Sedimentary Geology, 57 (1988) 75–105
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Paleoenvironments of the Mid-Ordovician (Upper Caradocian) Trenton limestones of southern Ontario, Canada: Storm sedimentation on a shoal-basin shelf model

M.E. BROOKFIELD and C.E. BRETT

Department of Land Resource Science, Guelph University, Guelph, Ont. N1G 2W1 (Canada)
Department of Geological Sciences, Rochester University, Rochester, NY 14627 (U.S.A.)

(Received November 19, 1986; revised and accepted August 28, 1987)

Abstract

Brookfield, M.E. and Brett, C.E., 1988. Paleoenvironments of the mid-Ordovician (Upper Caradocian) Trenton limestones of southern Ontario, Canada: Storm sedimentation on a shoal-basin shelf model. Sediment. Geol., 57: 75–105

The mid-Ordovician (Caradocian) limestones of southern Ontario were deposited on a shelf undergoing collision with a magmatic arc. Within the general deepening-upwards sequence, shoals and islands complicate the facies patterns. Around these shoals and islands, carbonate sediments can be divided into nine lithotypes reflecting shallow agitated, to deep, quiet marine environments. Many of these lithotypes show good evidence of storm deposition. The lithotypes can be grouped into natural associations which define shoal, intershoal, slope and basinal facies—though the basins were probably less than 100 m deep. The closest recent analogues of these Ordovician environments occur on the Arabian shelf of the Persian Gulf, and on the Sahul shelf of northern Australia which is undergoing collision with the Banda arc. In both these environments, local shoal-basin shelf topography controls the detailed carbonate shelf sedimentation, which on a large scale is controlled by storm and tsunami effects on a seaward sloping ramp. Such shoal-basin and ramp models now seem more suitable in explaining carbonate facies in epeiric seas, than the flat slope models previously proposed. Glacio-eustatic sea-level changes may have controlled the larger aspects of carbonate sedimentation on the Ordovician shelf, as they did and continue to do now, on the recent shelves. Such changes may explain the localization of the variety of Ordovician hardgrounds which we previously described.

Introduction

In a previous paper (Brett and Brookfield, 1984), we noted the variation in hardground types and faunas in terms of a shoal-basin model of Trenton Limestone deposition. In this paper we note in more detail the specific environmental features of the sequence and compare them to those of modern carbonate shelf environments. As in our earlier study, the area covered is between Orillia and Peterborough, southern Ontario (Fig. 1).

Shoal-basin topographic differentiation is not usually considered characteristic of extensive epeiric seas (Shaw, 1964). Sedimentation models for these seas normally relate facies changes to variations in wind-generated currents and depth over flat uniform shelves (Irwin, 1965). Though not usually explicitly stated, the flat surface of deposition is considered to form by sedimentation progressively smoothing out any irregularities there may have been on the original transgressed landscape. However, most modern shelves, despite their ancestry, preserve significant relief in coastal and even offshore areas, due to combinations of tectonic, erosional and depositional variations and to fluctuating sea levels. Like Pratt and James (1986), who studied a Lower Ordovician tidal

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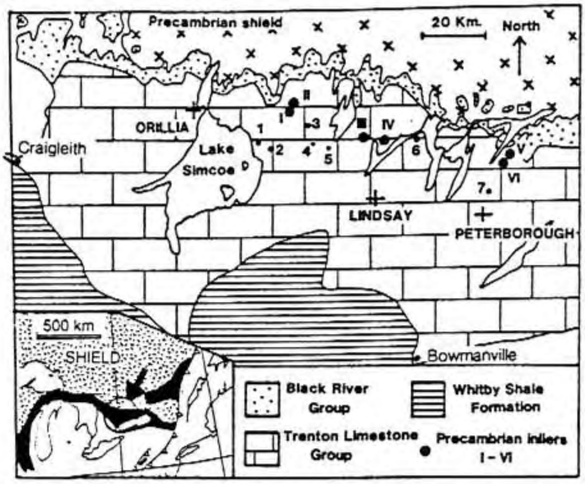


Fig. 1. Location map: localities cited in text. *I* = Rohallion inlier; *IV* = Red Rock inlier; *1* = Gamebridge quarry; *2* = Bolsover roadcut; *3* = Kirkfield quarry; *4* = Glenarm roadcut; *5* = Glenarm ditch; *6* = Little Bob quarry; *7* = Peterborough north quarry.

flat-shelf carbonate sequence in Newfoundland, we find that local sea-floor topographic differentiation provides a more satisfying explanation of facies distributions in the Trenton Limestone sea than does the flat shelf model. This interpretation is also more in accord with modern carbonate shelf sedimentation, particularly in those areas such as the Arabian and Sahul shelves which are closest to the Trenton Limestone sea in terms of tectonics, bathymetry and possibly climate (Fig. 2). Almost identical lithotypes and facies have been described from the European Triassic by Aigner (1985) and a similar storm-controlled shoal-basin morphology inferred.

The rational for this article is thus to support a shoal-basin, rather than a flat epeiric sea model for carbonate shelf sedimentation; and also to note how closely—despite their greater extent—they approximate to some modern carbonate shelves.

We also consider that, unless there is good evidence to the contrary, ancient carbonates should be interpreted by actualistic comparison with the whole spectrum of modern carbonates—from caves to deep sea and from poles to tropics. Too much reliance is still placed on purely tropical shelf carbonate models for ancient limestones (cf. Scholle et al., 1983). Nevertheless, since the present authors disagree, an alternative to the tropical shelf model is discussed elsewhere (Brookfield, in press).

Tectonic setting and stratigraphy

Southern Ontario lies on the southeastern edge of the Canadian shield, which was consolidated during the Grenville orogeny (ca. 1000 Ma), peneplaned by the Cambrian, and has been a stable craton ever since. Tectonic activity is restricted to simple faulting, and moderate to steep dips are found only around Precambrian inliers, where such dips are due both to initial inclination around shoal areas in the Ordovician sea and to later compaction around them (McIlreath, 1971). Apart from the facies distributions, discussed later, there is little sign of synsedimentary faulting during deposition of the Ordovician limestones. However, the nature of the outcrops and sedimentation around the Precambrian inliers is more understandable if minor synsedimentary faulting is invoked. In central New York State, there is now good evidence that complex facies distributions can be attributed to a mosaic of fault blocks formed during collision of the mid-Ordovician shelf with an island arc (Cisne et al., 1982) (Fig. 2). We suggest that this Taconic event may also have had a minor influence in the study area; though others have related the complex facies changes to original facies mosaics and oscillating eustatic sea level (Titus, 1983).

Regardless of the precise cause, during the mid-Ordovician the Canadian shield was inundated by the sea in one of the greatest eustatic rises of sea level recorded in the geological record. The transgression in southern Ontario is marked by a simple stratigraphic sequence from supratidal and tidal flat clastics and carbonates, through lagoonal carbonates, into offshore carbonates (Fig. 3). Within the carbonate sequence, the facies distributions are complicated by Precambrian peninsulas, shoals and islands in the Ordovician sea. This, it seems to us, has led to the present complex and confusing stratigraphic terminology (Fig. 3). In our previous paper, we used Liberty's (1969) terminology. But in fifteen years field work, the senior author has never been able to dis-

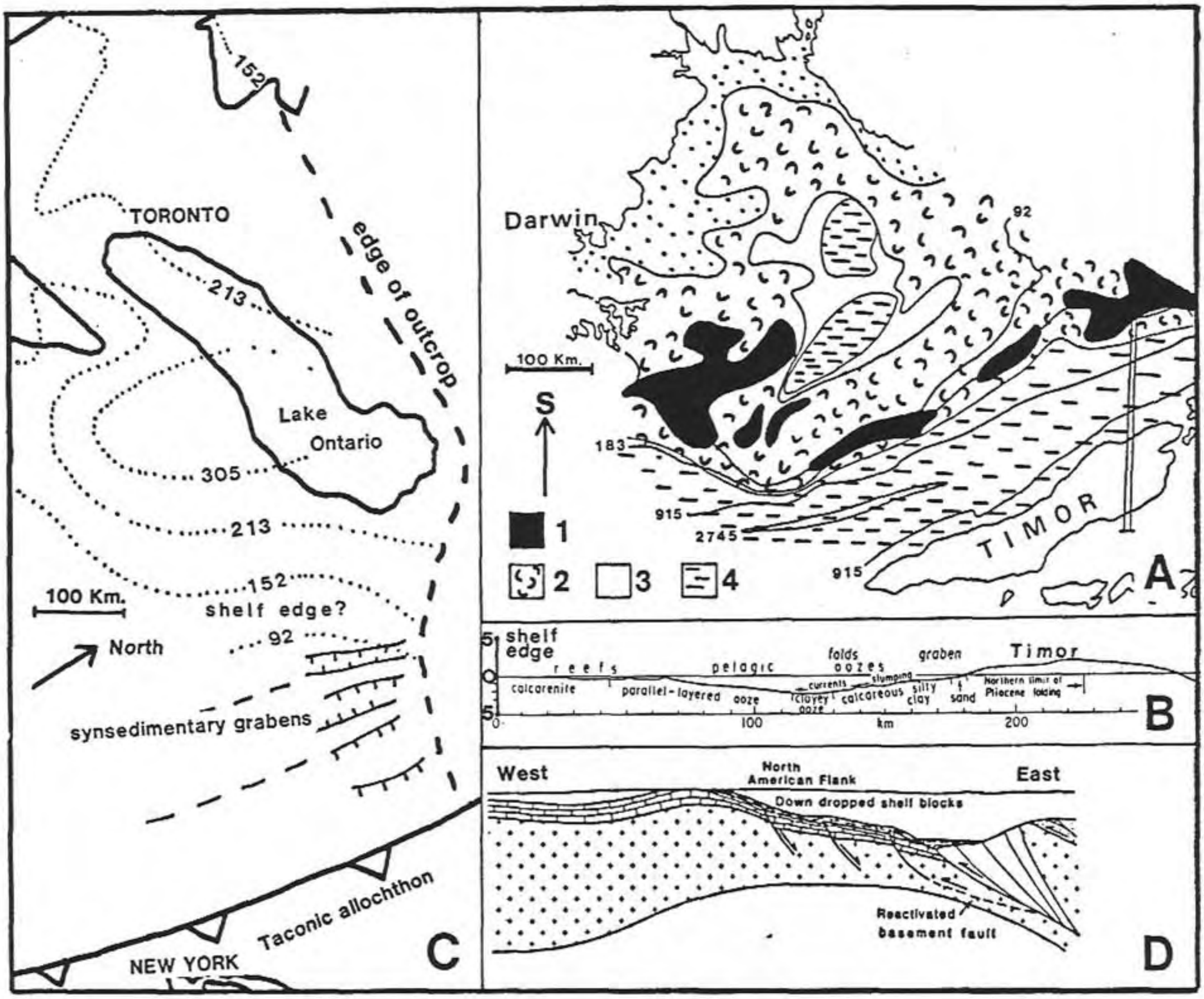


Fig. 2. Comparison of Middle Ordovician of eastern North America with recent Timor-Sahul shelf. Note orientation and scales of maps are the same. (A) Facies and bathymetry of the recent Timor–Sahul shelf area. *1* = calcarenites (shell sand grainstones); *2* = muddy calcarenites (shell sand packstones); *3* = clayey marl (wackestones); *4* = calcareous clay (mudstones). From Van Andel and Veevers (1967). (B) Cross-section across the Timor trough (double line on A), showing sedimentary environments. Vertical exaggeration × 3. From Veevers et al. (1978). (C) Mid-Ordovician slope and shelf in front of emplacing Taconic allochthon. Isopachs are total Black River/Trenton Limestone Groups thicknesses (since individual Group thicknesses are not available for whole area), and are converted from original feet measurement. Southeasterly thinning of Groups is lateral facies passage into trough shales. Facies distributions have not yet been studied at a fine enough time scale. From Fettke (1948), Sanford (1960), Flagler (1966) and Cisne et al. (1982). (D) Schematic cross-section showing inferred plate-tectonic situation for mid-Ordovician (not to scale). From Shanmugam and Lash (1982).

tinguish the various units in the field, and the supposed formations simply represent a general tendency towards decrease in bioclastics and increase in detrital clay upwards in the succession. As Steele-Petrovich (1986) found in the Ottawa valley to the northeast, it is very difficult to place recognisable lithofacies into the traditional formations of Fig. 3. In addition, the supposed uppermost bioclastic Verulam unit consists of lenticular crinoidal bank units at probably different stratigraphic levels. We therefore simply use the term Trenton Limestones for all limestone units above the Coboconc Limestone—a persistent, massive, easily recognised and mapped limestone, containing the last abundant coral fauna until the late Ordovician (Okulitch, 1939; Liberty, 1969). The

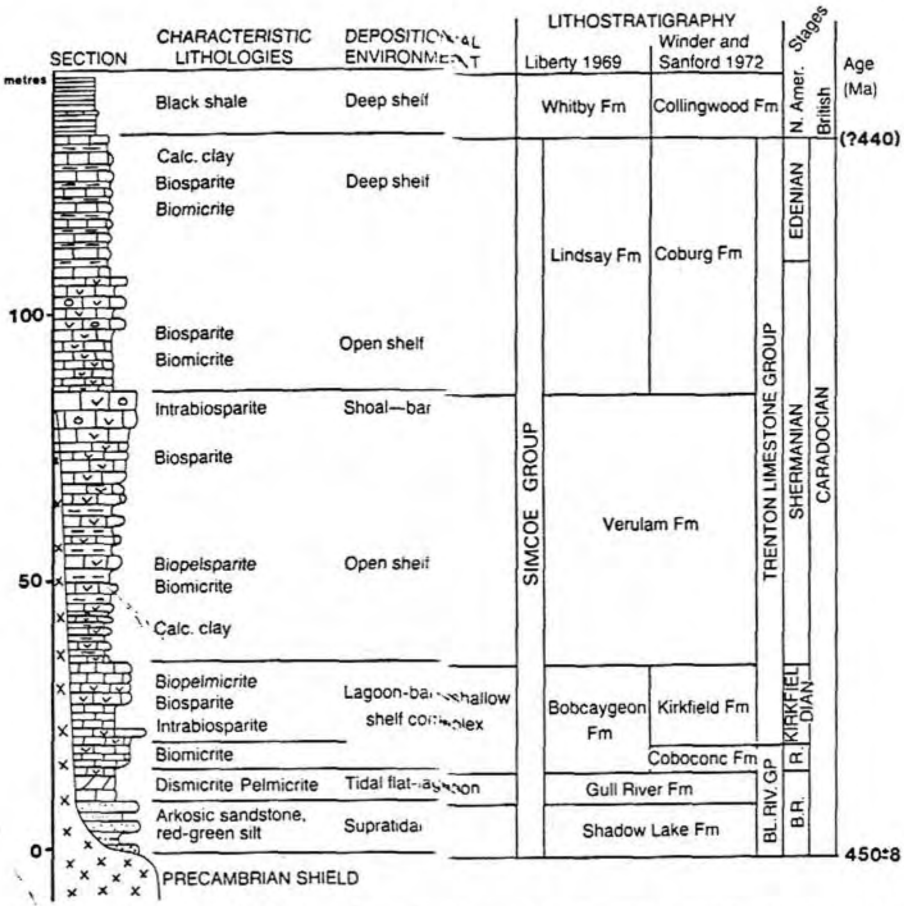


Fig. 3. Generalized stratigraphic section, lithology and terminology of Ontario mid-Ordovician. Ages and dates from Sweet and Bergström (1976), Ludwigsen (1978) and Odin (1986).

upper contact of the Trenton Limestones is the fairly thin transition zone between the fine-grained uppermost Trenton Limestone and the black shales of the Whitby Formation: this contact can only be seen in Bowmanville quarry and at Craigleith (Fig. 1).

