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Palaeogeography, Palaeoclimatology, Palaeoecology 166 (2001) 249–276

PALAEO

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Trace fossil assemblages in a Middle Triassic mixed siliciclastic-carbonate marginal marine depositional system, British Columbia

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Received 20 July 1999; accepted for publication 1 August 2000

Abstract

A diverse ichnofossil assemblage characterizes the mixed siliciclastic-carbonate marginal marine succession of the upper Liard Formation (Middle Triassic), Williston Lake, northeastern British Columbia. Sedimentary facies within this succession consist of five recurring facies associations: FA1 (upper shoreface/foreshore); FA2 (washover fan/lagoon); FA3 (intertidal flat); FA4 (supratidal sabkha) and FA5 (aeolian dune). Shoreface/foreshore sediments (FA1) accumulated on a storm-dominated, prograding barrier island coast and are characterized by a low-diversity *Skolithos* assemblage (*Diplocraterion*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Skolithos* and *Thalassinoides*). Washover fan/lagoonal sediments (FA2) are dominated by trophic generalists. (*Cylindrichnus*, *Gyrochorte*, *Palaeophycus*, *Planolites*, *Skolithos*, *Trichichnus* and an unusual type of bivalve resting trace), consistent with deposition in a setting subject to periodic salinity and oxygenation stresses. Intertidal flat deposits (FA3) are characterized by a diverse mixture of dwelling, feeding, and crawling forms (*Arenicolites*, *Cylindrichnus*, *Diplocraterion*, *Laevicyclus*, *Lingulichnus*, *Lockeia*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Siphonichnus*, *Skolithos*, *Teichichnus*, *Taenidium*, and *Thalassinoides*, reflecting the presence of adequate food resources in both the substrate and in the water column. Vertical burrow-dominated trace fossil assemblages within thin, sharp-based sand beds are interpreted as intertidal tempestites and reflect post-event colonization of the intertidal zone by shoreface organisms. Supratidal sabkha deposits (FA4) are characterized by an exceptionally low-diversity trace fossil assemblage (*Cylindrichnus*, *Monocraterion* and rare diminutive *Ophiomorpha*). Solution collapse breccia and root traces overprint many primary physical and biogenic sedimentary structures, reflecting numerous cycles of desiccation and flooding. Aeolian dune deposits (FA5) consist of unfossiliferous, exceptionally well-sorted sandstone beds.

Keywords: Triassic; ichnology; intertidal; supratidal; mixed siliciclastic-carbonate

1. Introduction

The upper Liard Formation along Williston Lake in the Peace River foothills of northeastern British Columbia consists of a complex succession of interstratified carbonate and siliciclastic sediments. These strata represent an overall shallowing-upward succession of progradational shoreface to marginal marine parasequences (Zonneveld and Gingras, 1997; Zonneveld et al., 1997a,b; Zonneveld, 1999) that accumulated on a gently sloping continental ramp on the northwestern Pangean continental margin.

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PII: S0031-0182(00)00212-1

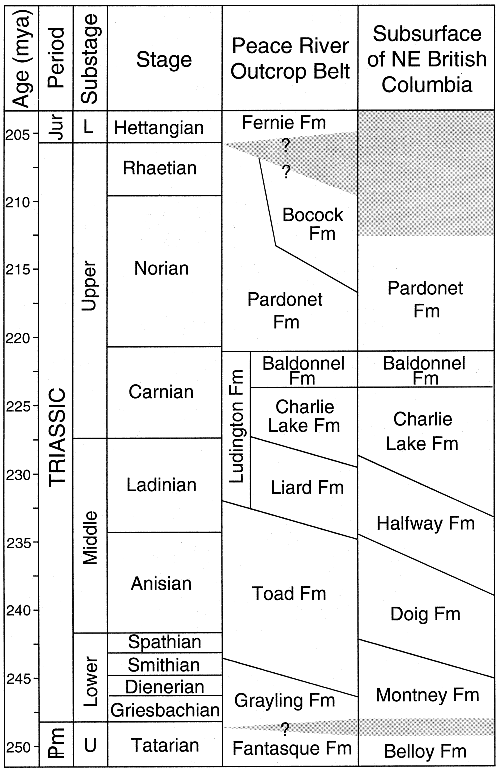


Fig. 1. Triassic stratigraphy in northeastern British Columbia (adapted from Gradstein et al., 1994; Tozer, 1994). Contacts between Lower and Middle Triassic formations are drawn to reflect their diachronous nature.

Although many studies dealing with recent mixed carbonate-siliciclastic systems discuss the flora and fauna that are present, most studies addressing ancient systems concentrate on physical depositional processes, and only peripherally consider trace and body fossil assemblages. The objectives of this paper are to: (1) present a depositional model for mixed siliciclastic-carbonate marginal marine intervals within the upper Liard Formation (Fig. 1) at Williston Lake, northeastern British Columbia (Fig. 2); (2) describe the distribution and diversity of trace fossils and body fossils within the various lithofacies associations; and (3) assess the controls influencing deposition within mixed siliciclastic-carbonate marginal marine environments.

1.1. Location of measured sections

This study focuses on Middle Triassic marginal marine deposits along the Peace Reach of Williston Lake (Fig. 2). Williston Lake is located approximately 80 km west of Fort St. John, British Columbia, in the Rocky Mountain Trench. The lake was created in 1967 by construction of the W.A.C. Bennett Dam on the Peace River. Exposure along Williston Lake is scoured annually by seasonal fluctuations in water level, keeping the outcrop relatively free of talus and debris.

Marginal marine strata were analyzed at three outcrop sections: Brown Hill, Glacier Spur, and Beattie Ledge (Fig. 2). The Glacier Spur and Brown Hill, outcrops consist of thick successions (320 and 580 m, respectively) of Middle Triassic (upper Anisian and Ladinian) proximal offshore, shoreface and marginal marine deposits. The Beattie Ledge outcrop consists of 250 m of Middle Triassic (Ladinian) shoreface and marginal marine deposits.

1.2. Stratigraphic setting

Triassic strata in the Western Canada Sedimentary Basin (Fig. 1) are composed of a westward-thickening marine and marginal marine succession of siliciclastic, carbonate, and evaporite sediments that were deposited on the western margin of the North American craton. Excellent exposures of the Liard Formation along the shores of Williston Lake provide insight into the depositional mechanisms of mixed siliciclastic-carbonate systems. The Liard Formation (Fig. 1) was defined by Kindle (1946) for a 180 m succession of calcareous sandstone and arenaceous limestone conformably overlying the Toad Formation (Fig. 1) on the Liard River. It was extended southwards by Pelletier (1964) and Gibson (1971) to include strata between the Toad and Charlie Lake Formations as far south as the Pine River, British Columbia. Within the Williston Lake region, the Liard Formation conformably overlies the Toad Formation, and consists of an overall shallowing-upward succession of approximately 15 progradational, mixed siliciclastic-carbonate shoreface parasequences (Zonneveld et al., 1997a,b; Zonneveld, 1999). In the study area, the Liard is conformably overlain by the predominantly

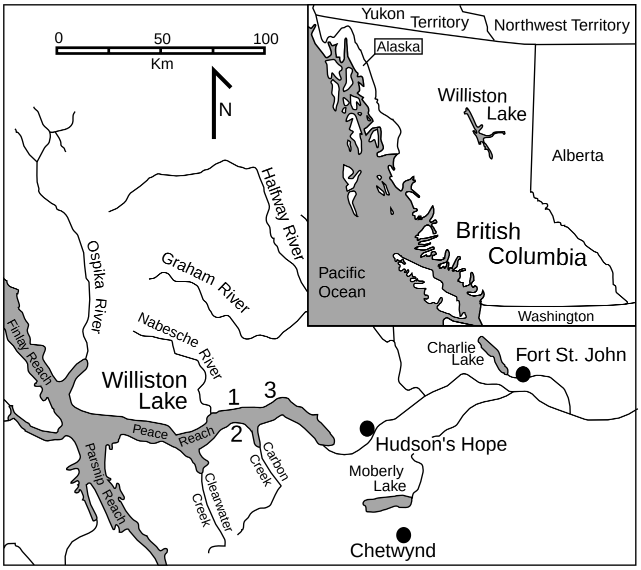


Fig. 2. Map of the study area along the Peace Reach of Williston Lake. The three localities discussed in this report are denoted by the numbers 1 (Brown Hill), 2 (Glacier Spur) and 3 (Beattie Ledge). Inset shows the location of Williston Lake in northeastern British Columbia, Canada.

marginal marine to nonmarine Charlie Lake Formation (Fig. 1).

Biostratigraphic analysis indicates that the upper Liard Formation is uppermost Ladinian in age (Zonneveld et al., 1997b). Although most of the units discussed in this paper do not contain biostratigraphically useful fossils, conodonts have been collected from horizons above and below the study interval. *Budurovignathus mungoensis* obtained from strata 5 m below the base of the study interval at Glacier Spur and Brown Hill (Zonneveld et al., 1997b) is characteristic of the upper Ladinian *sutherlandi* Zone (Mosher, 1973). Four ammonoid genera were collected from strata 10 m above the top the study interval at both Brown Hill and Glacier Spur (Zonneveld et al., 1997b; Zonneveld, 1999). These ammonoids, *Nathorstites macconnelli*, *Daxatina canadensis*, *Muensterites glaciensis* and *Lobites ellipticus*, are all diagnostic of the sutherlandi Zone (Tozer, 1994) indicating upper Ladinian deposition.

1.3. Tectonic setting

The Liard and Charlie Lake Formations represent a period of mixed siliciclastic-carbonate deposition on the western margin of the topographically low, North American craton during the Middle and Late Triassic. The Williston Lake area is situated immediately north of the Peace River embayment, a major tectonic downwarp initiated by the collapse of the Paleozoic Peace River Arch (Barss et al., 1964; Cant, 1988). Although some workers have suggested that tectonism had minimal effect on Triassic deposition in western Canada (Gibson and Barclay, 1989; Gibson and Edwards, 1990), it has been postulated that slump deposits and overthickened shoreface facies associations in the subsurface Doig Formation (Middle Triassic) formed due to seismic activity and/or growth faulting, possibly as a result of movement along an active margin (Wittenberg, 1992, 1993). Recently, several studies have documented the role of high angle normal faulting on synsedimentary tectonism in the Triassic of the Western Canada Sedimentary Basin (Evoy and Moslow, 1996; Evoy, 1997; Caplan and Moslow, 1997).

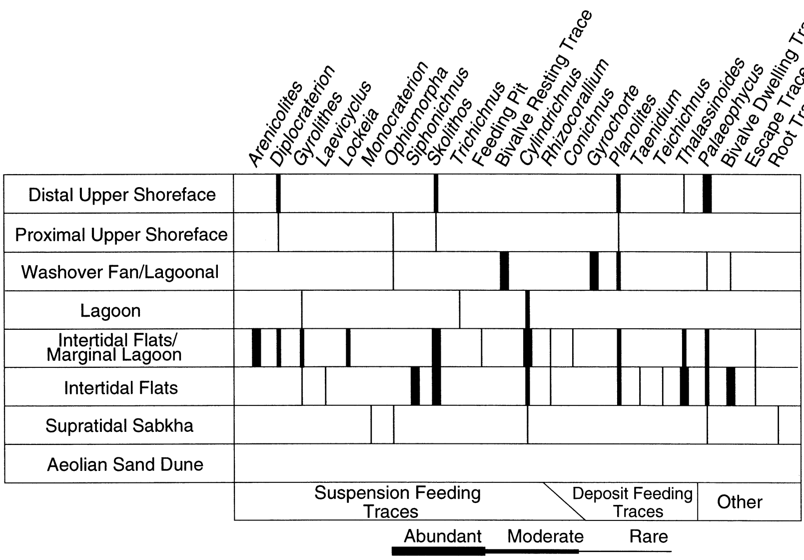
1.4. Paleoenvironmental setting

There is little evidence of the paleoclimate in the study area during the Middle Triassic. Paleogeographic analyses based in part on paleomagnetic data suggest a paleolatitude of approximately 30°

Table 1
Sedimentary facies characteristics in the Liard Formation, Brown Hill, Glacier Spur and Beattie Ledge, Williston Lake, British Columbia.Ar = *Arenicolites*; Co = *Conichnus*; Cy = *Cylindrichnus*; Di = *Diplocraterion*; Gy = *Gyrochorte*; La = *Laevicyclus*; Lo = *Lockeia*; Mo = *Monocraterion*; Op = *Ophiomorpha*; Pa = *Palaeophycus*; Pl = *Planolites*; Si = *Siphonichnus*; Sk = *Skolithos*; Ta = *Taenidium*; Te = *Teichichnus*; Th = *Thalassinoides*; Tr = *Trichichnus*; BRT = bivalve resting trace; BDT = bivalve dwelling trace; BAT = bivalve adjustment trace; Fug = fugichnia; Root = root traces; Pit = feeding pits

