UNIVERSITY OF ALBERTA

SEDIMENTOLOGY AND SEQUENCE BIOSTRATIGRAPHIC FRAMEWORK OF A MIXED SILICICLASTIC-CARBONATE DEPOSITIONAL SYSTEM, MIDDLE TRIASSIC, NORTHEASTERN BRITISH COLUMBIA

BY

JOHN-PAUL ZONNEVELD ©

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"Certain faults will be obvious to the reader, of course, and for these I wish to apologize. I quite agree that much of the book will read coarse, rude, bad-tempered, violently prejudiced, unconstructive -even frankly antisocial in its point of view. Serious critics, serious librarians, serious associate professors of English will if they read this work dislike it intensely; at least I hope so. To others I can only say that if this book has virtues they cannot be disentangled from the faults; that there is a way of being wrong which is also sometimes necessarily right.

It will be objected that the book deals too much with mere appearances, with the surface of things, and fails to engage and reveal the true underlying reality of existence. Here I must confess that I know nothing whatever about true underlying reality, having never met any. There are many people who sat they have, I know, but they've been luckier than I.

For my own part I am pleased enough with surfaces -in fact they alone seem to me to be of much importance. Such things for example as the grasp of a child's hand in your own, the flavour of an apple, the embrace of a friend or lover, the silk of a girl's thigh, sunlight on rock and leaves, the feel of music, the bark of a tree, the abrasion of granite and sand, the plunge of clear water into a pool, the face of the wind-what else is there? What else do we need?"

Edward Abbey, 1967, Desert Solitaire

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled SEDIMENTOLOGY AND SEQUENCE BIOSTRATIGRAPHIC FRAMEWORK OF A MIXED SILICICLASTIC-CARBONATE DEPOSITIONAL SYSTEM, MIDDLE TRIASSIC, NORTHEASTERN BRITISH COLUMBIA, submitted by JOHN-PAUL ZONNEVELD in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

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DATE: January 19, 1999

This dissertation is dedicated to two people:

To my wife, Shima Dorice Zonneveld,
for her love, support and patience.

To Dr. William S. Bartels, friend, mentor and cohort,
for a decade of guidance and friendship.

ABSTRACT

The Middle Triassic of northeastern British Columbia consists of the Toad and Liard Formations in outcrop, and the Doig, Halfway, and basal Charlie Lake Formations in the subsurface. These units consist of a complex succession of siliciclastic, carbonate and minor amounts of evaporite sediments deposited on the northwestern margin of Pangaea. Outcrop along Williston Lake, and core within the Tommy Lakes Field were analyzed to assess lateral and vertical lithofacies relationships and to construct a detailed sequence biostratigraphic framework for the Middle Triassic of northeastern British Columbia.

The outcrop succession at Williston Lake includes six recurrant lithofacies associations; I) shelf/ramp turbidites; II) clastic offshore-shoreface; III) wave-dominated transgressive shoreface; IV) mixed siliciclastic-carbonate shoreface; V) brachiopod-echinoderm biostrome; and VI) mixed siliciclastic-carbonate marginal marine (intertidal flat, lagoon supratidal sabkha). Four recurrent lithofacies associations were identified at Tommy Lakes Field: I) offshore-lower shoreface; II) tidal inlet channel; III) barred barrier island shoreface and IV) mixed siliciclastic-carbonate marginal marine (intertidal flat, lagoon supratidal sabkha).

The Middle Triassic succession in outcrop consists of at least seven third-order sequences deposited within two second-order sequences. The basal four of these sequences are Anisian (TA1-TA4) in age and are limited in outcrop exposure to a single, basinal site. The Ladinian succession consists of three sequences (TL1-TL3). Correlation into the subsurface east of the study area confirms that the TL2\TL3 sequence boundary occurs at the base of a regionally correlatable bioclastic sandstone/packstone marker horizon, informally refered to as the "A" Marker limestone.

The Middle Triassic stratigraphic succession within the Tommy Lakes region comprises at least fourteen parasequences within three third-order depositional sequences (HDI, HDII and CLI). The HDII\CLI sequence boundary in the subsurface occurs at the base of the "A" Marker Limestone and is coeval with the outcrop TL2\TL3 sequence boundary.

Controls governing and promoting mixed siliciclastic-carbonate deposition within marginal marine lithofacies associations in the Middle Triassic of northeastern British Columbia include an arid climate, fluctuations in sediment supply, variability in sedimentation style and source, a significant and productive source of biogenic carbonate, lateral shifts in lithofacies and a texturally mature sediment source. Siliciclastic sediments within the study area were derived from aeolian transport, longshort drift from depocentres within and outside the study area, and episodic fluvial input to the shoreface. Nonsiliciclastic sediments within the study interval were derived primarily from marine biogenic sources and are dominated by bioclastic sand and silt.

It is hypothesized that a paleotopographic high separated basinward sites (Ursula Creek) from landward sites (Brown Hill, Glacier Spur, Beattie Ledge and Aylard Creek). This high created a landward sub-basin and resulted in severe basinward sediment starvation. Evidence supporting the presence of a paleotopographic high include severe thinning of Ladinian sediments in basinward sections, inverse profiles in basinal (retrogradational) and landward (progradational) settings, deepening in a "landward" direction, erosional removal of parasequences at basinal sites that are preserved in more "landward" localities, and an abrupt shift in depositional patterns between the Ladinian and the Carnian.

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I would like to thank my supervisory committee, Dr. Thomas F. Moslow, Dr S. George Pemberton, and Dr. Charles R. Stelck for guidance, and for patience with an often stubborn and contentious student. My external committee members, Dr. Bruce S. Heming (Biological Sciences, University of Alberta) and Dr. Ashton F. Embry (Geological Survey of Canada, Calgary), provided invaluable insight and unique perspective into a variety of aspects of this dissertation.

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Dr. Thomas F. Moslow, Dr. Richard W. Evoy and Dr. Charles M. Henderson continue to provide insight and unique perspective into deposition along the northwestern coast of Pangaea during the Middle Triassic. Charles and his loyal lab crew processed and identified the numerous conodont samples collected throughout this project. The preliminary sequence biostratigraphic framework discussed in this dissertation would not exist without their efforts. Many of the ideas and interpretations discussed in this dissertation were generated through discussions with Dr. Charles R. Stelck, professor emeritus at the University of Alberta. Dr. Stelck visited many of the outcrop localities discussed in this dissertation in the days when the Peace River flowed where Williston Lake sits today, long before helicopters, jet boats, or paved roads existed in the Peace country.

Special thanks to the Ichnology Research Group at the University of Alberta, in particular Dr. S. George Pemberton, Murray K. Gingras, Eric S. Hanson, Stephen M. Hubbard, Jason M. Lavigne and Thomas D.A. Saunders for guidance and companionship through the murky underworld of trace fossils.

Financial support for the Middle Triassic outcrop and subsurface research project was generously provided by Petro Canada Resources, Numac Energy, Canadian Hunter Exploration Limited and Pancanadian Petroleum. Dr. Phillippe Erdmer generously provided the expedition with mobility (in the form of a zodiak inflatable and outboard motor).

The efforts of the residents of the isles of Islay and Skye are once again acknowledged for helping to bring a touch of civilization to the north country and for making evening camp-fire discussions on Triassic geology and paleontology particularly enjoyable.

Triassic field workers (1996 through 1998), Williston Lake, British Columbia. Top left, Kevin Brett and the author at Aylard Creek. Top right, Charles (conodont dude) Henderson at Ursula Creek. Centre left (clockwise), Tom Saunders, Barton Blakney, Kevin Brett and Murray (Lopez) Gingras at Adams Creek. Centre right, the author (Ali Baba) and Murray Gingras (Mustapha) at Casablanca train station, Morocco (chasing modern analogues). Bottom left (from left), the author (Pancho), Kevin Brett, Barton Blakney, Ian Armitage, Murray Gingras (Lopez) and Tom Saunders at Adams Creek. Bottom right (top) Shawn Rapp (Attila) and Lisa Amati (Dayglo Red) near Beattie Ledge. Bottom right (bottom), Kevin Brett near Beattie Ledge).

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CHAPTER 1.

INTRODUCTION

"....the Muschelkalk of the Germans,.....contains many organic remains belonging to species perfectly distinct from fossils of the lias, and equally so from those of the carboniferous era next to be mentioned."

Charles Lyell, 1833

General Overview

Triassic strata in the northern part of the Western Canada Sedimentary Basin comprise one of the most complete and best preserved early Mesozoic successions in the world (Gordey *et al.*, 1991). These units consist of a westward thickening succession of marine and continental siliciclastic, carbonate and evaporite sediments deposited on the western margin of the North American craton (Gibson and Barclay, 1989).

Triassic strata in the Western Canada Sedimentary Basin have been subdivided into three facies assemblages (Gibson and Barclay, 1989; Moslow and Davies, 1992). These subdivisions are interpreted to reflect three major transgressive-regressive marine cycles which correlate closely with the three Triassic Epochs; I) Early Triassic (Griesbachian through Spathian), II) Middle Triassic (Anisian through early Carnian) and III) Late Triassic (Carnian through Rhaetian) (Gibson and Barclay, 1989). Each of these cycles is characterized by an apparently rapid transgressive phase followed by a relatively prolonged regressive phase (Embry, 1988). Numerous lower order transgressive-regressive events (third order sequences) occur within each major cycle.

Within its type area, the Triassic has also been subdivided into three parts, the Bunter, Muschelkalk and Keuper (von Alberti; 1834). Although the initial segregation was based on lithology, these three subdivisions reflect large scale fluctuations in sea-level. Although the precise ages of these subdivisions are difficult to ascertain, due primarily to the nonmarine nature of the initial and final stages (Bunter and Keuper), they are approximately correlative with the Early (Bunter) Middle (Muschelkalk) and Late (Keuper) Triassic epoch subdivisions (Aigner and Bachmann, 1992; Embry, 1997). In a summery of sequence stratigraphic data from eight localities worldwide (Arctic Canada, East Siberia, Norway, Germany, Italy, China, southwestern United States, and the Western Canada Sedimentary Basin), Embry (1997) showed that these large scale cycles are global in extent.

This study deals primarily with facies assemblage II (Middle Triassic), consisting of the Doig, Halfway and basal Charlie Lake Formations in the subsurface and the Toad and Liard Formations in the Peace River outcrop belt (Table 1). Middle Triassic strata comprise one of the most economically important stratigraphic intervals within the northern Western Canada Sedimentary Basin. Recent estimates suggest that over half of total in-place Triassic gas reserves remain undiscovered (Bird *et al.*, 1994).

Until recently, Triassic deposits in the Western Canada Sedimentary Basin were primarily mapped using lithostratigraphic methods. As a result, a wide variety of names have been introduced to refer to the same succession of rocks in different parts of the basin. A synopsis of stratigraphic nomenclature currently in use for Triassic strata of northeastern British Columbia is presented in Table 1. Until detailed chronostratigraphic studies spanning the entire Western Canada Sedimentary Basin are provided (outcrop and subsurface), precise correlation between regions remains somewhat tenuous and conjectural. It is intended that this thesis provide a framework for correlation between Middle Triassic strata between the outcrop belt and the subsurface of the Western Canada Sedimentary Basin.

Objectives

This dissertation deals with various aspects of sequence architecture and deposition in a Middle Triassic mixed siliciclastic-carbonate depositional system. Vertical and lateral facies relationships within lithofacies and lithofacies associations in the Grayling, Toad and Liard Formations at Williston Lake (Figure 1), and within their subsurface equivalents, the Doig, Halfway, and lower Charlie Lake Formations are documented, the provenance of significant bioclastic accumulations within these units is assessed and finally, the results are compared to subsurface units within Tommy Lakes Field (Figure 1), a laterally equivalent hydrocarbon reservoir in the subsurface of northeastern British Columbia.

This study has four main objectives: 1) to develop sedimentary facies models for Middle Triassic strata in both outcrop and core utilizing sedimentology, ichnology, and invertebrate paleontology. 2) to initiate a biostratigraphic study of Halfway (and equivalent) outcrops and subcrop using conodonts and ammonoids to aid in establishing both lateral and vertical relationships between the Tommy Lakes region, the foothills outcrop belt, and other Triassic reservoirs within the Western Canada Sedimentary Basin; 3) to develop a detailed sequence stratigraphic model for the middle Triassic in the Tommy Lakes region, using core and wireline logs in the Tommy Lakes Field and using measured outcrop sections and outcrop gamma-ray scans in the Williston Lakes region in the Rocky Mountain foothills of British Columbia; and 4) to determine the stratigraphic equivalence of Middle Triassic strata in the Williston Lake region to the Doig, Halfway and basal Charlie Lake Formations in the subsurface of the Western Canada Sedimentary Basin, particularly the Tommy Lakes region.

Peace River Outcrop Belt

Triassic Strata in northeastern British Columbia are exposed in a narrow belt extending from the Yukon border near Watson Lake (Mile Post 632 on the Alaska Highway) to Kakwa Provincial Wilderness Park on the Alberta border. The subsurface component of this study centres around outcrop exposed along the shores of Williston Lake (Figures 1 and 2). Williston Lake is located approximately 80km west of Fort St. John, British Columbia along the Peace River and along the Rocky Mountain Trench (Figure 1). The lake was created in 1967 by construction of the W.A.C. Bennett Dam on the Peace River.

Previous work (i.e. McLearn, 1930; 1940; 1941a& b; Gibson and Edwards, 1992, and

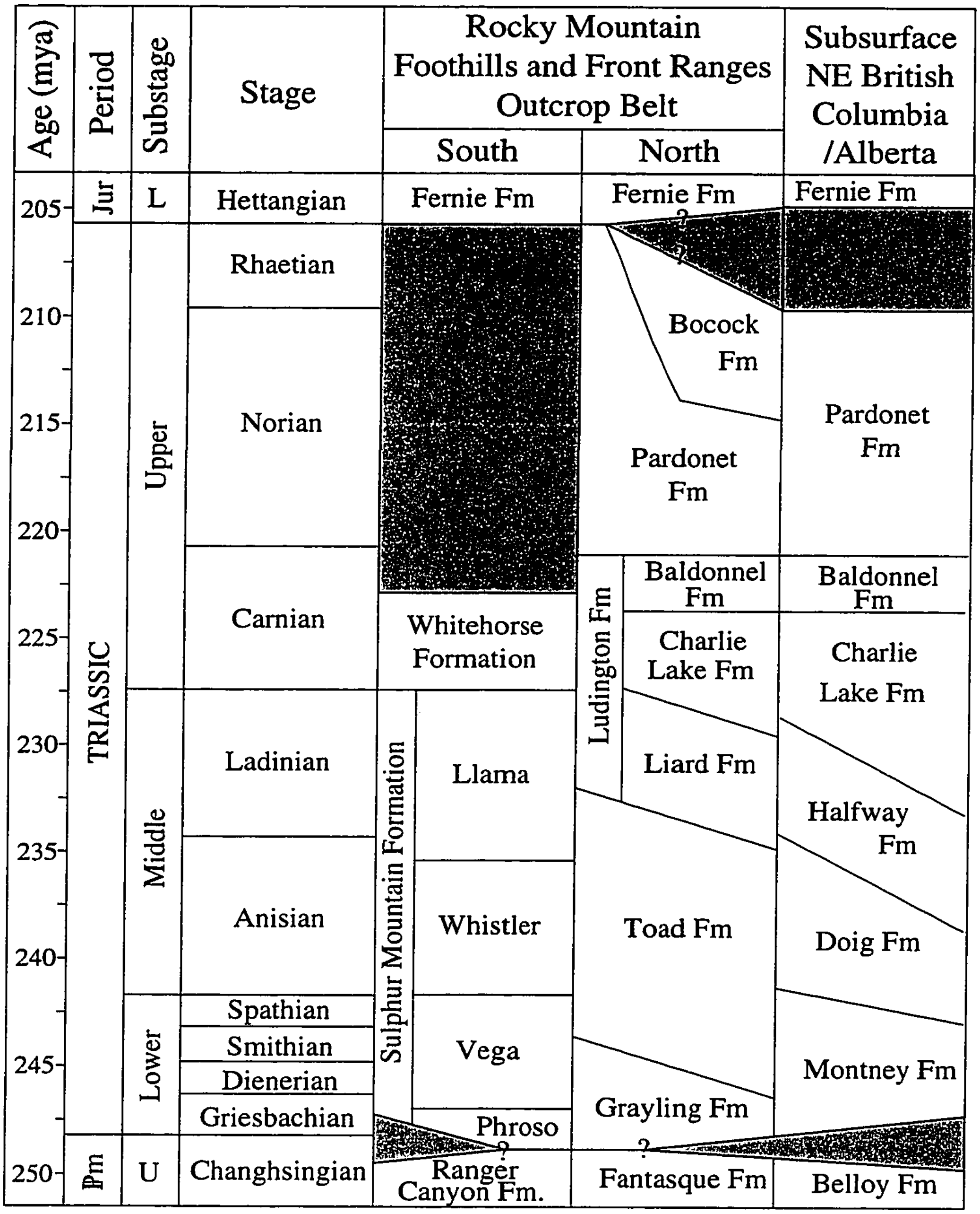

Table 1. Triassic stratigraphic nomenclature, subsurface and outcrop, northeastern British Columbia (adapted from Gradstein et al., 1994; Tozer, 1994). Formation contacts in the southern outcrop belt follow Orchard and Tozer (1997). Lower and Middle Triassic Formation contacts in the subsurface and northern part of the outcrop belt are drawn to reflect their diachronous nature, and are not absolute. Numerous intra and extraformational unconformities occur within the Triassic of Western Canada although they are not shown here. Emplacement of the basal Grayling Formation and Sulphur Mountain Formation (Phroso Member) contacts within the Upper Changhsingian (uppermost Permian) follows Henderson (1997). Triassic chronostratigraphy utilized here follows the recommendations of the IUGS Subcommision on Triassic Stratigraphy (Gradstein et al., 1994) in retaining the Rhaetian as a valid stage.

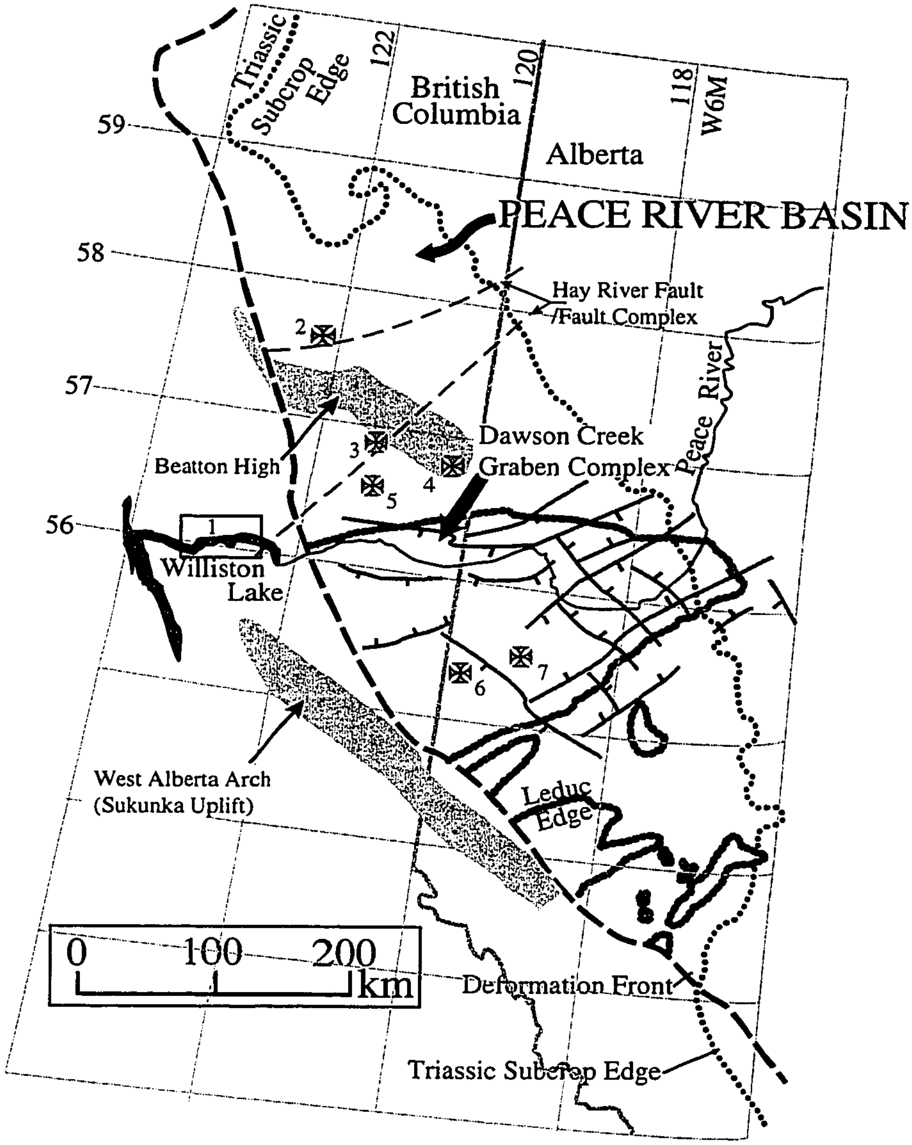

Figure 1. Regional map showing the location of pertinent Triassic structural and paleogeographical features, Western Canada Sedimentary Basin (Adapted from Davies, 1997). The Triassic Peace River Basin is centred on the late Paleozoic Peace River embayment. The erosional subcrop edge of Triassic sediments is indicated by the dotted line. The eastern limit of Laramide deformation is shown by the heavy dashed line. The Sukunka Uplift (Richards, 1989) and Beatton High (Henderson et al., 1994) are late Paleozoic structural elements which may have affected Triassic deposition within the study area. Faults within the Dawson Creek Graben Complex have been shown to have had a pronounced effect on Triassic deposition within the Peace River Basin. The outcrop portion of this study centres on the Peace Reach of Williston Lake (1). Also shown are Tommy Lakes Field, (2; the subsurface portion of this study), Wargren and Umbach fields (3; Young, 1997), Peejay Field (4; Caplan, 1992; Caplan and Moslow, 1997), Buick Creek, Cache Creek, Fireweed and Stoddart-West fields (5; Evoy, 1995; 1997; Evoy and Moslow, 1995), Sinclair Field (6; Wittenberg, 1992; 1993) and Wembley Field (7; Willis and Moslow, 1994a; 1994b)

Pelletier, 1964) has documented several vertically extensive and well-exposed Triassic outcrops along the margins of the lake. Although damming of the lake resulted in the inundation of the classic Triassic Peace River localities visited by F.H. McLearn in the early part of this century (McLearn, 1921; 1937; 1940; 1941a; 1941b), numerous new localities were created along the shores of the lake. These new localities are, as a rule, more completely exposed. Access to localities along the lake is limited to approximately four to six weeks per year, between mid-May (after spring ice break-up) and mid-June (prior to peak spring runoff and seasonal high water). Seasonal fluctuations in lake level scour detrital material from outcrop exposure and prevent vegetation from overgrowing the outcrop.

Previous Work

The presence of Triassic strata on the Peace River was first recognized by Selwyn in 1875 (Selwyn, 1877). Middle Triassic strata were first recognized on the Peace River at Beattie Hill (Figures 2 and 3) by a Geological Survey of Canada expedition led by F. H. McLearn in 1917 (McLearn, 1921; 1940; Tozer, 1984). He did not have opportunity to revisit the site and expand upon his earlier work until the late 1930's (McLearn, 1940; Tozer, 1984). Although he concentrated primarily on the Upper Triassic, several publications in the early 1940's summarized the Middle Triassic field work of McLearn and his field assistants on the Peace River (McLearn, 1940; 1941). Many of these assistants have subsequently lent their names to geographical landmarks in the Peace River foothills (*i.e.* R.A.C. Brown, A.J. Childerhose, W. Jewitt, A.B. McLay, and C.R. Stelck).

In his stratigraphic description of Beattie Ledge, McLearn (1940) also made brief reference to Middle Triassic exposure at Aylard Creek, recognizing its equivalence with the Beattie Hill succession. McLearn (1941) recognized the significance of the Brown Hill, summarizing biostratigraphic zonations and discussing its equivalence with other sites, including east and west Glacier Ridge on the south side of the river opposite Brown Hill. McLearn continued to publish on the biostratigraphy of northeastern British Columbia through the 1960's (McLearn, 1953; 1960; 1966; 1969).

Field workers from the Geological Survey of Canada have continued research on the Middle Triassic in the Peace River Foothills. Irish (1965; 1970) produced the first detailed and comprehensive geological maps of the area. Gibson (1971; 1975) summarized the Triassic lithostratigraphy within the study area. Gibson continued Triassic field work in the study area until his recent retirement (Gibson and Edwards 1990; 1992).

Database and methodology

Five sites along the shores of the Peace Reach of Williston Lake display exposure of Middle Triassic strata and comprise the outcrop component of this study. Locality names, National Topographic System 1:50,000 map sheet name and number, and coordinates (latitude and longitude) are supplied for each locality in Table 2. All five localities discussed in this report (Ursula Creek, Brown hill, Glacier Spur, Beattie Ledge and Aylard Creek) occur on the limbs of thrust faults in the Front Ranges of the Canadian Rocky Mountains.

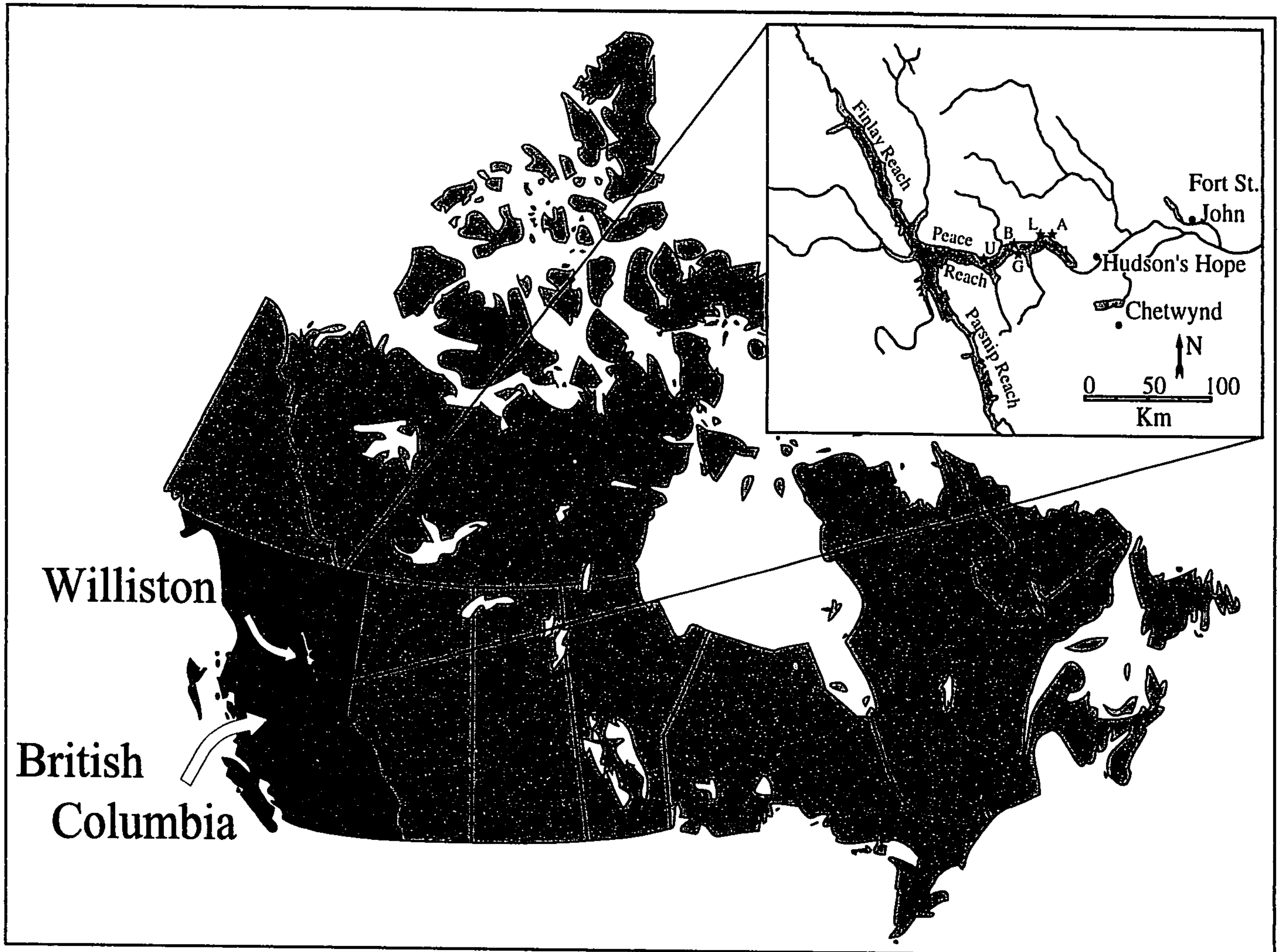

Figure 2. Location map of the study area in northeastern British Columbia, Canada. Inset map shows the location of localities along the Peace Reach of Williston Lake discussed in this report. These localities include Ursula Creek (U), Glacier Spur (G), Brown Hill (B), Beattie Ledge (L) and Aylard Creek (A).

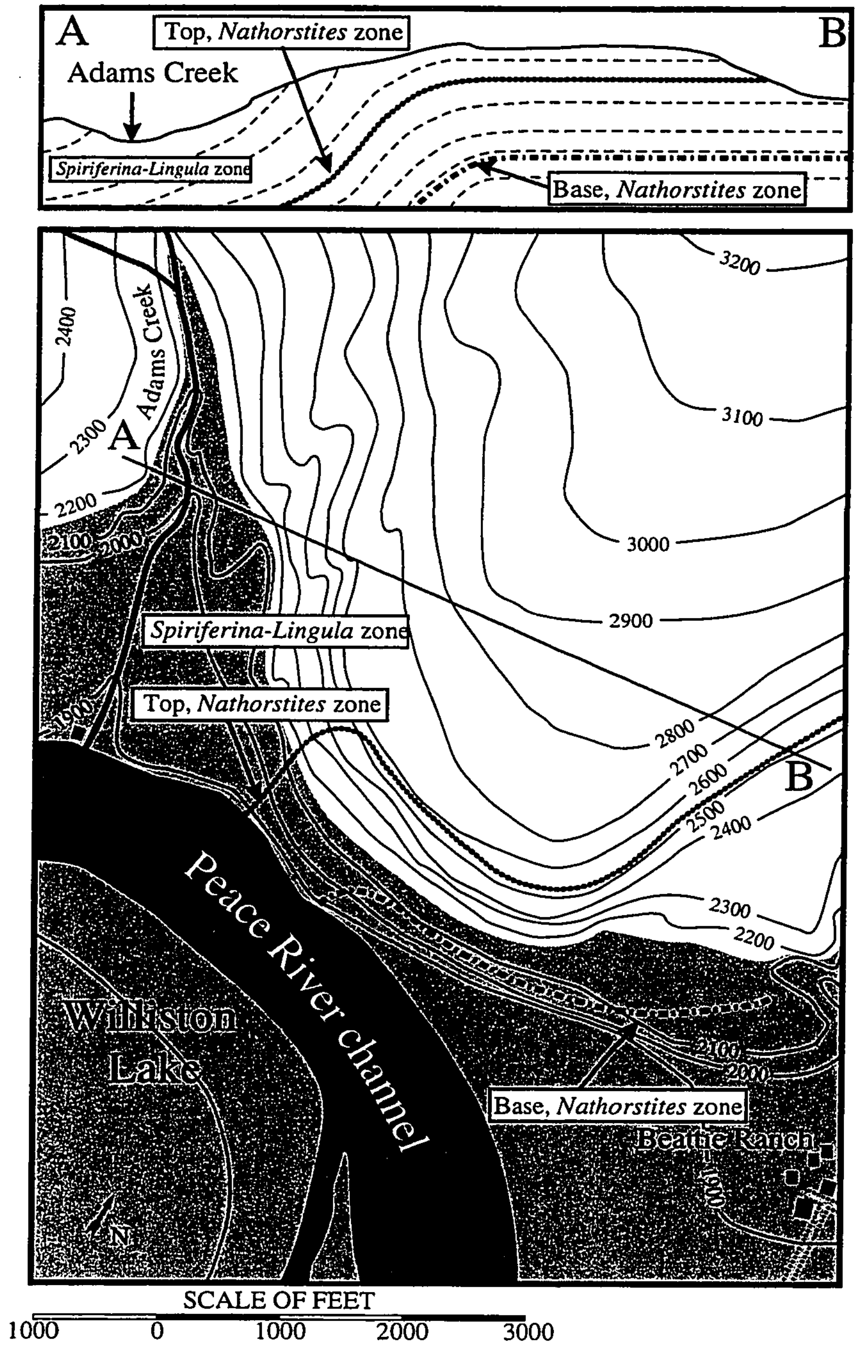

Figure 3. Outcrop map of Beattie Ledge, along the Peace River (now Williston Lake), northeastern British Columbia showing the former path of the Peace River (black) and the present location of the shore of Williston Lake (grey) during early spring (low water levels). A structural cross-section (A-B) is shown at the top of the page. Adapted from McLearn (1940). Ladinian biostratigraphic zones discussed in McLearn (1940) are also shown.

