DEEPENING-UPWARD SUBTIDAL CYCLES, MURRAY BASIN, SOUTH AUSTRALIA

JEFF J. LUKASIK* AND NOEL P. JAMES
Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada
e-mail: jlukasik@petro-canada.ca

ABSTRACT: Decimeter-scale, deepening-upward cycles are the basic depositional motif of Oligocene–Miocene Murray Supergroup limestones in the Murray Basin, southeastern Australia. Cycles formed in this large intracratonic basin on a centripetal, temperate-water epeiric ramp. They reflect generation by trophic resource-influenced carbonate production under mostly transgressive conditions. Listed from the base up, each cycle is ideally composed of five parts: Part A—biotically depauperate carbonates reflecting relatively shallow-water, restricted, variably stressed highly mesotrophic environments; Part B—increasingly biotically diverse limestones recording progressively more physical energy and less mesotrophic conditions upward; OM_1—a conspicuous hardground to firmground surface formed during late transgression to stillstand during which wave sweeping and reworking contributed to omission and lithification; Part C—relatively biotically diverse, epifauna-dominant sediments that were highly abraded during periods of condensed sedimentation under marginally oligotrophic conditions; and OM_2 (cycle boundary)—a rarely conspicuous surface representing arrested sedimentation and variable cementation as trophic resources increased and conditions for carbonate production deteriorated. Ten cycle types are grouped into four major styles; clay cycles, mollusc cycles, echinoid cycles, and bryozoan cycles. These are interpreted to form a lithological continuum from inner restricted terrigenous locales to outer, open marine, bryozoan-colonized environments.

Deepening-upward cycles were profoundly sensitive to autogenic factors such as nutrient influx, terrigenous content and turbidity, hydrodynamic energy, water temperature, salinity, and water depth manifested in this intracratonic setting. Although these cycles share a similar sedimentological motif and hydrodynamic energy-based cycle-capping process with open shelf, epicratonic, shallowing-upward subtidal cycles of Tertiary age, they formed in a very different way reflecting the distinctive intracratonic environment in which they formed. Murray Basin cycles preserve a record of relative sea-level rise whereas open shelf cycles accumulated mostly during relative sea-level fall.

INTRODUCTION

One of the fundamental elements of carbonate sedimentology and stratigraphy is the meter-scale, shallowing-upward cycle (James 1984; Tucker and Wright 1990; Pratt et al. 1992; Goldhammer et al. 1993). This building block of many platforms and ramps is an integral part of the philosophical approach to understanding carbonate sedimentology. Although most meter-scale carbonate cycles are demonstrably shallowing-upward with peritidal or subaerial exposure caps (Wilson 1975; Tucker and Wright 1990; Walker and James 1992; Read 1998), deepening-upward, exposure-capped cycles can also occur (Fischer 1964; Haas 1991; Soreghan and Dickinson 1994; Lehrmann and Goldstein 1999) but are relatively uncommon. Outside of the tropical to subtropical peritidal realm, open marine, wholly subtidal cyclicity is less well documented and arguably not so easily interpreted because of a lack of specific paleoenvironmental sedimentary features like mudcracks and ooid grainstones. As summarized by Osleger (1991), ''shallowing-upward'' is a typical, expected, and explainable motif in predominantly subtidal rocks. However, mid-Cenozoic carbonate subtidal cycles generated within the largely shallow, low-energy dominated intracratonic Murray Basin of southeastern Australia possess attributes logically interpreted as deepening-upward, thus suggesting this is not the rule. The purpose of this report is to document these deepening-upward, temperate-water cycles, interpret their origin, and indicate why such contrary units might form.

GEOLOGICAL SETTING

Rocks of this study constitute the thin (< 150 m), generally flat-lying Oligo–Miocene Murray Supergroup within the Murray Basin, South Australia (Lukasik and James 1998; Lukasik 2000). The Murray Basin is one of many similar Cenozoic basins situated along the southern Australian margin (Fig. 1). It is a large (450 000 km²), shallow, intracratonic depression formed during Cretaceous rifting of Australia from Antarctica (Veevers 1991) filled with carbonate and lignitic, siliciclastic, fluvio-deltaic sediments of Eocene to Pliocene age (Brown and Stephenson 1991). Shallow, low-energy carbonates of late Oligocene to middle Miocene age were deposited in the western portion of the basin (the area of this study) and separated somewhat from the open ocean by the Padthaway Ridge (Fig. 1), an episodically emergent granitic archipelago. Sediments accumulated on a centripetal epeiric ramp behind this barrier within an extensive, shallow, temperate-water inland sea approximately 200–500 kilometers from the shelf edge. Facies analysis and regional basinal lithological trends (Radke 1987; Brown and Stephenson 1991; Lukasik and James 1998; Lukasik et al. 2000) show that this broad epeiric ramp deepened from shallow inboard, low-energy, restricted marine facies and tidal flats to deeper offshore, open marine, wave influenced facies (Fig. 2). High-energy sedimentation was limited to an offshore zone of winnowing by waves, shallow paleotopographic highs across the Padthaway Ridge, and nearshore environments affected by storm surge (Lukasik et al. 2000).

Exposure is superb: strata crop out as cliffs along the River Murray in South Australia nearly continuously for more than 175 kilometers (Fig. 1). Most rocks are densely fossiliferous and heavily bioturbated. Lateral and vertical facies changes are often subtle and best defined on variations in gross lithology and macrofaunal dominance. Preservation of uncompressed, thin-walled delicate biota and spherical to circular trace fossils verifies minimal compaction.

This study is focused on rocks representing the subtidal realm, generated offshore from a wide belt of episodically emergent siliciclastic tidal flats (Radke 1987; Brown and Stephenson 1991). Regressive incursions of clay and marl sandwiched between packages of offshore carbonates argues that although not all facies are present at any one time, there was always a paleogeographic continuum between siliciclastic and carbonate environments. Biotic and lithological trends suggest that trophic resource levels here increased consistently towards the shoreline (Fig. 2) as reflected by successively more restricted marine, less fossiliferous, and increasingly clay-rich facies inboard (Brown and Stephenson 1991; Lukasik et al. 2000). Details of the stratigraphy, sedimentology, and environmental setting are further outlined in Lukasik and James (1998) and Lukasik et al. (2000).

METHODS

Placed in a chronostratigraphic framework using foraminiferal event datums (also see Lukasik et al. 2000), rock units were correlated between many closely spaced cliff sections, each of which was measured in detail

* Present address: Petro-Canada Oil and Gas, P.O. Box 2844, Calgary, Alberta T2P 3E3, Canada.

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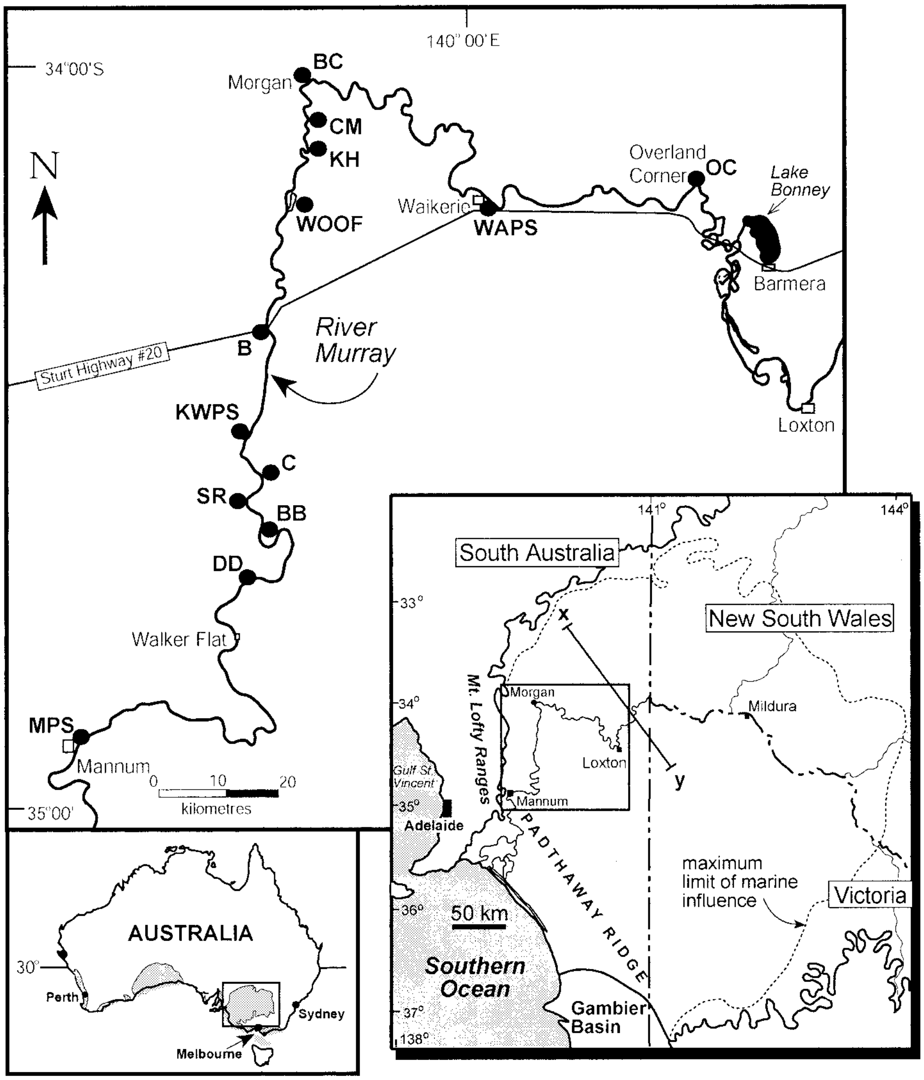


FIG. 1.—Location map of the Murray Basin and the primary section localities along the River Murray in South Australia. **MPS,** Mannum Pumping Station; **DD,** Devon Downs; **BB,** Big Bend Conservation Area; **SR,** Swan Reach; **C,** Cudgee; **KWPS,** Kura Wira Pumping Station; **B,** Blanchetown bridge; **WOOF,** Wood's Flat; **KH,** Kanyaka Houseboats; **CM,** Cadell Formation type section; **BC,** Bryant's Creek Conservation Area; **WAPS,** Waikerie Pumping Station; **OC,** Overland Corner. Line x–y is the approximate paleogeographic location of the cross section in Figure 2.

(Fig. 3). Visual tracing and walking of units, where possible, confirmed stratigraphic correlation. Because of the highly fossiliferous nature of these strata and their dissimilar lithification and faunal preservation patterns, the paleontology, taphonomy, and ichnology (ichnofacies, ichnofabrics, and tiering) were determined qualitatively in the field (see Lukasik et al. 2000 for full details). Ichnological study relied heavily on general ichnofabric pattern analysis (cf. Bromley and Ekdale 1986), ichnofacies, and their dominant taxa (cf. Bromley and Asgaard 1991) as they pertained to sediment induration, overprinting, and omission surface recognition. Quantitative ichnotaxa abundance data are estimated as a percentage of the total rock surface.

Analysis of trophic resources and determination of relative water depth are fundamental components of the paleoenvironmental and depositional interpretations of these strata. Trophic resource analysis relied on the integration of biotic and sedimentological attributes already established for basin-scale facies distribution through time (Lukasik et al. 2000). Actualistic studies have shown that organism diversity and abundance can be related to trophic resource levels at the time of deposition. Changes in the trophic resource continuum from nutrient-poor, relatively oligotrophic conditions to nutrient-rich, relatively eutrophic states affect the turbidity of the water column and the character of the substrate (e.g., Hallock 1987). Such changes in the physiochemical environment have a profound effect on the

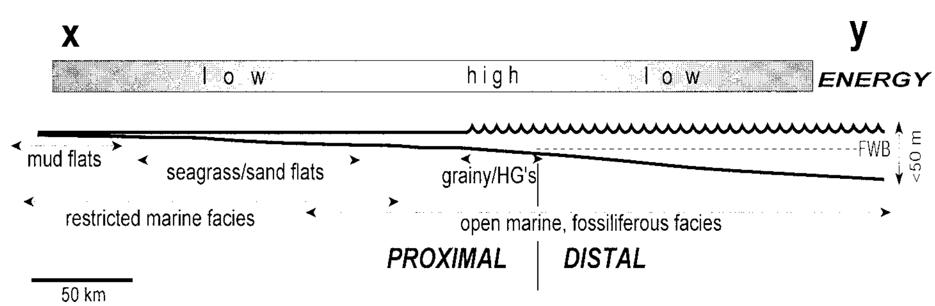


FIG. 2.—The Murray Basin epeiric ramp model (after Lukasik et al. 2000). A broad inboard proximal ramp of predominantly low-energy open to restricted marine facies are separated from low-energy (below FWB) open marine distal facies by a narrow zone of high-energy, wave-reworked, open marine facies. Storm processes affect the seafloor across the ramp.

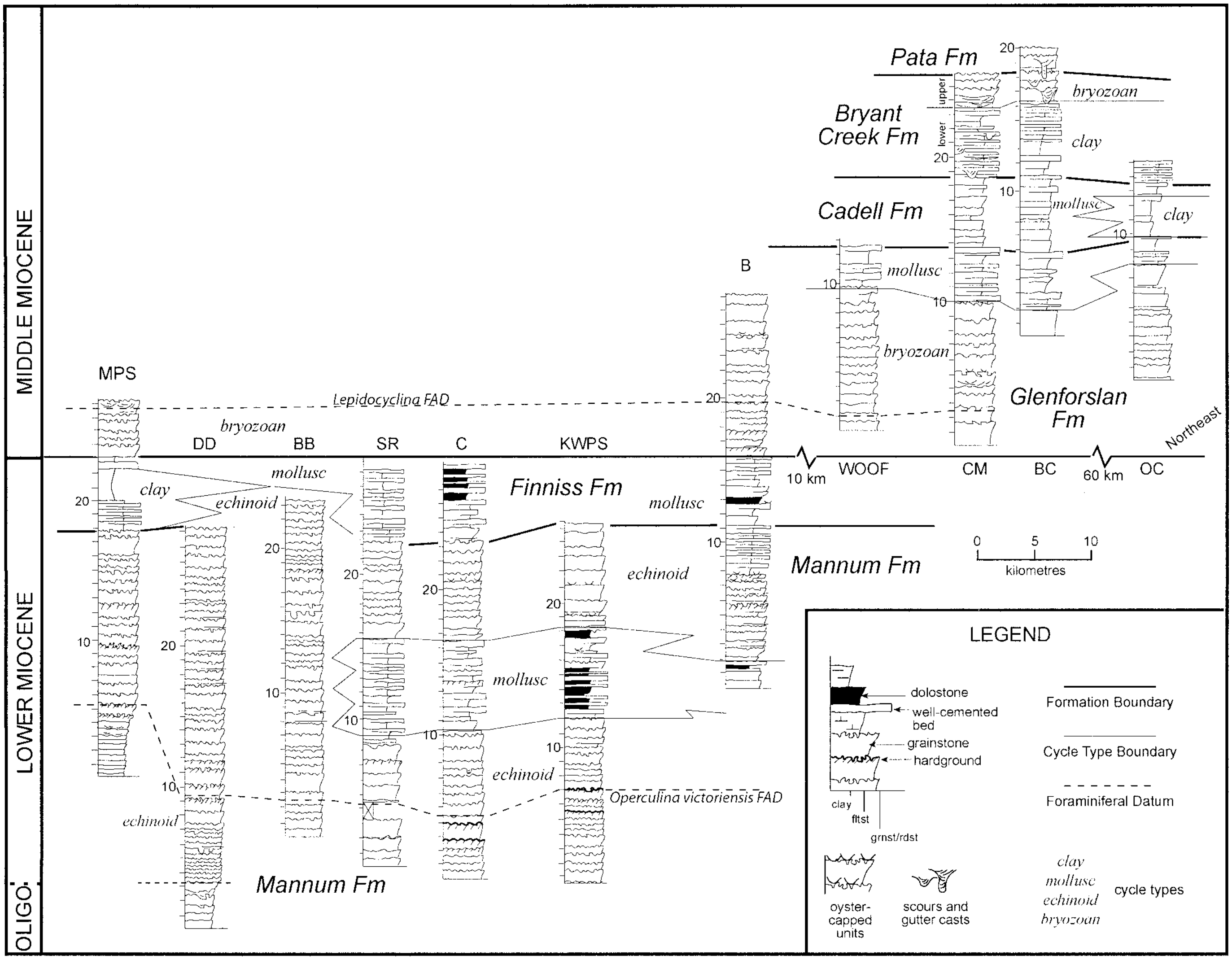


FIG. 3.—Stratigraphic correlation, lithological character, and distribution of basic cycle types of the primary sections located in Figure 1. Profiles reflect weathering patterns influenced by original rock texture. Foraminiferal events help to constrain the chronostratigraphic correlation. The contact between the Finniss and Glenforslan formations (lowest middle Miocene) forms the horizontal datum. Vertical scale is in meters.

diversity, dominance, type, and trophic structure of the macrofaunal assemblages and on microfaunal composition (e.g., Valentine 1971; Stanton and Dodd 1976; Hallock and Schlager 1986; Hallock 1988; Brasier 1995a, 1995b). Interpretation of the range of trophic resource levels for each cycle type in the Murray Basin relied upon comparison of their composite facies attributes (Fig. 4).