Methods

In order to determine depositional environments, we have used a process-response method. We follow the "stratinomic" approach as outlined by Aigner (1985) for "it seems desirable and promising to study individual beds and strata in great detail in order to understand the dynamic processes that generate stratification". Bed-by-bed analysis often identifies single sedimentation events, and also the non-depositional events which may be preserved, e.g. cementation, boring and encrusting. Furthermore, concentration on single beds as facies elements helps in evaluation and modification of facies models and paleoenvironmental interpretations (Aigner, 1985). Our approach has been to attempt to distinguish lithotypes, interpret the process which formed them, and reconstruct a plausible local environment in which such lithotypes could develop.

We use the term "lithotype" for our units since they are recognized on a combination of both micro- and macro-studies and refer basically to depositional events. The alternative term "microfacies" is thus inappropriate (Flügel, 1982).

Associations of lithotypes occurring naturally and repetitively in sections were then grouped into a few facies, which we consider define broad environmental complexes. We have used genetic names for these complexes, such as shoal facies, basin facies, etc., partly because descriptive terms were already used in the lithotype descriptions, and partly to emphasize the interpretative nature of the facies: others may interpret the lithotypes differently.

Petrography and diagenesis were studied with polished slabs, thin sections and (mostly) with acetate peels, which were often stained to determine carbonate mineralogy using Dickinson's (1966) and Evamy's (1969) techniques. In selected cases we also separated insoluble residues and counted bioclastic types, following the procedures of Smosna and Warshauer (1978).

We have used a mixture of terminologies to describe lithology, characterizing carbonate grain size as clay, silt, sand and gravel. Folk's (1962) classification is used to denote grain and matrix type, and Dunham's (1962) classification for depositional texture. Thus, for example, we may describe a sediment as: fine-grained, well-sorted, low-angle thinly cross-laminated biosparite grainstone. We prefer the use of two nouns rather than an adjective-noun combination (e.g. biosparitic grainstone) to emphasize that each term is a separate classification. Scholle's (1978) definitions and terms are used for carbonate cements and matrix.

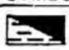
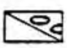
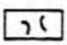
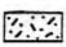
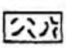
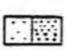
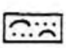
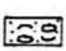
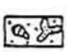
Percentages and proportions of constituents were estimated with standard percentage diagrams and charts. A variety of these are now available for different shades, shapes and sizes of particles, and Flügel (1982) has demonstrated statistically that such estimates are as accurate as point counts —and they are quicker to do.

Lithotypes

An apparently bewildering variety of lithotypes occurs in the Trenton Limestones. These we have subdivided according to grain-size, sorting, de-

TABLE 1

Lithotype symbols, short description and Wilson's (1975) equivalent microfacies

	SYMBOL	WILSON'S (1975) FACIES EQUIVALENTS	LITHOLOGY	SEDIMENTARY STRUCTURES
1			Dark grey, detrital shale	Lamination, minor burrowing
2		SMF 8	Calcareous claystones and nodular biomicrite mudstones.	Heavy, small-scale bioturbation
3		SMF 9	Poorly sorted coarse to fine grained biomicrite wackestones and packstones.	Heavy, small-scale bioturbation
4		SMF 10	Medium to coarse grained rounded well sorted biomicrite wackestones.	Heavy, small-scale bioturbation
5		SMF 5	Poorly sorted coarse to fine grained biosparite grainstone and biomicrite packstone.	Heavy, small-scale bioturbation plus dwelling burrows
6		SMF 2	Well sorted fine grained biopelsparite and biosparite grainstones (calcisiltites).	Fine parallel, ripple, cross lamination: grading.
7		SMF 12	Well sorted fine to coarse grained biosparite grainstone (calcarenites).	Planar to festoon cross bedding.
8		SMF 24	Moderate to poorly sorted conglomeratic coarse to fine grained biosparite grainstone	Planar to festoon cross bedding: channels
9			Moderately to poorly sorted red algal-bryozoan grainstone, packstone, wackestone and boundstone.	None

positional texture and structure. A finer subdivision was made, where necessary, on the dominant bioclastic grains. Trends in other constituents such as clay content, which happily followed the lithotype divisions are reported in the appropriate section. A rather unexpected result of this study was the regularity of lithotype variations within sequences—despite their apparent complexity.

Lithotypes and origin

The lithotypes distinguished are described below, with Wilson's (1975) facies equivalents, where comparable, in parentheses (Table 1): we have also noted comparable Persian Gulf microfacies where appropriate, since it is our contention that, physically at least, the recent Arabian shelf and Ontario Ordovician shelf are close analogs.

Lithotype 1. Dark grey, slightly calcareous, laminated, burrowed detrital clays (Figs. 4 and 8)

These occur as relatively rare, thin partings on top of limestone beds. Where present, they seem to owe their survival to rapid burial by bioclastic

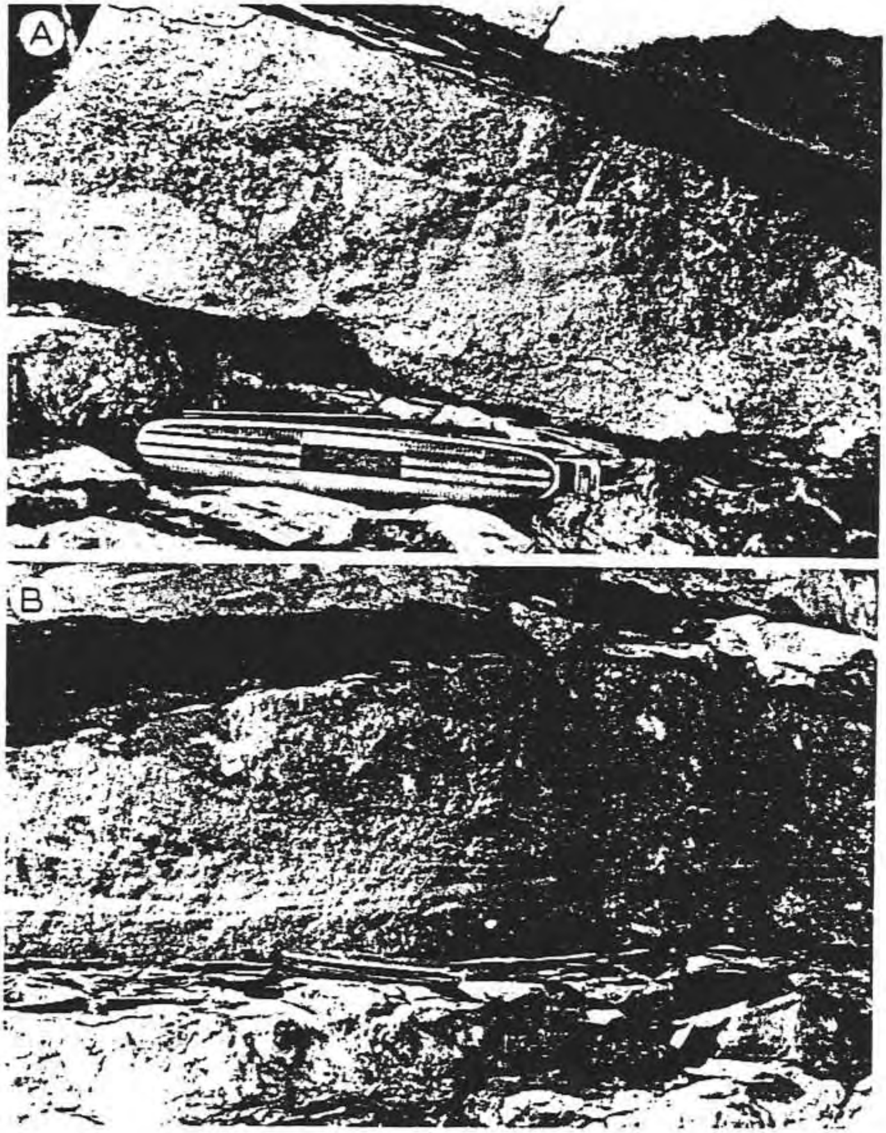


Fig. 4. Lithotype 1. Dark grey calcareous clays. Clastic clays draping bioclastic limestones; Kirkfield quarry (location 3). Knife is 8.5 cm long.

layers, or to rapid deposition of at least several centimetres of clay. These clays may contain up to 40% of carbonate, but normally contain less than 10%. Macrofossils are usually absent, apart from thin layers of broken graptolites and rare *Lingula*. Rarely, the trace fossils *Planolites* and *Chondrites* penetrate down from the tops of the clay layers and are filled either with clayey micrite (lithotype 2) or bioclastic material (lithotypes 3 and 4). But these post-date deposition since the clays are not internally bioturbated by deposit feeders. These features indicate relatively rapid deposition in calm water.

The presence of pelagic organisms (graptolites), absent in other lithotypes; the low carbonate content, contrasting markedly with other lithotypes; and the absence of bioturbation, suggest unusual conditions. Similar sediments occur in the deeper parts of the Persian Gulf (Purser, 1973) and the clays may thus reflect transgressions. On the other hand, unusual floods or storms may have carried clay and pelagic organisms onto the normally

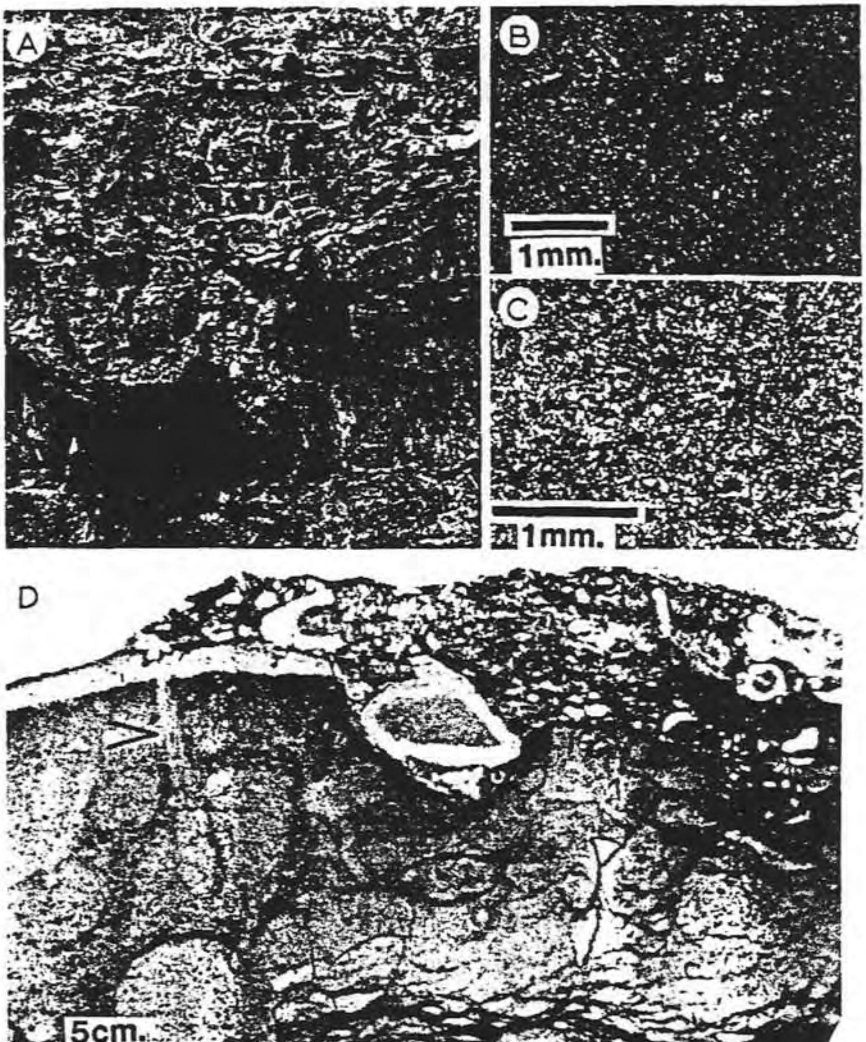


Fig. 5. Lithotype 2. Bioturbated calcareous mudstones and wackestones. (A) Interbedded with lithotype 3. Gamebridge quarry (location 1). Hammer head is 18 cm long. Note broad channel cut into lithotype 3 and filled with lithotype 2 (above hammer). (B) and (C) Peels. Detail of lithotype 2 from A. (D) Edrioasteroid bed, Kirkfield (location 3). Note differential compaction from top hardground (boring arrowed), and erosion of nodular limestone after breaching of hardground surface (on right).

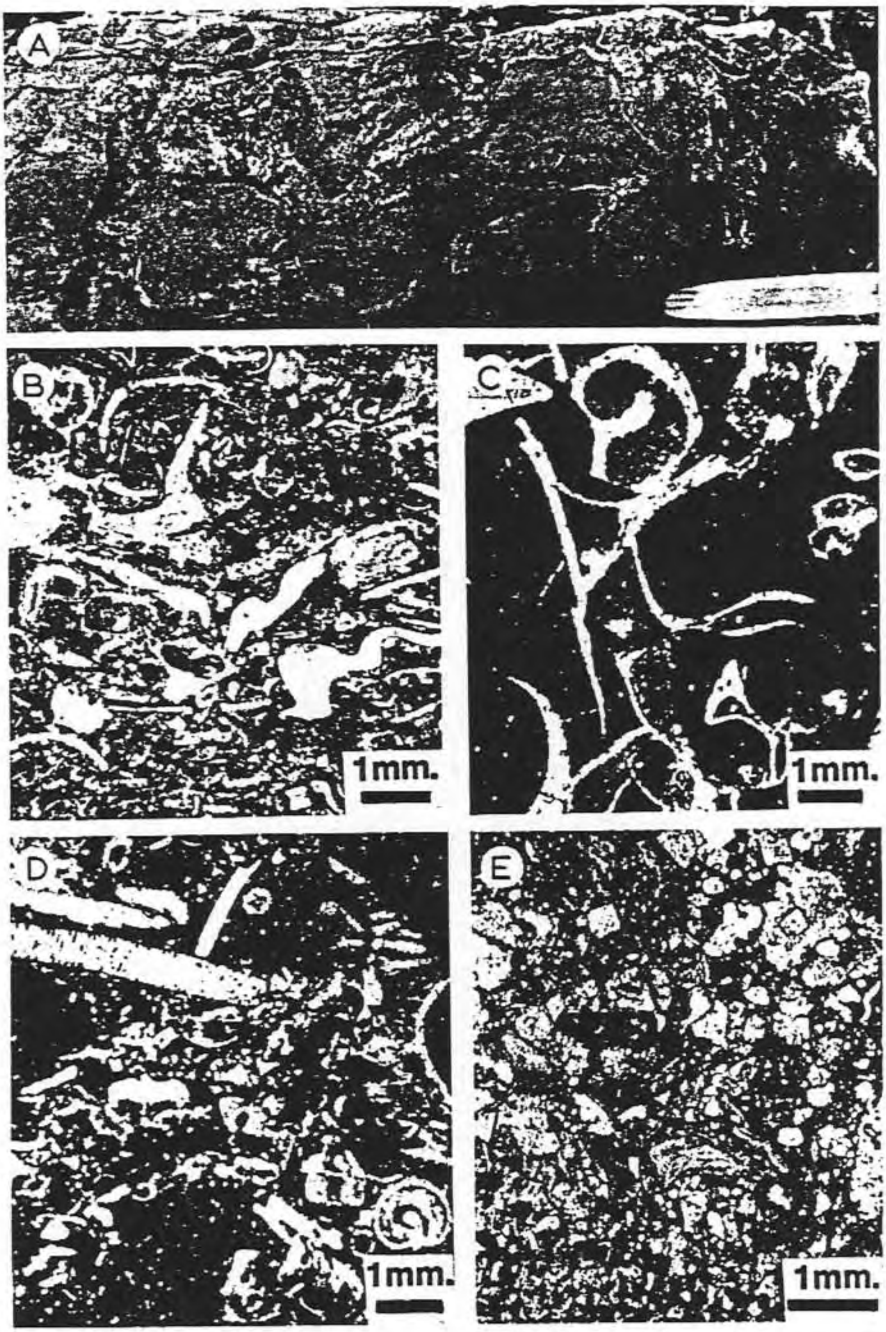


Fig. 6. Lithotype 3. Biomicrite packstones and wackestones. (A) Filling dwelling burrows in lithotype 6. Kirkfield quarry (location 3): 6 cm of knife showing. (B) Brachiopod-dominated subdivision, with trilobite, ostracod and gastropod fragments. Glenarm roadcut, upper beds (location 4). (C) Gastropod-dominated subdivision; Glenarm ditch (location 5), filling of channel cut into hardground. (D) Brachiopod-dominated subdivision; Glenarm roadcut (location 4); diverse bioclasts bioturbated in with mudstone. (E) Dolospar replacing dwelling burrow filling, Glenarm roadcut (location 4).

carbonate-dominated shelf. Such floods are recorded in historic times in the Tigris-Euphrates river system feeding the Persian Gulf (Genesis 7: 17–20).