Locality	**Location (NTS, lat./long.)**	**Thickness of Lower-Middle Triassic strata exposed (approx.) & formations present**
Aylard Creek	Jones Peak, 94-B/2 56° 09' 26"N, 122° 33' 16"W	-140m, upper Toad Formation, lower Liard Formation.
Beattie Ledge	Jones Peak, 94-B/2 56° 09' 22"N, 122° 34' 51"W	-215m, upper Toad Formation, lower & upper Liard Formation.
Brown Hill	Jones Peak, 94-B/2 56° 06' 09"N, 122° 52' 12"W	-630m, Toad Formation, lower & upper Liard Formation.
Glacier Spur	Jones Peak, 94-B/2 56° 04' 58"N, 122° 52' 04"W	-325m, Toad Formation, lower & upper Liard Formation.
Ursula Creek	Point Creek, 93-O/14 55° 59' 40"N, 123° 10' 27"W	-120m, Grayling Formation, Toad Formation, Ludington Formation.

Table 2. Localities with exposure of Lower and Middle Triassic strata exposed along the Peace Reach of Williston Lake. National Topographic System 1:50,000 map sheet name and number, coordinates (latitude and longitude), Lower and Middle Triassic formations exposed and approximate total thicknesses of these units are supplied for each locality. Brown Hill, Glacier Ridge and Ursula Creek also have appreciable thicknesses of Upper Triassic strata (Charlie Lake, Baldonnel and Pardonet formations) exposed, however, these units are not discussed here.

Ursula Creek, Brown Hill and Glacier Spur are structurally simple, consisting of sub-vertically emplaced (75°-90°) eastward (Ursula Creek) and westward (Brown Hill and Glacier Spur) dipping strata on the limbs of thrust faults. Beattie Ledge and Aylard Creek are somewhat more complex. Beattie Ledge occurs on the west side of a minor thrust fault and consists of small monocline (Figure 3). Aylard Creek is located on the eastern side of the same thrust fault and consists of a succession of minor, low-angle anticlines and synclines. Faults do not occur within any of these localities however, simplifying stratigraphic analysis.

Detailed stratigraphic sections were measured at each locality. Attention was paid to lithology, physical and biogenic sedimentary structures, and bioclastic or fossil composition. Bounding surfaces were closely analyzed and described. Lithofacies were described both vertically and horizontally (in as much as exposure allowed) to assess lateral variability in physical and biogenic sedimentary structures and in sediment composition. Representative samples were collected at regular intervals for thin- and polished-section analysis. Trace and body fossils were photographed and described in terms of associations and overall abundance. Samples of all trace and body fossils were collected. This collection shall be housed in the Royal Tyrrell Museum of Palaeontology in Drumheller Alberta where it shall be accessible to all future field workers.

Gamma-ray readings were taken at all measured sections using a portable hand-held scintillometer (Scintrex BGS-4), to facilitate correlation between outcrop sections and better delineate marine flooding surfaces. Five radiation count readings, separated by ten second intervals, were obtained at 0.60 m intervals following the methodology of Slatt *et al.* (1992). The highest and lowest values were discarded and the remaining three averaged to obtain the value for each horizon.

Bulk samples for conodont analysis were collected within adjacent marine strata to place the sections within a biostratigraphic framework. Special attention was paid to bounding surfaces during selection of conodont sampling sites. Samples were collected above and below all ravinement surfaces, whether they were deemed to be chronologically extensive unconformities or not, and at all significant flooding surfaces. Gamma ray scintillometry proved invaluable in selecting conodont sampling sites. Samples characterized by high gamma ray readings proved more likely to produce conodont elements than lithologically similar samples characterized by lower readings. In total, 1250m of section and 2100 gamma-ray intervals were measured. One hundred and twenty bulk samples weighing a total of approximately 245 kilograms were collected for conodont analysis.

Stratigraphic Setting

The outcrop portion of this study deals with three main lithostratigraphic units, the Grayling, Toad and Liard Formations (Table 1). The Grayling Formation was named for a thick succession of dolomitic siltstones and shales, fine-grained sandstones and silty micrites and dolomicrites (Kindle, 1944), outcropping along the banks of the Grayling River near its junction with the Liard River. Exposure of the Grayling Formation along Williston Lake is limited to the basal part of the Ursula Creek section where it consists primarily of black silty shale and dark brown siltstone. Fossils were not observed in the Grayling Formation within the study area. The Grayling is the temporal equivalent of the lower part of the Montney Formation in the subsurface to the east, the Phroso Siltstone Member of the Sulphur Mountain Formation (Table 1) in the outcrop belt along the Rocky Mountain Front of southwestern Alberta, and the Toad Formation in the eastern portion of the outcrop belt.

The Toad Formation was described by Kindle (1944) for a thick succession of dark grey calcareous siltstone, silty limestone and silty shale exposed near the mouth of the Toad River in northeastern British Columbia. Toad outcrop within the study area is comprised predominantly of dark shales, siltstone and fine-grained sandstone, deposited in a proximal shelf to slope setting. Toad outcrop at Ursula Creek is comprised primarily of dark shale, silty shale, siltstone, and rare bioclastic packestone lenses, deposited in a distal shelf to slope setting.

Although fossiliferous elsewhere in the outcrop belt (Gibson, 1975) the Toad Formation was not found to be particularly fossiliferous at Williston Lake. Fossils observed within the Toad Formation at Williston Lake include a variety of brachiopod, ammonoid, bivalve and fragmentary fish fossils, as well as a wide variety of trace fossils. The Toad is considered to be the equivalent of the upper Montney and lower Doig Formations in the subsurface to the east, and to the upper part of the Sulphur Mountain Formation in the southern Rocky Mountain Foothills outcrop belt (Table 1). Within the study area, the Toad conformably overlies the Grayling Formation and is conformably overlain by the Liard Formation.

The Liard Formation was named for resistant dolomitic to calcareous sandstone, siltstone and sandy limestone exposed on an island in, and on the south bank of the Liard River near a particularly treacherous stretch of the river known as Hades Gate (Kindle, 1946). Liard formation outcrop within the study area is comprised of a series of progradational, overall coarsening-upwards, mixed siliciclastic-carbonate-evaporite, shoreface to marginal marine parasequences (Zonneveld *et al.,* 1997).

The unit has proven extremely fossiliferous within the study area. Fossils thus far identified include a variety of ammonoids, bivalves (including pteriids, trigonids, pectenids), gastropods, brachiopods (lingulids, acrotretids, spiriferids, and terabratulids), echinoids, crinoids ophiuroids, bryozoans and decapod crustaceans, along with fragmentary remains of fish, and marine reptiles, as well as an impressive array of trace fossils. The Liard is considered to be the equivalent to the Halfway and upper Doig Formations in the subsurface to the east, and to the Llama Member of the Sulphur Mountain Formation in the southern Rocky Mountain foothills outcrop belt. Within the study area, the Liard is conformably overlain by the carbonates and evaporites of the marginal marine to nonmarine Charlie Lake

Formation.

Doig/Halfway/basal Charlie Lake Interval in subcrop

The Middle Triassic, comprising the Halfway, Doig and basal Charlie Lake Formations in the subsurface (Figure 1), is one of the most economically important stratigraphic intervals within the northern Western Canada Sedimentary Basin, accounting for approximately 40% of established natural gas reserves in British Columbia (CAPP statistics, 1994). Both sandstone and coquina form reservoirs within these units (Chunta, 1969; Campbell and Horne, 1986; Caplan, 1993; Evoy and Moslow, 1995; Willis and Moslow, 1994a & b).

Previous work

The Halfway and Doig Formations are dominantly siliciclastic units restricted to the subsurface of the Western Canada Sedimentary Basin of northeastern British Columbia and northwestern Alberta. Laterally continuous, chronostratigraphically significant marker surfaces have been identified extending down from the lower Charlie Lake into the Halfway and Doig Formations in the Wembley and Sinclair fields of west-central Alberta and the Peejay Field of northeastern British Columbia (Caplan, 1992; Willis, 1992; Wittenberg, 1992) indicating that these units were deposited penecontemporaneously. These units are considered chronostratigraphically equivelent to the Toad and Liard Formations in the Peace River outcrop belt in the Rocky Mountain Foothills.

The Halfway Formation was initially described by Hunt and Ratcliffe (1959) as the first gray marine sandstone below the predominantly terrigenous strata of the Charlie Lake Formation. As a result, all such sandstones have subsequently been lithostratigraphically correlated as a single regressive sheet sandstone (Hunt and Ratcliffe, 1959; Armitage, 1962). Other middle Triassic units (*i.e.* the Doig and Charlie Lake Formations) were similarily lithostratigraphically defined (Armitage, 1962; Hunt and Ratcliffe, 1959). Since the advent of sequence stratigraphy in the early 1980's, emphasis has been placed on analyzing the Middle Triassic of the Western Canada Sedimentary basin within a chronostratigraphic framework (*i.e.* Arnold, 1994; Caplan, 1992; Caplan and Moslow, 1997; Evoy, 1995; 1997; Evoy and Moslow, 1995; Willis, 1992; Willis and Moslow 1994a; 1994b; Wittenberg, 1992; 1993). This study continues this trend. It is intended that this thesis provide a framework within which the Middle Triassic of northeastern British Columbia can be defined on a regional sequence biostratigraphic basis.

Tommy Lakes Region

The Tommy Lakes field is located in northeastern British Columbia, approximately 170 km northwest of Fort St. John (Figures 1 and 2). The field as presently defined consists of map quadrangles 94-G-09, the western part of 94-H-12, and the southern part of 94-G-16, and is approximately 48,750 hectares in size (Figure 4). Tommy Lakes Field, along with the townships surrounding the field comprise the subsurface portion of this investigation. Approximately 120 wells penetrate the Doig-Halfway-Basal Charlie Lake interval within the

Tommy Lakes region. Fifty-six of these wells contain core through the study interval. All core from the Tommy Lakes region, as well as core from an additional fifty wells outside the immediate Tommy Lakes area were analyzed to facilitate lithofacies and sequence biostratigraphic analysis. Correlation between Tommy Lakes Field and the outcrop belt along Williston Lake has proven possible by the identification of several key sequence stratigraphically significant surfaces present in both the subsurface and in the outcrop belt.

Regional Stratigraphy

In the subsurface of the Western Canada Sedimentary Basin, Middle Triassic (Anisian-Ladinian) strata are subdivided into three lithostratigraphic units: the Doig, Halfway and basal Charlie Lake formations (Table 1). Within the Tommy Lakes region, Middle Triassic strata unconformably overlie the lower Triassic Montney Formation and are unconformably overlain by younger Mesozoic (Jurassic and Cretaceous) strata.

The Doig Formation consists primarily of grey siltstone and dark shale (Armitage, 1962), although within the study area the Doig contains a significant proportion of very fine-grained sandstone. The top of the Doig Formation is defined as the base of the Halfway Formation and is characterized by a sharp decrease in gamma radioactivity (Dawes, 1990). Although the Doig-Halfway contact has been described as a disconformity (Campbell and Horne, 1986; Dawes, 1990; Young, 1997), recent work has shown that it is not a regionally correlatable unconformity (Willis 1994a; Wittenberg, 1992; Evoy, 1995; 1997; Evoy and Moslow, 1995).

The Halfway Formation consists of grey, fine to medium-grained, calcareous sandstone (Hunt and Ratcliffe, 1959). Thick, cross-bedded bioclastic accumulations are locally common within both the Halfway and Doig formations (Campbell and Horne, 1986; Barclay and Leckie, 1987; Leckie and Rosenthal, 1987; Willis and Moslow, 1994a & b; Caplan and Moslow, 1997; Zonneveld et al., 1997). Within the study area the Halfway Formation is conformably and gradationally overlain by the dolomitic mudstone/sandstone of the Charlie Lake Formation. The Halfway and Doig formations and the basal part of the Charlie Lake Formation are chronostratigraphically equivalent to the Toad and Liard formations in the Rocky Mountain Foothill.

The Charlie Lake Formation conformably overlies the Halfway Formation within the study area. It is a highly heterolithic unit, consisting of sandstone, limestone, dolostone, cyanobacterial laminites, evaporites, red beds and solution collapse breccia (Hunt and Ratcliffe, 1959). The Charlie Lake contains three formally defined members (Artex, Inga, Coplin and Boundary), numerous informal members and several regional unconformities (Moslow and Davies, 1992). Although the Charlie Lake Formation has generally been referred to as an Upper Triassic unit (Dawes, 1990), the Halfway-Charlie Lake contact corresponds with a shift in lithofacies and in inferred depositional environment, and thus is an inherently diachronous contact. Preliminary biostratigraphic data suggests that the contact may be Ladinian or uppermost Anisian in eastern subcrops.

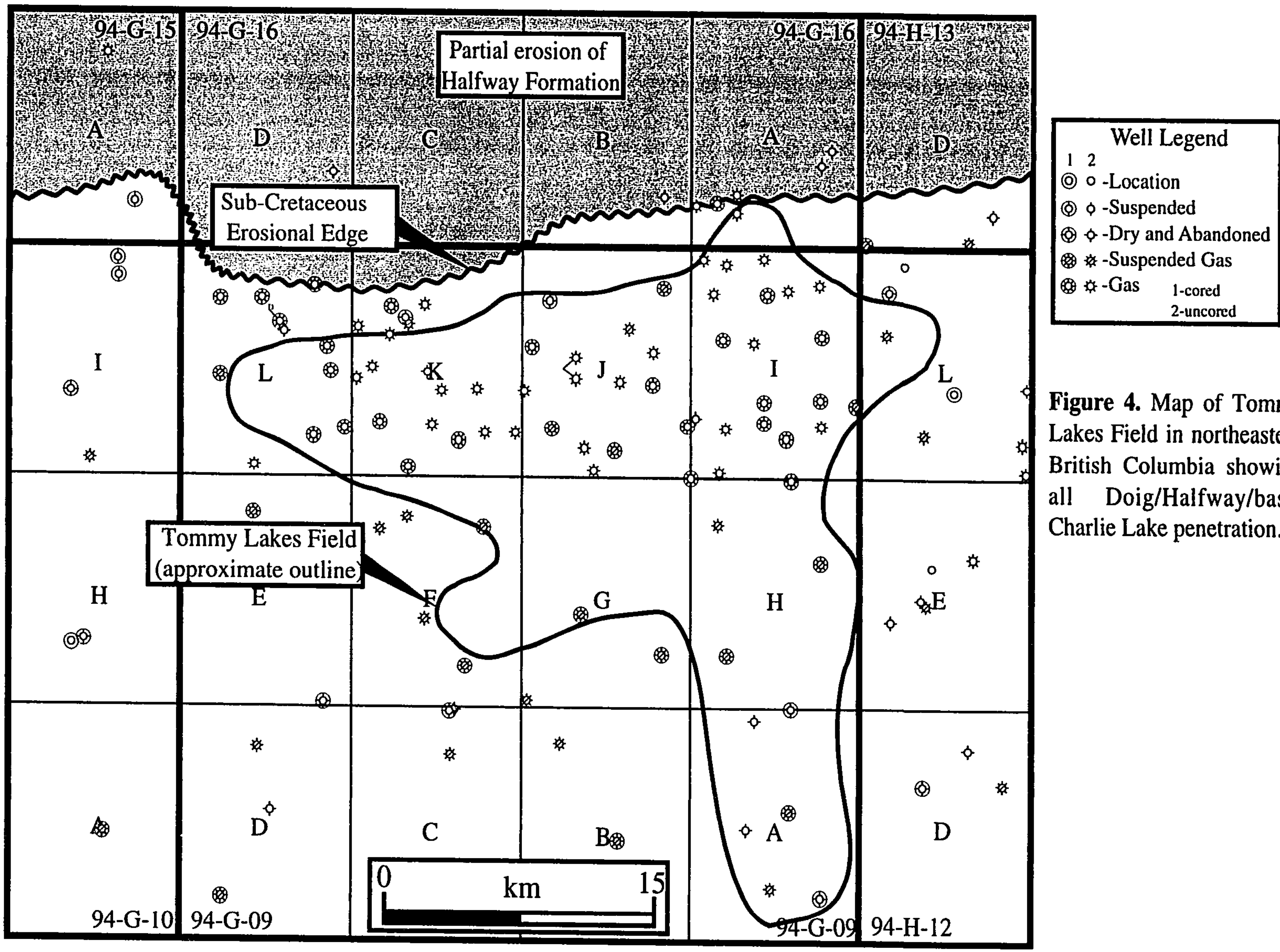

Figure 4. Map of Tommy Lakes Field in northeastern British Columbia showing all Doig/Halfway/basal Charlie Lake penetration.

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CHAPTER 2.

LITHOFACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS IN A MIXED SILICICLASTIC-CARBONATE COASTAL DEPOSITIONAL SYSTEM, UPPER LIARD FORMATION, TRIASSIC, NORTHEASTERN BRITISH COLUMBIA.

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> *"The calcareous masses usually termed coral reefs, are by no means exclusively composed of zoophytes, but also a great variety of shells; some of the largest and heaviest of known species contributing to augment the mass. In the south Pacific, great beds of oysters, mussels,* pinnae marinæ, *and other shells, cover in great profusion almost every reef; and, on the beach of coral reefs, are seen the shells of echini and the broken fragments of crustaceous animals. Large shoals of fish also are discernible through the clear blue water, and their teeth and hard palates are probably preserved, although a great portion of their soft cartilaginous bones may decay."*
>
> Charles Lyell, 1831

INTRODUCTION

Background and Objectives:

Triassic strata in the Western Canada Sedimentary Basin comprise a westward thickening succession of marine and marginal marine siliciclastics, carbonates and evaporites deposited on the western margin of the North American craton. As observed in this study, Middle Triassic outcrop within the Peace River foothills region consist of an an overall shallowing upward series of progradational, mixed siliciclastic-carbonate shoreface parasequences. Until recently, Triassic strata in the Western Canada Sedimentary Basin were primarily mapped utilizing lithostratigraphic methodologies. As a result, a wide variety of names have been introduced to refer to the same succession of rocks in different parts of the basin. A synopsis of stratigraphic nomenclature currently in use for Triassic strata of northeastern British Columbia is presented in Table 1. Until detailed chronostratigraphic studies spanning the entire Western Canada Sedimentary Basin are provided (outcrop and subsurface), precise correlation between regions remains somewhat tenuous and conjectural.

The Middle Triassic, consisting of the Halfway and Doig formations in the subsurface (Table 1), is one of the most economically important stratigraphic intervals within the northern Western Canada Sedimentary Basin, accounting for approximately 40% of established natural gas reserves in British Columbia (Canadian Association of Petroleum Producers, 1994). Both sandstone and bioclastic units form hydrocarbon reservoirs within these units (Chunta, 1969; Campbell and Horne, 1986; Caplan, 1992; Evoy and Moslow, 1995; Willis and Moslow, 1994a & b). The bioclastic units have been interpreted as tidal inlet channels (Barclay and Leckie, 1986; Campbell and Horne, 1986; Caplan, 1992; Evoy and Moslow, 1995; Willis and Moslow, 1994a & b) as shoreface deposits (Evoy and Moslow; 1995; Wittenberg, 1992), and as sediment gravity flows (Wittenberg, 1992).

The upper Liard Formation is considered to be the outcrop equivalent of the Doig and Halfway Formations (Arnold, 1994; Gibson and Edwards, 1990). The present study discusses lithofacies associations and depositional environments within the upper 220 metres of the Liard Formation. Excellent exposure of the Liard Formation along the shores of Williston Lake (Figures 1 & 2) provides rare insight into the depositional mechanisms of mixed siliciclastic-carbonate systems.

This paper documents sedimentary characteristics and sedimentologic origins of facies, vertical and lateral facies relationships within the different lithofacies associations, and assesses the provenance of significant bioclastic accumulations. These units are compared to bioclastic accumulations in laterally equivalent hydrocarbon reservoirs in the subsurface of northern Alberta and northeastern British Columbia.

Regional Stratigraphy

The Liard Formation was first defined by Kindle (1946) for an 180m succession of calcareous sandstone and arenaceous limestone conformably overlying the Toad Formation in the vicinity of Hades Gate on the Liard River, northeastern British Columbia. Kindle (1944) had originally included these strata in the Toad Formation but separated them on the basis of their thicker bedding, coarser nature, and greater proportion of carbonate units. The unit 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 is conformably overlain by the predominantly marginal marine to nonmarine Charlie Lake Formation (Figure 2). The Liard represents a period of mixed siliciclastic-carbonate deposition on the western margin of a topographically low, tectonically stable North American craton. Although the Pangean supercontinent had already divided into two parts by the mid-Triassic (Smith *et al.*, 1994), tectonic activity is believed to have had an effect on sediment source, supply and deposition in the Western Canada Sedimentary Basin (Wittenberg, 1992; 1993).

Study Area

Williston Lake, located approximately 80km west of Fort St. John, British Columbia (Figure 1), in the Rocky Mountain Trench, was created in 1967 by construction of the W.A.C. Bennett Dam on the Peace River. Previous work (MacLearn, 1941a & b; Gibson and Edwards, 1990b; Pelletier, 1964) has documented several vertically extensive and well-exposed Triassic outcrops along the margins of the Peace River, and subsequently along Williston Lake. This study concentrates on middle Triassic strata at two localities on the

PERIOD/SERIES/STAGE				PEACE RIVER OUTCROP BELT	SUBSURFACE OF NE BRITISH COLUMBIA
TRIASSIC	UPPER	RHAETIAN		BOCOCK FM	PARDONET FM
		NORIAN		PARDONET FM	PARDONET FM
		CARNIAN		LUDINGTON FM: BALDONNEL FM	BALDONNEL FM
				LUDINGTON FM: CHARLIE LAKE FM	CHARLIE LAKE FM
	MIDDLE	LADINIAN		LUDINGTON FM: LIARD FM	HALFWAY FM
		ANISIAN		TOAD FM	DOIG FM
	LOWER	OLENEKIAN	SPATHIAN	TOAD FM	MONTNEY FM
			SMITHIAN		
		INDUAN	DIENERIAN	GRAYLING FM	
			GRIESBACHIAN		

Table 1. Triassic stratigraphic nomenclature, subsurface and outcrop, northeastern British Columbia (adapted in part from Tozer, 1994). Contacts between Lower and Middle Triassic formations are drawn to reflect their diachronous nature and are not absolute. Triassic chronostratigraphy used here follows the recommendations of the IUGS Subcommision on Triassic Stratigraphy (Gradstein *et al.* 1994) in retaining the Rhaetian as a valid stage. The table is not drawn to absolute chronologic scale.

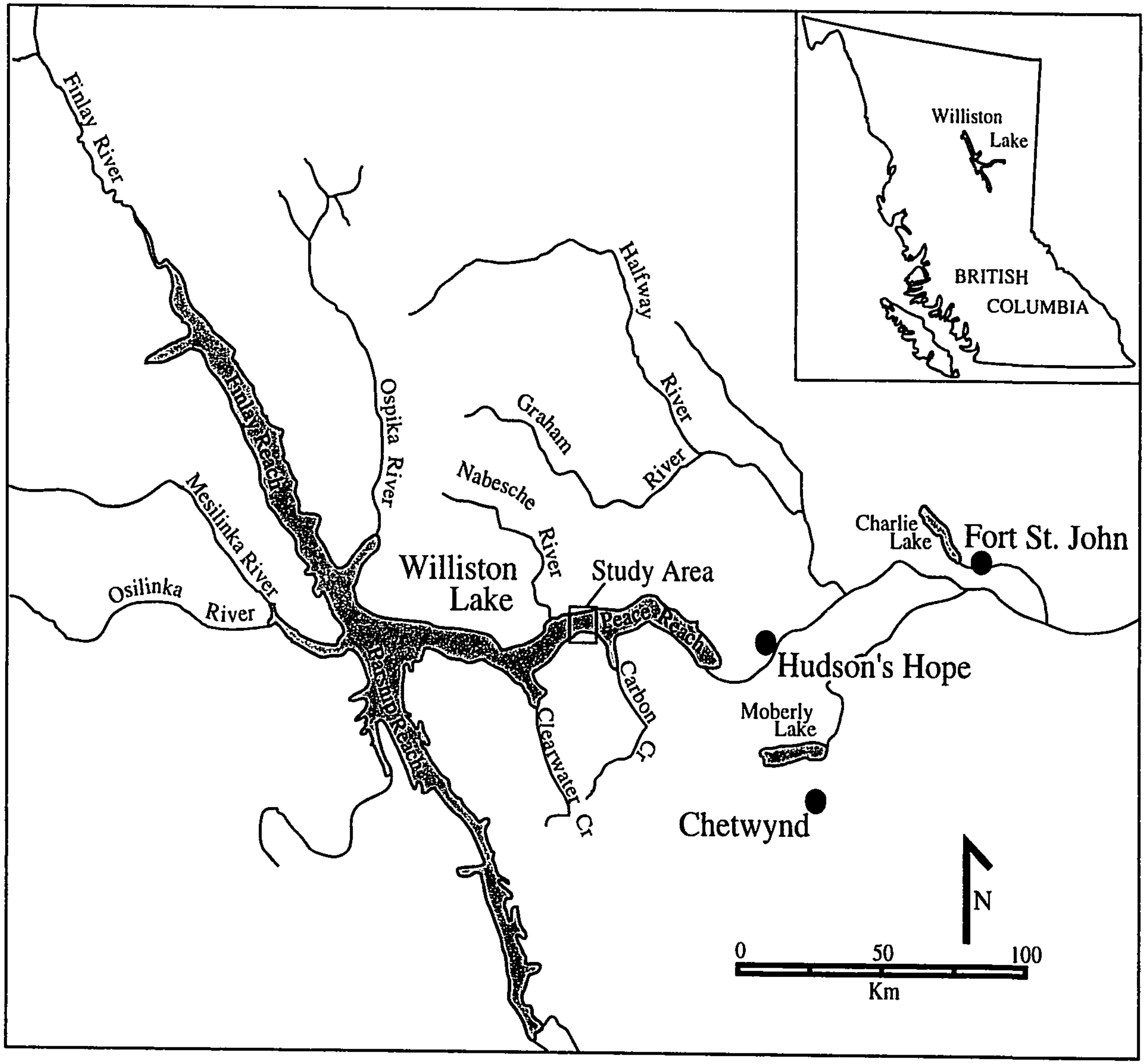


Fig. 1. Map of Williston Lake, northeastern British Columbia. The inset map in the upper right corner shows the location of Williston Lake in British Columbia. The two localities discussed in this report are located in the box inset at the centre of the map (see Figure 2).

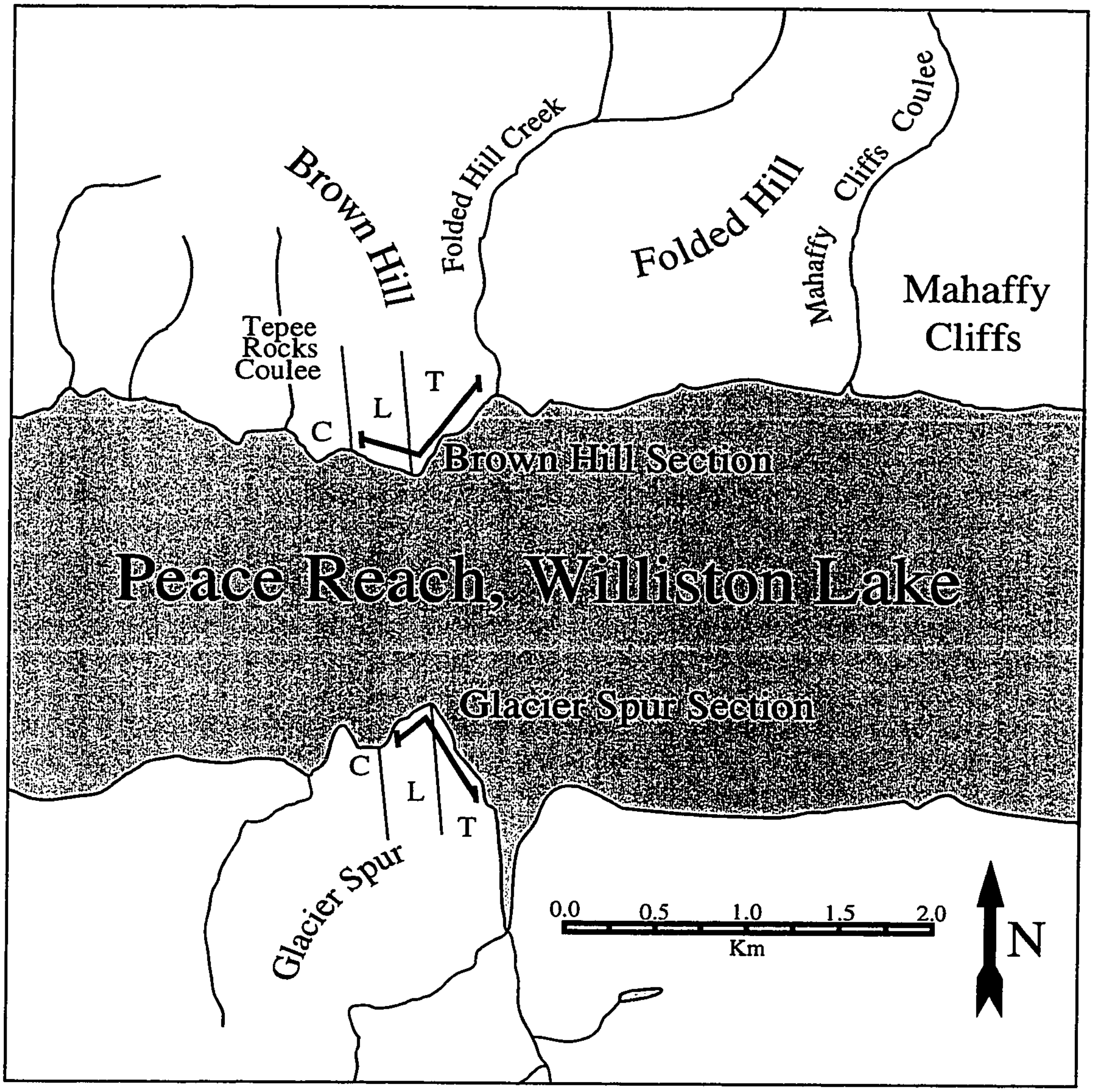


Figure 2. Detailed location map of the study area, showing the contacts between the Toad (T), Liard (L), and Charlie Lake (C) formations. The formations all dip to the west at 75-80°, on a strike of 170°. The two outcrop sites, Brown Hill on the north side of the lake, and Glacier Spur on the south side of the lake are on direct depositional strike from one another, and separated by a distance of approximately 2km.

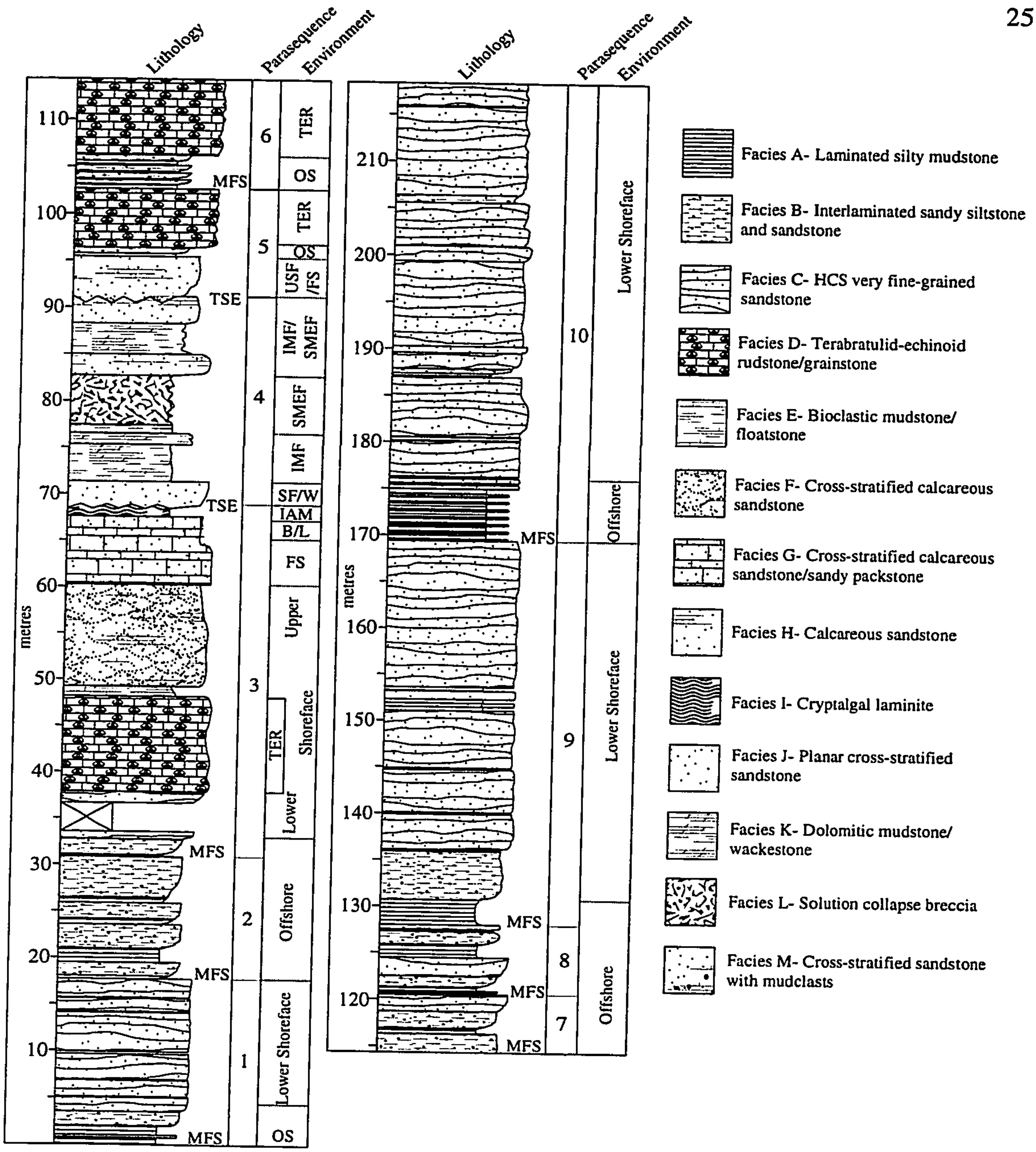


Figure 3. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Brown Hill. The section has been separated into 10 parasequences, although some (*i.e.* parasequences 2, 7 and 8) likely comprise several amalgamated parasequences. MFS= Marine Flooding Surface; TSE= Transgressive Surface of Erosion; RS= Ravinement Surface; OS=Offshore; LSF= Lower Shoreface; TER= Terebratulid-Echinoid Reef; USF= Upper Shoreface; FS= Foreshore; SF/W= Shoreface/Washover Fan; B/L= Backshore/Lagoonal; IAM= Intertidal Mud Flat; SMEF= Supratidal Evaporite Mud Flat.