Relative water depths were determined using presence/absence and abundance criteria of extant fauna with known depth constraints (including photosymbiont-bearing foraminifers such as *Marginopora*, *Lepidocyclina*, *Operculina*, and *Amphistegina*, pinnid bivalves, and seagrass-dwelling organisms) integrated into their composite facies spectrum. For details, see Lukasik et al. (2000).

MURRAY BASIN SUBTIDAL CYCLES

General Sedimentological Attributes

The sub-meter-scale subtidal cycle forms the fundamental building block of these strata. Each cycle has a predictable upward facies succession containing consistently similar patterns of relative lithologic, biotic, ichnologic, and taphonomic change (Fig. 5). Such commonality indicates the presence of a basic five-part, idealized subtidal cycle motif applicable to all occurring within these strata. The general interpretation of this motif is outlined below, followed by details of the different depositional cycle types that support it.

Part A.—Where preserved, this faunally poor, least bioturbated and locally laminated basal part of the cycle is a barren to molluscan clay or clay-rich horizon. On the basis of comparison with similar facies at a basinal scale, this interval represents relatively restricted marine deposition within shallowest environments that contain the highest trophic resource levels (Lukasik et al. 2000). The sedimentary record at this level in the cycle can be partially to completely obliterated by downward bioturbation associated with deposition of overlying sediment. In such cases, part A is merged with the poorly defined omission surface (OM_2) capping the underlying cycle (Fig. 5).

Part B.—Part B is interpreted to represent deepening-upward sedimentation under progressively decreasing trophic resources. Forming the bulk of the cycle, sediments of Part B are mostly bioturbated and locally coarsen upward, coinciding with a corresponding increase in faunal diversity and abundance. Multiple overprinted softground (*Cruziana*) and firmground (*Glossifungites*) ichnofacies suites (Bromley and Asgaard 1991; Goldring

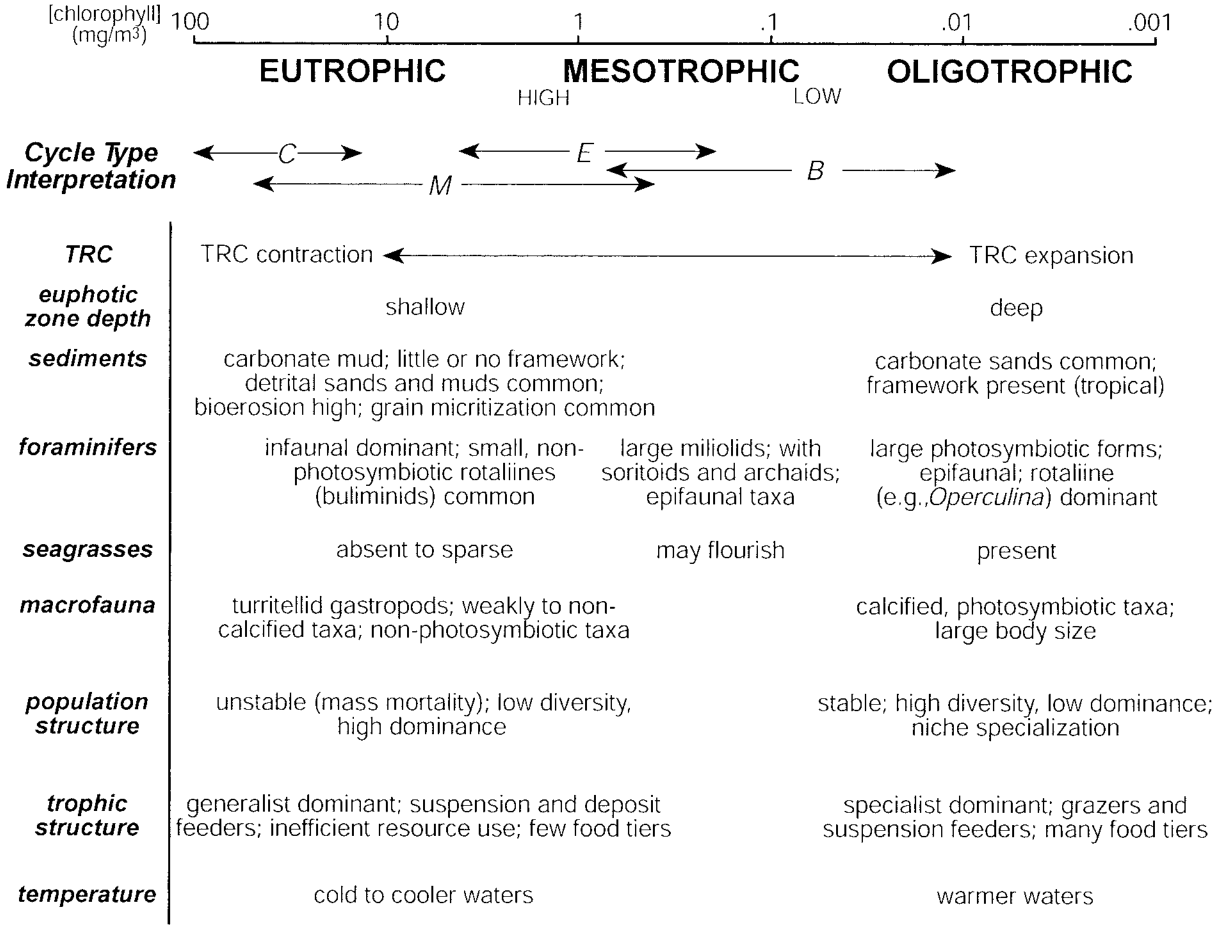


FIG. 4.—Faunal and sedimentological attributes of the trophic resource continuum (TRC; after Lukasik et al. 2000, compiled from Valentine 1971; Stanton and Dodd 1976; Hallock and Schlager 1986; Hallock 1987, 1988; Allmon 1988, 1992; Shepherd et al. 1989; Brasier 1995a, 1995b). Ranges of facies within different cycle types are plotted to approximate interpreted trophic resources available during their deposition. The mesotrophic interval is subdivided into high and low, reflecting the gradational continuum between the TRC end members. C = clay cycles, M = mollusc cycles, E = echinoid cycles, B = bryozoan cycles, TRC = trophic resource continuum.

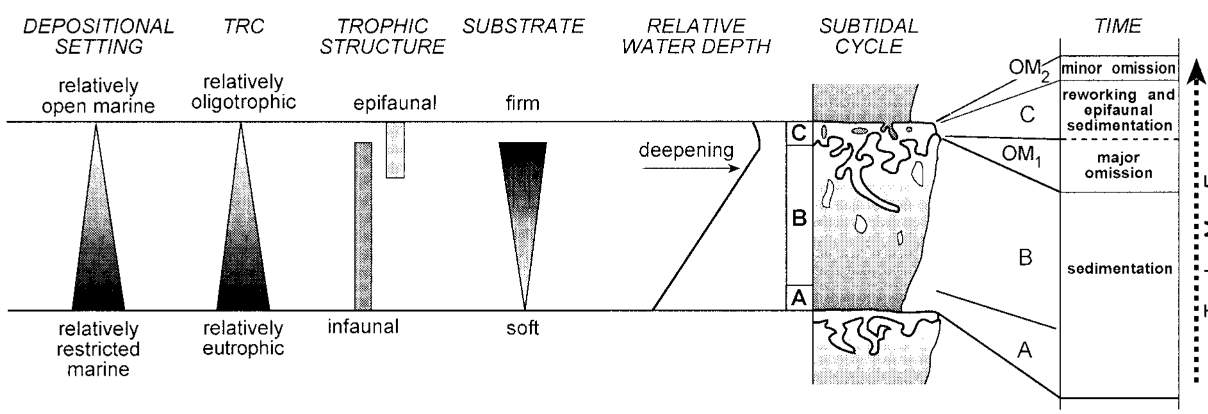
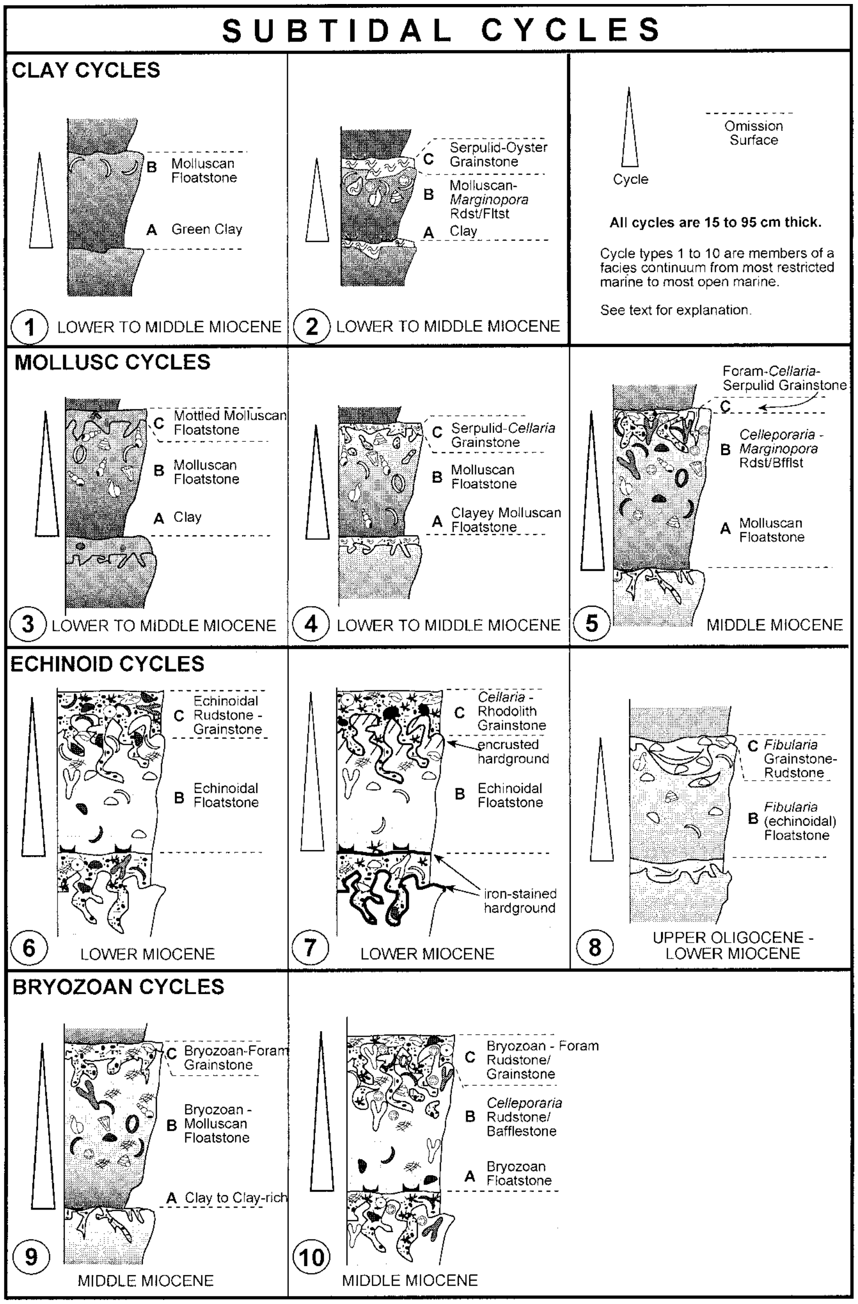


FIG. 5.—The idealized, sub-meter-scale, subtidal cycle from the Murray Basin. Separated into five parts, facies within the cycle range from those of relatively eutrophic, restricted marine settings (A), upward to facies of progressively more oligotrophic, open marine environments (B). Part B is capped by an indurated omission surface (OM_1) that divides the predominantly infaunal biotic assemblages of Parts A and B from the epifaunal dominant assemblages of Part C. Part C is the most open marine part of the cycle. It is typically relatively thin, and composed of reworked sediments with or without physical scouring and reworking features. The cycle is capped by a sedimentologically minor omission surface (OM_2). The cycle is interpreted to represent deepening-upward sedimentation from Parts A to B, followed by a relatively thin record of sea-level stillstand expressed by the omission surfaces and relatively condensed sedimentation within Part C.



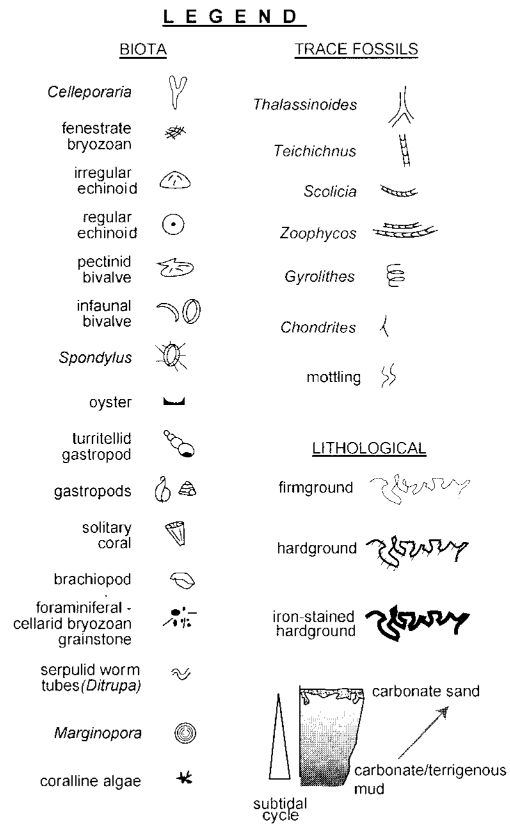


FIG. 6.—**A)** Ten subtidal cycle types separated into four major styles based on their facies composition. Cycle types one to ten (clay to bryozoan) form a gradational facies continuum from restricted to open marine with a corresponding expansion of the trophic resource continuum from eutrophy to low mesotrophy. All cycles range in thickness from 15 to 95 cm. **B)** Legend of symbols used for all figures.

1995), different types and crosscutting relationships of burrow fill, and evidence for episodic physical reworking indicate a complex accumulation history.

OM$_1$.—Induration increases upward, terminating in a conspicuous firmground or a hardground omission surface, OM$_1$ (Fig. 5). This hiatus represents a period of low net sedimentation likely associated with but not confined to increased wave and storm energy in a widening sea.

Part C.—A thin (1–20 cm thick) relatively grainy unit overlies the convoluted OM$_1$ omission surface. This grainstone to rudstone is interpreted to represent sedimentation in the deepest, most open marine environments. Winnowed biota from Part B, other epifaunal skeletons, intraclasts, crustose coralline algae, relatively high particle abrasion, fragmentation and/or encrustation rates, and locally prevalent physical sedimentary and scouring structures together imply condensed deposition under conditions of relatively high energy.

