments may be comparable.

The depositional models proposed for the Sands are similar to those proposed for many other Jurassic sand bodies deposited in shallow epeiric seas subject to eustatic sea-level changes and concomitant extensional tectonics. The Upper Jurassic, Abbotsbury Ironstone is interpreted to represent deposition of fine-grained quartz sand and ferruginous ooliths on a bar separating lagoonal environments to the north-west from a deeper basin to the south-east (Brookfield, 1973). Quartz sands from the Upper Jurassic, Upper Calcareous Grit of Dorset are interpreted to have formed a subtidal, marine grass covered bar (Talbot, 1974). The Upper Jurassic, Aldinger Elv Member of East Greenland consists of bioturbated and laminated sands with interbedded shell beds and is ascribed to deposition as a shoreface attached submerged marine bar (Fürsich and Heinberg, 1983). Sequences of alternating clastic and bioclastic sediments from the Upper Jurassic of France contain similar bed geometries and sequences, sedimentary structures and trace fossils to the Sands and are likewise interpreted as shoaling and deepening, storm-dominated shallow marine sequences (Fürsich and Oschmann, 1986). Strongly bioturbated, coarsening-upwards Jurassic sand bodies with variably distributed calcite cements also form important hydrocarbon reservoirs in the North Sea, e.g. the Fulmar Formation (Johnson *et al.*, 1986; Stewart, 1986); the Viking Group of the Troll Field (Hellem *et al.*, 1986; Osborne and Evans, 1987); Stø formation of the Troms I Area (Olaussen *et al.*, 1984) and Piper Sandstone of the Piper Field (Maher, 1981). The Stø formation is also of Upper Lias age and contains a suite of trace fossils similar to those in the Lias Sands of southern England and likewise contains thin carbonate-cemented horizons associated with increased fossil concentrations which are ascribed to deposition on storm-dominated offshore bars (Olaussen *et al.*, 1984).

Summary

The Sands are interpreted to have been deposited on a shoal area separating a shallow carbonate shelf to the north from a silty, deeper basin to the south. Deposition was usually from weak traction currents and fall-out from suspension. As a consequence of low rates of deposition these silty sands, which represent 'fairweather' deposition, were intensely bioturbated. Occasional intense storms are interpreted to have deposited sheet-like, coarser grained bioclast-rich beds which are interbedded with the fairweather sediments. The indication provided by the trace fossils that the storm beds formed firm grounds provides evidence of early initiation of cementation withion these beds.

Petrography

The petrography of the sediments is described in more detail elsewhere (Boswell, 1924; Davies, 1967; Knox *et al.*, 1982; Kantorowicz *et al.*, 1987) and only a brief summary is presented here. Mineralogically, the Upper Lias Sands contain a wide variety of detrital and authigenic minerals. However, despite this diversity, modal analyses of samples from the Marchwood borehole and outcrop sections indicate a gradation between two petrographic end-members (Kantorowicz *et al.*, 1987). These are porous, clay-rich sediments and clay-poor, bioclast-rich deposits (*Table 1*). Examination of the location of these samples indicates that the clay-rich samples correspond to the 'fairweather sediments' and the bioclast-rich samples to the 'storm deposits' recognised at outcrop and in core. In general, the fairweather sediments are weakly cemented, and the storm deposits tightly cemented. The sediments are therefore described below with respect to the clay-rich or cemented end-members.

Clay-rich sands

These are generally porous, very fine to fine-grained subarkoses. They are texturally immature, containing abundant silt-sized quartz grains and up to 26% detrital clay. The framework is matrix-supported with widespread crushed and deformed micas. Scattered bioclasts including brachiopod shells and echinoderm plates were observed in core samples although only belemnites were identified in the outcrop samples.

The high proportion of detrital clay present in these sediments hindered the development of early, framework-supporting, carbonate cements and the beds were compacted prior to the formation of weakly developed later stage cements (*Figure 14*).

Cemented sands

These are texturally mature, clast-supported, fine to very fine grained bioclast-rich sandstones. The bioclasts present include brachiopod and bivalve shells which contain extensive iron oxide-lined algal borings, gastropods, echinoderm plates, forams, ammonites, belemnites and bryozoa. Berthierine ooids are common in the Marchwood Borehole but were not observed in outcrop samples.