Facies	Physical sedimentary structures	Biogenic structures	Body fossils	Depositional environment
A1: Silstone/Sandstone	Plane parallel laminae, flow ripples, HCS, rare oscillation ripples	Sc, Th, Sp, Lk, Pa, Pl	Scattered lingulids, bivalves, and reptile bones	Offshore/shoreface transition
A2: Sandstone (very fine)	Amalgamated hummocky cross-stratified beds, planar bedding, current and oscillation ripples	Ar, Di, Cy, Pa, Pl, LkLi, R o, Sk, Te, Th, BDT, fug	Brachiopods, bivalves, fish, and ammonoids	Lower shoreface
B1: Calcareous sandstone (very fine to fine)	Predominantly tough cross-stratified, rare hummocky (and Swaley?) cross-stratification, rare oscillation ripples	Di, Sk, Pa, Pl, fug	Scattered brachiopod and echinoderm debris	Distal upper shoreface
B2: Cross-stratified, calcareous, bioclastic sandy packstone	Trough to planar cross-stratification at base, grading up into planar-tabular laminae. Inversely graded	Op, Pl, Sk	Bioclastic debris, brach., bivalves, rare bones	Proximal upper shoreface/ foreshore
C1: Calcareous	Appears massive, planar lam. to trough cross-stratification, beds thicken upwards (5–10 to 30 cm)	Gc, Pa, Pl, bivalve resting trace	Rare *Lingula* and bioclastic debris	Washover fan/lagoon
C2: Planar cross-laminated bioclastic sandstone	Low-angle planar cross-laminated, oscillation ripple lamination	Gc, Pa, Pl, bivalve resting trace	Rare spiriferid and lingulid brachiopods	Washover fan/lagoon
D1: Fenestral laminated	None noted	Algal laminae	None noted	Lagoonal/intertidal flat
D2: Dolomitic mudstone	Planar laminae, syneresis cracks	Cy, Gy, Tr	rare lingulids, bivalves, and gastropods	Lagoonal/intertidal/supratidal flats
E: Dolomite sandstone	Heterolithic wavy laminae, flaser bedding, symmetrical ripples, dessication cracks, rill marks	Cy, Gy, La, Pa, Pl, Rh, Si, Sk, Te, Th, BDT, pit	bivalves, gastropods, lingulid fragments	Interdial flats
F: Dolomitic silstone	Planar laminations, current and oscillation ripples, heterolithic wavy laminae, polygonal mudcracks	Ar, Cy, Co, Di, Gy, Lo, Pa, Pl, Rh, Sk, Th, pit	*Lingula*, gastropods bivalve fragments	Intertidal flats/marginal lagoon
G: Solution collapse breccia	Solution collaspse of other lithofacies	Root	None noted	Supratidal sabkha
H: Calcareous sandstone (fine to medium)	Predominantly trough cross-stratification grading up into current ripple laminae, mudclast lags	None observed	Rare bivalve shell lags	Tidal inlet channels
I: Ripple-laminated dolomitic silstone/ mudstone	Wavy to ripple laminated, adhesion ripples	Cy, Mo, Op, root traces	None observed	Supratidal sabkha
J: High-angle cross-stratified sandstone	High-angle cross-stratified, planar cross-bedding, rare oscillation ripples, inversely graded laminae	None observed	None observed	Aeolian and dune

Table 2
Paleoenvironmental distribution of trace fossils in the study interval of the Liard Formation



North (Habicht, 1979; Tozer, 1982; Wilson et al., 1991). Paleocurrent measurements of aeolian sandstone beds indicate a dominant wind direction from the northeast (Arnold, 1994). The predominantly southwest-oriented air flow is believed to have created a seasonal offshore flow of marine surface water which was compensated for by upwelling of colder, nutrient-rich, possibly anoxic water onto the shelf (Moslow and Davies, 1992). Regional cross-bedding and ripple mark data in the Liard Formation suggests a predominantly northwest–southeast trending paleoshoreline (Pelletier, 1965). Physical sedimentary structures in upper shoreface deposits adjacent to the study interval are consistent with deposition in a high-energy setting, accompanied by strong longshore drift, probably from the north (Pelletier, 1965; Campbell and Horne, 1986).

The extensive distribution of evaporite minerals in the Charlie Lake Formation suggests arid conditions during the Triassic (Gibson and Barclay, 1989; Zonneveld et al., 1997a). Although evaporite minerals were not observed in the study area, their deposition is inferred by the presence of several thick and laterally extensive solution collapse breccias (likely resulting from the dissolution of anhydrite beds).

2. Depositional framework and trace fossil assemblages

Within the study interval, 14 lithofacies are recognized in the upper Liard Formation. These are defined on the basis of lithology, bounding surfaces, primary physical and biogenic sedimentary structures, and fossil assemblages (Table 1). A summary of the paleoenvironmental distribution of trace fossils observed within the study interval is presented in Table 2. Detailed sections were measured at Brown Hill (Fig. 3), Glacier Spur (Fig. 4), and Beattie Ledge (Fig. 5) to describe sedimentary facies and to assess vertical and lateral facies variability (trace fossil and body fossil symbols used in Figs. 3–5 are summarized in Fig. 6). Brown Hill and Glacier Spur are located approximately 2 km apart on depositional strike from one another (Fig. 2). Beattie Ledge is located approximately 18 km east (updip) of the other two sites (Fig. 2). Stratigraphic relationships between the three sites are discussed later in the paper.

This paper limits its discussion to lithofacies interpreted as marginal marine. Other lithofacies were

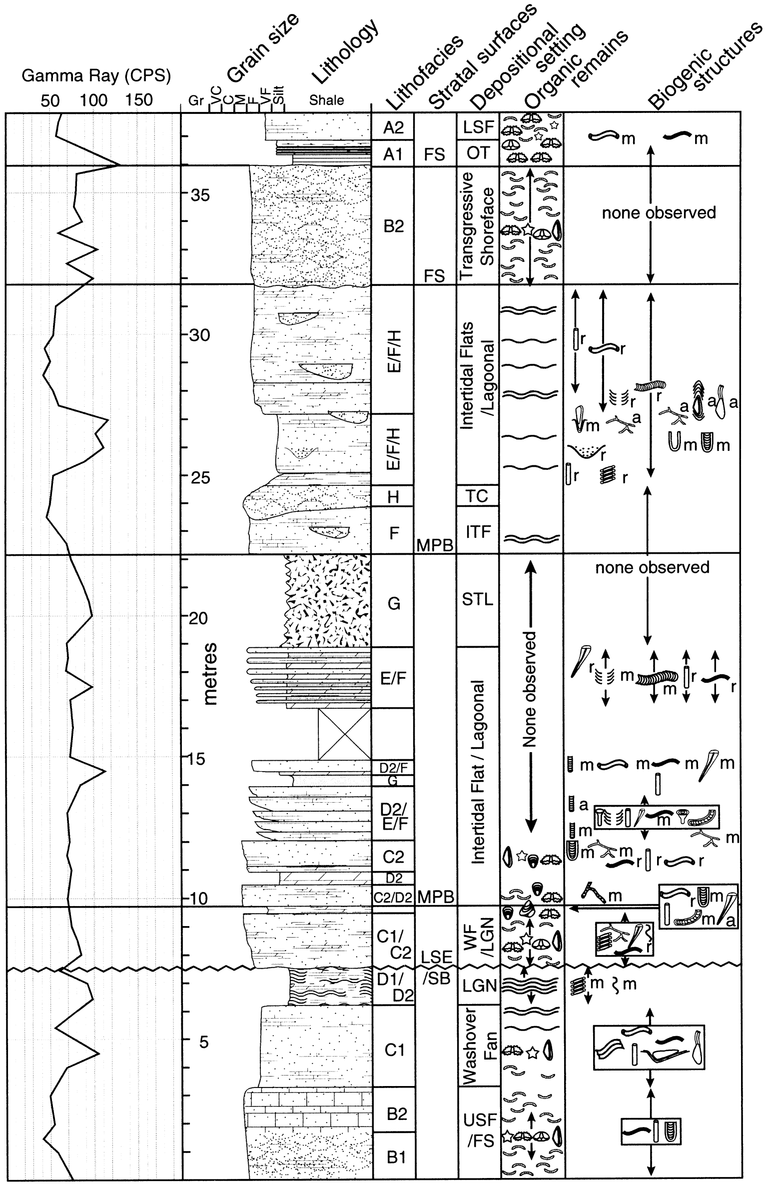


Fig. 3. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Brown Hill. Outcrop gamma readings are measured in counts per second (CPS). FS = Flooding Surface; MPB = Marginal Marine Parasequence Boundary; LSE/SB = Lowstand Surface of Erosion/Sequence Boundary; TSE = Transgressive Surface of Erosion; OT = Offshore Transition; LSF = Lower Shoreface; USF = Upper Shoreface; FS = Foreshore; TSF = Transgressive Shoreface; WOF = Washover Fan; LGN = Lagoonal; ITF = Intertidal Flat; TIC = Tidal Inlet Channel; STS = Supratidal Sabkha. Trace fossil and body fossil symbols are summarized in Fig. 6. Lithofacies patterns are summarized in Fig. 7.

described in Zonneveld et al. (1997b) and are not discussed here. Lithofacies interpreted as marginal marine oscillate repeatedly in five recurring progradational facies associations. These facies associations are: FA1 (upper shoreface/foreshore), FA2 (washover fan/lagoon), FA3 (intertidal flat), FA4 (supratidal sabkha) and FA5 (aeolian dune) (Fig. 7).

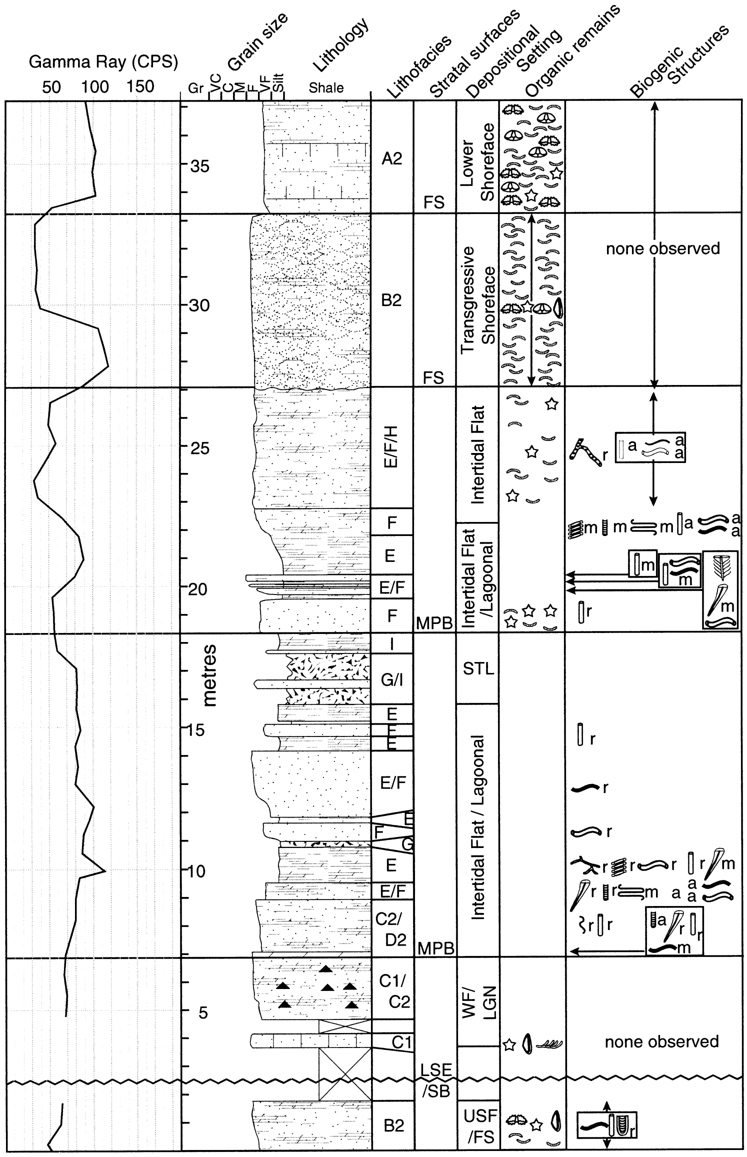


Fig. 4. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Glacier Spur. Outcrop gamma readings are measured in counts per second (CPS). FS = Flooding Surface; MPB = Marginal Marine Parasequence Boundary; LSE/SB = Lowstand Surface of Erosion/Sequence Boundary; TSE = Transgressive Surface of Erosion; OT = Offshore Transition; LSF = Lower Shoreface; USF = Upper Shoreface; FS = Foreshore; TSF = Transgressive Shoreface; WOF = Washover Fan; LGN = Lagoonal; ITF = Intertidal Flat; TIC = Tidal Inlet Channel; STS = Supratidal Sabkha. Trace fossil and body fossil symbols are summarized in Fig. 6. Lithofacies patterns are summarized in Fig. 7.