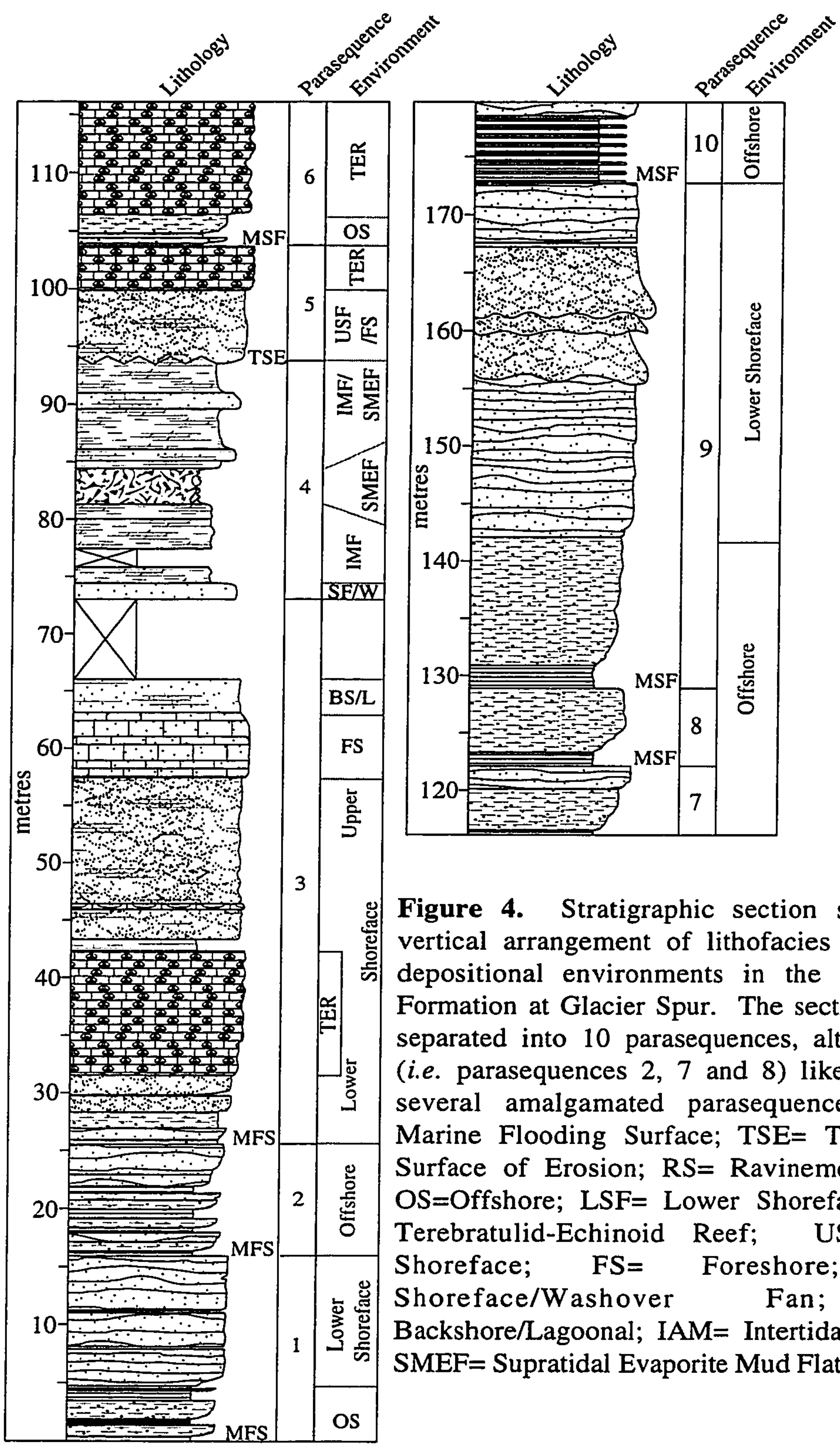


Figure 4. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Glacier Spur. The section has been separated into 10 parasequences, although some (*i.e.* parasequences 2, 7 and 8) likely comprise several amalgamated parasequences. MFS= Marine Flooding Surface; TSE= Transgressive Surface of Erosion; RS= Ravinement Surface; OS=Offshore; LSF= Lower Shoreface; TER= Terebratulid-Echinoid Reef; USF= Upper Shoreface; FS= Foreshore; SF/W= Shoreface/Washover Fan; B/L= Backshore/Lagoonal; IAM= Intertidal Mud Flat; SMEF= Supratidal Evaporite Mud Flat.

Peace Reach of Williston Lake, approximately 50km upstream of the dam (Figure 2). These localities comprise some of the most extensive exposures of middle Triassic strata within the Rocky Mountain outcrop belt. Exposure at outcrops along Williston Lake is scoured every year by seasonal fluctuations in water level.

Detailed sections were measured at Brown Hill (Figure 3) and Glacier Spur (Figure 4) to describe sedimentary facies and to assess vertical and local lateral facies variability. The two sites are located approximately 2km apart on depositional strike from one another, and are considered to be equivalent, both chronologically and stratigraphically.

Biostratigraphy

Preliminary biostratigraphic analysis suggests that the upper Liard Formation is Uppermost Ladinian in age. Conodonts have been recovered from several horizons within the study interval. *Epigondolella? mungoensis* recovered from the base of parasequence 3 at Glacier Spur (Figure 4.) is characteristic of the upper Ladinian *sutherlandi* Zone. This species may be the oldest representative of the genus, which is more characteristic in and evolves rapidly through the Carnian and Norian. There is some disagreement regarding the generic assignment depending on the relative significance of upper and lower surface morphological features as well as on interpreted phylogenetic relationships, however the species is considered diagnostic of the Upper Ladinian (Mosher, 1973). Four genera of ammonoids were collected from the top of parasequence 6 at both Brown Hill and Glacier Spur (Figures 3 and 4). These ammonoids, *Nathorstites macconnelli, Daxatina canadensis, Muenesterites glaciensis* and *Lobites ellipticus*, are all diagnostic of the *sutherlandi* Zone (Tozer, 1994). *Paragondolella navicula navicula* and an unusual form of *Metapolygnathus* sp. recovered from the base of parasequence 9 at Brown Hill (Figure 3), may be suggestive of early Carnian deposition.

SEDIMENTARY FACIES AND FACIES ASSOCIATIONS

Thirteen sedimentary facies have been recognized in the upper Liard Formation within the study area, identified on the basis of lithology, bounding surfaces, primary physical and biogenic sedimenary structures, and bioclastic or fossil composition (Table 2). Sedimentary facies within the study area occur within three recurring progradational facies associations. These facies associations are: a) clastic offshore/shoreface, b) mixed siliciclastic-carbonate shoreface, and c) mixed siliciclastic-carbonate marginal marine.

Facies A- Laminated black silty shale

Description- Facies A consists of thinly bedded, planar laminated black silty shale containing fractions (<10%) of disseminated very fine-grained sand and thin (1.0-20.0cm), normally graded layers of silt to very-fine grained sand (Figure 5), often load casted.

Body fossils observed within this unit include rare fish (palaeoniscid) and chondricthyan ('shark') scales, ammonoid impressions on bedding planes, and scattered shells of the inarticulate brachiopod *Lingula*. A single specimen of *Lingula* was observed in growth position within facies A, indicating that at least some of these shells are autochthonous rather than transported from a shallower environment (Figure 6). Trace fossils consist of a low diversity, distal *Cruziana* assemblage comprising *Palaeophycus, Lingulichus, Helminthopsis, Phycosiphon incertum, Scalarituba missouriensis* and *Chondrites*.

Interpretation- Facies A was deposited in the proximal offshore, below mean storm-weather wave base. The finely laminated shales are primarily a product of suspension deposition. The disseminated sand fraction and much of the silt may have been sourced by aeolian transport from contemporaneous continental environments (Arnold, 1994). Aeolian transport has been shown to be an important mechanism in delivering disseminated terrigenous sediments to ocean basins downwind of arid regions (Windom and Chamberlain, 1978). Thin, normally graded laminae of silt and very-fine grained sand within this facies may be attributed to offshore transport and deposition via sediment gravity flows (Reineck and Singh, 1972; Nelson, 1982). In several cases, particularly at the base of parasequence 10 at both Brown Hill and Glacier Spur, these coarser laminae are very evenly spaced (Figure 5), possibly reflecting either storm seasonality or a longer duration climactic cyclicity.

Facies B- Interlaminated sandy siltsone and very fine-grained sandstone.

Description- Interlaminated siltstone and sandstone of facies B conformably overlie the laminated black shale of facies A. Thin (0.5-25cm) shale beds similar to those of facies A occur throughout the unit, more commonly near the base. Sedimentary structures include plane parallel laminations (Figure 7a), current ripples, and horizons of poorly developed, low relief hummocky cross-stratification. Better developed hummocky cross-stratification and a mix of current and oscillation ripples occurs towards the top of facies B, particularly in parasequences 9 and 10 (Figures 3 and 4).

Body fossils consist of scattered lingulid valves, and isolated fish and marine reptile skeletal elements. Trace fossils consist of a low diversity medial *Cruziana* assemblage of *Scolicia, Thalassinoides suevicus, Spongeliomorpha, Lockeia, Palaeophycus* and *Planolites*.

Interpretation- The presence of abundant hummocky cross stratified horizons indicates that this unit was emplaced within the zone of storm-wave reworking. With the exception of hummocky cross-stratification, the unit is characterized by an absence of high-energy sedimentary structures. Facies B was deposited within the transitional zone between the offshore and the shoreface. The unit coarsens upwards overall reflecting the gradational shallowing/shoaling nature of these sediments.

Facies C- Hummocky cross-stratified very fine-grained sandstone.

Description- Facies C is comprised almost exclusively of well sorted, very fine- to fine-grained quartzose sandstone, and is interbedded with thin mudstone lenses. The unit is predominantly hummocky cross-stratified (Figure 8a). Individual beds range in thickness from 10 to 60cm, averaging approximately 20-30cm (Figure 8b). Upper bedset contacts are

FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	FOSSILS	DEPOSITIONAL ENVIRONMENT
A	Black silty shale	Plane parallel laminae, discontinuous normally graded sand/silt laminae, and current ripple laminae,	Pa,He,Li,Ph, Sc,Ch	*Lingula*, rare fish, bivalves & ammonoids	Offshore
B	Siltstone/Sandstone	Plane parallel laminae, flow ripples, HCS, rare oscillation ripples.	Sc,Th,Sp,Lk,Pa, Pl	scattered lingulids, bivalves, & reptile bones	Offshore/Shoreface Transition
C	Sandstone (very fine)	Amalgamated HCS beds, planar bedding, current and oscillation ripples.	Di,Sk,Th,Pa,Cy, Te,Ro,Si,Lk,Ar	brachiopods,bivalves, fish, & ammonoids	Lower Shoreface
D	Bioclastic rudstone/grainstone	Obscured by abdt. bioclasts. Beds thicken upwards (30-60cm). Grading not observed. Abrupt bounding surfaces.	None observed	terebratulid brachs echinoids, & crinoids	Reef Mound
E	Bioclastic floatstone/mudstone	low-angle planar laminae, thinly bedded, normally graded?	Pl	echinoids, crinoids, brachs, fish, decapods	Back Reef
F	Calcareous sandstone (very fine to fine)	Predominantly TCS, rare HCS (SCS?), rare oscillation ripples	Di,Sk, Pa, Pl	scattered brachiopod & echinoderm debris	Distal Upper Shoreface
G	Cross-stratified, calcareous bioclastic sandy packstone (fine to medium)	Trough to planar cross-stratification at base, grading up into planar-tabular laminae. Inversely graded.	None observed	bioclastic debris, brachs, bivalves, rare icthyosaur bones	Proximal Upper Shoreface/ Foreshore
H	Calcareous bioclastic sandstone	Appears massive, planar lam. to TCS, beds thicken upwards (5-10 to 30cm)	Sk, Pa, Is, BRT	rare *Lingula* and bioclastic debris	Backshore/ Lagoonal
I	Cryptalgal laminite	None noted	Algal laminae	None noted	Intertidal/Supratidal Mud Flats
J	Planar cross-stratified sandstone	low-angle planar cross-stratification, oscillation ripple lamination	Sk, Pa, Is, BRT	rare spiriferid and lingulid brachs	Shoreface/Foreshore Washover Fan
K	Dolomitic mudstone/wackestone	Planar laminations, current and oscillation ripples, polygonal mudcracks	Di,Sk,Pa,La, Cy, Pl,Rh	*Lingula*, bivalve frags, gastropods	Intertidal/Supratidal Mud Flats
L	Solution collapse breccia	Solution collaspse of other lithofacies	None observed	None noted	Supratidal
M	Calcareous sandstone (fine to medium)	Predominantly TCS grading up into current ripple laminae, mudclast lags	None observed	Rare bivalve shell lags.	Tidal Inlet Channels

Table 2. Summary of sedimentary facies characteristics in the Liard Formation, Brown Hill and Glacier Spur, Williston Lake, British Columbia. Acronyms used here are the same as those used in figure 18.

Figure 5. Outcrop photograph of recessive interlaminated black silty shale (Sh) and more prominent sandy siltstone/very fine-grained sandstone (St), lithofacies A, base of parasequence 10 (169.5-175.0m), Brown Hill. Scale in centre of photograph is 15cm. Beds are dipping at 82°. Up is to the left.

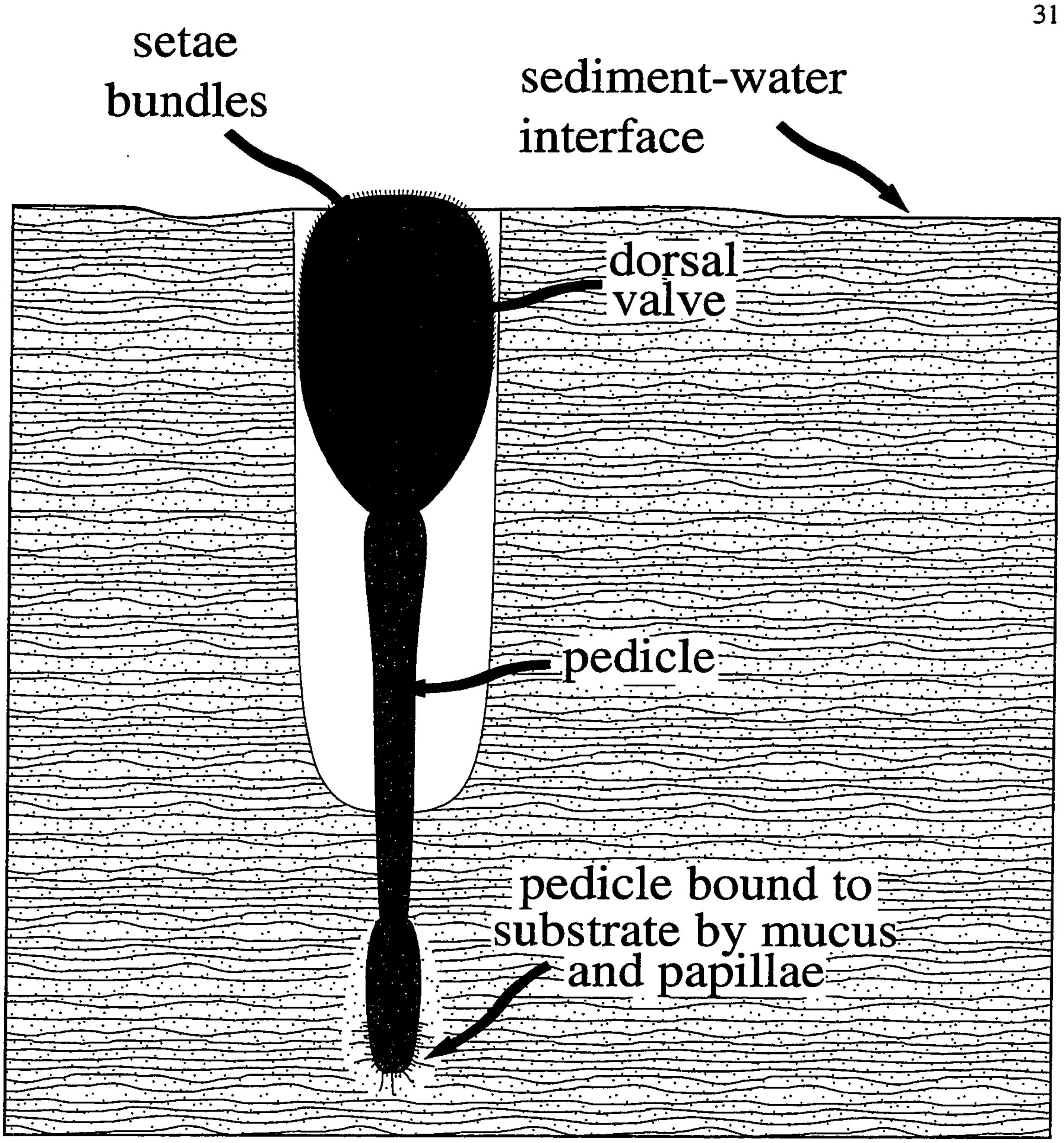


Figure 6. Line drawing of the inarticulate brachiopod *Lingula* sp. in growth position. The pedicle is cemented to the base of the burrow by mucus secretions and tiny papilae or rootlets. Unlike the calcium carbonate shells of articulate brachiopods, lingulid shells are composed of a mixture of chitinous material and calcium phosphate. The dorsal and ventral valves are morphologically similar.

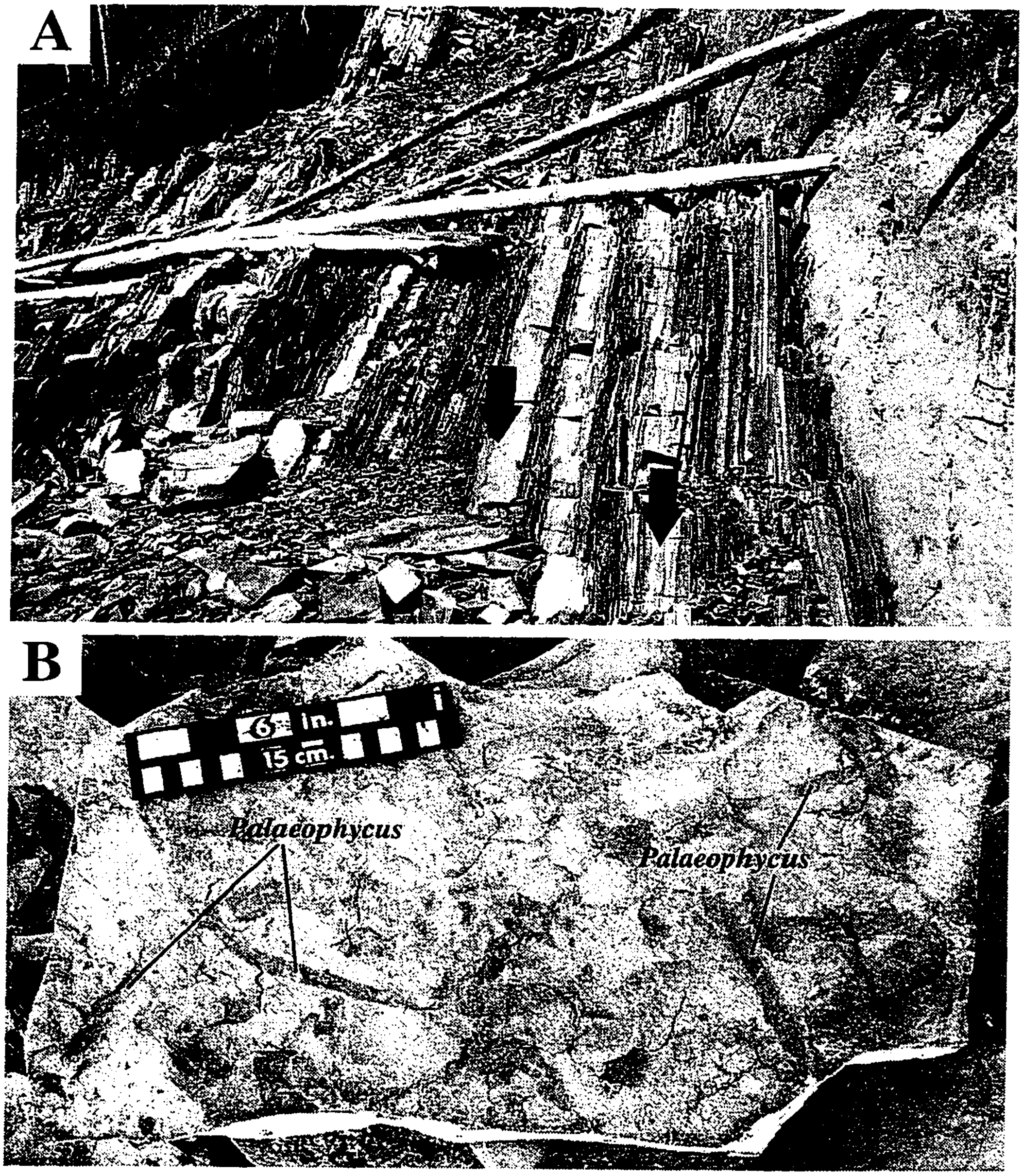


Figure 7a. Outcrop photograph of planar laminated and cross-ripple laminated (solid arrows) siltstone and very fine-grained sandstone, lithofacies B, parasequence 1 (0.0-10.0m), Brown Hill. Rock hammer is 32cm in length. Up is to the left. **Figure 7b.** Outcrop photograph of a bedding plane with abundant *Palaeophycus* burrows, lithofacies B, base of parasequence 9 (128.0m), Brown Hill.

sharp, except where intensely bioturbated. Lower bedset contacts are sharp, and exhibit load-casting with underlying thick shale beds. Other physical sedimentary structures include planar bedding (lower flow regime), oscillation ripple laminations, and current ripple laminations. Mud, rip-up clasts are common near the base of some of the bedsets.

Body fossils include scattered brachiopods (spiriferids, terebratulids and lingulids), bivalves (pteriids, trigonids, and pectenids), ammonoids, gastropods, and a single calcisponge. Trace fossils are usually limited to the top few centimetres of sandstone bedsets and consist of a diverse, mixed *Cruziana-Skolithos* ichnofacies assemblage of *Diplocraterion parallelum* (Figure 9a), *Skolithos*, *Thalassinoides suevicus* (Figure 9b), *Palaeophycus striatus*, *Palaeophycus tubularis*, *Planolites montanus*, *Cylindrichnus*, *Teichichnus*, *Roselia* (Figure 10a), *Siphonites* (Figure 10b) *Lockeia* and *Arenicolites*.

Interpretation- Deposition of lithofacies C is interpreted as a storm-dominated lower shoreface with individual beds interpreted as tempestites. Hummocky cross-stratification is common throughout the shoreface, but is most commonly preserved within the lower shoreface to proximal offshore transition (Hamblin and Walker, 1979).

Facies D- Terabratulid-echinoid rudstone/grainstone.

Description- Facies D consists of a sandy, calcareous, bioclastic rudstone to grainstone with minor sandy laminae and lenses (Figures 11a & b). The unit is overwhelmingly dominated by whole and fragmentary terebratulid brachiopods (*Aulacothyroides liardensis;* Figure 12a), crinoid columnals, and cidaroid echinoid (*Miocidaris* sp.) spines and interambulacral plates. The basal metre of the unit is extremely sandy, and contains predominantly fragmentary bioclastic material. The sand component above the basal metre is minimal. Fossil debris is predominantly deposited concordant to bedding. Although internal bedding is not discernable, the bedsets are arranged in a series of amalgamated lenses. Many of these lenses are comprised almost exclusively of whole terebratulid brachiopods, others are comprised predominantly of fragmentary brachiopod and echinoid debris. The upper contact of the unit is sharp with the sandy bioclastic floatstone of lithofacies E.

Several of the terabratulid brachiopods collected display compact groups of microscopic holes or pits, possibly examples of the trace fossil *Podichnus* isp. In modern brachiopods these pits are created by chemicals secreted by the pedicle of another brachiopod as a means of creating a holdfast (Bromley and Surlyk, 1973). The groups of pits are circular and compact, rarely exceeding 1-2mm in diameter, consistent with brachiopod pedicle shape and size. The size and geometry of these pit concentrations is inconsistent with traces made by sponges or other benthic boring organisms. The unit also contains several partially complete and articulated, albeit highly weathered, crinoids (Articulata, cf. *Holocrinus* sp.) on the upper surface, and isolated spiriferid brachiopods (*Spiriferina* sp.; Figure 12b) scattered throughout. Overall the bioclasts show few signs of transportation or abrasion. Trace fossils other than the brachiopod boring *Podichnus* were not observed.

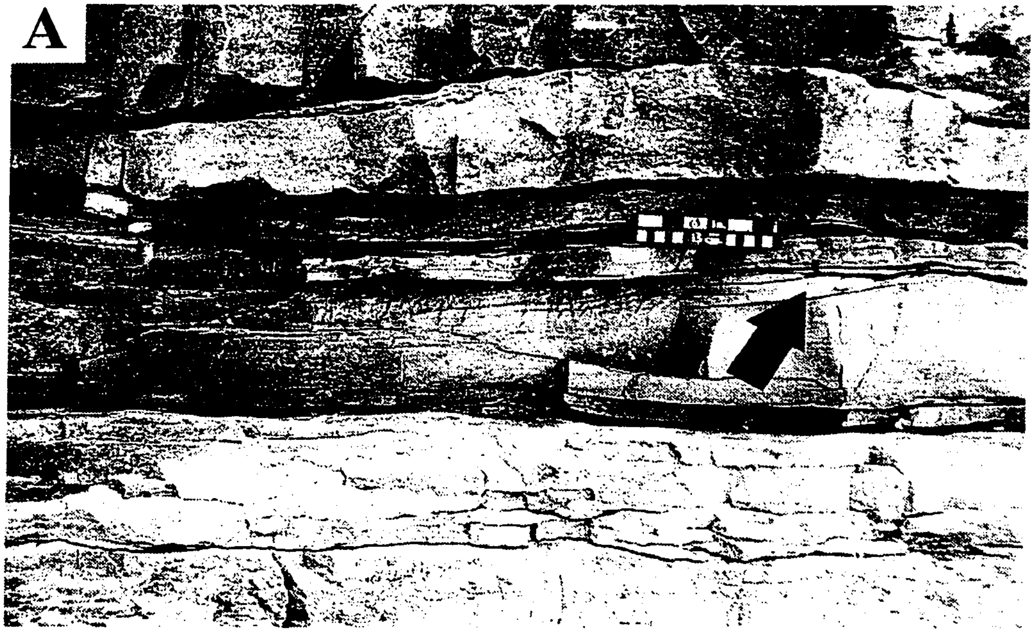
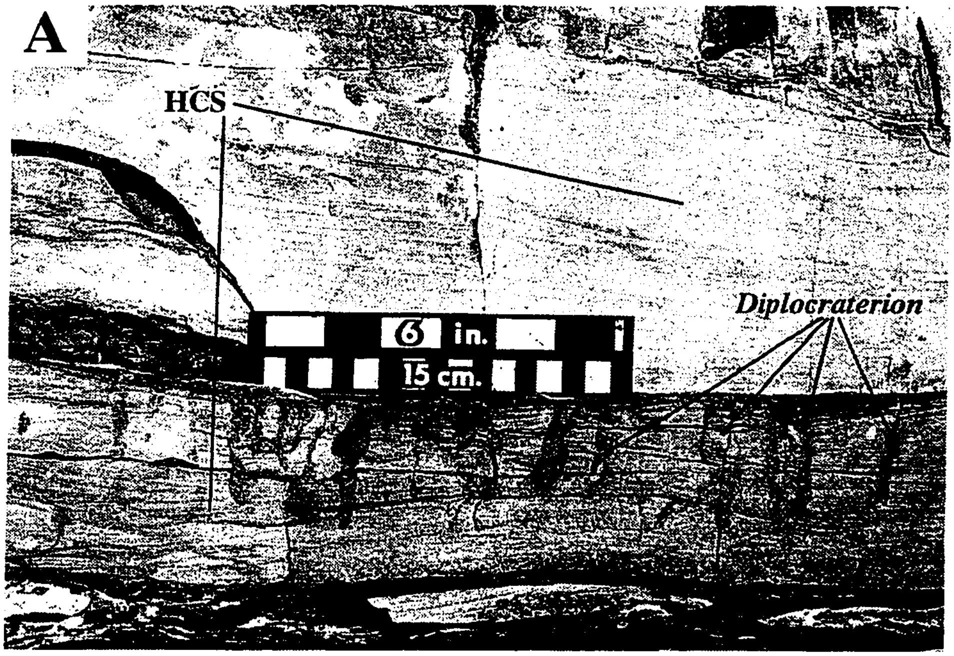


Figure 8a. Outcrop photograph of hummocky cross-stratified sand bed, lithofacies C, parasequence 9 (147.5m), Glacier Spur. Concave/ convex laminae (arrow) in HCS bed are visible immediately below scale. Up is to the top of the photograph. **Figure 8b.** Outcrop photograph of amalgamated storm-generated beds (tempestites, T), lithofacies C, parasequence 9 (165.0-168.0m), Brown Hill. The shotgun is approximately one metre in length. Beds are dipping at 75-80°, up is to the left.



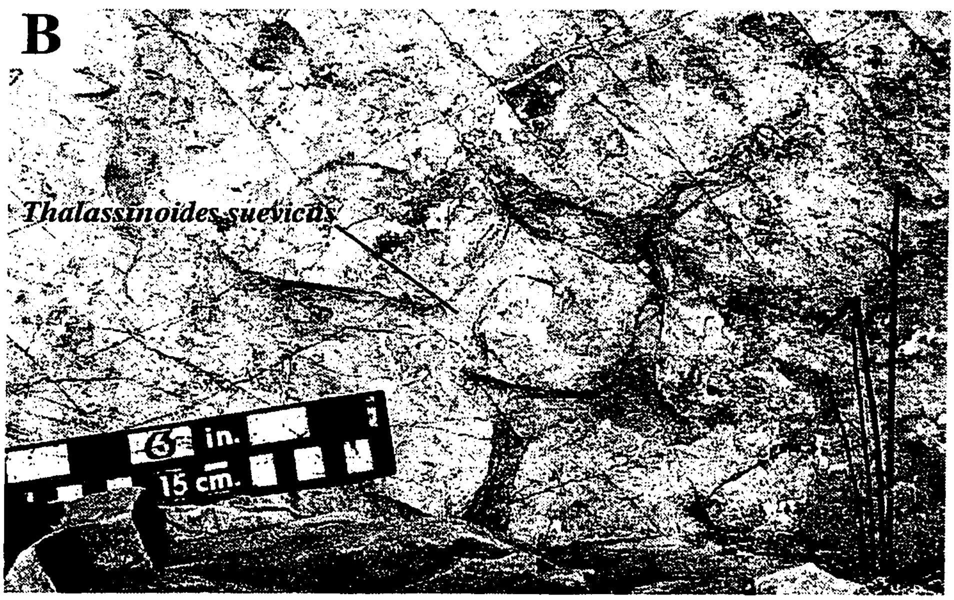


Figure 9a. Outcrop photograph of burrowed tempestites, lithofacies C, parasequence 1 (12.0m), Brown Hill. The tops of *Diplocraterion* burrows penetrating the basal hummocky cross-stratified (HCS) storm bed are removed by the next storm event, as evidenced by the erosive base of the upper hummocky cross-stratified (HCS) storm bed. **Figure 9b.** Outcrop photograph of the ichnofossil *Thalassinoides suevicus* on the bedding plane of a lower shoreface sandstone unit, lithofacies C, parasequence 1 (10.5m), Glacier Spur.