OM$_2$.—A second, more subdued omission surface forms the upper cycle boundary (Fig. 5) and seems to be associated with relative sea-level stillstand from maximum transgression to early regression. This surface is expressed as an iron-stained and/or oyster-encrusted weakly convoluted hardground, or as a sharp flat surface in contact with Part A. Where best preserved, this contact separates facies of most disparate nature (e.g., relatively open marine carbonate sands of Part C from overlying relatively restricted marine clays interpreted as Part A of the overlying cycle).

Ten different cycle types with this general five-part motif can be recognized (Fig. 6; Table 1), each ranging in thickness from 15 to 95 cm. They fall naturally into four groups; clay cycles, mollusc cycles, echinoid cycles, and bryozoan cycles (see Fig. 3 for their stratigraphic distribution). The paleogeographic distribution of cycle types across the epeiric ramp reflects a gradational nearshore (clay cycles) to offshore (echinoid and bryozoan cycles) expansion of the trophic resource continuum (TRC) in

TABLE 1.—*Biotic, taphonomic, and ichnologic attributes of subtidal cycles from the Murray Basin.*

Cycle Type	Scale (cm)	Dominant Biota	Taphonomy	Bioturbation	Major Omission Surface	Interpretation
		Clay Cycles				
1	25–90	rare infaunal bivalves, turritellid gastropods and bryozoans; pyrite tubules present	excellent faunal preservation; shell disarticulation common	tiered; *Cruziana* into *Chondrites*, overprinted by *Glossifungites*	weakly convoluted firmground	shallow restricted marine, nearshore; dysoxic to oxic condition fluctuation; eutrophic to highly mesotrophic
2	10–30	bivalves (taxodont), gastropods, *Marginopora, Ditrupa*, pectinids, oysters, schizasterid echinoids, bryozoans (*Idmidronea*)	articulated oysters in clay; fragmented biota in grainstone; shell disarticulation prominent; encrustaton low	*Cruziana* overprinted by *Glossifungites* on a 20–50 cm scale; rudstone to grainstone scour fill commonly with *Skolithos*-type ichnofacies	weakly convoluted firmground, commonly scoured 5–40 cm depth	shallow, highly mesotrophic, nearshore restricted marine to seagrass setting; storm surge influenced
		Mollusc Cycles				
3	40–90	infaunal bivalves, pinnid, turritellid, and volutid gastropods, solitary corals, scaphopods, oysters, miliolid foraminifers with *Marginopora*	excellent preservation; bivalves commonly articulated, *Atrina* and *Panopea* in life position; abrasion minimal	pervasively mottled, overprinted by *Glossifungites* suite with clay-filled burrow networks; laminated clays present at base	weakly to moderately convoluted firmground; rare, shallow scours	shallow, low-energy, eutrophic to highly mesotrophic conditions; seagrasses
4	30–60	as above; plus grainstones with cellarid bryozoans, *Ditrupa, Fibularia*, oysters, pectinids, and brachiopods	articulation and disarticulation in floatstone; slight abrasion, encrustation and fragmentation in locally cross-stratified grainstones	slightly mottled, based into pervasively mottled floatstone overprinted by *Glossifungites*	weakly convoluted firmground overlain by thin (1–4 cm) grainstone	Shallow marine, highly mesotrophic to mesotrophic conditions
5	30–80	infaunal bivalves, gastropods, corals with celleporid and fenestrate bryozoans, *Spondylus*, irregular echinoids, oysters, pectinids, and *Marginopora*; *Operculina*, cellarids, serpulids, brachiopods, and pectinids in grainstone	shell disarticulation; intact *Spondylus* common; minimal abrasion and fragmentation except in grainstones; encrustation high in grainstones; *Celleporaria* often encrusted and bored	slightly to pervasively mottled, overprinted by *Glossifungites* suite; grainstones weakly cross-stratified	moderately convoluted firmground	Shallow, mesotrophic conditions from seagrass to bryozoan meadow
		Echinoid Cycles				
6	25–90	irregular echinoids (*Lovenia, Monostychia, Fibularia, Eupatagus*), fenestrate and celleporid bryozoans, infaunal bivalves, turritellid and cassid gastropods, solitary corals, brachiopods, serupulid worm tubes, oysters, pectinids; with *Operculina* and *Amphistegina* foraminifers	disarticulation and abrasion common to prevalent; fragmentation locally common; encrustation generally low	overprinted *Cruziana* and *Glossifungites* suites on a 50–60 cm scale; multiple burrow and fill events mottled base	moderately to highly convoluted firmground to hardground	shallow, mesotrophic conditions; offshore open marine; sparsely covered open sand flat
7	25–90	as in 6, with additional crustose coralline algae and larger amounts of cellarid bryozoans, serpulid worm tubes (*Ditrupa*), and *Operculina*/*Amphistegina* foraminifers	disarticulation, fragmentation, abrasion, and encrustation very high in rudstone to grainstone; hardgrounds rarely to totally encrusted by corallines, bryozoans, serpulids, and/or oysters	overprinted *Cruziana* and *Glossifungites* suites on a 50–60 cm scale; omission surfaces shallowly bored	highly convoluted hardground; locally iron-stained, bored and encrusted, overlain by intraclastic rudstone to grainstone	offshore, open marine setting within the zone of wave winnowing; iron-stained hardgrounds during periods of high trophic resources
8	40–70	irregular echinoids (*Fibularia, Lovenia*), pectinids, serpulids, bryozoans, solitary corals, infaunal bivalves, volutid gastropods, regular echinoids, brachiopods	disarticulation common; abrasion and encrustation low; fragmentation moderate to high in rudstones	*Cruziana* overprinted with *Glossifungites*; multiple events; scour fill rudstones laminated at base with *Skolithos* Ichnofacies	weakly to moderately convoluted firmground scoured to depths up to 40 cm	highly mesotrophic conditions; fluctuating oxygen levels associated with changes in energy; cool waters
		Bryozoan Cycles				
9	50–90	bryozoans (cellarid, fenestrate, celleporid), irregular and regular echinoids, brachiopods, pectinid and infaunal bivalves, *Spondylus*, gastropods, *Operculina* and *Amphistegina* foraminifers	common; abrasion minimal to moderate (grainstones); fragmentation minimal	grading into *Cruziana* suite overprinted by *Glossifungites*; cross-stratified grainstone	moderately convoluted firmground overlain by thin grainstone	mesotrophic, open marine conditions; fluctuating low and high energy from seagrass to bryozoan meadows offshore
10	30–70	*Celleporaria*, bryozoans (as above), irregular and regular echinoids, pectinids, oysters, infaunal bivalves and gastropods, turritellids, crustose coralline algae, brachiopods, solitary corals, with *Operculina, Amphistegina, Marginopora* foraminifers	disarticulation common; abrasion minimal; fragmentation minimal; encrustation very high in rudstone and grainstone	overprinted *Cruziana* and *Glossifungites* suites on a 50 cm scale; multiple burrow and fill events	moderately convoluted firmground; rarely oyster encrusted	shallow, low mesotrophic conditions; open marine, offshore bryozoan meadows with seagrasses; low energy setting; warm subtropical waters

Weakly convoluted = 1–3 cm surficial relief.
Moderately convoluted = 4–8 cm surficial relief.
Strongly convoluted = 8+ cm surficial relief.

progressively deeper waters (Fig. 7; Lukasik et al. 2000). Physical sedimentary structures and reworking of sediments are most prevalent in the deepest-water, most offshore echinoid and bryozoan facies.

Clay Cycles

Clay cycles (cycle Types 1, 2; Table 1; Fig. 6) are thin ($\sim$ 20–40 cm) coarsening-upward successions of clay (Part A) and pervasively bioturbated molluscan floatstone (Part B). Fossils consist of epifaunal bivalves (especially oysters and mussels), small gastropods, and a few bryozoans. Echinoids are limited to those morphologically adapted to locomotion in clays (e.g., *Schizaster*). Foraminifers include small infaunal detritivores (*Bolivina* and *Uvigerina*), miliolids, and *Marginopora* (Type 2 cycles). Extent and degree of bioturbation increases upward from part A to B (Fig. 8A, B). Part A is dominated by *Chondrites* (30–40%), *Gyrolithes* (10–15%; Fig.

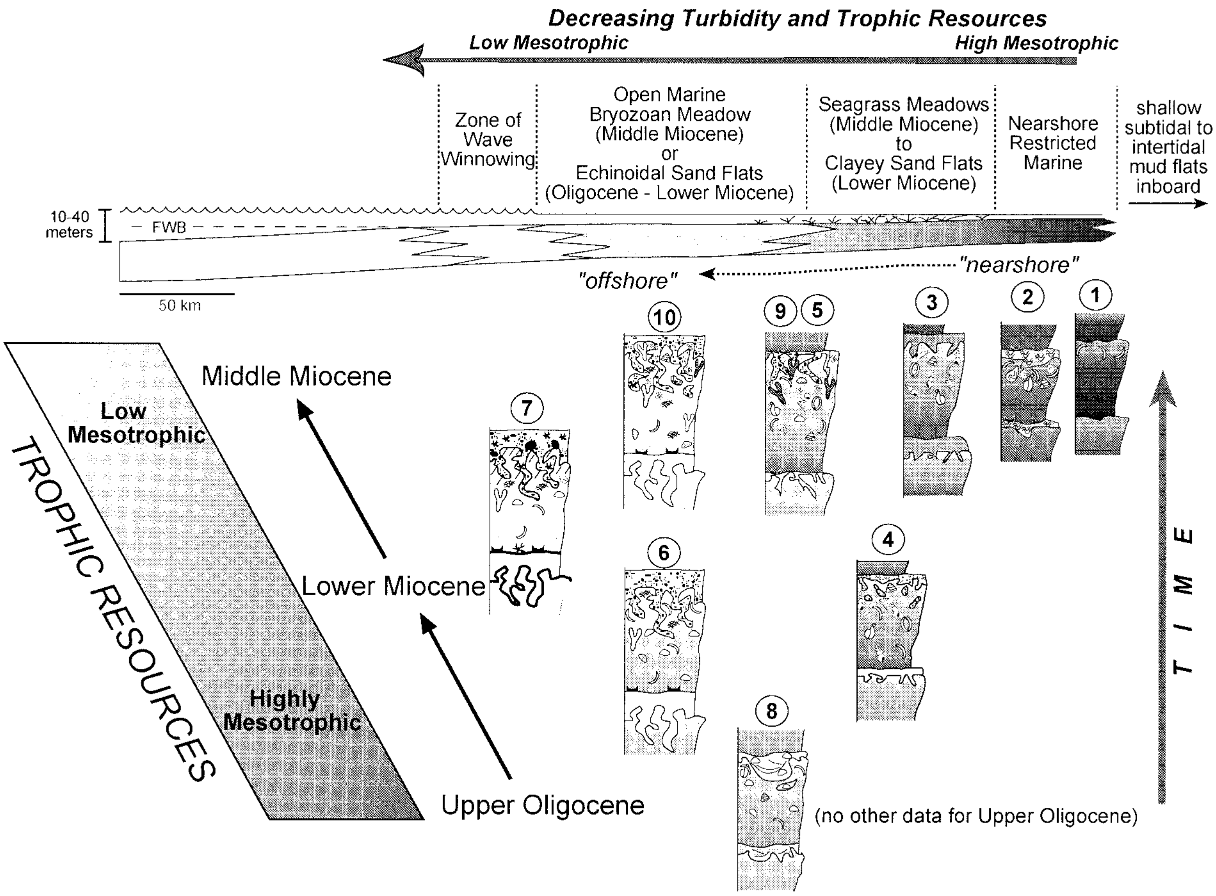


FIG. 7.—Cycle types through time and space. Temporal and interpreted paleogeographic location of cycle types across the Murray Basin epeiric ramp. Clay cycles (Types 1 and 2) accumulated in shallow, nearshore restricted marine environments. Mollusc cycles (Types 3–5) accumulated in slightly deeper nearshore, low-energy, muddy sand flat (early Miocene) to seagrass meadow (middle Miocene) environments. Echinoid cycles (Types 6–8) represent deposition within offshore, low-energy to high-energy, open marine environments dominated by highly mesotrophic echinoid sand flats in the early Miocene. Bryozoan cycles (Types 9 and 10) reflect deposition under favorable, offshore, open marine bryozoan meadows generated under conditions of relatively low mesotrophy. All facies lie within the euphotic zone. All are interpreted as subtidal.

8D), *Thalassinoides* and *Teichichnus* (20–50%), all of which are filled with sediment from Part B above. *Thalassinoides* is re-penetrated by clay-filled *Chondrites* from the base of the overlying cycle. Part B is modified by *Thalassinoides, Teichichnus, Scolicia,* and *Zoophycos* (70–90%) with lesser *Skolithos* (5%) and clay-filled *Thalassinoides* and *Chondrites* (10–15%). Where present, thin (1–4 cm) grainstones of Part C (Fig. 8C), composed of up to 80% serpulid worm tubes and 15% bryozoan fragments, contain the only fragmented and encrusted biota in the cycle and overlie pot scoured surfaces. Scours measure 5–50 cm in depth and up to 100 cm in width. Bioturbation comprises overprinted tiers that repeat on a 10–50 cm scale. Firmgrounds are weakly convoluted (Fig. 8B, C, D).

Interpretation.—Judging from their limited biota, barren to sparsely fossiliferous clay composition, abundance of *Chondrites,* and oxygen-related tiered bioturbation patterns (cf. Savrda and Bottjer 1986), clay cycles are interpreted to represent deposition in shallow nearshore, restricted marine environments subjected to repeating levels of stressful conditions such as fluctuations in oxygen level and/or salinity (Fig. 7). Upward facies trends throughout these cycles suggest depositional conditions graded from a highly mesotrophic–eutrophic, dysoxic, euryhaline (?), quiet, inimical seafloor (Part A) upward to increasingly less eutrophic, more oxygenated and stenohaline (?), shallow marine seagrass environments (Part B) susceptible to scouring by storm surge events (OM and Part C; cf. Myrow 1992). Scours are comparable to seagrass meadow blowouts documented from southeastern Florida (Wanless 1981). Frozen tiers of bioturbation in Type 2 cycles may be related to storm depositional processes (cf. Orr 1994).

Similar lithofacies occur in the subsurface (Geera Clay and Winnambool formations) as a strandline fringe along the inboard margin of the basin (Radke 1987; Brown and Stephenson 1991). Tidal channels veneered with quartz-pebble conglomerates occurring locally on the omission surfaces of Type 1 cycles near Waikerie (Giles 1972; Lukasik et al. 2000) also lend support to the notion that these cycles represent shallow, nearshore, restricted marine environments.

Age.—Clay cycles occur in the lower Miocene Finniss Formation, and in the middle Miocene Cadell and lower Bryant Creek formations (Fig. 3).