The diagenetic history of these sediments is complex with widespread evidence of carbonate precipitation and dissolution, some of which must have proceeded simultaneously (*Figure 15*). Petrographical examina-

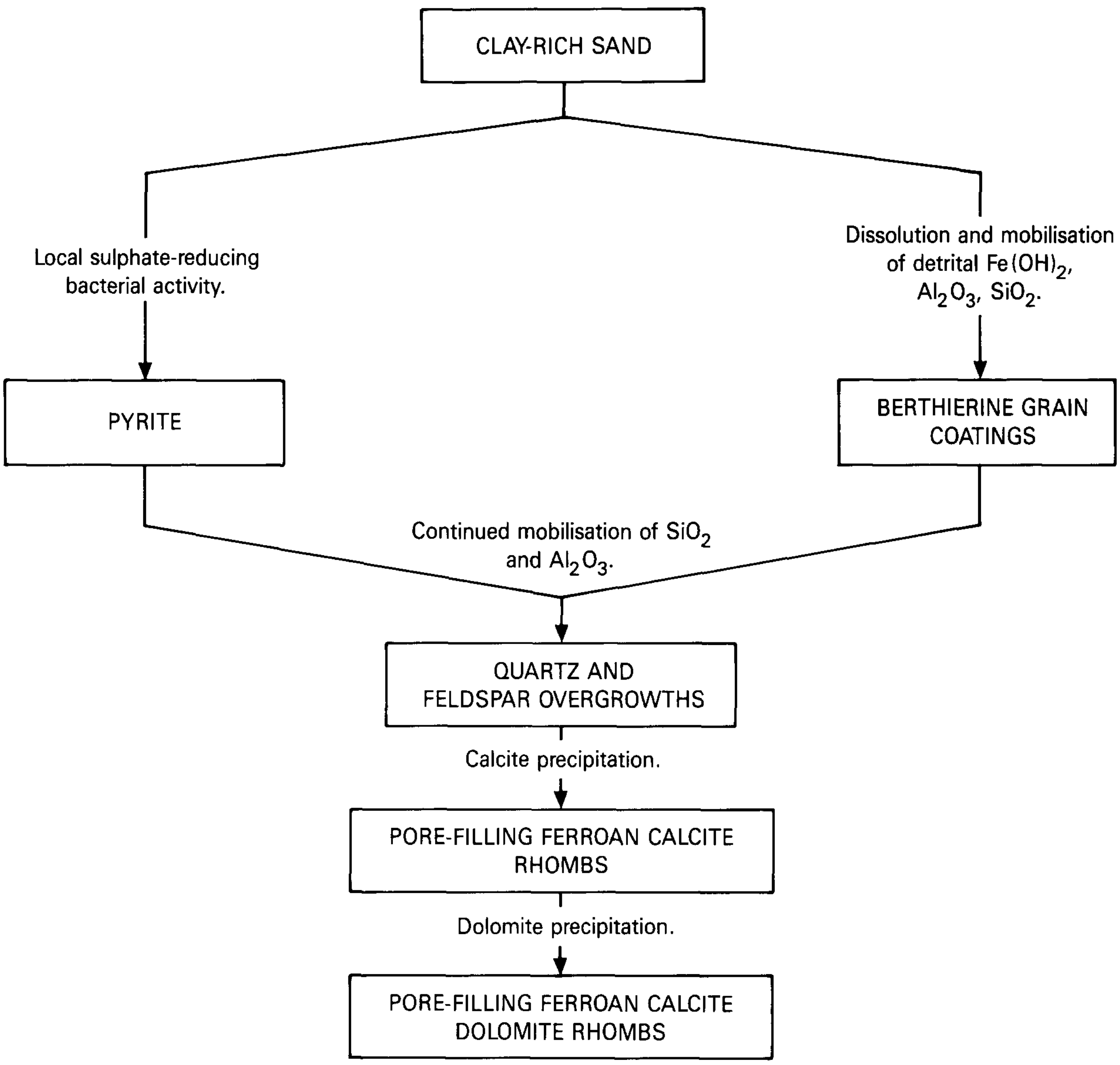


Figure 14 Flow chart of diagenetic modifications to clay-rich (fairweather) sands in the Upper Lias Sands