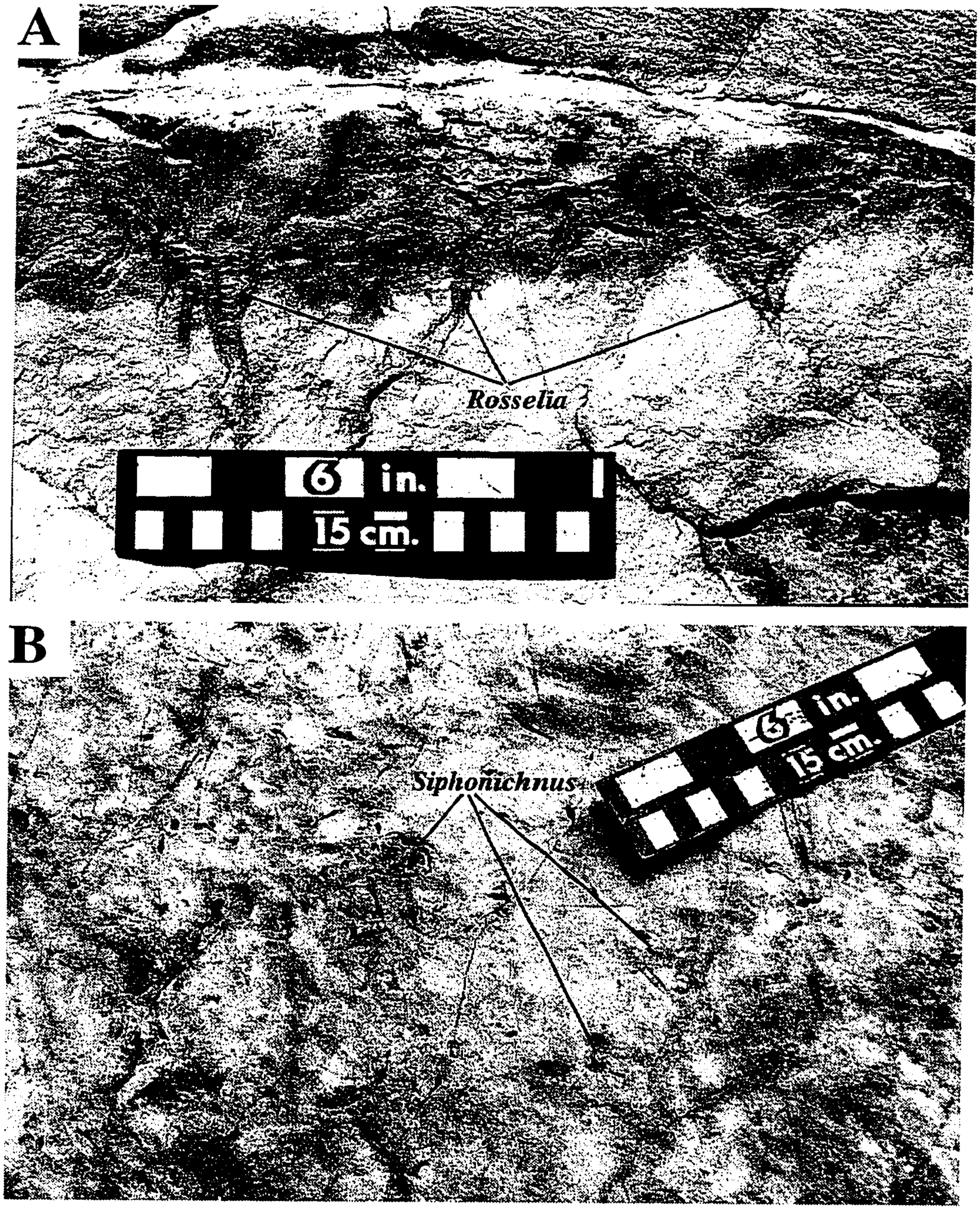


Figure 10a. Outcrop photograph of funnell-shaped *Rosselia* burrows, lithofacies C, parasequence 1 (6.0m), Brown Hill. Up is to the top of the photograph. **Figure 10b.** Outcrop photograph of abundant *Siphonichnus* ichnofossils on the bedding plane of a lower shoreface sandstone unit, lithofacies C, parasequence 10 (198.0m), Brown Hill. *Siphonichnus* is the dwelling structure of a burrowing bivalve. In most specimens, only a siphon opening is visible, however the specimen at the centre of the photograph exhibits a faint, heart-shaped halo representing the burrow lining.

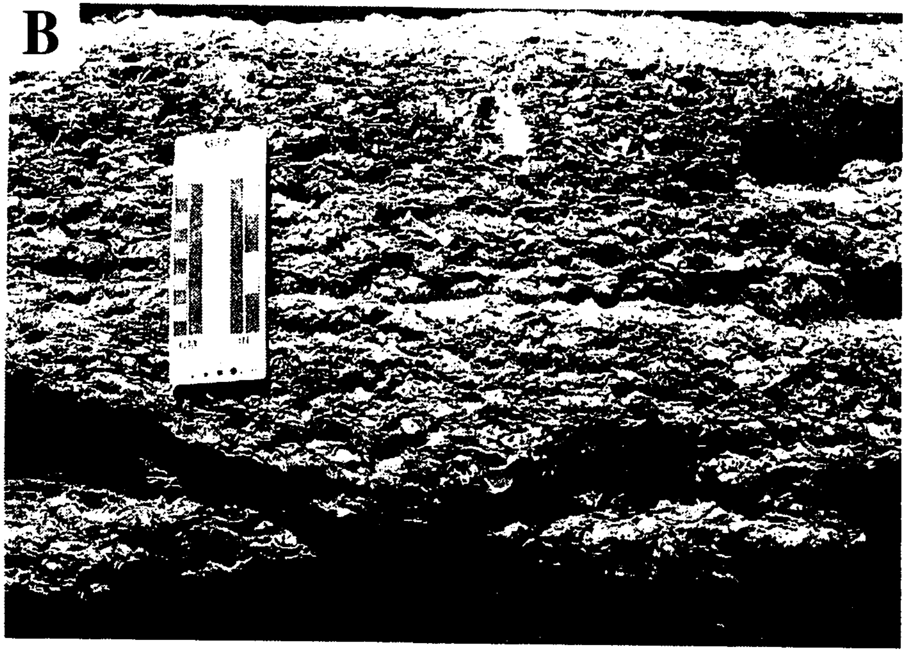


Figure 11a. Outcrop photograph of amalgamated terebratulid-echinoid shell accumualtions, lithofacies D, parasequence 3 (39.0-43.0m), Glacier Spur. Rock hammer in right center of photograph is 32cm in length. Beds are dipping at 75-80°. Up is to the right. **Figure 11b.** Outcrop photograph showing detail within figure 11a, lithofacies D, parasequence 3 (42.5m), Glacier Spur. Up is to the top of the photograph. Bed is approximatel 35cm thick.

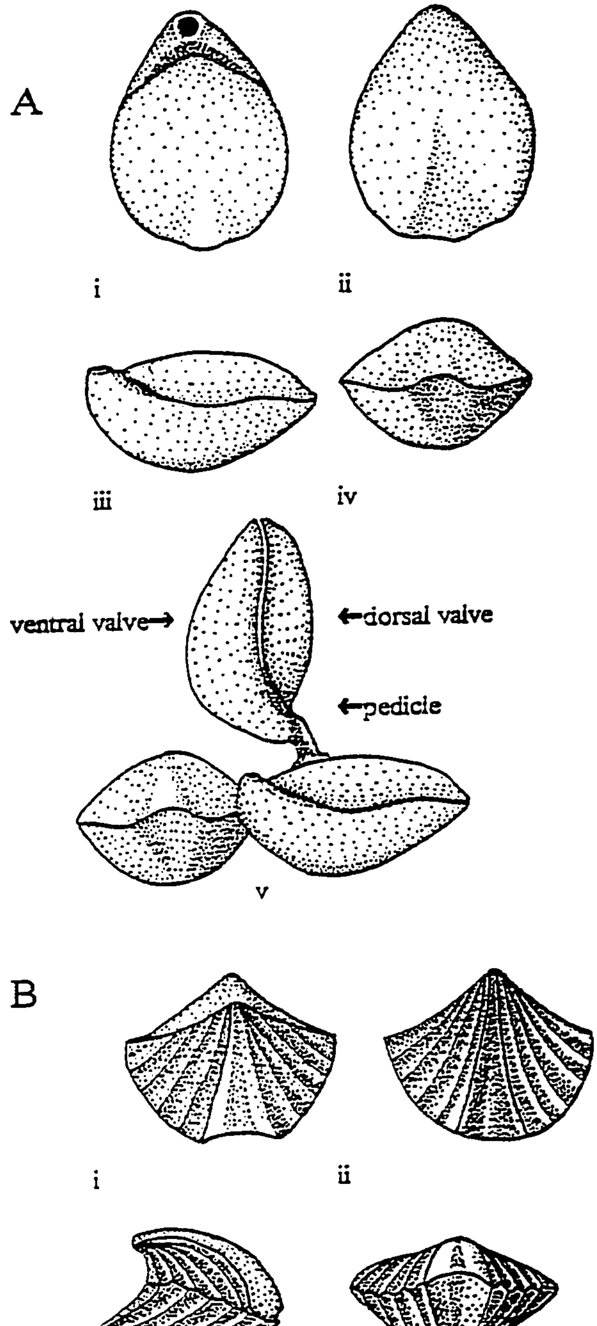


Fig. 12a. Line drawings of *Aulacothyroides liardensis* showing dorsal view (i), ventral view (ii), side view (iii), anterior view (iv) and living position. **12b.** Line drawings of *Spirifirina borealis* showing dorsal view (i), ventral view (ii), side view (iii), and anterior view (iv).

Interpretation- The sandy, highly fragmented shell accumulations at the base of the unit are interpreted as storm-generated skeletal concentrations. Calcareous rich tempestites often have recrystallized micritic layers at their tops and bases caused by the dissolution and subsequent reprecipitation as micrite, of aragonitic shell material (Seilacher and Aigner, 1991). This may happen quite quickly after deposition, producing a more consolidated substrate, and inadvertently providing a locus for colonization by hardground preferring organisms (Hagdorn, 1982; Seilacher and Aigner, 1991). The overlying layers of unabraded and articulated terebratulids and scattered echinoid skeletal elements reflect the subsequent colonization of these patches of stable substrate, a process referred to as allogenic taphonomic feedback (Kidwell and Jablonski, 1983; Kidwell, 1991). Lenses of fragmentary brachiopods reflect storm reworking of locally derived skeletal material. Although echinoids as a group can live in essentially any marine or marginal marine environment, cidaroid echinoids are rarely found on unconsolidated sediments, prefering rocky or stable substrates (Smith, 1984). Early Triassic echinoids were probably algal-grazers or scavengers (Schubert and Bottjer, 1995). Similarily, terebratulids and early, stemmed, articulate crinoids prefer comparably stable substrates. Crinoids are particularly rare in sandstones, except as scattered, disarticulated plates. Triassic articulate crinoids probably anchored to a stable substrate such as hardgrounds or by a cemented holdfast (Hagdorn, 1982).

The absence of interfingering with hummocky cross-stratified sandstone layers (lithofacies C), the preponderance of hard substrate preferring organisms, and the minimal abrasion of bioclastic debris makes it unlikely that lithofacies D represents amalgamated proximal storm deposits. Facies D is interpreted as a terebratulid-echinoid dominated reef mound (*sensu* James and Geldsetzer, 1989) or shell bank within the lower shoreface. Although the Liard terabratulid-echinoid skeletal accumulations did not possess true skeletal frames, the organisms did preferentially attach themselves to each other, as evidenced by the presence of *Podichnus* isp. on many of the whole brachiopods.

Facies E- Bioclastic floatstone/mudstone

Description- Facies E consists of a sandy, calcareous, bioclastic floatstone within a calcitic mud/silt matrix. Bedding is difficult to discern in this unit, but generally is comprised of low-angle planar laminations. Sandstone lenses, characteristic of facies C, increase in abundance towards the top of the unit.

The unit contains scattered acrotretid (cf. *Discinisca* sp.) and terabratulid brachiopods (*Aulacothyroides liardensis*), a variety of bivalves, abundant echinoid debris including a single complete specimen (*Miocidaris* sp.), scattered crinoid debris, isolated fish skeletal elements, including a tooth plate from the palaeonisciform fish *Bobasatrania* sp., and several other unidentified actinopterygian tooth plates, and abundant decapod crustacean remains (Erymididae, new genus? and new species). The decapod remains comprise a wide assortment of randomly oriented whole organisms, isolated claws, carapaces, and other elements. *Planolites* was the only trace fossil noted within Facies E.

Interpretation- Facies E is a transitional facies between facies D (reef mounds) and F (middle shoreface), and shows influences of both environments. The matrix is comprised predominantly of mud to silt sized micrite. Thin-section analysis suggests that at least the coarser components of the matrix consist of bioclastic detritus. Modern bioclastic banks affected by seasonal storm activity are non-symmetrical, having a steep, coarse-grained windward side and a more gently sloping leeward side comprised of calcitic mud. The chaotic assemblage of whole and partial decapods is also indicative of event deposition, probably storm activity (Brett and Seilacher, 1991). Most of the echinoid and crinoid fragments were deposited on bedding planes, likely due to natural attrition between storm events. Thick, flat tooth plates in fish are common in molluscivores or other predation on hard-shelled organisms. The presence of a variety of actinopterygian tooth plates, including that of a bobosatranid, in the back reef environment may be evidence that these animals fed on reef organisms in a manner similar to that of parrotfish on modern coral reefs.

Facies E is interpreted as a back reef (bank) or leeward (shoreward) accumulation of bioclastic silt and siliciclastic sand.

Facies F- Cross-stratified calcareous sandstone

Description- Facies F consists of well-sorted, very-fine to fine grained quartzose sandstone. The unit is predominantly trough cross-stratified (Figure 13a). Individual bedsets thicken upwards from 45-90cm thick beds at the base to 80-180cm thick beds at the top of the unit. Bedset contacts appear sharp and are occasionally erosive (Figure. 13a). Other physical sedimentary structures include horizons of swaley cross-stratification near the base and rare oscillation ripple lamination. Facies F gradationally overlies the bioclastic floatstone of facies E and is abruptly overlain by the planar tabular cross-stratified sandstone/packstone of facies G.

Body fossils consist primarily of scattered crinoid ossicles and columnals, and rare echinoids and terebratulid brachipods. Trace fossils are rare, but include *Diplocraterion parallelum*, *Skolithos*, *Thalassinoides suevicus*, *Palaeophycus tubularis*, and *Planolites montanus*.

Interpretation- The facies is characterized by a diverse, vertical-burrow dominated trace fossil assemblage characteristic of the *Skolithos* ichnofacies. The abundant scour surfaces (Figure 13a), trough to planar cross-stratification and *Skolithos* trace fossil assemblage are indicative of deposition in a moderate to high-energy setting. Facies F is interpreted as being deposited in the upper shoreface.

Facies G- Cross-stratified calcareous bioclastic sandy packstone

Description- Facies G comprises a thick succession of cross-bedded to cross-laminated, calcareous, bioclastic sandy packstone. It is fine- to medium-grained, and comprised of rounded calcareous bioclasts, quartzose sand, and contains abundant, scattered chert pebbles (Figure 13b). Sorting of the sediment is bimodal. The sand fraction is

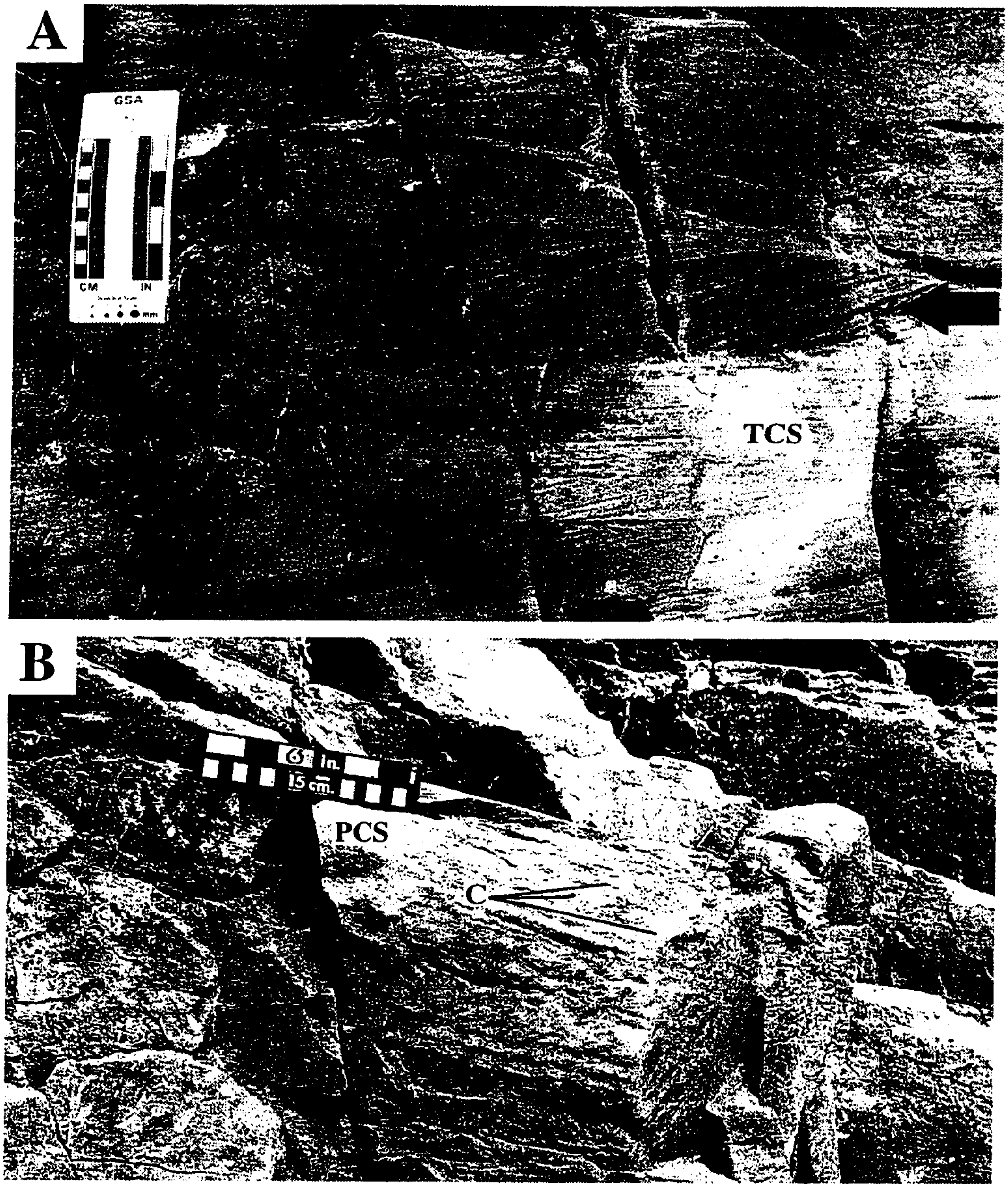


Figure 13a. Outcrop photograph showing trough cross-stratification (TCS) and tangential foreset laminae (arrow) of a migrating sandwave, lithofacies F, parasequence 3 (55.0m), Glacier Spur. **Figure 13b.** Outcrop photograph showing planar cross-stratification (PCS) and chert pebble (C) in calcareous, bioclastic, sandy packstone of lithofacies G, parasequence 3 (60.0m), Brown Hill.

moderately well-sorted, while the calcareous bioclasts are highly fragmented and poorly sorted. Physical sedimentary structures consist of trough to planar cross-bedding near the base, and planar tabular cross-lamination towards the top.

The bioclastic material consists primarily of highly abraded, well-rounded bivalve fragments. Spiriferid brachiopods (*Spiriferina* sp.), rare, scattered lingulid brachiopods (*Lingula* sp.), and very rare terebratulid brachiopods (*Aulacothyroides liardensis*) are also present. Isolated, highly eroded reptile (ichthyosaur?) bone fragments were observed near the top of the unit. Trace fossils were not observed within facies G.

Interpretation- The sand fraction and chert pebbles of Facies G comprises the coarsest sediment observed within the study area. Moderately well-sorted quartz sand, the absence of trace fossils and the highly abraded nature of the bioclasts, are indicative of deposition in a high-energy setting. The trough to planar cross-stratified beds of the basal part of facies G were deposited within the proximal upper shoreface (surf zone). The planar cross-laminated bioclastic deposits in the upper part of facies G are charactersitic of swash zone or foreshore deposition.

Facies H- Calcareous bioclastic sandstone

Description- Facies H is comprised of fine-grained, well-sorted sandstone, containing scattered bioclasts and chert pebbles. Bedsets range from 5-25cm in thickness. Bounding surfaces between individual bedsets are usually sharp, but not erosional. Physical sedimentary structures, although generally obscured by weathering and bioturbation consist of horizontal to subhorizontal laminations. Facies H gradationally overlies the sandy bioclastic packstone of Facies G, and is abruptly overlain by the cryptalgal laminated carbonate mudstone of Facies I.

Facies H is characterized by a moderately diverse *Psilonichnus* trace fossil assemblage (Frey and Pemberton, 1987), consisting of *Skolithos*, *Palaeophycus*, *Isopodichnus*, and an as yet undescribed type of bivalve resting trace (Figure 14a). Body fossils consist of rare scattered bioclastic debris and rare *Lingula* sp. valves.

Interpretation- The trace fossil assemblage and physical sedimentary structures within facies H are consistent with deposition in a more quiescent setting than underlying units, particularly facies F and G. Facies H is interpreted as a backshore/lagoonal deposit. Individual sharp-based sandstone beds may be a product of storm washover events.

Facies I- Cryptalgal laminite

Description- Facies I (Figure 14b) consists of algal laminated, sandy, calcareous to dolomitic, mudstone to siltstone characterized by microscopic wavy or 'wrinkly' laminations. In many cases, the laminae are separated into repetitive sets of siltstone and mudstone laminasets, with periodic but regularly spaced sandstone laminae, composed primarily of very-fine to fine-grained, frosted quartz grains. The facies usually occurs as thin 20 to 40cm thick beds or lenses interbedded within the dolomitic mudstone/wackestone of Facies J

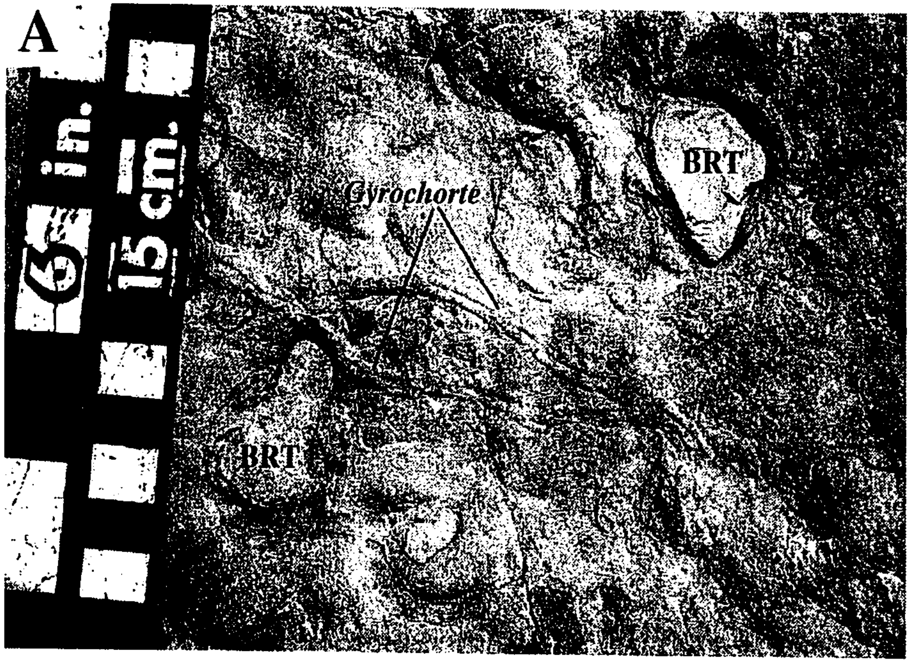


Figure 14a. Outcrop photograph showing *Gyrochorte* and bivalve resting traces (BRT) on a lithofacies H bedding plane, parasequence 3 (66.0m), Brown Hill. **Figure 14b.** Outcrop photograph showing incision of lithofacies J, shoreface sandstones (J) into lithofacies I, Cryptalgal laminite (I), parasequence 4-5 contact (large arrows, 68.5m), Brown Hill. Note rip-up clasts (small arrows) of lithofacies I aligned parallel to bedding in lithofacies J. Pogo stick shows 10cm. increments.

(intertidal mud flats), however a thick (1.5m) bed occurs on top of facies H (backshore/lagoonal) in parasequence 3 (Figure 3), and is eroded by transgressive shoreface sandstones of lithofacies J (Figure 14b).

Interpretation- Algal flats are common constituents of modern arid-climate intertidal settings (Warren, 1989). The mudstone-siltstone algal lamination is interpreted as deposition of sediment during periodic (neap-spring?) tidal flooding. Thicker sandier laminae may be attributed to severe, semi-annual dust storms. Simlar dust storms have been observed to deposit layers of very fine sand and silt on algal mats in the Persian Gulf (Shinn, 1983).

Facies J- Planar cross-stratified sandstone

Description- Facies J consists of an overall coarsening upwards succession of well-sorted, very-fine to fine-grained sandstone. The unit is predominantly low angle planar cross-stratified, and possibly low-angle trough cross-stratified, but also contains oscillation ripple laminated layers throughout. The basal contact of Facies J incises into lithofacies I (cryptalgal laminite) and is characterized by a lag of angular, imbricated rip-up clasts (Figure 14b). The upper contact is also erosional, and is overlain by the dolomitic mudstone of Facies K (intertidal/supratidal mudflats).

The unit contains scattered spiriferid and lingulid brachiopods. The basal metre of lithofacies J contained no trace fossils. The upper 2 metres of lithofacies J contains an ichnofossil assemblage similar to that observed in lithofacies H, consisting of *Skolithos*, *Palaeophycus*, *Isopodichnus*, and an as yet undescribed type of bivalve resting trace.

Interpretation- The rip-up clasts are identical in composition to lithofacies I. Although the lithologies of lithofacies H (washover/lagoonal) and J are quite different, their trace-fossil assemblages are identical, and as mentioned above, are assigned to the *Psilonichnus* ichnofacies.

Facies J is interpreted as an amalgamation of shoreface, foreshore, and washover fan deposits. The upper surface contains abundant steep-walled pits or furrows, possibly evidence of burial, compaction, and subsequent re-exhumation. This surface has been observed at Middle Triassic (upper Ladinian) sites approximately 15km away, and is interpreted as a sequence boundary. Lithofacies J is strikingly similar to the basal beds of transgressive barrier island deposits within the Halfway Formation at Wembley Field, Alberta (Willis and Moslow, 1994b).

Facies K- Dolomitic mudstone-wackestone.

Description- Facies K is predominantly dolomitic sandy/silty mudstone to wackestone. Many of the mudstone laminae have large mudstone intraclasts. The unit is thoroughly interbedded with algal mounds (Figure 15a), cryptalgal layers (facies I), and minor calcareous (channel) sandstone (facies M). Physical sedimentary structures include planar laminations, current and symmetrical oscillation ripples (Figure 16a & b), and

Figure 15a. Outcrop photograph showing intertidal algal pods (ap) and laminated dolomitic mudstone (LAM) in lithofacies K, parasequence 4 (86.5m), Brown Hill. **Figure 15b.** Outcrop photograph of bedding plane surface showing large dessication cracks in lithofacies K (dolomitic mudstone-wackestone), parasequence 4 (72.0m), Brown Hill.

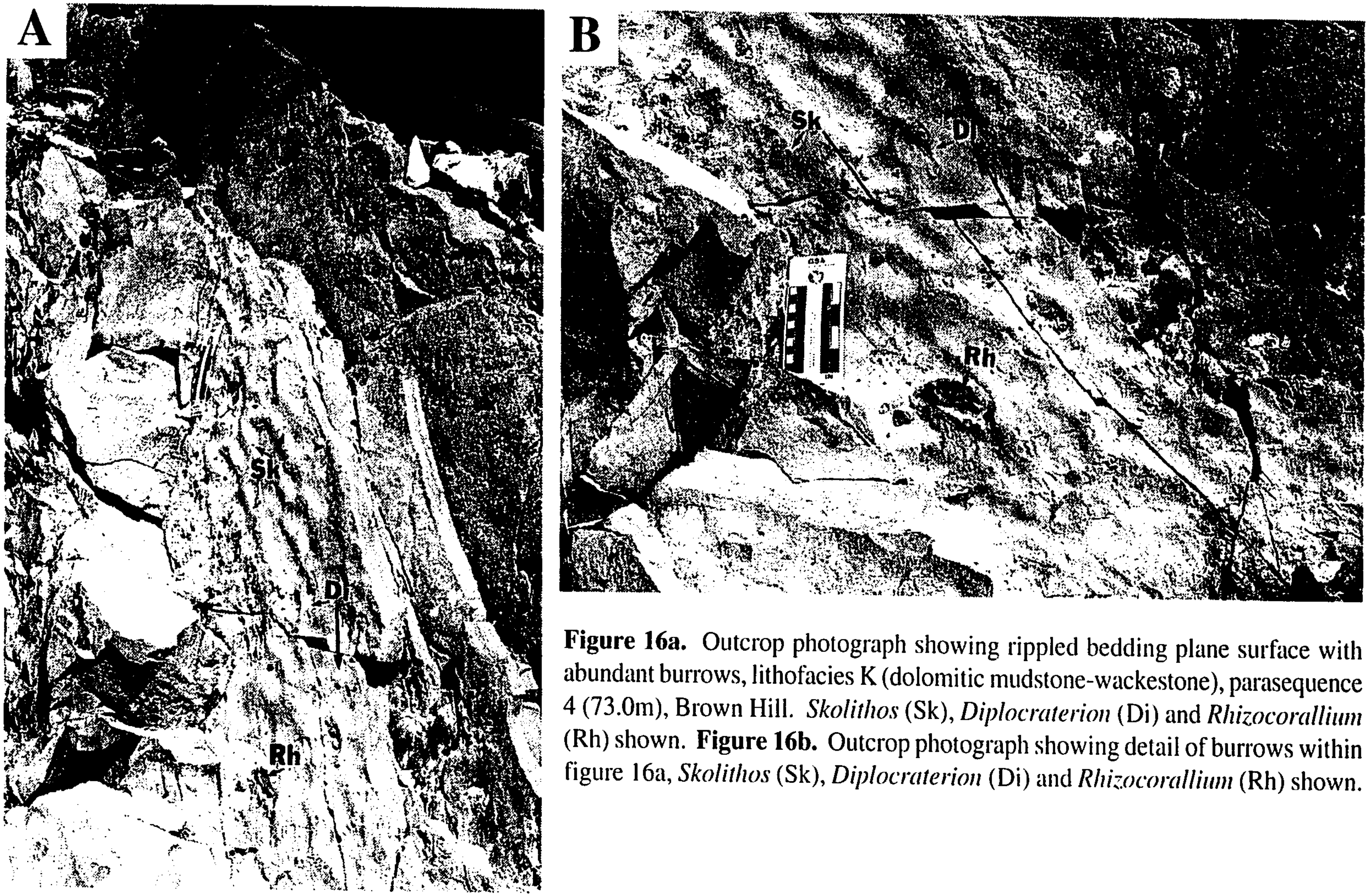


Figure 16a. Outcrop photograph showing rippled bedding plane surface with abundant burrows, lithofacies K (dolomitic mudstone-wackestone), parasequence 4 (73.0m), Brown Hill. *Skolithos* (Sk), *Diplocraterion* (Di) and *Rhizocorallium* (Rh) shown. **Figure 16b.** Outcrop photograph showing detail of burrows within figure 16a, *Skolithos* (Sk), *Diplocraterion* (Di) and *Rhizocorallium* (Rh) shown.

abundant polygonal dessication cracks (Figure 15b). Body fossils include isolated *Lingula* valves, bivalve fragments and gastropods. Trace fossils include *Diplocraterion parallelum*, *Skolithos*, *Laevicyclus*, *Palaeophycus*, *Planolites*, and a single specimen of *Rhizocorallium* (Figure 16a & b).

Interpretation- The laminated layers are interpreted as seasonal or storm-influenced tidal deposits (Schinn, 1983). The presence of symmetrical, oscillatory ripples is suggestive of wave-generated transport during periodic submergence. All trace fossils observed originated from, or occured within, units with rippled bedding plane surfaces and are consistent with intertidal deposition (Figure 16a & b). Extensive periods of exposure and fluctuating salinity levels in an arid, hypersaline, supratidal setting severely constrain the presence of burrowing organisms. The presence of abundant minor channel sands and current ripples in the mudflat facies indicates ebb-dominated flow in an intertidal setting and possibly the presence of back-barrier tidal creeks. Algal mats are most extensive and best preserved in intertidal zones (Hagan and Logan, 1975), although in this setting they are also more susceptible to destruction by aquatic grazers.

Mudcracks are suggestive of deposition within the supratidal zone. Although mudcracks can form in the intertidal zone, they are rarely preserved in that setting. Non-channel related mudstone intraclasts are characteristic of supratidal flats and are indicative of event deposition. Scattered bivalve fragments and *Lingula* valves within these layers were likely removed from the intertidal zone and deposited in the supratidal zone by storm activity (Hagan and Logan, 1975). Overall, the sedimentological and paleontological evidence is suggestive of an environment oscillating between supratidal and intertidal settings.

Facies L- Solution Collapse Breccia

Description- Facies L consists primarily of a mix of silty dolomitic and calcareous mudstone and cryptalgal laminite clasts ranging in size from 1-15cm in length, within a calcareous mud matrix. Although clast orientation is difficult to assess, due to the highly weathered nature of the outcrop, most of the clasts appear to be emplaced parallel to bedding.

Interpretation- Facies L was deposited in an arid supratidal setting similar in environment to the modern Trucial Coast in the Persian Gulf (Butler *et al.*, 1982; Warren, 1989). This facies is interpreted as a solution collapse breccia resulting from post-depositional dissolution of evaporite minerals and the subsequent collapse of interlaminated and overlying tidal flat mudstones and algal laminites. Although evaporites are deposited in both the supratidal and intertidal zones in modern arid settings, thick and extensive evaporite deposition predominates in lower supratidal settings (Warren, 1989). The abundance of thin algal laminites, and dessication cracked dolomitic mudstone laminae within the solution collapse breccia are characteristic of the lower to middle supratidal zone (Butler *et al.* 1982).

Facies M- Calcareous sandstone with mud clasts

Description- The sandstone of Facies M is predominantly medium- to fine-grained, with abundant angular to rounded mudclasts at the bases of individual bedsets (Figure 17a & b). The bedsets are predominantly trough cross-stratified at the base, grading into subtle current ripple cross-lamination towards the top. Upper bounding surfaces are gradational, lower are erosional (Figure 17a & b), often incising deeply into the underlying sandstones of Facies C. The unit contains localized concentrations of bivalve shell fragments. Trace and body fossils were not observed within this unit.