Two ichnofacies, *Skolithos* and *Psilonichnus*, are pertinent to this study. Their importance and distribution are outlined in the following section.

2.1. Facies association 1 (FA1): upper shoreface/ foreshore (description)

Facies Association 1 consists of facies B1 and B2.

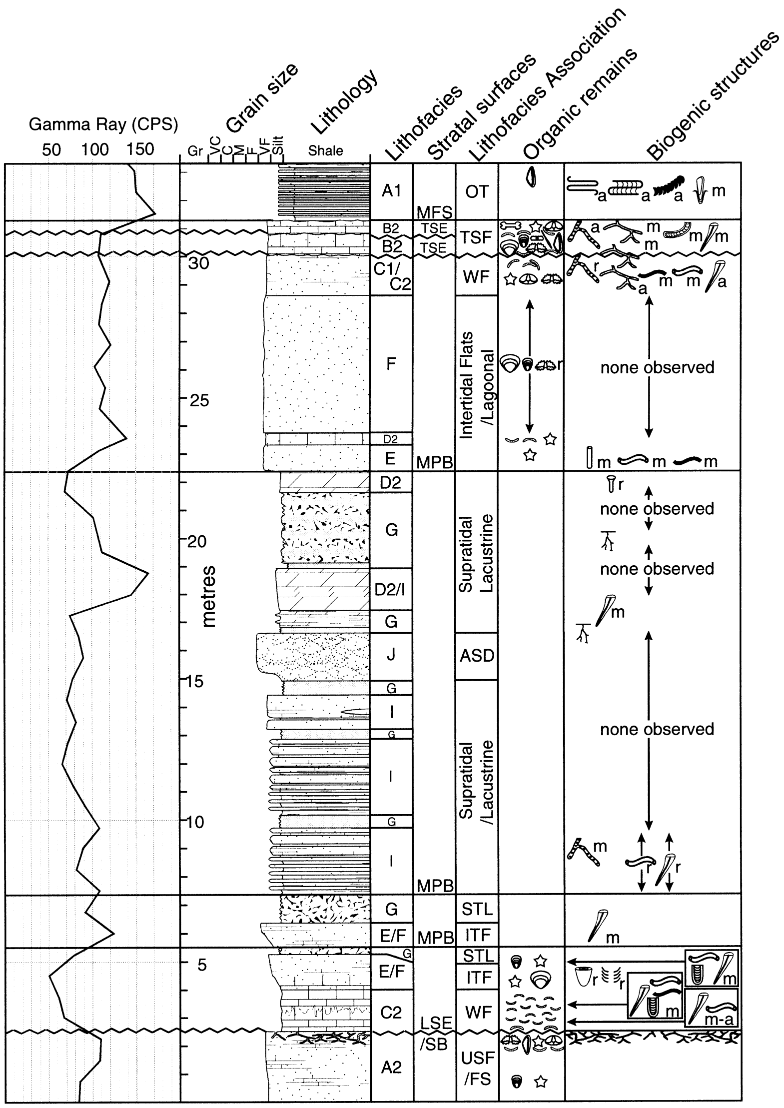


Fig. 5. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Beattie Ledge. Outcrop gamma readings are measured in counts per second (CPS). FS = Flooding Surface; MPB = Marginal Marine Parasequence Boundary; LSE/SB = Lowstand Surface of Erosion/Sequence Boundary; TSE = Transgressive Surface of Erosion; OT = Offshore Transition; LSF = Lower Shoreface; USF = Upper Shoreface; FS = Foreshore; TSF = Transgressive Shoreface; WOF = Washover Fan; LGN = Lagoonal; ITF = Intertidal Flat; TIC = Tidal Inlet Channel; STS = Supratidal Sabkha. Trace fossil and body fossil symbols are summarized in Fig. 6. Lithofacies patterns are summarized in Fig. 7.

Facies B1 is predominantly trough cross-stratified sandstone. Swaley cross-stratification capped by oscillation ripple laminae is locally observed. Bedsets range in thickness from 45–150 cm, and typically thicken upwards. The bases of beds are sharp and in many cases erosional. Facies B1 most commonly overlies calcareous, hummocky cross-stratified sandstone (Facies A2) and is overlain by planar tabular cross-stratified sandstone to sandy packstone (Facies B2). Body fossils within Facies B1 include scattered crinoid ossicles, echinoid debris (spines and interambulacral plates) and terebratulid brachiopods. Skeletal

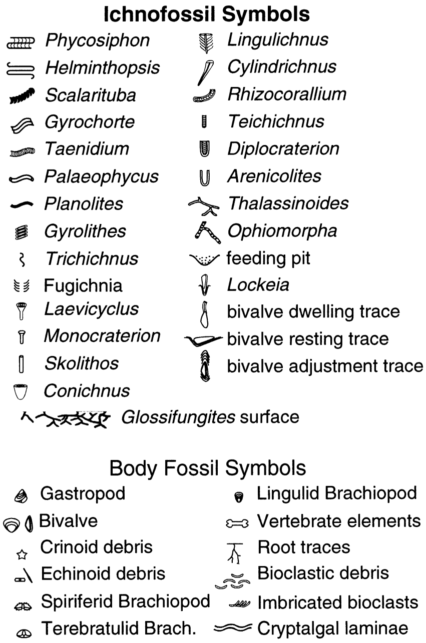


Fig. 6. Ichnofossil and body fossil symbols used in Figs. 3–5. r = rare; m = moderate, a = abundant.

debris is generally disarticulated, however, the degree of abrasion is low. The resident ichnofauna consists of a moderately low-diversity trace fossil assemblage. Trace fossils include *Diplocraterion parallelum*, *Ophiomorpha annulata*, *Palaeophycus tubularis*, *Planolites beverleyensis*, *Skolithos linearis* and *Thalassinoides suevicus*. With the exception of *Ophiomorpha* and *Thalassinoides* (10–20 mm diameter), the traces are small to moderate in size (3–10 mm diameter). The degree of bioturbation is low (ichnofabric index 1–3) and ichnofossils are sporadically distributed.

Facies B2 consists of trough to planar cross-bedded to planar tabular cross-laminated, calcareous sandstone and bioclastic sandy packstone. It is fine- to medium-grained, and composed of rounded calcareous bioclasts and quartzose sand. This facies also contains abundant, disseminated chert pebbles and chert pebble laminae. The sand fraction is moderately well-sorted, whereas the calcareous bioclasts are highly fragmented and poorly sorted. Bioclasts within Facies B2 consist primarily of highly abraded bivalve, crinoid, echinoid, and brachiopod (spiriferid and terebratulid) fragments. Laterally restricted

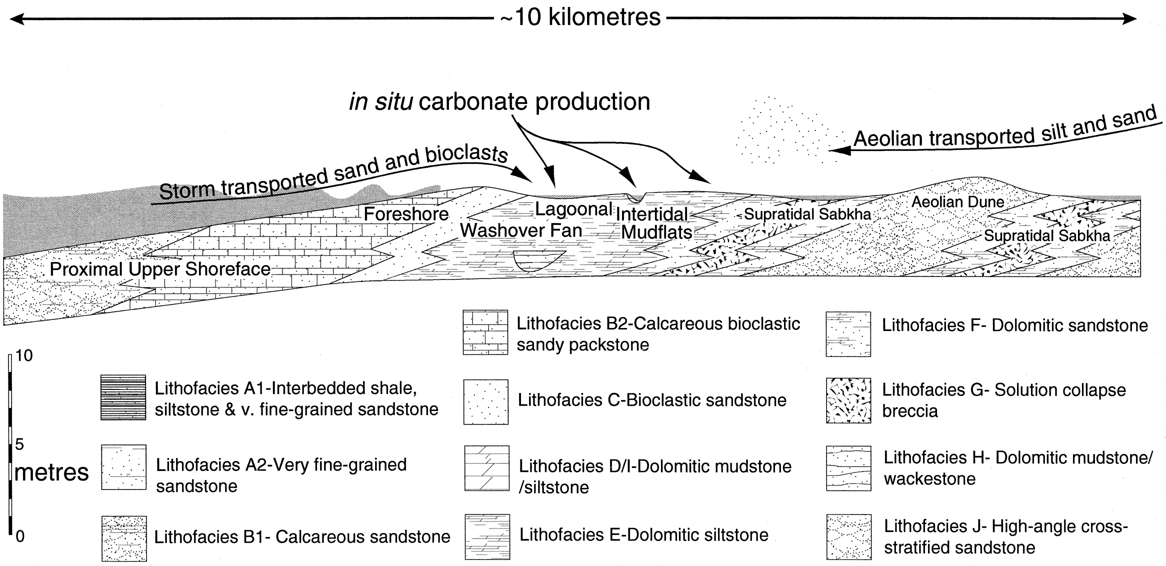


Fig. 7. Postulated lateral distribution of major environments and lithofacies of the upper Liard mixed siliciclastic-carbonate marginal marine succession within the study area showing main sediment sources.