Lithotype 2. Heavily bioturbated calcareous mudstones and wackestones, often nodular (SMF 8) (Fig. 5)

These are common throughout the sections. Their very variable character depends on the variety of distinct lithotypes deposited prior to, or during, bioturbation, the resulting proportion of carbonate to detrital clay, and the intensity of bioturbation. Though often sparse, macrofaunas are relatively diverse and dominated by brachiopods and crinoids. Shells are unmicritized and fragments frequently angular. These sediments, with a decrease in rate of deposition and/or reworking, pass into the fossiliferous limestones of lithotype 3.

Similar nodular lime mudstones are common in the more basinal parts of recent and ancient carbonate basins (Mullins et al., 1980; Markello and Read, 1981). In the Persian Gulf, bioturbated calcareous bivalve muds are the most widespread sediments in the deeper shelf areas and often separate shoal areas (Wagner and Van der Togt, 1973; Purser, 1973). Such bioturbated calcareous muds can easily transform to nodular limestones on diagenesis (Mullins et al., 1980) and may, if exhumed, develop quiet-water hardgrounds. These are common in Cretaceous chalk sequences, and have also developed on some Trenton Limestone beds—where they often bear rare and most beautifully preserved attached echinoderm faunas (Brett and Liddell, 1978; Brett and Brookfield, 1984).

Lithotype 2 corresponds to Wilson's (1975) standard microfacies 8, which he interprets as deposited in quiet water below wave base. Similar sediments were interpreted by Cook and Taylor (1977) as being deposited in shallow subtidal shelf environments, below wave base but in well-oxygenated water.

Lithotype 3. Poorly sorted, coarse- to fine-grained biomicrite packstones and wackestones (SMF 9) (Fig. 6)

This lithotype consists of individual beds up to 10 cm thick, frequently amalgamated to 50 cm, with laminations almost or entirely obscured by heavy small-scale bioturbation. Periodically, during pauses in sedimentation, large *Thalassinoides*-type dwelling burrows were excavated in the sediment (Fig. 6A). Longer pauses in sedimentation, and erosion, sometimes formed hummocky hardgrounds on exhumed, partially cemented, nodules and lithified layers. Like lithotype 2, the variability of this sediment is due to heavy bioturbation which mixed up distinct layers of detrital clay, micrite, shell-lag accumulations, and bioclastics (Fürsich, 1973). Shell fragments are subangular to angular, poorly sorted, rarely micritized, and represent diverse organisms.

We distinguish two distinct subdivisions of this lithotype on the basis of their fauna.

(3A) Brachiopod-crinoid dominated (Fig. 6B, D). These have a diverse fauna, often including trilobite, crinoid, ostracod, bivalve and gastropod fragments (cf. Fig. 6B).

Analogous muddy carbonate sands of the Persian Gulf occur as widespread sheets at depths of 20–60 m between shoals on the Arabian shelf.

(3B) Gastropod-dominated (Fig. 6C). Gastropod-dominated sediments usually occur associated with channel-fill hardgrounds, probably because the gastropods grazed their algal turf cover. Most marine hard surfaces, down to 300 m depth in some situations, are encrusted with algae of different types, though the coralline red algae penetrate deepest (Littler et al., 1986). Wagner and Van der Togt (1973) recorded similar sediments from shallow protected areas of the Persian Gulf.

Both subdivisions are cemented by fine, non-ferroan calcite microspar. Dolomite replacement of dwelling burrow fillings is common (Fig. 6E), and has been recorded from recent deep marine carbonate slope burrows off the Bahamas (Mullins and Neumann, 1979). Occasionally, small-scale cross-lamination and parallel lamination are preserved.

Wilson (1975) interprets his equivalent microfacies, SMF 9, to be formed in shallow shelf environments at, or just below, wave base; or, in the case of gastropod-dominated sediments, in "lagoonal" areas. The characteristics of lithotype 3 are relatively slow deposition from suspension in quiet water, with periodic non-deposition to allow the attached epifauna to survive, followed by bioturbation.

Lithotype 4. Medium- to coarse-grained, rounded, well-sorted, unlaminated, biomicrite wackestone (SMF 10) (Fig. 7)

This relatively rare lithotype shows textural inversion. Shell fragments, dominantly of brachiopods and crinoids, are well-rounded and well-sorted, and float in a clayey, highly bioturbated micrite matrix. Shells were fragmented and rounded in more agitated areas and were then transported into quieter water by turbidity currents or storms, and then mixed into finer sediment by burrowers. Flügel (1982) noted that such worn bioclasts originated on high-energy shoals and were then moved down local slopes into quieter deeper water. In contrast to the wave and current worked sediments of lithotypes 5 and 6, these sediments seem to have simply been dumped rapidly into quiet water.

Lithotype 5. Poorly sorted, coarse- to fine-grained biosparite grainstones and biomicrite packstones, which may show crude size grading (Fig. 7C, D and 8)

This lithotype consists of lenses of broken, angular fragments of brachiopods, crinoids, trilobites and rare bryozoa, with occasional bivalves, gastropods and pellet aggregates (Fig. 8A, B). It frequently alternates with lithotypes 2 and 3, and forms shell lenses concentrated during periods of increased turbulence and reduced deposition (Fig. 7C, D).

Shells in lithotype 5 are sporadically micritized, and microborings are often pyritized; a lumpy micrite matrix is characteristic (Fig. 8A, B). Micrite also frequently fills irregular ?*Planolites* burrows, and these burrow fills are occasionally replaced by dolosparite. Gastropod-rich beds may contain up to 5% of peloids and quartz silt is relatively common, reaching 10% in some samples. In the grainstones, an early equant to bladed spar fringe cement is followed by a larger equant pore-filling cement, or the fringe spar coarsens towards pore centres. In the packstones, the micrite is frequently recrystallized in microspar.

This lithotype represents more agitated more periods with non-deposition, either in a shelf or "lagoonal" situation. Certain of the beds (Fig. 7D) resemble starved ripples, and some (Fig. 7C) resemble Aigner's (1982) distal tempestites. If so, these beds are closely related to microfacies 6 below. At any rate, encrusting bryozoa, and occasional edrioasteroids on bed tops (Fig. 8D) indicates hardground formation and hence non-deposition for long periods after laying down of these beds.

Lithotypes 5 and 2 may be associated in single beds (Fig. 7C). These can be interpreted as in situ storm reworked deposits. The lower unit shows protected micrite fillings of shells in a poorly sorted packstone fabric—a winnowed lag deposit (see also Fig. 8D, F). The overlying lithotype 2 unit is bioturbated, but records relic fine lamination, suggesting traction deposition of sediment falling out of suspension. Two storm events are recorded in Fig. 7C, separated by a period of bioturbation (cf. Aigner, 1985). Characteristically, a much longer period of non-deposition and erosion is recorded at the bed top, where diverse encrusting faunas used shell fragments, or even exhumed molluscan internal moulds, for attachment (Fig. 8C, D) (Waddington, 1980) and where dwelling burrows predate lithification and hardground formation in many cases (Fig. 8E, F). These beds, reworked in situ, contrast with the transported fabrics of lithotypes 4 and 6, which suggests, as does the poorer sorting and generally finer grain size, distal storm deposits (Aigner, 1985).

This lithotype is the source of magnificent slabs, with beautifully preserved fossils on their upper surfaces, indicative of abrupt burial of communities by mud layers (Seilacher et al., 1985). There are no close recent Persian Gulf analogies, though the coarser units of the bivalve muddy sands are basically similar to more wave reworked lithotype 3 (Wagner and Van der Togt, 1973).

Lithotype 6. Well-sorted, fine-grained biopelsparite and biosparite grainstone (calcisiltites), typically finely laminated and graded (SMF 2) (Fig. 9 and 10)

This lithotype forms beds between 1 and 10 cm thick (Fig. 9A), with sharp planar bases, and

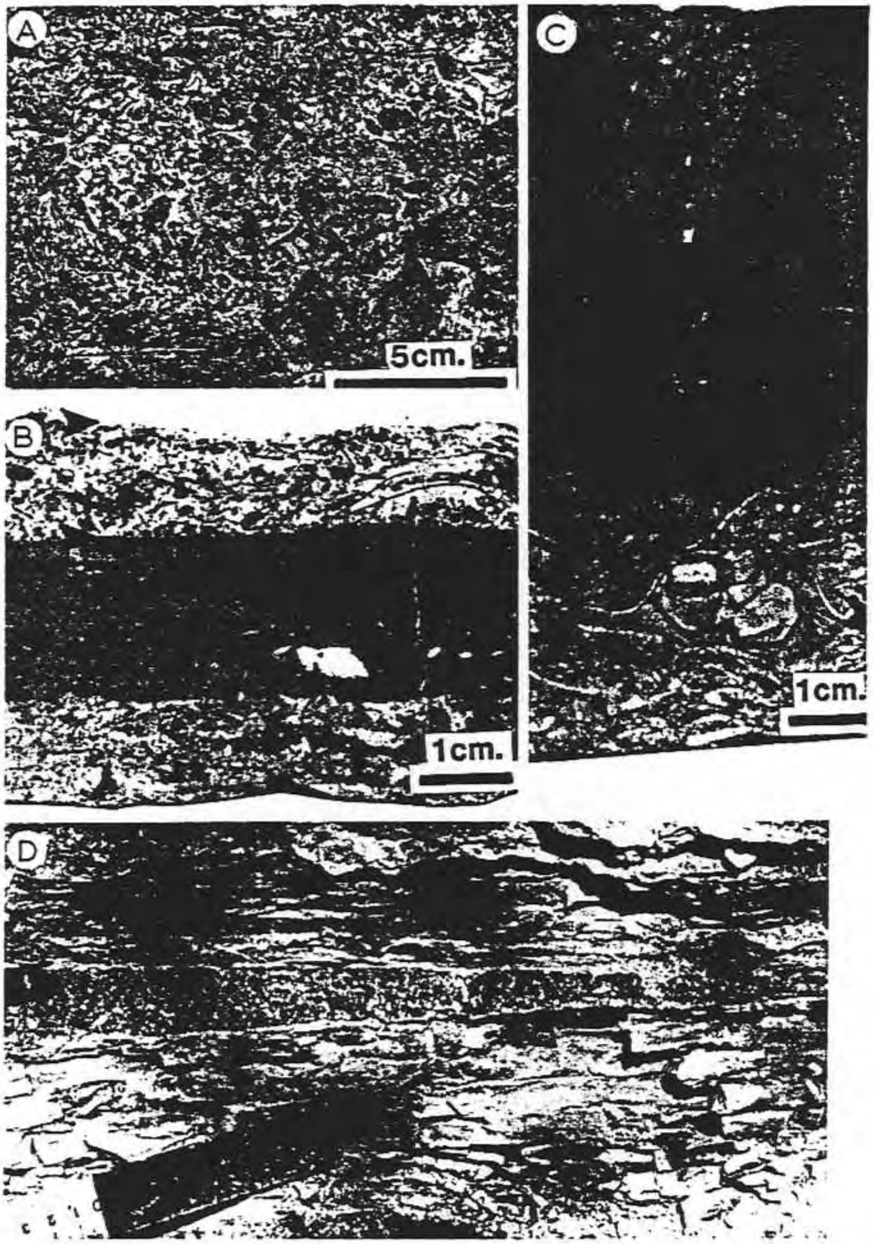


Fig. 7. Lithotype 4. Rounded. well-sorted biomicrite wackestone. (A) Intraclastic unit, Kirkfield quarry (location 3). (B) Lithotype 4 on graded lithotype 6, resting on lithotype 5, Gamebridge quarry, lowermost hardground (location 1). Multiple hardgrounds (arrowed), both with encrusting faunas. Hardground developed on lithotype 6, was bored, then covered with lithotype 4, which was cemented and partially eroded down to the original hardground. The composite surface was then recolonized (see Brett and Brookfield, 1984). (C) Lithotype 5 at base of multiply graded bed of lithotype 3. (D) Lithotype 5 as lenticular lense in calcareous mudstone (lithotype 2): scale in cm.

normally irregular bioturbated tops in which whole fossils are common. Gradations exist between this lithotype and lithotype 5. Individual beds may show coarse cross-laminated bioclastic grainstone bases, passing up into hummocky, planar or low-angle cross-laminated, fine-grained bioclastic grainstones or packstones, which are often capped by micrite mudstones or biomicrite wackestones (Figs. 9B–E and 10). Shell fragments, dominantly brachiopods and crinoids, are rounded to suban-