Interpretation- The deeply incised lower bounding surfaces, basal mudclast lags and fining upward grain size within sandstone beds and upwards gradation from trough cross-bedding to current ripple lamination are inferred to be a product of unidirectional currents prone to a waning of flow. This facies is interpreted as a backbarrier, likely tidally influenced, channel. The mudclasts (Figure 17b) are predominantly comprised of dolomitic mudstone/wackestone (lithofacies K) and rarely, cryptalgal laminated mudstone (lithofacies I).

FACIES ASSOCIATIONS AND STRATIGRAPHIC RELATIONSHIPS

Association A- Progradational Clastic Offshore/Shoreface

Lithofacies association A (lithofacies A, B, C, and L) is comprised of a coarsening upwards, offshore to lower shoreface succession of facies (Figure 18), locally incised by tidal channels (Figure 19), that forms a distinct progradional parasequence. All lithofacies comprising facies association A show indications of storm-influenced deposition.

Facies association A was deposited on a storm-dominated, prograding barrier island shoreline. In a typical facies association A parasequence, thin distal tempestites grade upwards into thick, amalgamated storm deposited beds, that reflect the reworking of essentially all non-storm deposition. The overall fine-grained and well-sorted nature of these sediments reflects both storm winnowing and a texturally mature, perhaps impoverished sediment supply. Lower shoreface sands in parasequence 10 at Glacier Spur are incised by tidal channels (Figures 4 & 19). These tidal channels are comprised predominantly of fine- to medium-grained sand, with basal lags of dolomitic mud-clasts. The lack of coarser allochthonous material and the textural maturity of the sands again reflects the lack of proximity to a point-source of clastic sediment. Tidal inlet deposits were not noted within laterally equivalent units at Brown Hill (Figures 18) or in any lower parasequences at Glacier Spur (Figure 4) or Brown Hill (Figure 3), thus inferring their restricted temporal and geographic distribution.

Association B- Progradational Mixed Siliciclastic-Carbonate Shoreface

Facies association B (lithofacies A through I), a coarsening upwards, mixed siliciclastic-carbonate, shoreface succession (Figure 20), is relatively heterolithic in comparison to facies association A. The terebratulid-echinoid reefs within facies association

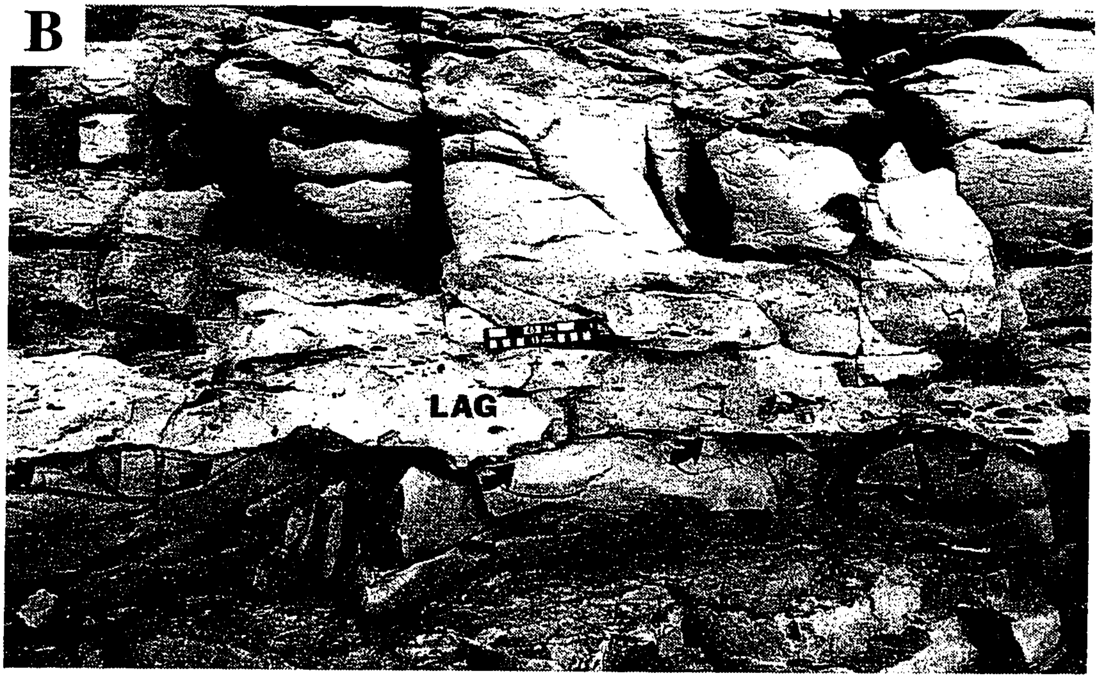


Figure 17a. Outcrop photograph showing tidal channel incision (arrows) and basal mud-clast lag (LAG), lithofacies M, parasequence 10 (156.0m), Glacier Spur. **Figure 17b.** Outcrop photograph showing detail of basal mud-clast lag (LAG) and tidal channel incision surface (arrows), lithofacies M, parasequence 10 (156.0m), Glacier Spur.

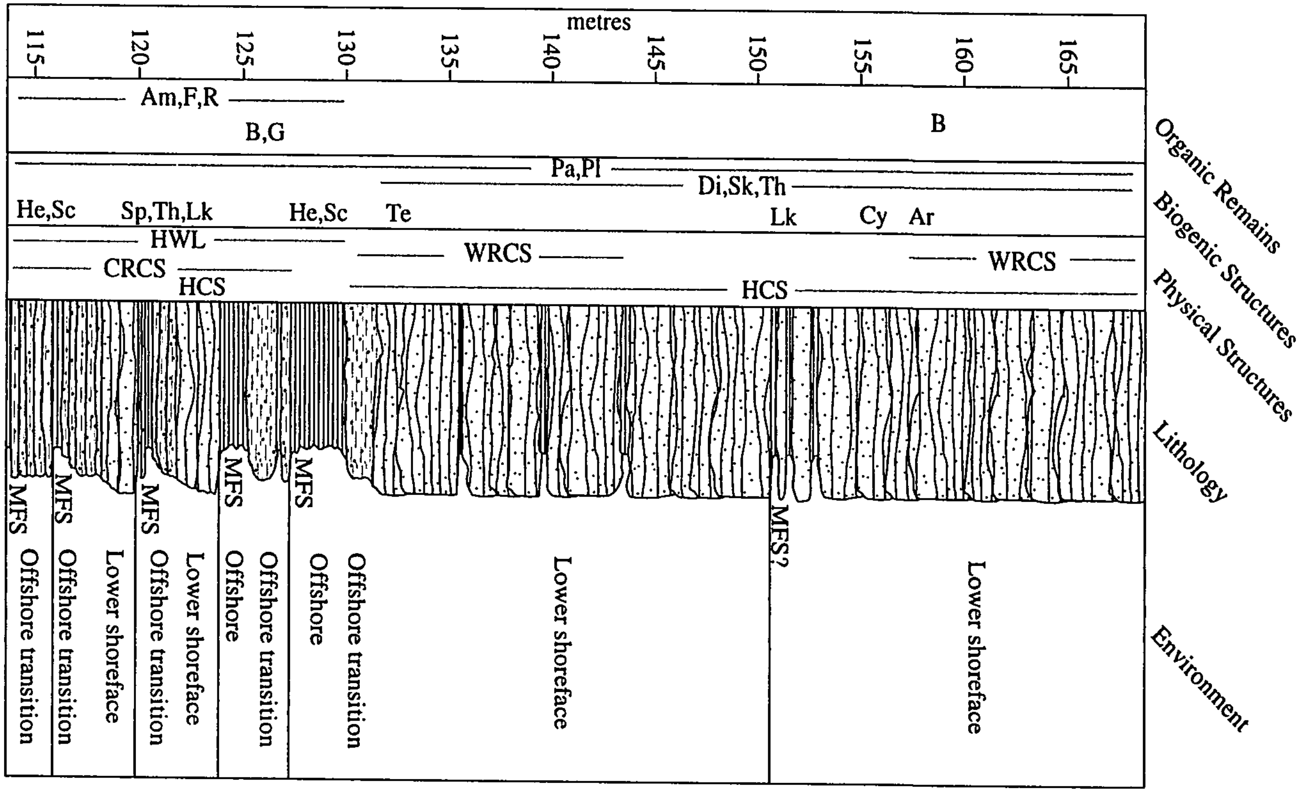


Figure 18. Detailed stratigraphic section showing the vertical arrangement of lithofacies in facies association A (parasequences 7-9) at Brown Hill. Acronyms utilized in this and all succeeding figures are as follows. Organic remains: A= Acrotretid brachiopods; Am= Ammonoids; B= Bivalved molluscs; C= Crinoids; D= Decapod crustaceans; E= Echinoids; F= Fish scales and bone fragments; G= Gastropods; L= Lingulid brachiopods; R= Marine Reptile bone fragments; S= Spirifirid brachiopods; T= Terebratulid brachiopods; Solid lines indicate that the fossil is pervasive, gray lines indicate that it is common. Trace Fossils: Ar= *Arenicolites*; Bi= Bivalve resting trace (not *Lockeia* isp.); Cy= *Cylindrichnus*; Di= *Diplocraterion*; He= *Helminthopsis*; Is= *Isopodichnus; La=Laevicyclus*; Li= *Lingulichnus;* Lk= *Lockeia* Pa= *Palaeophycu*; Ph= *Phycosiphon;* Pl= *Planolites* Rh= *Rhizocorallium* Sc= *Scalarituba*; Si= *Siphonichnus;* Sk= *Skolithos;* Sp= *Spongelliomorpha;* Te= *Teichichnus;* Th= *Thalassinoides*. Physical Sedimentary Structures: CAL= Cryptalgal lamination; CRCS= Current Ripple Cross-Stratification; HWL= Heterolithic Wavy Lamination; HCS= Hummocky Cross-Stratification; PCS= Planar Cross-Stratification; TCS= trough Cross-Stratification; WRCS= Wave Ripple Cross-Stratification. MFS= Marine Flooding Surface; TSE= Transgressive Surface of Erosion; RS= Ravinement Surface.

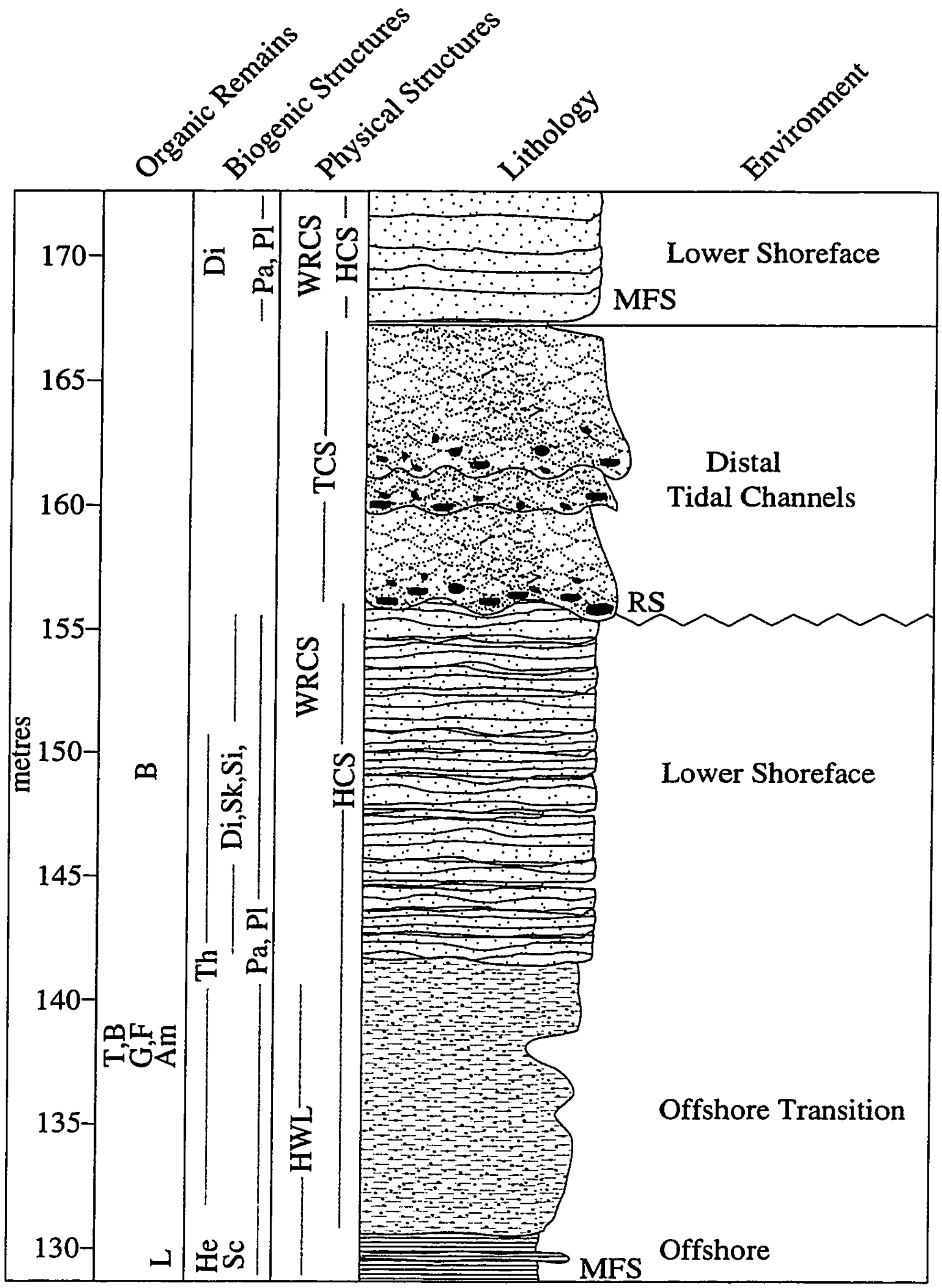


Figure 19. Detailed stratigraphic section showing the vertical arrangement of lithofacies in facies association A (parasequence 10,) at Glacier Spur. Lithofacies symbols and acronyms are the same as those utilized in Figure 3 and 18.

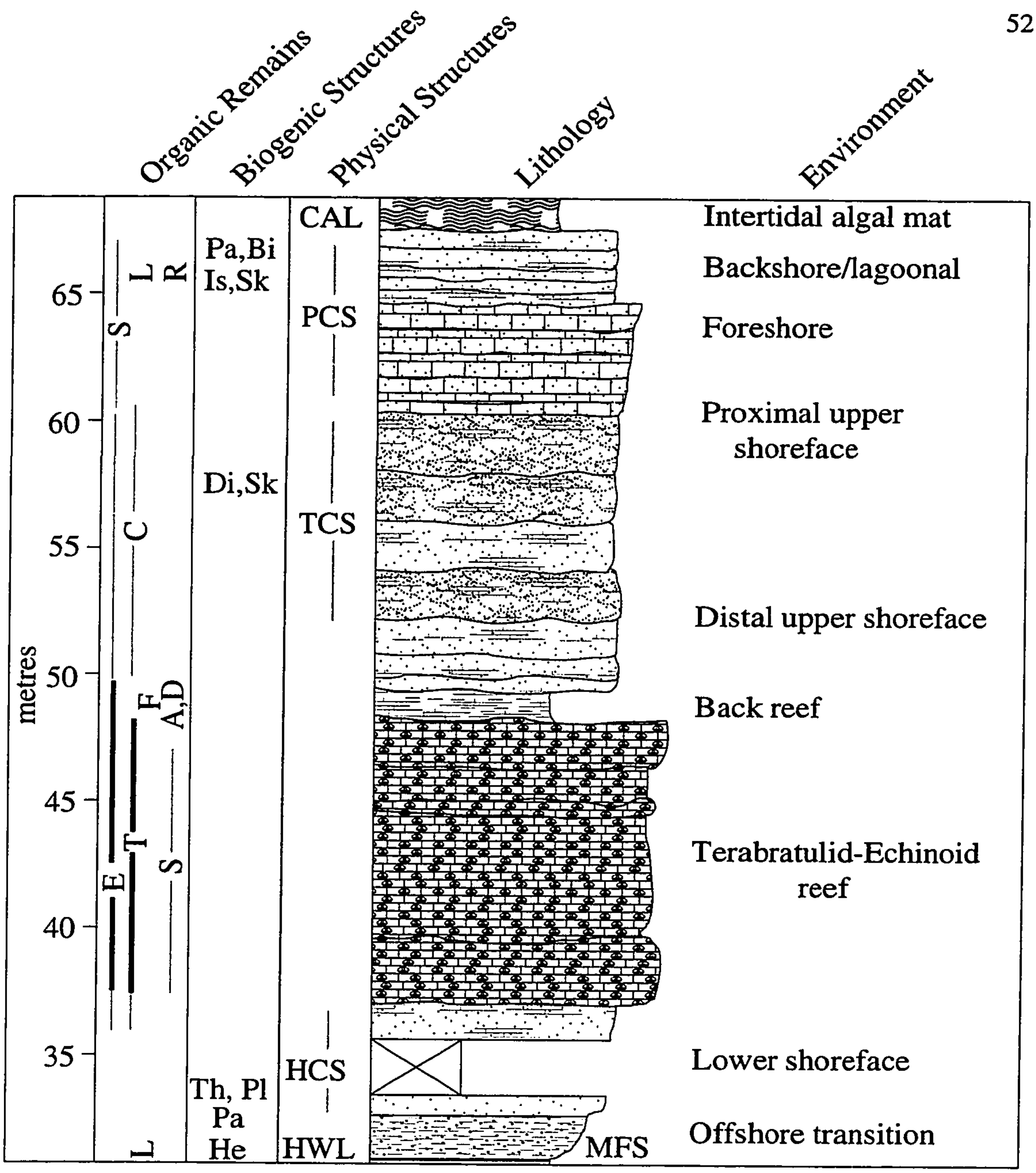


Figure 20. Detailed stratigraphic section showing the vertical arrangement of lithofacies in facies association B (parasequence 3) at Brown Hill. Lithofacies symbols and acronyms are the same as those utilized in Figure 3 and 18.

B1 remain relatively consistent in thickness and composition between Brown Hill and Glacier Spur (Figures 3 & 4), a distance of approximately 2km. Similar deposits have been observed at Beattie Ledge and Aylard Creek, approximately 20km east (updip) of the two outcrops described here. The reefs were deposited within the distal lower shoreface to proximal offshore transition, near mean fairweather wave base (Figure 20) decreasing the risk of burial by suspended sediment in any but the most severe storms.

Association C- Mixed Siliciclastic-Carbonate Marginal Marine

Facies association C (lithofacies F and I through M) constitutes an intertidal-supratidal succession of mudflats, evaporites, and minor tidal channels (Figure 21). The intertidal-supratidal mudflat succession that constitutes facies association C represents the shallowest deposition within the study interval. The abundance of cryptalgal laminites, algal pods, dolomitic intertidal muds and supratidal evaporites are characteristic of deposition in an environmental setting similar to the modern marginal marine environments of the Persian Gulf. The applicability of the Persian Gulf as a modern analogue for deposition along the west coast of Pangea during the Middle Triassic is however limited and potentially misleading, and is simply used here as a modern setting with potentially similar depositional mechanisms.

DISCUSSION

Depositional models for Middle Triassic bioclastic accumulations

Bioclastic accumulations are a product of a number of different processes. Coquinas and bioclastic sandstones within the subsurface Halfway and Doig Formations have been largely attributed to tidal inlet channel deposition (Barclay and Leckie, 1986; Campbell and Horne, 1986; Caplan, 1992; Willis and Moslow, 1994a). Other examples include transgressive shoreface deposits (Wittenberg, 1992; Caplan, 1992; Willis and Moslow, 1994b; Evoy and Moslow, 1995), and sediment gravity flows (Wittenberg, 1992; 1993). Thick bioclastic accumulations in the Upper Triassic Ludington Formation have been interpreted as pelecypod shell banks (Gibson and Hedinger, 1989) or alternately as submarine channel complexes (Gibson, 1993). The following is a brief summation of the characteristics of the pertinent types of Triassic bioclastic accumulations, and a discussion of how they differ from the Liard terebratulid-echinoid reef mounds.

Bioclastic tidal channel deposits

Tidal inlet channel deposits in the Halfway Formation within western Alberta and northeastern British Columbia are characterized by a basal lag comprised of black shale and dolomitic mudclasts, crudely imbricated bioclasts and a normally graded profile (Barclay and Leckie, 1986; Caplan, 1993; Willis and Moslow, 1994a). Bioclastic material in both subsurface and outcrop tidal inlet channels is highly abraded, decreases in size and abundance upwards, is crudely imbricated, and is comprised predominantly of bivalve fragments (Caplan, 1992).

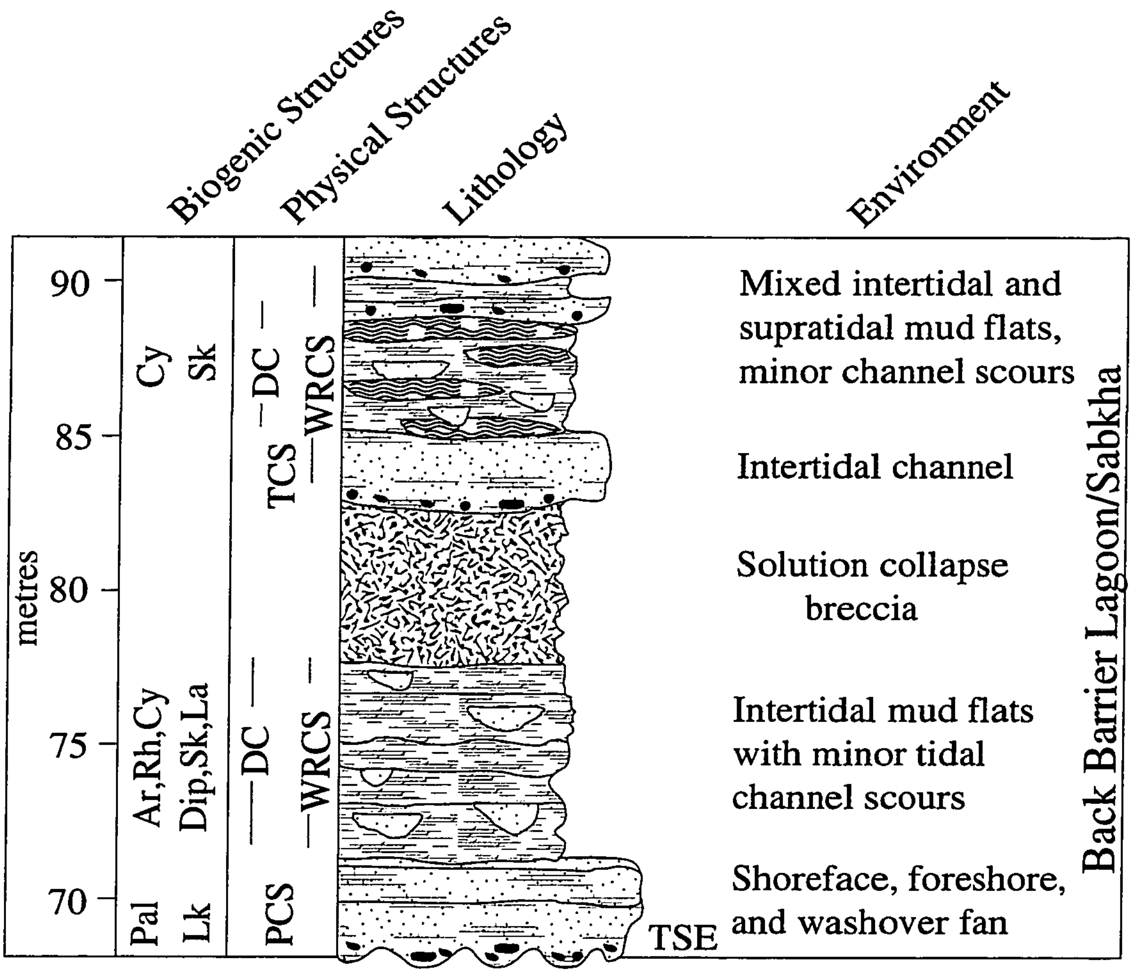


Figure 21. Detailed stratigraphic section showing the vertical arrangement of lithofacies in facies association C (parasequence 4), at Brown Hill. Lithofacies symbols and acronyms are the same as those utilized in figure 3 and 18.

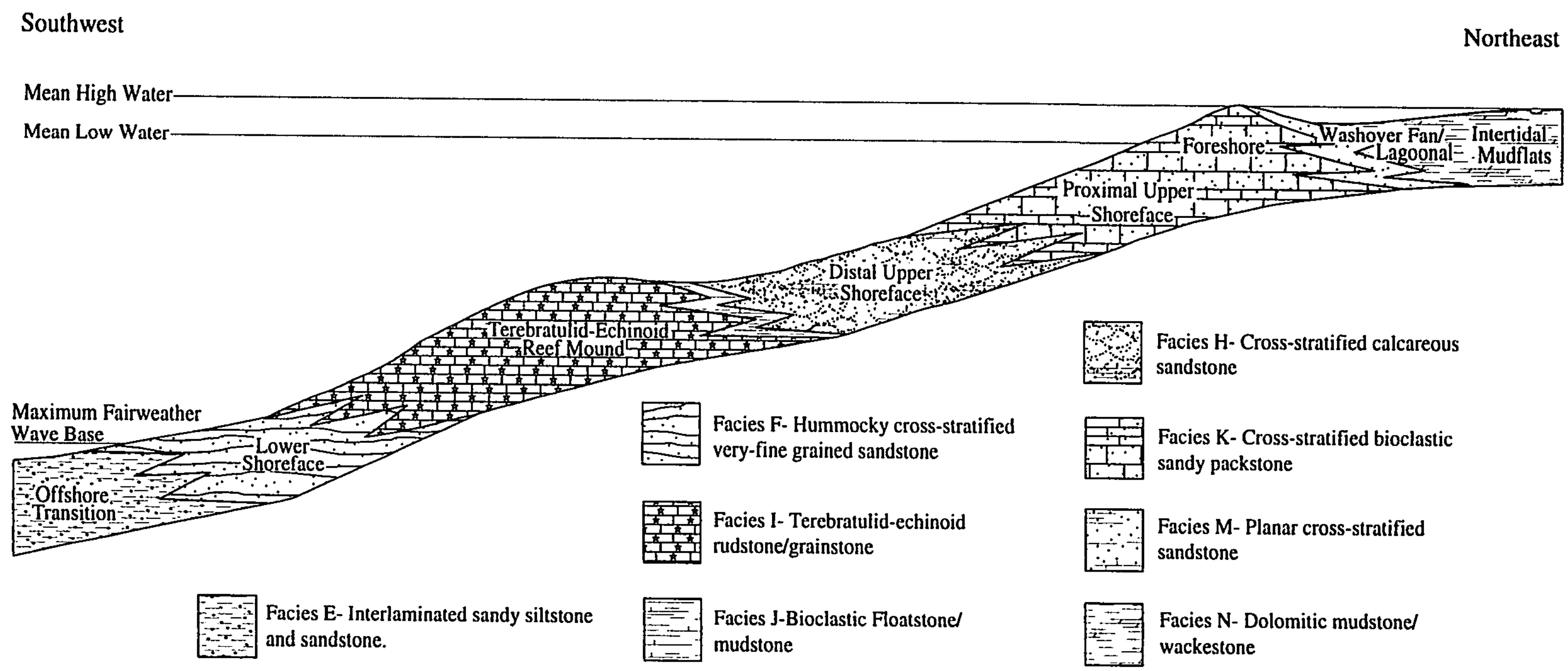


Figure 22. Postulated lateral distribution of major environments and lithofacies of the upper Liard mixed siliclastic-carbonate shoreface within the study area. Lithofacies patterns are the same as those utilized in Figure 3. Not drawn to scale.

Bioclastic transgressive shoreface sandstones

Transgressive shoreface bioclastic sandstones in the Halfway and Doig Formations in western Alberta and northeastern British Columbia are matrix supported, normally graded and comprised predominantly of pelecypod and locally, lingulid shells (Caplan, 1992; Wittenberg, 1993). The bioclastic material is generally quite abraded. Ideally, these deposits should be laterally correlatable on a more regional scale than tidal inlet channel deposits. Lithofacies G (parasequence 3 at both Brown Hill and Glacier Spur) provides an outcrop analogue to these subsurface units.

Bioclastic tempestites and turbidites.

Calcareous turbidites often resemble clastic turbidites by the presence of grading, partial to complete Bouma sequences, and lateral continuity (Eberli, 1991). Calcareous tempestites and turbidites are notoriously difficult to distinguish internally, and in the absence of diagnostic physical structures such as hummocky cross-stratification or Bouma sequences are probably most effectively differentiated by the nature of their bounding surfaces and their relationship with other lithofacies.

Tempestites are more commonly erosive and, especially in proximal settings incise to underlying deposits. Sole marks are bipolar and commonly consist of gutter casts or scouring (Einsele and Seilacher, 1991). Turbidites are characterized by uni-directional sole marks and by load casting (Einsele and Seilacher, 1991). During storm deposition calcareous sand behaves differently than siliciclastic sand (Seilacher and Aigner, 1991). Although quartz grains are considerably denser than calcite, aragonite or phosphate clasts of equal size, bioclasts within these deposits are usually considerably larger. In a mixed siliciclastic-carbonate system, bioclastic storm deposits should therefore grade laterally and vertically with quartzose-carbonate sand layers (Aigner, 1982; 1985), reflecting deposition during waning-flow conditions.

Since bioclastic turbidites, similar to their siliciclastic counterparts are commonly (although not exclusively) deposited in a distal setting, individual deposits are comprised of bioclasts that differ from those in autochthonous communities within interbedded pelagic deposits (Einsele and Seilacher, 1991). Bioclastic tempestites in comparison are generally comprised of bioclasts similar to faunas in pre- and post-event deposits (Seilacher and Aigner, 1991).

The Ludington and Baldonnel submarine channel complexes are comprised of an amalgamation of fragmented and abraded bivalve, and to a lesser extent brachiopod, and echinoderm bioclasts within a deep water distal shelf/upper slope environment (Gibson, 1993). Bioclastic fragments within Doig sediment gravity flow deposits are normally graded, poorly sorted, and are comprised of lingulid brachiopod and recrystallized bivalve shell fragments (Wittenberg, 1992).

Liard terebratulid-echinoid reefs.

Investigations of Triassic sediments in western North America have produced very

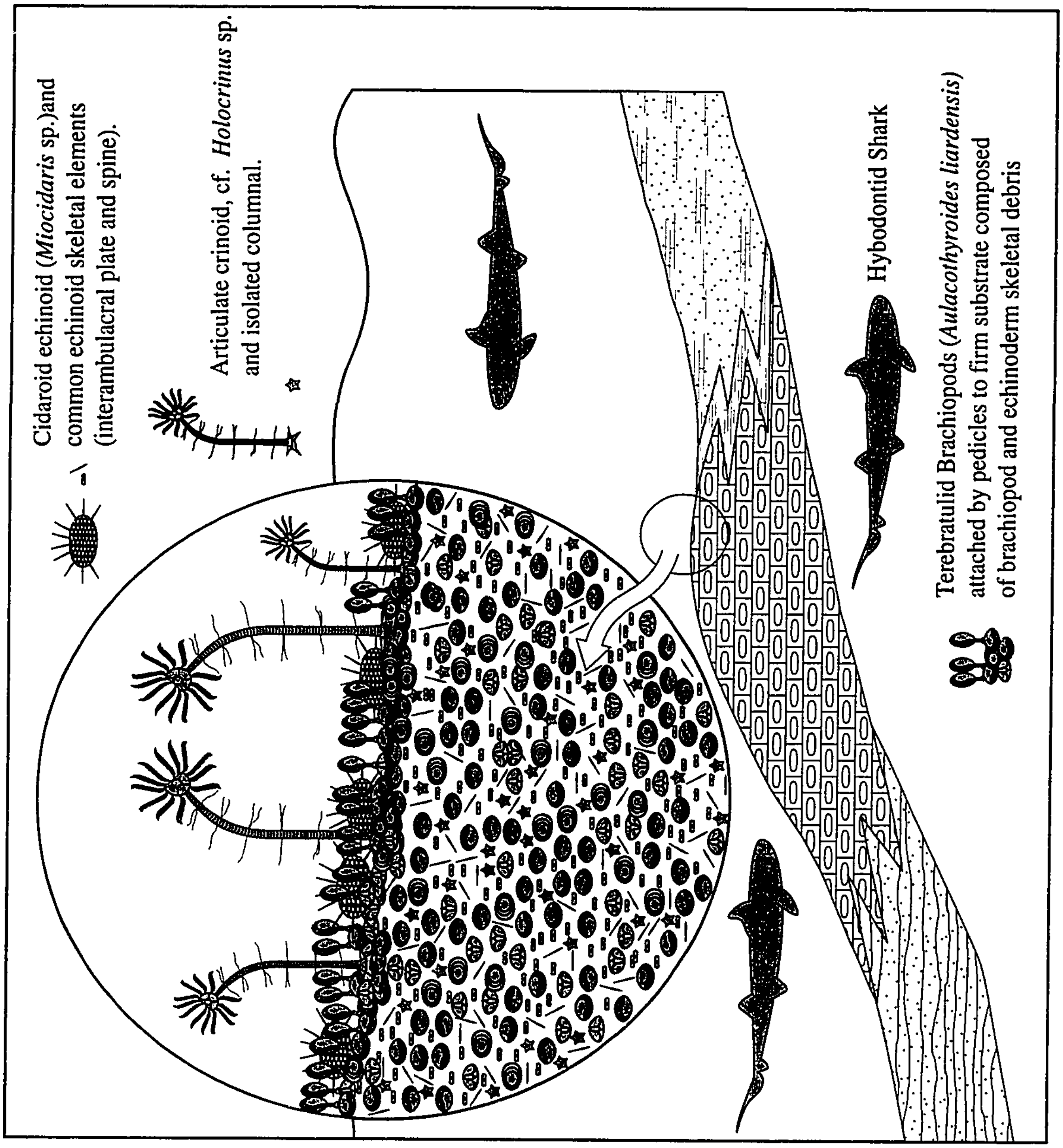


Figure 23. Hypothetical reconstruction of terebratulid-echinoid reef mound, showing main reef-building organisms and examples of typical bioclasts. Lithofacies patterns are the same as those used in figure 6-1. Not drawn to scale.

few examples of reefs. Framework reefs are unknown from the early Triassic (Flügel, 1994). Most middle Triassic framework reefs are concentrated in the Tethys Sea (Flügel, 1994). Patch reefs have been reported from Upper Triassic accretionary terranes in the Yukon (Reid and Ginsberg, 1986), and Vancouver Island (Stanley, 1989). Although some of these are framework reefs, many are sediment mounds produced by skeletal debris and sediment producing organisms with little or no framework, analagous to the Liard reefs and modern *Halimeda* bioherms (Davies and Marshall, 1985; Reid and Ginsberg, 1986). Isolated corals occur within the Upper Triassic Baldonnel Formation at Pardonet Hill and along the Nabesche River. The Liard terebratulid-echinoid bioherms or reef mounds are the earliest record of reef-building organisms from the Triassic of western Canada.