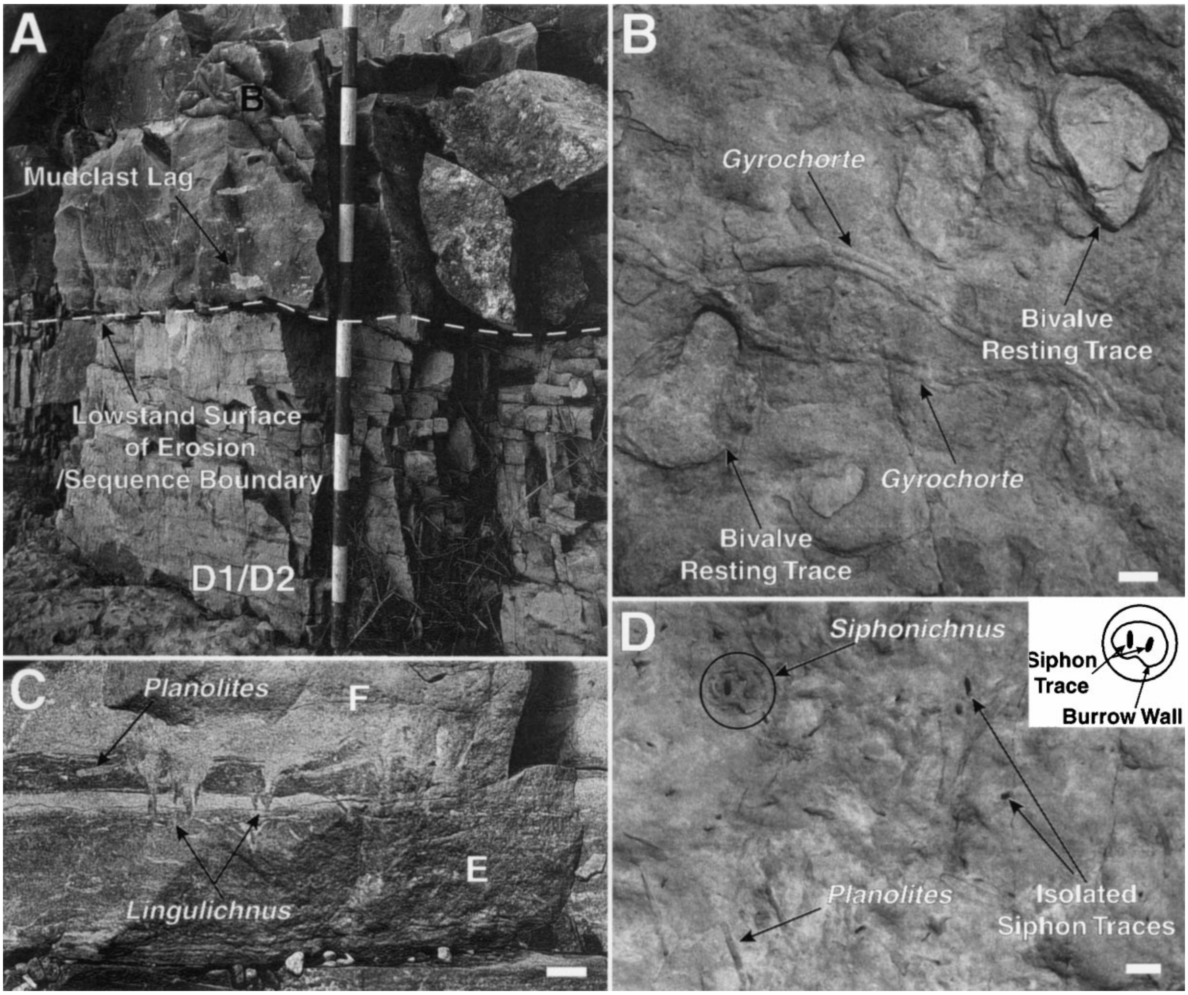


Fig. 8. (A) Outcrop photograph showing erosional incision of lithofacies B, shoreface sandstone (B) into lithofacies D, fenestral laminated dolomite (D), Brown Hill. This ravinement surface has been interpreted as a lowstand surface of erosion and as a sequence boundary. Measuring staff has 10 cm increments. (B) Outcrop photograph showing *Gyrochorte comosa* and bivalve resting traces on a lithofacies C bedding plane, parasequence L10, Brown Hill. Scale bar at bottom right is 1 cm. (C) Outcrop photograph of Lithofacies E and F, intertidal flat dolomitic siltstone and sandstone, in vertical section showing Planolites and small *Lingulichnus verticalis*, parasequence L12, Glacier Spur. Scale bar at bottom right is 1 cm. (D) Outcrop photograph of lithofacies E (intertidal flat sandstone) bedding plane showing the bivalve dwelling trace *Siphonichnus*. In bedding plane aspect (shown), each trace consists of one or a pair of vertical tubes that are often surrounded by a faint subcircular to kidney-shaped burrow. Other elliptical shaft openings surrounding this trace are likely other bivalve siphon traces. Scale bar at bottom right is 1 cm. Inset at top right shows a line drawing of the circled *Siphonichnus* specimen showing the kidney-shaped causative burrow and two distinct siphon openings.

concentrations of whole, generally abraded mollusc and brachiopod shells occur intermittently throughout this unit. Isolated, highly eroded reptile (ichthyosaur?) bone fragments occur near the top of lithofacies B2 at Brown Hill. *Planolites* isp. is the only trace fossil observed within Facies B2.

2.2. FA1: Upper shoreface/foreshore (interpretation)

Abundant scour surfaces and trough to planar cross-stratification are indicative of deposition in an environment dominated by deposition from traction, frequent wave reworking and intermittent, high current velocities. The sharp, locally erosive bases of bedsets are suggestive of storm generated waning-flow transport. Furthermore, remarkably similar trace fossil assemblages are associated with shoreface deposits in Cretaceous strata of the Western Canadian Sedimentary Basin and are characteristic of the proximal *Skolithos* ichnofacies (Pemberton and MacEachern, 1995). Accordingly, Facies B1 is interpreted as being representative of deposition on the upper shoreface. Moderately well-sorted quartz sand, the sporadic nature of trace fossil occurrences, and the highly abraded nature of the bioclasts further support this interpretation.

Trough to planar cross-stratified beds observed in the basal portion of Facies B2 are interpreted as having been deposited within the proximal upper shoreface (or inner rough zone). Welded planar bedsets that characterize the bioclastic deposits in the upper part of Facies B2 are indicative of shoreline progradation and signal a switch to deposition within the swash zone. In summary, the sedimentological and ichnological data indicate that FA1 most likely accumulated on a storm-dominated, prograding barrier island coast (Zonneveld et al., 1997b).

2.3. Facies association 2 (FA2): washover fan/lagoon (description)

Facies association 2 is composed of facies C1, C2, D1 and D2. Facies C1 is composed of fine-grained, well-sorted sandstone, containing chert pebbles and abundant bioclastic material. Horizontal to subhorizontal laminae, although commonly obscured by weathering and biogenic reworking, are the dominant physical bedform. Near the base of the Brown Hill Liard section, lithofacies C1 gradationally overlies a sandy bioclastic packstone interpreted as proximal upper shoreface (Zonneveld et al., 1997b), and is abruptly overlain by fenestral-laminated carbonate mudstone (Facies D1).

Facies C2 consists of an overall coarsening upwards succession of well-sorted, very-fine to fine-grained sandstone. Facies C2 is predominantly low angle planar cross-stratified to planar-laminated, but it also contains wave ripple laminated layers throughout. Bedsets range from 5 to 25 cm in thickness. Thin dolomitic siltstones characterized by fenestral and microbial laminae occur throughout. Near the base of the Brown Hill Liard section, the basal contact of facies C2 incises deeply into facies D and is characterized by a lag of angular rip-up clasts deposited concordant with bedding (Fig. 8A).

Facies C1 and C2 contain a low-diversity trace fossil assemblage, consisting of *Skolithos linearis*, *Palaeophycus tubularis*, *Planolites beverleyensis*, *Gyrochorte* isp. (Fig. 8B), and an undescribed type of bivalve resting trace (Fig. 8B). Facies C is characterized by a moderate amount of bioturbation (ichnofabric index 2–4). Facies C1 contains scattered bioclastic material including rare, whole spiriferid and lingulid brachiopods, and abundant brachiopod and echinoderm skeletal debris. Body fossils within facies C2 consist of rare, scattered bioclastic debris and rare *Lingula* sp. valves.

Facies D1 consists predominantly of planar to undulatory laminated dolomite with abundant thin, normally graded siltstone and sandstone laminae. Abundant diminutive fenestrae (birdseye structures) occur within facies D1. Facies D2 consists of planar laminated dolomitic mudstone with siltstone, sandstone and bioclast laminae, and abundant synaeresis cracks (Fig. 9b). Facies D generally occurs as thin (0.5–20 cm) beds interbedded with lithofacies C1, C2, D2, E and F. An unusually thick occurrence (~1.7 m) of facies D (interlaminated D1 and D2) occurs near the base of the Brown Hill section. This unit is erosionally overlain by facies C2 (mixed shoreface, foreshore and washover fan). Trace fossils and body fossils were not observed within facies D1. Facies D2 contains *Trichichnus* isp. and diminutive *Cylindrichnus*, as well as rare lingulid, bivalve, and gastropod body fossils. The degree of bioturbation is low throughout lithofacies D (ichnofabric index 1–3).

2.4. Facies association 2 (FA2): washover fan/lagoon (interpretation)

Facies C1 is interpreted as a washover fan/lagoonal deposit. Facies C2 is interpreted as an amalgamation of foreshore, washover fan, and lagoonal deposits. The massive appearance of the basal beds of lithofacies C2 at Brown Hill is due primarily to a lack of grain size variability. Individual sharp-based sandstone beds are interpreted as a product of storm washover events. The low-diversity trace fossil assemblage is dominated by trophic generalists, consistent with

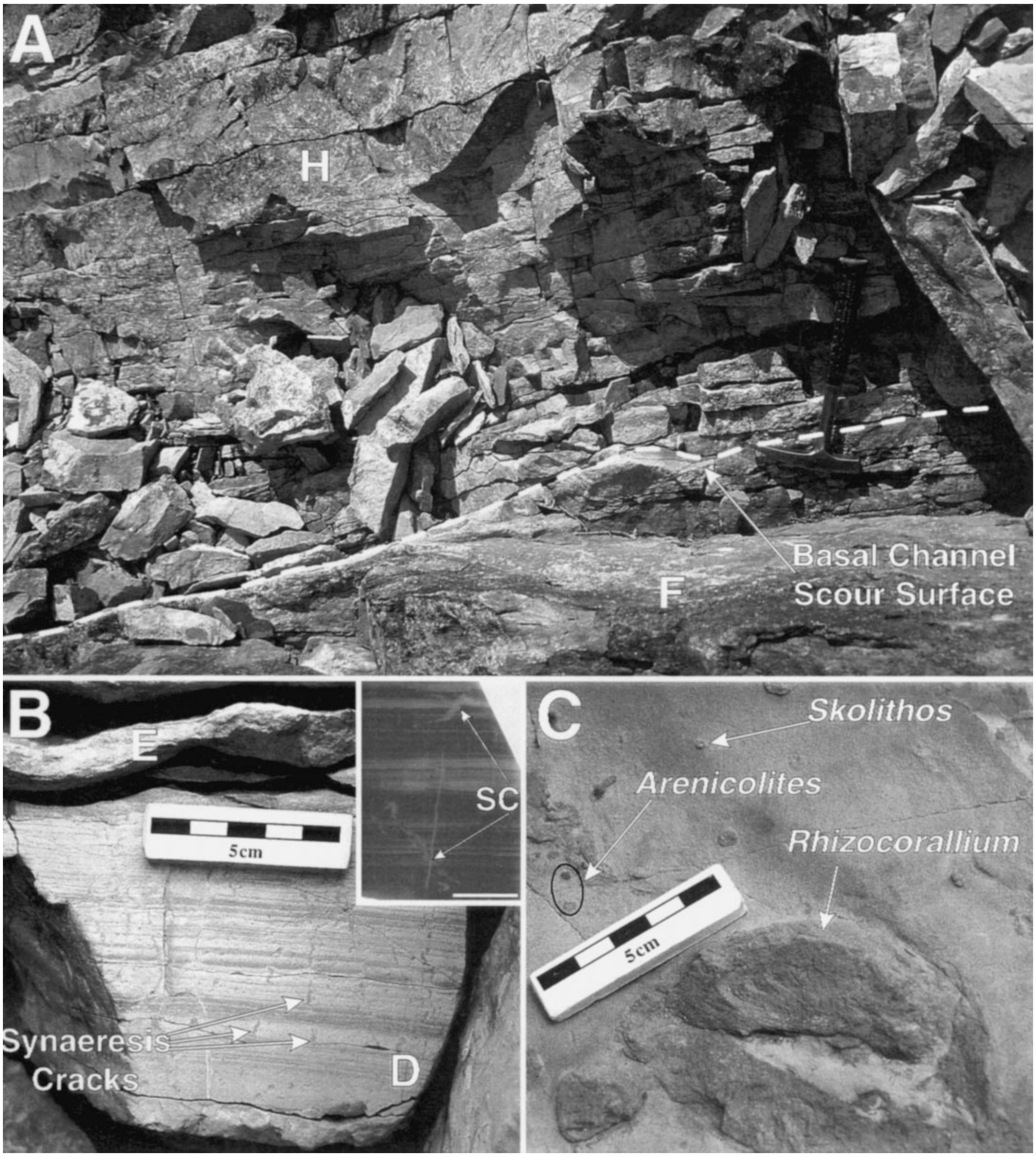


Fig. 9. (A) Outcrop photograph showing tidal channel incision (lithofacies H) into intertidal flat dolomitic siltstone and sandstone (lithofacies E and F), parasequence L12, Brown Hill. Rock hammer is approximately 30 cm in length. (B) Outcrop photograph showing vertical section of synaeresis cracks within laminated dolomitic mudstone (lithofacies D) deposited within a lagoonal setting, parasequence L11, Brown Hill. Inset shows polished slab showing planar lamination cross-cut by synaeresis cracks. Scale bar is 1 cm in length. (C) Outcrop photograph showing rippled bedding plane surface with abundant burrows including *Arenicolites* and *Rhizocorallium* and *Skolithos*, lithofacies E (dolomitic siltstone), parasequence L12, Brown Hill.

deposition in a setting subject to periodic salinity and oxygenation stresses (Pemberton et al., 1982; Gingras et al., 1999).

Facies D1 and D2 were deposited within a back barrier lagoon setting. Facies D1 is interpreted as a microbal laminite. Undulatory or wrinkled laminae result from subtle variations in microbal growth/ reproduction rates (Cadée, 1998). Fenestrae or birdseye structure results from shrinkage of microbal laminae during desiccation, and from gas generated during microbal decay (Shinn, 1983). Microbal mats form in protected subtidal intertidal and supratidal settings, but they are most commonly preserved on intertidal flats (Hagan and Logan, 1975).