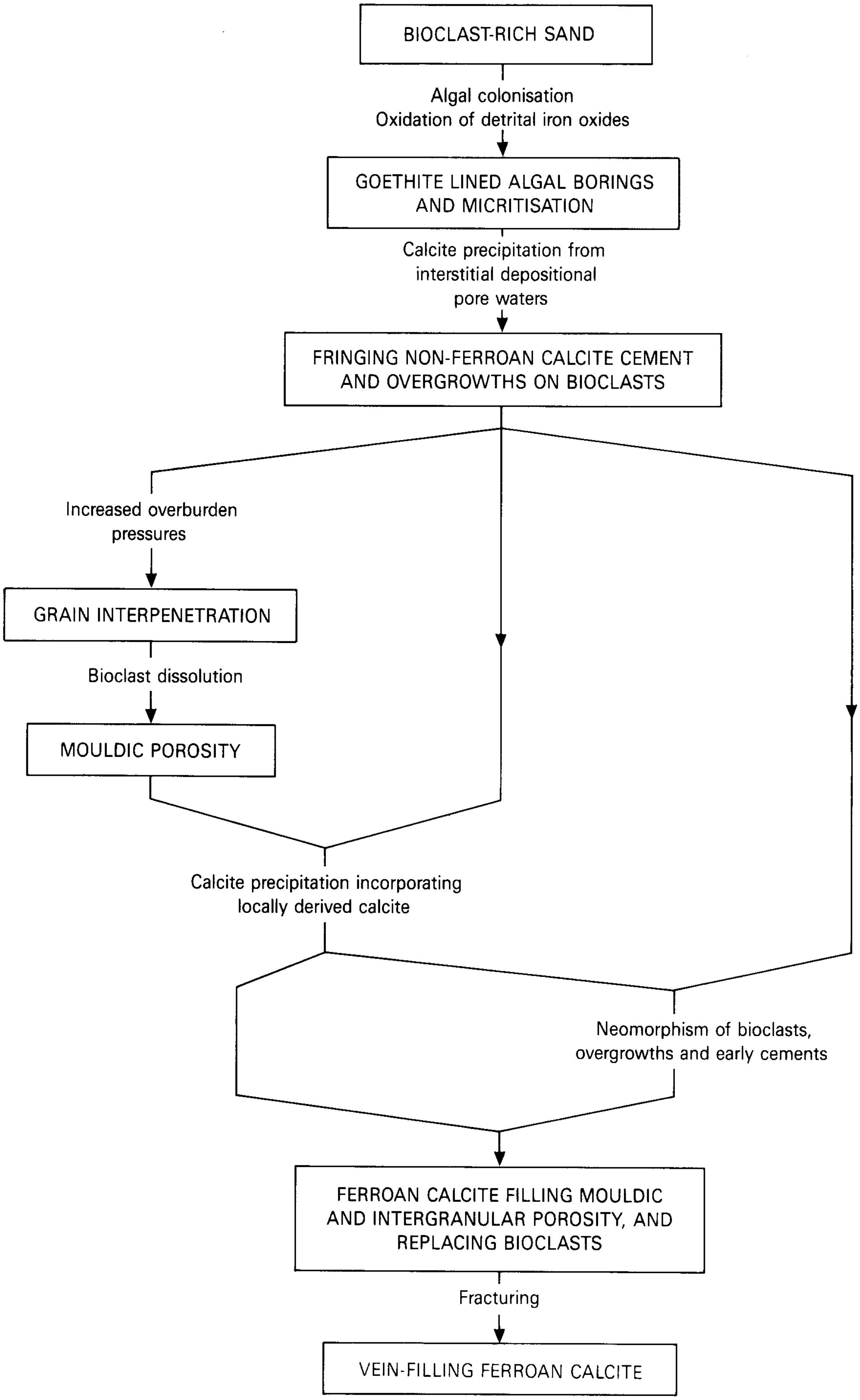


Figure 15 Flow chart of diagenetic modifications to cemented (storm) sands in the Upper Lias Sands. (From Kantorowicz *et al.*, 1987)