Figure 22. is a diagrammatic illustration showing the distribution of major environments and lithofacies in the mixed siliciclastic-carbonate shoreface facies association (lithofacies association B). The three distinct terebratulid-echinoid reef mounds (figures 3 & 4) observed within the study area all occur near mean fairweather wave base, adjacent to the lower shoreface-offshore transition boundary (Figure 22).

The terebratulid-echinoid rudstone/grainstone that constitutes lithofacies D differs greatly from other Middle Triassic bioclastic accumulations in both composition and texture. Rather than bivalve fragments, the unit is comprised predominantly of whole terebratulid brachiopods and echinoid skeletal debris, although terebratulid fragments and crinoid ossicles are also common (Figure 23). The bioclasts as a whole show few signs of abrasion. The presence of partial and complete crinoids and echinoids, and articulated terebratulid brachiopods within this unit is particularly significant, and emphasizes their local derivation. The fauna, including that of the back reef deposits (lithofacies E), comprises a distinctly marine assemblage including terebratulid spiriferid and acrotretid brachiopods, echinoids, scattered crinoid debris, a variety of bivalves, isolated fish skeletal elements, and abundant decapod crustacean remains.

Several environmental/ecological criteria are essential for the development of terebratulid-echinoid reefs. These are: a) initial storm-induced concentration of shell material to create islands or zones of stable substrate and thus promote colonization by crinoids, cidaroid echinoids, and terebratulid brachiopods; b) a decrease or cessation in siliciclastic input to the shoreface, allowing reef mound (bioherm) building organisms the chance to colonize these patches of stable substrate, and dominate deposition within the lower shoreface, and c) aerobic conditions in the lower shoreface allowing for a healthy and robust reef fauna.

CONCLUSIONS

Sedimentary facies within the upper Liard Formation at Williston Lake comprise three distinct facies associations: (A) progradational clastic offshore/shoreface, (B) progradational mixed siliciclastic-carbonate shoreface, and C) mixed siliciclastic-carbonate marginal marine.

Fluctuation between clastic dominated deposition in the lower part of the study interval, mixed clastic-carbonate deposition in the middle part of the study interval, and a return to clastic domination towards the top of the Liard Formation may reflect a fluctuation in clastic sediment supply. Although lithofacies association B does reflect overall shallower deposition, the absence of significant bioclastic buildup at the lower shoreface-offshore transition within lithofacies association A suggests a more consistent supply of terrigenous clastic sediment.

Lithofacies association A consists of a coarsening upwards offshore to lower shoreface facies succession locally incised by tidal channels. Lithofacies association B is a coarsening upwards, mixed siliciclastic-carbonate shoreface succession. Lithofacies association C is a mixed siliciclastic-carbonate intertidal-supratidal succession. Although most sedimentary facies described here, with the exception of facies L tidal channels, are consistent in thickness and composition between the two outcrop sites discussed, further detailed field work is needed to establish regional trends within lithofacies associations in the upper Liard Formation.

Middle Triassic bioclastic accumulations are important reservoirs in the subsurface of northern Alberta and northeastern British Columbia. Bioclastic packstones/grainstones and sandstones within the Halfway and Doig formations, consisting primarily of abraded bivalve and brachiopod fragments, are deposited in a variety of settings, including transgressive shoreface lags, tempestites, turbidites, and tidal channel fill.

Of the lithofacies described, thick (6-11m) bioclastic units (lithofacies D) within facies association B have the greatest potential as subsurface hydrocarbon reservoirs. However, these units differ significantly from other described Middle Triassic bioclastic accumulations in composition, texture and in depositional setting. The units consist of thick accumulations of unabraded terebratulid and spirifirid brachiopods, echinoids and crinoids that exhibit neither normal nor inverse grading. The features are interpreted as lower shoreface terebratulid-echinoid dominated reef mounds. The mechanism described here consists of colonization of storm created hard substrates by terebratuld brachiopods, articulate crinoids and cidaroid echinoids during a period of diminished siliciclastic influx. Subsurface equivalents have not previously been recognized, but if present, would likely serve as significant hydrocarbon reservoirs.

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CHAPTER 3.

DEPOSITIONAL FRAMEWORK AND TRACE FOSSIL ASSEMBLAGES IN A MIXED SILICICLASTIC-CARBONATE MARGINAL MARINE DEPOSITIONAL SYSTEM, MIDDLE TRIASSIC, NORTHEASTERN BRITISH COLUMBIA

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"Call the desert barren, harsh, bitter, dreary and gloomy, acrid and arid, lifeless, hopeless, ugly as sin, ghastly as the gates of hell-he will happily agree with you. Because in his heart lies the secret belief that the awful desert is really beautiful, that hell is home. And if others think he's crazy, so much the better; he is reluctant to share his love anyway."

Edward Abbey, 1984

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 units comprise an overall shallowing-upward series of progradational shoreface to marginal marine parasequences (Zonneveld and Gingras, 1997; Zonneveld *et al.*, in press). Sediments accumulated along a gently sloping shoreface/continental ramp on the northwestern Pangean continental margin.

Sedimentary depositional systems and sedimentation styles are strongly affected by the organisms living within them. Correspondingly, sediment characteristics and sedimentation styles strongly influence the abundance, diversity and types of plants and animals that live within a system. In addition, organisms or their skeletal components often act as sediment particles, particularly within carbonate or mixed siliciclastic-carbonate systems. Within arid environments, particularly those with minimal siliciclastic input, the ability of a system to produce biogenic sediment is especially significant. Infaunal and epifaunal organisms are particularly sensitive to changes in their surroundings. The presence, distribution, and variety of trace fossils present in a system may reveal valuable inFormation on environmental parameters such as salinity, oxygenation, and sedimentation rates.

Although most studies dealing with recent mixed systems discuss, at least in part, the flora and fauna that inhabit these depositional systems, 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) develop a depositional model for mixed siliciclastic-carbonate marginal marine intervals within the upper Liard Formation (Figure 1) at Williston Lake, northeastern British Columbia (Figure 2); 2) describe the distribution and diversity of trace and body fossils within the various lithofacies associations; and 3) assess the controls promoting deposition within mixed siliciclastic-

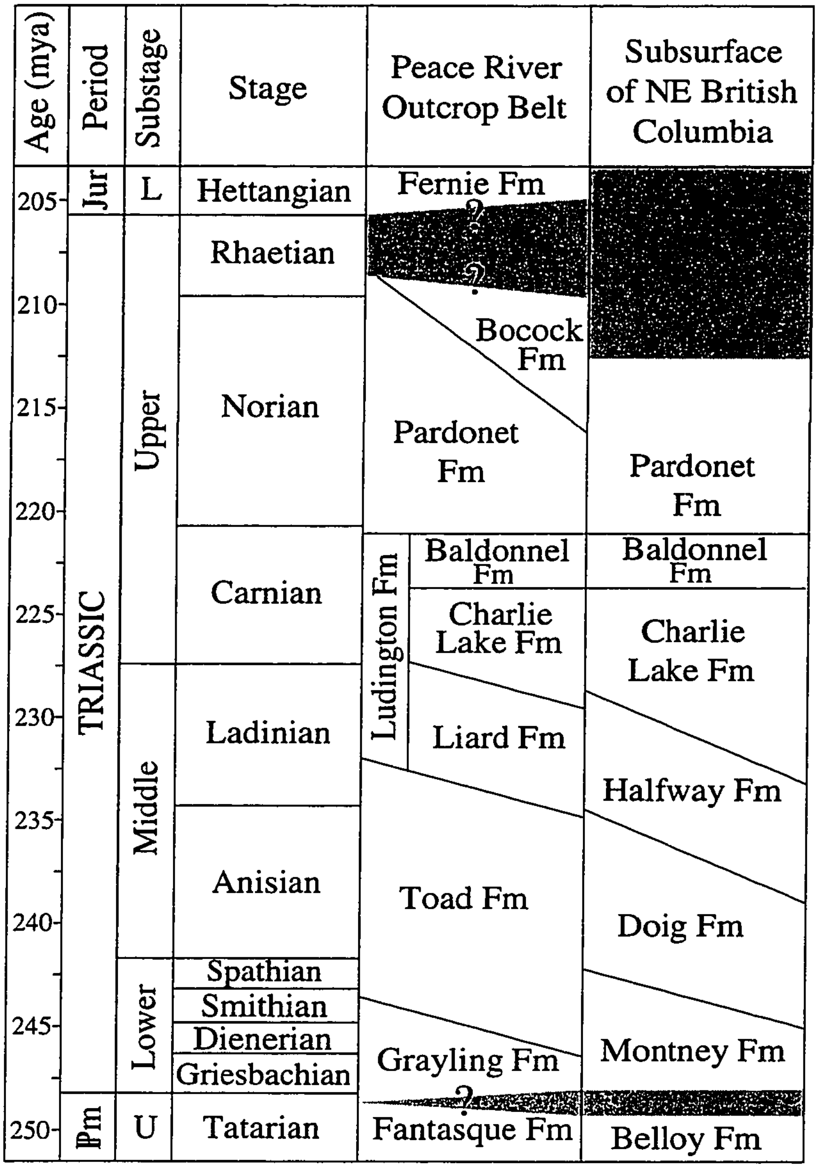


Figure 1. Triassic stratigraphic nomenclature, subsurface and outcrop, northeastern British Columbia (adapted from Gradstein et al., 1994; Tozer, 1994). Contacts between Lower and Middle Triassic formations are drawn to reflect their diachronous nature.

carbonate marginal marine environments.

Location of Measured Sections

The focus of this study is Middle Triassic marginal marine deposits along the Peace Reach of Williston Lake (Figure 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 (Figure 2). Glacier Spur and Brown Hill, approximately 40 kilometers west of the W.A.C. Bennett Dam consist of thick successions (320 m and 580 m respectively) of Middle Triassic (upper Anisian and Ladinian) proximal offshore, shoreface and marginal marine deposits. Beattie Ledge approximately 20 kilometers west of the W.A.C Bennett Dam, consists of an approximately 250 m thick succession of Middle Triassic (Ladinian) shoreface and marginal marine deposits. This paper deals solely with Ladinian age marginal marine deposits at each of these sites.

Sampling and Descriptive Procedures

Detailed stratigraphic sections were measured at each locality. Attention was paid to lithology, bounding surfaces, primary physical and biogenic sedimenary structures, and bioclastic or fossil composition. Lithofacies were described both vertically and horizontally to assess lateral variability in physical and biogenic sedimentary structures and in sediment composition. Trace and body fossils were photographed and described in terms of associations and overall abundance. Representative samples were collected at regular intervals for thin- and polished-section analysis. Bulk samples for conodont analysis were collected within adjacent marine strata to place the sections within a biostratigraphic framework.

Gamma-ray readings, using a portable scintillometer, were taken at all measured sections to facilitate correlation between outcrops and better delineate marine flooding surfaces. Five radiation count readings, separated by ten second intervals, were obtained at 0.60 m intervals following the methodology of Slatt *et al.* (1992). The highest and lowest values were discarded and the remaining three averaged to obtain the value for each horizon.

Stratigraphic Setting

Triassic strata in the Western Canada Sedimentary Basin (Figure 1) are composed of westward-thickening marine and marginal marine siliciclastic, carbonate, and evaporite facies deposited on the western margin of the North American craton. The present study concentrates on marginal marine and nonmarine strata in the upper part of the Liard Formation. Excellent exposure of the Liard Formation along the shores of Williston Lake provides insight into the depositional mechanisms of mixed siliciclastic-carbonate systems.

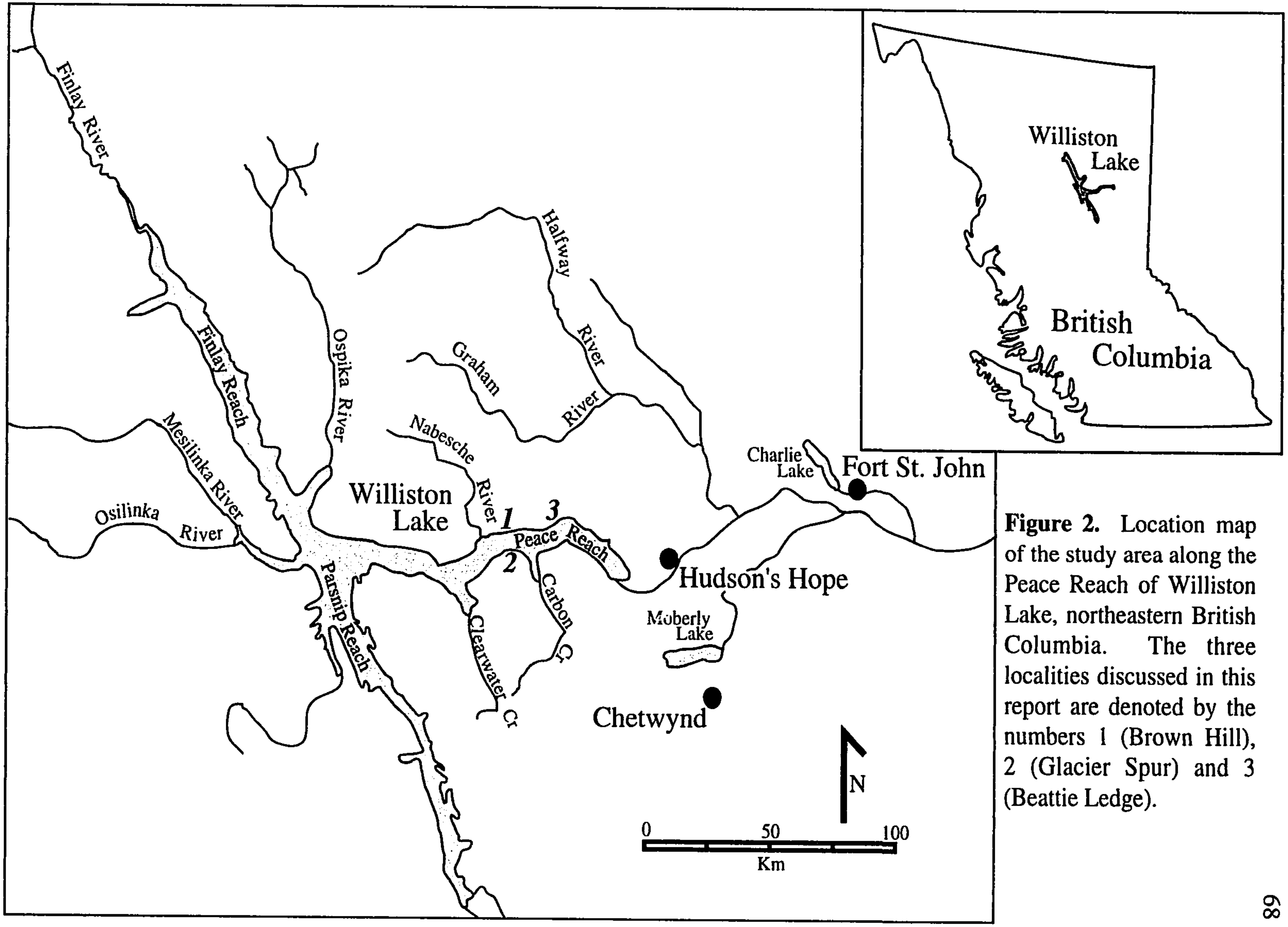


Figure 2. Location map of the study area along the Peace Reach of Williston Lake, northeastern British Columbia. The three localities discussed in this report are denoted by the numbers 1 (Brown Hill), 2 (Glacier Spur) and 3 (Beattie Ledge).

The Liard Formation (Figure 1) was first defined by Kindle (1946), based on an 180 m succession of calcareous sandstone and arenaceous limestone conformably overlying the Toad Formation (Figure 1) in the vicinity of Hades Gate 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 series of approximately fifteen progradational, mixed siliciclastic-carbonate shoreface parasequences (Zonneveld *et al.*, in press). Within the study area, the Liard is conformably overlain by the predominantly marginal marine to nonmarine Charlie Lake Formation (Figure 1).

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

The upper Liard Formation within the study area is the lithostratigraphic equivalent of the subsurface Halfway and Charlie Lake Formations (Figure 1). In the absence of detailed regional chronostratigraphic studies, precise correlation between the outcrop belt and the subsurface remains somewhat tenuous and conjectural. The Upper Liard Formation in the study area is believed to be the chronologic equivalent of the Charlie Lake Formation (predominantly nonmarine) in the subsurface to the east of the study area, and to the Toad Formation (predominantly offshore to offshore transition) in the western part of the outcrop belt (Figure 1).

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 Upper 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 (Evoy and Moslow, 1996); Evoy, 1997; and Caplan and Moslow,

1997) have documented the role of high angle normal faulting on syn-sedimentary tectonism in the Triassic of the Western Canada Sedimentary Basin.

Paleoenvironmental Setting

There is little substantiated evidence as to the nature of the climate of the study area during the middle Triassic. Paleogeographic analyses based in part on paleomagnetic data suggest a paleolatitude of approximately 30° north latitude (Habicht, 1979; Tozer, 1982; Wilson *et al.*, 1991). Paleocurrent measurements on 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 trends of cross-bedding and ripple marks in the Toad and Liard Formations suggest 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 (Campbell and Horne, 1986; Pelletier, 1965).

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

Depositional framework and trace fossil assemblages

Fourteen lithofacies have been recognized in the upper Liard Formation within the study interval, identified on the basis of lithology, bounding surfaces, primary physical and biogenic sedimentary structures, and fossil composition (Table 1). A summary of the environmental distribution of trace fossils observed within the study interval is presented in Table 2. Detailed sections were measured at Brown Hill (Figure 3), Glacier Spur (Figure 4), and Beattie Ledge (Figure 5) to describe sedimentary facies and to assess vertical and lateral facies variability. Trace fossil and body fossil symbols used in figures 3, 4 and 5 are summarized in Table 3. Brown Hill and Glacier Spur are located approximately two kilometres apart on depositional strike from one another (Figure 2). Beattie Ledge is located approximately eighteen kilometres east (updip) from the other two sites (Figure 2). Sequence 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 described in Zonneveld *et al.*, (1997) and are not discussed here. Lithofacies interpreted as marginal marine oscillate frequently within five recurring progradational facies associations. These facies associations are: I) upper shoreface/foreshore, II) washover fan/lagoon, III) intertidal flat, IV) ephemeral lacustrine and V) aeolian dune (Figure 6).

FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	BODY FOSSILS	DEPOSITIONAL ENVIRONMENT
A1	Siltstone/Sandstone	Plane parallel laminae, flow ripples, HCS, rare oscillation ripples.	Sc, Th, Sp, Lk, Pa, Pl	scattered lingulids, bivalves, & reptile bones	Offshore/Shoreface Transition
A2	Sandstone (very fine)	Amalgamated HCS beds, planar bedding, current and oscillation ripples.	Ar,Di,Cy,Pa,Pl,LkLi,Ro,Si,Sk,Te,Th, fug	brachiopods,bivalves, fish, & ammonoids	Lower Shoreface
B1	Calcareous sandstone (very fine to fine)	Predominantly TCS, rare HCS (SCS?), rare oscillation ripples	Di, Sk, Pa, Pl, fug	scattered brachiopod & 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, brachs, bivalves, rare bones	Proximal Upper Shoreface/Foreshore
C1	Calcareous bioclastic sandstone	Appears massive, planar lam. to TCS, beds thicken upwards (5-10 to 30cm)	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 brachs	Washover fan/ Lagoon
D1	Fenestral laminated dolomite	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	Dolomitic sandstone	Heterolithic wavy laminae, flaser bedding, symmetrical ripples, dessication cracks, rill marks	Cy,Gy,La,Pa,Pl,Rh,Sk, Si,Te,Th, BAT fug, pit	bivalves, gastropods, lingulid fragments	Intertidal Flats
F	Dolomitic siltstone	Planar laminations, current and oscillation ripples, heterolithic wavy laminae, polygonal mudcracks	Ar,Cy,Co,Di,Gy,Lo, Pa,Pl,Rh,Sk,Th, pit	*Lingula*, bivalve frags, gastropods	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 TCS grading up into current ripple laminae, mudclast lags	None observed	Rare bivalve shell lags.	Tidal Inlet Channels
I	Ripple-laminated dolomitic siltstone/mudstone	Wavy to ripple laminated, adhesion ripples	Cy, Mo, Op, root traces	None Observed	Supratidal Sabkha
J	High-angle cross-stratified sandstone	Planar cross-bedding, rare oscillation ripples, inversely graded laminae	None observed	None Observed	Aeolian Sand Dune

Table 1. Summary of 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 = *Siphonites;* Sk = *Skolithos;* Ta = *Taenidium;* Te = *Teichichnus;* Th = *Thalassinoides;* Tr = *Trichichnus;* BRT = bivalve resting trace; BAT = bivalve adjustment trace; Fug = fugichnia; Root = root traces; Pit = feeding pits.

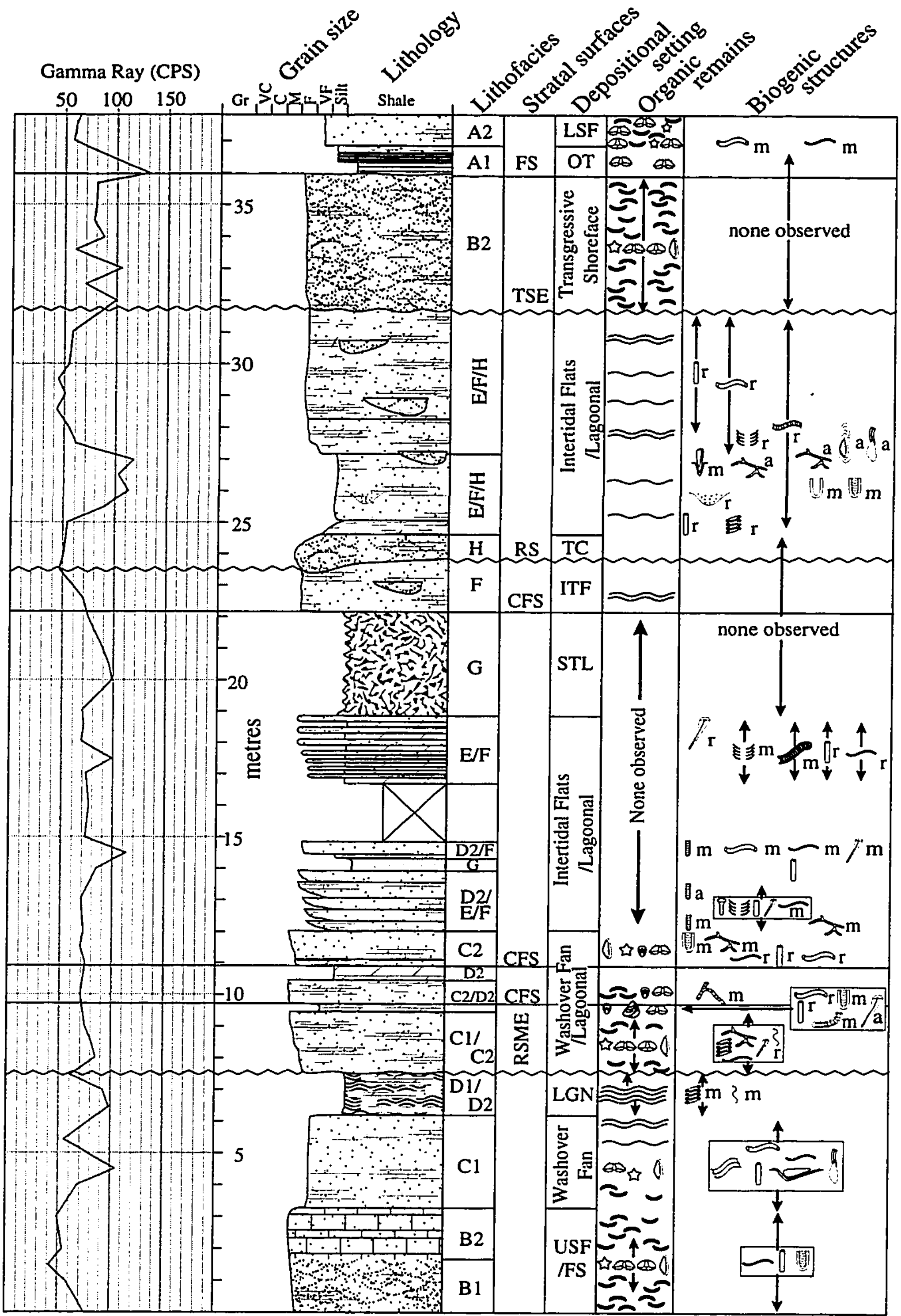


Figure 3. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Brown Hill. Outcrop gamma readings are measured in counts per second (CPS). FS= Flooding Surface; CFS; Correlative Flooding Surface; RS- Ravinement Surface; 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.Symbols are summarized in Table 3.

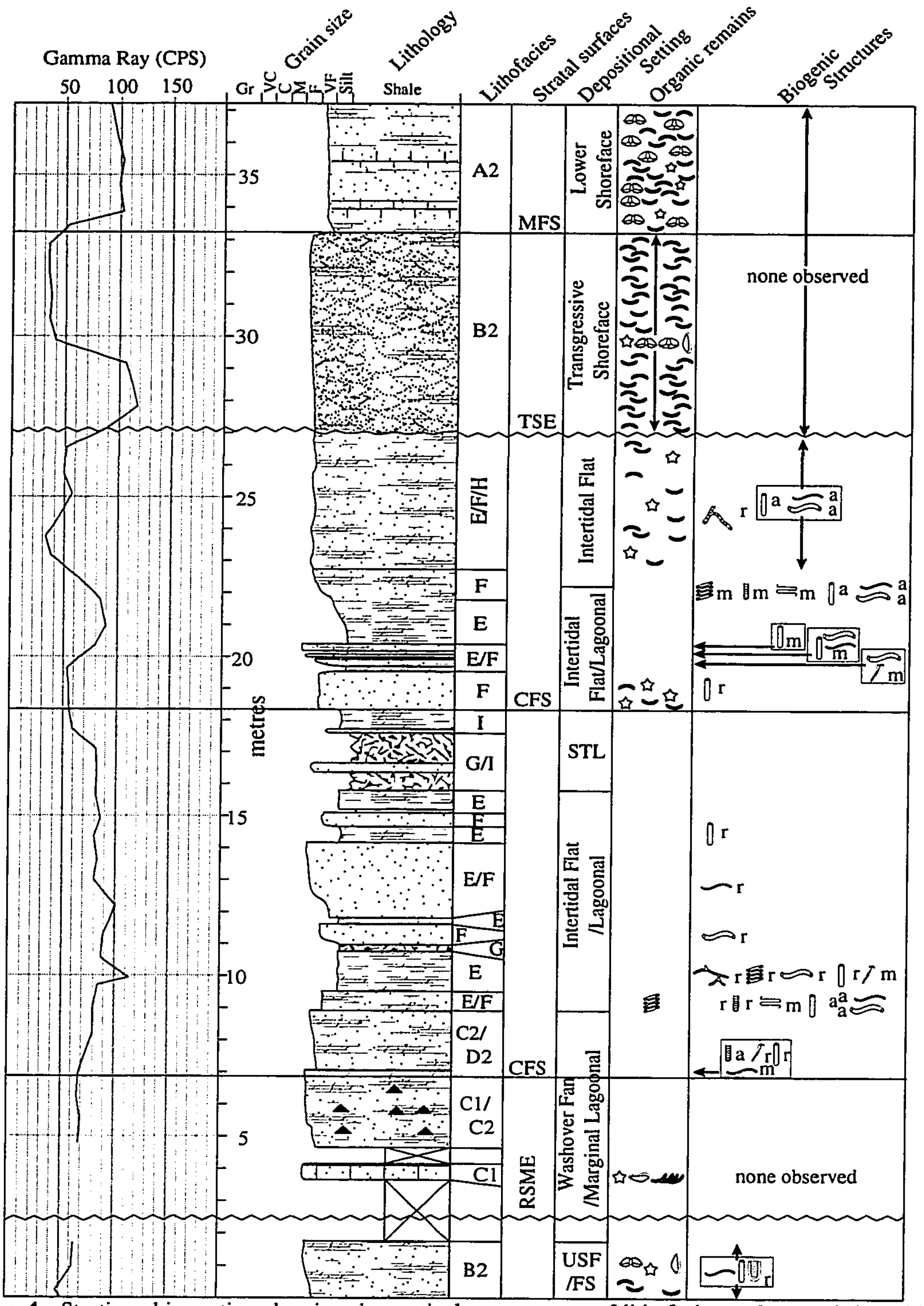


Figure 4. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Glacier Spur. Outcrop gamma readings are measured in counts per second (CPS). FS= Flooding Surface; CFS; Correlative Flooding Surface; RS- Ravinement Surface; 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. Symbols are summarized in Table 3.

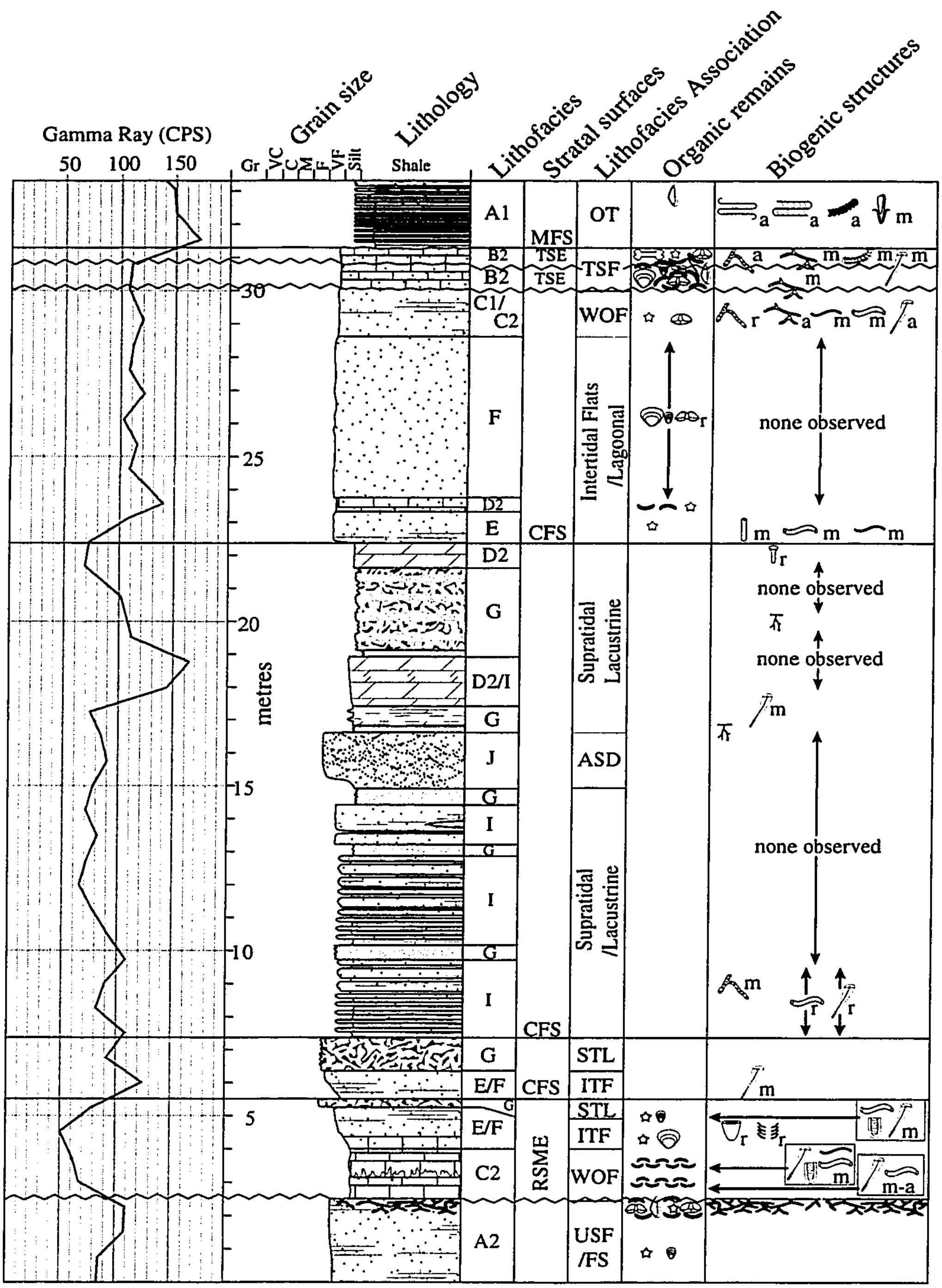


Figure 5. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Liard Formation at Beattie Ledge. Outcrop gamma readings are measured in counts per second (CPS). FS= Marine Flooding Surface; CFS= Correlative Flooding Surface; MFS= Maximum Marine Flooding Surface; RS- Ravinement Surface; 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; ASD= Aeolian Sand Dune. Symbols are summarized in Table 3.

