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The St George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas

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ABSTRACT

The St George Group consists of peritidal carbonate rocks deposited on the continental shelf of North America bordering the ancient Iapetus Ocean. These Lower Ordovician rocks are similar to other lower Palaeozoic limestones and dolostones that accumulated in epeiric seas and veneer cratonic areas worldwide. A wide variety of facies in the St George is grouped into seven lithotopes, interpreted to represent supratidal, intertidal and shallow, high- and low-energy subtidal environments. Rapid lateral facies changes can be observed in some field exposures, and demonstrated by correlation of closely spaced sections. The stratigraphic array of these lithotopes, although too irregular to be simplified into shallowing-upward cycles, suggests that they were deposited as small tidal flat islands and banks. Shallow subtidal areas around islands generated sediment and permitted tidal exchange. Tidal flat islands were somewhat variable in character at any one time, and evolved with changing regional hydrographic conditions.

The St George rocks suggest an alternative theory of carbonate sedimentation in large, shallow epeiric seas, namely as small islands and banks built by processes that operated in a tidal regime. Furthermore, this island model provides a framework for a mechanism of cyclic carbonate sedimentation, by which small-scale, peritidal cycles represent tidal flat islands that accreted vertically and migrated laterally as local sediment supply from neighbouring subtidal areas waxed and waned during relatively constant subsidence.

INTRODUCTION

The early Palaeozoic Era is recorded in much of continental North America and elsewhere by widespread sequences of carbonate rocks deposited in shallow water. These rocks were amongst the first to be recognized as the ancient counterparts of modern peritidal carbonate deposits such as those of Florida, Bahamas, Shark Bay and the Arabian Gulf (e.g. Beales, 1958). They were deposited in vast, tropical epeiric and continental shelf seas (Shaw, 1964; Irwin, 1965) that first flooded the margins and later the interiors of the tectonically stable cratons. Although sometimes differentiated locally into deeper, intracratonic sub-basins, most of these seas were very shallow.

In this paper we describe the peritidal carbonate lithologies of part of such a cratonic sequence, the Lower Ordovician St George Group of western Newfoundland. The vertical and lateral association of lithotopes is used to generate sedimentary models and it is concluded that the Early Ordovician sea in western Newfoundland was a mosaic of low-relief islands and banks surrounded by shallow subtidal areas which provided carbonate sediment and permitted tidal exchange. This conclusion contrasts with the prevailing view that these kinds of sediments were deposited in a tideless sea as regionally extensive, wholly or intermittently subaerially-exposed flats. We suggest that the stratigraphic record of much of the St George Group, and perhaps other, similar deposits, is a more or less cyclic succession of peritidal rocks because tidal flat islands and banks accumulated as localized responses to varying local sediment supply on a seafloor that was subsiding comparatively constantly.

STRATIGRAPHY

The North American continental plate remained in a tropical climatic zone for most of the Palaeozoic (Ross, 1976; Scotese *et al.*, 1979), and repeated continental flooding has resulted in an extensive veneer of dominantly carbonate rocks. The Cambro-Ordovician Sauk Sequence (Sloss, 1963) records the first major episode of cratonic flooding and accompanying carbonate sedimentation. Remnants of these carbonate sediments now occur as a discontinuous girdle around the continent and over much of the southern half (Fig. 1). Rocks of similar style were also deposited coevally in other areas such as China, south Asia, Siberia, Australia and Argentina (Burrett, 1973; Ross, 1975; Scotese *et al.*, 1979). In North America, these Cambro-Ordovician carbonates have been studied extensively since the last century. Palaeogeographically, they apparently share a broad lithofacies distribution consisting of mainly dolostones in the craton interior which grade and thicken to dominantly limestones toward the continental margin (Laporte, 1971; Harris, 1973; Ross, 1976). Sedimentological aspects have been locally treated in detail by numerous authors (for the Lower Ordovician part of the sequence, e.g. Sarin, 1962; Carozzi & Davis, 1964; Davis, 1966; Braun & Friedman, 1969; Stricker & Carozzi, 1973; Reinhardt, 1974; Mazzullo & Friedman, 1975, 1977; Rubin & Friedman, 1977; Mazzullo, 1978; Mazzullo *et al.*, 1978; Mossop, 1979; also Radke, 1980).

Shallow water carbonate rocks of Early Ordovician age in western Newfoundland (Fig. 2) rest on about 1 km of Lower, Middle and Upper Cambrian platform carbonate and terrestrial to shallow marine siliciclastic

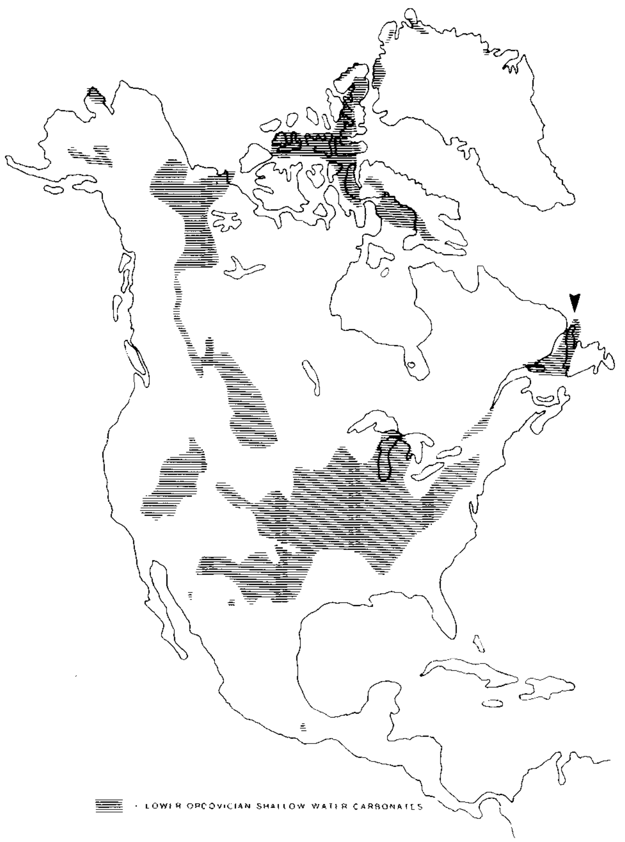


Fig. 1. Present outcrop and subsurface distribution of Lower Ordovician shallow water sediments in North America (arrow points to western Newfoundland), after Cook & Bally (1975).

sediments (James & Stevens, 1982) and all are included in the Humber Zone of the Appalachian Orogen (Williams, 1979). The Humber Zone is the tectonostratigraphic subdivision that comprises the deposits of the lower Palaeozoic outer continental shelf and margin in eastern North America which fringed the proto-Atlantic Iapetus Ocean (Williams & Stevens, 1974). To the east, Lower Ordovician carbonate rocks are either tectonized or overlain by allochthonous strata. To the west, they are buried by middle Palaeozoic sediments in the Gulf of St Lawrence Basin but emerge on the north-western edge of this basin as a thin (65 m) dolostone unit, the Romaine Formation, exposed in the Mingan Islands north of Anticosti Island. The Romaine rests directly on Precambrian basement (Twenhofel, 1938) and is late Canadian in age (Nowlan, 1981). Thus, during early Canadian time, the Newfoundland outcrop belt lay near the outer part of a shelf roughly 200–300 km wide; during the latter part of early Canadian time, the shelf was considerably wider, perhaps extending over much of the low-relief Precambrian Shield in Quebec and southern Labrador (Sanford, 1977).

The St George Group is provisionally subdivided into the Isthmus Bay Formation, Catoche Formation and Aguathuna Formation, in ascending order (Lévesque, 1977; Pratt, 1979; James & Stevens, 1982). Lévesque (1977) has shown that, in general, the

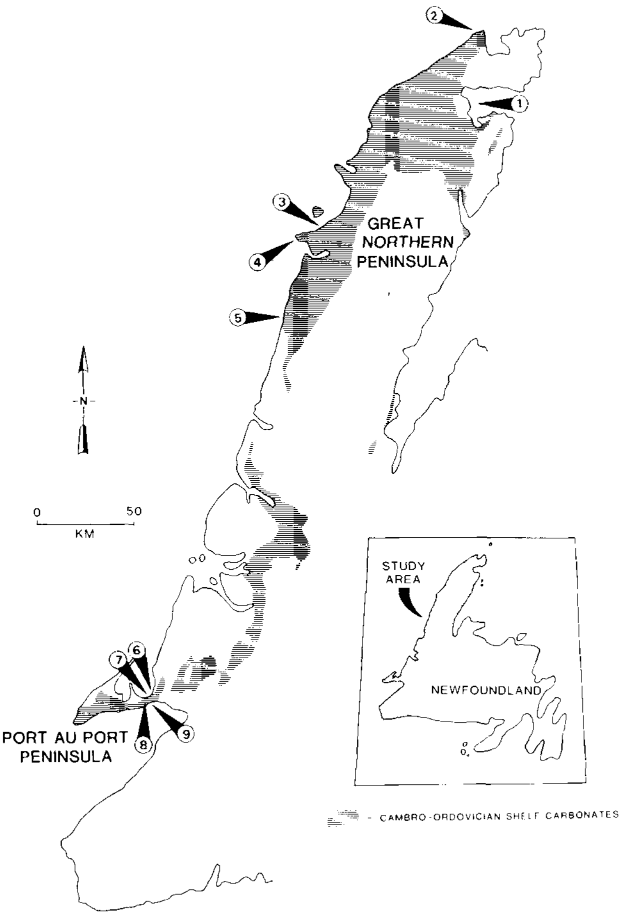


Fig. 2. Map of western Newfoundland showing distribution of Cambro-Ordovician shallow water carbonate rocks and location of nine measured sections (1 = Hare Bay; 2 = Boat Harbour; 3 = Eddies Cove West; 4 = Port au Choix; 5 = Table Point; 6 = NE of the Gravels which separate Port au Port Peninsula from mainland Newfoundland; 7 = NW of the Gravels; 8 = Aguathuna quarry; 9 = Isthmus Bay).

Isthmus Bay and Aguathuna consist of cyclic peritidal sequences, and the intervening Catoche is dominated by subtidal limestones (Fig. 3). They are locally overprinted by coarse, epigenetic dolomitization. A broadly similar succession can be recognized along the western margin of the Appalachian–Caledonian Orogen from the United States through eastern Canada to Greenland and Spitzbergen (Sando, 1957; Cowie & Adams, 1957; Swett & Smit, 1972; Fortey & Bruton, 1973). These divisions do not seem to be as readily recognizable, however, in the more dolomitic facies of the craton interior (e.g. Fisher, 1977; Cloud & Barnes, 1948).

The rocks of the St George Group are particularly instructive because they are superbly exposed as cleanly washed or unweathered coastal exposures. On the Great Northern Peninsula where bedding is subhorizontal, lateral facies changes can, in some instances, be observed directly over distances of hundreds of metres. Stratigraphic sections were measured in detail at nine places on the Great Northern Peninsula and Port au Port Peninsula (Figs 2 and 4).

LITHOLOGIES

This sedimentological analysis of the St George Group is the result of a detailed, bed-by-bed study of all its major outcrops in western Newfoundland. While lithologies are diverse, seven recurring lithotopes are distinguished (Table 1). These are interpreted, on the basis of lithological and palaeoecological data and the relationships to overlying, underlying and laterally equivalent units, to be the deposits of seven distinct, but intergradational, shallow-marine, peritidal palaeoenvironments.

Lithotope A—cryptalgal laminites

Description

These rocks are composed of uniform, occasionally discontinuous, millimetre-sized laminae (Fig. 5A) of lime mudstone and finely peloidal grainstone, with a microscopic fenestral fabric. Lamination is frequently wavy, sometimes doming to low-relief, laterally-linked hemispheroidal (LLH) stromatolites. Layers of laminae are often torn up into intraclasts, especially at contacts with overlying lithotopes (Fig. 5B), and may locally be buckled into small tepee structures. Discontinuous beds, up to several centimetres thick, of intraclastic and peloidal grainstone are occasionally

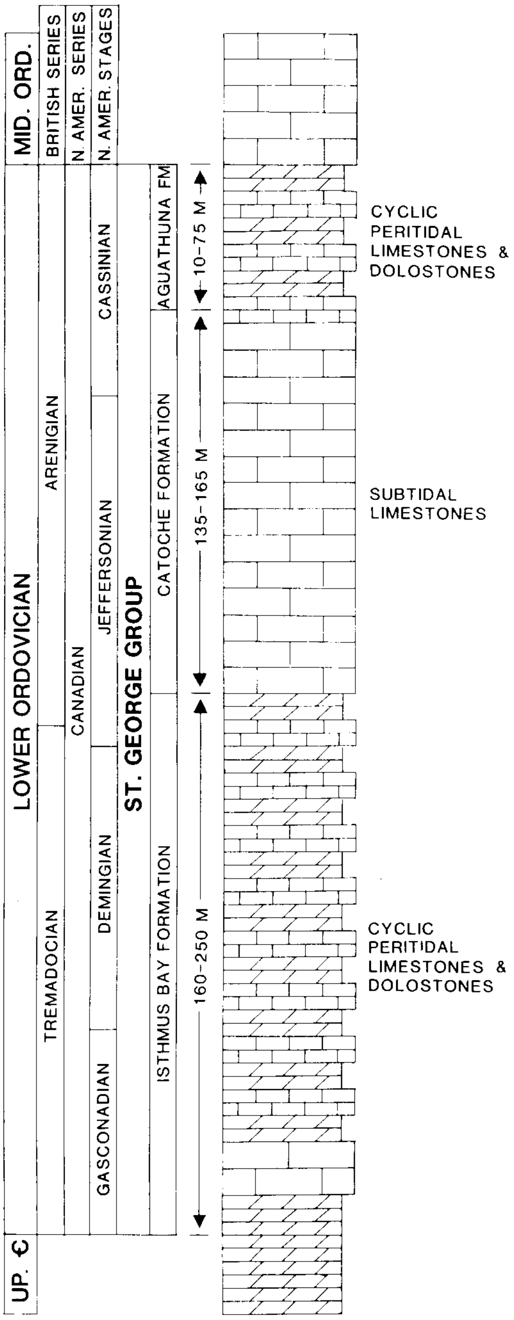


Fig. 3. Generalized stratigraphic section of the St George Group showing ages, overall lithological character, and provisional formation names.

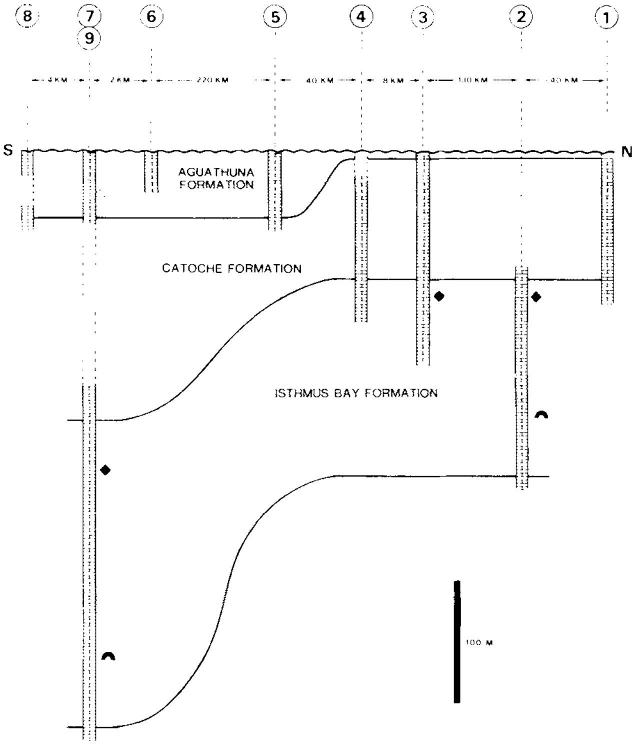


Fig. 4. Simplified correlation of stratigraphic sections measured in this study. Hemisphere symbol denotes thrombolite-*Renalcis* reef complexes (Pratt & James, 1982); diamond symbol denotes subaerial exposure horizon believed to be regionally correlatable.