Mollusc Cycles

Mollusc cycles (cycle types 3, 4, and 5; Table 1; Fig. 6) are burrow-mottled, fine-grained molluscan packstone and floatstone units with an average thickness of 40–60 cm. Part A is either a thin laminated clay (Type 3; Fig. 9A, B, C), a dolostone, or a clay-rich, slightly burrow-mottled, sparsely fossiliferous *Marginopora*–molluscan floatstone (Types 4 and 5; Fig. 10B). It grades upward across a burrowed contact into Part B, a miliolid–molluscan floatstone (Figs. 9, 10) that may or may not be rich in celleporarid bryozoans (Type 5; Fig. 10B, C). Fossil abundance and diversity increase upward towards the omission surface. Many constituents are found in life position, especially the pinnid bivalve *Atrina,* shallow and deep infaunal bivalves *Glycimeris* and *Panopea* respectively, spondylid bivalves, and less commonly the bryozoan *Celleporaria.* Part B terminates in a weakly to moderately convoluted firmground (OM_1) rich in infaunal

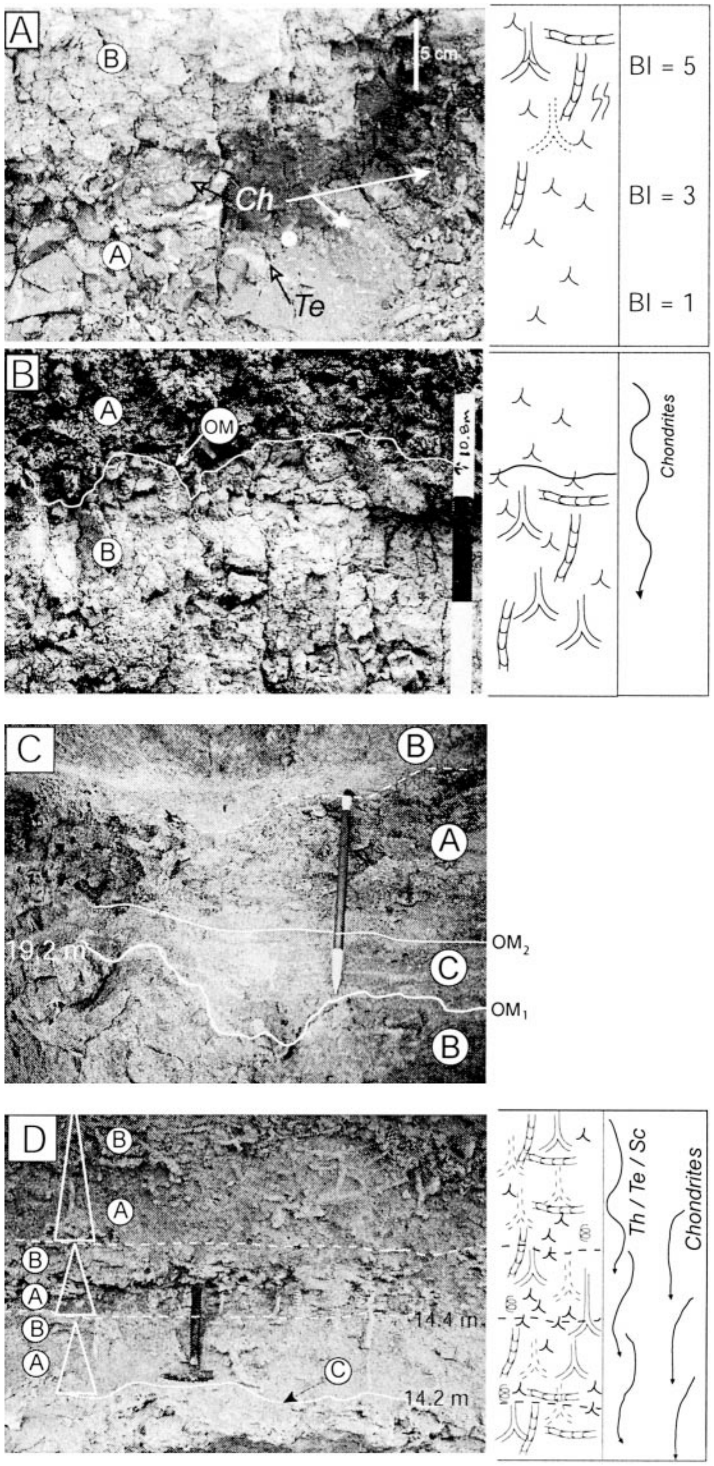


FIG. 8.—Clay Cycles. **A)** Cycle Type 1. Well-preserved tiering from pervasively bioturbated (*Cruziana* and *Glossifungites* ichnofacies) molluscan floatstone (Part B) downwards into a *Chondrites* (*Ch*) and *Teichichnus* (*Te*) burrowed laminated clay (Part A). BI = bioturbation index (Taylor and Goldring 1993). Section OC 10.2–10.7 m. **B)** Cycle Type 1. A weakly convoluted omission surface cycle contact (OM) at 10.8 m separates molluscan floatstone of the lower cycle (Part B) from the non bioturbated clay of the overlying cycle (Part A). Section OC 10.6–10.9 m. **C)** Cycle Type 2. Part A—laminated clay. Part B—indurated molluscan–*Marginopora* floatstone with a slightly scoured firmground omission surface (OM$_1$). Part C—serpulid–molluscan grainstone (weathered surface makes it difficult to see clearly). Section CM 19.15–19.35 m. **D)** Cycle Type 2. Three complete cycles showing the rhythmic nature of Part A clay and Part B molluscan floatstone. Well-preserved, offset suites of ichnofacies (*Chondrites*-dominated overprinting *Thalassinoides*/*Teichichnus*/*Scolicia*-dominated facies), and overlapping tiers. Section BC 14.0–15.0 m.

molluscs and the large, photosymbiont-bearing, benthic foraminifer *Marginopora.* The firmground zone is associated with a relative increase in epifaunal suspension feeders including oysters, brachiopods, pectinid bivalves, and bryozoans (celleporarids and fenestrates in particular) with spondylid bivalves and articulated oysters often wedged in firmground nooks and crannies (Fig. 10C). The firmground is rarely scoured (Fig. 9B) but always overlain by either a thoroughly bioturbated, mottled, molluscan floatstone (Type 3) or a thin (0.5–4 cm), patchy, cellarid bryozoan–serpulid worm tube grainstone (Types 4 and 5; Fig. 10A) locally rich in photosymbiont-bearing rotaliid foraminifers such as *Operculina* and *Amphistegina* (especially in Type 5). Sediments of Part C contain abraded, fragmented, and encrusted biota.

Bioturbation is complex, overprinted on a 30–100 cm scale (commonly penetrating down past lithological cycle boundaries), and consists of offset softground and firmground ichnofacies suites helpful in defining cycle boundaries (e.g., Figs. 9A, 10B). *Planolites* is pervasive throughout, except in basal clay layers where they are preserved (Part A; Fig. 9C). Bioturbation increases upward towards omission surface OM$_1$, ranging from a suite of

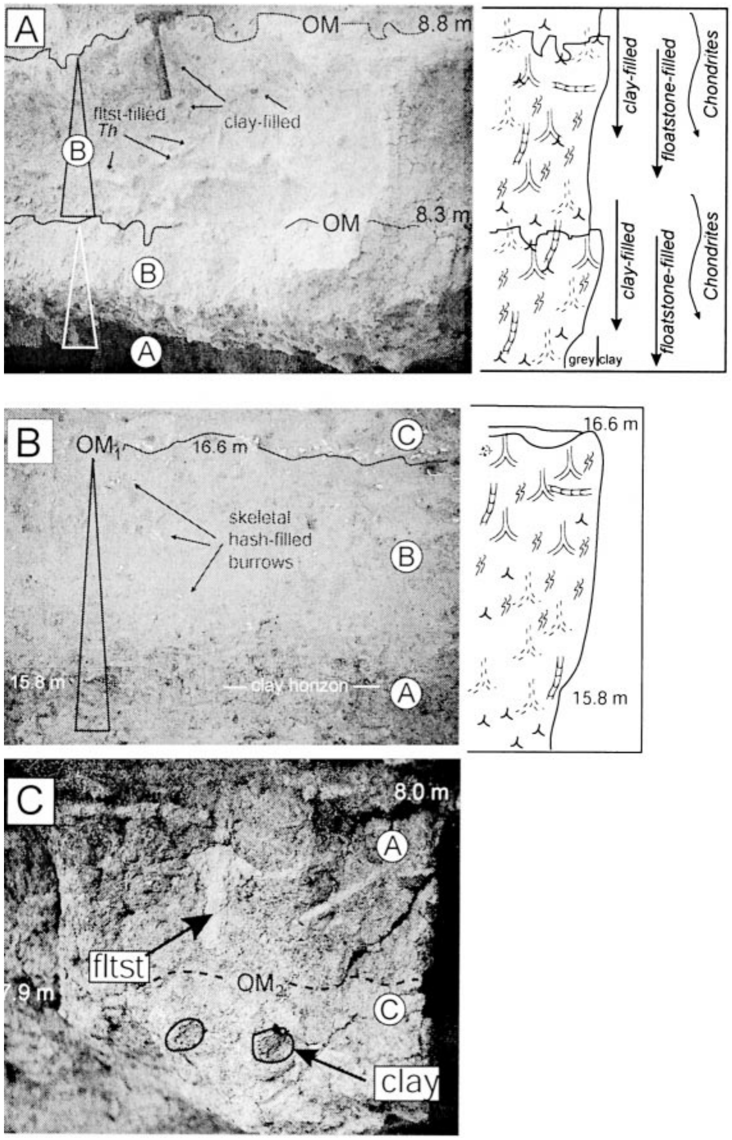


FIG. 9.—Mollusc Cycles. **A)** Cycle Type 3. Two mollusc cycles with well-preserved overlapping ichnofabrics. Clay-filled *Chondrites*, and *Chondrites*-burrowed *Thalassinoides* traces that are present in the upper part of each cycle actually initiate in the lower part of the overlying cycle (early in the overlying cycle's Part B deposition). These clay-filled burrows cut older traces in the underlying cycle filled with molluscan floatstone. Firmground omission surfaces (OM) cap the cycles. Section BC 8.0–8.8 m. **B)** Cycle Type 3. A complete cycle ranging upward from the basal laminated clay (Part A) that grades into a thoroughly mottled molluscan floatstone (Part B) capped by a shallowly scoured firmground omission surface (OM_1) and is overlain by a patchy and thin molluscan skeletal hash (Part C). This hash fills burrow networks throughout part B. At the base of the cycle, clay-filled *Chondrites* burrows initiate in Part A at 15.8 m and extend into the upper part of the underlying cycle. Section CM 15.8–16.6 m. **C)** Cycle Type 3. A vertical section through the cycle boundary and overlying Part A clay horizon. The lower cycle boundary (OM_2) grades sharply from well-mixed floatstone (light gray) into the laminated clay (dark gray) of Part A. Clay-filled *Thalassinoides* traces initiate from the surface delineated as the cycle boundary at 7.9 m. Floatstone-filled traces (fltst) originating in Part B cut down into the laminated clay (Part A) from above. Section BC 7.9–8.0 m.

Chondrites and *Gyrolithes* near the base, to a suite incorporating *Scolicia, Teichichnus, Zoophycos,* and *Thalassinoides* near the top (e.g., Figs. 9, 10A, C). Crosscutting relationships of multiple and overlapping *Thalassinoides* populations defined by different burrow fills (e.g., *Thalassinoides* filled with molluscan floatstone crosscut by skeletal hash-filled burrows that are in turn cut by clay-filled burrows) illustrate a temporal hierarchy of sedimentation from oldest to youngest. Many molluscan floatstone and skeletal hash-filled traces are subsequently repenetrated by clay-filled *Chondrites* coming down from Part A of the younger cycle above. Traces of a single *Thalassinoides* population become stenomorphic with depth through the cycle, ranging from 6–7 cm in diameter near the firmground surface to 1–2 cm at the base (Fig. 10B). Ichnofabrics that overlap omission surfaces from above suggest that firmgrounds were never very hard. In those cycles where Part A basal clays are absent, late-stage open burrow networks within the underlying firmground (Fig. 9A) and/or in the thoroughly mottled floatstone of Part C (Fig. 9C) are typically filled with laminated clay. Such clay-filled burrow networks define omission surfaces where Part A clays have been either removed or subsequently mixed with the molluscan floatstone of Part B.

Interpretation.—Mollusc cycles share biotic attributes with both restricted-marine clay cycles and relatively open-marine bryozoan–echinoid cycles. They are interpreted to record accumulation within shallow, nearshore, mesotrophic to highly mesotrophic, seagrass to muddy sand flat settings (Fig. 7; Lukasik et al. 2000). Laminated clays and the presence of only a sparse molluscan assemblage in floatstones of Part A suggest sediment accumulation in low energy, stressed to restricted marine environments. Low-oxygen conditions are expressed by the abundance of clay-filled *Chondrites* at this level (Bromley and Ekdale 1984).

Progressively more oxygenated and open marine conditions prevailed through the deposition of Part B as expressed by an upward increase in faunal abundance and diversity, and an upward increase in the intensity of bioturbation. Increasing induration towards OM_1, which presumably resulted from decreasing rates of sediment accumulation, correspond to an infaunal to epifaunal biotic shift and the appearance of firmground burrows (*Glossifungites* Ichnofacies). An upward increase in faunal abundance and diversity coinciding with the appearance of photosymbiont-bearing foraminifers is interpreted to reflect a change in sedimentation from offshore seagrass meadows (Types 3 and 4) to increasingly deeper and more offshore seagrass–bryozoan (Type 5) environments (Fig. 7). *Celleporaria* (Type 5), the dominant macrofossil in this upper Part B facies, seems to

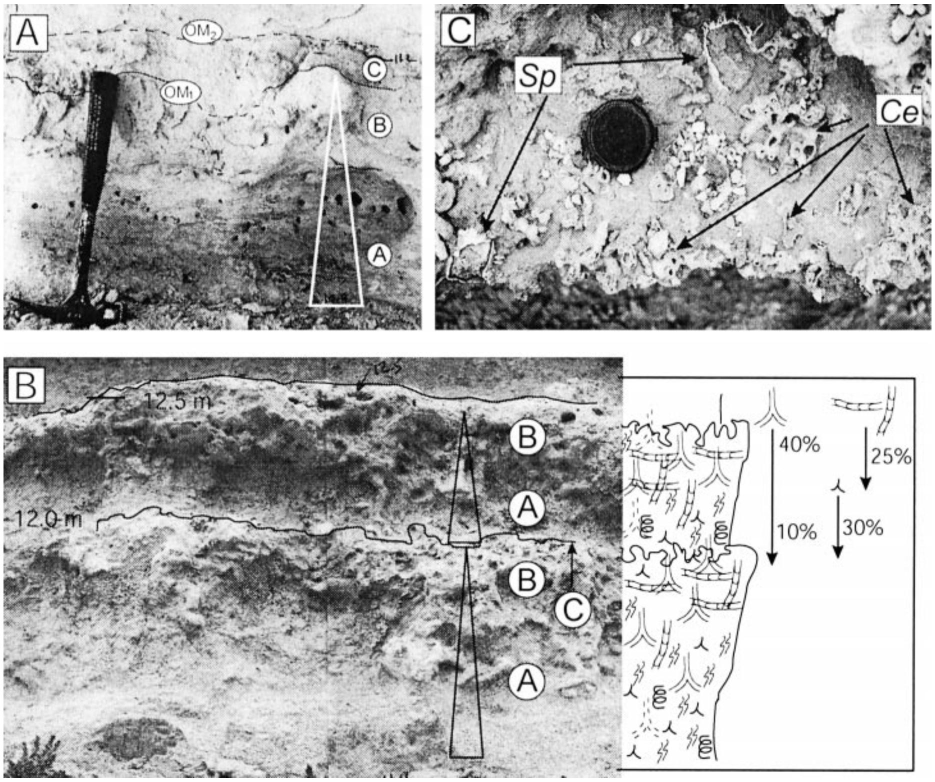


FIG. 10.—Mollusc Cycles. **A)** Cycle Type 4. Slightly burrow mottled clayey molluscan floatstone (Part A) grades upward into pervasively bioturbated molluscan floatstone (Part B) capped by a slightly convoluted firmground omission surface (OM_1). A thin serpulid worm tube–cellarid bryozoan grainstone (Part C) overlies OM_1 and is capped by OM_2. Section C 10.9–11.2 m. **B)** Cycle Type 5. Two complete subtidal cycles. Soft clayey molluscan floatstone (Part A) grades upward into indurated molluscan–*Celleporaria* rudstone–floatstone (Part B). A thin, patchy *Operculina*–cellarid bryozoan grainstone (Part C) overlies the firmground omission surface. A gradation of later stage firm-substrate burrows from a *Chondrites–Gyrolithes* assemblage in Part A upward into a *Thalassinoides–Teichichnus–Scolicia* assemblage in Part B overprints a thoroughly mottled softground ichnofabric. Section CM 11.2–12.5 m. **C)** Cycle Type 5. Looking down on an exhumed firmground surface reveals isolated colonies of *Celleporaria* (*Ce*) occurring in conjunction with articulated thorny oysters (*Spondylus*; Sp) that lived among the firmground convolutions. Lens cap is approximately 5 cm in diameter. Section CM 23.1 m (Bryant Creek Formation).

have flourished near to the open marine seagrass meadows of the middle Miocene (Fig. 7). Overall, the abundance of articulated bivalves and lack of widespread scours such as those present in the clay cycles suggest overall low-energy conditions prevailed throughout Part B deposition.