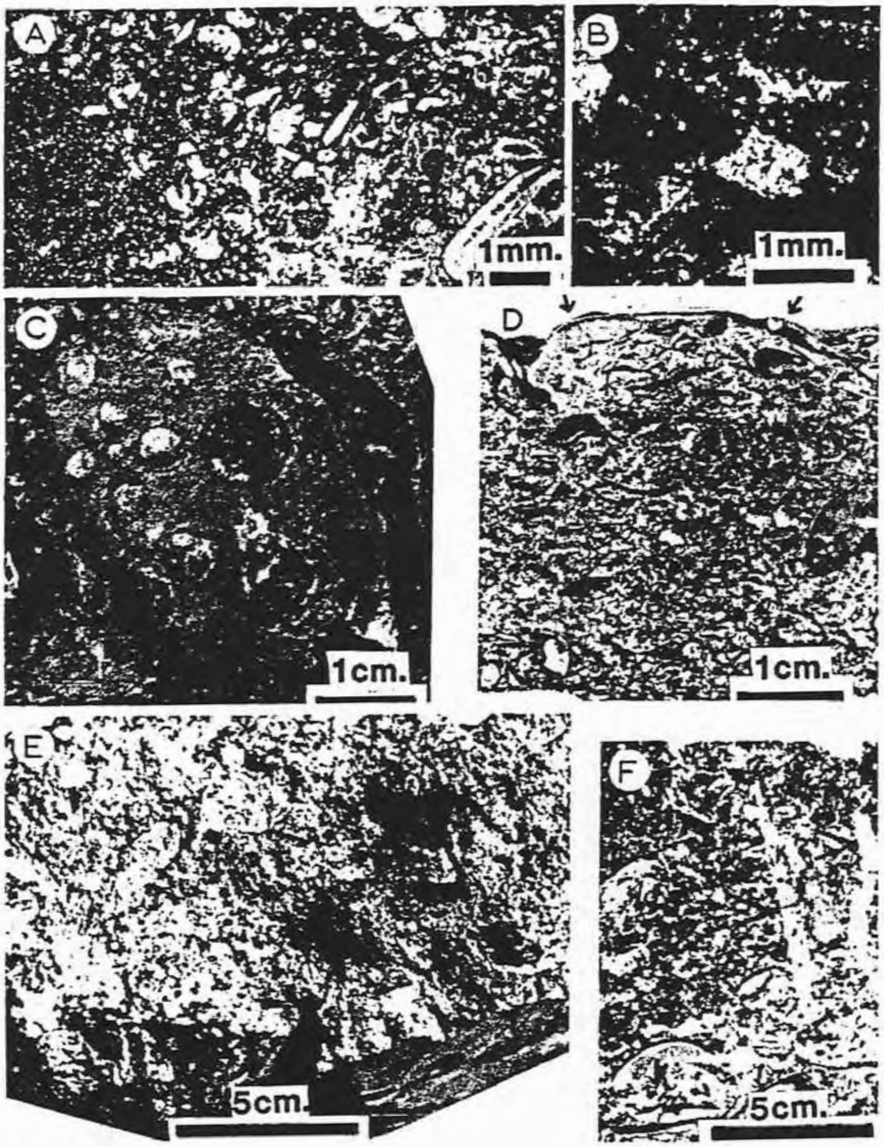


Fig. 8. Microfacies 5. Poorly sorted biosparite grainstones and biomicrite packstones. (A) Bioturbated packstone; Glenarm roadcut (location 4). (B) Detail of grainstone with pelletal accumulations. (C) Edrioasteroid (*Isorophusella*) encrusting internal mould of bivalve (cf., Waddington, 1980); Gamebridge quarry, top bed (location 1). (D) Cross-section of similar internal mould to C; arrowed are encrusting edrioasteroids and bryozoans; note poorly sorted, slightly graded biomicrite packstone; same location as C. (E) Quiet water irregular, mineral-stained hardground, with rare borings (centre right). (F) *Trypanites* borings (arrowed) in E. cutting cement and shells: note slight grading and "umbrella" effects below shells in graded bed.

gular and normally micritized and pyritized. Intraclasts are occasionally present—and these are often bored and micritized indicating early cementation: they were probably derived from hardgrounds. Occasionally, *Thalassinoides*-type dwelling burrows are present, and these are filled with either micrite or poorly sorted biomicrite mudstone and wackestone (Fig. 9E). Irregular hardgrounds, undercut in places, sometimes cap these beds (Fig. 9E, 10B and C) (Brett and Brookfield, 1984).

This lithotype most closely resembles Wilson's (1975) SMF 2—microbioclastic calcisiltite—deposited in basinal to lower slope environments. However, lithotype 6 (and to a lesser extent lithotype 5) have the "ideal" characteristics of resedi-

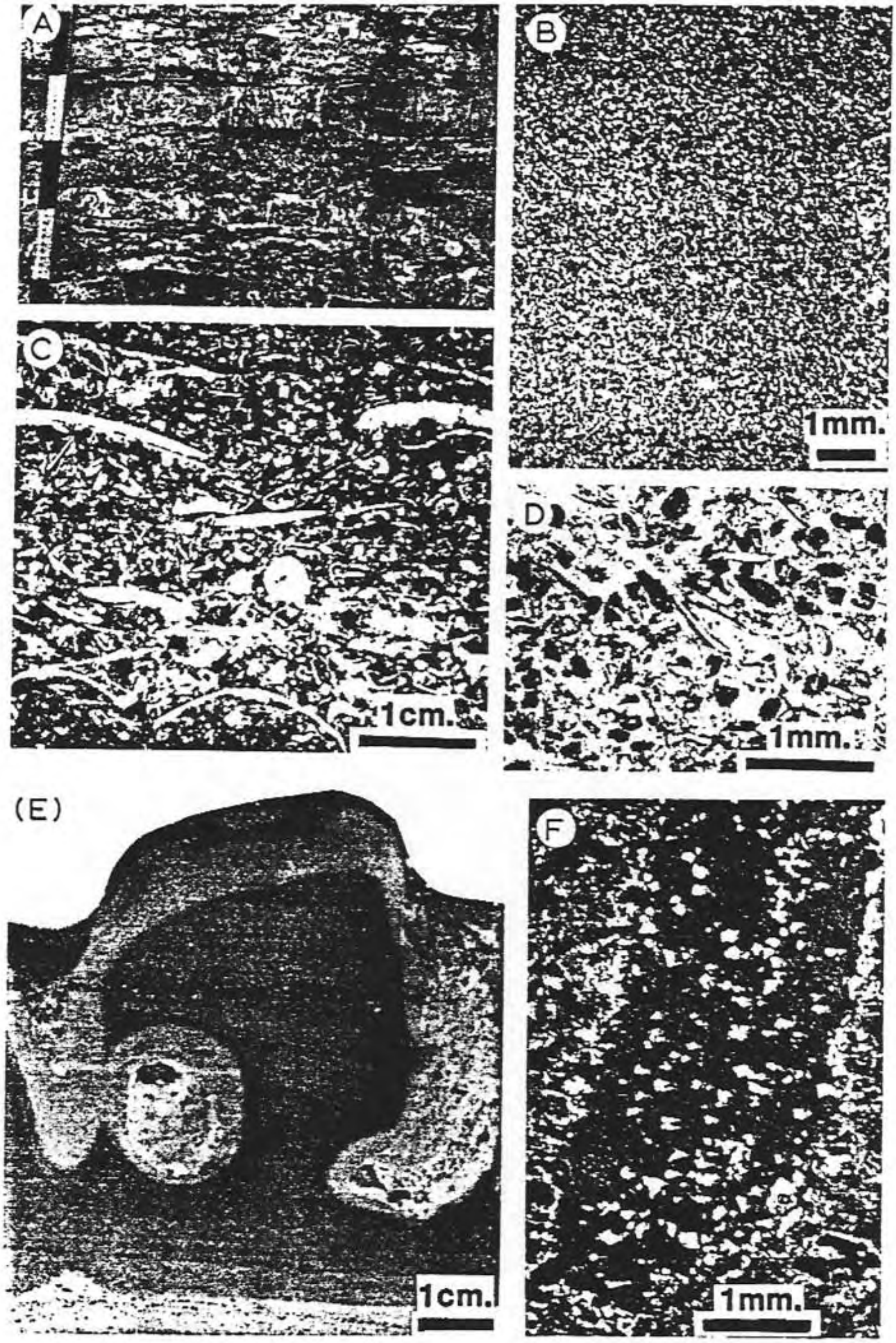


Fig. 9. Lithotype 6. Well-sorted graded fine-grained biopelsparite and biosparite grainstones. (A) General view interbedded with lithotype 2: Gamebridge quarry (location 1); metre stick in 10 cm divisions. (B) Detail of grading in biopelsparite; Peterborough north quarry (location 7). (C) Coarser-graded bed with concave down brachiopod fragments; Glenarm roadcut (location 4). (D) Detail of C, well-sorted biopelsparite grainstone. (E) Fine-grained graded biopelsparite grainstone: note low-angle cross-lamination, dwelling burrows, irregular rolling hardground on top and final claystone top to burrows; Peterborough north quarry, lower beds. (F) Detail of *Trypanites* boring in E (peel): note boring truncates fringe cements but penetrates pores, predating equant spar cement; central micrite fill contains dolospar.

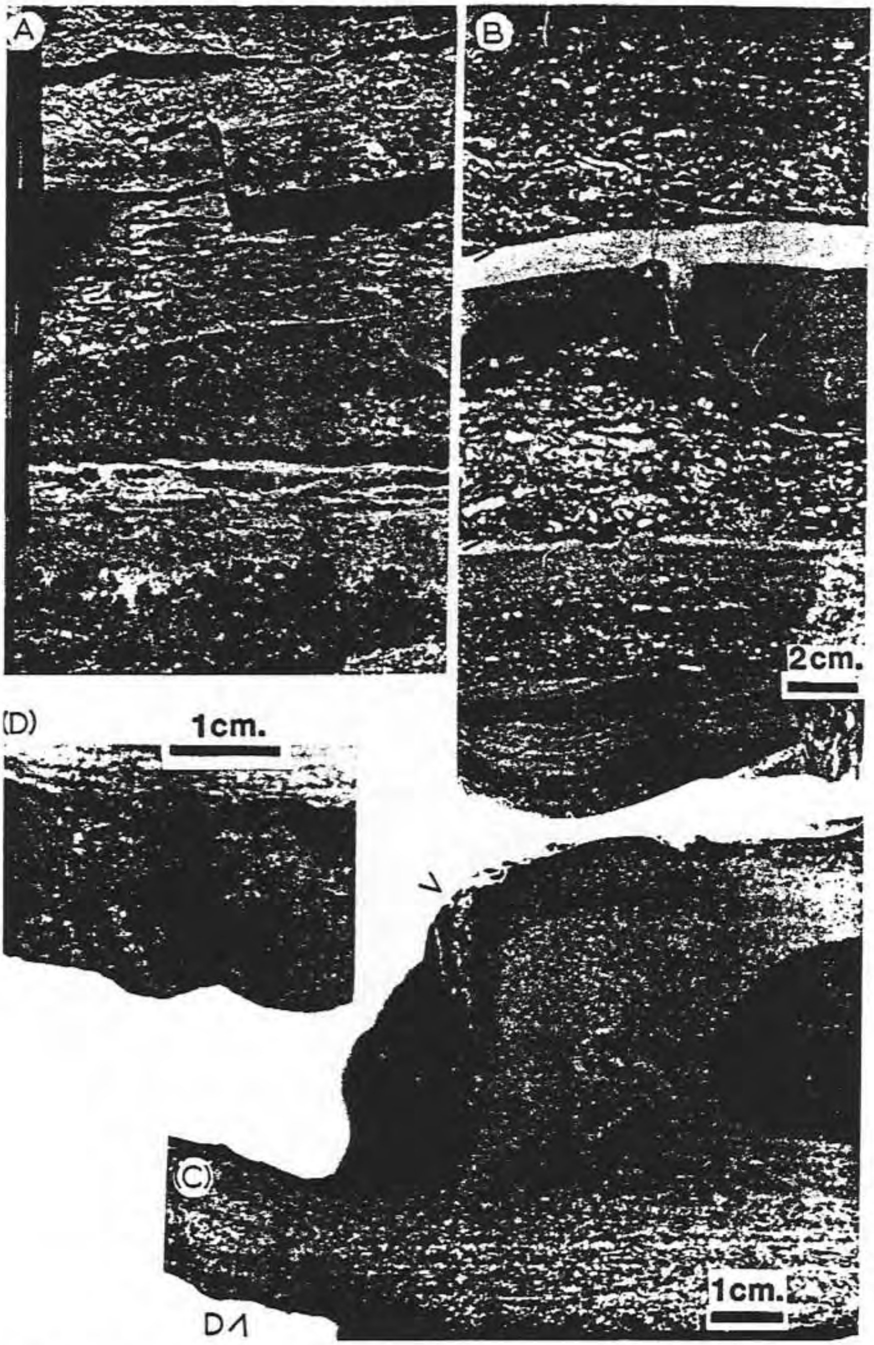


Fig. 10. Lithotype 6. Well-sorted graded calcisiltites. (A) Successive beds, interbedded with claystone; Peterborough north quarry, lower beds (location 7). Metre stick bands in tens of centimetres. "Stromatolitic" layer at base is simply a damp surface. (B) Section through centre bed of A, showing successive graded beds, all with hardgrounds on top (arrowed): base has "gutter" marks. (C) Eroded and undercut edge of cemented graded bed. Both upper and lower (inset *D*) surfaces were colonized by encrusting bryozoan and pelmatozoan fauna (cf. Brett and Brookfield, 1984); Peterborough north quarry.

mentation from storm-generated suspensions: fragmental bioclasts in graded beds (Aigner, 1985), hummocky cross-lamination (Harms et al., 1975), and concave-down shells showing "umbrella" effects in packstones (Kreisa, 1981). Each bed seems to have been deposited by one event, preceded and followed by periods of non-deposition long enough, at times, to compact the sediment surface sufficiently for dwelling burrows to be excavated or the sediment to be cemented to form hardgrounds, or both. On this interpretation, lithotype 6 would be a proximal tempestite, while lithotype 5 would be a distal tempestite: the distinction between the two reflecting intensity of storm action and/or depth (cf. Figs. 8 and 10). The abundance of these omission surfaces and hardgrounds throughout the Trenton Limestone sequence indicates a generally low net rate of deposition—in fact less than 0.015 mm y^{-1}.

The closest Persian Gulf equivalent are the bivalve sands which accumulate in shallow shelf areas, on the crests of offshore shoals and on the windward flanks of shallow shelf shoals (Purser, 1973). Closer analogies are, however, temperate carbonate shoals (Nelson et al., 1982; Nelson and Bornhold, 1983).

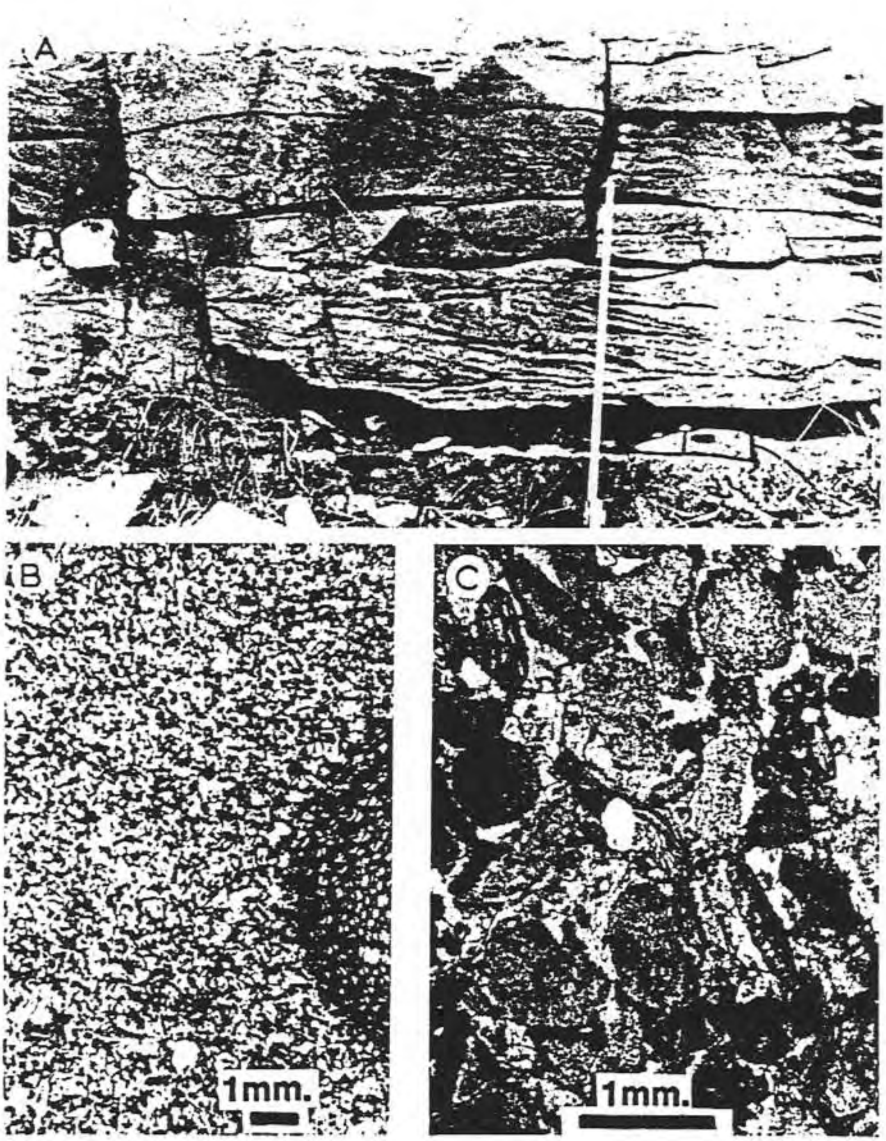


Fig. 11. Lithotype 7. Cross-laminated, well-sorted biosparite grainstones. (A) Roadcut, 2 km south of Cameron on highway 35, north of Lindsay; 50 cm of tape showing. (B) Thin-section, roadcut 5 km WSW of Glenarm. (C) Thin-section, same locality as A: allochems mostly pelmatozoan ossicles.