tion suggests that after precipitation of an early fringing or overgrowth cement, carbonate mineral diagenesis proceeded through the remobilization and eventual reprecipitation of both detrital and early-formed calcite. The calcium carbonate minerals present may have originally included aragonite and high-Mg calcite, but they appear to have homogenized to ferroan calcite during diagenesis. The rocks were subsequently fractured and the fractures cemented with ferroan calcite. It appears that these sediments were tightly cemented at this stage and the calcite introduced into the fractures did not enter intergranular porosity.

Diagenetic model

The cemented beds in the Sands contain two generations of carbonate cement. The first occurs as fringes or overgrowths on detrital grains. The second occurs as an intergranular pore-filling mosaic (Kantorowicz *et al.*, 1987; Figure 5), and involved the mobilization and redistribution of detrital and earlier formed calcite and aragonite (a) within the cemented beds themselves, and (b) from the clay-rich beds into the cemented beds. An explanation of the origin of these two generations must also explain their distribution, which is restricted largely to the originally bioclast-rich, clay-poor storm-deposited sediments.

Fringing cements. Fringing cements are not particularly diagnostic of any sedimentary environment. They simply require the presence of detrital carbonate grains onto which authigenic calcite and aragonite can nucleate (e.g. Jørgensen, 1976; Nelson and Lawrence, 1984). In the Upper Lias Sands, bioclasts were originally heterogeneously distributed, being concentrated within the storm deposits. Non-ferroan calcite or even aragonite fringing and overgrowth cements on the bioclasts probably stabilized the sediment framework mechanically, thus preserving an intergranular porous network within which later diagenetic modifications took place. Scattered bioclasts in the clay-rich sediments may have developed overgrowths, but the bioclasts were not concentrated enough to stabilize the framework and prevent compaction. It appears, therefore, that the distribution of fringing cements reflects the texture and mineralogy of the original sedimentary deposits.

Mosaic cements. After precipitation of the fringing cements the remaining intergranular porosity was cemented with calcite, much of which is now ferroan. Petrographically, there is widespread evidence that the cements were derived internally, not from the bioclasts in the cemented beds alone, but from bioclast dissolution in the adjacent clay-rich beds as well. It appears that the driving force responsible for the precipitation of the mosaic calcite was attempted equilibration of the originally detrital sedimentary assemblage with its pore waters (Kantorowicz *et al.*, 1987). The distribution of these mosaic cements reflects the texture and mineralogy of the sediments after the fringing cements had precipitated. The clay-rich beds were not mechanically stable and underwent compaction, progressively destroying intergranular microporosity. Patches of cement formed but the bioclasts in these sediments were progressively dissolved, and contributed calcite to cementation of the bioclast-rich beds. Most of the mosaic calcite precipitated within the porous network preserved by early fringe cementation of the bioclast-rich storm deposits. This progressive remobilization of calcite simply accentuated the original mineralogical differences between the fairweather- and storm-deposited sediments. This has been further compounded by outcrop weathering. Comparison of surface and subsurface samples reveals that Recent processes have removed calcite, dolomite and detrital and authigenic clays from the fairweather sediments. As a result, these beds are friable, less resistant, and easily weathered at outcrop. This creates the classic alternation of hard and soft beds seen in the cliffs today in Dorset (*Figure 8*).

Summary

Carbonate cementation in the Upper Lias Sands reflects the original texture of the sediments. A textural control on the location of cemented horizons was postulated by Knox *et al.* (1982) from examination of the Winterborne Kingston borehole, although they were unable to explain the origin of these primary, textural differences. Our observations indicate that clay-rich fairweather sediments are weakly cemented and have undergone compaction. Interbedded, clay-poor, bioclast-rich, storm-deposited sediments developed early fringing cements, resulting in little compaction. Porosity in these uncompacted beds has been infilled by later cementation resulting from redistribution of bioclast-derived carbonate. Bacterial activity is only weakly reflected in the carbonate compositions of these sediments suggesting that they have undergone largely closed system diagenesis. All the clay-free, storm-deposited sand observed here contains fringing calcite and is now tightly cemented.