On the basis of their biotic similarity with underlying Part B sediments, those of Part C are interpreted to represent a continuation of offshore open marine depositional conditions. Depending on the paleogeographic position of a cycle on the epeiric ramp, Part C is either a thoroughly mottled molluscan floatstone (Type 3) or a thin, open marine grainstone to rudstone (Types 4 and 5) with photosymbiont-bearing foraminifers, brachiopods, and cellarid bryozoans. Clay-filled burrows within Part C and/or oysters encrusting its upper surface indicate a period of omission capping the cycle (OM_2).

Age.—Mollusc cycles occur within all formations of the Murray Supergroup, but are best developed in the uppermost lower Miocene Finniss Formation and the middle Miocene Cadell Formation (Fig. 3).

Echinoid Cycles

Echinoid cycles (cycle Types 6, 7, and 8; Table 1; Fig. 6) constitute fossiliferous facies dominated by infaunal irregular echinoids (especially *Lovenia, Eupatagus, Fibularia,* and *Monostychia*). Cycles average 40–60 cm in thickness and are composed of only Parts B and C (Fig. 6). Part A is most commonly preserved as an omission surface in the form of a sharp to burrowed contact (OM_2) separating echinoid rudstone or grainstone of Part C from overlying Part B echinoid floatstone.

Part B forms the bulk of the cycle and is composed of echinoid floatstone locally rich in celleporid bryozoans (Type 6) and iron-stained carbonate sand grains. It contains an open marine, stenohaline fossil assemblage of brachiopods, bryozoans, crinoid ossicles, serpulid worm tubes, and pectinid bivalves in varying abundance plus a diverse array of infaunal bivalves and infaunal to epifaunal gastropods (Lukasik et al. 2000). Photosymbiont-bearing foraminifers including *Operculina* and *Amphistegina* range from scarce to abundant. The upper surface of Part B (OM_1) varies from a moderately to highly convoluted hardground (Type 7; Figs. 11, 12A, B, C) that is uncommonly iron-stained, bored, and encrusted (Fig. 12D) to a moderately to highly convoluted firmground (Type 6; Fig. 12A) locally scoured to depths of 40 cm (Type 8; Fig. 13A, B). Small oyster bioherms reaching not more than 50 cm in width and 10 cm in height nucleate locally on hardground surfaces.

Part C is an echinoid–bryozoan rudstone (Figs. 12A, 13) or a cellarid bryozoan–coralline algal–serpulid worm tube grainstone with or without intraclasts (Fig. 12B, C). Fossils include those from Part B in addition to an epifauna that colonized the indurated omission surface. Low-amplitude pot scours (as per Myrow 1992) reaching depths of 20 cm cutting into firmground omission surfaces (OM_1) are common. Part C sediments fill open burrow networks within Part B. Such fillings are locally so dense that they form up to 70% of the total rock volume (Figs. 11, 12A, 13C), making it difficult to determine the nature of the original sediment matrix. Bioturbation is overprinted and pervasive (e.g., Figs. 11, 12A), creating complex ichnofabrics with indistinct burrows that are not readily identified.

Interpretation.—The nature of the biota and common iron staining of carbonate sand grains suggest highly mesotrophic (see Fig. 4), open marine depositional conditions (Lukasik et al. 2000). Given the basinal distribution trend of facies, these cycles are thought to have accumulated in shallow to moderate water depths outboard of the seagrass meadows and open clayey sand flats (Fig. 7). The infaunal trophic structure and overall high abrasion and fragmentation rates of shelly biota often associated with scours suggest that the seafloor was susceptible to reworking by storms, the evidence being sparse epifauna and paucity of rooted organisms able to hold the substrate in place. Rudstones and grainstones of Part C, particularly when associated with hardground development, likely reflect an offshore zone of wave winnowing that prevented accumulation and promoted lithification.

Age.—Echinoid cycles are restricted to upper Oligocene and lower Miocene strata (Mannum Formation; Fig. 3).

Bryozoan Cycles

Bryozoan cycles (cycle Types 9, 10; Table 1; Fig. 6), averaging 40–60 cm in thickness, are extremely fossiliferous units with a well preserved,

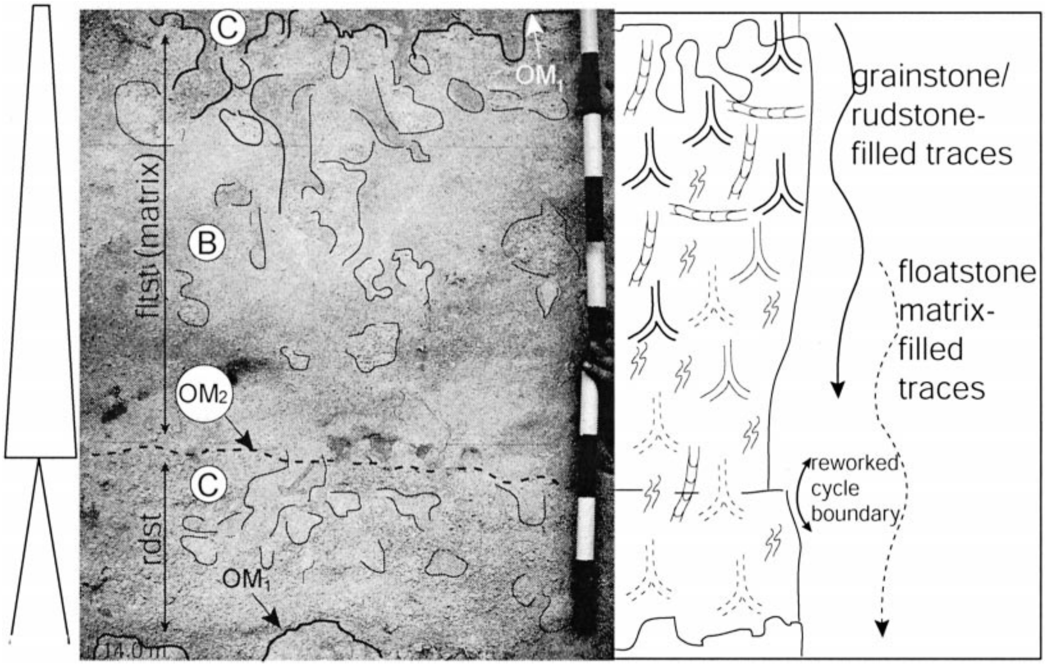


FIG. 11.—Echinoid cycle Type 6 (upper Oligocene to lower Miocene Mannum Fm). The upper part of one cycle and the lower two-thirds of the overlying cycle are shown. Part A is not present but is interpreted to be coincident with the sharply gradational, burrowed cycle contact (OM_2). Echinoid floatstone of Part B is thoroughly mottled with burrow networks filled with various generations of sediment indicating a complex depositional history. Part B terminates in a moderately to convoluted firmground to hardground surface (OM_1) overlain by the echinoid–bryozoan rudstone of Part C. Section BB 14.0–15.0 m.

highly diverse and abundant biota. Part A is a bryozoan floatstone to rudstone (Type 10) with a bryozoan–foraminiferal packstone matrix that is occasionally clay-rich (Type 9; Fig. 14A). Dominant biota include celleporid bryozoans, pectinid bivalves, infaunal echinoids, solitary azooxanthellate corals, and oysters. Part A passes gradationally upward into bryozoan floatstone, rudstone, to bafflestone of Part B (Figs. 14A, B, C) with a corresponding increase in faunal diversity and abundance. *Celleporaria* locally formed coalescing boxwork-style thickets often populated by articulated pectinid and spondylid bivalves (Fig. 14D). A moderately convoluted firmground omission surface (OM_1), typically associated with large, photosymbiont-bearing *Marginopora* foraminifers, caps Part B.

Part C is coralline algal–bryozoan–foraminifer rudstone to grainstone with a highly diverse biota reflecting all trophic levels from deep burrowing suspension feeders (e.g., *Panopea*) and deposit feeding echinoids (especially the bulbous *Cyclaster*), to high-story epifaunal suspension feeders (*Celleporaria*; Lukasik et al. 2000). Minimal abrasion and fragmentation

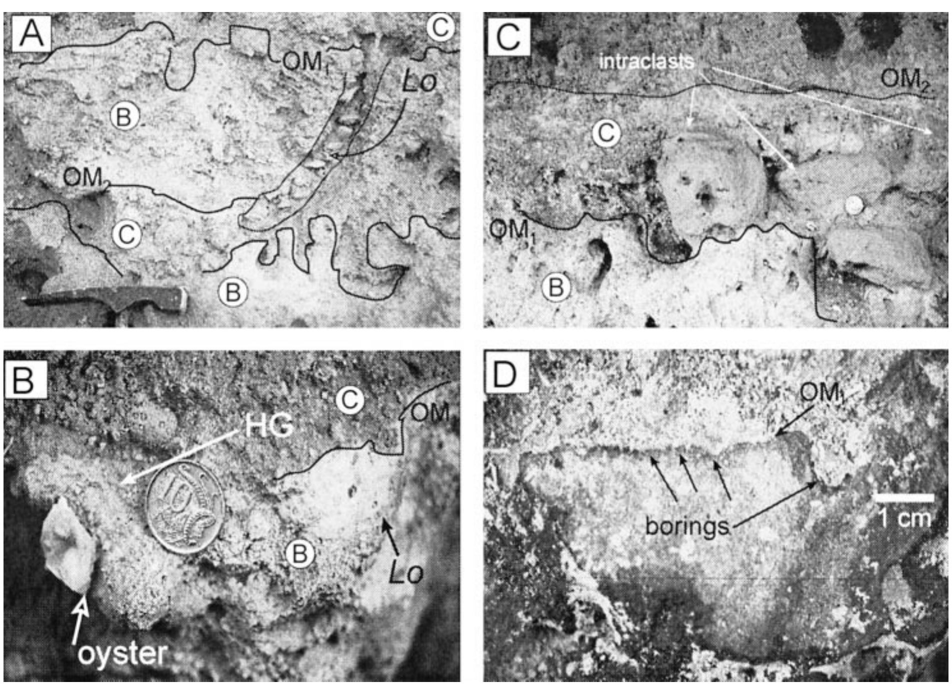


FIG. 12.—Echinoid Cycles. **A)** Cycle Type 6 (upper Oligocene to lower Miocene Mannum Fm). Cycle showing extensive burrow fill (Part C), nearly completely obliterating the Part B cycle matrix. Irregular echinoids (*Lovenia;* Lo) fill a distinct *Thalassinoides* burrow from the omission surface (OM_1) right down to the underlying cycle boundary (OM_2). Section DD 8.8–9.2 m. **B)** Cycle Type 7 (lower Miocene Mannum Fm). Close-up of an OM_1 hardground surface encrusted with oysters. Infaunal echinoids (*Lovenia*; Lo) are encrusted with coralline algae. Part C coralline algal–bryozoan grainstone overlies the omission surface. Section B 5.8 m. Coin is approximately 1.5 cm wide. **C)** Cycle Type 7. Hardground surface (OM_1) at 21.05 m is overlain by coralline algal- and bryozoan-encrusted intraclasts resting in a bryozoan–echinoid rudstone matrix (Part C). Intraclasts are commonly bored and, less frequently, associated with vermetid gastropods. Section SR 20.7–21.15 m. **D)** Cycle type 7. Cross-sectional close-up view of borings into the iron-stained OM_1 hardground surface. Section KWPS 6.8 m.

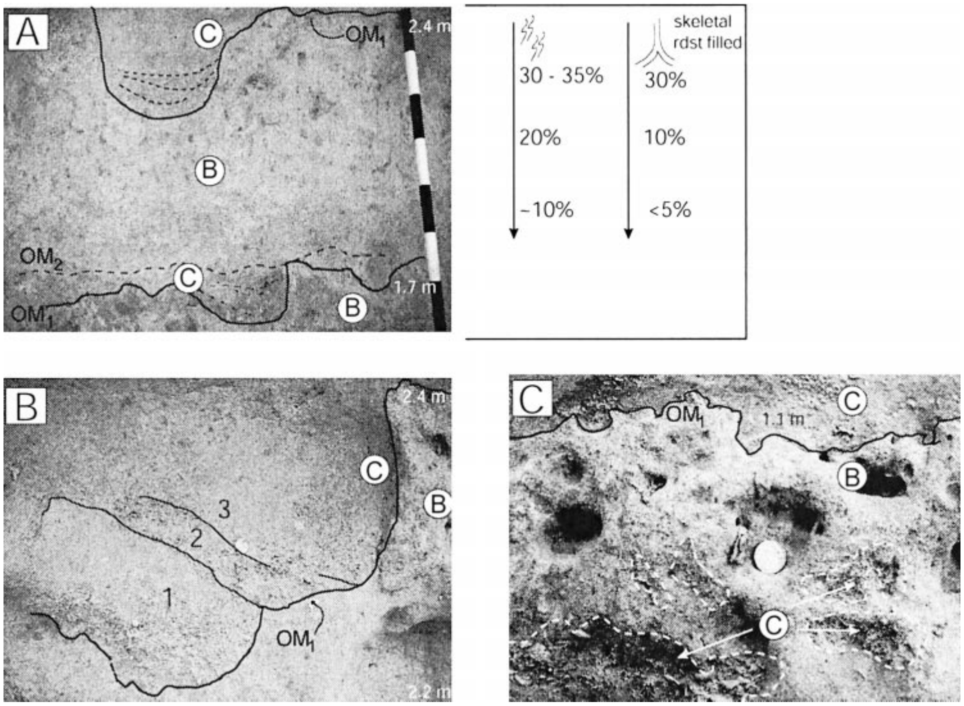


FIG. 13.—Echinoid Cycle. Type 8 (upper Oligocene, lower Mannum Formation). **A)** A complete subtidal cycle showing the scoured OM_1 omission surfaces, and percentage of background mottling vs. traces filled with Part C skeletal rudstone (rdst). Section DD 1.6–2.4 m. **B)** Amalgamated scour and fill episodes (1, 2, and 3) cutting into the firmground OM_1 omission surface that caps Part B. Echinoid rudstone scour fill (Part C) preserves primary sedimentary structures. They likely represent episodic depositional events due to storms. Coin at contact between fills 2 and 3 is approximately 1.5 cm in diameter. Section DD 2.2–2.4 m. **C)** Slightly convoluted firmground omission surface overlain by Part C echinoid (*Fibularia*) rudstone that fills previously open burrows underlying the omission surface. Coin is roughly 1.5 cm in diameter. Section DD 1.0–1.1 m.

of skeletal elements are offset by high epibiotic encrustation. Deep burrowing infaunal echinoids are often found heavily encrusted with a variety of epizoans. Grainstones are locally cross-laminated. The upper omission surface (OM_2) is in gradational contact with Part A. Sharp surfaces are relatively rare.

Largely similar biotic elements and sediment composition throughout the bryozoan cycle unit results in vague and graded boundaries between internal cycle components that are difficult to discern. Bioturbation is generally pervasive and overprinted to a depth exceeding one meter, with traces filled by multiple generations of sediment from different levels of the cycle and the cycle above (e.g., Fig. 14D, E). The upper portion of Part B, including the primary omission surface (OM_1), is usually blended together with the rudstones of Part C to form a homogeneously mixed fossiliferous horizon associated with a vaguely defined omission surface. However, where this cycle portion is best preserved, it is clear that the omission surface is riddled with open network burrows filled with sediment from Part C. Estimates of rudstone burrow fill exceeding 70% of the total area immediately below the firmground omission surface fall to $\sim$25% in the lower parts of the same cycle. Similar to the fabrics developed through dense networks of ''tubular tempestites'' (Tedesco and Wanless 1991), the burrow fill can be so complete that it almost totally obliterates the original lithology of the upper portion of Part B (e.g., Fig. 14C, E).