Lithotype 7. Planar to festoon cross-laminated, well-sorted, fine- to coarse-grained biosparite and biopelsparite grainstones (SMF 12) (Fig. 11)

In this lithotype, bioclasts are normally dominated by pelmatozoan plates, mainly crinoid columnals, with variable amounts of brachiopod, bryozoa and gastropod fragments. Quartz silt may reach 5%, and peloids 10%, of the sediment. Normally this cleanly washed sediment is cemented by an early equant to bladed fringe spar cement and syntaxial overgrowths on echinoderms, followed by a later pore-filling equant spar cement.

Thick, trough cross-bedded units are rarely burrowed and contain high percentages of pelmatozoan fragments. Thinner beds may show sequential changes from indeterminate bioturbation to dwelling burrows of *Thalassinoides*-type, whose fillings may show early geopetal fillings of dolosparite-replaced micrite, overlain by ferroan calcite spar; or the burrows may be filled with poorly washed biomicrite packstones. Hardgrounds have not been recorded in this lithotype.

This lithotype, analogous to Wilson's (1975) SMF 12, formed in agitated environments of con-

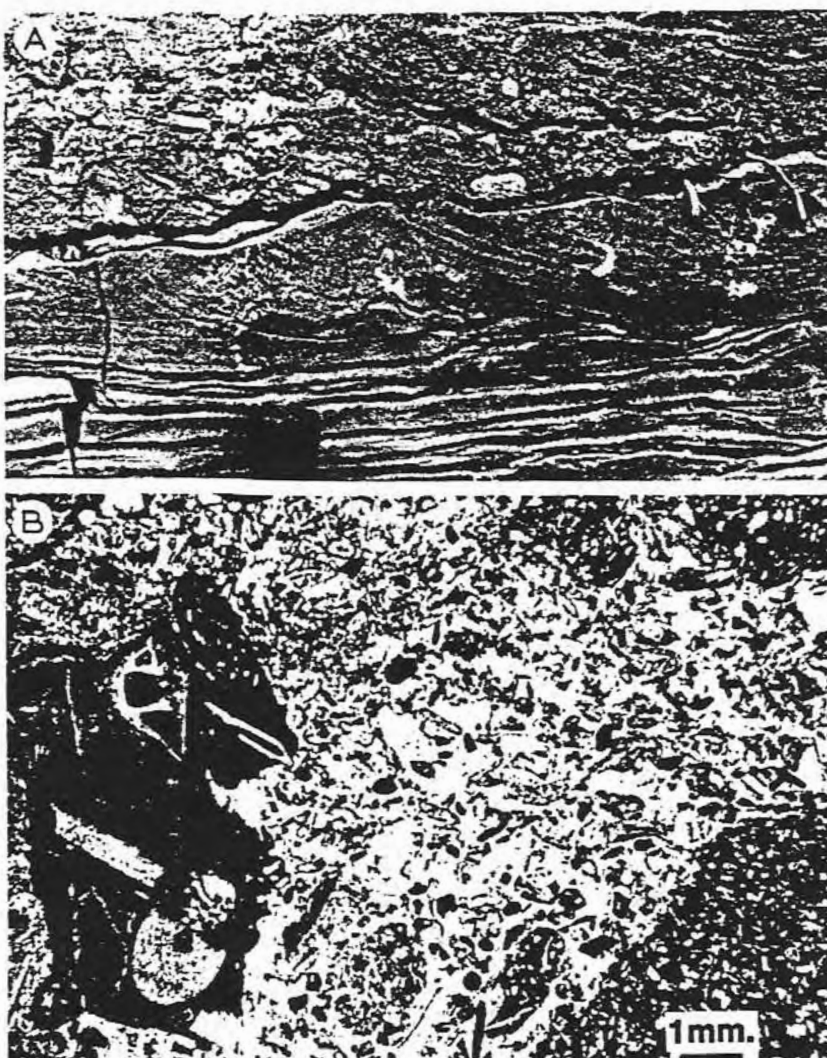


Fig. 12. Lithotype 8. Conglomeratic intrabiosparite grainstone. (A) Overlying lithotype 7 in channel; roadcut 5 km WSW of Glenarm; width of hammer top is 3.5 cm. (B) Thin-section, same location as A; varied intraclasts in dominantly pelmatozoan grainstone matrix.

stant wave or current action. The thicker units show the features of migrating bioclastic dunes. Similar well-sorted bioclastics are commonly found on recent shallow shelves as migrating tidal sand bars. Coral-algal sands of the Persian Gulf, though compositionally distinct, form sand bars and "tails" on offshore shoals (Purser, 1973).

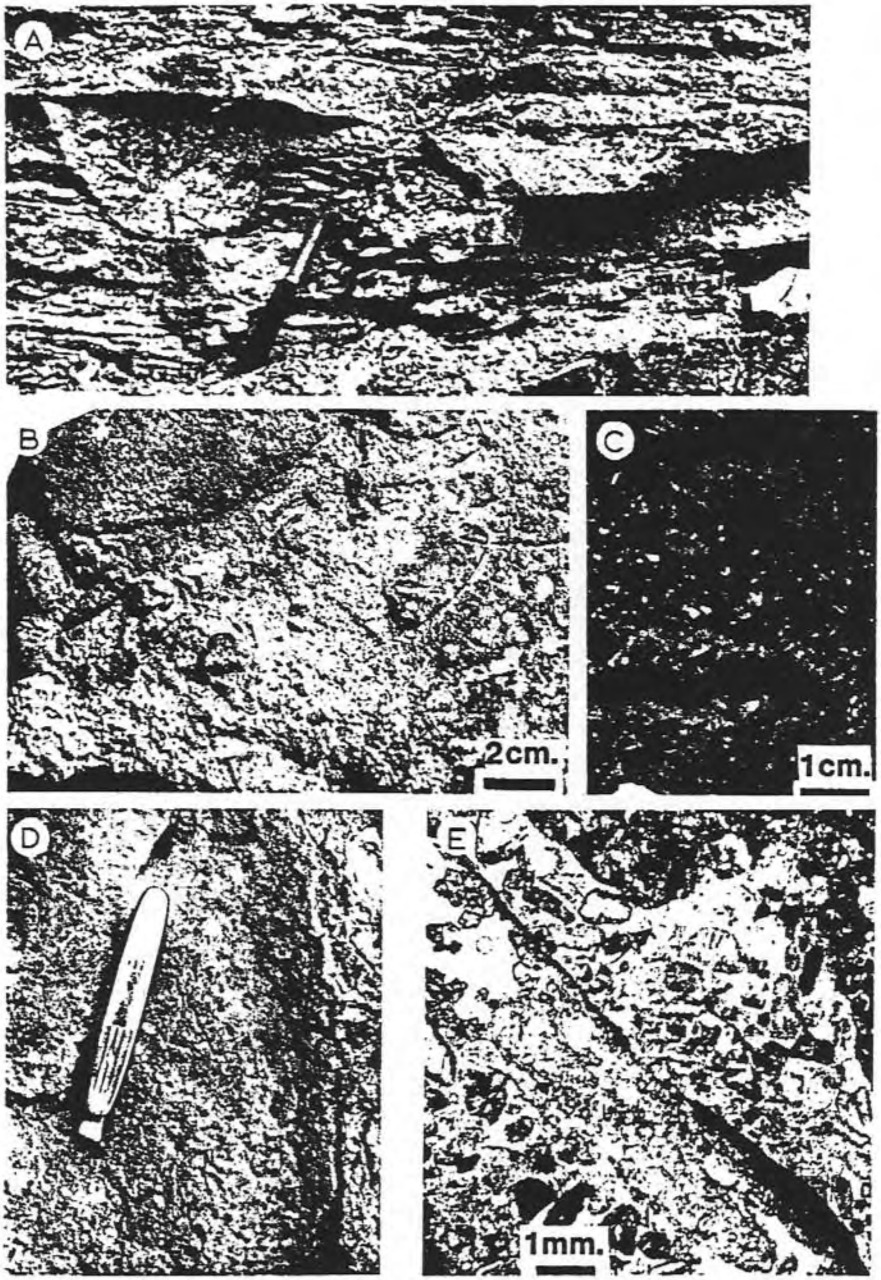


Fig. 13. Lithotype 8. (A) Irregular channels; Peterborough north quarry. (B) Surface of channel fill, showing rounded and bored intraformational pebbles: note that some borings predate pebble formation; others, together with encrusting pelmatozoans, bryozoans and edrioasteroids, post-date pebble formation; Glenarm roadcut. (C) Detail of channel fill; eroded pebbles with hardground crust in grainstone; Glenarm roadcut. (D) Surface of channel showing collapse of hardground surface, with boring and encrusting faunas, into *Thalassinoides* burrows; Glenarm ditch; knife is 8.5 cm long. (E) Detail of *Trypanites* boring into intraclastic grainstone of D: note dolospar fill.

Lithotype 8. Moderately to poorly sorted, tabular to festoon cross-laminated and channellized, conglomeratic coarse- to fine-grained intrabiosparite grainstones (SMF 24) (Figs. 12, 13 and 14)

Bioclastic grains consist mostly of brachiopods, echinoderms and erect branching bryozoa; the last normally more abundant than in the other lithotypes. Micritization of shells is very sporadic. In-

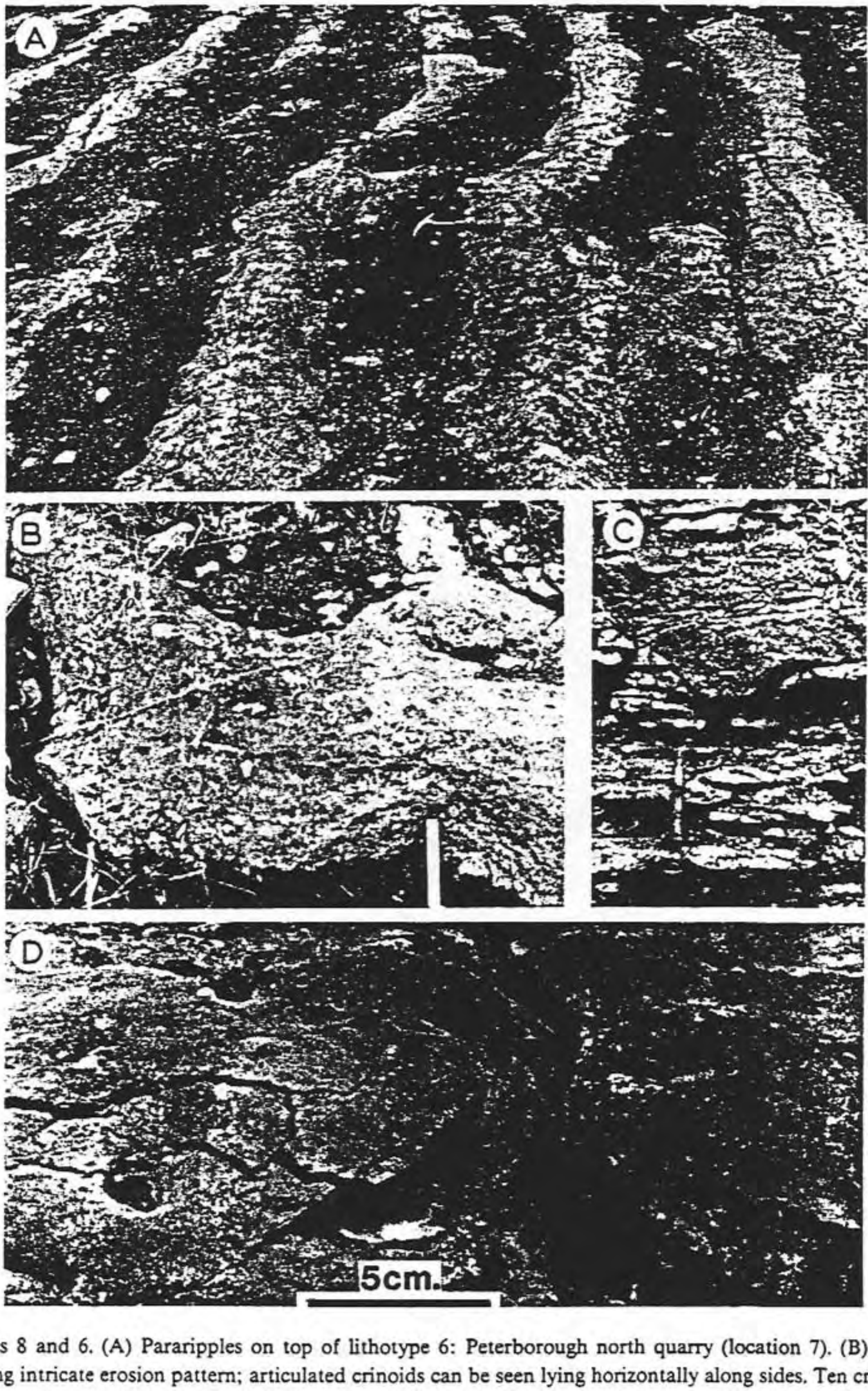


Fig. 14. Lithotypes 8 and 6. (A) Pararipples on top of lithotype 6: Peterborough north quarry (location 7). (B) Upper surface of lithotype 6, showing intricate erosion pattern; articulated crinoids can be seen lying horizontally along sides. Ten cm of tape showing: Peterborough north quarry (location 7). (C) Grainflow channel (lithotype 8); Gamebridge quarry (location 1). (D) Detail of Glenarm ditch hardground (location 5). Upper bed is lithotype 6 over lower bed of lithotype 8. Fracture down centre is synsedimentary fault, offsetting beds before formation of hardground with encrusting bryozoa and heavy *Trypanites* boring.

traclasts vary in texture from micrite to dolosparite-replaced micrite to cemented biosparite grainstone (Fig. 12). Quartz silt is commonly up to 10%, while peloids are rare.