This interpretation differs significantly from that of Davies (1967) who interpreted the weakly cemented sands to result from rapid deposition and the strongly cemented sands to represent slower deposition or periods of non-deposition during which cementation took place.

Recognition from wireline logs

The strongly cemented horizons represent major barriers to vertical fluid flow through the Sands. In the Wytch Farm oil field strongly cemented horizons in the Sands have porosities of less than 10% and negligible permeability compared to porosities of the order of 32% and permeabilities of 300 mD in the intervening horizons (Colter and Havard, 1981). Where such horizons are laterally continuous, they will have a significant effect on volumetric calculations and production policy (e.g. perforation intervals and offtake rates). However in most reservoirs, recognition of such cements may depend largely on interpretations from wireline logs.

The tight horizons of the Winterborne Kingston borehole are recognisable on sonic (BHC), microlaterolog (MLL) and density/neutron logs (FDC/CNL) with the best indication being provided by fast peaks on the sonic log (*Figure 3*). In the Marchwood borehole sonic and neutron porosity logs can be used to identify all of the tightly cemented, and some of the more strongly cemented horizons recognised in the core (*Figure 4*). Whilst sonic and density/porosity logs may be used to detect the presence of the tight streaks, their resolution is such that they yield little information concerning the thickness and spacing of the individual horizons.

Table 1

SUMMARY OF THE CHARACTERISTICS OF STORM AND FAIRWEATHER DEPOSITED HORIZONS OF THE UPPER LIAS (BRIDPORT) SANDS

Description		Resistant, carbonate cemented very fine sand to coarse silt	Friable, clay-rich very fine sand to coarse silt
Inferred depositional process		Deposition from storm generated traction currents	Deposition from weak 'fair weather' traction currents and fallout from suspension
Reservoir properties*		$\Phi < 10\%$; k-negligible	$\Phi = 30\%$; $k = 300mD$
Log Recognition	Sonic Neutron Density	Fast peaks Low High	Low Moderate Low
Trace fossils		Predominantly vertical/oblique burrows	Mixed vertical/oblique and horizontal burrows
Petrographical characteristics	Detrital constituents Sorting Grain: matrix ratio Texture Compactional effects Porosity	Bioclasts, quartz, clay and ooliths Good 3–4:1 Mature, clast supported None observed Mouldic and shrinkage within ooliths	Quartz and clay Moderate 2:1 Immature, matrix supported Deformed micas throughout Intergranular and microporosity
Palynofacies characteristics	Type Organic content Sorting Palynomaceral content	A Poor Good-moderate Dominated by small palynomaceral 4 Palynomacerals 1–3 absent or rare Microplankton > sporomorphs	D/E Good Poor Dominated by palynomacerals 2 and 4 Palynomacerals 1 and 3 common Sporomorphs > microplankton Structureless organic matter present

* In Wytch oilfield (from Colter & Havard, 1981)[1].

Several authors have shown that, in the absence of core, the form of the tight streaks may be deduced from dipmeter response (e.g. Maher, 1981). The four-arm dipmeter tool offers the opportunity to compare resistivity response simultaneously at eight locations on the borehole wall with very high vertical resolution. Examination of the microresistivity traces from the Marchwood borehole provide improved resolution of tight streak thickness, whilst comparison of the relative depths at which 'events' occur on each of the traces provides information on their morphology (Bryant and Kantorowicz, in prep.). It is often assumed that laterally continuous cemented horizons have planar upper and lower contacts, whilst discontinuous concretions may be recognised by curved contacts. This assumption receives some support from examination of the outcrops at Bridport, where many of the laterally continuous horizons have planar upper and lower contacts (*Figure 8b*). However, many of the concretions are of sufficiently large dimensions that curvature of their surfaces may not be detectable in a borhole, whilst several of the laterally continuous horizons have extremely irregular contacts (*Figure 6b*).

Conclusions

A number of significant points arise from this study of the Upper Lias Sands.