Table 1. Summary of principal lithological characteristics of lithotopes

Lithotype	Lithological characteristics	Gradation	Environment
A—cryptalgal laminites	Cryptalgal lamination, common mudcracks, frequently doming to low-relief LLH stromatolites	Vertically with B,C,D and E, laterally to D and E	Supratidal
B—stromatolites	Laterally-linked hemispheroidal shape, simple to compound lamination	Vertically with A, laterally to D	Intertidal
C—burrowed dolostone	Thin-bedded dolostone, burrowed, unfossiliferous	Vertically with A and D	Intertidal
D—wavy- and nodular-bedded carbonates	Thin-bedded grainstone and lime mudstone, usually extensively dolomitized, parallel, lenticular, wavy, flaser and nodular bedding, planar and cross-lamination, sporadic burrowing	Vertically with A and C, laterally to A and B	Intertidal
E—thin-bedded lime mudstone and grainstone	Thin- to medium-bedded grainstone, lime mudstone, and wackestone, fossiliferous, burrowed beds, cross-lamination	Vertically with A, laterally to A	Intertidal
F—thrombolite mounds	Cryptalgal mounds of thrombolites (unlaminated stromatolites), fossiliferous, burrowed, flanked by fossiliferous grainstone	Laterally to G	Subtidal
G—fossiliferous wackestone	Medium-bedded wackestone and lime mudstone, fossiliferous, burrowed, scattered grainstone channels, lenses and beds	Laterally to F	Subtidal

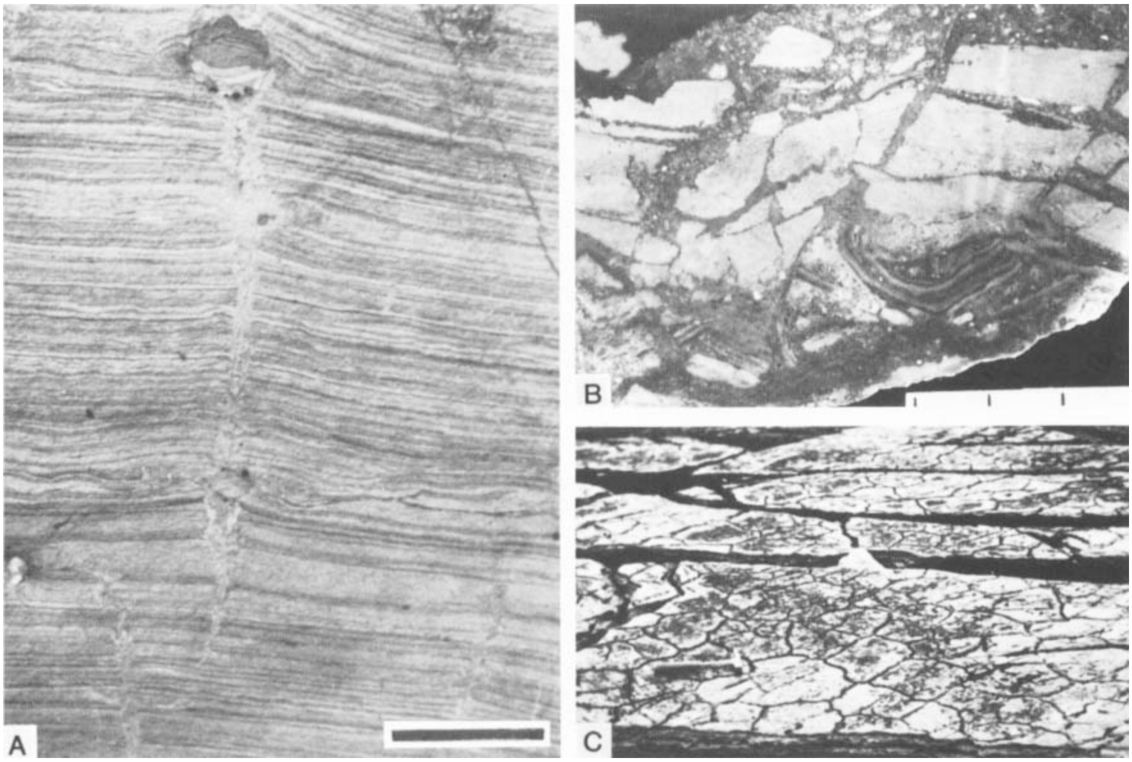


Fig. 5. Cryptalgal laminites (lithotope A), Isthmus Bay Formation. (A) Vertical outcrop view of algal-bound dolostone laminae split by deep prism cracks. Isthmus Bay; scale bar is 5 cm. (B) Vertically oriented slab of ripped up and curled cryptalgal laminite clasts overlain by brecciated dolostone (lithotope D). Isthmus Bay; scale divisions in centimetres. (C) Bedding plane view of mudcracks. Boat Harbour; hammer is 33 cm long.

intercalated. Mudcracks (Fig. 5C) are common but deep prism cracks (Fig. 5A) are rare. This lithotope is usually dolomitized to some degree leading to alternating laminae of fine-crystalline dolostone and limestone, or fine-crystalline dolostone with laminae outlined by colour and crystal size differences.

Several cryptalgal laminite units contain isolated and coalesced chert nodules that deform and truncate enclosing laminae. These cherts consist of either flamboyant megaquartz containing anhydrite inclusions, or microquartz or rarely flamboyant megaquartz containing dusty inclusions which outline a relict, felted lath texture (Fig. 6A).

Distribution

Cryptalgal laminites are found only in the Isthmus Bay and Aguathuna Formations, and units range in thickness from 0·1 to 1·5 m. At Boat Harbour, they have been observed to grade laterally to wavy- and lenticular-bedded carbonates (lithotope D) and thin-bedded lime mudstone and grainstone (lithotope E). Cryptalgal laminates often dome into stromatolites (lithotope B) and vertical intergradation with wavy- and lenticular-bedded carbonates (lithotope D) is common throughout. Vertical transitions into bioturbated rocks (lithotopes C and E) are marked by burrowed and disturbed cryptalgal laminites.

Interpretation

This lithotope is common in many carbonate sequences and arguments for its environmental interpretation have been frequently put forward (e.g. Aitken, 1967). It is generally considered to have been formed by the trapping and binding of fine-grained sediment by blue-green algal mats. This is suggested by the uniform nature of individual laminae, their buckling and doming, and fenestral pores. The mats are considered, on the basis of many modern examples (e.g. Hardie, 1977), to have formed on supratidal and upper intertidal flats. This is confirmed in the rocks

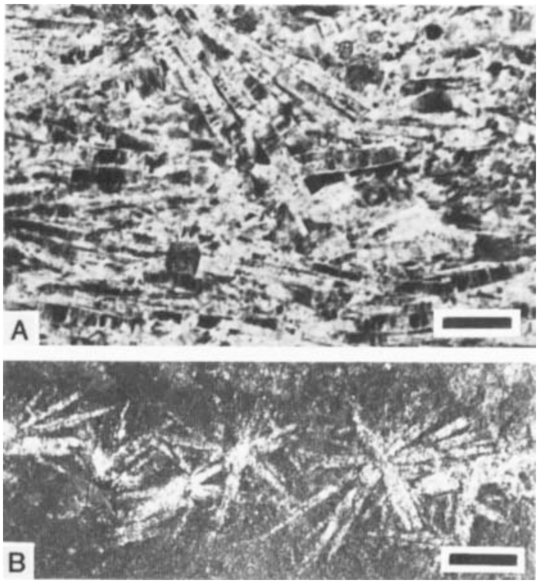


Fig. 6. Evidence for evaporites. (A) Thin section photomicrograph of chert bed (lithotope A) showing dusty inclusions outlining lath texture. Aguathuna Formation, Table Point; scale bar is 50 μm. (B) Bedding surface of dolostone (lithotope D) with rosettes of needles composed of coarsely crystalline dolomite aggregates. Isthmus Bay Formation, Eddies Cove West; scale bar is 1 cm.

and by their lateral continuity, mudcracks, rip-up clasts and tepee structures. The paucity of bioclasts and relative scarcity of coarse sediment reflect, in general, deposition by suspension away from subtidal areas; discontinuous grainstone beds are probably storm deposits. Some chert nodules are morphologically similar to nodular and enterolithic anhydrite and contain petrographic evidence of precursor anhydrite, features used by others (e.g. Young, 1979) as implying an origin by evaporite replacement. Elevated salinities may have commonly occurred in the subaerially exposed sediments, but the rarity of these nodules indicates that evaporite precipitation was *minor* and *local*.

Lithotope B—stromatolites

Description

This lithotope consists of domal stromatolites in various combinations of laterally-linked hemispheroidal (LLH) shapes (Fig. 7A). They have low relief, diameters ranging from less than 0·2 to 2 m, and possess internal laminae which are often wavy or define smaller laterally-linked hemispheroids.

Distribution

These stromatolites occur mostly in the lower part of the Isthmus Bay Formation and in the Aguathuna Formation as units less than 0·3 m thick. They pass laterally into and are immediately over- and underlain by wavy- and lenticular-bedded carbonates (lithotope D) (Fig. 7B), or are developed by doming of underlying cryptalgal laminites (lithotope A). Mudcracks are common but fossils and burrows are scarce in closely associated rocks.

Interpretation

Laterally-linked hemispheroidal stromatolites are interpreted to have grown in the intertidal zone, in

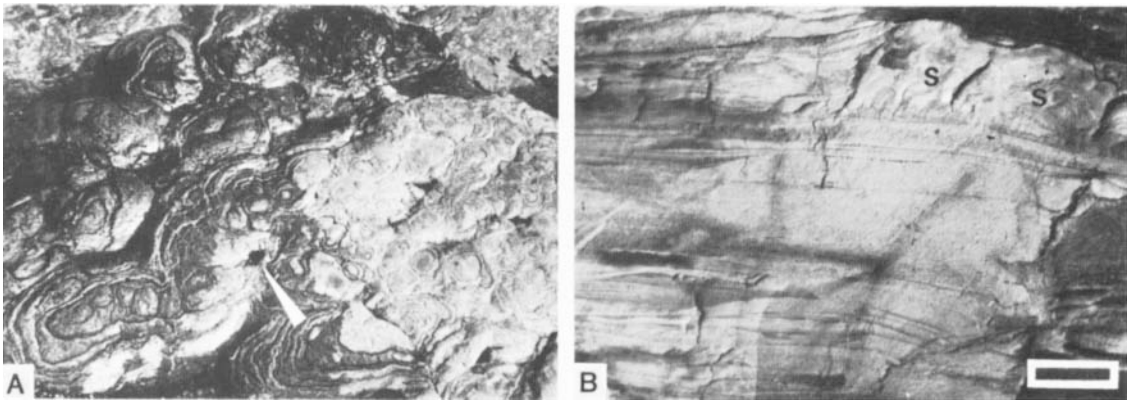


Fig. 7. Stromatolites (lithotope B). (A) Bedding plane view of laterally linked hemispheroids with compound internal lamination outlining smaller hemispheroids. Aguathuna Formation, NE Gravels; lens cap (arrowed) is 6 cm across. (B) Vertical outcrop view of wavy- and lenticular-bedded dolostone (lithotope D) enclosing stromatolites (S). Isthmus Bay Formation, Isthmus Bay; scale bar is 5 cm.

localities away from subtidal areas and protected from strongly erosive tidal currents, because of: (1) mudcracks in associated wavy- and lenticular-bedded rocks (lithotope D) which indicate periodic subaerial exposure; (2) rarity of fossils and burrows which suggests other than normal marine conditions; (3) the low-relief, LLH morphology as opposed to columnar stacked hemispheroidal (SH) form which argues for low energy (Hoffman, 1976); and (4) vertically associated cryptalgal laminites (lithotope A) which implies stromatolite growth in the intertidal zone (Pratt & James, 1982). The laminated internal fabric indicates episodic but regular addition of sediment on to the blue-green algal mats.

Lithotope C—burrowed dolostone

Description

This lithotope consists of fine- to medium-crystalline dolostone that is extensively burrowed to completely burrow-mottled and churned, thin-bedded (where preserved) and unfossiliferous (Fig. 8). Burrows are uncompacted, sediment-filled vertical and horizontal types.

Distribution

Burrowed dolostones occur as relatively thick (0·5–5·5 m) units, but are uncommon and, like stromatolites, occur only in the Isthmus Bay and Aguathuna Formations. Vertical gradation into wavy- and lenticular-bedded dolostone (lithotope D) is frequent and is marked by a gradual decrease in the amount of bioturbation with concomitant preservation of physical sedimentary structures. Where burrowed dolostones overlie cryptalgal laminites (lithotope A), burrows extend downward and disturb the cryptalgal laminae.

Interpretation

The absence of fossils in the dolostones suggests deposition under conditions different and removed from normal, sediment-generating subtidal areas. The burrow-mottled nature indicates, however, some submergence by waters of near normal salinity. Occurrence as thick units, however, argues for a depositional setting that was a persistent sediment trap rather than short-lived tide ponds or lagoons. The thin-bedded nature implies episodic accretion; intergradation with wavy- and lenticular-bedded rocks (lithotope D) in the degree of bioturbation suggests deposition in the intertidal zone. Burrowed dolostones are therefore interpreted to have been deposited on intertidal flats in tranquil areas protected from erosion by tidal currents, where there was intermittent sedimentation with nearly pervasive bioturbation. Destruction of primary current bedding in this manner is characteristic of modern carbonate tidal flats in humid areas (e.g. Hardie, 1977).

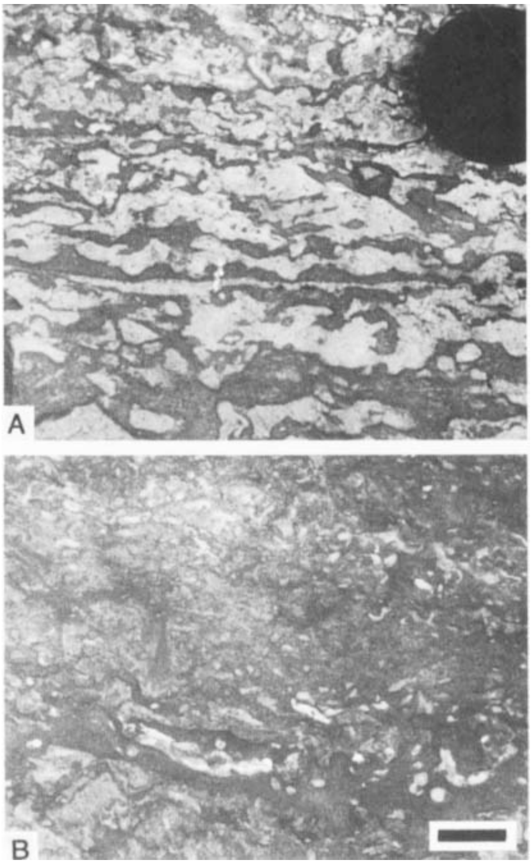


Fig. 8. Burrowed dolostone (lithotope C), Isthmus Bay Formation, Isthmus Bay. (A) Vertical outcrop view of burrowed and churned dolostone showing relict thin bedding. Lens cap is 6 cm across. (B) Vertically oriented slab of burrow-mottled dolostone showing numerous, uncompacted burrow cross-sections and relict thin bed with a bioturbated upper surface. Scale bar is 2 cm.

Lithotope D—wavy- and lenticular-bedded carbonates

Description

Rocks of this lithotope are variable but are typified by thin bedding (less than 5 cm thick) and partial to complete dolomitization. They range from interbedded dolostone, lime mudstone and peloidal grainstone to fine- to medium-crystalline dolostone. Bedding types include cross and continuous and discontinuous planar lamination, parallel, wavy, lenticular, flaser and nodular bedding (Fig. 9A–D); scoured surfaces are common. Grainstones are often intraclastic (Fig. 9E) and cross-laminated, sometimes graded and herringbone cross-laminated, but rarely oolitic; quartz sand and silt grains are absent. Cross-lamination is occasionally visible in lime mudstone lenses, nodules and wavy beds. Bioclasts are usually rare to absent in this lithotope, except in the Catoche Formation where they are common. Whole fossils are rare, although scattered, large planispiral gastropods and lingulid brachiopods do occur. Stacked hemispheroidal and columnar stromatolites (Fig. 7B), mudcracks, syneresis cracks, vertical, U-shaped spreiten-burrows (*Diplocraterion*, Fig. 9A, B) and, less commonly, horizontal sediment-filled burrows (*Chondrites* and *Planolites*) occur in scattered beds. Burrows are often selectively dolomitized and soft-sediment compacted. Planar, microbored erosion surfaces on grainstone beds (Fig. 9F) are rare. Rosettes of up to 2 cm long needle- and lath-shaped aggregates of coarse dolomite are present in one unit of lenticular-bedded dolostone (Fig. 6B).

Distribution

Wavy- and lenticular-bedded limestones and dolostones occur abundantly in the Isthmus Bay and Aguathuna Formations but rarely in the Catoche Formation. Units of this lithotope range in thickness from 0·2 to about 3 m and are not traceable laterally on a regional scale and often not on a local scale as well. On the Great Northern Peninsula, one unit passes laterally to cryptalgal laminites (lithotope A) over a distance of 100 m; the two lithotopes are commonly juxtaposed vertically. Stromatolites (lithotope B) are characteristically flanked by these rocks (Fig. 7B). Vertical intergradation with burrowed dolostone (lithotope C) is common and marked by an increase in the amount of bioturbation.

Interpretation

This lithotope is interpreted to have been deposited in the intertidal zone because of: (1) the thin bedding which indicates episodic deposition by bedload and suspension transport; (2) the suite of sedimentary structures and bedding types which is typical of modern siliciclastic intertidal sediments (de Raaf & Boersma, 1971; Reineck & Singh, 1980, pp. 432–434; Demicco, 1983); (3) mudcracks; (4) the rare, low-diversity, indigenous fauna of gastropods and lingulids; (5) the sporadic nature of bioturbation, with dominance of U-shaped spreiten- and horizontal sediment-filled burrows, a common intertidal association (e.g. Crimes, 1977); (6) the dolomite laths and needles which appear to be replaced anhydrite crystals that probably formed locally in lenses of sediment during extreme desiccation; and (7) the lateral and vertical transition to cryptalgal laminites (lithotope A). The bedding types and sedimentary structures are mainly indicative of intermittent sediment movement by waves (de Raaf, Boersma & van Gelder, 1977) and tidal currents. In addition, most cross-laminated intraclastic grainstones probably reflect storm-generated transport; some may be lags of channels that migrated laterally although distinctly downcut channels were not recognized. Soft-sediment compaction and post-lithification, burial dolomitization and pressure solution have affected many of the sedimentary structures (Pratt, 1982). Peloidal grainstone ripples may have been compacted into wavy-, lenticular- and nodular-bedded lime mudstone. Primary lime mudstone interbeds were often dolomitized. Partial dolomitization of peloidal grainstone and lime mudstone also produced nodular and lenticular bedding where residual limestone nodules and lenses do not appear to reflect primary sedimentary structures.