Interpretation.—Given their abundance of photosymbiotic foraminifers, coralline algae, and extremely diverse bryozoan biota, these cycles are interpreted to represent deposition in open marine, low mesotrophic, shallow marine waters located in offshore seagrass and bryozoan meadows (Fig. 7). The overall paucity of physical sedimentary structures, lack of fragmented and abraded shelly biota, intense and pervasive bioturbation, and excellent faunal preservation suggest that minimal hydrodynamic influence and reworking prevailed throughout most of the depositional history of each cycle. Such attributes probably reflect extensive epifaunal (bryozoan) substrate cover that resisted hydrodynamic reworking of the substrate. Only Part C contains evidence for accumulation under agitated conditions that lead to substrate reworking and temporal condensation. Evidence includes a mixture of fossils from different trophic levels, high encrustation rates, and the presence of crustose coralline algae. Faunal abundance and diversity, in combination with basic lithological trends, reveal an increasingly open marine signature upward through the cycle that is interpreted to represent deposition in progressively deeper, offshore, and higher-energy environments towards the zone of wave winnowing (Fig. 7).

Age.—Bryozoan cycles are temporally restricted to strata of upper lower Miocene and middle Miocene age (uppermost Mannum, Glenforslan, and upper Bryant Creek formations; Fig. 3). Middle Miocene bryozoan cycles formed in a paleogeographic location similar to those responsible for the generation of the older echinoid cycles, but in an environment of lower trophic resources (Lukasik et al. 2000).

Distribution of Subtidal Cycles

The stratigraphic distribution of cycle Types 1–10 reveals a progression of facies development both laterally and vertically through time (Fig. 15). In general, echinoid facies comprise lower Miocene strata while bryozoan cycles are confined to middle Miocene units. Mollusc and clay cycles occur throughout the succession. Together, the echinoid–bryozoan and clay cycle types form the end members of an interpreted environmental and paleogeographic continuum across the epeiric ramp (Fig. 7). Laminated clay, limited biotic diversity and abundance, discrete burrowing, and shallow tiering of trace fossils within clay cycles are interpreted to reflect their development under generally low-energy conditions of high trophic resources, fluctuating oxygen levels, and likely euryhaline conditions in an

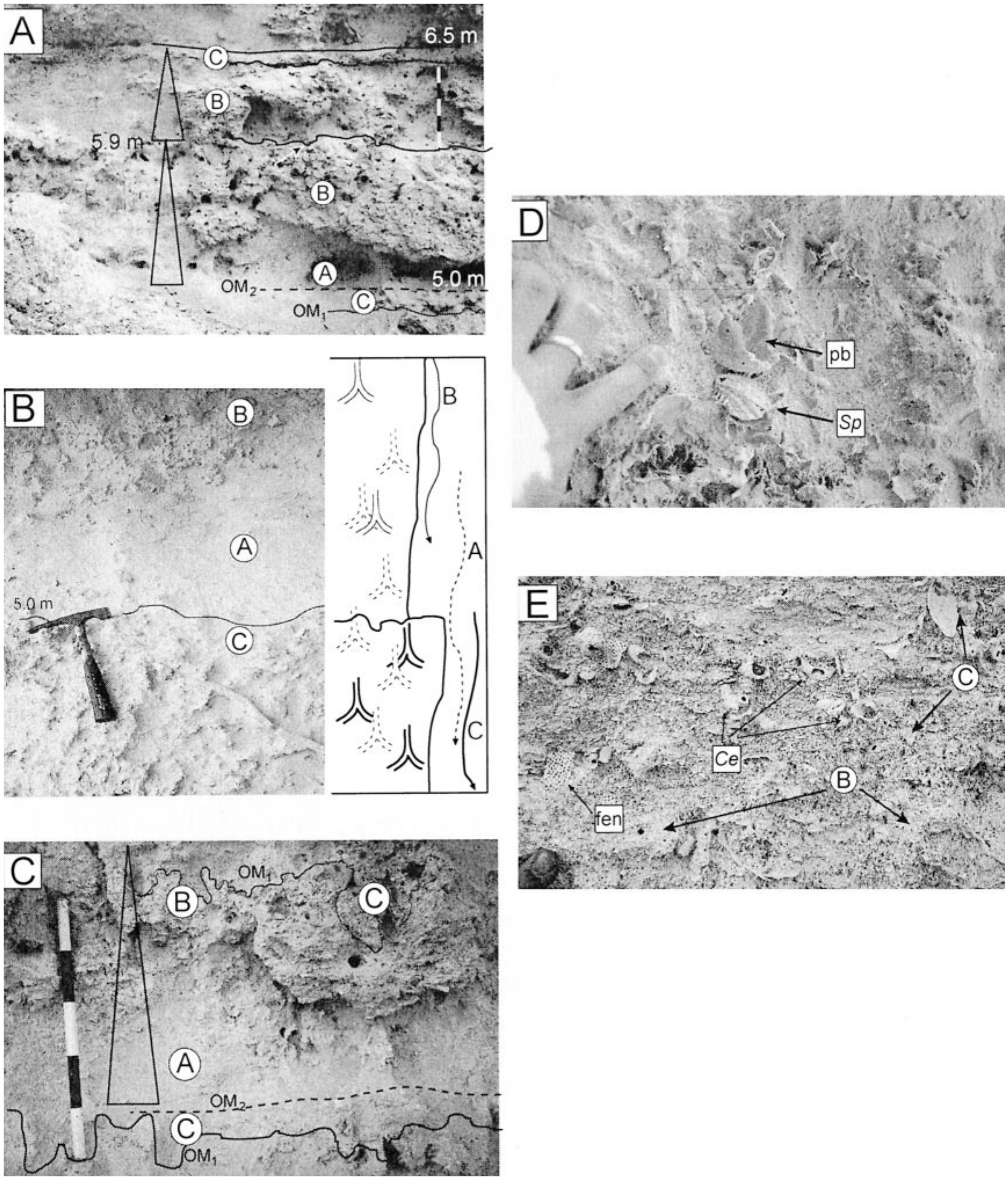


FIG. 14.—Bryozoan Cycles. **A)** Cycle Type 9 (middle Miocene, Glenforslan Fm). Two complete subtidal cycles. Thin clay of part A grades upward in the bryozoan floatstone of Part B. A thin bed of cellarid bryozoan–foraminifer–serpulid worm tube grainstone (Part C) overlies the moderately convoluted omission surface. Section OC 4.8–6.7 m. **B)** Cycle Type 10 (middle Miocene, Glenforslan Formation). Clayey bryozoan floatstone (Part A) grades upward into bryozoan floatstone of Part B. The upper part of the cycle is indistinct, with the firmground surface, upper part of Part B, and the bryozoan rudstone of Part C blending together, resulting in a jumbled mass of biota. Different generations of burrow fill from their respective parts of the cycle help in distinguishing cycle components. Section WOOF 4.6–5.5 m. **C)** Cycle Type 10. Complete subtidal cycle. Bryozoan floatstone (Part A) grades upward into more fossiliferous floatstone to rudstone (Part B) terminating in a firmground omission surface. Bryozoan rudstone of Part C overlies this surface and fills open burrow networks in the upper portion of Part B. Section B 18.9–19.5 m. **D)** Cycle Type 10. Articulated pectinid bivalves (pb) and *Spondylus* (Sp) within the open burrow networks of Part B. Section WOOF 4.7 m. **E)** Cycle Type 10. Bryozoan rudstone–grainstone burrow fill of Part C (with fenestrate bryozoans and *Celleporaria*) nearly completely obliterates the bryozoan floatstone sedimentary record of Part B. Finger for scale. Section OC 4.6–4.7 m.

overall nearshore, restricted marine setting. In contrast, carbonate sands, pervasive bioturbation, deep tiering, and relatively high abundance and diversity of biota in the bryozoan and echinoid cycles are interpreted to record accumulation under relatively oligotrophic, well-oxygenated, stenohaline conditions in an offshore, open marine environment. Mollusc cycles formed in the transition zone between these restricted and open marine environments (Figs. 7, 15). They share biota, bioturbational patterns, and lithological elements commonly found in the clay and echinoid–bryozoan cycle types. Because of these shared attributes with the relatively incomplete end-member cycle types, mollusc cycles possess many features critical to deciphering the nature of subtidal cyclicity in this system.

Lithostratigraphic correlation, supported by local visual and physical

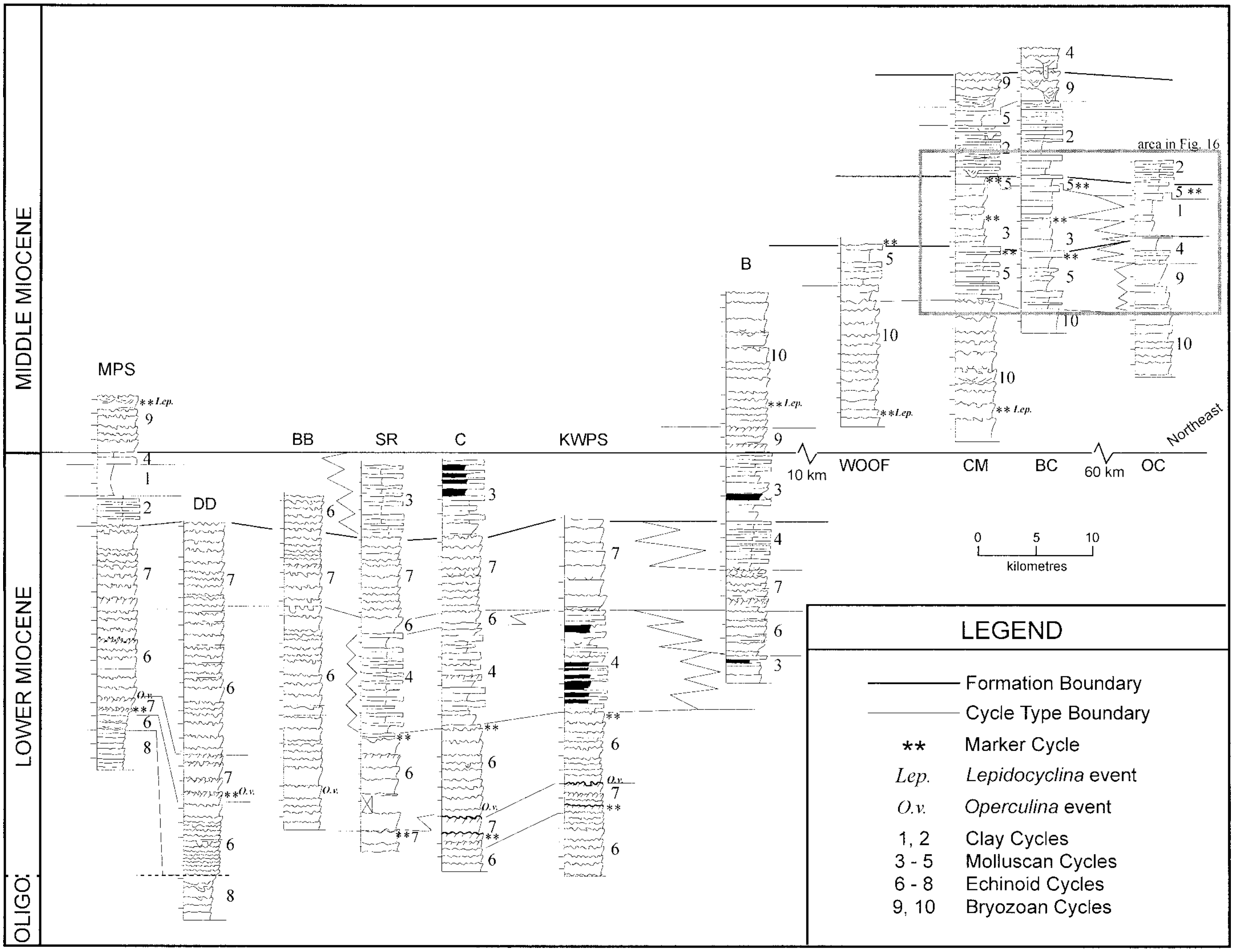


FIG. 15.—Stratigraphic distribution of cycle types. Echinoid cycles are confined to the lower Miocene. Bryozoan cycles occur only in middle Miocene strata. Clay and mollusc cycles form laterally adjacent to both echinoid and bryozoan cycles but are mostly confined to stratigraphic levels in the lower and middle Miocene, where they are laterally adjacent to each other. Locations of sections are noted in Figure 1. Stratigraphic datum is the Finniss–Glenforslan formation contact. Vertical scale is in meters. See Figure 3 for sedimentological character legend. Box in the upper right corner defines the stratigraphy focused upon in Figure 16.

tracing of cycles in the middle Miocene Glenforslan, Cadell, and Bryant Creek formations (Fig. 16) reveals that cycles commonly extend over distances of several tens of kilometers. Using distinctive marker beds, lateral correlation of these decimeter-scale cycles in outcrop can exceed 80 kilometers, limited only by the extent of exposure. Between Waikerie and Overland Corner, clay cycles grade laterally into coeval mollusc cycles of the Cadell Formation and bryozoan cycles grade westward into mollusc cycles of the upper Glenforslan Formation (Fig. 16). Although outcrop is extensive, individual lower Miocene Mannum and Finniss formation cycles are physically traceable only over short distances (1–10 kilometers). Stratigraphic packages of distinct cycle types, however, are correlatable over larger distances (Figs. 3, 15).

DISCUSSION

How Do They Form?

We propose an allogenic, eustatic mechanism for the generation of these subtidal cycles (Figs. 17, 18). Trends of internal facies and trophic resources within each cycle correspond to onshore–offshore, shallow–deep, relatively eutrophic–oligotrophic basin-scale facies trends (Lukasik et al. 2000). Wide lateral continuity, uniformity of cycle thickness, and a persistent, progressive pattern of change in facies and trophic resource upward within all cycle types point to a consistent external mechanism for their formation. A lack of significant development of regressive facies in combination with consistently complete cycles spanning all depositional environments argues against accumulation under punctuated, episodic cyclicity (PACs of Goodwin and Anderson 1985). The relatively quiet intracratonic setting (Wellman 1987) makes cycle generation through jerky subsidence or tectonism unlikely. On the other hand, autogenic controls such as variable marine cementation, wave reworking, storm scouring, patchy biotic community establishment, and subtle paleotopographic seafloor relief doubtlessly contributed towards cycle variability and lateral discontinuity.

Part A.—Cycle deposition is envisaged to have begun in relatively shallow, low-energy, euryhaline to stenohaline, variably restricted to open marine environments with relatively high trophic resources (Part A; Fig. 17) during early transgression (Fig. 18). The muddy seafloor had only scarce infaunal bivalves and gastropods, and the terrigenous sediments contained little oxygen (cf. Savrda and Bottjer 1986).