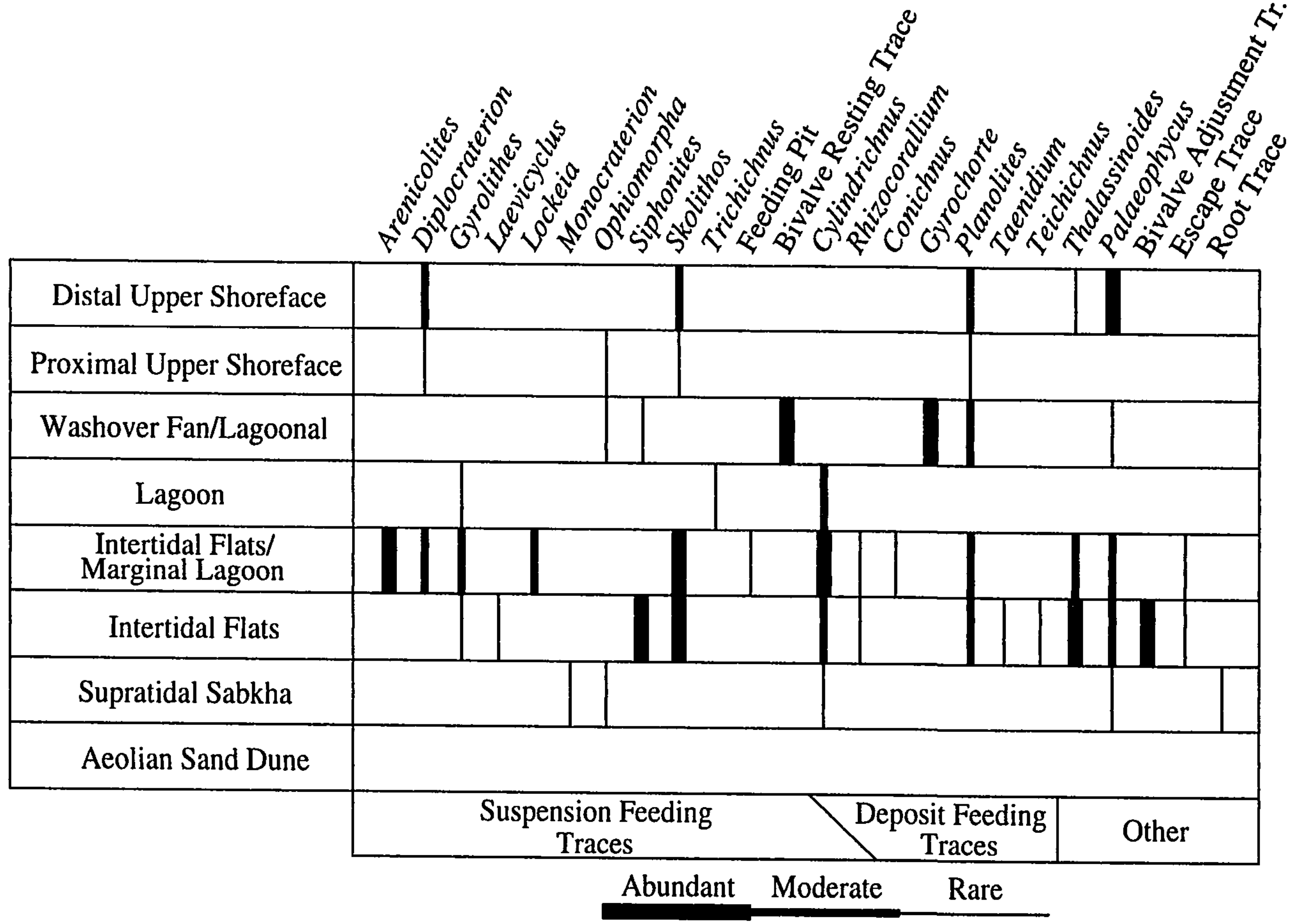


Table 2. Summary diagram showing the environmental distribution of trace fossils within the study interval.

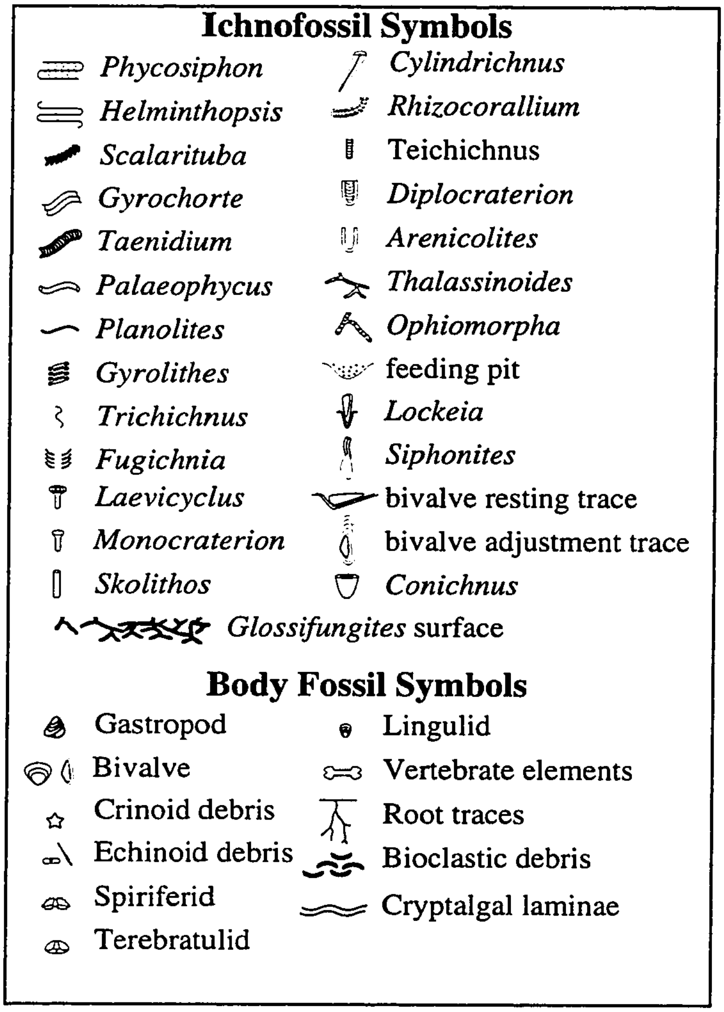


Table 3. Ichnofossil, and body fossil symbols used in figures 3-5. r= rare; m= moderate, a= abundant.

The traces discussed here are compared and contrasted with established ichnofacies models. The original ichnofacies described by Seilacher (1967, 1968); *Skolithos, Cruziana, Zoophycos* and *Nereites,* were subsequently augmented with the *Scoyenia* (Seilacher, 1967, 1978), *Psilonichnus* (Frey and Pemberton, 1978; 1987) and *Mermia* ichnofacies (Buatois and Mángano, 1995). Three substrate-controlled ichnofacies also occur; *Glossifungites* (Seilacher, 1967, 1978; Pemberton and Frey, 1985), *Trypanites* (Frey and Seilacher, 1980) and *Teredolites* (Bromley *et al.*, 1984).

Table 2 summarizes the environmental distribution of trace fossils within the study interval. Two ichnofacies, *Skolithos* and *Psilonichnus,* are pertinent to this study. The *Skolithos* ichnofacies is characterized by predominantly vertical, cylindrical and u-shaped burrows, and is evincive of comparably high energy depositional settings (Frey and Pemberton, 1984; Frey *et al.*, 1990; Pemberton and MacEachern, 1995). The *Psilonichnus* ichnofacies is characterized by an assortment of small, vertical shafts, larger J-, Y-, and U-shaped dwelling structures, invertebrate and vertebrate crawling traces and tracks, and cyanobacterial mats (Frey and Pemberton, 1984; Pemberton and MacEachern, 1995). It represents a mixture of moderate to low-energy marine and marginal marine conditions, including the backshore, dune, washover fan, intertidal flat and supratidal flat environments (Frey and Pemberton, 1984; 1987). These enviroments are affected by marine influences such as tides, waves, and storm surges as well as fluvial and aeolian processes (Pemberton and MacEachern, 1995; 1996).

Lithofacies Association I: Upper Shoreface/Foreshore

Lithofacies association I consists of two distinct lithofacies (B1 and B2). Lithofacies B1, is predominantly trough cross-stratified. Individual bedsets range in thickness from 45-150 centimetres in thickness, and exhibit an overall thickening-upwards trend. Bedset contacts are sharp and in many cases erosive. Other physical sedimentary structures include horizons of swaley cross-stratification near the base capped by oscillation ripple laminae, suggestive of storm generated waning-flow deposits. Lithofacies B1 overlies calcareous, hummocky cross-stratified sandstone (lithofacies A2) and is overlain by planar tabular cross-stratified sandstone to sandy packstone (lithofacies B2). Body fossils within lithofacies B1 consist primarily of scattered crinoid ossicles and columnals, echinoid debris (spines and interambulacral plates) and terebratulid brachiopods. Trace fossils within lithofacies B1 include *Diplocraterion parallelum, Ophiomorpha annulata* (Figure 7), *Palaeophycus tubularis, Planolites beverleyensis, Skolithos linearis* and *Thalassinoides suevicus*. This moderately low diversity, vertical-burrow dominated trace fossil assemblage is characteristic of the *Skolithos* ichnofacies.

Lithofacies 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 comprised of rounded calcareous bioclasts and quartzose sand. Lithofacies B2 also contains abundant, scattered chert pebbles and chert pebble laminae. The sand fraction is moderately well-sorted, whereas the calcareous bioclasts are highly fragmented and poorly

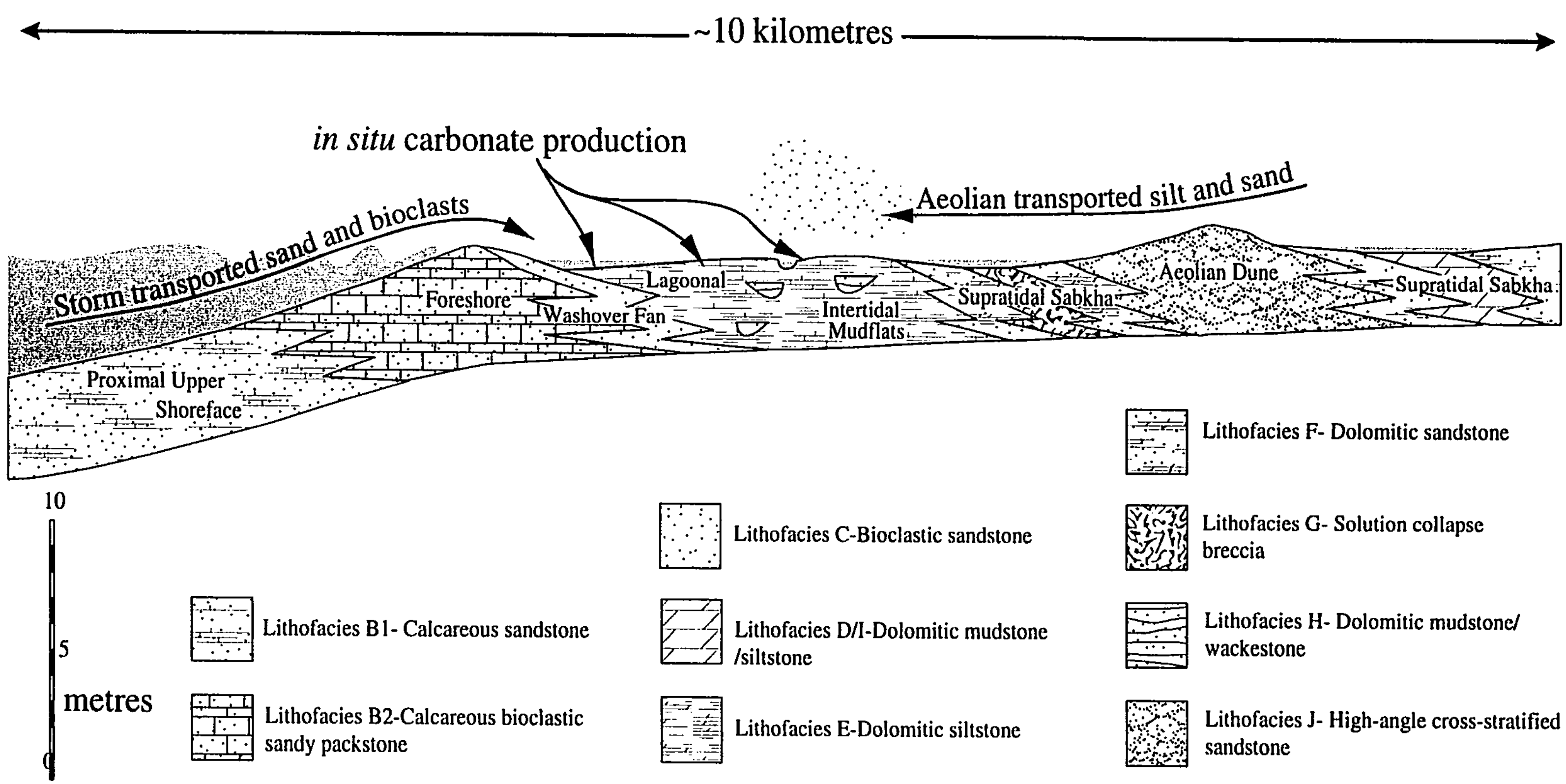


Figure 6. Postulated lateral distribution of major environments and lithofacies of the upper Liard mixed siliclastic-carbonate shoreface within the study area showing main sediment sources.

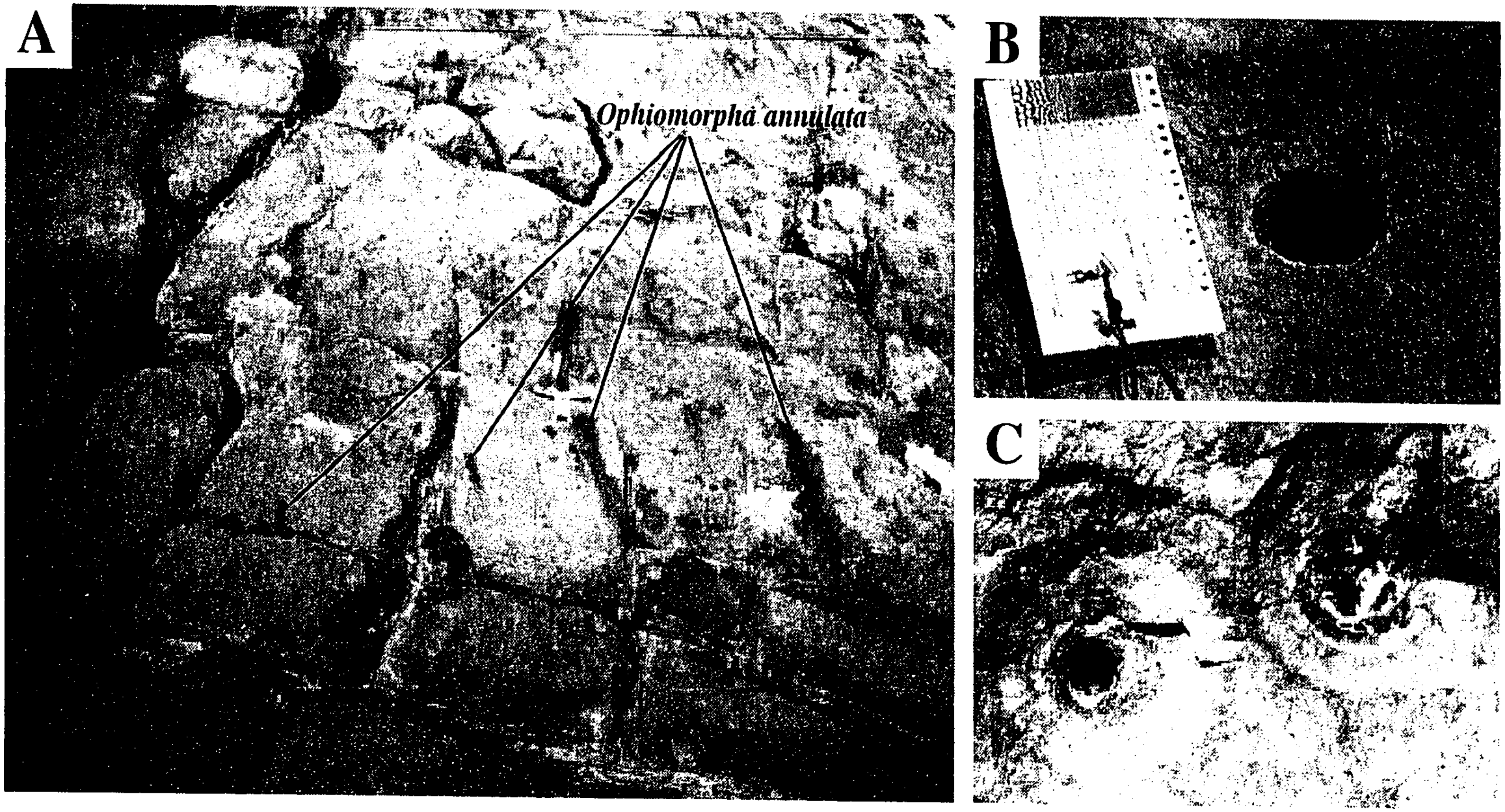


Figure 7a. Outcrop photograph of bedding plane with abundant *Ophiomorpha annulata*, lithofacies B1, parasequence L14/L15 contact (maximum marine flooding surface), Beattie Ledge. The fecal pellet lining has been replaced with iron oxide minerals, resulting in the long streaks of rust below many of the burrow openings. The rock hammer at centre is 32cm long.
Figure 7b. A close-up view of a single *Ophiomiorpha annulata* burrow on a bedding plane. The less resistant internal filling of the burrow has preferentially eroded out, leaving a hollow annulated mold. Scale bars in both insets are 1cm in length.
Figure 7c. A close-up view of two *Ophiomorpha annulata* burrow openings. The halo surrounding both burrows is attributed to preferential fluid flow through the burrows altering the diagentic properties of the rock.

sorted. The sand fraction and chert pebbles of Lithofacies B2 comprises the coarsest siliciclastic sediment observed within the study area. Bioclasts within lithofacies B2 consists of a highly abraded, variably rounded mix of bivalve, crinoid, echinoid, and brachiopod (spiriferid and terebratulid) fragments. Isolated, highly eroded reptile (ichthyosaur?) bone fragments occur near the top of lithofacies B2 at Brown Hill. *Planolites* was the only trace fossil observed within lithofacies B2.

The abundant scour surfaces, trough to planar cross-stratification and *Skolithos* ichnofacies assemblage are indicative of deposition in an environment characterized by traction deposition, frequent wave reworking and high current velocities. Lithofacies B1 is interpreted as being deposited in the upper shoreface. Moderately well-sorted quartz sand, the paucity of trace fossils and the highly abraded nature of the bioclasts support this interpretation. The trough to planar cross-stratified beds of the basal part of lithofacies B2 were deposited within the proximal upper shoreface (surf zone). Welded planar bedsets characterizing bioclastic deposits in the upper part of lithofacies B2 reflect deposition within the swash zone or foreshore. Shoreface/foreshore sediments accumulated on a storm-dominated, prograding barrier island coast (Zonneveld *et al.* 1997).

Lithofacies Association II: Washover Fan/Lagoon

Lithofacies association II is comprised of two distinct facies: lithofacies C (fine-grained sandstone) and lithofacies D (dolomitic mudstone). Facies C1 is comprised of fine-grained, well-sorted sandstone, containing chert pebbles and abundant bioclastic material. Physical sedimentary structures, although generally obscured by weathering and biogenic reworking consist of horizontal to subhorizontal lamination. 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.*, in press), and is abruptly overlain by fenestral-laminated carbonate mudstone (Facies D1).

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

Lithofacies C1 and C2 are characterized by a moderately diverse trace fossil assemblage, consisting of *Skolithos linearis*, *Palaeophycus tubularis*, *Planolites beverleyensis*, *Gyrochorte* sp., and an as yet undescribed type of bivalve resting trace (Figure 8b). Lithofacies C1 contains scattered bioclastic material including rare, whole spiriferid and lingulid brachiopods, and abundant brachiopod and echinoderm skeletal debris. Body fossils within lithofacies C2 consist of rare scattered bioclastic debris and rare *Lingula* sp. valves.

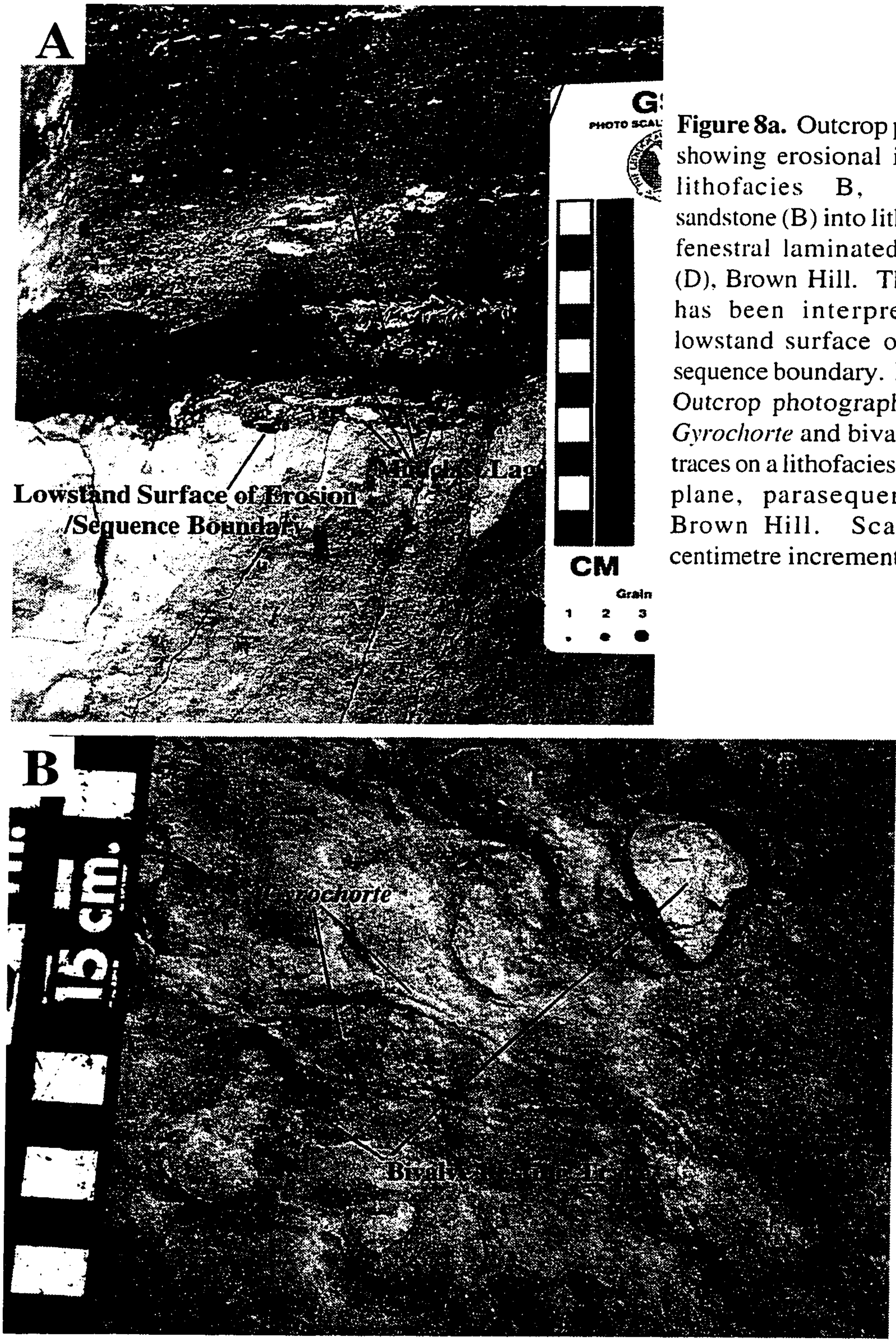


Figure 8a. Outcrop photograph showing erosional incision of lithofacies B, shoreface sandstone (B) into lithofacies D, fenestral laminated dolomite (D), Brown Hill. This surface has been interpreted as a lowstand surface of erosion/ sequence boundary. **Figure 8b.** Outcrop photograph showing *Gyrochorte* and bivalve resting traces on a lithofacies C bedding plane, parasequence L10, Brown Hill. Scales show centimetre increments.

Lithofacies C1 is interpreted as a washover fan/lagoonal deposit (Zonneveld *et al.*, in press). Lithofacies 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.

Lithofacies D1 consists predominantly of planar to undulatory laminated dolomite with abundant thin, normally graded silt and sand laminae. Abundant diminutive fenestrae (birdseye structures) occur within lithofacies D1. Lithofacies D2 consists of planar laminated dolomitic mudstone with silt, sand and bioclast laminae, and abundant synaeresis cracks (Figure 9b). Lithofacies D generally occurs as thin (0.5 to 20 centimetre) beds interbedded with lithofacies C1, C2, D2, E and F. An unusually thick occurrence (~1.7m) of Lithofacies D (interlaminated D1 and D2) occurs near the base of the Brown Hill section. This unit is erosionally overlain by lithofacies C2 (mixed shoreface, foreshore and washover fan). Trace fossils were not observed within lithofacies D1. Lithofacies D2 contains *Trichichnus* and diminutive *Cylindrichnus*, as well as rare lingulid, bivalve, and gastropod fossils.

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

Lithofacies D2 differs from D1 primarily by the presence of synaeresis cracks and absence of undulatory laminae or fenestrae. Synaeresis cracks form sub-aqueously during reorganization of porous clays, often as a result of salinity-induced volume changes in clay minerals (Collinson and Thompson, 1989). Frequent interlamination of these two subfacies suggests deposition within closely related depositional environments. Alternatively, this interlamination may reflect seasonal variations in the presence and lateral extent of cyanobacterial mats. Cyanobacterial mats tend to inhibit burrowing by infaunal organisms explaining the absence of trace fossils within lithofacies D1. The sandstone, siltstone and bioclast laminae within both lithofacies represent deposition during storm washover events (Aigner,1985). Alternatively these 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.*, 1997).

Physical sedimentary structures within lithofacies association II reflect deposition in a setting in which current strength varied considerably. Bedforms such as planar cross-stratification and oscillation ripple laminae reflect traction dominated deposition. Planar lamination of clay and silt sized sediment typically results from suspension deposition.

Planar laminated dolomitic mudstone (lithofacies D1 and D2) with numerous sharp-based, normally graded laminae, reflect dominantly suspension deposition within a quiescent setting, punctuated by short duration intervals dominated by traction deposition. Although the lithologies of lithofacies C1 and C2 differ somewhat, their trace-fossil assemblages are identical. Lithofacies association II is similar to the basal beds of transgressive barrier island deposits within the Halfway Formation at Wembley Field, Alberta described by Willis and Moslow (1994).

Lithofacies Association III: Intertidal Flat

The intertidal flat succession (lithofacies association III), is comprised primarily of dolomitic sandstone (lithofacies E) and muddy dolomitic siltstone (lithofacies F) with abundant dolomitic mudstone beds and laminae (lithofacies D2). Lithofacies E consists of flaser bedded to planar bedded very fine-grained sandstone. Other physical sedimentary structures observed within lithofacies E include current, interference and symmetrical oscillation ripples, and polygonal desiccation cracks. Laterally restricted furrows characterized by massive to laminated fill occur within lithofacies E.

Lithofacies F consists of dolomitic muddy siltstone and is characterized primarily by planar lamination and lesser wavy lamination. Polygonal mudcracks, sandstone laminae and are common within lithofacies F. Interference ripples and possible runzel marks also occur within lithofacies F. Lithofacies E and F usually occur together and are intergradational. Several beds within both lithofacies E and F are massive in appearance with respect to physical sedimentary structures.

Dolomitic mudstone/siltstone intraclasts are common within both lithofacies E and F and are generally oriented concordant with bedding. Laterally restricted (0.25 to 4.25 metres wide), trough cross-bedded to current ripple-laminated calcareous sandstone lenses with erosive bases (lithofacies H) are locally common (Figure 9a). Dendritic furrow networks on Lithofacies E and F bedding planes are interpreted as rill marks. Abundant cyanobacterial mounds and laminae (lithofacies D1) also occur within lithofacies association III.

The same suite of body fossils occur within lithofacies E and F. These include rare bivalves, gastropods, and scattered lingulid brachiopod fragments, generally deposited concordant to bedding. Abraded crinoid, echinoid, terebratulid brachiopod and spiriferid brachiopod fragments are common within thin, normally graded sand layers.

Trace fossils within lithofacies F include *Arenicolites* sp. (Figure 10b), *Diplocraterion parallelum*, *Cylindrichnus concentricus* (Figure 9c), *Laevicyclus* sp., *Lockeia siliquaria*, *Palaeophycus tubularis* (Figure 10a), *Planolites beverleyensis* (Figures. 10a, 10b, 10d), *Rhizocorallium jenense* (Figure 9b), *Skolithos linearis* (Figures 9c, 10b, 10c), *Taenidium serpentinum* (Figures 10a, 10b, 10d) and *Thalassinoides* sp. (Figure 10c).

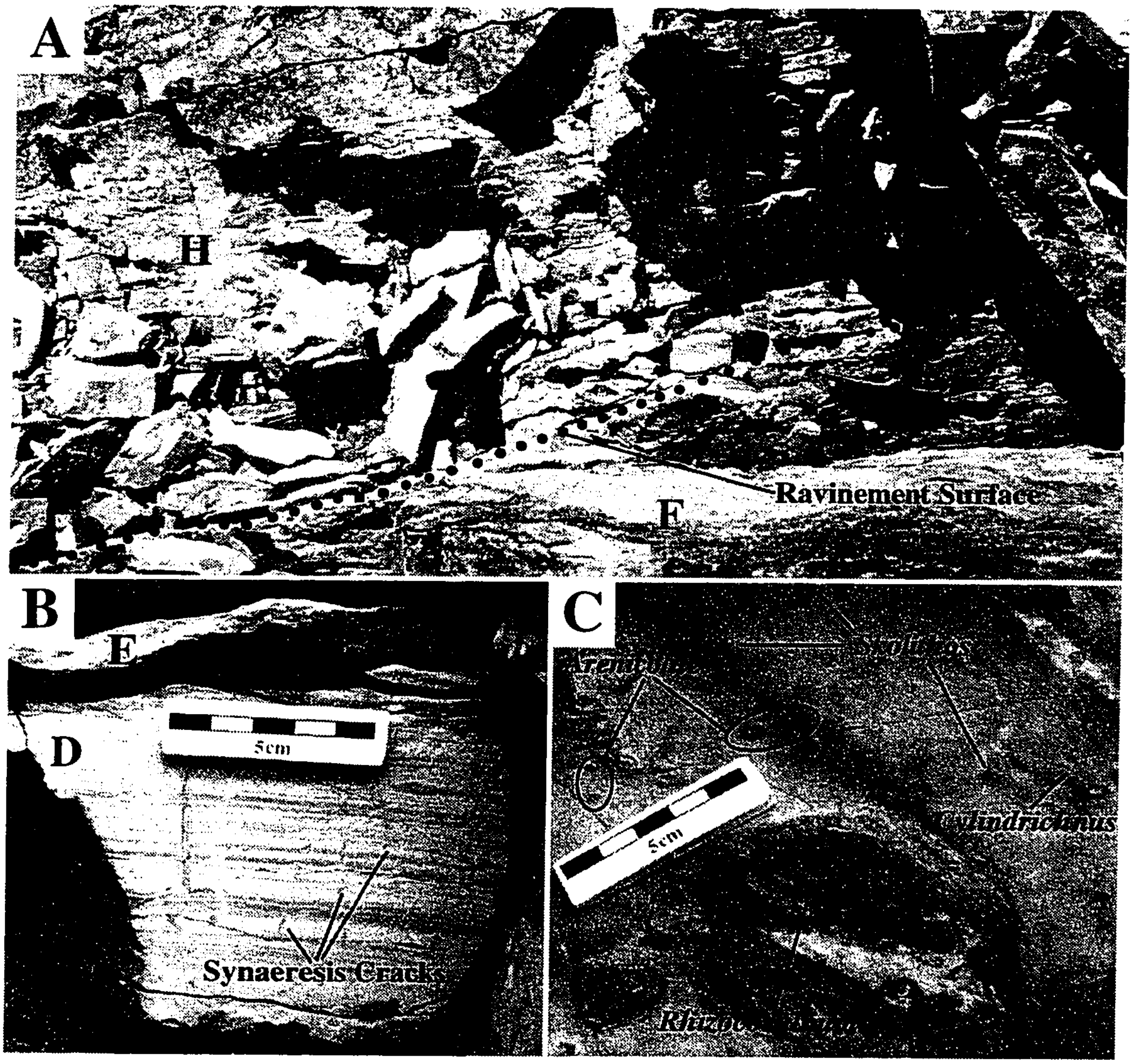


Figure 9a. Outcrop photograph showing tidal channel incision (ravinement surface, lithofacies H) into intertidal flat dolomitic siltstone and sandstone (lithofacies F), parasequence L12, Browh Hill. Rock hammer is approximately 30 cm in length. **Figure 9b.** Outcrop photograph showing synaeresis cracks within laminated dolomitic mudstone (lithofacies D) deposited within a lagoonal setting, parasequence L11, Brown Hill. **Figure 9c.** Outcrop photograph showing rippled bedding plane surface with abundant burrows including *Arenicolites*, *Cylindrichnus*, *Rhizocorallium*, and *Skolithos*, lithofacies E (dolomitic siltstone), parasequence L12, Brown Hill.