De Raaf & Boersma (1971) and Reineck & Singh (1980, p. 455) have cautioned that it is difficult to distinguish with certainty between intertidal and shallow subtidal sediments in ancient siliciclastic sequences. Although the disparate nature of the lithologies grouped in this lithotope is considered to be due to factors typical of the intertidal zone, such as variability in current strength and direction, normally fine grain size of sediment, variable amount of bioturbation, wave energy, storms and subaerial exposure, some units may have been deposited under very shallow subtidal conditions where many of these processes also operate.

Lithotope E—thin-bedded lime mudstone and grainstone

Description

This lithotope is characterized by laterally continuous, interbedded thin- to medium-bedded (beds less than 0·1 m thick), cross-laminated grainstone (Fig. 10A),

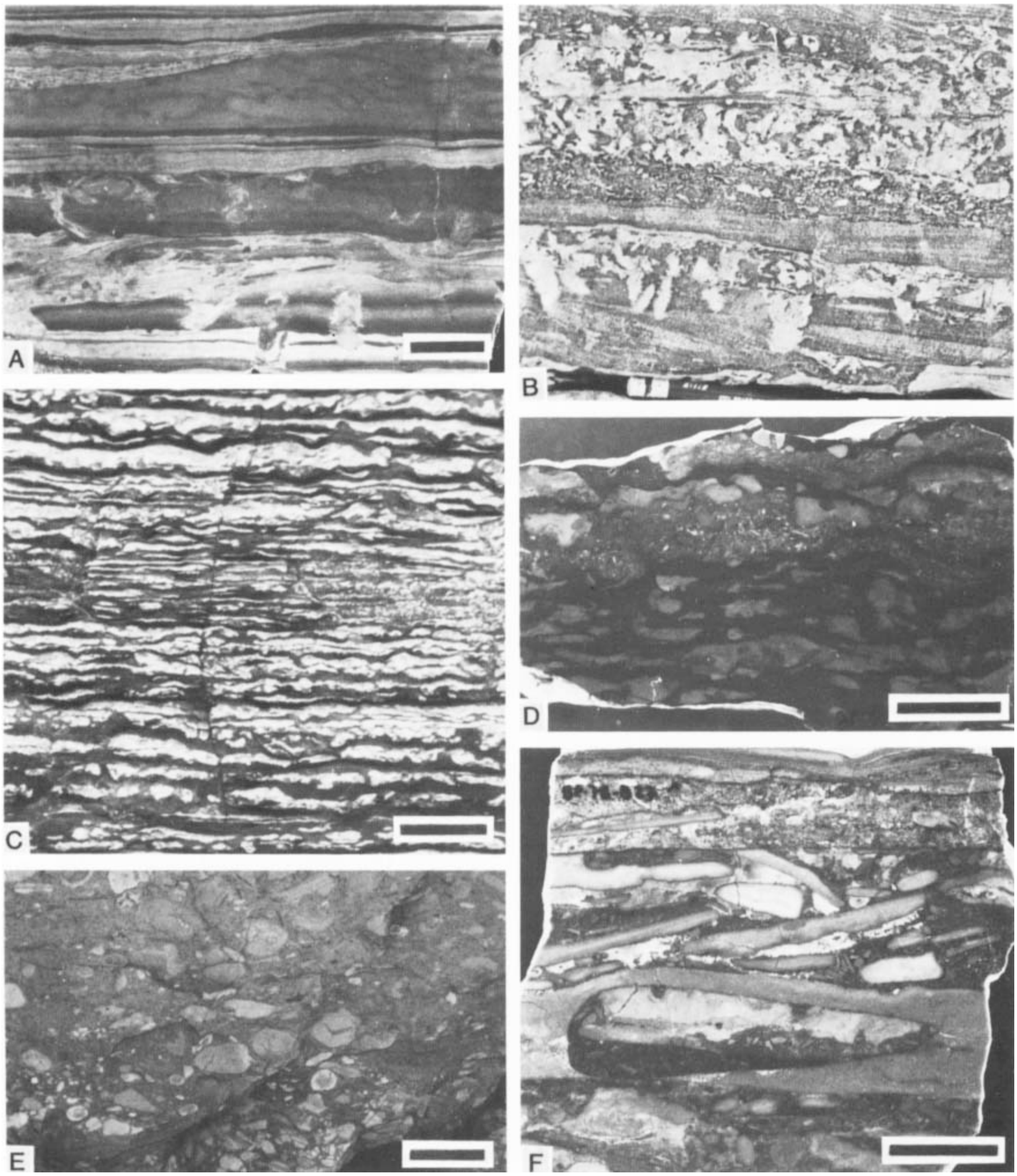


Fig. 9. Wavy- and lenticular-bedded carbonates (lithotope D). (A) Vertically oriented slab of thin-bedded dolostone showing parallel lamination, lenticular bed in a scour and scattered bioturbation by vertical spreiten-burrows (*Diplocraterion* at bottom) and horizontal *Chondrites* (fine mottles in upper left). Isthmus Bay Formation, Isthmus Bay; scale bar is 2 cm. (B) Vertical outcrop view of cross-laminated grainstone showing variable current direction and local disruption by dolomitized burrows. Isthmus Bay Formation, Isthmus Bay; pencil is 7 mm wide. (C) Vertical outcrop view of nodular and lenticular lime mudstone beds with dolostone interbeds. Isthmus Bay Formation, Isthmus Bay; scale bar is 5 cm. (D) Vertically oriented slab of thin- and nodular-bedded, locally bioclastic and intraclastic grainstone with dolomitic lime mudstone interbeds. Catoche Formation, Eddies Cove West; scale bar is 2 cm. (E) Vertical outcrop view of grainstone composed of large, rounded intraclasts. Isthmus Bay Formation, Isthmus Bay; scale bar is 5 cm. (F) Vertically oriented slab of intraclastic grainstone showing several planar erosion surfaces. Isthmus Bay Formation, Isthmus Bay; scale bar is 2 cm.

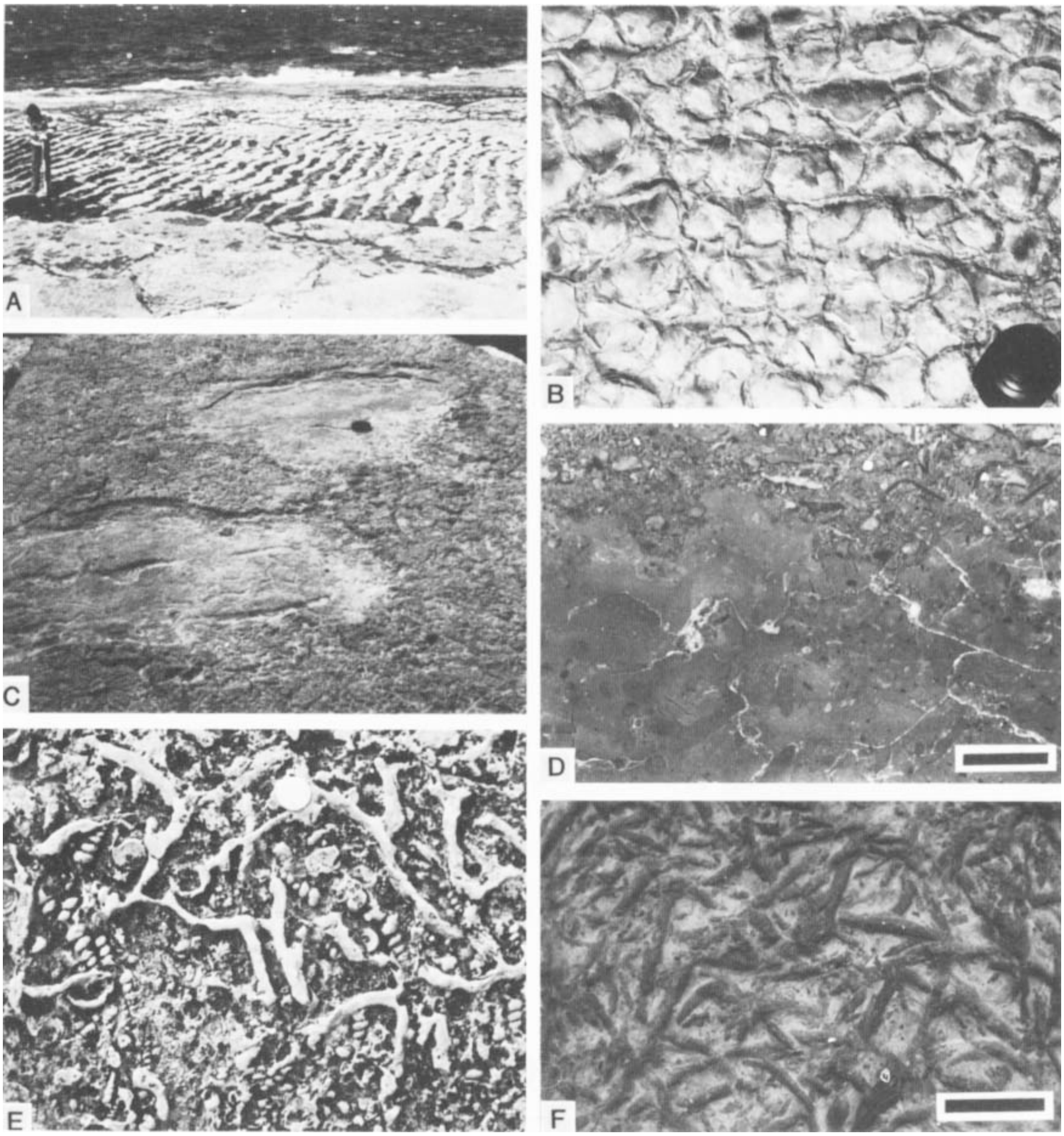


Fig. 10. Thin-bedded lime mudstone and grainstone (lithotope E). (A) Bedding plane view of rippled grainstone. Isthmus Bay Formation, Eddies Cove West; staff with 20 cm divisions held by boy. (B) Bedding plane view of mudcracked ripples. Isthmus Bay Formation, Port au Choix; lens cap is 6 cm across. (C) Bedding plane view of depressions (crossed by *Cruziana*-like furrows) scoured out of burrowed lime mudstone. Isthmus Bay Formation, Eddies Cove West; lens cap is 6 cm across. (D) Vertically oriented slab of lime mudstone containing horizontal burrows (*Planolites*), erosively overlain by bioclastic grainstone. Isthmus Bay Formation, Isthmus Bay; scale bar is 1 cm. (E) Bedding plane view of dolomitized horizontal burrows (*Planolites*) and gastropod steinkerns. Isthmus Bay Formation, Eddies Cove West; coin is 2 cm across. (F) Underside of bedding plane showing bottoms of U-shaped spreiten-burrows (*Diplocraterion*). Isthmus Bay Formation, Port au Choix; scale bar is 5 cm.

burrowed lime mudstone (Fig. 10D) and, sporadically, wackestone, with frequent dolomitic partings. Herringbone cross-lamination, mudcracks (Fig. 10B), synaeresis cracks and scoured surfaces (Fig. 10C, D) are occasionally present. Horizontal *Chondrites*, *Planolites* (Fig. 10D, E), spar-filled tubes and non-ornamented, *Cruziana*-like furrows (Fig. 10C) and U-shaped burrows (*Diplocraterion*, Fig. 10F, and *Arenicolites*) are common in lime mudstone beds, often penetrating ripple tops of underlying grainstones. Hardgrounds, as microbored erosion surfaces, are developed on rare grainstone and wackestone beds in the Isthmus Bay Formation. Grainstones are peloidal, bioclastic (Fig. 10E), intraclastic (Fig. 10D) and rarely oolitic; quartz grains are absent. Small thrombolite mounds, less than 0·1 m in diameter, occur in scattered beds. This lithotope differs from wavy- and lenticular-bedded rocks (lithotope D) in that beds are thicker, often burrowed, laterally continuous and undolomitized; discontinuous planar lamination and flaser, wavy and lenticular bedding are absent.

The thin-bedded lime mudstone and grainstone lithotope hosts the only example discovered in the St George Group of a large, elongate grainstone body not directly associated with thrombolite mounds (lithotope F). This feature is 1·9 m thick and at least tens of metres wide, and one margin can be traced 700 m along sea-cliffs before it disappears under cover. The grainstone body consists mainly of cross-bedded and herringbone cross-bedded, intraclast grainstone and packstone, with intercalated thin- and nodular-bedded, locally burrowed lime mudstone, grainstone and dolostone (lithotope D) (Fig. 11). The intraclasts are imbricated, commonly oversteepened, and are composed of flat and rounded, sometimes laminated, lime mudstone and finely peloidal grainstone. Many cross-beds exhibit reactivation surfaces and scoured bases, and many are normally graded with large intraclasts at the bases; cross beds dip approximately E/W. The grainstones seem to interfinger with laterally equivalent thin-bedded rocks (lithotope E) and the sequence is sharply underlain and overlain by burrowed wackestone (lithotope G).

Distribution

The thin-bedded lime mudstone and grainstone

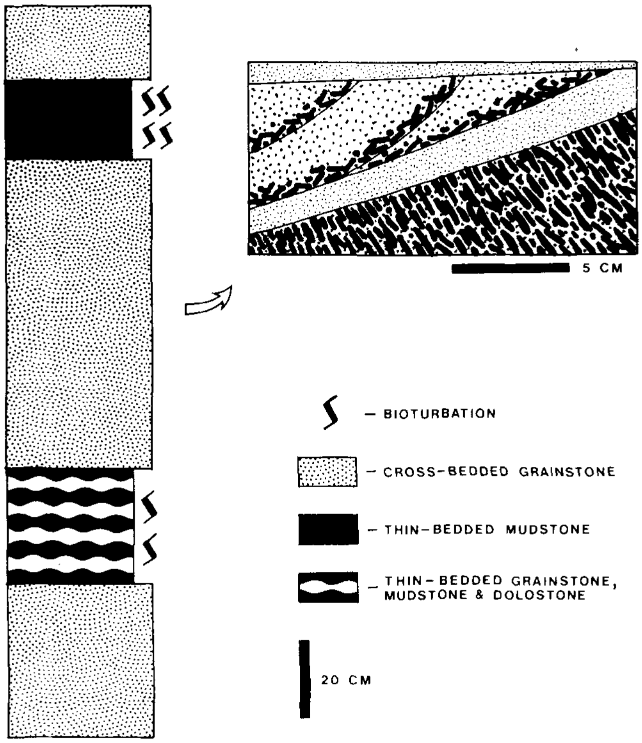


Fig. 11. Stratigraphic section of grainstone channel sequence exposed at Port au Choix, with close-up outcrop sketch of steeply dipping cross-beds, reactivation surfaces and imbricated and graded intraclasts.

lithotope is most common in the upper part of the Isthmus Bay and lower part of the Catoche Formations. Units tend to be thick, on the order of several metres, but up to about 50 m on Port au Port Peninsula. This lithotope is vertically juxtaposed with all lithotopes except stromatolites (lithotope B) and burrowed dolostone (lithotope C). Contacts with underlying cryptalgal laminites (lithotope A) are often marked by burrowed and disturbed cryptalgal laminae. Lateral gradation to cryptalgal laminites (lithotope A) has been observed on the Great Northern Peninsula.

Interpretation

This lithotope is interpreted to have been deposited in the intertidal and shallowest subtidal zones because: (1) periodic subaerial exposure and desiccation are indicated by mudcracks; (2) herringbone cross-lamination suggests reversing tidal currents; (3) vertical U-shaped and horizontal sediment- and spar-filled burrows are a common intertidal and shallow subtidal association (e.g. Crimes, 1977); and (4) there is lateral gradation to supratidal cryptalgal laminites (lithotope A). The fossiliferous nature of the grainstone beds suggests nearness to subtidal areas. Most grainstone beds are probably the result of short-distance storm transport as their thickness suggests episodic movement of relatively large volumes of sediment. Dolomitic partings are probably dolomitized lime mudstone seams deposited from suspension during slack water. Sedimentation was somewhat intermittent to account for occasional synsedimentary lithification, formation of hardgrounds, and the presence of empty, spar-filled burrows. The lack of bedding types found in wavy- and lenticular-bedded rocks (lithotope D) suggests a different intertidal depositional setting. It is envisaged as a narrow, continuous strand and adjacent shallowest subtidal area, comparatively protected from vigorous current activity and frequent traction movement of silt- and sand-sized sediment which were characteristic of the wavy- and lenticular-bedded carbonates (lithotope D).