Facies D2 differs from D1 primarily by the presence of synaeresis cracks and absence of undulatory laminae or fenestrae. Synaeresis cracks form subaqueously during reorganization of porous clays, commonly as a result of salinity-induced volume changes in clay minerals (Plummer and Gostin, 1981). Common interlamination of these two subfacies suggests deposition within closely spaced depositional environments. Alternatively, this interlamination may reflect seasonal variations in the presence and lateral extent of microbal mats. Microbal mats tend to inhibit burrowing by infaunal organisms explaining the absence of trace fossils within facies D1. The sandstone, siltstone and bioclast laminae within both lithofacies may represent deposition during storm washover events (Aigner, 1985). Alternatively, fine-grained clastic laminae may represent deposition during periodic (neap-spring?) tidal flooding (Shinn, 1983) or possibly severe dust storms originating in the arid interior east of the study area (Davies, 1997; Zonneveld et al., 1997b).

Physical sedimentary structures within FA2 reflect deposition in a setting in which current strength varied considerably. Bedforms such as planar cross-stratification and wave ripple laminae reflect traction dominated deposition. Planar lamination of clay and silt sized sediment typically results from suspension deposition. Planar laminated dolomitic mudstone (facies D1 and D2) with numerous sharp-based, normally graded sandstone, siltstone and bioclast laminae, reflect dominantly suspension deposition within a quiescent setting, punctuated by short duration intervals dominated by traction deposition. Although the lithologies of facies C1 and C2 differ somewhat, their trace-fossil assemblages are similar.

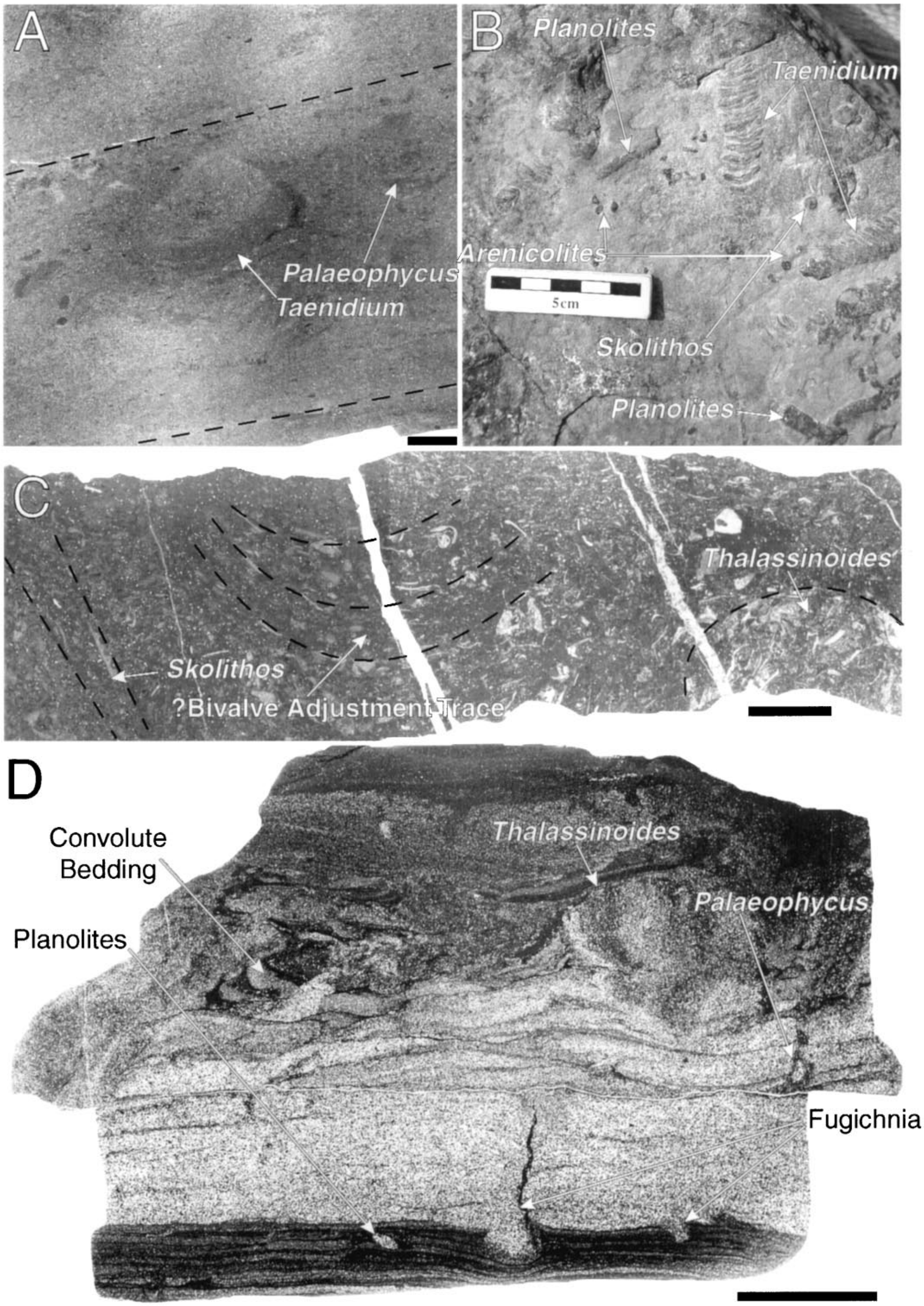
2.5. Facies association 3 (FA3): intertidal flat (description)

Facies Association 3 (FA3) is composed primarily of dolomitic sandstone (Facies E), muddy dolomitic siltstone (Facies F) and interlaminated dolomitic mudstone (Facies D2). Sharp-based, laterally restricted (0.25–4.25 m wide), trough cross-bedded to current ripple-laminated, calcareous sandstone lenses (Facies H) are locally observed (Fig. 9A).

Facies E consists of very fine-grained dolomitic sandstone. Flaser bedding and wavy to planar bedding are the dominant physical bedforms. Other physical sedimentary structures include massive bedding, current, interference- and symmetrical-oscillation ripples, and polygonal desiccation cracks. Laterally restricted furrows (scours) characterized by massive to laminated fill are locally present. Facies F consists of dolomitic muddy siltstone and is characterized by planar lamination and subordinate wavy lamination and massive bedding. Polygonal mudcracks, interference ripples, runzel marks and sandstone laminae are common features on facies F.

Facies E and F occur together and share gradational contacts. Notably, several interbeds within both facies are massive appearing. Dolomitic mudstone/siltstone intraclasts are common within these facies; the clasts are generally oriented concordant with bedding. Importantly, rill marks are observed on discrete bedding planes. Abundant microbal mounds and laminae (Facies D1) are common components of FA3. The body fossil assemblages observed in Facies E and F are nearly identical. These include rare bivalves, gastropods, and scattered lingulid brachiopod fragments deposited concordant to bedding. Abraded crinoid, echinoid, terebratulid brachiopod and spiriferid brachiopod fragments are also common, albeit in thin, normally graded sand layers.

Seven ichnospecies have been identified in Facies E, including *Cylindrichnus concentricus*, *Lingulichnus verticalis* (Fig. 8C), *Palaeophycus tubularis*, *Planolites beverleyensis* (Fig. 8C), *Siphonichnus* isp. (Fig. 8D), *Skolithos linearis*, *Teichichnus* isp. and *Thalassinoides suevicus*. In general, the trace fossils descend from the base of thin (2–10 cm) normally graded sand interbeds. In contrast, Facies F is dominated by eleven ichnospecies. These are *Arenicolites* isp. (Fig. 10B), *Diplocraterion parallelum*, *Cylindrichnus concentricus*, *Laevicyclus* isp., *Lockeia siliquaria*, *Palaeophycus tubularis* (Fig. 10A), *Planolites beverleyensis* (Fig. 10B and D), *Rhizocorallium jenense* (Fig. 9C), *Skolithos linearis* (Figs. 9C and 10B), *Taenidium serpentinum* (Fig. 10A and B) and *Thalassinoides* isp. (Figs. 9C and 10D). Ichnofauna in


A
Palaeophycus
Taenidium
B
Planolites
Taenidium
Arenicolites
5cm
Skolithos
Planolites
C
Skolithos
?Bivalve Adjustment Trace
Thalassinoides
D
Convolute Bedding
Planolites
Thalassinoides
Palaeophycus
Fugichnia

Facies F are unevenly distributed and the degree of bioturbation is highly variable. Some interbeds are unburrowed, whereas others are completely churned (ichnofabric index 4–5). Finally, trace fossils in Facies E and F are quite small (generally <3 mm diameter).

2.6. Facies association 3 (FA3) (interpretation)

In general, the sediment caliber (very fine- to fine-grained sand) and the bedforms associated with Facies E reflects deposition dominated by bedload transport, normally under lower flow regime conditions (e.g. flaser bedding, and current- and interference -ripples). The presence of oscillatory ripples infers wave reworking during periodic submergence. Parting lineations on the base of planar laminated sandstone, however, were imposed by high current velocities and suggest deposition during upper plane bed conditions (Allen, 1982a). In contrast, Facies F is characterized by comparably fine-grained sediment (muddy silt with abundant dolomitic mud laminae). Layers of finely laminated mud and muddy silt intercalate with current ripple-laminated and flaser to lenticular bedded siltstone. These are indicative of an environment characterized by mixed traction and suspension deposition.

These strata represent deposition within an intertidal sedimentary environment. The presence of desiccation cracks, rill and runzel marks, and a locally stressed to absent ichnofauna provide strong evidence for this. Furthermore, subaqueous sedimentary features are abundant, these include interference ripples, flaser bedding; and parting lineations. These data are bolstered by a pervasive trace fossil assemblage that is most consistent with subtidal to intertidal bathymetric conditions. These characteristics are discussed in detail in the ensuing paragraphs.

Deposition within the intertidal zone occurs under a wide variety of flow conditions. Current strength varies from essentially still-water conditions at high tide to upper plane bed conditions during ebb runoff (de Boer, 1998; Clifton and Phillips, 1980). The sedimentological differences noted between Facies E and F indicate that sediment accumulation occurred in various intertidal flat sub-environments. This is consistent with the heterogeneity inherent to intertidal flat deposits (Peterson, 1991; Cadée, 1998). Ideally, FA3 represents the progradation of the inner- (Facies E) over the outer- (Facies F) intertidal flat. This is similar to several Holocene to recent intertidal flat deposits that have been documented to exhibit a seaward-coarsening textural distribution. These examples include Willapa Bay, Washington (Gingras et al., 1999), Bahia La Choya on the Gulf of California (Flessa and Ekdale, 1987; Fürsich et al., 1991), the North Sea Coast of Britain (Evans, 1965; Evans, 1975) Germany (Reineck, 1967; Klein, 1977) and the Netherlands (Van Straaten and Kuenen, 1957; Klein, 1977).

Both Facies E and F contain numerous indicators of occasional subaerial exposure. Rill marks and polygonal mudcracks are particularly common. Rill marks (small-scale, millimeters to centimeters in width, channels or rivulets) commonly occur in intertidal, and are the result of erosion during drainage of the exposed intertidal flats (Allen, 1982b). Runzel marks (pock marks in sand attributed to sediment removal by windblown foam; Klein, 1977) were noted on several bedding planes in Facies F and also indicate subaerial exposure. Laterally restricted, sharp-based sand lenses (Facies H) are characterized by trough

Fig. 10. (A) Photomicrograph of intertidal/lagoonal mottled sandstone (lithofacies F) in vertical section, parasequence L11, Beattie Ledge. Thin-section and polished-section analysis reveals extensive biogenic reworking by a low-diversity, diminutive deposit-feeding assemblage. The centre zone (bound by dashed lines) has been extensively reworked by diminutive infaunal organisms (threadworms?), overprinting and obscuring larger burrows such as *Paleophycus* and *Taenidium*. The scale bar at bottom right is 1 cm in length. (B) Outcrop photograph showing *Arenicolites*, *Planolites*, *Skolithos* and *Taenidium* on lithofacies E (dolomitic siltstone) bedding plane, parasequence L11, Brown Hill. (C) Photomicrograph of a bioclastic sandstone lense (vertical section) within the lower intertidal zone (lithofacies association C) showing a mixed suspension/deposit-feeding assemblage comprised of *Skolithos*, *Thalassinoides* and bivalve adjustment traces, parasequence 10, Beattie Ledge. The dashed lines show the bivalves adjustment to net sediment aggradation during the animals lifetime and is defined by allochem alignment. The scale bar at bottom right is 1 cm in length. (D) Photomicrograph of a thin, normally graded, sand layer interpreted as an intertidally emplaced storm surge deposit with Fugichnia emanating from pre-event laminated sediments, parasequences L12, Brown Hill. The traces *Planolites* and *Taenidium* reflect post-event colonization by a dominantly horizontal deposit-feeding assemblage. The scale bar at bottom right is 1 cm in length.

cross-stratification and current ripple-laminae. These represent minor tidal run-off creeks and are similar to those observed in modern and Pleistocene intertidal creeks observed at Willapa Bay, Washington (Clifton and Phillips, 1980; Gingras et al., 1999). Scouring out of rill marks and minor tidal creeks is initiated by drainage of the intertidal flat during lower tidal levels (Klein, 1977; Wells et al., 1990).