1 Trace fossil and palynofacies evidence indicates that the large scale, amplified, coarsening-upwards sequences of the Upper Lias Sands result from deposition on one or more, submerged shoals or ridges in a shallow marine shelf environment which, on the basis of the preserved sequence, was dominated by storm processes. Thickness variations of the Sands indicate non-uniform subsidence. Further work on regional correlation is required to better understand the relationship between sedimentation and tectonics.

2 The Sands are compartmentalised by numerous, laterally continuous sheets of carbonate-cemented sand. These tight horizons result from preferential cementation of bioclast-rich, clay-poor storm-deposited sediments.

3 Differential cementation of the Sands is a consequence of two complementary effects:

  a Elevated levels of bioclastic carbonate in the storm sediments permitted the early development of fringing cements which maintained on open pore network, subsequently infilled by mosaic calcite.

  b High levels of detrital clay in the fairweather sediments inhibited early cementation and these sediments were subsequently compacted.

4 In core the storm-deposited sediments are characteristically bioclast-rich, clay-poor and contain predominantly vertical burrows, whilst fairweather sediments are characteristically bioclast-poor, clay-rich and contain both vertical and horizontal burrow systems.

5 In core samples palynomorph assemblages in storm-deposited sediments are better sorted, depleted with respect to palynomorphs/palynomacerals and contain predominantly small fragments of palynomaceral 4. More mixed palynomorph/palynomaceral assemblages dominated by terrestrially derived plant debris characterise the fairweather sediments.

6 On logs the tight horizons are recognisable by fast sonic peaks, high density and low neutron log responses. Definition of tight streak thickness may be improved by using the microresistivity traces from the dipmeter.

The above criteria are summarized in *Table 1* and may be useful in predicting the likely occurrence of laterally extensive, carbonate-cemented, tight streaks where well spacing is too great to establish this by log correlation. However, the criteria have been determined for a storm dominated shelf sequence and care should be exercised in applying them to reservoir bodies deposited in other environments.

Acknowledgements

We are indebted to Shell Internationale Research Maatschappij and Shell Internationale Petroleum Maatschappij for permission to publish this paper. Data from the Marchwood borehole are published with the permission of the Director of the British Geological Survey (NERC). All figured palaeontological material is in the Palaeontological Collections of the British Geological Survey at Keyworth, Nottinghamshire. We are also grateful to the British Geological Survey, two anonymous referees and our colleagues in KSEPL for discussions.

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APPENDIX 1

Trace fossil descriptions

Diagnosis of the environment of deposition of sands usually relies on recognition of patterns of grain-size variation and sequences of sedimentary structures. However, where sedimentation rates are slow or faunas abundant these primary features may be totally removed by the activities of burrowing organisms. The resulting burrows are a variety of 'trace fossil', i.e. imprints left by organisms. Study of trace fossils has revealed that many are environmentally restricted owing to sensitivities of the trace-making organisms, e.g. abundance of food, amount of light, salinity, etc. Thus where burrowing has removed all primary sedimentary structures the burrows themselves may be used to make deductions concerning the depositional environment.

In the shallow marine environment trace fossil groups (=ichnofacies) frequently show a depth-related zonation, giving rise to littoral (*Skolithos*), sublittoral (*Cruziana*) and bathyal (*Zoophycus*) ichnofacies (Seilacher, 1967). Trace fossils may also provide information on the timing of diagenetic processes such as compaction and cementation. Different groups of trace fossils characterise unconsolidated substrates, semi-consolidated substrates or 'firm grounds' (*Glossifungites* ichnofacies) and fully cemented substrates or 'hard grounds' (*Tripanites* ichnofacies) (Ekdale *et al.*, 1984).

The majority of trace fossils identified in the Upper Lias Sands are characteristic of the sublittoral (shelf) *Cruziana* ichnofacies. Trace fossils of the *Skolithos* ichnofacies are less common and occur preferentially in the well-cemented beds, thereby indicating either shallowing and/or increased energy levels. A similar sequence of ichnofacies has been reported from storm-dominated shelf sediments elsewhere (Pemberton and Frey, 1984). The trace fossils may be further subdivided into forms characteristic of semi-consolidated substrates (*Glossifungites* ichnofacies) and unconsolidated substrates. Furthermore the burrows are 'tiered' (*sensu* Bromley and Ekdale, 1986) such that younger, uncompacted burrows of the *Glossifungites* ichnofacies are superimposed on compacted burrows which were formed earlier and at shallower depths (*Figures 5* and *12*).