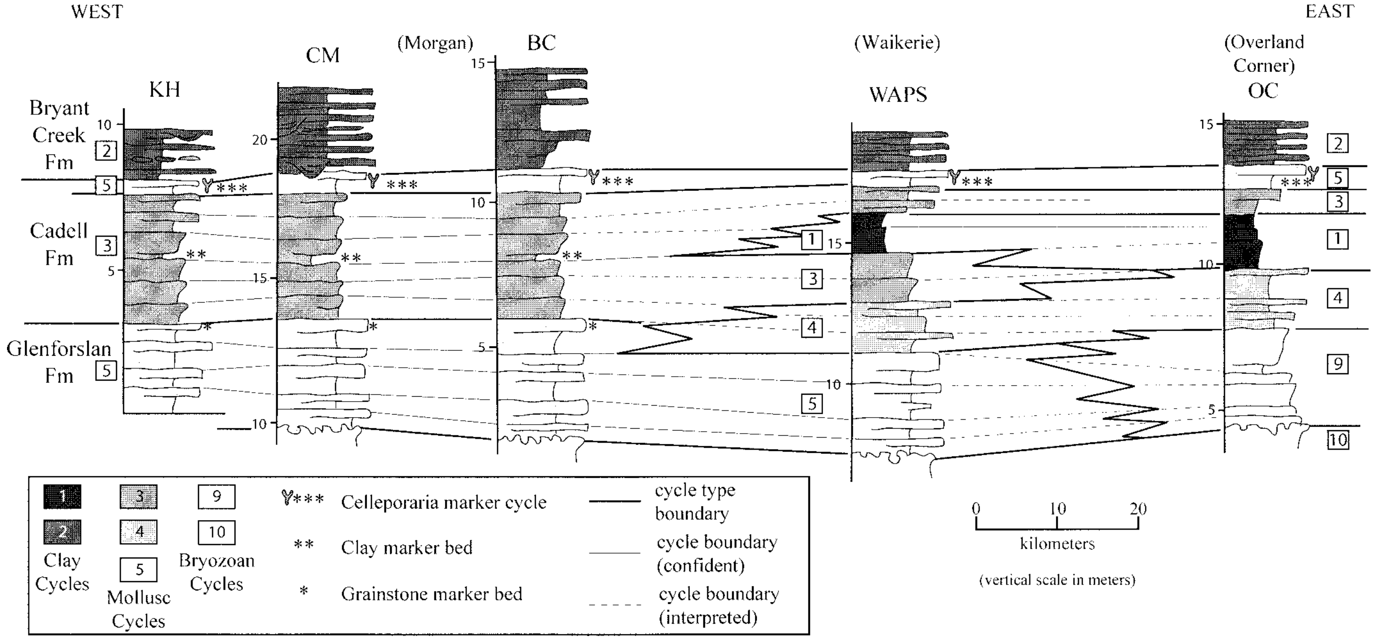


FIG. 16.—Cycle and cycle type correlation for the upper Glenforslan and Cadell formations from south of Morgan to Overland Corner, South Australia (see Fig. 1). Key marker beds (labeled as such) help to provide stratigraphic control over large distances. Lateral facies transitions on a cycle scale occur between Morgan and Overland Corner to the east (see text). Cycles are confidently correlated between KH, CM, and BC on the basis of closely spaced sections and intermittent visual tracing of units along the extent of outcrop. Their correlation towards the east is interpretive, based on regional vertical facies changes (Finniss–Glenforslan formation contact and the Cadell–Bryant Creek formation contacts), location of the *Celleporaria* marker cycle, and the *Lepdiocyclina* foraminiferal event in the lower Glenforslan Formation.

Part B.—Accumulation continued as sea level rose (Fig. 17). Increased biotic diversity upward in the cycle attests to increasingly more open and more mesotrophic to oligotrophic conditions (Fig. 18). The changes were accompanied by increasingly complex and overprinted trace fossil suites that registered a progressively more indurated substrate and more numerous physical sedimentary structures that recorded increasing hydrodynamic energy (cf. Bromley and Ekdale 1986; Wetzel and Aigner 1986; Taylor and Goldring 1993; Orr 1994).

OM_1.—Further transgression resulted in a trend towards maximum deepening and development of maximum fetch. All these factors combined to

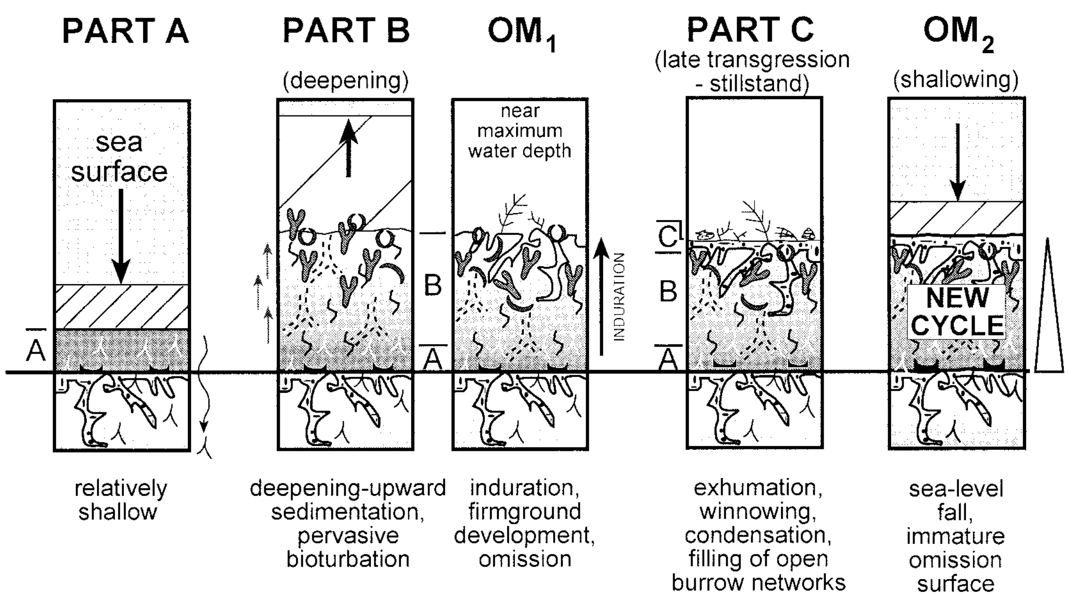


FIG. 17.—Subtidal-cycle generation in response to eustatic fluctuation, using mollusc cycle Type 5 as an example (common in upper Glenforslan Formation; e.g., Fig. 15B). Part A accumulated in the shallowest marine setting. Part B represents relatively consistent sedimentation through sea-level rise. Pervasive bioturbation implies softground to firmground substrate evolution. A primary omission surface (OM_1) is developed at or near the point of maximum water depth as a response to hydrodynamic reworking that kept carbonate accumulation at a minimum. Firmground to hardground surfaces with open network burrows developed as a result. Part C accumulated during relative sea-level stillstand under the most open marine, energetic conditions of any in the cycle. Epifauna dominate. High taphonomic indices imply sediment reworking, exhumation, and condensation. Grainy sediment filled open burrow networks. A second omission surface (OM_2) formed during relative sea-level stillstand to fall, capping the cycle. See text for full explanation.

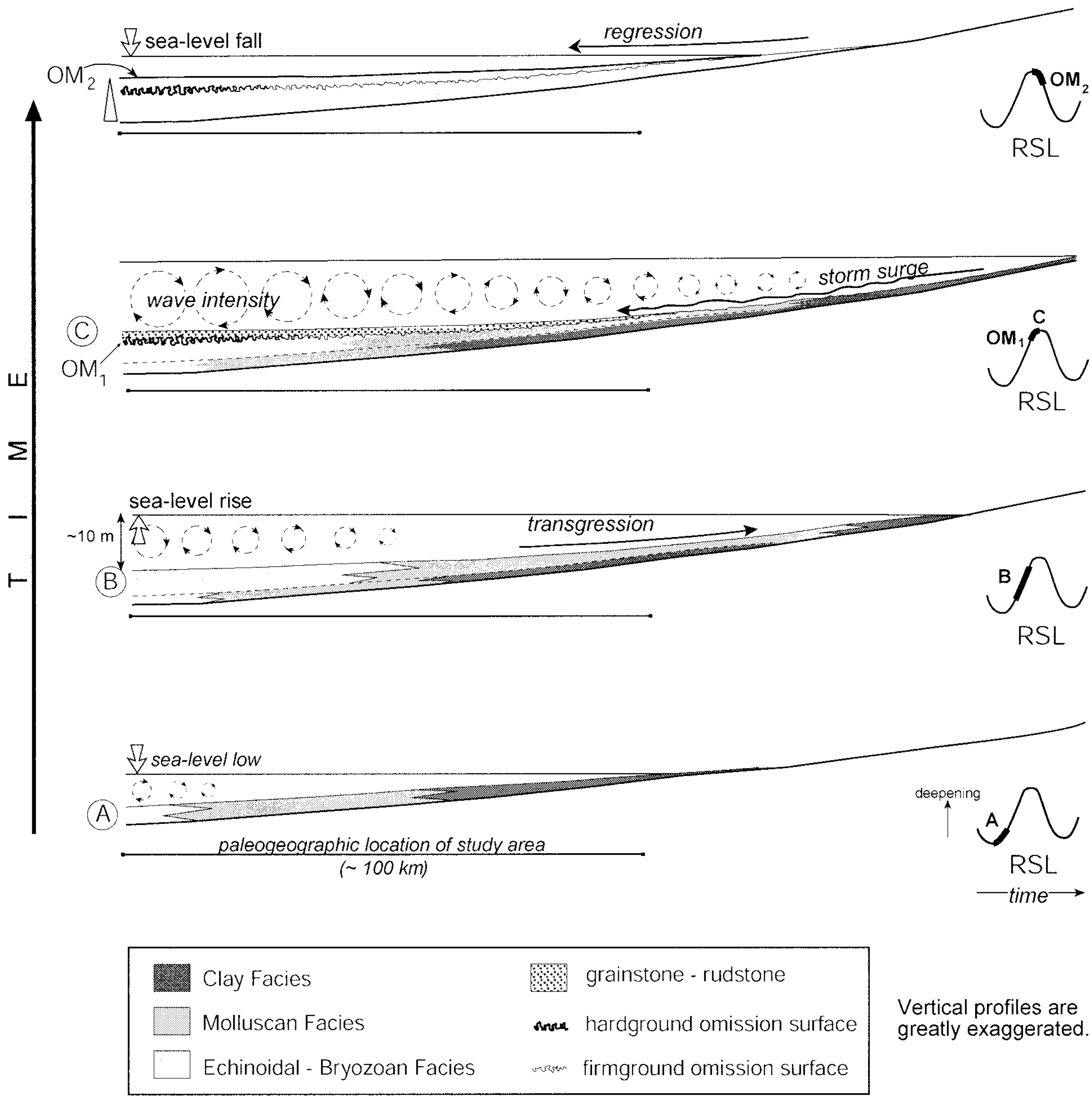


FIG. 18.—Paleogeographic cycle generation model. Generation of subtidal cycles across the epeiric ramp in response to sea-level fluctuation. Echinoid–bryozoan cycles form offshore, while clay–mollusc cycles form nearshore. Part A accumulates during the period of early transgression. A continued rise in sea level results in a transgression of facies across the ramp responsible for the ''deepening-upward'' facies signature in Part B. As sea level continues to rise, a critical threshold is reached where waves create an expanded agitated environment on the seafloor resulting in the development of an indurated omission surface (OM_1). Hardgrounds predominate in the offshore zone of wave winnowing where wave intensity is highest. Wave energy becomes attenuated inboard. Part C is generated during relative sea-level stillstand, or maximum transgression. Grainy, reworked sediments are most common in the offshore, high-energy, open marine settings, but accumulation is kept low by wave processes. Primary omission surfaces are scoured inboard by storm surge. A secondary omission surface (OM_2) likely develops in response to a collapse of the carbonate factory during late sea-level stillstand to fall, leading to a subsequent basinward regression of facies belts.

increase hydrodynamic energy throughout the shallow basin to the point where, even though the seafloor was an active carbonate factory, there was little sediment accumulation and most was transported away (viz. the shaved shelf model of James et al. 1994). Cycles at this level of omission surface development were effectively accumulating under conditions of stillstand due to a slowing of relative sea-level rise. Physical evidence for sediment omission includes sea-floor sedimentation (to variable degrees across the ramp), condensed trophic level structure in biotic elements, and development of a *Glossifungites* ichnofacies with open network burrows. Outboard, resultant hardgrounds were iron-stained (e.g., Fig. 12D—echinoid cycles) during times of high trophic resources (e.g., Hallock and Schlager 1986) whereas those produced during relatively oligotrophic periods were mostly unstained (e.g., Fig. 12B, C—bryozoan cycles). Inboard, reworking by fair-weather waves may have decreased owing to damping by friction across the wide, shallow seafloor (Keulegan and Krumbein 1949; Irwin 1965), resulting in the formation of firmground surfaces only (Fig. 18C).

Part C.—There was also sedimentation during this period between max-

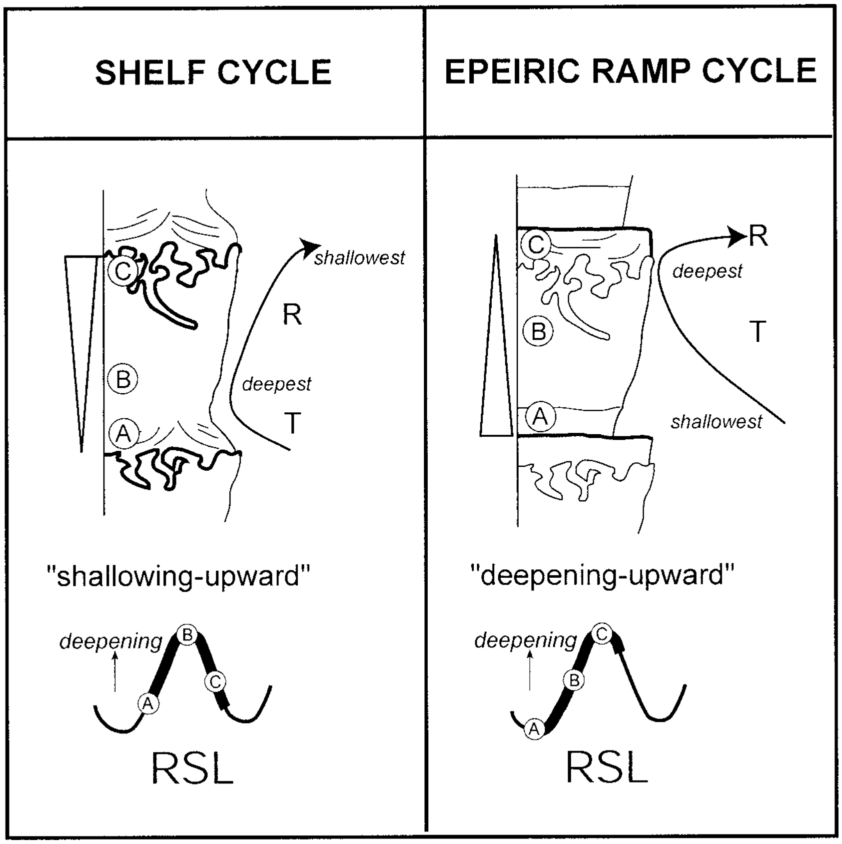


FIG. 19.—A comparison between models of open-shelf and epeiric-ramp subtidal cycles from Cenozoic cool-water carbonate settings. Shelf cycles shallow-upward toward an omission surface, whereas epeiric-ramp cycles deepen upward to the omission surface. Basal grainstones of **A)** open-shelf cycles are typically considered to be the shallowest-water facies and are interpreted as transgressive deposits. Similar grainstones in **B)** epeiric-ramp cycles are closely related to their underlying omission surfaces and are interpreted to represent relatively deep-water deposits generated during late transgression.

imum transgression and early regression. Deposits consisted of epibionts, and their associated epifauna that grew on hardground to firmground surfaces. High taphonomic indices, the highest in the cycle, record extensive abrasion, fragmentation, and encrustation. Taphonomic feedback (Kidwell and Jablonski 1983; Kidwell 1991) is conspicuous. Sediments fill extensive omission burrow networks excavated into Part B. Paleogeographically, grainy sediments that thin in shoreward cycles are interpreted to reflect decreasing hydrodynamic energy (Fig. 18C). These same sediments and associated omission surfaces, however, are extensively scoured because of the increasing effectiveness of storms in shallowest nearshore environments. Overall, the mixture of fossils from different trophic regimes displaying a wide range of taphonomic signatures atypical of the rest of the cycle indicates that the deposits likely represent condensed, time-averaged units formed under a wide range of environmental conditions.

OM_2.—This omission surface caps the cycle but is rarely as well developed or as prominent as OM_1. It is a surface of admittedly ambiguous nature that lacks sedimentological evidence for subaerial exposure. OM_2 is locally obscured by bioturbation (Fig. 11) or merges with OM_1 inshore (Figs. 8B, 10B, 18). The physical development of this surface (i.e., its cementation, trophic structure condensation, and development of omission burrow networks) is less pronounced compared to the OM_1 surface, which implies generation under different conditions, which may include lower hydrodynamic energy and/or formation over a shorter time and/or formation during periods of decreased marine cementation. Yet at the same time, where preserved, it marks the most profound boundary in the cycle, separating outboard, relatively open marine sediment (Part C) from relatively inboard, restricted marine facies (Part A). Given its placement within the cycle scheme, the most parsimonious explanation is that it represents a development of deteriorating environmental conditions inimical to carbonate production ultimately associated with relative sea-level fall (Figs. 17, 18). Thus, OM_1 is interpreted to record high energy while OM_2 reflects arrested production.