The paucity of flaser and lenticular bedding within much of FA3 is attributed to a lack of argillaceous mud within the system. In this respect, these sediments are similar to intertidal deposits at Langebaan Lagoon, South Africa. Langebaan is recent mixed siliciclastic-carbonate marginal marine depositional system in which a low argillaceous mud content is attributed to the absence of fluvial input (Flemming, 1977).

Although specimens of *Lingula* are common within intertidal deposits, the trace fossil *Lingulichnus* (Fig. 8C) is rare in these strata. Long (up to 12 cm), narrow (1–4 mm in width), vertical tubes, usually paired, are common in the upper intertidal flat. Where observed on bedding planes, the tube-pairs are usually surrounded by a sub-circular or kidney-shape halo (Fig. 8D). With the exception of paired rather than a single internal tube, these trace fossils are similar to the bivalve dwelling trace fossil *Siphonichnus*, described from the Lower Permian of South Africa (Stanistreet et al., 1980). The paired tubes are interpreted as the inhalant and exhalant siphons of a burrowing bivalve (similar to *Macoma nasuta*, commonly observed in modern deposits). The sub-circular halo surrounding the tube pairs indicates the long-abandoned position of the once vertically situated shell. Forms with spreite both above and below the living chamber lend a variation to this theme and are interpreted to represent bivalve adjustment traces formed in a response to sedimentation or erosion (Fig. 10C).

The massive- or mottled-appearance characteristic of several horizons in FA3 is due primarily to extensive small-scale burrow reworking (Fig. 10A). The intertidal trace fossil assemblage includes a diverse mixture of dwelling, feeding, and crawling (motile/grazing) forms. This trace fossil assemblage is considerably more diverse than the *Psilonichnus* ichnofacies and contains forms more indicative of a mixed, albeit stressed, *Skolithos*/*Cruziana* ichnofacies. This mix of trace fossils is the signature of an abundant, diverse infauna. The ethologic diversity represented by the ichnofauna resulted from the availability of abundant food resources in both the substrate and in the water column. Trophic mixing due to resource partitioning was elegantly demonstrated by Wetzel and Uchman (1998) using Cretaceous flysch deposits as a model. Also, a similar diversity and assemblage of traces has been observed in the middle intertidal zone at Willapa Bay, where reliance on various food resource is not obligatory and may switch between tidal cycles (Gingras et al., 1999). As with the lower intertidal zone of Spencer Gulf, Australia (Belperio et al., 1988), and the outer intertidal flats of the Bahia La Choya region in the Gulf of California (Flessa and Ekdale, 1987) the Liard intertidal is dominated by trace fossils attributable to various crustaceans, polychaetes, bivalves, and gastropods.

Previous studies have suggested that the Liard Formation was deposited on a storm-dominated, prograding barrier island shoreline (Zonneveld et al., 1997b; Zonneveld, 1999). Thin (2–15 cm thick) normally graded sand layers, many with abundant bioclasts, are intercalated with the planar laminated to heterolithic wavy laminated dolomitic siltstone and mudstone of Facies E and F (Fig. 10D). Many of the vertical trace fossils such as *Arenicolites* isp., *Cylindrichnus concentricus*, *Laevicyclus* isp., *Rhizocorallium jenense* and *Skolithos linearis* preferentially emanate from the rippled upper surface of these layers (Figs. 9C and 10D). These sandy layers are interpreted as the result of storm washover and reflect post-event opportunistic colonization by a comparably diverse infauna. The diversity of tracemakers within these beds as well as the paucity of associated fugichnia may imply that the tracemakers were imported from the shoreface in conjunction with storm surges.

2.7. Facies association 4 (FA4): supratidal sabkha (description)

Facies association 4 (FA4) is a highly variable succession of calcareous to dolomitic mudstone, siltstone, sandstone and breccia beds (facies D2, E, G and I). Pedogenic alteration of calcareous and dolomitic clayey siltstone is common within facies association IV. Facies G (solution collapse breccia) and facies I (ripple-laminated dolomitic mudstone/siltstone) are unique to FA4.

Fig. 11. Outcrop photograph of rippled surface (relatively straight-crested oscillation ripples) of a calcareous sandstone (lithofacies I) interpreted as marginal lacustrine, parasequence L11, Beattie Ledge. Camera lense cap is 4.5 cm in length.

Facies G consists of a breccia composed of clasts characteristic of other lithofacies. Post-depositional dissolution of evaporite minerals (gypsum and anhydrite) resulted in the collapse of interlaminated dolomitic and calcareous mudstone, siltstone, sandstone and algal-laminated wackestone beds. The clasts comprising these solution collapse breccia beds range in size from 1–60 cm in length, within a calcareous mud matrix. Although primarily oriented subparallel to bedding, many occur at oblique angles.

Facies I consists of wavy to ripple-laminated dolomitic siltstone and mudstone (Fig. 11). Ripple types within this unit include straight-crested, bifurcating oscillation ripples and adhesion ripples. Body fossils were not observed within facies I. A low-diversity trace fossil assemblage, consisting of *Cylindrichnus*, isp., *Monocraterion*and isp., rare diminutive *Ophiomorpha* isp., occurs within facies I. Root traces and pedogenic slickensides in association with sharply contrasting color horizons are common within FA4.

2.8. Facies association 4 (FA4): supratidal sabkha (interpretation)

FA4 is interpreted to represent the deposits of a series of shore proximal supratidal sabkhas, salinas and lakes (Fig. 7). The Liard sabkhas/salinas were located within an arid supratidal setting, similar to the recent Spencer Gulf/Coorong region of southern Australia (von der Borch et al., 1975; von der Borch and Lock, 1979). Evaporite deposition predominates in supratidal settings (Warren, 1989). Root traces and pedogenic slickensides indicate pedogenic alteration of calcareous and dolomitic clayey siltstone within FA4. Pedogenic slickensides commonly occur in soils subjected to frequent wetting and drying, which cause the soil to shrink and swell (Retallack, 1988). The presence of numerous pedogenicly altered dolomitic and calcareous mudstone, siltstone and sandstone beds indicates prolonged periods of subaerial exposure.

The common oscillation between thin microbal laminites, dolomitic mudstone beds with polygonal dessication cracks, ripple-laminated dolomitic siltstone, solution collapse breccia beds, and pedogenically altered sediments reflects an environment prone to frequent cycles of desiccation and inundation. The sabkhas were recharged by continental ground water as well as periodic influx of marine water resulting from storm surges and spring tides and were intermittently colonized by a low-diversity assemblage of organisms. The paucity and diminutive nature of trace fossils within these facies reflects the harsh nature of life in continental settings along the Liard coast. Extensive periods of exposure and fluctuating salinity levels in an arid, hypersaline setting severely constrained the ability of burrowing organisms to flourish.

Dolomite is particularly common in the Liard Formation within sabkha/salina deposits proximal to the shoreline. Although it is difficult to prove that dolomitization occurred prior to lithification, several factors support a penecontemporaneous or near penecontemporaneous origin for these dolomitic units. First, details of trace fossils and sedimentary structures (desiccation cracks, ripple marks, fluid escape structures, etc.) in dolomitic mudstones and sandstones are preserved and are neither disrupted nor obscured by diagenetic alteration. Second, rip-up clasts deposited as lags at the base of tidal creek/channel deposits are similar in structure and composition to intertidal mudflat lithofacies, Both calcareous and dolomitic mudclasts are present in individual lags suggesting dolomitization of some horizons prior to erosion and redeposition. Third, solution collapse breccia beds contain an amalgamation of calcareous and dolomitic mudstone, siltstone, and sandstone clasts implying authigenic dolomitization of individual beds and cementation of both dolomitic and calcareous horizons prior to solution collapse. Fourth, in many cases dolomitic horizons are separated from each other by calcareous horizons that show no signs of dolomitization. Finally, fully marine deposits in adjacent strata are characterized by an absence of dolomite. Although selective dolomitization can occur at any time subsequent to deposition, these factors strongly imply syndepositional or early post-depositional dolomitization.

2.9. Facies association 5 (FA5): aeolian dune (description)

Facies association 5 (FA5) consists of a single facies (J). Facies J consists of very well-sorted, fine-grained sandstone, exhibiting well-defined foresets within large-scale, largely planar cross-bedding. Sand grains are subrounded to well rounded and exhibit frosting. Rare oscillation rippled bedding planes were observed. Laminae are thin (2–4 mm), inversely graded, and parallel. Individual laminasets steepen upwards within beds, and are generally concave upward. Bedsets are tabular to wedge-planar and vary in thickness from 10 to 45 cm in thickness. Neither trace fossils nor body fossils were observed in lithofacies I. Within the study interval, facies J occurs interbedded with thin pedogenically altered calcareous and dolomitic mudstone beds (facies G and I).

2.10. Facies association 5 (FA5): aeolian dune (interpretation)

FA5 is interpreted to have been deposited by aeolian sand dunes or sand sheets within a coastal continental environment. The presence of well-sorted fine-grained sandstone within inversely graded laminasets is suggestive of aeolian-ripple lamination (Hunter, 1981; Arnold, 1994). Shear sorting during grain flow results in inversely graded laminae (Kocurek, 1996). During ripple migration, most of each ripple is removed leaving a thin, residual lamina which is buried by the succeeding ripple resulting in thin, parallel laminae bound by planar bounding surfaces (Schenk, 1983).

Within the study interval, aeolian sandstone units occur only at Beattie Ledge, interbedded with pedogenically altered dolomitic and calcareous siltstones interpreted as marginal ephemeral lacustrine (lithofacies G and I).

3. Discussion

3.1. Environmental constraints on Liard ichnofossil assemblages

The Liard Formation was deposited on a storm-dominated, prograding barrier island shoreline (Zonneveld et al., 1997b). The co-occurrence of extensive intertidal flats, as well as a protective barrier ridge, is consistent with deposition along a mesotidal coastline (Hayes, 1979). Storms strongly affected the accumulation of sediment and the genesis of bedforms within the study interval. Thin, sharp-based, normally graded sand and bioclastic sand layers, common within FA2 (washover fan/lagoonal), FA3 (intertidal flats), and FA4 (supratidal sabkha) reflect washover deposition during storm surges. Bioclasts within these units are composed primarily of fully marine forms (echinoderms and articulate brachiopods). A trace fossil assemblage dominated by vertical forms (*Arenicolites*, *Cylindrichnus*, *Laevicyclus*, *Ophiomorpha*, *Rhizocorallium*, and *Skolithos*) within these layers is interpreted to reflect storm surge transport and subsequent opportunistic colonization by a normally marine infauna (Pemberton and MacEachern, 1997).

The Liard marginal marine succession at Williston Lake was deposited in an arid environmental setting similar to the Recent and Pleistocene northern Gulf of California (Flessa and Ekdale, 1987; Aberhan and Fürsich, 1991; Fürsich et al., 1991) and the Spencer Gulf/Coorong region in Australia (Burne et al., 1980; Gostin et al., 1984). High evaporation rates coupled with limited influx of freshwater in these areas produce comparably high salinity levels adjacent to the coastline (Gostin et al., 1984; Flessa and Ekdale, 1987). Thick and extensive sabkha deposits (FA4), both within the study interval and in the overlying Charlie Lake Formation, imply local hypersaline conditions.

Water temperature and salinity increase from the mouth towards the heads of arid system coastal embayments (Gostin et al., 1984; Flessa and Ekdale, 1987). This condition is particularly severe in microtidal settings where water in back barrrier lagoons are incompletely exchanged by daily tidal currents. Invertebrate faunas in hypersaline settings (salinity in excess of 45‰) are characterized by extremely low specific diversity. Low ichnotaxonomic diversity as well as a primarily diminutive forms within FA4 (coastal sabkha; Table 2) is a reflection of elevated salinity levels (de-Gibert and Ekdale, 1999).