Although only one margin of the thick grainstone unit is exposed, it is probably a narrow, linear tidal channel, reversing currents being indicated by herringbone cross-bedding. A channel rather than a shoal or beach is suggested by: (1) its occurrence as a solitary feature within intertidal rocks; (2) lack of bioclasts; (3) intercalated lime mudstone; (4) its intraclastic lithology; (5) graded bedding; and (6) lack of evidence for a positive geometry. The channel was intermittently the site of strong, storm-generated current activity from the oceanward side, giving rise to steeply dipping beds exhibiting reactivation surfaces, grading and imbricated pebbles. During more quiescent periods, thin-bedded and bioturbated lime mudstone, grainstone and dolostone (lithotope D) were deposited.

Lithotope F—thrombolite mounds

Description

Mound structures are generally between 0·4 and 2 m in both diameter and thickness (Fig. 12) and often coalesce to form circular to elongate patches or banks, with grooved margins and separated from each other by channels, that can be a few metres thick and over 100 m in width. They are flanked by cross-laminated grainstone that grades laterally to fossiliferous wackestone (lithotope G). Both mounds and flanking beds are highly fossiliferous, containing gastropods, rostroconchs, cephalopods, trilobites, pelmatozoan debris, brachiopods and locally corals and sponges. The mounds are made of clot-like thrombolites (unlaminated stromatolites; see definition in Pratt & James, 1982) in a burrowed wackestone matrix. Thrombolites are prostrate to columnar in attitude, and consist of clotted and peloidal micrite with fine fenestral pores lined or filled with synsedimentary, equant to radial fibrous or bladed calcite cement.

Several horizons of eroded thrombolite mounds occur in the Isthmus Bay Formation. In one example, small, eroded mounds or heads were encrusted by bulbous stromatolite domes which were themselves planed off and covered with undulating cryptalgal laminites. In a second example, lithified mounds and partially lithified flanking grainstone were exposed to several superimposed phases of erosion and filling by grainstone of the resulting potholed surface (Fig. 13A). Eroded thrombolite mounds are overlain by intraclastic grainstone and cryptalgal laminites (Fig. 13B) in a third case that appears to be regionally correlatable (Fig. 4).

Distribution

Thrombolite mounds are ubiquitous in the Isthmus Bay and Catoche Formations but uncommon in the Aguathuna Formation. They pass laterally to fossiliferous wackestone (lithotope G) and are vertically juxtaposed with cryptalgal laminites, wavy- and lenticular-bedded carbonates and thin-bedded lime mudstone and grainstone (lithotopes A, D and E, respectively).

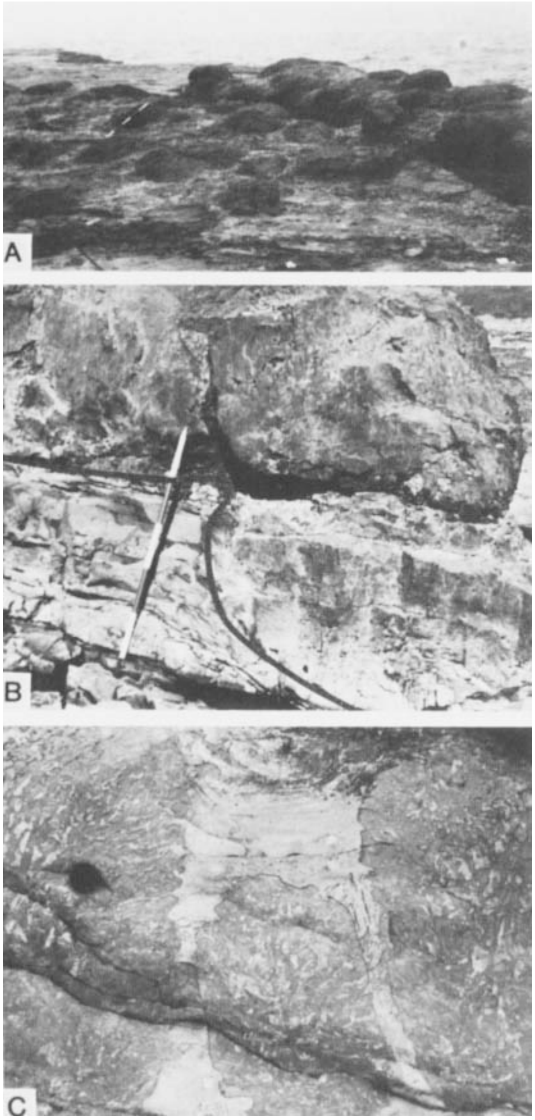


Fig. 12. Thrombolite mounds (lithotope F). (A) Bedding plane view of exhumed, metre-sized mounds (darker coloured than enclosing grainstone). Isthmus Bay Formation, Boat Harbour; staff with 20 cm divisions. (B) Vertical cross-section of a single mound flanked by grainstone (to the left of the black line in lower part) and passing upwards into a bank composed of coalesced mounds. Isthmus Bay Formation, Boat Harbour; staff with 20 cm divisions. (C) Vertical cross-section of three small mounds with partially dolomitized flanking grainstone and wackestone between upward-divergent thrombolites. Isthmus Bay Formation, Isthmus Bay; lens cap is 6 cm across.

At Hare Bay on the Great Northern Peninsula, mounds coalesced laterally and vertically forming extensive complexes up to 100 m thick and probably at least 1 km in width (Stevens & James, 1976). This is the easternmost exposure of the St George Group and closest to the inferred basinal deposits of Iapetus Ocean.

Interpretation

These mound structures are cryptalgal and are similar to thrombolite mounds described by Aitken (1967) from lower Palaeozoic rocks in the Canadian Rocky Mountains. They are interpreted (Pratt & James, 1982) to be true ecological reefs that grew in agitated shoal conditions in the subtidal zone because of flanking grainstones, synsedimentary cement and their burrowed and fossiliferous nature. Very shallow water is also indicated by the scattered occurrences of eroded mounds and vertical juxtaposition with cryptalgal laminites (lithotope A) and the intertidal lithotopes D and E.

Lithotope G—fossiliferous wackestone

Description

This lithotope consists mainly of burrowed to bioturbated, fossiliferous wackestone. Beds of bioturbated lime mudstone and scattered beds, lenses and narrow linear channels (Fig. 14B), less than 0·1 m thick, of peloidal, intraclastic, bioclastic and cross-laminated grainstone are sporadically interbedded, particularly in the Catoche Formation. Grainstone channels cut down less than 0·1 m into host wackestone. Bedding is medium to thick (Fig. 14A), but often difficult to recognize because of stylolitization. Burrows are horizontal, undeformed, often spar-filled and outlined in many cases by diagenetic dolomite of early burial origin (Pratt, 1982). Bioclasts are unabraded and common fossils include trilobites, gastropods, rostroconchs, nautiloids, *Girvanella* and pelmatozoan debris. Rare hardgrounds or firmgrounds occur in wackestones of this lithotope in the Isthmus Bay and Aguathuna Formations.

Distribution

In the Catoche Formation, continuous units of this lithotope are many metres thick and broken only by scattered, thin beds of nodular-bedded limestone (lithotope D) or horizons of thrombolite mounds

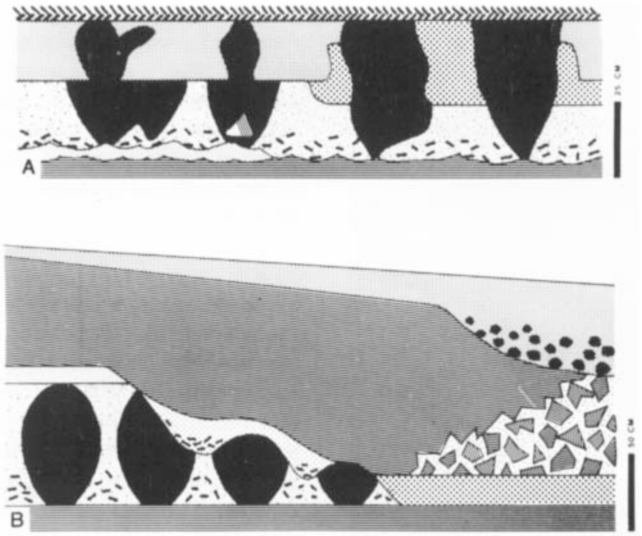


Fig. 13. Simplified outcrop sketches (slightly shortened) of sequences with eroded thrombolite mounds. Isthmus Bay Formation, Isthmus Bay. (A) Mounds (coloured black) and flanking grainstone formed on eroded cryptalgal laminites and grainstone, showing three episodes of exhumation and erosion before their crests were planed off and covered with herringbone cross-laminated intraclastic grainstone. (B) Mounds formed on cryptalgal laminites were deeply eroded and covered with grainstone and more cryptalgal laminites. The upper cryptalgal laminites are collapse brecciated and correlative with subaerial exposure horizons at Eddies Cove West and Boat Harbour (Fig. 4).

(lithotope F). Units of fossiliferous wackestone in the Isthmus Bay and Aguathuna Formations are thinner (less than 2 m thick), contain less mudstone, and are vertically associated with inter- and supratidal lithotopes. Thrombolite mounds grade laterally to burrowed wackestone.

Interpretation

These rocks are interpreted as having been deposited in the shallow subtidal zone under fully marine conditions, as has been previously suggested by Lévesque (1977). An open subtidal environment is indicated by: (1) widespread nature and thickness of the lithotope; (2) lack of evidence for subaerial exposure; (3) lack of cryptalgal laminites (lithotope A) and rarity of intertidal lithotopes in the Catoche Formation; (4) lateral gradation to thrombolite mounds (lithotope F); (5) ubiquitous bioturbation; and (6) abundant fossils. The thinness of beds of this lithotope in the Isthmus Bay and Aguathuna Formations and occurrence in vertical association with intertidal and supratidal sediments argue that subtidal conditions in those formations were more short-lived and less open than in the Catoche Formation. Freer connection with the ocean during Catoche time is also indicated by the appearance of pelagic trilobites (Fortey, 1979, p. 66). These sediments were probably deposited above wave-base on the open, shallow sea floor that supported a locally concentrated benthos with scattered patches and small channels of lime sand winnowed by currents and storms. This may be somewhat similar to modern seagrass-stabilized mudbanks (e.g. Davies, 1970), except that these present-day structures have relatively high relief and channels between them are deeply incised. This suggests that the Lower Ordovician subtidal sea bottom may not have been cohesively bound by rooted organisms (prior to the appearance of seagrasses which only evolved at the end of the Mesozoic), although the ubiquitous occurrence of *Girvanella* (calcified filamentous blue-green algae) does suggest that subtidal sediment surfaces were often loosely stabilized by flocculent algal mats (Pratt, in preparation).

ANALYSIS

Tidal origin of current structures

The interpretation of the St George lithologies as mainly tidal deposits is similar in most cases to that

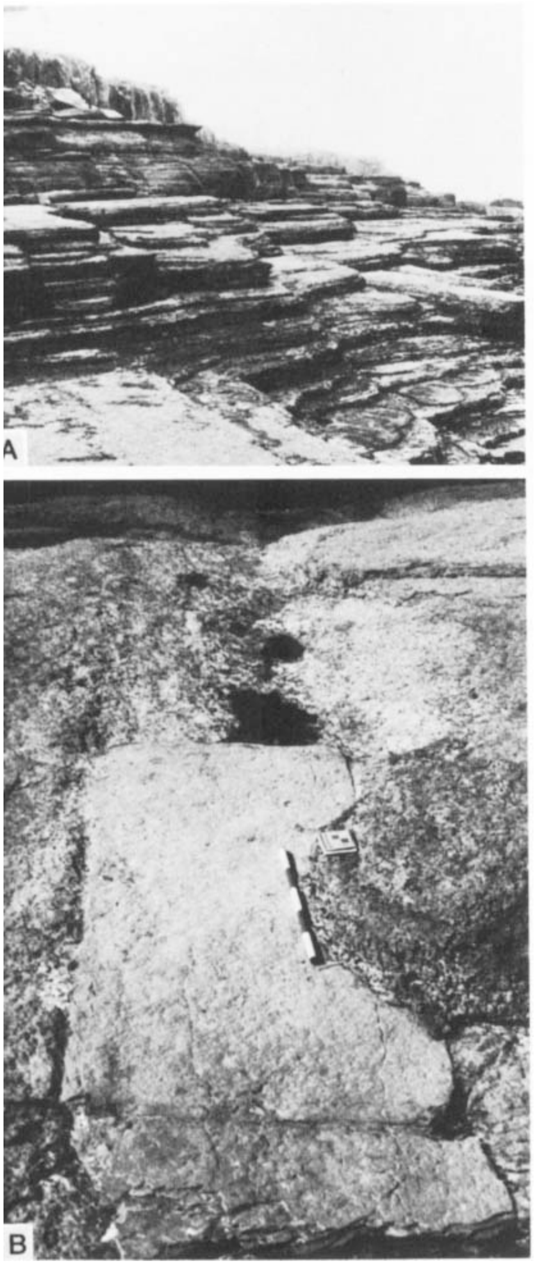


Fig. 14. Fossiliferous wackestone (lithotope G). (A) Shoreline exposure showing laterally continuous, even bedding. Catoche Formation, Boat Harbour; lighthouse building at top left. (B) Bedding plane view of thin, linear grainstone channel (lighter coloured pavement), oriented approximately NW/SE and cut into burrowed wackestone. Catoche Formation, Eddies Cove West; staff with 20 cm divisions.

put forward by previous workers for similar deposits (specific Lower Ordovician references and others, e.g. Matter, 1967; Laporte, 1967; Walker, 1973; Schwarz, 1975) and is justified for the following reasons: (1) herringbone cross-stratification implies reversing currents of equal intensity, especially in the channel sequence (Fig. 10) where these currents must have been particularly strong; (2) flaser, lenticular and wavy bedding indicate alternating bedload and suspension transport; (3) mudcracks form on subaerial exposure as wet sediments desiccate; (4) local burrowing activity requires frequent and regular inundation; (5) sediment laminae of stromatolites are trapped during episodic suspension transport; (6) patch reefs and ooids form in environments characterized by some degree of continuous turbulence; (7) linear channels and elongate patch reefs indicate consistently directed currents; (8) evaporites are rare suggesting that, in general, sediments were not exposed for prolonged periods; and (9) lateral transitions from cryptalgal laminites (lithotope A) to lithotopes D and E indicate horizontal changes in degree of desiccation and therefore topographic relief. Although non-tidal mechanisms could be invoked to explain some of these characteristics *individually*, it does not seem realistic to do so for them *combined*: an origin within a tidal regime provides the most parsimonious explanation. Klein (1977) and Klein & Ryer (1978) have similarly argued this for the *suite* of sedimentary structures seen in siliciclastic counterparts. There is no doubt that powerful storms were responsible for much sediment deposition (cf. Dott, 1974), such as the coarser grainstone beds and laminae in intertidal and supratidal lithotopes, and wind-generated waves must have often reworked finer sediment, because these two forces are naturally associated with tidal environments. However, features diagnostic of wave and storm action on shores not strongly affected by tides, such as beaches and storm ridges (e.g. Wright, 1984), appear to be rare or absent in the St George. Conversely, many lithological characteristics seen in the St George do not seem to occur in sediments of those environments, like lakes, where storms and waves are the only depositional processes, but rather are known from localities dominated by tides. In particular, the wavy- and lenticular-bedded carbonates (lithotope D) are remarkably similar to Recent siliciclastic tidal sediments.

Lateral separation of lithotopes

The different lithologies and lithologic features of the St George all record shallow water deposition; the three basic zones associated with tidal flats, supratidal, intertidal and subtidal, are represented by seven lithotopes, the relative abundance of which varies stratigraphically and geographically (Fig. 15). Application of Walther's Law rules that these lithotopes were deposited coevally.

Inspection of the lithotope summary presented in Table 1 reveals that there is one clear supratidal lithotope (A) and two clear subtidal lithotopes (F and G) which can be confidently interpreted on the basis of modern examples and the fossil record. It is less clear from lithological characteristics alone, however, as to the exact palaeobathymetric placing of the four intertidal lithotopes (B,C,D and E) between these bounding end-members. When the lateral and vertical interrelationships are taken into account the original disposition of sedimentary environments can be demonstrated or inferred.

The supratidal lithotope (A) has been observed to grade laterally into wavy- and lenticular-bedded carbonates (lithotope D) and thin-bedded lime mudstone and grainstone (lithotope E), and vertically into all intertidal sediments (lithotopes B,C,D and E). Thus, observable field relationships indicate that supratidal sediments were deposited coevally with all four intertidal lithotopes. This implies that these intertidal sediments were themselves accumulating in four, laterally equivalent and possibly adjacent but *separate* tidal flat environments (Figs 16 and 17). That these four lithotopes do not just reflect different bathymetric levels of the *same* intertidal flat is also argued by their stratigraphic distribution (Fig. 15): absence of lithotope E in the lower Isthmus Bay Formation on Port au Port Peninsula, its near absence in the Aguathuna Formation, and near absence of lithotope C in the Isthmus Bay Formation on the Great Northern Peninsula. On the other hand, their commonly close vertical and lateral associations show that they cannot reflect climatic fluctuations.