Most of the beds are very poorly sorted, with intraclasts, ranging up to several centimetres in diameter, floating in a poorly sorted biosparite matrix (Figs. 12 and 13B). Festoon and low-angle tabular cross-bedding are common in the thicker units. Complex, frequently undercut, hardgrounds indicate contemporary cementation and erosion. Thinner beds, interbedded with shales, often have sequential trace fossil assemblages, from indeterminate bioturbation to sharply defined *Thalassinoides*-type dwelling burrows, and furthermore may have even bases and locate margins characteristic of grain flows (Fig. 14B). Channels may be very broad (as at Glenarm) or anastomosing and deeply incised (as at Peterborough north quarry) Figs. 12A, 13B and 14C). Frequently, pebbles are concentrated at the edges of channel fills and, during filling of the channels, often overlapped onto the unchannellized surfaces (Fig. 13A, B). All these features are consistent with "plug-flow" transport (Middleton and Hampton, 1973). Hence, many of these conglomeratic beds are submarine debris flows. Water-saturated sediment slid, either slowly or rapidly, into deeper water, frequently carving channels into the soft underlying sediment as it moved. Another alternative is that this lithotype represents large channeled scour fills (gutter marks), which were attributed by Aigner (1982, 1985) to storm wave action. Although the large megarippled upper surfaces of some beds are consistent with deep swell reworking (Fig. 14A), the deeply incised and anastomosing basal channels are unlikely to have been formed by storm waves. Furthermore, the presence of articulated crinoids, with even fine pinnules attached, lining some of the channels indicate very rapid burial of empty channels without disarticulating or damaging the crinoids. Complex hardgrounds often occur on successive beds and illustrate the long periods of non-deposition and erosion between sedimentation events (fig. 14D). In fact the relationships of diagenesis, erosion, boring and encrusting is so complicated as to be indecipherable at times (Brett and Brookfield, 1984).

This lithotype shows the usual two-stage cementation by an early equant to bladed fringe spar and syntaxial echinoderm overgrowth cement, followed by a pore-filling spar cement. In beds with hardgrounds, the diagenetic sequences are much more complicated (Brett and Brookfield, 1984).

Lithotype 8 resembles Wilson's (1975) SMF 24 microfacies which he considered to be lag deposits of tidal channels; though most of the deposits noted here undoubtedly represent slides into deeper water.

Lithotype 9. Poorly sorted, often massive, oncoidal, intrabiosparite grainstones, intrabiomicrite packstones and wackestones (SMF 13, 22 in part) (Figs. 15 and 16)

The characteristic features of this lithotype are oncoids of bryozoans, and red and green algae (bryoids, rhodoids, chloroids to the cognoscenti—see Peryt, 1983, and Richter, 1983), together with broken and often rounded fragments of bryozoans, crinoids, brachiopods and ostracods, in a sparite or micrite matrix (Fig. 15). Lithotype 9 occurs only close to, and typically resting unconformably on, Precambrian metamorphic inliers (Fig. 16). It usually contains abundant sand grains with rarer pebbles and even boulders of Precambrian rock (Fig. 16A). On some inliers, notches may be Ordovician wave-cut platforms (Fig. 16C). The mixture of sharp, angular shell fragments with rounded, sometimes micritized and phosphatized shell fragments, and the roundness of many large shell and rock fragments in poorly sorted carbonates, indicates textural inversion and thus the mixing of several generations of fragments from diverse micro-environments. Steep slopes must have existed around some inliers: for example at Red Rock (Fig. 1), boulder-bearing oncoidal biosparite grainstones and packstones (Figs. 15B and 16A) lie with an initial dip of 20° against an almost vertical cliff of Precambrian granite, rising even now 10 m above the sediment. Elsewhere, gentle slopes and quiet water can be inferred from poorly sorted, biomicrite mudstones enclosing large red algal and prasoporid bryozoan colonies in situ on the Precambrian surface; e.g. at Rohallion (Fig. 16B–D) and Red Rock (Fig. 15E). The bioclastic fraction of the sediment is dominated usually by dome- and stick-shaped bryozoans and red algae with subordinate brachiopods (Fig. 15). Many of the coarser sediments show pervasive stylolitization, often with bitumen accumulations (Fig. 15B, D). In fact, the Precambrian inliers probably acted as pressure solution centres during compaction and hydrocarbon migration.

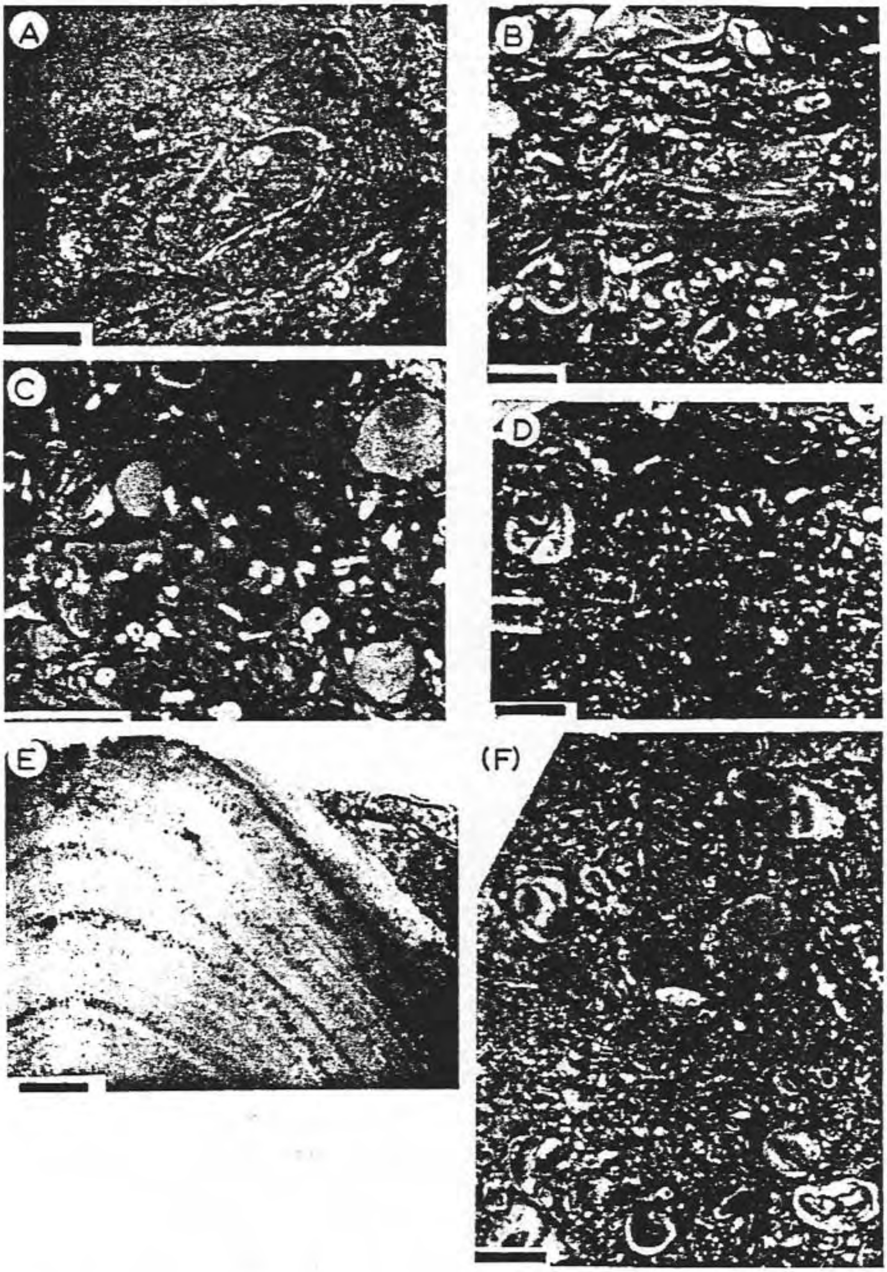


Fig. 15. Lithotype 9. Oncoidal sediments: details on polished slabs. All scales are 1 cm. (A) Eroded biomicrite clasts in algal-crinoidal-brachiopod biomicrite wackestone; Rohallion inlier (location I). (B) Bryozoan-rhodoid biosparite grainstone: Red Rock inlier (location IV); note compacted, stylolitic, bituminous layer at top. (C) Detail of crinoid-rhodoid biomicrite packstone; Red Rock inlier. (D) Detail of coral-crinoid-rhodoid biosparite grainstone; note stylolites along micrite lenses near top; Red Rock inlier (location IV). (E) *Prasopora* bryozoan colony in situ at Red Rock inlier (location IV). (F) Rhodoid grainstone (location VI).

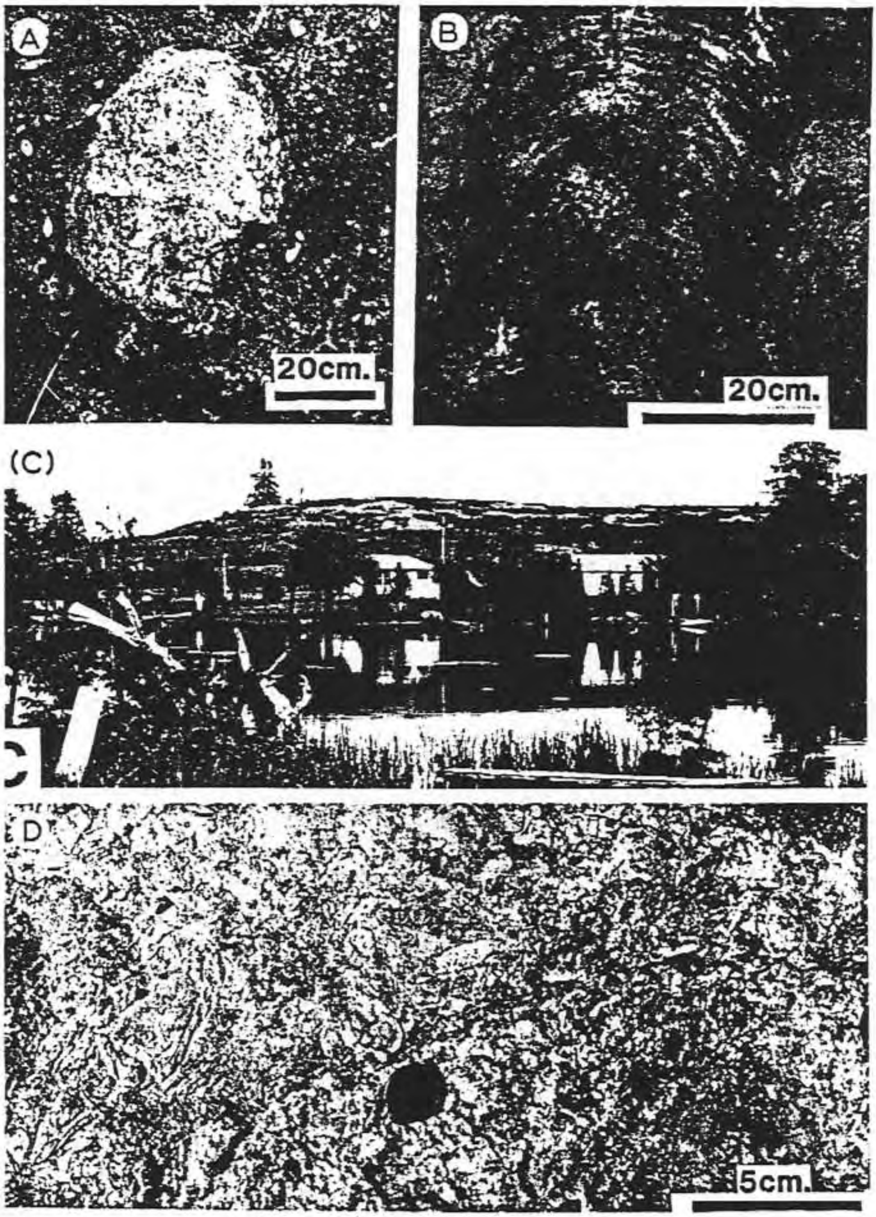


Fig. 16. Lithotype 9. (A) Precambrian granite pebble in Ordovician wackestone; Red Rock inlier (location IV). (B) Large red algae resting directly on Precambrian surface, in wackestone; Rohallion inlier (location I). (C) General view of Rohallion inlier (location I) from the west: topographic notch in Precambrian granite inlier to left with quiet-water biomicrite wackestones rest directly on encrusting organisms and Precambrian granite. (D) Biomicrite packstones and wackestone resting directly on Precambrian granites (below coin); Rohallion inlier (location I).

Recent, non-reef algal oncoids occur on soft-bottom, non-depositional shallow marine environments around bedrock shoals (Bosence, 1986). Lithotype 9 closely resembles the bryozoan–red algal association of temperate, shallow water marine carbonate environments (Hottinger, 1983; Burgess and Anderson, 1983). Nevertheless, a very shallow situation is not necessary. The biofacies recorded in lithotope 9 is closest to the *deeper* offshore shoals of the Persian Gulf and not to the shallow, coral-bearing shoals of the nearshore shelf (Purser, 1973).

Lithotype associations (facies)

Despite great variation in detail, we can distinguish four main facies, which range from inferred shallow shoal to deep shoal or intershoal facies, and from shallow to deep and "basinal" facies; though the actual depth of the "basinal" facies was probably less than 100 m.

Shoal facies

Shoal facies consist of two main associations: a shallow-water bryozoan–red algal association and a shallow crinoidal bioclastic bar association.

The bryozoan–red algal association consists essentially of lithotype 9, and is always in close proximity to Precambrian inliers. Occasionally a few interbeds of gastropod-bearing biomicrite wackestones (lithotype 5) occur. Analogous bryozoan–red algal associations are often found around recent bedrock highs in the western Mediterranean, in northern New Zealand and southern Australia, off northern Vancouver island and on Cobb seamount in the Pacific Ocean (Wass et al., 1970; Caulet, 1972; Nelson et al., 1982; Nelson and Bornhold, 1983; Farrow and Durant, 1985).

The shallow bioclastic bar association occurs in units up to several metres thick which consist of amalgamated sequences of cross-laminated skeletal grainstones (lithotype 7) with rare beds of conglomeratic bioclastics (lithotype 8) and biomicrites (lithotype 3) (Fig. 17B). There is a tendency for coarsening-upwards cycles to occur: from bryozoan wackestones through large-scale trough cross-bedded intrabiosparite grainstones (Fig. 18B). Cross-bedding usually shows a consistent paleocurrent direction towards the northeast—a regional feature (Cameron et al., 1972)—possibly due to longshore currents. Though similar cycles were considered by Wilson (1975) to mark regressive migration of bars across basinal muds, we consider it more likely, in view of the thinness of the cycles and the limited lateral extent of the bioclastic units (they form northward facing cuestas which die out laterally within a few kilometres), that the bryozoan wackestones simply represent slightly deeper water between migrating bars. This shoal facies occurs sporadically throughout the upper Verulam and lower Lindsay Formations, but forms only a very small part of the sequence. No hardgrounds were found in this facies—though erosion surfaces are common—and it shows no clear-cut evidence for subaerial exposure at any time during deposition.