High ichnotaxonomic diversity within back barrier subtidal and intertidal intervals (FA2 and FA3; Table 2) within the study area is consistent with deposition along a mesotidal coastline. Daily tidal cycles within mesotidal settings result in frequent turnover of seawater within back barrier settings, maintaining normal (or near normal) marine salinities ($\sim$30–35‰), conditions conducive to a healthy and robust infauna.

Many previous investigations have inferred that the intertidal zone is characterized by an abundance of deep, vertical traces while the subtidal zone contains predominantly horizontal forms (Walker and Laporte, 1970; Fürsich, 1975), others have shown that trace orientation is independent of bathymetry (Frey, 1970; Ireland et al., 1978; Narbonne, 1984; Gingras et al., 1999). The Liard intertidal succession (FA2 and FA3) contains a variety of both vertical and horizontal forms (Table 2), and a mix of dominichnia, repichnia, fodinichnia and cubichnia, supporting the latter hypothesis. This mix of ethologies may be related to rates of deposition within the intertidal zone. The variety and amount of buried organic material must be sufficient to compel individual species of tracemakers to shift from predominantly vertical, suspension-feeding lifestyles to predominantly horizontal, deposit-feeding lifestyle. If sedimentation rates are too high, the redox boundary will encompass most of the organic material and resources quickly become inaccessible. If sedimentation rates are too low, the organic material will concentrate near the sediment surface, and organisms will preferentially exhibit an interface-feeding lifestyle (i.e. a modified *Skolithos* behavior). When sedimentation rates are ideal, a thin zone of exploitable resources, several centimeters to decimeters in thickness, exists in which horizontal deposit feeders can thrive. Alternatively, this unique ethological mix may be related to variations in organismal behavior during spring and neap tidal cycles. This was demonstrated by Wetzel and Uchman, 1998, in deeper water deposits.

3.2. Dolomite in Liard marginal marine sediments

Dolomitization within the Liard lagoonal/intertidal and coastal sabkha settings is believed to have occurred in a manner similar to dolomitization in Holocene and recent sediments within lagoons and interdune ephemeral lakes in the Coorong region of Australia. These ephemeral lakes (salinas) are primarily recharged by continental groundwater (isolated from most marine influence), and undergo an annual desiccation cycle (Muir et al., 1980; von der Borch, 1976; von der Borch et al., 1975; von der Borch and Lock, 1979). Following a four-month dry period, seasonal landward rains cause a rejuvenation of groundwater flow (von der Borch et al., 1975). The water rises quickly, reviving algal mats that remained dormant through the dry season. The organic slurry which is developed attracts a large quantity of grazers. The shallow lake bottoms quickly turn into a thick slurry comprised of carbonate mud, organic ooze, and faecal pellets (Muir et al., 1980; von der Borch, 1976). Precipitation of dolomite in the landward lakes is attributed to the annual evaporitic concentration of groundwater (Muir et al., 1980). Precipitation of dolomite within the more seaward lakes however is attributed to mixing of comparatively low-salinity continental groundwater with marine-derived groundwater (Last, 1990; von der Borch, 1976; von der Borch et al., 1975).

Dolomite within Liard lagoonal/sabkha lithofacies associations is believed to have formed in a similar manner. Perhaps most significantly, Coorong style dolomitization along the northwest coast of Pangea implies seasonality in precipitation, and correspondingly in recharge of coastal sabkhas. Periodic, possibly annual, cycles of desiccation and subsequent flooding are attested to by the complex interstratification of evaporite minerals with silty dolomitic and calcareous mudstone and algal-laminated wackestone. Although evaporite minerals were not directly observed within the study area, they may be inferred from the presence of thick solution collapse breccias within the Liard sabkha successions.

3.3. Mixed siliciclastic-carbonate sedimentation

Mixed siliciclastic-carbonate sedimentation occurs primarily within arid settings characterized by low input of clastic sediment to the shoreface (Gostin et al., 1984; Flessa and Ekdale, 1987; Belperio et al., 1988). Low clastic input may be due to low relief and thus low sediment availability in the source area, or to minimal fluvial input to the shoreline. In arid settings, particularly those with a gently sloping shoreface, bioclastic accumulation may outpace siliciclastic deposition.

The Liard shoreface was characterized by a unique mixture of siliciclastic and bioclastic sedimentation (Fig. 7). Input of siliciclastic sand to the shoreface was likely derived from three sources: (1) Aeolian input from land; (2) fluvial input; and (3) longshore drift, likely from the north. Carbonate sediment in the Liard marginal marine succession are predominantly biogenic in origin and is derived from two distinct sources: (1) intertidal and subtidal bivalves, gastropods, and brachiopods; and (2) shoreward transport of subtidal brachiopod, bivalve, echinoid and crinoid skeletal debris during storms (Fig. 7).

The recent coastline of southern Australia receives negligible amounts of terrigenous sediments due to the arid climate and the paucity of perennial rivers (Fuller et al., 1994). Periodic fluvial input to the shoreface is suggested by the abundance of quartzose, fine-grained, hummocky cross-stratified sand in lower shoreface settings (Zonneveld et al., 1997b; Zonneveld, 1999), the presence of storm deposited, medium to coarse-grained sand infilling desiccation cracks and burrows within intertidal deposits, as well as disseminated chert granules and pebbles scattered within upper shoreface, foreshore, and washover fan deposits. The aridity and low-relief of the Pangean interior east of the study area resulted in intermittent fluvial discharge to the coast, and thus, limited siliciclastic input to the shoreface. Although deltaic deposits have not yet been identified in the Middle Triassic of western Canada, this may reflect difficulties associated with distinguishing deltaic deposits associated with ephemeral rivers from shoreface sediments. Deltas constructed during wet seasons or after severe inland rain storms in arid regions are quickly reworked, and the sediments redistributed between events (Semeniuk, 1996). Deltaic sediments are transported laterally via strong longshore currents and disseminated throughout the shoreface by normal wave action and onto intertidal flats by storm processes.

Nonsiliciclastic coastal sediments of northwestern Pangea were largely derived from marine biogenic sources and are dominated by bioclastic sand and silt (Fig. 7). Subtidal seagrass meadows within Spencer Gulf, Australia are a major source of skeletal carbonate material, acting as carbonate factories, trapping sediment and providing a comparably protected environment in which a wide variety of organisms can live (Belperio et al., 1988; Fuller et al., 1994). The roots and rhizomes of seagrass meadows also affect sediment accumulation by binding and stabilizing the sediments (Belperio et al., 1988). Shoreward transport of bioclastic carbonate is a significant source of intertidal sediment along the coast of southern Australia (Belperio et al., 1988; Fuller et al., 1994). While sea grasses are unknown from the Mesozoic, green and brown algae have proliferated throughout the Phanerozoic, and charophytes have persisted since the Silurian (Burne et al., 1980). Although roots and rhizomes are limited to plants with vascular systems, algae may act as a baffle, dissipating wave energy and algal hold-fasts may also bind sediment.

Reefs are also significant sources of biogenic carbonate in recent depositional systems. Although coral reefs were apparently absent in the study interval, the Liard lower shoreface was characterized by shore-parallel, laterally extensive, biostromes comprised predominantly of terebratulid brachiopods and cidaroid echinoids, but also containing abundant bivalves and crinoids (Zonneveld et al., 1997b; Zonneveld, 2001). The Liard biostromes served as prolific sources of biogenic carbonate to the upper shoreface, foreshore and backshore.

Siliciclastic and bioclastic grains display an inverse relationship within the Liard shoreface. Hummocky cross-stratified sandstones in lower shoreface settings are dominated by very fine- to fine-grained quartzose sand. Shoreface sediments become increasingly carbonate-rich towards the shoreline, and the swash zone or foreshore is dominantly bioclastic. Numerous papers have documented transport of nearshore siliciclastic sand into offshore environments dominated by carbonate mud via storm-generated geostrophic flow (i.e. Kreisa, 1981; Mount, 1984; Tucker, 1982). Shoreface successions such as the study interval characterized by landward enrichment in carbonate sediment and seaward enrichment in siliciclastic sediment are less well known.

The Liard upper shoreface/foreshore succession (FA1) is characterized by common concentrations of whole and abraded bioclasts. Wrack-line accumulations of mollusc shells along the coast of Georgia are governed primarily by longshore drift and tend to accumulate within beach re-entrants (Frey and Dörjes, 1988). During storms, this trend is reversed; mollusc shells are removed from the beach and redeposited further basinward (Frey and Dörjes, 1988; Frey and Pinet, 1978). Under fair weather conditions, settings prone to higher current velocities (i.e. beach protrusions) are characterized by lower shell-accumulation rates than more protected settings (Dörjes et al., 1986; Frey and Dörjes, 1988). Watson (1971) found that coastal configuration played a strong role in the concentration of shell material along Padre island, Texas. Onshore blowing winds on an elongate, concave shoreline produced a zone of longshore current convergence in the center of the concavity. Shells and coarse sand accumulate in the zone of convergence, and are concentrated by aeolian deflation of fine-grained sediment.

The aforementioned studies concentrated upon whole valves. Other than noting that unidentifiable fragments were relatively rare compared to whole valves, the hydraulic behavior of sand and gravel-sized bioclastic sediment was not discussed (Frey and Pinet, 1978; Frey and Dörjes, 1988). Upper shoreface sediment within the study interval is dominated by highly abraded bioclastic fragments, however similar mechanisms likely occurred in the Liard shoreface. Concentrations of whole mollusc and brachiopod shells may reflect the presence of shoreline embayments or re-entrants.

Similar-sized quartz grains and carbonate shell fragments are not hydraulic equivalents. Although the specific gravities of quartz (2.65), calcite (2.71) and aragonite (2.95) are not appreciably different, quartz sand grains in the Liard Formation are dominantly spherical, whereas the shape of carbonate shell debris is highly variable. Compounding this, bioclastic grains are characterized by numerous voids and pore spaces resulting in decreased specific gravity. Oblong clasts have a stronger predilection than spherical particles to remain in the foreshore since they have a tendency to flip landward by turbulent wave activity and are unaffected by the more passive backflow (Bartholomae et al., 1998). Oblong shell fragments would therefore tend to concentrate in the foreshore, unlike their more spherical siliciclastic counterparts. Thus, bioclastic enrichment of the foreshore is interpreted to be primarily a function of grain size and shape rather than sediment composition.

In the Liard Formation, very little fine-grained carbonate sediment (silt and very fine-grained sand) has been observed. This is attributed to the inherent instability of very fine-grained or smaller carbonate sediment. Similar observations have been made by Fürsich et al. (1991) in other mixed siliciclastic-carbonate depositional systems. Most carbonate material within the Liard Formation consists of medium-grained sand to gravel sized particles. Siliciclastic grains are limited in size within the Liard Formation, with the exception of rare chert granules, to very fine- to fine-grained sand. On beaches with bimodal grain distributions, opposite directions of cross-shore transport exist for coarse and fine-grained sediment (Nummedal, 1991). Bowen (1980) showed that for grains in equilibrium with a given slope and wave regime, finer grains move in an offshore direction,

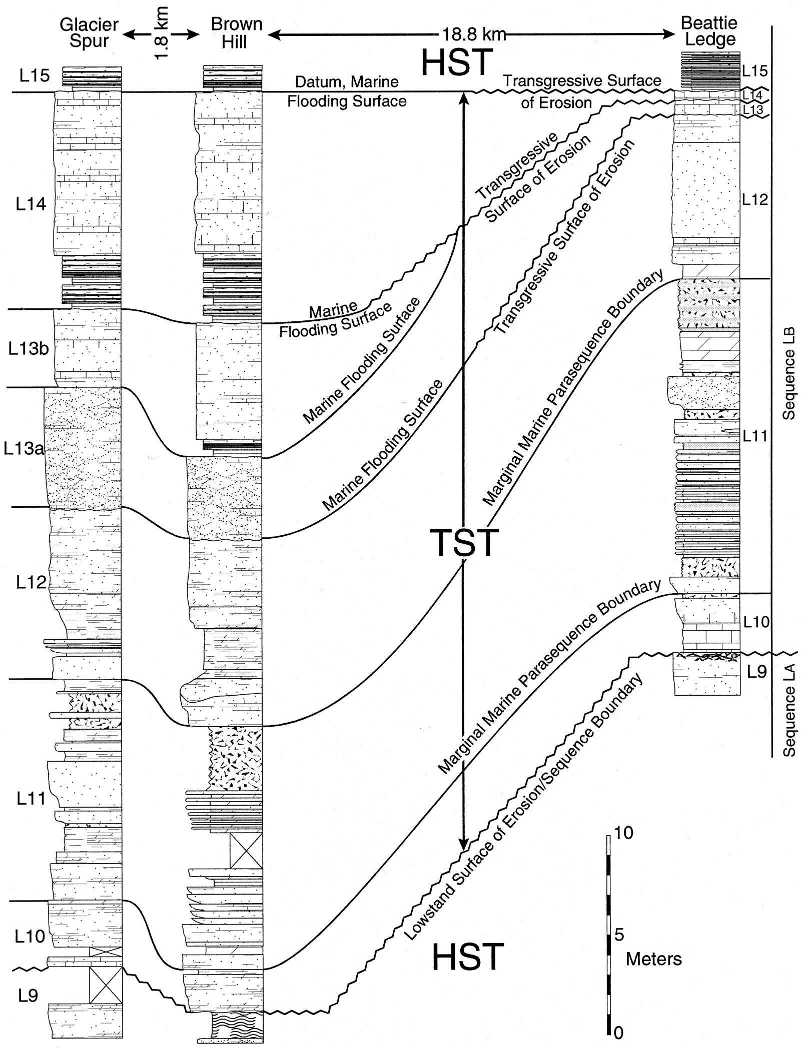


Fig. 12. Genetic stratigraphic correlation of the three intertidal sections logged in this study. The designators L9 through L15 follow the nomenclature of Zonneveld et al. (1997a) and refer to individual parasequences. HST = Highstand Systems Tract; TST = Transgressive Systems Tract.

while coarser grain sizes move onshore. This situation may have been reversed occasionally as storm-generated geostrophic flows transported the coarse fraction basinward.