Summary of environments

The scarcity of evaporite vestiges suggests that the St George was deposited under semi-arid to sub-humid,

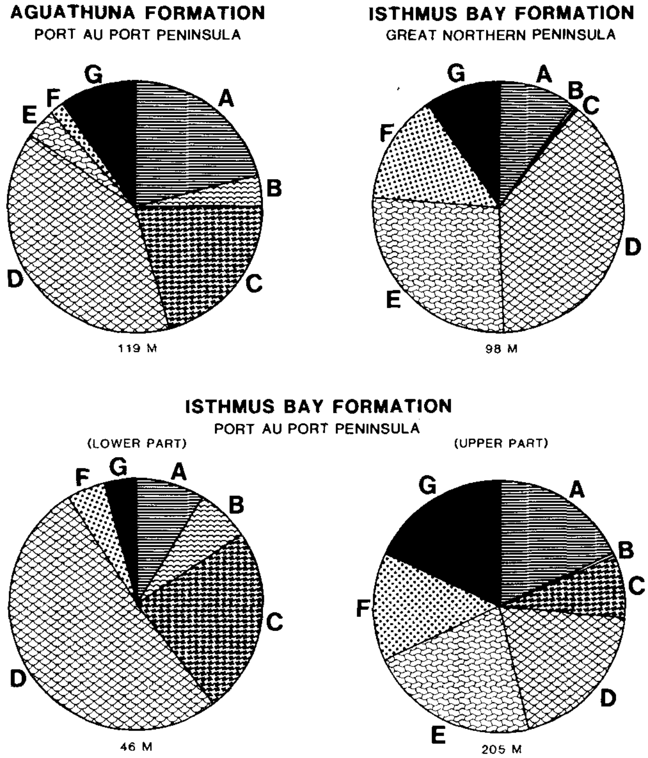


Fig. 15. Pie diagrams showing the relative amounts (total thickness) of the various lithotopes in each of the four informal subdivisions of the Isthmus Bay and Aguathuna Formations derived from patterns in Fig. 18. Lithotope symbols same as Fig. 20; numbers below each pie refer to the total thickness of strata considered.

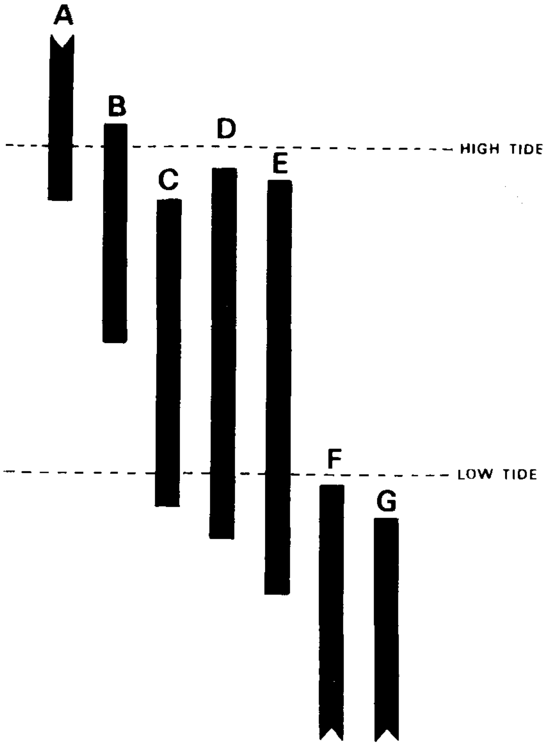


Fig. 16. Approximate relative bathymetric zonation of the seven lithotopes. Actual tidal height is unknown.

tropical condition. The subtidal zone hosted the most diverse benthos and is represented by both quiet-water and shoal deposits, the latter from growth of thrombolite mounds. Supratidal sediments are cryptalgal-laminated. On the other hand, intertidal rocks are complex and lithologically diverse, dependent on many factors such as the sedimentation rate, degree of bioturbation and wave, current and storm energy. Four lithotopes have been distinguished that suggest four different but coeval, principally intertidal depositional settings: (1) broad, actively accreting tidal flats in a windward location, exposed to variable conditions of sedimentation, current strengths and directions, bioturbation and desiccation (lithotope D); (2) laterally extensive but generally narrow flats, where sedimentation was more intermittent, perhaps in a slightly protected, leeward position bordering open subtidal areas (lithotope E); (3) well-protected tidal flats where bioturbation exceeded sedimentation leaving no preserved sedimentary structures (lithotope C); and (4) protected flats of low sedimentation rate, on which grew domal stromatolites (lithotope B). Major drainage channels dissected some of these tidal flats, as suggested by the thick, cross-bedded, intraclastic grainstone sequence (Fig. 11).

The Isthmus Bay and Aguathuna Formations consist of all lithotopes, arranged in a repetitive, or 'cyclic', pattern. Three subdivisions within the Isthmus Bay stand out from the distribution and repetition of lithotopes (Figs 15 and 18): (1) the Isthmus Bay of the Great Northern Peninsula, (2) the basal Isthmus Bay and (3) upper Isthmus Bay on Port au Port Peninsula. In contrast, the Catoche Formation is characterized chiefly by thick units of bioclastic wackestone (lithotope G), intercalated thrombolite mounds (lithotope F) and rare, thin units of thin- and nodular-bedded limestone (lithotope D), indicating dominantly open shallow subtidal conditions relieved occasionally by high- and low-energy shoaling with intertidal exposure. In the lower part of the Catoche, where the thin-bedded lime mudstone and grainstone (lithotope E) does occur and is thickest, broad shallow subtidal to low intertidal flats or banks accreted, perhaps protected by a barrier or shoal of thrombolite mounds which may have existed to the east.

While the entire St George ostensibly records an overall regressive-transgressive-regressive succession, water depths clearly remained very shallow throughout. The three divisions do not have to be attributed directly to three major fluctuations in relative sea-level rise. Perhaps deposition of the Catoche occurred during a time of stronger current activity from the Iapetus Ocean which prevented widespread tidal flat accretion and dispersed pelagic trilobites. One minor sea-level fall did occur, however, to form the subaerial exposure horizon in the upper Isthmus Bay Formation (Figs 4 and 13B). The Isthmus Bay is thickest on Port au Port Peninsula, indicating that total subsidence was greater there than to the north on the Great Northern Peninsula, but subsidence rates cannot be calculated owing to the inadequacy and conflicting nature of radiometric dates presently available (Ross & Naeser, 1984).

Facies sequences

Many previous studies of shallow water, peritidal carbonates have shown that vertical sequences can be explained logically by means of repeating, idealized, small-scale shallowing-upward cycles using subtidal and supratidal facies as bounding end-members (James, 1977b). The specific character of cycles is variable, depending whether grainstone shoals, reefs,

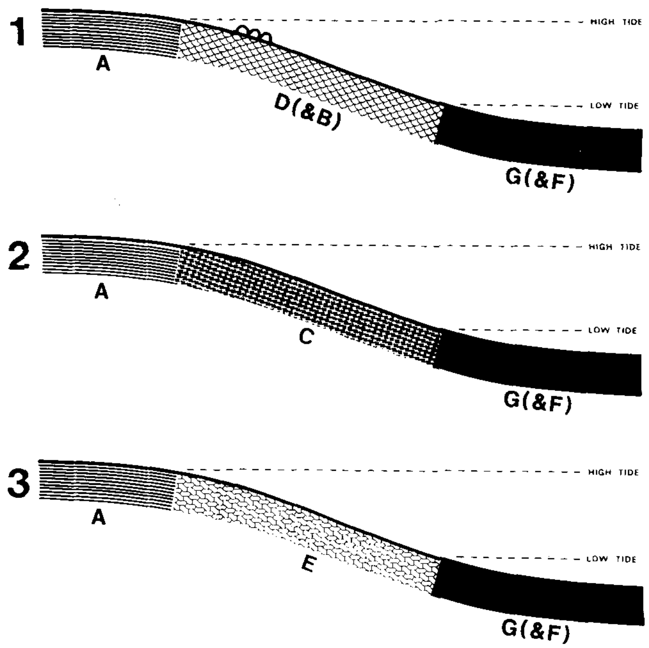


Fig. 17. Schematic bathymetric profiles of the various types of tidal flat environments recognized in the Isthmus Bay and Aguathuna Formations. Stromatolites (lithotope B) included in 1. Lithotope symbols same as Fig. 20.

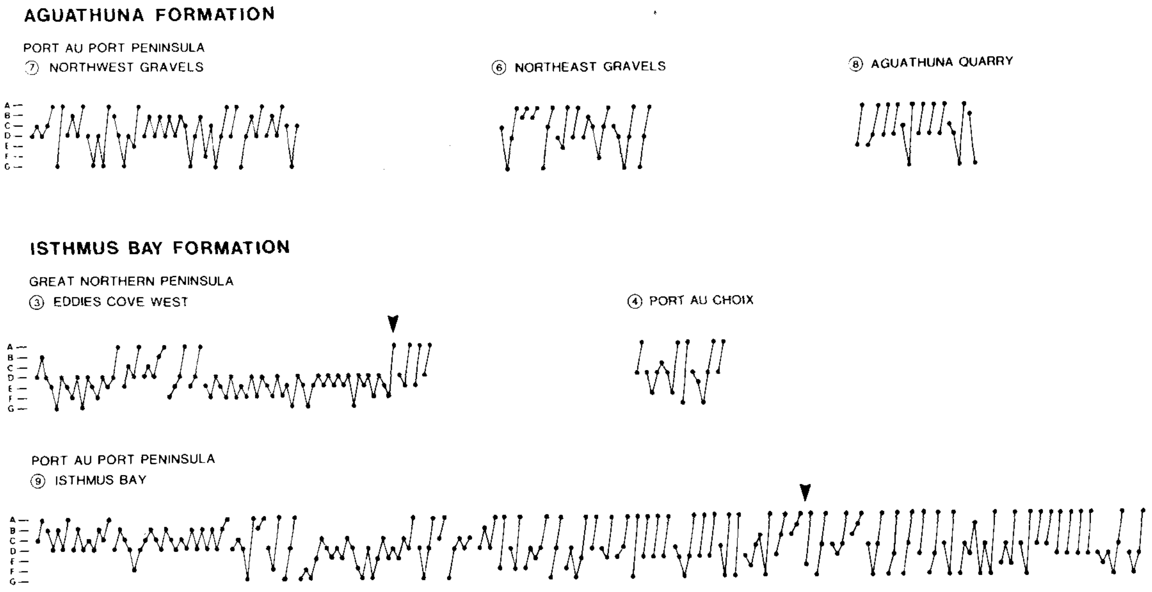


Fig. 18. Plot of the stratigraphic distribution of lithotopes in the Isthmus Bay and Aguathuna Formations for the six best exposed localities, with stratigraphic top to the right. Lithotopes arranged vertically so that supratidal is at top and subtidal is at bottom; succeeding lithotopes are joined by lines, except after A to denote the climax of a shoaling episode, i.e. to the supratidal zone. Arrows mark the position of the regionally correlatable exposure horizon in the Isthmus Bay Formation which can be used to compare the lithotope pattern between Eddies Cove West and Isthmus Bay (see Fig. 4). No stratigraphic thickness is implied by the dot spacing.

AGUATHUNA FORMATION
PORT AU PORT PENINSULA

	A	B	C	D	E	F	G
A		4	4	14	1	0	3
B	2		2	7	0	1	1
C	2	0		3	0	1	5
D	14	9	2		3	0	5
E	4	0	0	1		0	0
F	0	0	2	0	0		0
G	4	0	2	8	0	0	

ISTHMUS BAY FORMATION
GREAT NORTHERN PENINSULA

	A	B	C	D	E	F	G
A		0	0	6	4	1	1
B	1		0	1	0	0	0
C	0	0		3	0	0	0
D	8	2	2		14	6	2
E	2	0	1	8		7	4
F	2	0	0	9	3		0
G	1	0	0	5	1	0	

ISTHMUS BAY FORMATION
PORT AU PORT PENINSULA

(LOWER PART)

	A	B	C	D	E	F	G
A		2	1	4	0	0	1
B	2		4	7	0	0	0
C	2	1		6	0	0	0
D	3	9	4		0	2	1
E	0	0	0	0		0	0
F	1	0	0	1	0		0
G	1	0	0	1	0	0	

(UPPER PART)

	A	B	C	D	E	F	G
A		0	3	12	15	5	9
B	2		0	1	0	0	1
C	2	2		4	1	0	1
D	15	1	2		8	3	8
E	15	1	5	5		2	3
F	4	0	0	4	1		2
G	7	0	0	11	6	1	

Fig. 19. Matrices of the four subdivisions of the Isthmus Bay and Aguathuna Formations (derived from Fig. 18) showing the numbers of contacts between lithotopes. Letters arranged horizontally are the overlying lithotopes and those arranged vertically are the underlying lithotopes. For example, in the Aguathuna Formation lithotope A is overlain by B four times, by C four times, by D 14 times, and so on.

beaches and so forth were present. Naturally, strata do not always consist of superposed cycles: symmetric (shallowing-upward and mirror-image deepening-upward) cycles may be common, or cycle components may be missing altogether. The absence of components may be due to non-deposition associated with rapid transgression, or reworking by scour or bioturbation during environmental shifts.

The vertical distribution of lithotopes of the Isthmus Bay and Aguathuna Formations was plotted for the most continuous sections (Fig. 18) and inspection shows that ideal shallowing-upward cycles are rare. For each of the four informal subdivisions of the Isthmus Bay and Aguathuna, a matrix was constructed to display the number of over- and underlying contacts between each lithotope (Fig. 19). The volumetric abundance of lithotopes (Fig. 15), the most typical stratigraphic order in which they occur and the most common vertical associations displayed in the matrices suggest that the character of each subdivision can be represented by a hypothetical lithotope *sequence* (Fig. 20). Sequences are composite in that more than one supratidal level may be present, but oversimplifying the oscillation of lithotopes to shallowing-upward cycles is avoided.

Facies models

The traditional model of peritidal carbonate sedimentation on continental shelves and epeiric seas, regardless of age, is a shoreline model, which is based on modern analogues of coastal tidal flats in various tropical areas. By this concept, peritidal sediments are considered to fringe the land surface or, occasionally, the lee sides of reefs or grainstone shoals (James, 1977b) and in the case of large, shallow epeiric seas, form laterally continuous, regionally broad belts many tens, or even hundreds, of kilometres in width (Shaw, 1964; Irwin, 1965). It is difficult, however, to rationalize the St George within this shoreline model because: (1) tidal flat sequences only a few metres in thickness must have prograded a minimum of 200–300 km; (2) detrital quartz grains are virtually absent; and (3) lateral facies changes occur rapidly over very short distances. These facies changes can be walked out and observed directly where bedding is horizontal, and deduced by correlation of closely spaced sections; no consistent landward direction seems to be indicated by the pattern of lithotope changes. Figure 21 is presented as a correlation of two sections of the Aguathuna Formation, located 2 km apart. This demonstrates that peritidal lithotopes tend to be laterally impersistent in the St George, a fact also shown by Ross (1951, p. 7) and Mazzullo *et al.* (1978, p. 113) for correlative strata in Utah and New York, respectively, by Fairchild (1980, p. 427) for late Precambrian dolostones, by Palmer & Halley (1979, p. 51, fig. 33; Halley, 1975, p. 287) for Middle Cambrian tidal flat limestones, by Davis (1966, fig. 4) and Harris (1966, fig. 3) for Upper Cambrian stromatolitic dolostones, by Jones & Dixon (1975, fig. 11) for a Silurian sequence, and by Laporte (1971, p. 727) in a general discussion of lower and middle Palaeozoic examples, indicating that tidal environments changed rapidly even over short distances. Correlation of Lower Ordovician carbonate rocks in Wisconsin by Raasch (1952, figs 2 and 3) shows that this was not just an outer shelf phenomenon but also appears to have been characteristic of peritidal sediments deposited well within the craton interior. These peritidal sediments must therefore have accumulated in a situation where there were contemporaneously submerged and emergent areas in close proximity to one another. On an open shelf, such a situation suggests the presence of contemporaneous