Shallowing-Upward vs. Deepening-Upward Cool-Water Subtidal Cycles

Although cool-water carbonate cycles from the open shelf and epeiric ramp settings of extensive Cenozoic basins of southern Australia have a lithological motif similar to those from the Murray Basin, their genetic interpretation is quite different. Models of both cycles (Fig. 19) show the same pattern of upward facies development from the conspicuous omission surface, to overlying grainy reworked sediments and finally into relatively fine-grained low-energy facies. Their different interpretation, however, highlights the significance of platform-specific hydrodynamics and its effect on the nature of the carbonate factory during generation of small-scale allogenic cycles.

Shelf cycles are typically interpreted as ''shallowing-upward'' on the basis of their internal patterns of facies development and hydrodynamic reworking placed into context with their corresponding depositional model (e.g., Osleger 1991; James and Bone 1994; Boreen and James 1995). In open shelf cycles, shallowest water facies are typically some of the highest-energy, comprising basal transgressive grainstones and rudstones that directly overlie cycle bounding, firmground to hardground omission surfaces (Fig. 19). The lower part of the cycle represents deepest water accumulation, typically below wave base, followed by relative sea-level fall and a return to inner shelf, relatively shallow water, high-energy deposition above wave base. The firmground or hardground omission surface capping the subtidal cycle is generated in response to reworking of the seafloor within this relatively shallow zone.

In contrast, Murray Basin epeiric ramp facies are primarily low-energy accumulations, moderated by storms, that deepen offshore into a zone of wave sweeping (Lukasik et al. 2000). Given this epeiric ramp setting, where highest-energy facies accumulated offshore, internal upward gradation into increasingly open marine, fossiliferous, and reworked sediments through the subtidal cycle is interpreted to reflect deepening-upward sedimentation through transgression (Fig. 19). The cycle boundary is drawn between the relatively deep-water, higher-energy Part C grainstones and omission surfaces generated during maximum (late) sea-level transgression to stillstand and the overlying shallowest-water, relatively low-energy facies of Part A, representing periods of lowstand to early transgression.

The enclosed to semi-enclosed setting of this intracratonic basin strongly influenced the nature and development of small-scale cycles compared to those which accumulated within coeval open shelf settings (e.g., James and Bone 1994; Boreen and James 1995; Shubber et al. 1997). The Murray Basin inland depositional system was particularly sensitive to fluctuations in the trophic resource continuum (TRC), likely driven by changes in climate and water temperature (Lukasik et al. 2000; Lukasik and James in review). This, in turn, determined the nature of the carbonate factory and its facies patterns across the epeiric platform. Conversely, open shelf settings elsewhere in southern Australia did not seem to be as strongly affected by changes in the TRC. In fact, Cenozoic and modern accumulation on open shelf cool-water systems in southern Australia is governed more by wave reworking (cf. Boreen and James 1993; James et al. 1994; James 1997) than overall trophic resource influenced productivity. This distinction seems fundamental to interpreting the differences between small-scale cycles generated in shallow marine, high-energy and low-energy depositional settings.

SUMMARY AND CONCLUSIONS

1. Sub-meter-scale subtidal cycles across the Murray Basin epeiric ramp share biotic and sediment attributes. They represent a continuum of facies and trophic resources from relatively shallow, restricted proximal to deeper distal, open marine ramp environments. Facies changes are gradational throughout, reflecting the gradational nature of the trophic resource continuum and its significance for facies development across the epeiric ramp.
2. Part A facies are best developed in nearshore cycles, whereas Part C facies are best expressed in offshore facies. Cycle boundaries are zones of condensed sedimentation or amalgamation.
3. Cyclicity was driven by eustasy. Each cycle represents progressively more open water accumulation during sea-level rise. The capping cycle boundary (OM_2) separates open marine facies interpreted to have accumulated during maximum transgression and stillstand (Part C) from overlying deposits (Part A) that accumulated during subsequent lowstand to early transgression under relatively shallow water restricted marine conditions.
4. Carbonate accumulation during periods of relative sea-level change was not equal. Early transgressive deposits (Part A) accumulated gradually in low-energy environments. In contrast, late transgressive to stillstand deposits (Part C) are thin because of continuous reworking by high-energy events. Such differences are a function of both intrinsic (wave reworking and community replacement) and extrinsic (eustasy) factors.
5. Subtidal cycles from the Murray Basin are distinctive in that most of the cycle represents accumulation under transgression capped by a thin interval of facies and/or a surface reflecting a relative stillstand to early shallowing event. Although semantics could argue that these cycles inevitably ''shallow upward'' at their upper bounding limit, most of the cycle accumulated during transgression and are thus considered here as mostly ''deepening-upward.'' This is in direct contrast to the more usual shallowing-upward cycle in which a relatively thin basal transgressive facies is overlain by largely regressive deposits forming the bulk of the unit.

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REFERENCES

Allmon, W.D., 1988, Ecology of recent turritelline gastropods (Prosobranchia, Turritellidae): current knowledge and paleontological implications: Palaios, v. 3, p. 259–284.

Allmon, W.D., 1992, Role of temperature and nutrients in extinction of turritelline gastropods: Cenozoic of the northwestern Atlantic and northeastern Pacific: Palaeogeography Palaeoclimatology Palaeoecology, v. 92, p. 41–54.

Boreen, T., and James, N.P., 1993, Holocene sediment dynamics on a cool-water carbonate shelf: Otway, southern Australia: Journal of Sedimentary Petrology, v. 63, p. 574–588.

Boreen, T., and James, N.P., 1995, Stratigraphic sedimentology of Tertiary cool-water limestones, SE Australia: Journal of Sedimentary Research, v. B65, p. 142–159.

Brasier, M.D., 1995a, Fossil indicators of nutrient levels. 1: Eutrophication and climate change, *in* Bosence, D.W.J., and Allison, P.A., eds., Marine Palaeoenvironmental Analysis from Fossils: Geological Society of London, Special Publication 83, p. 113–132.

Brasier, M.D., 1995b, Fossil indicators of nutrient levels. 2: evolution and extinction in relation to oligotrophy, *in* Bosence, D.W.J., and Allison, P.A., eds., Marine Palaeoenvironmental Analysis from Fossils: Geological Society of London, Special Publication 83, p. 133–150.

Bromley, R.G., and Asgaard, U., 1991, Ichnofacies: a mixture of taphofacies and biofacies: Lethaia, v. 24, p. 153–163.

Bromley, R.G., and Ekdale, A.A., 1984, *Chondrites*: A trace fossil indicator of anoxia in sediments: Science, v. 224, p. 872–874.

Bromley, R.G., and Eckdale, A.A., 1986, Composite ichnofabrics and tiering of burrows: Geological Magazine, v. 123, p. 59–65.

Brown, C.M., and Stephenson, A.E., 1991, Geology of the Murray Basin, southeastern Australia: Australia Bureau of Mineral Resources, Geology and Geophysics, v. 235.

Fischer, A.F., 1964, The Lofer cyclothems of the alpine Triassic, *in* Merriam, D.F., ed., Symposium on Cyclic Sedimentation: Geological Survey of Kansas, Bulletin 169, p. 107–149.

Giles, S.D., 1972, Stratigraphic investigations of the Tertiary sequences, western Murray Basin, South Australia [Honours thesis]: University of Adelaide, 96 p.

Goldhammer, R.K., Lehmann, P.J., and Dunn, P.A., 1993, The origin of high-frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso Gp, west Texas): constraints from outcrop data and stratigraphic modeling: Journal of Sedimentary Petrology, v. 63, p. 318–360.

Goldring, R., 1995, Organisms and the substrate: response and effect, *in* Bosence, D.W.J., and Allison, P.A., eds., Marine Palaeoenvironmental Analysis from Fossils: Geological Society of London, Special Publication 83, p. 151–180.

Goodwin, P.W., and Anderson, E.J., 1985, Punctuated aggradational cycles: a general hypothesis of episodic stratigraphic accumulation: Journal of Geology, v. 93, p. 515–33.

Haas, J., 1991, A basic model for Lofer cycles, *in* Einsele, G., Ricken, W., and Seilacher, A., eds., Cycles and Events in Stratigraphy: Berlin Springer-Verlag, p. 722–732.

Hallock, P., 1987, Fluctuations in the trophic resource continuum: a factor in global diversity cycles?: Palaeoceanography, v. 2, p. 457–471.

Hallock, P., 1988, The role of nutrient availability in bioerosion: consequences to carbonate buildups: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 63, p. 275–291.

Hallock, P., and Schlager, W., 1986, Nutrient excess and the demise of coral reefs and carbonate platforms: Palaios, v. 1, p. 389–398.

Irwin, M.L., 1965, General theory of epeiric clear water sedimentation: American Association of Petroleum Geologists, Bulletin, v. 49, p. 445–459.

James, N.P., 1984, Shallowing-upward sequences in carbonates, *in* Walker, R.G., ed., Facies Models: Geological Association of Canada, Geoscience Canada, Reprint Series 1, p. 213–228.

James, N.P., 1997, The cool-water carbonate depositional realm, *in* James, N.P., and Clarke, J.A.D., eds., Cool-Water Carbonates: Sedimentary Geology, Special Publication 56, p. 1–20.

James, N.P., and Bone, Y.B., 1994, Palaeoecology of cool-water, subtidal cycles in mid-Cenozoic limestones, Eucla Platform, southern Australia: Palaios, v. 9, p. 457–476.

James, N.P., Boreen, T.D., Bone, Y., and Feary, D.A., 1994, Holocene carbonate sedimentation on the west Eucla Shelf, Great Australian Bight: A shaved shelf: Sedimentary Geology, v. 90, p. 161–177.

Keulegan, G.H., and Krumbein, W.C., 1949, Stable configuration of bottom slope in a shallow sea and its bearing on geological processes: American Geophysical Union, Transactions, v. 80, p. 855–861.

Kidwell, S.M., 1991, Chapter 5, The stratigraphy of shell concentrations, *in* Allison, P.A., and Briggs, D.E.G., eds., Taphonomy: New York, Plenum Press, p. 212–290.

Kidwell, S.M., and Jablonski, D., 1983, Taphonomic feedback: Ecological consequences of shell accumulations, *in* Tevesz, M.J.S., and McCall, P.L., eds., Biotic Interactions in Recent and Fossil Benthic Communities: New York, Plenum Press, p. 195–248.

Lehrmann, D.J., and Goldstein, R.K., 1999, Secular variation in parasequence and facies stacking patterns of platform carbonates: a guide to application of stacking pattern analysis in strata of diverse ages and settings, *in* Harris, P.M., Saller, A.H., and Simo, J.A., eds., Advances in Carbonate Sequence Stratigraphy: Application to Reservoirs, Outcrops, and Models: SEPM, Special Publication 63, p. 187–226.
Lukasik, J., 2000, Shallow, low-energy, temperate-water carbonates from the Cenozoic Murray Basin, South Australia [Ph.D. thesis]: Queen's University, 284 p.
Lukasik, J., and James, N.P., 1998, Lithostratigraphic revision and correlation of Oligo–Miocene Murray Supergroup, western Murray Basin, South Australia: Australian Journal of Earth Sciences, v. 45, p. 889–902.
Lukasik, J.J., James, N.P., McGowran, B., and Bone, Y.B., 2000, An epeiric ramp: low-energy, cool-water carbonate facies in a Tertiary inland sea, Murray Basin, South Australia: Sedimentology, v. 47, p. 851–881.
Myrow, P.M., 1992, Pot and gutter casts from the Chapel Island Formation, southeast Newfoundland: Journal of Sedimentary Petrology, v. 62, p. 992–1007.
Orr, P., 1994, Trace fossil tiering within event beds and preservation of frozen profiles: an example from the Lower Carboniferous of Menorca: Palaios, v. 9, p. 202–210.
Osleger, D., 1991, Subtidal carbonate cycles: Implications for allocyclic vs. autocyclic controls: Geology, v. 19, p. 917–920.
Pratt, B.R., James, N.P., and Cowan, C.A., 1992, Peritidal carbonates, *in* Walker, R.G., and James, N.P., eds., Facies Models; Response to Sea Level Change: Geological Association of Canada, p. 303–322.
Radke, B.M., 1987, Sedimentology and diagenesis of sediments encountered by Victoria Department of Mines Piangil West-1, Murray Basin, southeastern Australia: Australia Bureau of Mineral Resources, Division of Continental Geology, Groundwater Series 3, Record 1987/25.
Read, J.F., 1998, Phanerozoic carbonate ramps from greenhouse, transitional and ice-house worlds: clues from field and modelling studies, *in* Wright, V.P., and Burchette, T.P., eds., Carbonate Ramps: Geological Society of London, Special Publication 149, p. 107–136.
Savrda, C.E., and Bottjer, D.J., 1986, Trace-fossil model for reconstruction of palaeo-oxygenation in bottom waters: Geology, v. 14, p. 3–6.
Shepherd, S.A., McComb, A.J., Bulthuis, D.A., Neverauskus, V., Steffenson, D.A., and West, R., 1989, Decline of seagrasses, *in* Larkum, A.W.D., McComb, A.J., and Shepherd, S.A., eds., Biology of Seagrasses: Amsterdam Elsevier, Aquatic Plant Studies 2, p. 346–393.
Shubber, B., Bone, Y.B., James, N.P., and McGowran, B., 1997, Warming-upward subtidal cycles in mid-Tertiary cool-water carbonates, St. Vincent Basin, South Australia, *in* James, N.P., and Clarke, J.A.D., eds., Cool-Water Carbonates: Sedimentary Geology, Special Publication, v. 56, p. 237–248.
Soreghan, G.S., and Dickinson, W.R., 1994, Generic types of stratigraphic cycles controlled by eustacy: Geology, v. 22, p. 759–761.
Stanton, R.J., and Dodd, J.R., 1976, The application of trophic structure of fossil communities in palaeoenvironmental reconstruction: Lethaia, v. 9, p. 327–342.
Taylor, A.M., and Goldring, R., 1993, Description and analysis of bioturbation and ichnofabric: Geological Magazine, 150, p. 141–148.
Tedesco, L.P., and Wanless, H.R., 1991, Generation of sedimentary fabrics and facies by repetitive excavation and storm infilling of burrow networks, Holocene of South Florida and Caicos Platform, B.W.I.: Palaios, v. 6, p. 326–343.
Tucker, M.E., and Wright, V.P., 1990, Carbonate Sedimentology: Oxford, U.K. Blackwell, 482 p.
Valentine, J.W., 1971, Resource supply and species diversity patterns: Lethaia, v. 4, p. 51–61.
Veevers, J.J., 1991, Mid-Cretaceous tectonic climax, Late Cretaceous recovery, and Cainozoic relaxation in the Australian region, *in* Williams, M.A., DeDekker, P., and Kershaw, A.P., eds., The Cainozoic in Australia: A Re-Appraisal of the Evidence: Geological Society of Australia, Special Publication 18, p. 1–15.
Walker, R.G., and James, N.P., 1992, Facies Models: Response to Sea Level Change: St. John's, Newfoundland, Geological Association of Canada, 409 p.
Wanless, H.R., 1981, Fining-upwards sedimentary sequences generated in seagrass beds: Journal of Sedimentary Petrology, v. 51, p. 445–454.
Wellman, P., 1987, Eastern highlands of Australia; its uplift and erosion: Australia, BMR, Journal of Australian Geology and Geophysics, v. 10, p. 277–286.
Wetzel, A., and Aigner, T., 1986, Stratigraphic completeness: Tiered trace fossils provide a measuring stick: Geology, v. 14, p. 234–237.
Wilson, J.L., 1975, Carbonate Facies in Geologic History: Heidelberg, Springer-Verlag, 471 p.

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