3.4. Sequence stratigraphy

The marginal marine succession that is the focus of this paper overlies a regionally significant lowstand surface of erosion/sequence boundary (Zonneveld, 1999). This sequence boundary is preserved as an erosional unconformity at Brown Hill (Fig. 8A) and as a *Glossifungites* demarcated discontinuity at Beattie Ledge (Figs. 12 and 13A and B). The erosional unconformity at Brown Hill consists of fenestral laminated dolomite (lithofacies D2) unconformably overlain by transgressive shoreface sandstone (lithofacies B2). The *Glossifungites* ichnofacies includes trace fossils which penetrate firm, unlithified substrates, specifically those which have been subaerially exposed

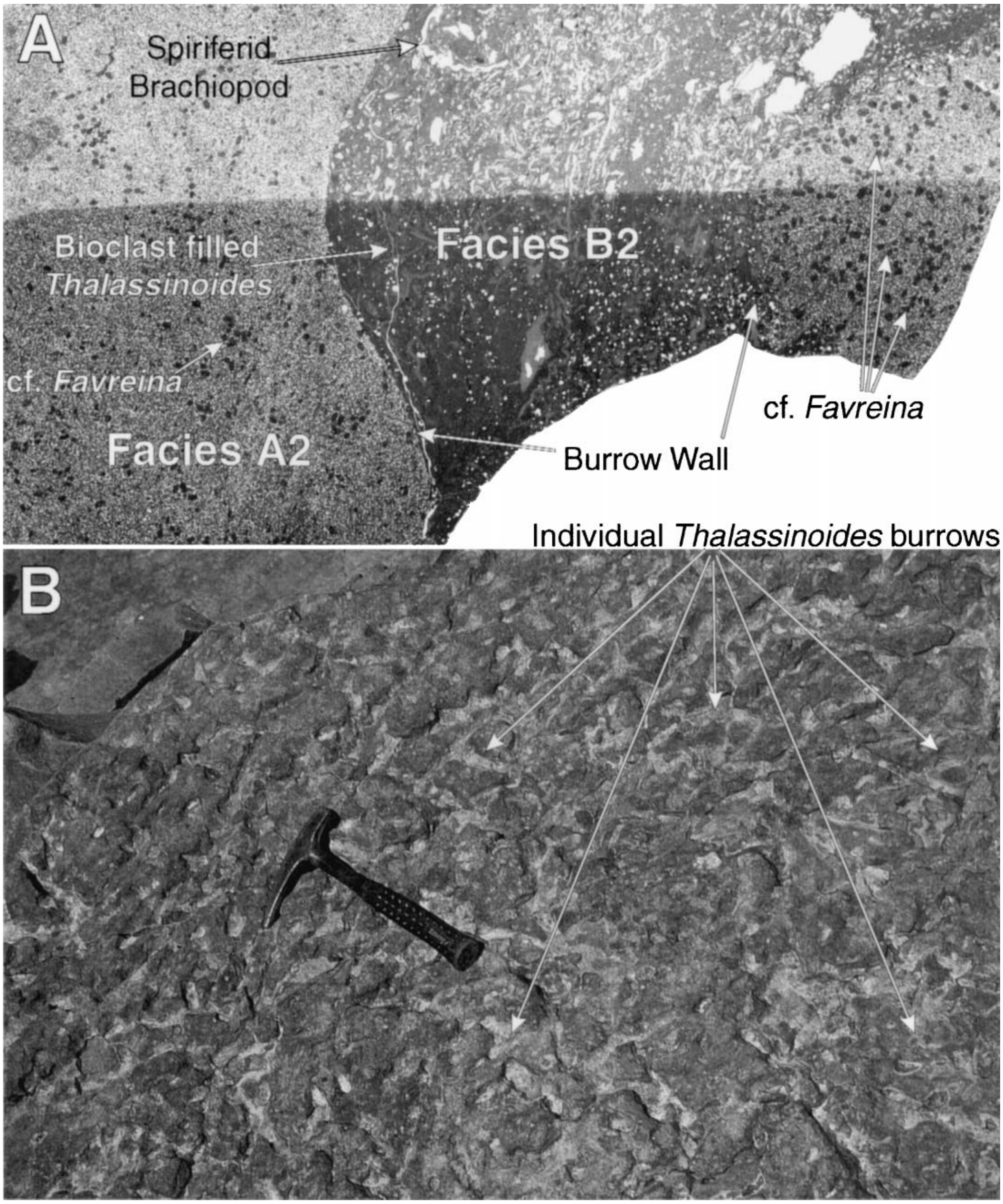


Fig. 13. (A) Photomicrograph showing a cross-sectional view through an individual *Thalassinoides* burrow within the Beattie Ledge *Glossifungites* demarcated discontinuity. The burrow infilling is comprised of a bioclastic hash containing echinoid, crinoid and spirifirid brachiopod debris. The matrix is comprised of very fine-grained sand. Tiny dark spots within both the surrounding matrix and the burrow infilling are fecal pellets, tentatively assigned to the genus *Favreina*. The photomicrograph is 6 cm wide. (B) Outcrop photograph of the *Glossifungites* surface demarcating the LA/LB sequence boundary at Beattie Ledge (top of parasequence L9). The Rock hammer at center is 32 cm in length.

or buried and subsequently re-exhumed (Pemberton and MacEachern, 1995). Although discontinuities characterized by *Glossifungites* assemblages may feature a variety of ichnotaxa, the Beattie Ledge surface is characterized by a monotypic assemblage of sharp-walled, unlined *Thalassinoides* (Fig. 13B). The bioclast-filled burrows penetrate a well-sorted, very-fine grained, calcareous sandstone with abundant micritized fecal pellets (decapod?) interpreted as lower to distal upper shoreface (Fig. 13A).

Parasequences immediately overlying the sequence boundary (L10, L11, L12, L13 and L14) are interpreted as the sequence L_B transgressive systems tract and represent an abrupt basinward shift in facies (Fig. 12). These parasequences constitute a thick (25–30 m) aggradational to slightly retrogradational succession of lagoonal, intertidal flat, supratidal lacustrine and aeolian sand dune lithofacies associations.

Thin, laterally persistent, transgressive shoreface bioclastic sandstones at the base of parasequence L13a incise into intertidal deposits at the top of parasequence L12 at all three localities (Fig. 12). Similar to bioclastic sandstones at the base of the Brown Hill and Glacier Spur sections, these units are matrix supported, normally graded and composed of a brachiopod–echinoderm–bivalve shell hash. These units are interpreted as transgressive shoreface deposits and signify a return to fully marine deposition within the study area. Parasequences L13a, L13b and L14 comprise a strongly retrogradational package and represent the culmination of the sequence L_B transgressive systems tract.

Parasequence L14 is capped by an abrupt flooding surface (Fig. 12). At the three localities discussed here, this surface separates underlying brachiopod-dominated, bioclastic sandstones (interpreted as transgressive shoreface) from overlying laminated black shale and siltstone (interpreted as proximal offshore to offshore transition). The maximum marine flooding surface, signifying transition to highstand conditions, occurs within this shale/siltstone package.

4. Conclusions

Sedimentary facies in the marginal marine succession of the upper Liard Formation at Williston Lake comprise five facies associations. FA1 consists of a coarsening upward, mixed siliciclastic-carbonate shoreface to foreshore succession of strata characterized by a low-diversity *Skolithos* assemblage (*Diplocraterion*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Skolithos* and *Thalassinoides*). Physical sedimentary structures in FA2, interpreted as washover fan/lagoonal are consistent with deposition in a less energetic setting than the underlying units. Numerous sharp-based sandstone beds reflect episodic deposition. The stressed trace fossil assemblage (diminutive *Cylindrichnus*, *Gyrochorte*, *Palaeophycus*, *Planolites*, *Skolithos*, *Trichichnus*, and an unusual type of bivalve resting trace) is indicative of deposition in a setting characterized by periodic salinity (and/or oxygenation) fluctuations.

FA3, interpreted as an intertidal flat succession, is characterized by a diverse array of vertical and horizontal trace fossils attributable to a variety of crustaceans, polychaetes, bivalves, and gastropods (*Arenicolites*, *Cylindrichnus*, *Diplocraterion*, *Laevicyclus*, *Lingulichnus*, *Lockeia*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Siphonichnus*, *Skolithos*, *Teichichnus*, *Taenidium* and *Thalassinoides*). Trace fossils in the upper intertidal deposits of the Liard Formation represent a mix of indigenous infauna and storm-transported, opportunistic colonizers. The presence, diversity and abundance of deposit-feeding ichnofossils within intertidal deposits are related to substrate oxygenation and food availability and may be useful indicators of sedimentation rate. Bioclastic sandstone beds, interpreted as intertidally emplaced storm washover deposits, contain a robust assemblage of post-event opportunistic colonizers, possibly imported from seaward in conjunction with storm-transported sediments.

Coastal sabkha/salina deposits (FA4) are characterized by dolomitic siltstone/mudstone and solution collapse breccias composed of silty dolomitic and calcareous mudstone and algal-laminated wackestone. This succession is characterized by a low-diversity trace fossil assemblage, consisting of *Cylindrichnus*, *Monocraterion*and rare diminutive *Ophiomorpha*. Solution collapse breccia and root traces overprint many primary physical and biogenic sedimentary structures providing evidence of periodic cycles of desiccation and flooding. Similar to recent and Holocene lakes in the Coorong region of Australia, dolomite within these deposits formed by primary precipitation during annual evaporitic concentration of groundwater, and by periodic mixing of comparably low-salinity continental groundwater with marine-derived groundwater. Coorong-style dolomitization implies seasonality in precipitation along the northwest coast of Pangea. FA5, well-sorted fine-grained sandstone within inversely graded laminasets, is interpreted to represent aeolian dune deposits. This association is characterized by a complete absence of trace fossils.

Siliciclastic sediment in the study area was likely derived from aeolian transport and longshore currents from depocentres outside the study area. Carbonate sediment in the study area was derived primarily from marine biogenic sources and are dominated by bioclastic sand and silt. Controls governing and promoting mixed siliciclastic-carbonate deposition in marginal marine lithofacies associations in the upper Liard and Charlie Lake Formations include an arid climate, fluctuations in sediment supply, variability in sedimentation style and source, and lateral shifts in lithofacies.

Acknowledgements

The authors would like to thank Drs H. Allan Curran, Ashton F. Embry, Richard W. Evoy, Bruce S. Heming, Robert B. MacNaughton, Thomas F. Moslow and Charles R. Stelck, Finn Surlyk, Lenore P. Tedesco and two anonymous reviewers for criticizing the manuscript and for their many useful comments. Special thanks to Dr Michael W. Caldwell, Kevin D. Brett and Barton J. Blakney for outstanding field assistance. We are grateful to Petro Canada Resources, Numac Energy, Canadian Hunter Exploration Limited and Pancanadian Petroleum for their financial support. This paper is Geological Survey of Canada Contribution No. 2000153.

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