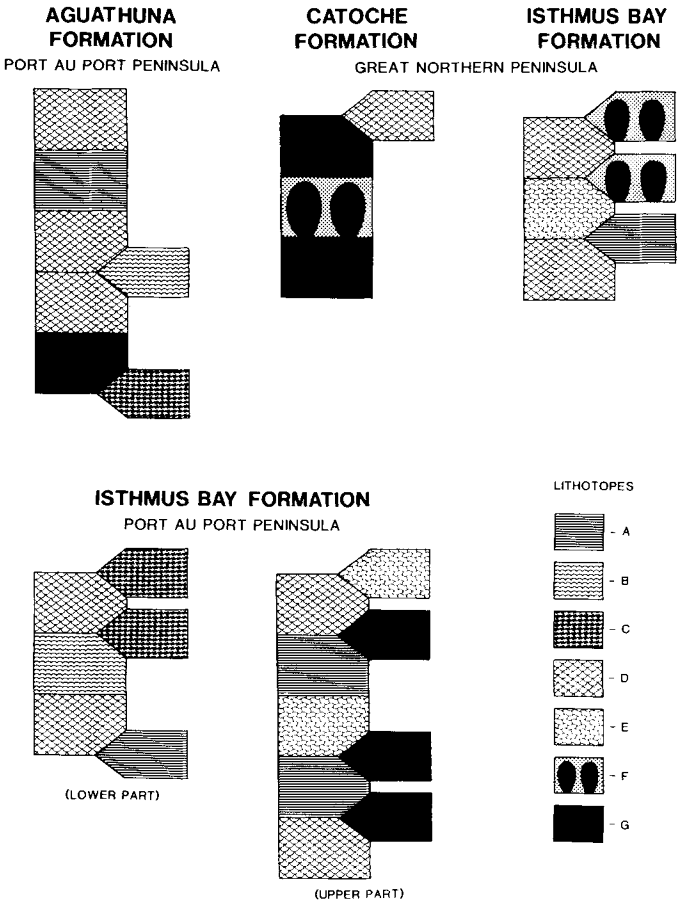
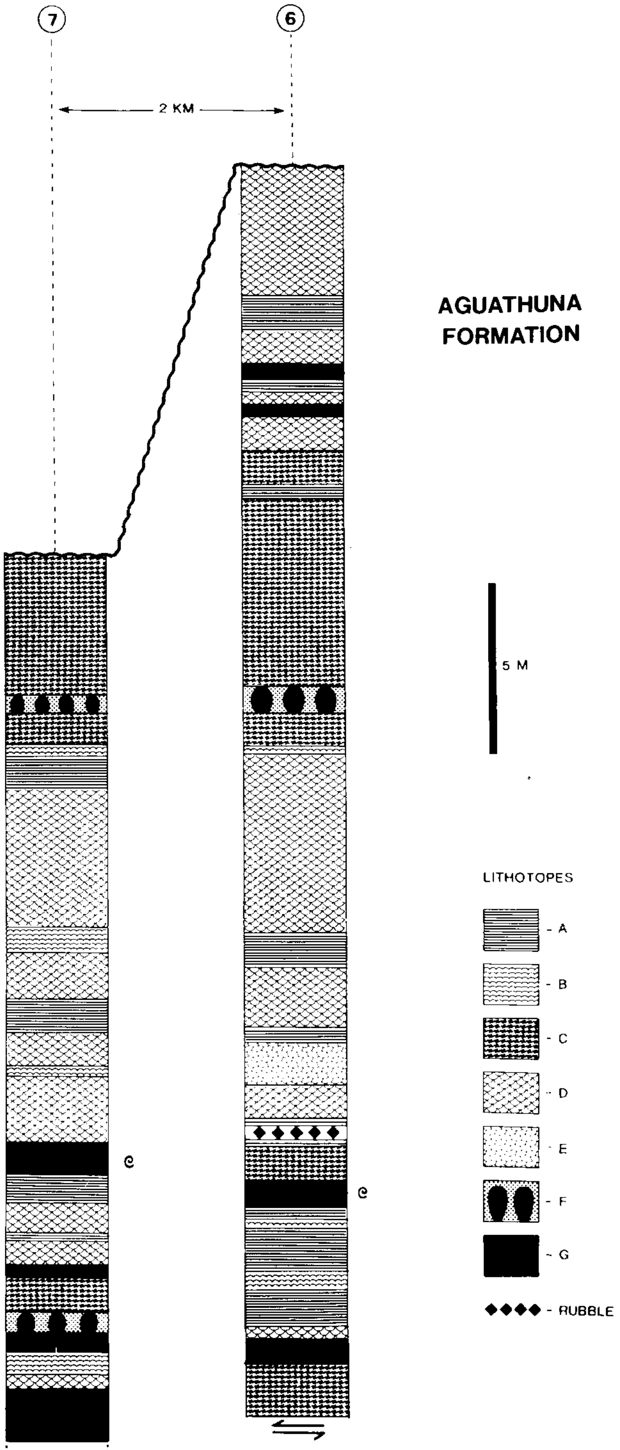


Fig. 20. Lithotope sequences derived from the relative abundance of lithotopes (Fig. 15) and most common under- and overlying relationships (Fig. 19) for the three informal subdivisions of the Isthmus Bay Formation, the Aguathuna Formation and the Catoche Formation. Lithotopes drawn to one side of columns are those that occur less frequently. No thickness implied. (Lithotope A = cryptalgal laminites; B = stromatolites; C = burrowed dolostone; D = wavy- and lenticular-bedded carbonates; E = thin-bedded lime mudstone and grainstone; F = thrombolite mounds; G = fossiliferous wackestone.)

subtidal areas and scattered islands with supratidal caps. Thus, during Isthmus Bay and Aguathuna time, the continental shelf in western Newfoundland is envisaged to have been a *mosaic* of low-relief, intertidal and supratidal banks and islands; during Catoche time, subtidal conditions predominated and such banks and islands were very scattered. The lateral impersistence of Holocene sediment types within and between islands and banks in Florida Bay (Enos & Perkins, 1979) and Belize (Ebanks, 1975) shows that a similar mosaic pattern has arisen and continued in modern settings.

Hypothetical, simplistic facies maps of typical islands (Fig. 22) are prepared using the vertical lithotope sequences for the Isthmus Bay and Aguathuna Formations. In a general sense, islands are assumed to be elongate, parallel to prevailing currents (from the open Iapetus Ocean), and lithotope characteristics suggest that windward and leeward areas existed and affected local current action and sediment supply. Cryptalgal laminites (lithotope A) are considered to have covered continuously exposed, supratidal areas. Wavy- and lenticular-bedded sediments (lithotope D) accumulated on windward intertidal flats, but, on the whole, some distance from fossiliferous subtidal areas, with stromatolites (lithotope B) locally


7
6
2 KM
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LITHOTOPES
- A
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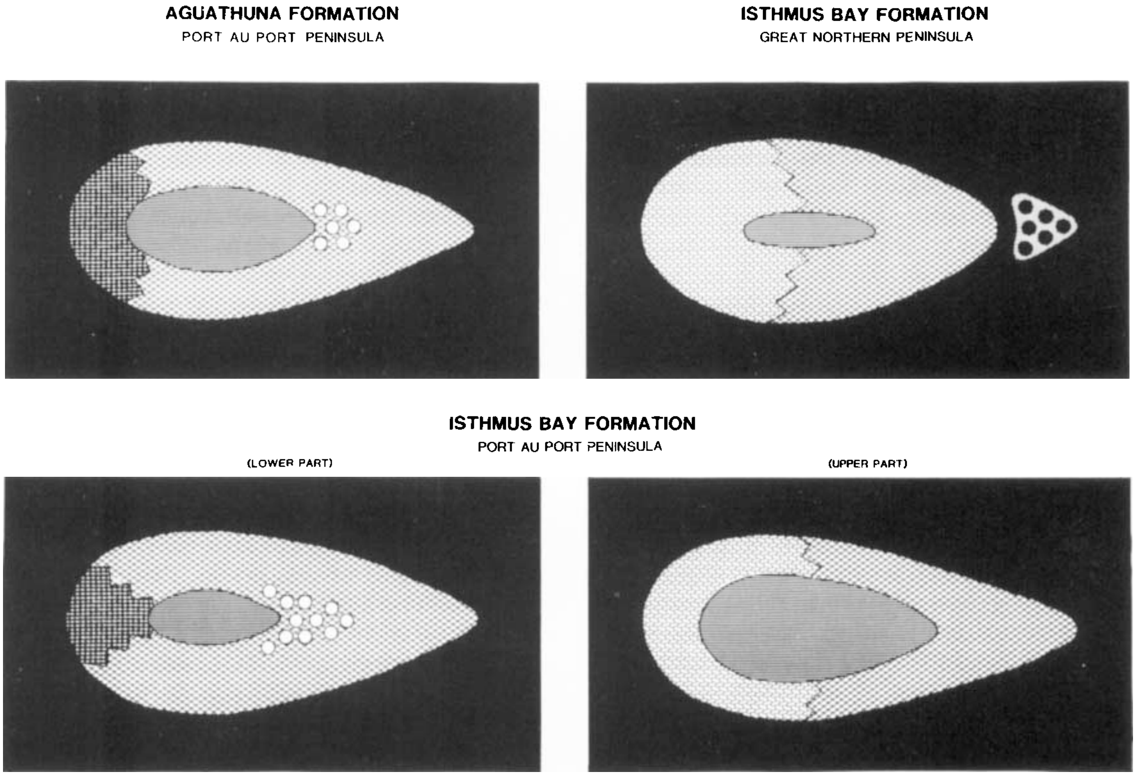

AGUATHUNA FORMATION
PORT AU PORT PENINSULA

ISTHMUS BAY FORMATION
GREAT NORTHERN PENINSULA

ISTHMUS BAY FORMATION
PORT AU PORT PENINSULA

(LOWER PART)

(UPPER PART)

Fig. 22. Diagrammatic island facies maps for the four informal subdivisions of the Isthmus Bay and Aguathuna Formations, drawn on the basis of lithotope sequences (Fig. 20). Islands are assumed to be generally elongate, parallel to a prevailing current from the right side. Lithotope symbols same as Fig. 20 except for stromatolites (lithotope B) which appear as white circles.

developed where there was sufficient protection. Thrombolite mounds (lithotope F) formed subtidal shoals in windward areas. In more tranquil, leeward intertidal and shallowest subtidal areas, sporadic sedimentation produced thin-bedded lime mudstone and grainstone (lithotope E), whereas complete bioturbation in other leeward flats gave rise to burrowed dolostone (lithotope C). Surrounding these islands were subtidal areas in which accumulated fossiliferous wackestone (lithotope G). Judging from facies changes observed directly or from correlation over very short distances (Fig. 21), islands were probably less than about 10 km in size; tidal height was probably in the range of a few metres, based on the general rarity of the large-scale bedforms characteristic of a macrotidal regime. Lateral changes, as well as the smaller total volume and thinness of units of fossiliferous wackestone (lithotope G) during deposition of the Isthmus Bay and Aguathuna, suggest that islands were only a few to a few tens of kilometres apart at those times.

Changes in character of the Isthmus Bay and Aguathuna within and between sections indicate that the distribution of sediment types around islands and banks varied geographically and temporally, which would have been caused by local or regional sedimentological factors such as current strengths and directions and fluctuating sedimentation rate. Variation in thickness of the lithotopes can be attributed to

Fig. 21. Suggested correlation of two sections of the Aguathuna Formation located 2 km apart NW and NE of the Gravels that separate Port au Port Peninsula from mainland Newfoundland. The sections are hung on the base of a distinctive sequence of burrowed dolostone (lithotope C) and thrombolite mounds (lithotope F) in the upper part; further down in the section is a correlatable horizon of fossiliferous wackestone (lithotope G) containing silicified gastropod opercula (shown by spiral symbol). This or any other correlation shows that many lithotopes are laterally discontinuous.

fluctuating local sedimentation rates which governed the stability of individual island positions. The entire stratigraphic unit of the Isthmus Bay and Aguathuna Formations combined, in a three-dimensional sense, accumulated as islands and banks accreted vertically and migrated laterally over each other and neighbouring subtidal deposits.

DISCUSSION

Fundamental to the study of shallow water carbonate sediments and their geologic record is the fact that sediment particles are generated in the basin of deposition (Folk, 1959). Moreover, most of these particles are produced by organisms, in the subtidal zone; tidal flats consist of allochthonous sediment (James, 1977a). The efficiency of sediment generation is governed by such factors as water depth, area, salinity and oxygenation of the subtidal zone. Tidal flats, in general, can be thought of as sediment sinks accreting and migrating laterally with time as relative sea level rises. Because of this dynamism, the rock record of shallow water carbonates is very often dominated by tidal flat sediments, but this dominance may belie the relative distribution and extent of the original environments. In the following discussion, it is argued that tides *must* have functioned in most ancient, broad, shallow epeiric seas. We propose a general model of carbonate sedimentation in those seas that fits geological observations and incorporates tides and superimposed storms as the most important processes controlling deposition. Finally, it is contended that many shallowing-upward cycles are the stratigraphic record of peritidal carbonate sediments accreting, according to our model, as islands during relatively continuous subsidence.

Role of tides

The patterns of tides in modern oceans, seas and coastal areas are complex and incompletely understood responses to many different variables, some of which are astronomical, while others are intrinsic to individual bodies of water, such as friction, bottom topography, ice cover, water depth, basin geometry, shoreline configuration and distribution of islands (Defant, 1961, chapters 11–14). Nevertheless, tidal patterns in ancient, carbonate-depositing epeiric seas can be estimated in a most general way. These seas were probably too shallow to have developed significant tides of their own, but the Earth–Moon system undoubtedly caused a gravitational pull to be exerted on oceanic water masses in the Early Ordovician; Krohn & Sündermann (1982) calculated a significant oceanic tidal range of 0·5 to 1 m for the western Iapetus Ocean in the Middle Ordovician. Bottom friction, a commonly cited objection to tides in epeiric seas (e.g. Hallam, 1981, chapter 5), can be a major factor in damping tidal height, but only if the bottom topography is sufficiently irregular to cause appreciable turbulence in the bottom layer. Friction in broad, tropical epeiric seas must have been relatively small, however, because there was no way of creating the necessary *highly rugged* sea bottom (other than by local patch reef development and transgression across a heavily karstified surface). Rather than being damped by shallow water, tidal height normally increases dramatically as oceanic tides approach shallower water. Such an increase must therefore have occurred in ancient epeiric seas. Furthermore, the great breadth of these seas was not a damping factor in itself: Klein & Ryer (1978) and Cram (1979) have shown that, in principle, tidal height increases with increasing continental shelf width. Irregular coastlines and islands may disturb tidal patterns and, in some areas, decrease tidal height locally if there is some reflection or diffraction and interference. In ancient epeiric seas, however, hydrographic forces themselves directly *created* the seafloor configuration (except for reefs): tidal waves and currents were not forced into a pre-existing array of rocky islands, straits and other obstructions over which they had no control, as they are in most modern situations. Tidal currents can be important agents of water exchange and sediment movement in straits, around sand ridges, in channels between barrier bars and on some tidal flats (e.g. Basan, 1973). Studies of most modern tidal flat complexes, however, suggest that the day-to-day effect of tides on sedimentation patterns tends to be minimal, whereas major changes and periods of sediment accretion on tidal flats occur during seasonal and cyclonic storms. On open, shallow carbonate shelves, it is well documented that storms create sand shoals that may become islands (e.g. Stoddart, 1962; Ball, Shinn & Stockman, 1967). Similar processes probably also acted in consort on ancient tidal flats, in that major storms often initiated or created islands and banks which were then sculpted and modified by tides, waves and later storms to balance best with ambient hydrographic conditions.

Based on observation of extant processes, there is difficulty in predicting the reaction of epeiric seas to self-generated sediment input, because no modern seas of comparable scale exist and because the Quaternary has been characterized by large excursions of sea-level. Nevertheless, it would be expected that a dynamic equilibrium would be reached between the rates of sediment input (by *in situ* generation), relative sea-level rise and sediment removal (by accretion and dispersal into the oceans) which is directly controlled by hydrographic forces (chiefly tides and storms). This is likely because: (1) the rate of carbonate sediment production decreases if subtidal areas become areally restricted or too shallow; (2) surplus sediment would be shed into deeper water and peritidal environments would prograde; and (3) hydrographic forces would inherently shape the seafloor to suit their most favourable circulation pattern; while this pattern may change with time, the sea would never completely choke itself of sediment.

The tidal island facies model

The historic concept of epeiric, clear water sedimentation (Shaw, 1964; Irwin, 1965) has been used as a guiding principle for many in the last 20 years (e.g. Lochman-Balk, 1971; Hallam, 1981, chapter 5). This concept dictates that in ancient, shallow epeiric seas, hundreds to thousands of kilometres wide, tides were damped out by friction with the shallow sea bottom and salinities increased landward. However, some aspects of this model, such as the suggested salinity gradient and the predicted presence of regionally widespread, low-energy conditions and episodes of platform-wide, subaerially or intermittently subaerially exposed sediments, are open to question (Schopf, 1980, pp. 66–67). Other implications do not seem to be borne out by the rock record: units ought to be lithologically homogeneous on a regional scale but, in many cases, such as the St George, they are not. The long periods of regional subaerial exposure would have been accompanied by intensive freshwater diagenetic alteration, but this is also not always observed. In addition, carbonate and siliciclastic rocks of epeiric seas exhibit abundant evidence of deposition by tides or storms superimposed on tides (Klein, 1977; Klein & Ryer, 1978; Johnson, 1978, pp. 237–238); these features cannot be adequately rationalized by the conventional epeiric sea theory in which waves and storms alone must generate them.