Thus the trace fossil evidence is crucial in indicating:

a that the bioturbated sands were deposited in a sublittoral shelf setting; and
b that differentiation of the presently well-cemented and weakly cemented horizons had commenced within the zone of active burrowing (›1 m depth).

Since they may be of importance to the geological interpretation of similar shelf sand reservoirs the trace fossils are briefly described below.

ARENICOLITES Salter, 1857
Arenicolites sp.
(Not illustrated)

Description — Vertical to oblique U-tubes without spreiten. Tubes are cylindrical, up to 5 mm in diameter, up to 0.35 m long, with a smooth mud-lined wall.

Remarks — Thought to represent the dwelling structures of deposit- or suspension-feeding organisms. Frequently the burrows are seen to originate in the less-well-cemented sands and pass through better cemented horizons.

CHONDRITES Sternberg, 1833
Chondrites sp.
Figure 5a and *b*

Description — Systems of inclined branching dendritic burrows up to 5 mm, but more commonly 1–2 mm in diameter.

Remarks — Shallow feeding burrows attributed to the activities of a deposit feeding sipunculid worm (Simpson, 1957). The burrows are common to both the well-cemented and poorly cemented beds and show less compaction in the former.

OPHIOMORPHA Lundgren, 1891
?Ophiomorpha sp.
(Not illustrated)

Description — Branched burrow system of straight or curving shafts linked to sub-horizontal tunnels with mud-lined walls up to 20 mm in diameter.

Remarks Interpreted to represent the dwelling/feeding activities of crustaceans (Frey *et al.*, 1978). These burrows may represent lined crustacean burrows in the cleaner, better cemented sands which are equivalent to unlined burrows (*Thalassinoides*) in the muddier sand.

PLANOLITES Nicholson, 1873
Planolites sp.
Figure 5f

Description — Cylindrical horizontal to sub-horizontal burrows 1–2 mm in diameter.

Remarks — These burrows are apparently facies-independent (Crimes, 1970). They are most obvious as cleaner sand-filled tubes in the muddier sands.

RHIZOCORALLIUM Zenker, 1836
Rhizocorallium sp.
Figure 5a and *b*

Description — Horizontal to slightly oblique, U-shaped burrows with flat-lying spreiten between the arms of the U. The arms are typically 20–30 mm wide. The burrows are often retrusive, giving the impression of *Teichichnus* or small-scale trough cross-bedding (*cf.* Sellwood, 1970; Fig. 3).

Remarks — Interpreted by Hantzschel (1975) to represent feeding and/or dwelling burrows of crustaceans. The retrusive forms are commonest in the well-cemented beds.

SKOLITHOS Haldeman, 1840
Skolithos sp.
Figure 6c

Description — Vertical or sub-vertical, simple tubes of constant diameter, filled with structureless sediment. Up to 10 mm in diameter and 0.25 m in length. Both lined and unlined forms occur.

Remarks — Interpreted to represent the dwelling burrows of polychaete worms (Curran and Frey, 1977). These burrows occur preferentially in the better cemented beds.

TEICHICHNUS Seilacher, 1955

Teichichnus sp.

Figure 5a and *b*

Description — Stacked flat-lying gently curving tubes, 2–3 mm in diameter.

Remarks — Records the progressive vertical movement of a horizontal burrow system. Commonest in muddier sands.

THALASSINOIDES Ehrenberg, 1944

Thalassinoides sp.

Figures 5a and *b, 6a* and *b*

Description — Horizontal branching burrows up to 30 mm in diameter forming polygonal networks.

Remarks — Interpreted as crustacean feeding and/or dwelling burrows. Most conspicuous at the junctions of well and poorly cemented sands where they are preferentially cemented (cf. Fürsich, 1973; Fürsich and Oschmann, 1986).

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