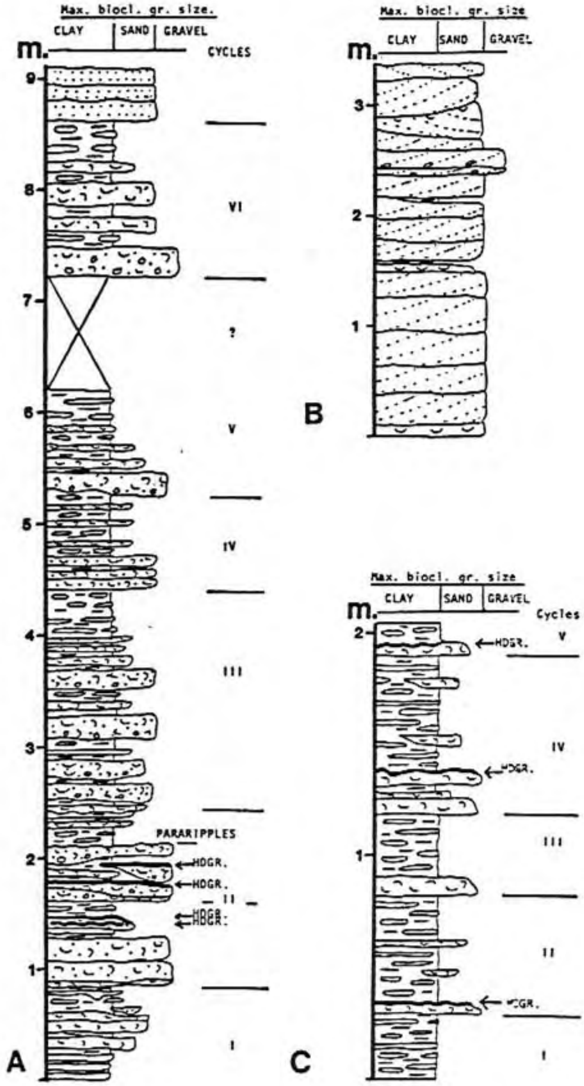


Fig. 17. Stratigraphic sections. (A) Peterborough north quarry: mostly proximal cycle units. (B) Roadcut, south of Cameron: shoal bioclastic bar association. (C) Bolsover roadcut: distal cycle association.

Intershoal or deep shoal facies

Deeper shoal, interbar or "lagoonal" deposits, interbedded with the shoal bioclastics, consist of

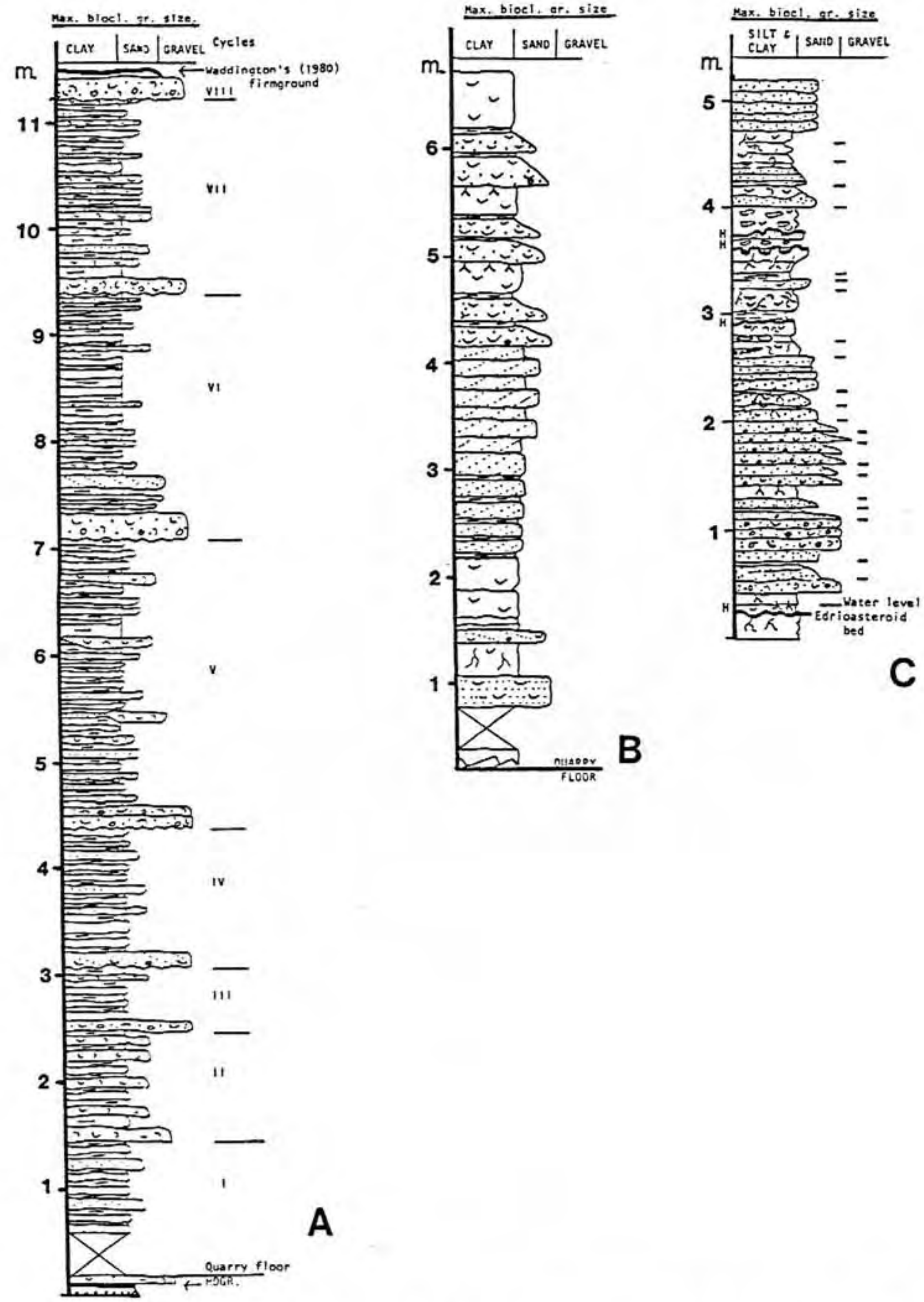


Fig. 18. Stratigraphic sections. (A) Gamebridge quarry; distal to proximal cycle passage. (B) Little Bob quarry; diverse shoal facies association. (C) Kirkfield quarry; shoal edge facies (proximal-type cycles) and bioclastic bar association. *H*, on left, are hardground horizons; dashes on right are omission surfaces with encrusting organisms.

bivalve- and gastropod-bearing heavily bioturbated biomicrite packstones and wackestones (lithotype 3), interbedded with grainstones and nodular limestone (lithotypes 2 and 5).

Well-defined sequences of "interbar" and "shoal bar" facies are rare. More typical is an irregular alternation of lithologies, representing an original mosaic environmental distribution, exemplified by the mid-Trenton limestones at Kirkfield quarry (Fig. 18C), which contains several hardgrounds. This exposure, famous for its echinoderm fauna, is now flodded up to the level of the edrioasteroid-bearing hardground described by Brett and Liddell (1978). Above this bed is an apparently somewhat disordered sequence of all the lithotypes distinguished in this paper. Basically, however, two shoal bar associations (basal 2 and top 1 m of the section) sandwich an intershoal or shoal margin sequence. The beds below the topmost shoal bar are also similar, in some respects, to the proximal cycles described below.

The intershoal and deep shoal facies at Kirkfield developed marginally to two topographic highs represented by Precambrian inliers to the northwest (Fig. 1). Abundant and diverse faunas in the quarry show that these were offshore shoals.

Shallow to deep shoal margin and "basinal" facies

Most sections of the mid-Trenton limestones consist of alternations of coarse biosparite or intrabiosparite grainstones (lithotypes 5 and 8), alternating with nodular, highly bioturbated biomicrite wackestones (lithotype 4), poorly washed biosparite packstones (lithotype 3) and calcareous claystones and shales (lithotype 2). Despite great variation in detail, these beds are usually arranged in fining-upwards cycles of two end-member types (Figs. 17A, C and 18A).

Shallow shoal margin, or *proximal* cycles, consist of intrabiosparite grainstones filling channels (lithotype 8), passing up into well-sorted fine-grained biosparite grainstones (calcisiltites) (lithotypes 6 and 7) and finally into nodular biomicrite wackestones and mudstones and calcareous claystones (lithotypes 2 and 3). Deep shoal margin, "basinal", or *distal* cycles, consist of biosparite grainstones and packstones (lithotype 5), overlain by nodular biomicrite wackestones, mudstones and calcareous claystones (lithotypes 2 and 3). Hardgrounds are typically associated with the coarser beds. However, it must be emphasized that most of the beds coarser than micrite indicate relatively rapid deposition, followed by intense bioturbation (usually including an omission suite of dwelling burrows) and followed by non-deposition for extended periods of time—as shown by the abundant encrusting faunas atop many beds. Thus, each coarse bed represents rapid introduction of shell material, and sometimes eroded intraclasts, into a low-energy environment. This was followed by many years of non-deposition, with frequently lithification, erosion and hardground development, before deposition of (usually) calcareous claystones and biomicrites.

Distal cycles occur at Gamebridge and near Bolsover (locations 1 and 2 in Fig. 1): proximal cycles are developed at Glenarm and near Peterborough (locations 4–7, Fig. 1). The transition from distal to proximal cycles is recorded in the shallowing-upwards megasequence at Gamebridge quarry, which includes eight cycles, the highest of which begins with beds including Waddington's (1980) firmground. This contains edrioasteroids encrusting internal moulds of bivalves.

Proximal cycles

The fully developed proximal cycles, with a mean thickness of about 2m, consists of the following four units from bottom to top, with calcareous claystone seams (lithotypes 1 and 2) throughout.

Unit a consists of lithotype 8—coarse, poorly sorted intrabiosparite or biosparite grainstones, in cross-bedded, cross-cutting lenses, or channellized. In paces grain flow is shown by locate, steeply inclined margins, (often smoothed by well-sorted biosparite grainstones), by "floating" large intraclasts, and by preservation along channel sides of delicate, articulated crinoids. The sediments cemented early and were frequently subjected to strong erosion both before and after cementation. Current scouring of the channel fillings and enclosing clays frequently led to partial erosion of the irregular anastomosing channels, and sometimes overhangs developed. Both normal and overhanging surfaces were frequently colonized by encrusting and boring organisms and parts of the cemented channel fillings were sometimes eroded to form platter-like pebbles which also show encrusting and boring. These various hardgrounds have been described in detail by Brett and Brookfield (1984).

Unit b consists of lithotype 7, fine- to medium-grained, well-sorted parallel or cross-laminated biosparite grainstones, usually in several beds. These beds suggest reworking of shell material by strong currents resulting in parallel and cross-laminated carbonate sands formed as migrating sheets and megaripples. The low amplitude and long wavelengths of some examples (Figs. 10A and 14A) suggest deep storm surges. However, these processes were only intermittently active as shown by the interbedded calcareous clays and nodular limestones. The calcarenites were frequently cemented and then eroded, developing irregular hardgrounds on their upper surfaces.

Unit c consists of lithotypes 5 and 6, very fine grained, well-sorted, often graded, biosparite and biomicrosparite grainstones and packstones (calcisiltites) with coarser shell fragments concentrated at their bases; usually in several beds alternating with calcareous claystones (lithotype 2). This unit represents quieter-water conditions. The grading in each bed is primary and not due to bioturbation, since laminae are preserved and the shells are concave down: the latter also precludes turbidity currents. The beds are often cemented early, and increasing current strength after deposition is shown by later erosion, coarse shell material which fills omission trace fossils and sometimes the development of hummocky hardgrounds. Many of lithotype 5 and 6 beds, which form the bulk of this unit, have almost ideal "storm" sequences (Figs. 9 and 10) (cf. Kreisa, 1981). We suggest that much of unit c was deposited in water below wave base by waning currents following storms.

Unit d consists of lithotypes 2–4, nodular bioturbated biomicrite mudstones and wackestones, alternating with bioturbated calcareous clays. This unit may also contain lenses of poorly sorted biosparite grainstones (lithotype 5), probably starved ripple deposits. The nodular biomicrites and calcareous claystones (lithotypes 2 and 3) appear to represent the background sedimentation into which the other sediments were periodically introduced. Rarely, thin unbioturbated micrites have relatively sharp contacts with enclosing calcareous claystones. The nodular biomicrites contain abundant broken brachiopods which are less abundant in the claystones. Despite the occasional development of hardgrounds on calcisiltites and biosparites interbedded with the nodular limestones, no hardgrounds have been found within the nodular limestones. Like modern Bahamian nodular carbonates we suggest that unit d formed by in situ nodular cementation of interbedded shelly carbonate and calcareous clay, aided by bioturbation which has also disrupted the original layering (Bromley, 1975; Mullins et al., 1980). The abundance of detrital clay suggests a clastic source from a different direction than the often shallow-water-derived bioclastics with which the nodular limestones are interbedded.

Units a–c show abundant evidence of rapid deposition of individual beds followed by extensive periods of non-deposition, hardground formation, and colonization of the bed surfaces by omission trace-fossil forming organisms and attached organisms. Hardgrounds are commonest in units b and c.

Distal cycles

These cycles are thinner, less completely developed than proximal cycles, generally lack intraclast bearing beds and are not channellized. Each cycle consists of a basal bed of lithotype 6, well-sorted biosparite, overlain by lithotypes 2–5, nodular biomicrite mudstones and wackestones alternating with bioturbated calcareous claystones. This is the c–d transition of the proximal cycles. Hardgrounds are frequently developed on the c unit: they are mostly irregular, hummocky and undulating, with frequent biological corrosion and mineral staining: there was usually little prior erosion of the underlying beds (Brett and Brookfield, 1984).

Origin of cycles

In order to explain these cycles, we must account for the following:

(1) The rapid introduction of coarse material into an environment characterized by non-deposition or calcareous clay and micrite deposition.

(2) The long periods of non-deposition following the introduction of the coarser material, dur-

ing which the beds were frequently lithified, eroded, bored and encrusted.

(3) The interbedding of calcareous clays, even between the coarsest units of the cycles.

(4) The decrease in micritization of shell fragments in going from unit a to unit d.

In order to explain these features, we suggest that proximal cycles were deposited on ancient bypass slopes. Schlager and Chermak (1979) suggested the following criteria for this environment: bioturbated muddy sediment, erosion surfaces including steep, cliff-like hardgrounds, channel fills with lenses of coarse sand and gravel. Hopkins (1977) described similar Devonian foreslope sequences of interbedded breccia, thick calcarenites and thinly bedded calcarenites and argillaceous calcarenites alternating with calcareous clays. These features are all found in the proximal cycles, which can also be compared with the channel fills of siliciclastic fans (Walker, 1984)—though the Ordovician examples described here are on a much smaller scale. Though many of the proximal cycle beds appear to have been deposited by storms, the regular cyclical alternation of facies, the presence of grain flows and the general fining-upward nature of each cycle, interrupted by prolonged periods of non-deposition. are more consistent with a channellized fan system than with random storm fluctuations on a wide shelf.

Distal cycles compare well with the basin interior sediments of Schlager and Chermak (1979), which show alternations of graded, medium sand- to silt-sized carbonates and bioturbated carbonate oozes.