It is therefore proposed that many shallow, carbonate-depositing epeiric seas consisted of low-relief, supratidal islands and intertidal banks surrounded by open water (Fig. 23). Such a model was envisaged by Laporte (1967, p. 91) for similar limestones of Early Devonian age in New York, yet this concept has not been subsequently developed even though it seems to account for the characteristics of many typical lower Palaeozoic, shallow water carbonate successions. Naturally, the character of islands, such as shape, size and facies distribution, varied somewhat with distance from the open ocean, variation in tidal height, prevailing wind direction, location of storm and hurricane belts and so on. The spacing of islands probably varied too, but in a self-limiting way so that they were not too close to overly restrict water circulation and the sediment-generating capacity of subtidal areas. Extensive subtidal areas with few islands also existed in epeiric and shelf seas, such as

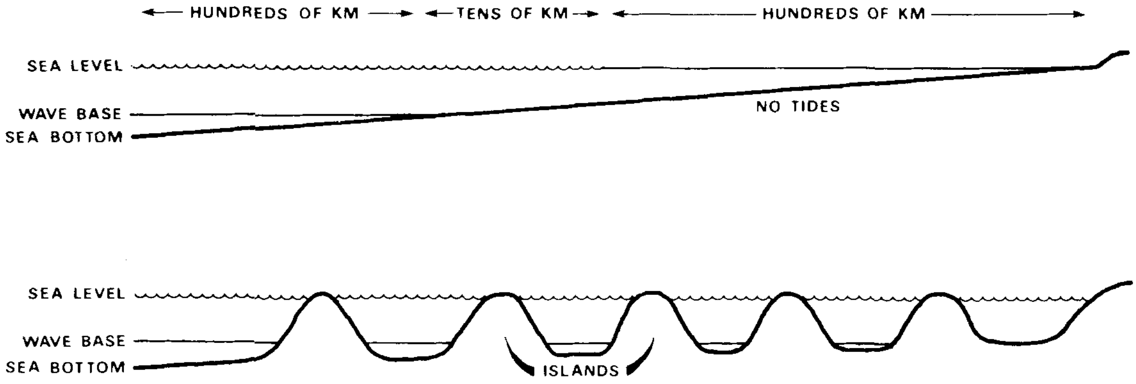

Fig. 23. Schematic, vertically exaggerated cross-sections of epeiric seas. Upper is the traditional representation (after Irwin, 1965) showing a high-energy zone, tens of kilometres across, shielding a wide, restricted, landward zone on the right where tides are absent. Lower is the representation suggested in this study where tides penetrate epeiric seas via subtidal areas surrounding tidal flat islands. Shelf margin characteristics not depicted; not to scale.

in the Catoche and more so in some Upper Cambrian strata in western (Brady & Rowell, 1976) and eastern (Markello & Read, 1982) United States. These subtidal areas could further have affected tidal resonance and caused increased tidal height, as suggested by Aitken (1978) for Cambrian carbonate rocks of western Canada.

The origin of peritidal cycles

Normalization of a shallow water carbonate succession to a series of small-scale cycles almost always involves simplification of a complex and heterogeneous stratigraphic record. Nearness to the 'ideal' cycle was governed by the stability, in space and time, of environmental parameters that directly control the primary facies pattern and its record as sediments accrete. In addition, it has usually been assumed that cycles reflect the regional or world-wide process of relative sea-level fluctuation, wrought by subsidence or eustasy associated with glaciation or changes in volume of mid-oceanic ridges (see summary in Duff, Hallam & Walton, 1967; also Hallam, 1978; Tucker, 1985, pp. 152–155). Subsidence is initially assumed in all situations to accommodate the preserved sediments. Recent, geophysically based studies (Vail, Mitchum & Thompson, 1977) have attempted to show that there has been a signature of eustatic sea-level fluctuation superimposed on regional subsidence. The small-scale ordering of facies in a sedimentary succession has then been thought to 'fine-tune' these curves of relative sea-level change with second- and third-order oscillations.

Transgressive-regressive cycles in general, or peritidal, asymmetric, shallowing-upward cycles specifically, have long been viewed as related to fluctuating subsidence rate and this mechanism has seemingly been documented many times by the practice of unrestrained correlation of units assumed to be synchronous on a basin-wide scale. For example, asymmetric peritidal cycles have been renamed 'punctuated aggradational cycles' (Anderson, Goodwin & Cameron, 1978; Goodwin & Anderson, 1980; Anderson, Goodwin & Sobieski, 1984) to imply that they formed during episodes of zero subsidence preceded and followed by sudden subsidence. On the other hand, Tucker (1977) considered the shoaling phases of symmetric peritidal cycles to have accreted to sea-level during times of static sea-level that alternated with sea-level rise by uniform subsidence. The related mechanism of eustatic sea-level fluctuation has also long been suggested as a cause of small-scale cyclicity in carbonate rocks (e.g. Fischer, 1964; Coogan, 1972; Demicco, 1982). This interpretation is especially compelling where there are numerous karstified horizons. Yet, changes in the rate of relative sea-level rise, by subsidence or eustasy, do not account for many other individual, *small-scale* peritidal cycles because these cycles and their components are not demonstrably correlatable on a regional or world-wide scale: no widespread events could have caused them. Furthermore, it is difficult to invoke such events because no present-day counterparts seem to exist. The same type of small-scale cycles ('autocycles' of Ginsburg, in Bosellini & Hardie, 1973) has been attributed by Ginsburg (1971) and Wong & Oldershaw (1980) to progradation of more localized tidal flats during continuous subsidence until the sediment supply is choked off over the entire platform when subtidal areas diminish; a new cycle begins when the sediment-generating subtidal area expands after continued subsidence (see review by Wilkinson, 1982). This model is partially inadequate on the scale of an entire epeiric sea because, as argued earlier, sediment production in subtidal areas would reach a self-regulating equilibrium before these areas became overly reduced: hydrographic forces would resist self-destruction of the shallow sea. Equilibrium would occur even during episodes of reduced relative sea-level rise, and be aided further by overall expansion of the shallow sea by progradation of the shelf margin (Matti & McKee, 1976; Kendall & Schlager, 1981).

Inherent in all these hypotheses is the implication that, for each cycle, the entire platform or sea shoals to sea-level, either all at once or diachronously as a prograding wedge, leading to a prolonged period of regional subaerial exposure. In the model proposed here, the entire platform is never exposed, nor is it ever all submerged: the vertical succession of peritidal cycles reflects instead the responses of individual tidal flat islands to variable local rates of sediment accumulation. Islands accrete and migrate laterally with time, since the rate of carbonate sedimentation is easily able to keep pace with rising sea-level in all circumstances of eustasy and subsidence that would be expected to have operated in epeiric seas (Schlager, 1981). Simple vertical accretion occurs if islands are stable in their position, but the rate of accretion of each island will inherently decrease once the depositional surface has reached the supratidal zone. Lateral progradation takes place until it is prevented when neighbouring subtidal areas are in danger of becoming too reduced for sediment generation and for ambient hydrographic forces, such as tides, to operate. Therefore, linking the envisaged importance of local or regional hydrography with the penchant of carbonate sedimentation to remain near sea-level at a more or less constant production rate and its inferred depositional style as tidal flat islands, an autoregulatory mechanism is invoked to account for peritidal deposition in epeiric and shelf seas: a *peritidal autocycle* forms by accretion of a local sediment wedge until it reaches or slightly exceeds high-tide level and lateral progradation is inhibited, when hydrographic forces will shift the focus of sedimentation to a different but nearby area; another cycle is deposited above the underlying one when the focus of sedimentation shifts back again after continued relative sea-level rise (Fig. 24). This process accounts for the variegated stratigraphic record that is observed in many peritidal sequences.

In the simplest case, we consider that relative sea-level rise was more or less constant in ancient epeiric seas. Fluctuations in the rate of relative sea-level rise probably occurred but would be difficult to detect in peritidal sequences, having been easily accommodated and masked by changes in the rate of sediment generation and any regional changes in hydrographic conditions that were necessary to maintain circulation. Any periods of sea-level fall punctuating overall relative rise would produce widespread, synchronous karst surfaces or horizons of intensive diagenesis. The suggestion of Klein (1971) that palaeotidal ranges can be estimated from thicknesses of the intertidal components of peritidal cycles therefore cannot be applied to carbonate sequences because it does not take into account variable local rates of sediment accumulation and net relative sea-level rise.

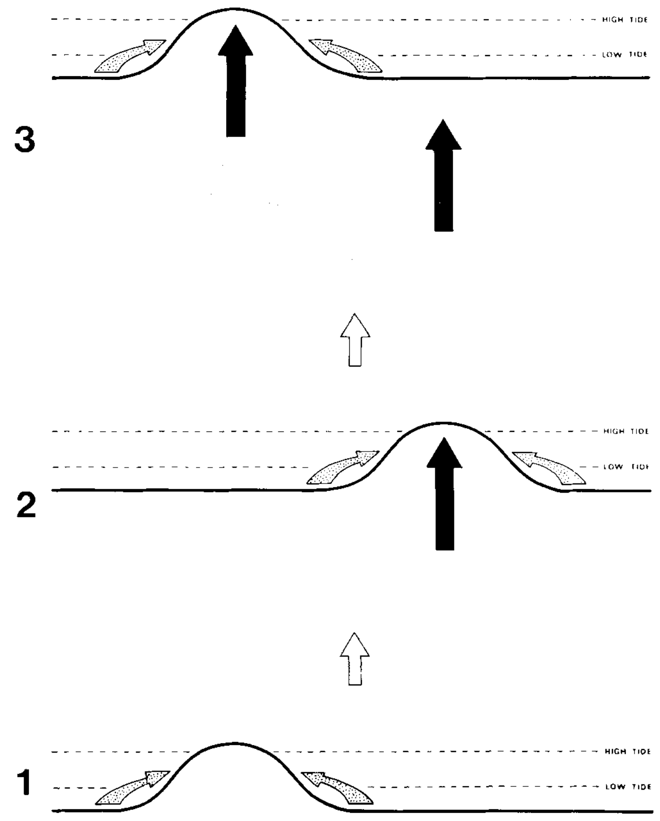

Fig. 24. Model of peritidal cycle formation by laterally shifting the focus of sedimentation and tidal flat accretion. In 1, sediment generated in the subtidal zone is transported (stippled arrows) to form a tidal flat which accretes to sea-level. In 2, the focus of sedimentation is switched by a slight alteration of hydrographic forces to a nearby area and the older tidal flat is covered by subtidal conditions. In 3, the focus of sedimentation switches back to the location of the first tidal flat. The final deposit is a stacking of laterally discontinuous, shallowing-upward peritidal cycles (black arrows). Not to scale.

CONCLUSIONS

The St George Group of western Newfoundland consists of limestones and dolostones of shallow water, peritidal aspect. They were deposited on a wide continental shelf bordering the proto-Atlantic Iapetus Ocean and part of the extensive epeiric sea that covered much of continental North America during early Palaeozoic time. They are lithologically similar to other lower Palaeozoic carbonate rocks deposited in cratonic interiors and thus display all the characteristics ascribed to carbonate deposits of epeiric seas. The vertical stacking of lithologies is, in this case, best characterized by a number of lithotope sequences, rather than by regular cycles. These lithotopes can be shown to represent relatively small tidal flats that accreted vertically and migrated laterally during more or less continuous subsidence. The tidal flats are interpreted to be supratidal islands and intertidal banks in the Early Ordovician epeiric sea. The three formations of the St George reflect geographic and temporal variation of island shape and facies distribution, a general response to changing regional hydrographic conditions rather than major fluctuations in rate of relative sea-level rise.

The island model developed here has no modern analogue but may have broad applications: it envisages many Phanerozoic epeiric seas as dotted by low-relief, tidal flat islands surrounded by open water (Fig. 25). These subtidal areas generated carbonate sediment and facilitated tidal exchange. The island model overcomes the contradictions inherent in fitting geological observations to the earlier, conventional theory of tideless epeiric seas. It also provides a general palaeogeographic framework in which tidal flats accrete as cyclic deposits from varying rates of local sediment input on a gently subsiding seafloor. External forces of eustatic sea-level fluctuation or sporadic subsidence need not be invoked for causing most small-scale carbonate cycles.

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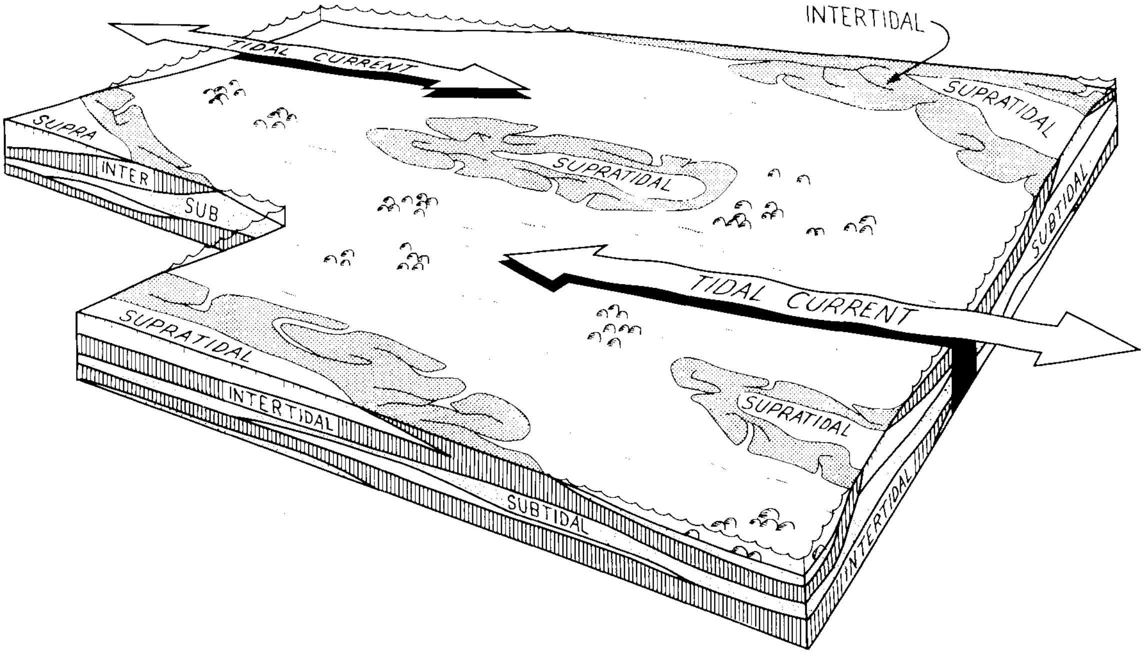

Fig. 25. Hypothetical, three-dimensional reconstruction of a portion of an epeiric sea showing five low-relief islands, oriented parallel to tidal currents, and local patch reef development (here as thrombolite mounds), with a possible stratigraphic record of laterally discontinuous sub-, inter-, and supratidal deposits.

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REFERENCES

AITKEN, J.D. (1967) Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta. *J. sedim. Petrol.* **37**,1163–1178.

AITKEN, J.D. (1978) Revised models for depositional grand cycles, Cambrian of the southern Rocky Mountains, Canada. *Bull. Can. Petrol. Geol.* **26**, 515–542.

ANDERSON, E.J., GOODWIN, P.J. & CAMERON, B. (1978) Punctuated aggradational cycles (PACs) in Middle Ordovician and Lower Devonian sequences. In: *Guidebook 50th Annual Meeting, N.Y. St. geol. Ass.* pp. 204–220.

ANDERSON, E.J., GOODWIN, P.W. & SOBIESKI, T.H. (1984) Episodic accumulation and the origin of formation boundaries in the Helderberg Group of New York State. *Geology*, **12**, 120–123.

BALL, M.M., SHINN, E.A. & STOCKMAN, K.W. (1967) The geologic effects of Hurricane Donna in south Florida. *J. Geol.* **75**, 583–597.

BASAN, P.B. (1973) Aspects of sedimentation and development of a carbonate bank in the Barracuda Keys, south Florida. *J. sedim. Petrol.* **43**, 42–53.

BEALES, F.W. (1958) Ancient sediments of Bahaman type. *Bull. Am. Ass. Petrol. Geol.* **42**, 1845–1880.

BOSELLINI, A. & HARDIE, L.A. (1973) Depositional theme of a marginal marine evaporite. *Sedimentology*, **20**, 5–27.

BRADY, M.J. & ROWELL, A.J. (1976) An Upper Cambrian subtidal blanket carbonate, eastern Great Basin. *Brigham Young Univ. geol. Stud.* **23**, 153–163.

BRAUN, M. & FRIEDMAN, G.M. (1969) Carbonate lithofacies and environments of the Tribes Hill Formation (Lower Ordovician) of the Mohawk Valley, New York. *J. sedim. Petrol.* **39**, 113–135.

BURRETT, C. (1973) Ordovician biogeography and continental drift. *Palaeogeogr. Palaeoclim. Palaeoecol.* **13**, 161–201.

CAROZZI, A.V. & DAVIS, R.A. (1964) Pétrographie et paléoécologie d'une série de dolomies à stromatolithes de l'Ordovicien inférieur de Wisconsin, U.S.A. *Arch. Sci. Genève*, **17**, 47–63.

CLOUD, P.E. (JR) & BARNES, V.E. (1948) The Ellenburger Group of central Texas. *Univ. Texas Publ. no.* 4621, 473 pp.

COOGAN, A.H. (1972) Recent and ancient carbonate cyclic sequences. In: *Cyclic Sedimentation in the Permian Basin*, 2nd ed. (Ed. by J. G. Elam and S. Chuber), pp. 5–16. West Texas Geological Society.

COOK, T.D. & BALLY, A.W. (eds) (1975) *Stratigraphic atlas of North and Central America.* Princeton University Press. 272 pp.

COWIE, J.W. & ADAMS, P.J. (1957) The Cambro–Ordovician geology of east Greenland. *Meddr Grønland*, **153**, 193 pp.

CRAM, J.M. (1979) The influence of continental shelf width on tidal range: paleoceanographic implications. *J. Geol.* **87**, 441–447.

CRIMES, T.P. (1977) Trace fossils of an Eocene deep-sea fan, northern Spain. In: *Trace Fossils 2* (Ed. by T. P. Crimes and J. C. Harper). *Geol. J. Spec. Issue* 9, 71–90.

DAVIES, G.R. (1970) Carbonate bank sedimentation, eastern Shark Bay, Western Australia. In: *Carbonate Sedimentation and environments, Shark Bay, Western Australia. Mem. Am. Ass. Petrol. Geol.* **13**, 85–168.

DAVIS, R.A. (1966) Willow River Dolomite: Ordovician analogue of modern algal stromatolite environments. *J. Geol.* **74**, 908–923.

DEFANT, A. (1961) *Physical Oceanography*, vol. II: New York, Macmillan, 598 pp.

DEMICCO, R.V. (1982) Shelf-lagoon and tidal flat facies of the Upper Cambrian Conococheague Limestone, central Appalachians (abstract). *Abst. Prog. geol. Soc. Am.* **14**, 14.

DEMICCO, R.V. (1983) Wavy and lenticular-bedded carbonate ribbon rocks of the Upper Cambrian Conococheague Limestone, central Appalachians. *J. sedim. Petrol.* **53**, 1121–1132.

DOTT, R.H. (Jr) (1974) Cambrian tropical storm waves in Wisconsin. *Geology*, **2**, 243–246.

DUFF, P.MCD.D., HALLAM, A. & WALTON, E.K. (1967) *Cyclic Sedimentation.* Elsevier, Amsterdam, 280 pp.

EBANKS, W.J. (JR) (1975) Holocene carbonate sedimentation and diagenesis, Ambergris Cay, Belize. In: *Belize Shelf—Carbonate Sediments, Clastic Sediments, and Ecology* (Ed. by K. F. Wantland and W. C. Pusey III). *Am. Ass. Petrol. Geol. Studies Geol., no. 2*, 234–296.

ENOS, P. & PERKINS, R.D. (1979) Evolution of Florida Bay from island stratigraphy. *Bull. geol. Soc. Am.* **90**, 59–83.

FAIRCHILD, I.J. (1980) Sedimentation and origin of a late Precambrian 'dolomite' from Scotland. *J. sedim. Petrol.* **50**, 423–446.

FISCHER, A.G. (1964) The Lofer cyclothems of the Alpine Triassic. In: *Symp. Cyclic Sedimentation* (Ed. by D. F. Merriam). *Bull. geol. Surv. Kansas*, **169**, 107–149.

FISHER, D.W. (1977) Correlation of the Hadrynian, Cambrian and Ordovician rocks in New York State. *N.Y. St. Mus. Sci. Ser. Map Chart Series* **25**, 75 pp.

FOLK, R.L. (1959) Practical petrographic classification of limestones. *Bull. Am. Ass. Petrol. Geol.* **43**, 1–38.

FORTEY, R.A. (1979) Lower Ordovician trilobites from the Catoche Formation (St. George Group), western Newfoundland. *Bull. geol. Surv. Can.* **321**, 61–114.

FORTEY, R.A. & BRUTON, D.L. (1973) Cambrian-Ordovician rocks adjacent to Hinlopenstretet, north Ny Friesland. *Bull. geol. Soc. Am.* **84**, 2227–2242.

GINSBURG, R.N. (1971) Landward movement of carbonate mud: new model for regressive cycles in carbonates (abstract). *Bull. Ass. Petrol. Geol.* **55**, 340.

GOODWIN, P.W. & ANDERSON, E.J. (1980) Punctuated aggradational cycles: a general hypothesis of stratigraphic accumulation (abstract). *Abstr. Prog. geol. Soc. Am.* **12**, 435.

HALLAM, A. (1978) Eustatic cycles in the Jurassic. *Palaeogeogr. Palaeoclim. Palaeoecol.* **23**, 1–32.

HALLAM, A. (1981) *Facies Interpretation and the Stratigraphic Record.* W.H. Freeman, San Francisco, 291 pp.

HALLEY, R.B. (1975) Peritidal lithologies of Cambrian carbonate islands, Carrara Formation, southern Great

Basin. In: *Tidal Deposits* (Ed. by R. N. Ginsburg), pp. 279–288. Springer-Verlag, Berlin.

HARDIE, L.A. (Ed.) (1977) *Sedimentation on the Modern Carbonate Tidal Flats of Northwest Andros Island, Bahamas.* Johns Hopkins University, *Stud. Geol. 22*, 202 pp.

HARRIS, L.D. (1966) Algal stromatolites of the Upper Cambrian Copper Ridge Dolomite in Union and Claiborne Counties, Tennessee. *U.S. geol. Surv. Prof. Pap. 550-C*, 48–53.

HARRIS, L.D. (1973) Dolomitization model for Upper Cambrian and Ordovician carbonate rocks in the eastern United States. *J. Res. U.S. geol. Surv.* **1**, 63–78.

HOFFMAN, P. (1976) Stromatolite morphogenesis in Shark Bay, Western Australia. In: *Stromatolites* (Ed. by M. R. Walter), pp. 261–271. Elsevier, Amsterdam.

IRWIN, M.L. (1965) General theory of epeiric clear water sedimentation. *Bull. Am. Ass. Petrol. Geol.* **49**, 445–459.

JAMES, N.P. (1977a) Facies models 7. Introduction to carbonate facies models. *Geosci. Can.* **4**, 123–125.

JAMES, N.P. (1977b) Facies models 9. Shallowing-upward sequences in carbonates. *Geosci. Can.* **4**, 126–136.

JAMES, N.P. & STEVENS, R.K. (1982) Anatomy and evolution of a lower Paleozoic continental margin, western Newfoundland. *Guidebook, int. Ass. Sedimentol. 11th int. Congr. Sediment.* 75 pp.

JOHNSON, H.D. (1978) Shallow siliciclastic seas. In: *Sedimentary Environments and Facies* (Ed. by H. G. Reading), pp. 207–258. Blackwell Scientific Publications, Oxford.

JONES, B. & DIXON, O.A. (1975) The Leopold Formation: an Upper Silurian intertidal/supratidal carbonate succession on northeastern Somerset Island, Arctic Canada. *Can. J. Earth Sci.* **12**, 395–411.

KENDALL, C.G.ST.C. & SCHLAGER, W. (1981) Carbonates and relative changes in sea level. *Mar. Geol.* **44**, 181–212.

KLEIN, G.DE V (1971) A sedimentary model for determining paleotidal range. *Bull. geol. Soc. Am.* **82**, 2585–2592.

KLEIN, G.DE V. (1977) Tidal circulation model for deposition of clastic sediment in epeiric and mioclinal shelf seas. *Sedim. Geol.* **18**, 1–12.

KLEIN, G.DE V. & RYER, T.A. (1978) Tidal circulation patterns in Precambrian, Paleozoic, and Cretaceous epeiric and mioclinal shelf seas. *Bull. geol. Soc. Am.* **89**, 1050–1058.

KROHN, J. & SÜNDERMANN, J. (1982) Paleotides before the Permian. In: *Tidal Friction and the Earth's Rotation II* (Ed. by P. Brosche and J. Sündermann), pp. 190–209. Springer-Verlag, New York.

LAPORTE, L.F. (1967) Carbonate deposition near mean sea-level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York State. *Bull. Am. Ass. Petrol. Geol.* **51**, 73–101.

LAPORTE, L.F. (1971) Paleozoic carbonate facies of the central Appalachian Shelf. *J. sedim. Petrol.* **41**, 724-740.

LÉVESQUE, R.J. (1977) *Stratigraphy and sedimentology of Middle Cambrian to Lower Ordovician shallow water carbonate rocks, western Newfoundland.* Unpublished MSc thesis, Memorial University of Newfoundland. 276 pp.

LOCHMAN-BALK, C. (1971) The Cambrian of the craton of the United States. In: *The Cambrian of the New World* (Ed. by C.H. Holland), pp. 79–168. Wiley Interscience, New York.

MARKELLO, J.R. & READ, J.F. (1982) Upper Cambrian intrashelf basin, Nolichucky Formation, southwest Virginia Appalachians. *Bull. Am. Ass. Petrol. Geol.* **66**, 860–878.

MATTER, A. (1967) Tidal flat deposits in the Ordovician of western Maryland. *J. sedim. Petrol.* **37**, 601–609.

MATTI, J.C. & MCKEE, E.D. (1976) Stable eustacy, regional subsidence, and a carbonate factory: self-generating model for onlap-offlap cycles in shallow-water carbonate sequences (abstract). *Abstr. Prog. geol. Soc. Am.* **8**, 1000–1001.

MAZZULLO, S.J. (1978) Early Ordovician tidal flat sedimentation, western margin of proto-Atlantic Ocean. *J. sedim. Petrol.* **48**, 49–62.

MAZZULLO, S.J. & FRIEDMAN, G.M. (1975) Conceptual model of tidally influenced deposition on margins of epeiric seas: Lower Ordovician (Canadian) of eastern New York and southwestern Vermont. *Bull. Am. Ass. Petrol. Geol.* **59**, 2123–2141.

MAZZULLO, S.J. & FRIEDMAN, G.M. (1977) Competitive algal colonization of peritidal flats in a schizohaline environment: the Lower Ordovician of New York. *J. sedim. Petrol.* **47**, 398–410.

MAZZULLO, S.J., AGOSTINO, P., SEITZ, J.N. & FISHER, D.W. (1978) Stratigraphy and depositional environments of the Upper Cambrian-Lower Ordovician sequence, Saratoga Springs, New York. *J. sedim. Petrol.* **48**, 99–116.

MOSSOP, G.D. (1979) The evaporites of the Ordovician Baumann Fiord Formation, Ellesmere Island, Arctic Canada. *Bull. geol. Surv. Can.* **298**, 52 pp.

NOWLAN, G.S. (1981) Stratigraphy and conodont faunas of the Lower and Middle Ordovician Romaine and Mingan Formations, Mingan Islands, Quebec (abstract). *Mar. Sedim. Atlantic Geol.* **17**, 67.

PALMER, A.R. & HALLEY, R.B. (1979) Physical stratigraphy and trilobite biostratigraphy of the Carrara Formation (Lower and Middle Cambrian) in the southern Great Basin. *Prof. Pap. U.S. geol. Surv. 1047*, 131 pp.

PRATT, B.R. (1979) *The St. George Group (Lower Ordovician), western Newfoundland: sedimentology, diagenesis and cryptalgal structures.* Unpublished MSc thesis, Memorial University of Newfoundland.

PRATT, B.R. (1982) Limestone response to stress: pressure solution and dolomitization—discussion and examples of compaction in carbonate sediments. *J. sedim. Petrol.* **52**, 323–328.

PRATT, B.R. & JAMES, N.P. (1982) Cryptalgal-metazoan bioherms of Early Ordovician age in the St. George Group, western Newfoundland. *Sedimentology*, **29**, 543–569.

DE RAAF, J.F.M. & BOERSMA, J.R. (1971) Tidal deposits and their sedimentary structures. *Geologie Mijnb.* **50**, 479–504.

DE RAAF, J.F.M., BOERSMA, J.R. & VAN GELDER, A. (1977) Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland. *Sedimentology*, **24**, 451–483.

RAASCH, G.O. (1952) Oneota Formation, Stoddard Quadrangle, Wisconsin. *Trans. Ill. Acad. Sci.* **45**, 85–95.

RADKE, B.M. (1980) Epeiric carbonate sedimentation of the Ninmaroo Formation (Upper Cambrian-Lower Ordovician), Georgina Basin. *BMR J. aust. Geol. Geophys.* **5**, 183–200.

REINECK, H.E. & SINGH, I.B. (1980) *Depositional Sedimentary Environments*, 2nd ed. Springer-Verlag, Berlin. 549 pp.

REINHARDT, J. (1974) Stratigraphy, sedimentology and

Cambro-Ordovician paleogeography of the Frederick Valley, Maryland. *My. geol. Surv. Rep. Invest.* **23**, 74 pp.

ROSS, R.J. (JR) (1951) Stratigraphy of the Garden City Formation in northeastern Utah, and its trilobite faunas. *Bull. Peabody Mus. nat. His. Yale Univ.* **6**, 161 pp.

ROSS, R.J. (JR) (1975) Early Paleozoic trilobites, sedimentary facies, lithospheric plates, and ocean currents. In: *Evolution and morphology of the Trilobita, Trilobitoidea and Merestomata* (Ed. by A. Martinsson). *Fossils Strata*, **4**, 307–329.

ROSS, R.J. (JR) (1976) Ordovician sedimentation in the western United States. In: *The Ordovician System* (Ed. by M.G. Bassett). pp. 73–105. University of Wales Press and National Museum of Wales.

ROSS, R.J. (JR) & NAESER, C.W. (1984) The Ordovician time scale—new refinements. In: *Aspects of the Ordovician System.* (Ed. by D. L. Bruton). *Contr. palaent. Univ. Oslo, No. 295*, 5–10.

RUBIN, D.M. & FRIEDMAN, G.M. (1977) Intermittently emergent shelf carbonates: an example from the Cambro-Ordovician of eastern New York State. *Sedim. Geol.* **19**, 81–106.

SANDO, W.J. (1957) Beekmantown Group (Lower Ordovician) of Maryland. *Mem. geol. Soc. Am.* **68**, 161 pp.

SANFORD, B.V. (1977) Ordovician rocks of Melville Peninsula, southeastern District of Franklin. *Bull. geol. Surv. Can.* **269**, 7–21.

SARIN, D.D. (1962) Cyclic sedimentation of primary dolomite and limestone. *J. sedim. Petrol.* **32**, 451–471.

SCHLAGER, W. (1981) The paradox of drowned reefs and carbonate platforms. *Bull. geol. Soc. Am.* **92**, 197–211.

SCHOPF, T.J.M. (1980) *Paleoceanography.* Harvard University Press, Cambridge. 341 pp.

SCHWARZ, H.-U. (1975) Sedimentary structures and facies analysis of shallow marine carbonates. *Contrib. Sediment.* **3**, 100 pp.

SCOTESE, C.R., BAMBACH, R.K., BARTON, C., VAN DER VOO, R. & ZIEGLER, A.M. (1979) Paleozoic base maps. *J. Geol.* **87**, 217–277.

SHAW, A.B. (1964) *Time in Stratigraphy.* McGraw-Hill, New York, 365 pp.

SLOSS, L.L. (1963) Sequences in the cratonic interior of North America. *Bull. geol. Soc. Am.* **74**, 93–114.

STEVENS, R.K. & JAMES, N.P. (1976) Large sponge-like reef mounds from the Lower Ordovician of west Newfoundland (abstract). *Abstr. Prog. geol. Soc. Am.* **8**, 1122.

STODDART, D.R. (1962) Catastrophic storm effects on the British Honduras reefs and cays. *Nature*, **196**, 512–515.

STRICKER, G.D. & CAROZZI, A.V. (1973) Carbonate microfacies of the Pogonip Group (Lower Ordovician), Arrow Canyon Range, Clark County, Nevada, U.S.A. *Bull. Centre Rech. Pau-SNPA*, **7**, 499–541.

SWETT, K. & SMIT, D.E. (1972) Paleogeography and depositional environments of the Cambro-Ordovician shallow-marine facies of the North Atlantic. *Bull. geol. Soc. Am.* **83**, 3223–3248.

TUCKER, M.E. (1977) Stromatolite biostromes and associated facies in the late Precambrian Porsanger Dolomite Formation of Finnmark, Arctic Norway. *Palaeogeogr. Palaeoclim. Palaeoecol.* **21**, 55–83.

TUCKER, M.E. (1985) Shallow-marine carbonate facies and facies models. In: *Sedimentology. Recent Developments and Applied Aspects.* (Ed. by P. J. Brenchley and B. P. J. Williams), pp. 147–169. *Spec. Publ. geol. Soc. London, 18.* Blackwell Scientific Publications, Oxford.

TWENHOFEL, W.H. (1938) Geology and paleontology of the Mingan Islands, Quebec. *Spec. Pap. geol. Soc. Am.* **11**, 132 pp.

VAIL, P.R., MITCHUM, R.M. (JR) & THOMPSON, S. (III) (1977) Seismic stratigraphy and global changes of sea level, part 4. Global cycles of relative changes of sea level. In: *Seismic Stratigraphy–Application to Hydrocarbon Exploration.* (Ed. by C.E. Payton), *Mem. Am. Ass. Petrol. Geol.* **26**, 83–97.

WALKER, K.R. (1973) Stratigraphy and environmental sedimentology of Middle Ordovician Black River Group in the type area—New York State. *Bull. N. Y. St. Mus. Sci. Serv.* **419**, 43 pp.

WILKINSON, B.H. (1982) Cyclic cratonic carbonates and Phanerozoic calcite seas. *J. geol. Educ.* **30**, 189–203.

WILLIAMS, H. (1979) Appalachian orogen in Canada. *Can. J. Earth Sci.* **16**, 792–807.

WILLIAMS, H. & STEVENS, R.K. (1974) The ancient continental margin of eastern North America. In: *The Geology of Continental Margins* (Ed. by C. A. Burk and C. L. Drake), pp. 781–796. Springer-Verlag, Berlin.

WONG, P.K. & OLDERSHAW, A.E. (1980) Causes of cyclicity in reef interior sediments, Kaybob reef, Alberta. *Bull. Can. Petrol. Geol.* **28**, 411–424.

WRIGHT, V.P. (1984) Peritidal carbonate facies: a review. *Geol. J.* **19**, 309–325.

YOUNG, H.R. (1979) Evidence of former evaporites in the Cambro-Ordovician Durness Group, northwest Scotland. *Sedim. Geol.* **22**, 287–303.

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