Environmental reconstruction: Modern and ancient analogies

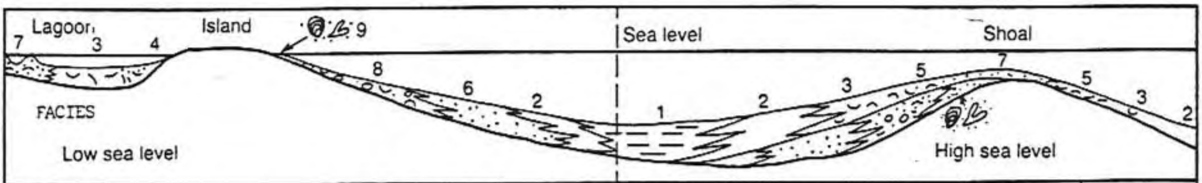
The characteristics of each lithotype and their typical arrangements are shown on Fig. 19. This summary may serve as the basis for an environmental reconstruction. assuming that the facies associations pass laterally into one another. Though this has yet to be proved, on this basis Fig. 20 shows a plausible reconstruction of the facies patterns around shoal areas in the Middle Ordovician sea. Since the facies contain stenochaline organisms and show no sign of coastal influence, an offshore shoal-basin environment seems most likely. The schematic reconstruction resembles the shallow-water lime sand/slope model of McIlreath and James (1984), some of the carbonate bank margin profiles of the Bahamas (Mullins and Neumann, 1979; Schlager and Chermak, 1979), some of the shoal-shelf basin profiles of the Persian Gulf (Purser, 1973) and the bank-basin profiles of norther New Zealand (Nelson et al., 1982).

The closest Recent analogies are: the offshore shoals of the Persian Gulf—where different types and depths of shoal have their counterparts in the Ordovician (Fig. 21); and the Three Kings plateau of New Zealand—where the faunas and their preservation are remarkably like the Ordovician ones (Nelson et al., 1982) (Figs. 22 and 23).

Ancient inferred carbonate ramp environments, usually on a larger scale, also have many similarities with our Ordovician environments (Cook and Taylor, 1977). Markello and Read (1981) described intrashelf Upper Cambrian basin and ramp facies with fining-upwards cycles, clearly like our distal and proximal cycles respectively. Almost identical facies were also described by Gawthorpe (1986) and Wright (1986) from the Carboniferous of Britain.

The dynamics of ramps differ markedly from rimmed carbonate shelves. Ramps are extremely susceptible to the effects of impinging ocean waves, including the catastrophic effects associated with shoaling tsunamis. As Aigner (1985) noted, it is thus hardly surprising that "storm" sedimentation forms such a large part of the Trenton Limestone sequence; particularly in view of its close juxtaposition to an active subduction zone and island arc (Fig. 2). Even the channellized units may owe their origin to deep storm surge channels funnelling suspended sediment offshore. The migration of these channels may account for the fining upwards sequences recorded above.

But, if the fining-upward cycles themselves can be attributed to the lateral migration of fan or slope channels, the concentration of hardground in one or two cycles in any one exposure (e.g., at Peterborough and Glenarm roadcut) suggests rather unusual conditions for these particular cycles. We do not know if this is due to local



LITHOTYPE	1	2	3	4	5	6	7	8	9
Symbol									
Grain type & depositional texture	Micrite/ Mudstone	Skeletal Mudstone/ Wackestone	Skeletal Wackestone/ Packstone	Skeletal Wackestone	Skeletal Packstone/ Grainstone	Skeletal/ Pellet Grainstone	Skeletal Grainstone	Intraclast Grainstone	Variable Boundstone
Bedding/ Sedimentary structures	Parallel lamination	Parallel lamination	Bioturbation Small-scale x-lamination	Bioturbation	Lensitic	Graded/ low-angle x-lamination	x-lamination	Channels/ x-bedding	—
Terrigenous clastic %	> 60 clay	~ 40 clay	< 10 clay	—	>5 Qtz. Silt	10 - 20 Qtz. Silt	< 5	< 5	< 5
Allochems %									
Intraclasts	—	—	—	—	0 - 10 (5)	5 - 30 (15)	5 - 25 (10)	10 - 50 (30)	0 - 80 (60)
Pellets	—	—	0 - 40	—	5 - 10	5 - 80	5 - 15	0 - ?20	—
Ooliths	—	—	—	—	—	—	—	—	—
Oncoids	—	—	—	—	—	—	?	tr	5 - 40
Shell frags	0 - 5	5 - 20	15 - 50	5 — 30	30 - 60	1 - 50	30 - 60	5 - 30	5 - 40
Allochem Micritization	0	< 5	< 5	< 5	0 - 50	< 5	0 - 60	50 - 70	15 - 25
Dominant Macrofossils	Planolites Chondrites	Brach/ Crinoid	Gastropods/ Brach./Crin.	Brach./ Crinoid	Brach./Bryo. Crinoid	Brach./ Crinoid	Brach./Bryo. Crinoid	Crinoid Brach./Bryo.	Bryozoa Red algae
Bioclasts %				too few samples					
Trilobites		—	—		0 - 1	—	—	—	—
Ostracods		—	20 - 50 (30)		< 5	0 - 5	—	—	tr - 10
Gastropods	rare	0 - 3 (<1)	0 - 50 (20)		0 - 15 (1.5)	0 - 2	0 - 1	0 - 10	?
Brachiopods		25 - 80 (55)	10 - 45 (25)		20 - 80 (50)	40 - 90 (65)	25 - 55 (40)	4 - 40 (30)	5 - 30 (20)
Bryozoans		0 - 2 (0.5)	—		0 - 20 (6)	0 - 2 (0.3)	0 - 2 (0.5)	2 - 50 (15)	15 - 60 (35)
'Crinoids'		20 - 70 (45)	5 - 90 (30)		20 - 80 (50)	15 - 50 (30)	45 - 80 (55)	30 - 90 (50)	1 - 40 (10)
Algae		—	—		0 - 1	—	—	0 - 1	10 - 80 (35)

Fig. 19. Summary of lithotypes and facies.

environmental or basin-wide controls. Biostratigraphic zonation and individual exposures are too small and scattered for us to be able to correlate individual cycles. In the Quaternary, rapid and repeated glacio-eustatic changes have alternately bared and submerged carbonate environments. Thus, almost the whole of the Arabian shelf of the Persian Gulf was dry land during the last glacia-

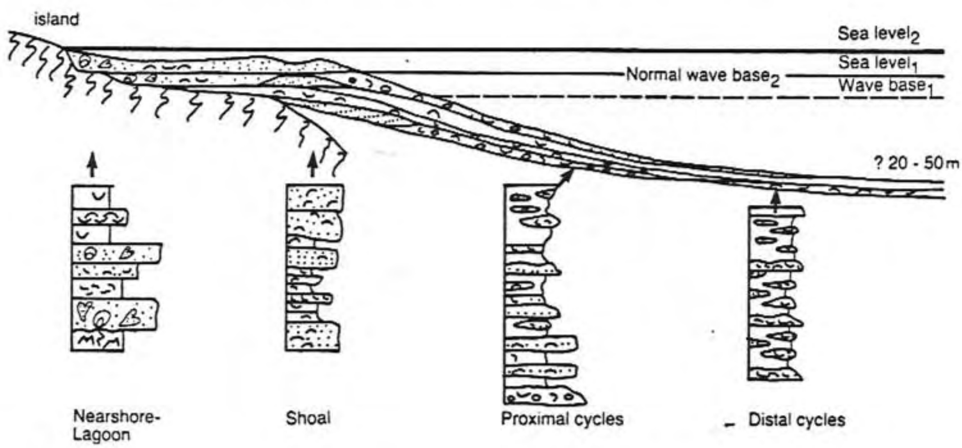


Fig. 20. Ideal model of mid-Ordovician sedimentation.

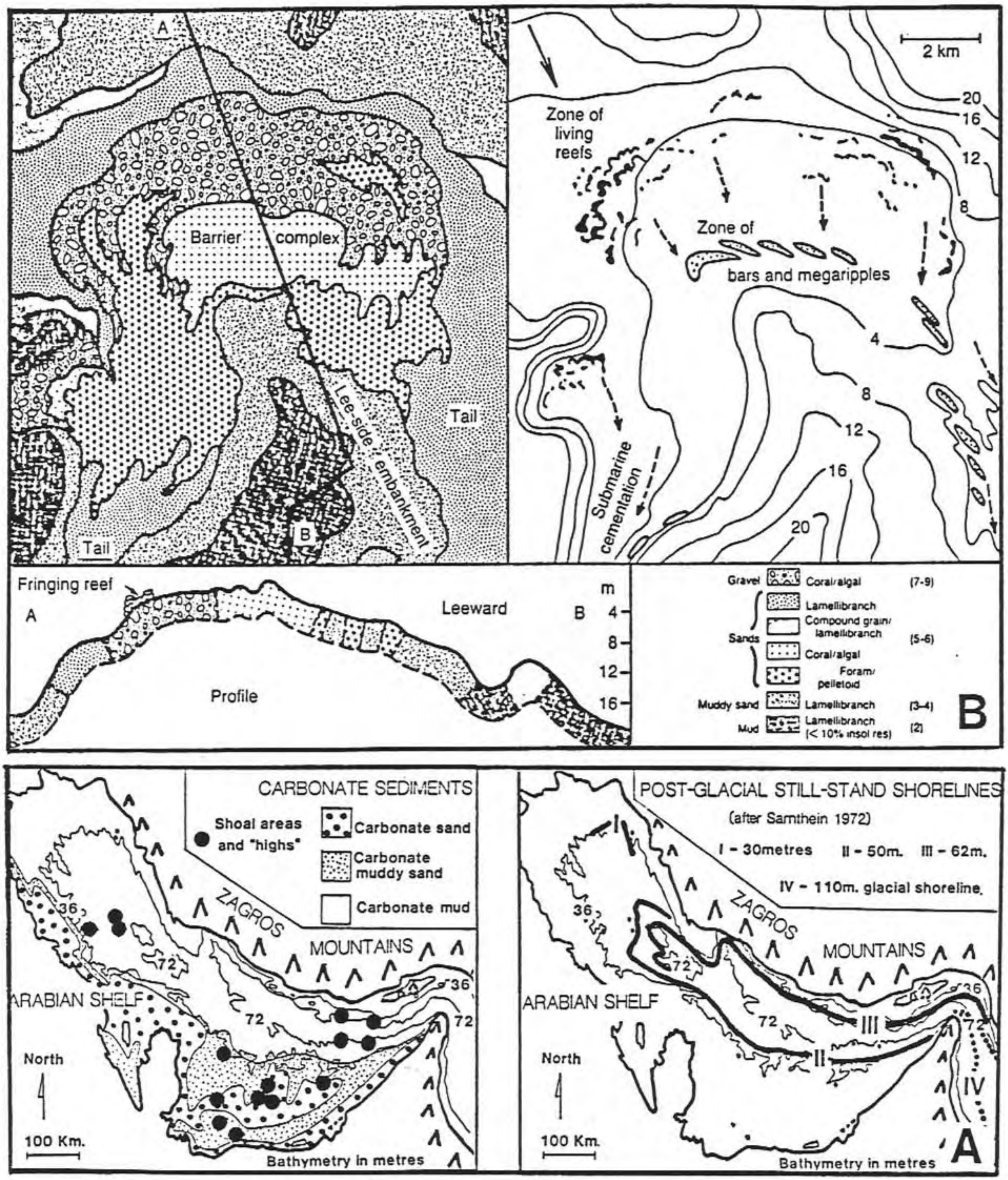


Fig. 21. Comparison with Persian Gulf. (A) General carbonate lithofacies and post-glacial shorelines (Sarnthein, 1972; Kessler, 1973). (B) Shallow Persian Gulf shoal; bathymetry and facies (Purser, 1973).

tion (Fig. 21) (Sarntheim, 1972; Kessler, 1973), and the rapid post-glacial transgression is represented by only a 1 m thick change in sediment type (Stoffers and Ross, 1979). We intend in future studies, examining in detail both sedimentary and faunal changes across Trenton Limestone sec-

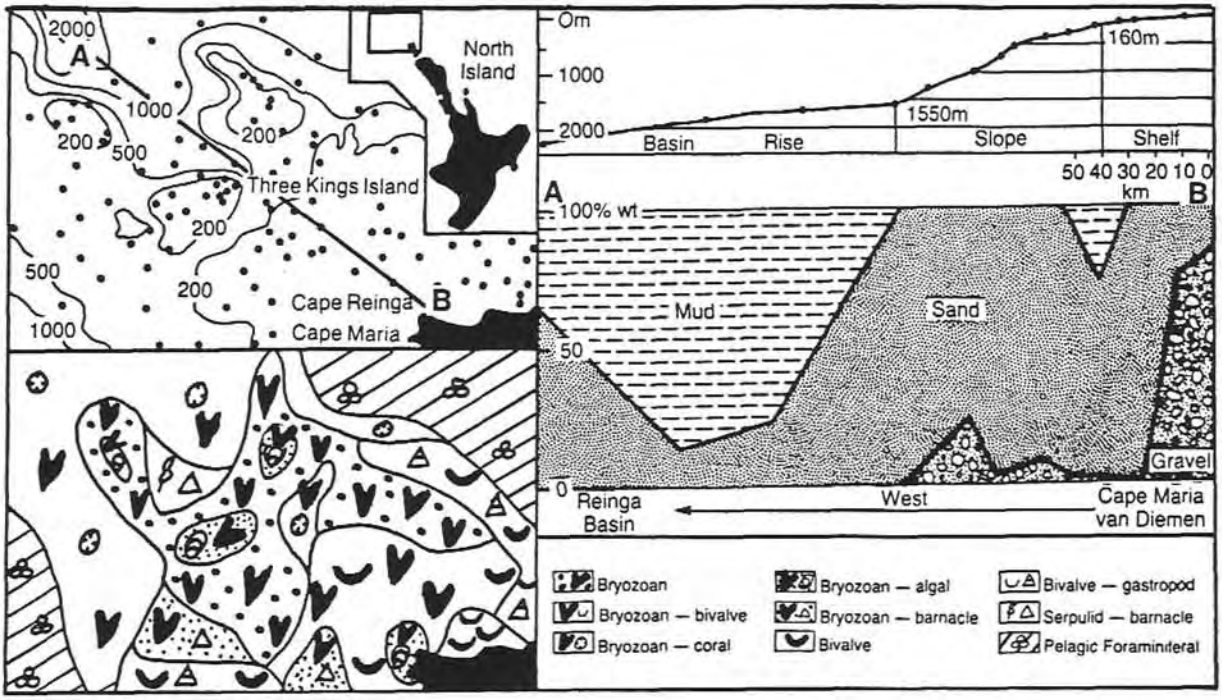


Fig. 22. Three Kings temperature plateau, New Zealand (Nelson et al., 1982).

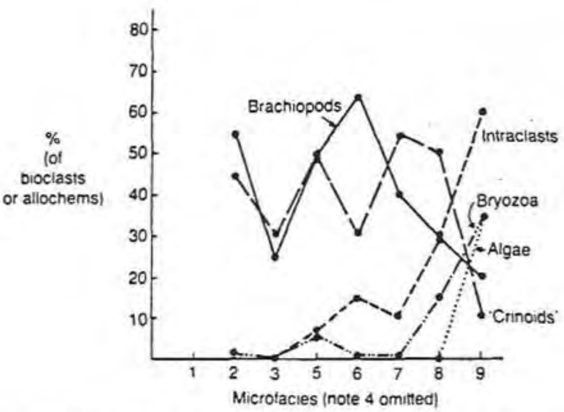


Fig. 23. Variation of important allochems among the Ordovician microfacies.

tions where we suspect glacio-eustatic control, exploring the Ordovician ramp both shorewards, into the Black River Limestones, and seaward into the thick slope limestones with their graded distal storm layers, and eventually, perhaps, arriving at the Ordovician arc itself.

Acknowledgements

M. Brookfield acknowledges the support of N.E.R.C. Canada operating grants over the last fifteen years.

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