Trace fossils within lithofacies E include *Cylindrichnus concentricus, Palaeophycus tubularis, Planolites beverleyensis, Skolithos linearis, Siphonites* sp., *Teichichnus* sp. and *Thalassinoides* sp. Many of the trace fossils emanate from thin (2-10 cm) normally-graded sand layers.

The grain size (very fine- to fine-grained sand) and dominant physical bedforms in lithofacies E reflects deposition dominated by bedload transport. Most of these bedforms likely occured under lower flow regime conditions (flaser bedding, planar bedding, current and interference ripples). The presence of oscillatory ripples infers wave-generated transport during periodic submergence. Parting lineations on the base of planar laminated sandstone laminae however reflect high current velocities and suggest occasional deposition during upper plane bed conditions (Allen, 1984a).

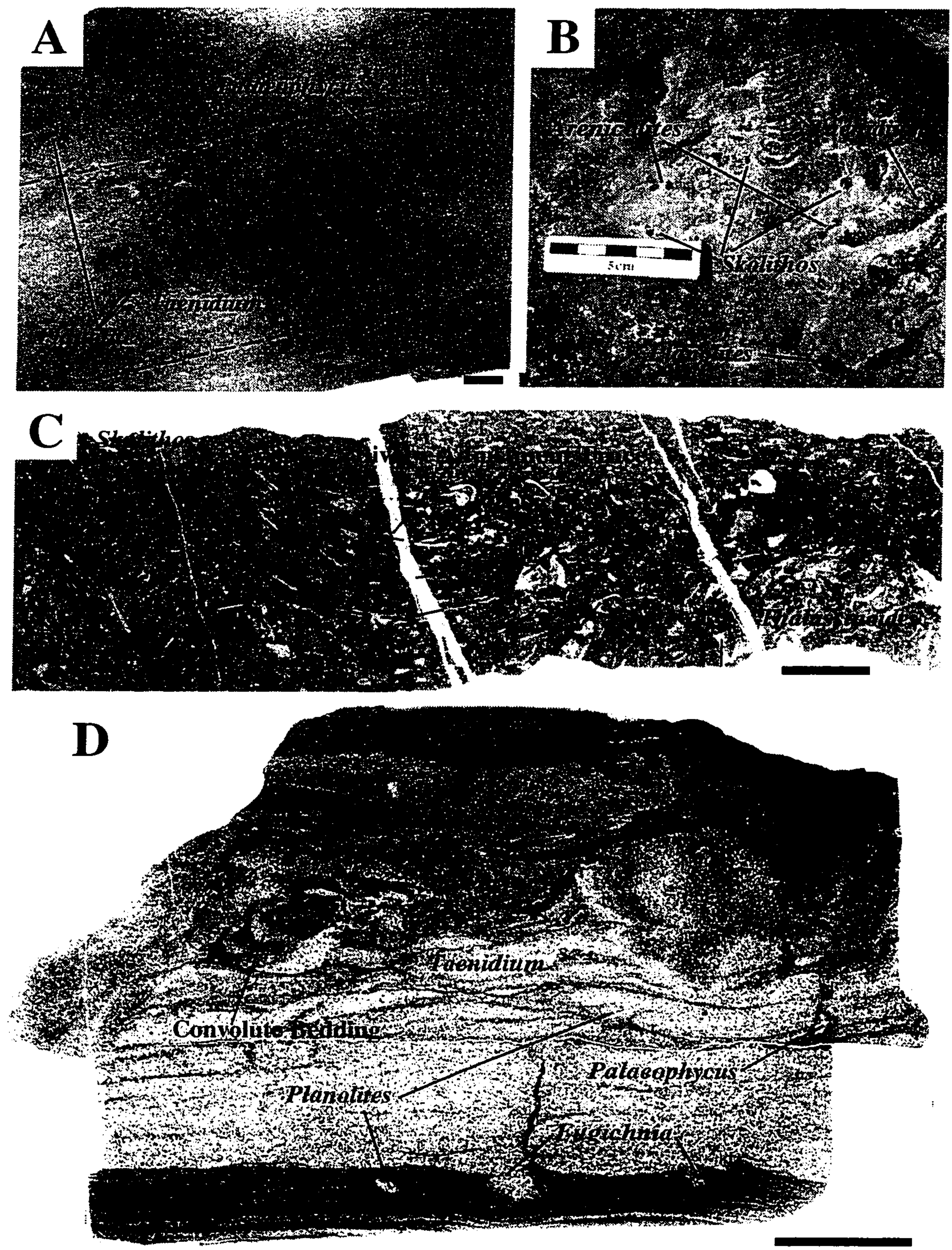
Lithofacies F is characterized by comparably fine grained sediment (muddy silt with abundant dolomitic mud laminae). Layers of finely laminated mud and muddy silt intercalate with current ripple-laminated and flaser to lenticular bedded siltstone reflecting an environment characterized by mixed traction and suspension deposition.

Lithofacies III is interpreted to reflect deposition within an intertidal flat succession. 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). Lithologic and primary physical bedform differences between lithofacies E and F reflect deposition in closely related intertidal flat sub-environments.

Lithofacies association II is interpreted to represent a gradation from lower or outer intertidal flat (lithofacies E) to inner intertidal flat (lithofacies association F). Many Holocene to Recent intertidal flat deposits exhibit a seaward-coarsening textural distribution analagous to the Liard intertidal succession. Examples include Bahia La Choya on the Gulf of California (Flessa and Eckdale, 1987; Fürisch *et al.*, 1991), and the North Sea Coast of Britain (Evans, 1965; 1975) Germany (Klein, 1977; Reineck, 1967) and the Netherlands (Klein, 1977; Van Straaten and Kuenen, 1957).

Both lithofacies E and F contain numerous indicators of occasional subaerial exposure. Rill marks and polygonal mudcracks are particularly common. Rill marks (small-scale, millimeters to centimetres in width, channels or rivulets) commonly occur in intertidal, reflecting 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 lithofacies F and are also good indicators of subaerial exposure. Laterally restricted, erosive-based sand lenses (lithofacies H) characterized by trough cross-stratification and current ripple-laminae are interpreted as minor tidal creeks. Scouring out of rill marks and minor tidal creeks was likely initiated by runoff from tidal pools or depressions during lower tidal levels (Klein, 1977; Wells *et al.*,

Figure 10a. Photomicrograph of intertidal/lagoonal mottled sandstone (lithofacies F), parasequence L11, Beattie Ledge. Thin-section and polished-section analysis reveals extensive biogenic reworking by a stressed 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*, *Planolites*, *Taenidium,* as well as the stopeing structures and probing structures of worms or worm-like organisms. The scale bar at bottom right is 1cm in length. **Figure 10b.** Outcrop photograph showing *Arenicolites*, *Planolites*, *Skolithos* and *Taenidium*, lithofacies E (dolomitic siltstone), parasequence L11, Brown Hill. **Figure 10c.** Photomicrograph of a bioclastic sandstone lense 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 1cm in length. **Figure 10d.** 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 0.5mm in length.


A
B
C
D
Skolithos
5cm
Taenidium
Convolute Bedding
Palaeophycus
Planolites
Fugichnia

1990).

The massive or mottled appearance characteristic of several horizons of lithofacies association III is due primarily to sediment homogenization by extensive small scale burrow reworking (Figure 10a). Difficulties in recognizing flaser and lenticular bedding within much of lithofacies association III is attributed to minimal argillaceous mud within the system. Similar to intertidal deposits at Langebaan Lagoon, South Africa, a recent mixed siliciclastic-carbonate marginal marine depositional system the low argillaceous mud content of lithofacies association III is attributed to a lack of fluvial input (Flemming, 1977).

Although specimens of *Lingula* are common within intertidal deposits, the trace fossil *Lingulichnus* has not been observed. Long (up to 12 cm), narrow (1-4 mm in width), vertical tubes, usually paired, are common in the upper intertidal flat. The tube-pairs are usually surrounded by a sub-circular to kidney-shape halo. These traces, referred to the ichnofossil *Siphonites* sp., are interpreted as the inhalant and exhalant siphons of a burrowing bivalve. Vertically oriented suboval forms with spreite both above and below, connected to the surface by one or a pair of narrow vertical tubes, are interpreted as a variation of *Siphonites* sp., and are interpreted to represent bivalve adjustment traces (Figure 10c).

The intertidal trace fossil assemblage is comprised of a mix of dwelling, feeding, and crawling forms, and is consistent with the *Psilonichnus* assemblage. Similar to 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 a variety of crustaceans, polychaetes, bivalves, and gastropods. The upper intertidal zone in the Liard Formation contains a mix of indigenous infauna and storm-transported, opportunistic colonizers.

Previous studies have suggested that the Liard Formation was deposited on a storm-dominated, prograding barrier island shoreline (Zonneveld *et al.*, in press). Thin (2-15 centimetre thick) normally graded sand layers, many with abundant bioclasts, are intercalated with the planar laminated to heterolithic wavy laminated dolomitic siltstone and mudstone of lithofacies E and F (Figures 10d). Many of the vertically oriented trace fossils such as *Arenicolites* sp., *Cylindrichnus concentricus*, *Laevicyclus* sp., *Rhizocorallium jenense* and *Skolithos linearis* preferentially emanate from the rippled upper surface of these layers (Figures 9c, 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.

Lithofacies Association IV: Supratidal Sabkha

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

Lithofacies I consists of wavy to ripple-laminated dolomitic siltstone and mudstone (Figure 11a). Ripple types within this unit include straight-crested, bifurcating oscillation ripples and adhesion ripples. Body fossils were not observed within lithofacies association I. A low-diversity trace fossil assemblage, consisting of *Cylindrichnus, Monocraterion* and rare diminutive *Ophiomorpha* occurs within the various lithofacies I.

Lithofacies G (Figure 11b) consists of a breccia comprised of clasts characteristic of other lithofacies and thus is not a true 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 centimetres in length, within a calcareous mud matrix. Although primarily oriented subparallel to bedding, many occur at oblique angles. Syn-depositional or early post-depositional cementation is implied by the size, angularity and final orientation of these clasts. Early cementation is common in numerous Recent marginal marine carbonate and mixed clastic-carbonate environments (Butler *et al.*, 1982; Semeniuk and Johnson, 1985; Shinn, 1983;Warren, 1989).

Root traces and pedogenic slickensides in association with sharply contrasting color horizons indicate pedogenic alteration of calcareous and dolomitic clayey siltstone within lithofacies association IV. Pedogenic slickensides commonly occur in soils subjected to frequent wetting and drying, which cause the soil to shrink and swell (Retallack, 1988).

Lithofacies association IV is interpreted to represent the deposits of a series of shore proximal sabkhas. 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.*, 1977; von der Borch and Lock, 1979). Evaporite deposition predominates in supratidal settings (Warren, 1989). The frequent oscillation between thin cyanobacterial laminites, dolomitic mudstone beds with polygonal dessication cracks, ripple-laminated dolomitic siltstone, solution collapse breccia beds, and pedogenically altered dolomitic and calcareous mudstone, siltstone and sandstone beds reflects an environment prone to frequent cycles of desiccation and inundation. These sabkhas were recharged by continental ground water as well as periodic influx of marine water resulted from storm surges and spring tides. The paucity and diminutive nature of trace fossils within these features 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 presence of burrowing organisms.

Dolomite is particularly common within sabkha/salina deposits proximal to the shoreline within the Liard Formation. Although it is difficult to prove that dolomitization occurred prior to lithification, several factors support a pennecontemporaneous or near penecontemporaneous origin for these dolomitic units. First, detailed structure in 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 syn-depositional or early post-depositional dolomitization.

Lithofacies Association V: Aeolian Dune

Lithofacies association V consists of a single lithofacies (J). Lithofacies J consists of well-sorted, fine-grained sandstone, exhibiting well-defined lamination within large-scale, largely planar cross-bedding. Rare oscillation rippled bedding planes were observed. Laminae are thin (2-4mm), inversely graded, closely packed and parallel. Individual laminasets steepen upwards within beds, and are generally concave upward. Bedsets are tabular to wedge-planar and vary in thickness from 10.0 to 45 centimetres in thickness. Lower bounding surfaces are coplanar with internal bedding. Neither trace fossils nor body fossils were observed in lithofacies I. Within the study interval, lithofacies J occurs interbedded with thin pedogenically altered calcareous and dolomitic mudstone beds (lithofacies G and I).

Lithofacies association V is interpreted as aeolian sand dunes or sand sheets deposited 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).

Aeolian deposits have previously been reported from the Upper Triassic Charlie Lake Formation at Brown Hill (Arnold, 1994; Gibson and Edwards, 1990). 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).

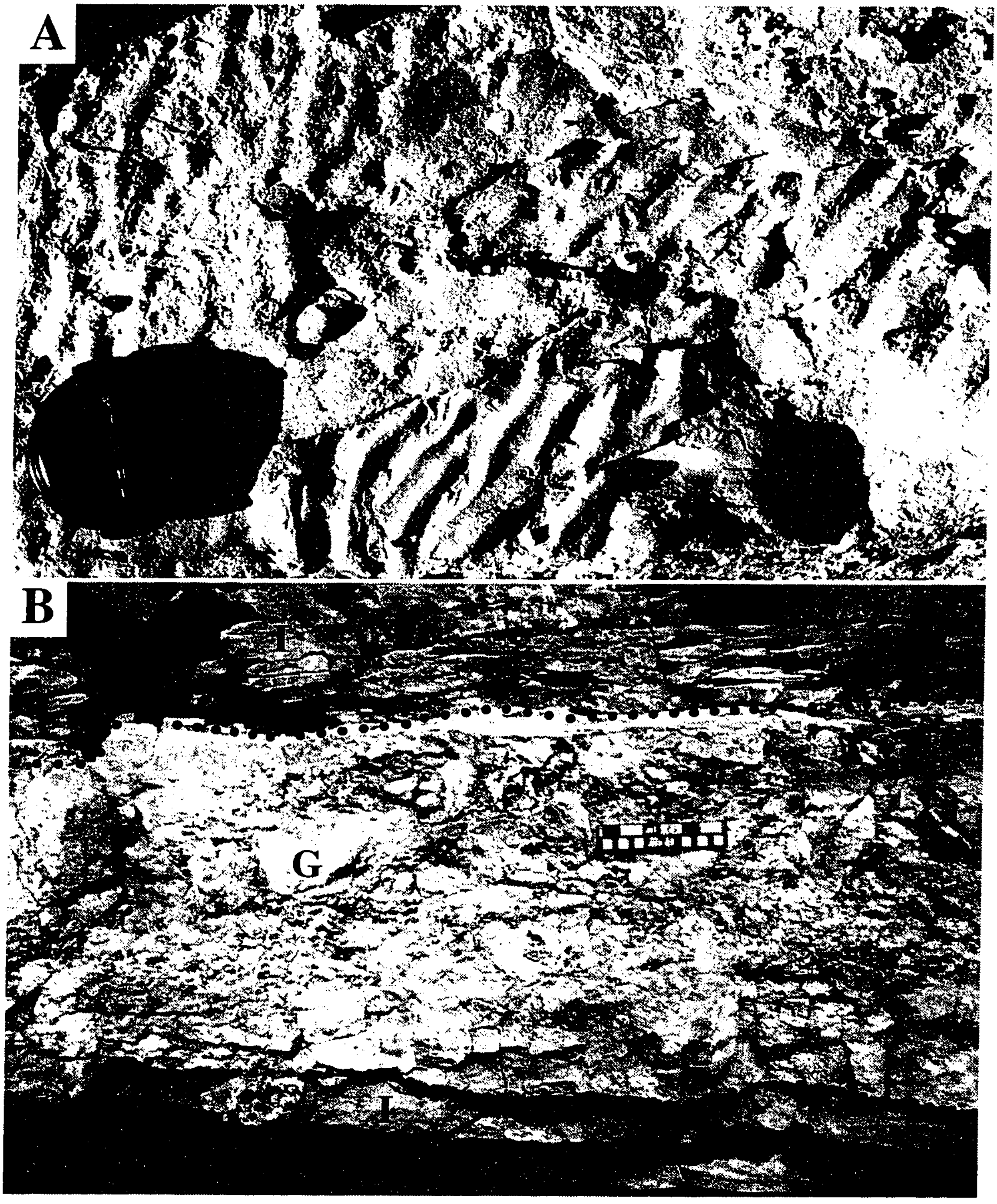


Figure 11a. Outcrop photograph of rippled surface (relatively straight-crested oscillation ripples) of a calcareous sandstone (lithofacies I) interpreted as marginal sabkha, parasequence L11, Beattie Ledge. Camera lense cap is 4.5cm wide. **Figure 11b.** Outcrop photograph of solution collapse breccia (lithofacies G) interbedded with ripple-laminated calcareous sandstone (lithofacies I), parasequence L11, Beattie Ledge.

Discussion

Environmental constraints on Liard ichnofossil assemblages

The Liard shoreface was deposited on a storm-dominated, prograding barrier island shoreline (Zonneveld *et al.*, 1997). The co-occurence of extensive intertidal flats, as well as a protective barrier ridge, is consistent with deposition along a mesotidal coastline. The effects of storms were particularly significant in 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 lithofacies associations II (washover fan/lagoonal), III (intertidal flats), and IV (supratidal sabkha) reflect washover deposition during storm surges. Bioclasts within these units are comprised primarily of fully marine forms (echinoderms and articulate brachiopods). A trace fossil assemblage dominated by vertically oriented 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.

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 (Aberhan and Fürisch, 1991; Flessa and Ekdale, 1987; Fürisch *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 successions (lithofacies association IV), 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 flushed by daily tidal cycles. Invertebrate faunas in hypersaline settings (salinity in excess of 45‰) are usually characterized by extremely low specific diversity. Low ichnotaxonomic diversity as well as a primarily diminutive forms within lithofacies IV (coastal sabkha; Table 2) is a reflection of elevated salinity levels.

High ichnotaxonomic diversity within back barrier subtidal and intertidal intervals (lithofacies associations II and III; Table 2) within the study area suggests probable 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 (~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 contains predominantly horizontal forms (Walker and Laporte, 1970; Fürisch, 1975), others have shown that trace orientation is independant of bathymetry (Frey, 1970; Ireland *et al.*, 1978; Narbonne, 1984). The Liard intertidal contains a variety of both vertical and horizontal forms (Table 2), and contains 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 tracemakers to shift from predominantly vertical, suspension-feeding lifestyles to predominantly horizontal, deposit-feeding lifestyle. If sedimentation rates are too high, the anoxic 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 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.

Dolomite in Liard Marginal Marine Sediments

Dolomitization within Liard lagoonal/intertidal and coastal sabkha settings is believed to have occurred in a manner similar to dolomitization in Holocene and recent sediments within shore proximal 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 cycle, 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. These shallow lakes 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 rejuvenation is 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 by the presence of thick solution collapse breccias within the Liard sabkha successions.

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; Belpario *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 accumlation may outpace siliciclastic deposition.

The Liard shoreface is characterized by a unique mixture of siliciclastic and bioclastic sedimentation (Figure 6). Input of siliciclastic sand to the shoreface was likely derived from three distinct sources: 1) Aeolian input from landward; 2) fluvial input, and 3) longshore drift, likely from the north. Carbonate sediments in the Liard marginal marine succession are predominantly biogenic in origin and are derived from two distinct sources: 1) intertidal and subtidal production from bivalves, gastropods, and brachiopods, and 2) shoreward transport of subtidally produced brachiopod, bivalve, echinoid and crinoid skeletal debris during storms.

The 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). The abundance of quartzose, fine-grained, hummocky cross-stratified sand in lower shoreface settings (Zonneveld *et al.*, in press), 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, are suggestive of periodic fluvial input to the shoreface. 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 within the Middle Triassic of western Canada, this may simply 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. Subtidal seagrass meadows within Spencer Gulf, Australia are a major source of skeletal carbonate material, acting as 'carbonate factories', trapping sediment and provide a comparably protected environment in which a wide variety of organisms can live (Belpario *et al.*, 1988; Fuller *et al.*, 1994). The roots and rhizomes of seagrass meadows also affect sediment accumulation by binding and stabilizing the sediments (Belpario *et al.*, 1988). Shoreward transport of bioclastic carbonate is a significant source of intertidal sediments along the coast of southern Australia (Belpario *et al.*, 1988; Fuller *et al.*, 1994). While sea grasses are unknown from the Mesozoic, Sea weed (green and brown algae) have proliferated throughout the Phanerozoic, and charophytes have persisted since the Silurian (Burne *et al.*, 1988).

Although roots and rhizomes are limited to plants with vascular systems, sea weed may act as a baffle, dissipating wave energy. Furthermore, their hold-fasts may also bind sediment to a degree.

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, reef mounds (or bioherms) comprised predominantly of terebratulid brachiopods, and cidaroid echinoids, but also containing abundant bivalves, crinoids, and possibly bryozoans (Zonneveld *et al.*, 1997). The Liard reef mounds 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.

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 Dörges, 1988). During storms, this trend is reversed; mollusc shells were removed from the beach and redeposited further basinward (Frey and Dörges, 1988; Frey and Pinet, 1978). Under fair weather conditions, settings prone to higher current velocities (*i.e.* beach protrusions) were characterized by lower shell-accumulation rates than more protected settings (Dörges et al., 1986; Frey and Dörges, 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 centre of the concavity. Shells and coarse sand accumulate in the zone of convergence, and are concentrated by aeolian deflation of fine-grained sediment.

These authors concentrated upon whole valves. Other than noting that unidentifiable fragments were relatively rare compared to whole valves, the hydraulic behavior of abraded sand to gravel sized bioclastic sediment was not discussed (Frey and Dörges, 1988; Frey and Pinet, 1978). Upper shoreface sediment within the study interval is dominated by highly abraded bioclastic fragments, however similar mechanisms likely occured in the Liard shoreface.

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 remarkably different, quartz sand grains within the Liard Formation are dominantly spherical wheras 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. Regardless, bioclastic enrichment of the foreshore is interpreted to be primarily a function of grain size rather than sediment composition.

Carbonate silt and very fine-grained sand is rare within the Liard shoreface. This phenomenon has been noted in other mixed siliciclastic-carbonate depositional systems (Furisch *et al.*, 1991) and is attributed to the inherent stalbility (*i.e* short shelf life) of very fine-grained or smaller carbonate sediment. 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, while coarser grain sizes move onshore. This situation may occasionally have been reversed as storm-generated geostrophic flows transported the coarse fraction basinward.

Sequence Stratigraphy

The Liard Formation within the study interval at Williston Lake is comprised of two sequences (Zonneveld *et al.*, 1997). The study interval spans the top of the sequence LA highstand systems tract as well as the sequence LB lowstand and transgressive systems tracts (Figure 12). This study deals primarily with lithofacies deposited in a marginal marine setting. Parasequence boundaries are generally more difficult to identify within marginal and nonmarine units than in adjacent marine deposits. Marginal marine parasequences are bound by marine flooding surfaces, and by their landward equivalents, referred to here as correlative flooding surfaces. As in their marine counterparts, correlative flooding surfaces are characterized by abrupt changes in depositional regime and a landward shift in sedimentary facies.

The LA /LB sequence boundary is preserved as an erosional unconformity at Brown Hill (Figure 8a) and as a *Glossifungites* surface at Beattie Ledge (Figure 13a). The erosional unconformity at Brown Hill consists of fenestral laminated dolomite (lithofacies D2) unconformably overlain by transgressive shoreface sandstones (lithofacies B2). The *Glossifungites* ichnofacies includes trace fossils which penetrate firm, unlithified substrates, specifically those which have been subaerially exposed or buried and subsequently re-exhumed (Pemberton and MacEachern, 1995). Although *Glossifungites* surfaces may feature a variety of ichnotaxa, the Beattie Ledge surface is characterized by a monotypic assemblage of sharp-walled, unlined *Thalassinoides* (Figure 13a). 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 (Figure 13).

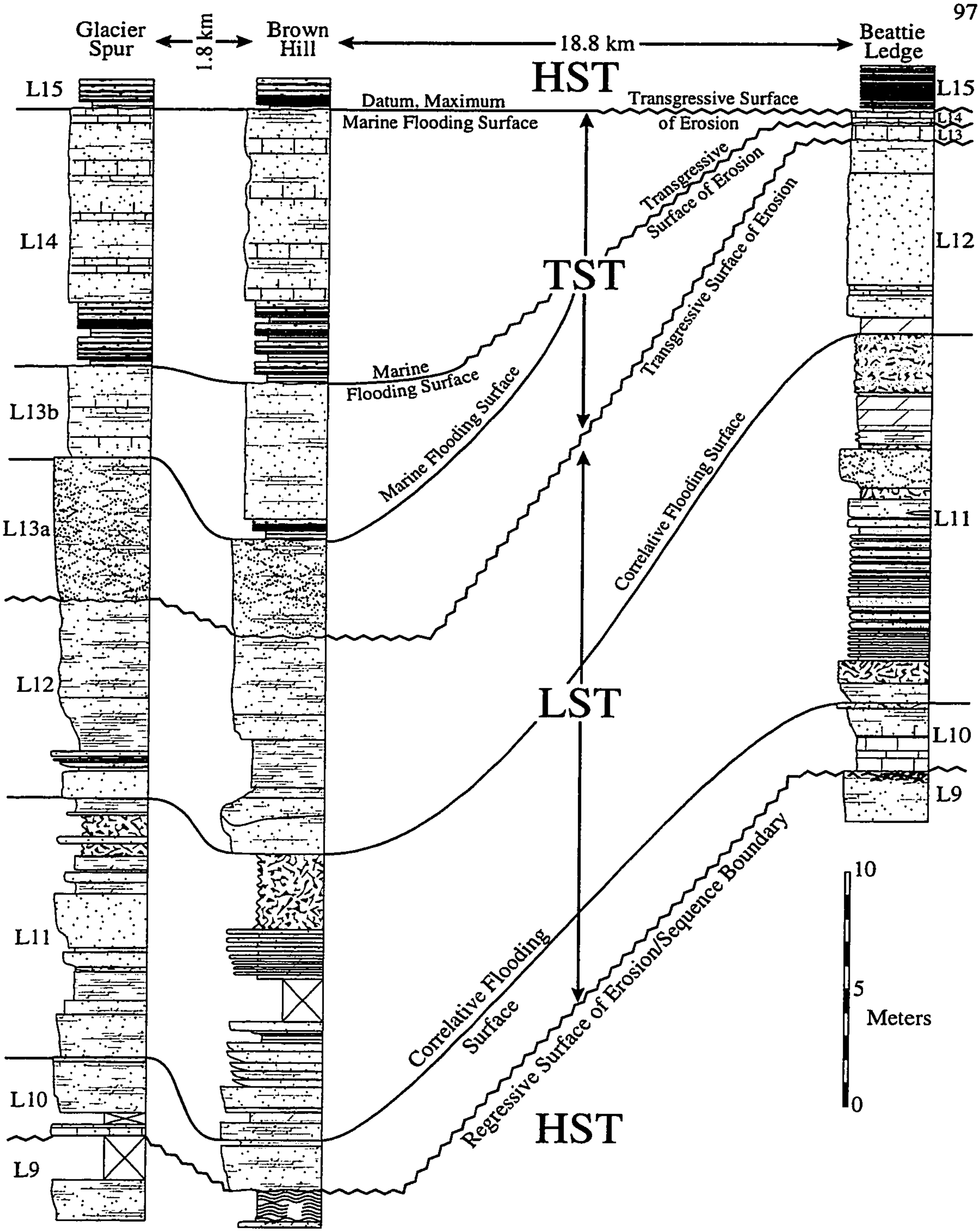


Figure 12. Genetic stratigraphic correlation of the three intertidal sections logged in this study. The designators L9 through L15 follow the nomenclature of Zonneveld et al. (1997) and refer to individual parasequences. HST= Highstand Systems Tract; TST= Transgressive Systems Tract; LST, Lowstand Systems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

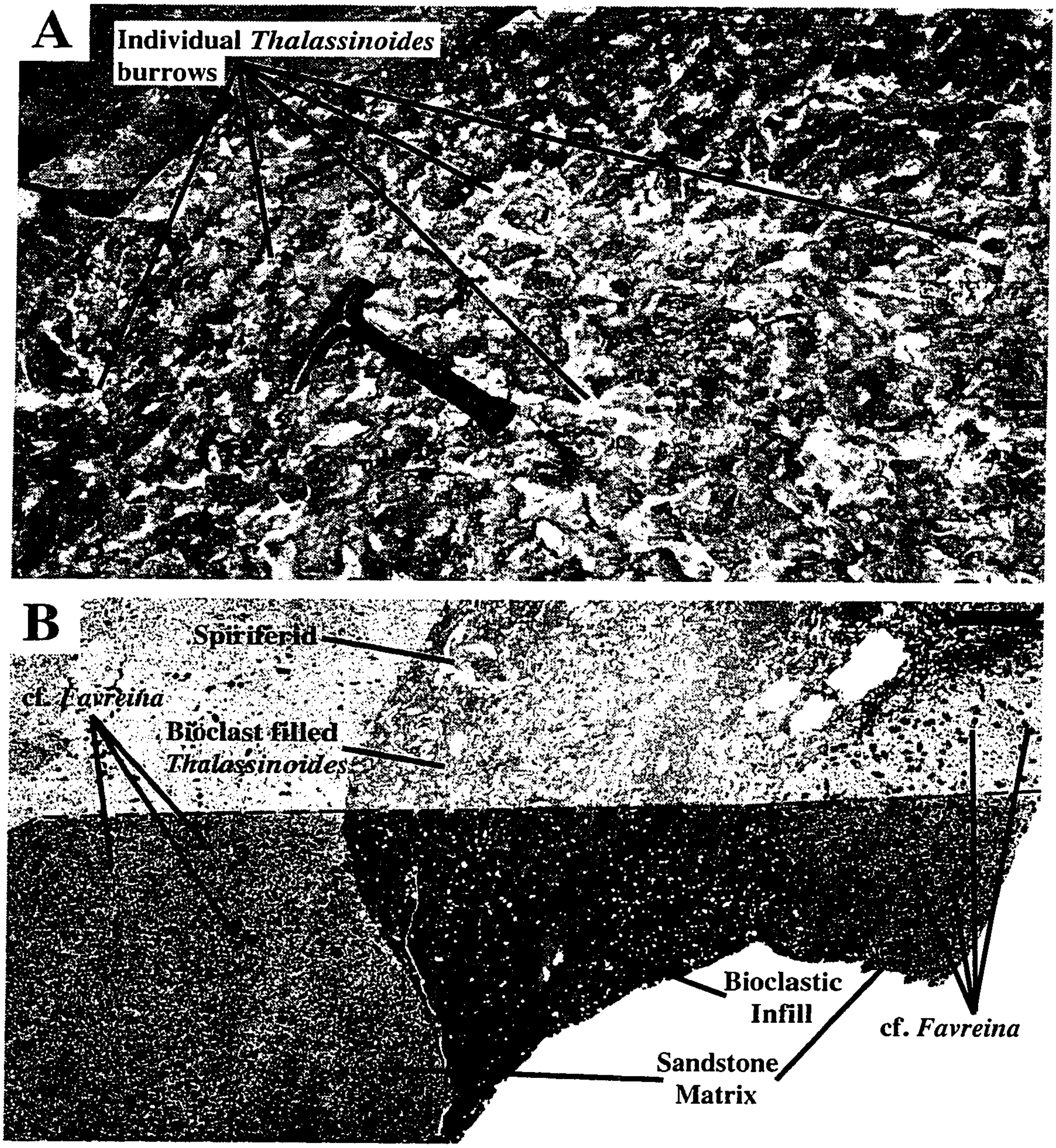


Figure 13a. Outcrop photograph of the *Glossifungites* surface demarcating the LA/LB sequence boundary at Beattie Ledge (top of parasequence L9). The rock hammer at centre is 32 cm in length. **Figure 13b.** Photomicrograph showing a cross-sectional view through an individual *Thalassinoides* burrow within the Beattie Ledge *Glossifungites* surface. The burrow infill consists of a bioclastic hash containing echinoid, crinoid and spirifirid brachiopod debris. The matrix is comprised of very fine-grained sandstone. Tiny dark spots within both the burrow infill and the surrounding matrix are faecal pellets, tentatively assigned to the genus *Favreina*. The scale bar in the top right corner is 5 mm in length.

Parasequences L10, L11, and L12 are interpreted as the sequence LB lowstand systems tract and represent a dramatic basinward shift in facies. These parasequences constitute a thick (25-30 m) aggradational to slightly progradational 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. Similar to bioclastic sandstones at the base of the Brown Hill and Glacier Spur sections, these units are matrix supported, normally graded and comprised of a brachiopod-echinoderm-bivalve shell hash. These units are interpreted as transgressive shoreface deposits and signify a return to marine deposition within the study area. Parasequences L13a, L13b and L14 comprise a retrogradational package and are interpreted as the sequence LB transgressive systems tract.

Parasequence L14 is capped by a maximum marine flooding surface, signifying transition to highstand conditions. At the three localities discussed here, this surfaceseparates underlying brachiopod-dominated, bioclastic sandstones (interpreted as transgressive shoreface) from overlying laminated black shale and siltstone (interpreted as proximal offshore to offshore transition). The transgressive shoreface bioclastic sandstones comprising the transgressive systems tract at the top of the Beattie Ledge section (Figure 14) are characterized by a monotypic assemblage of robust, thick-walled *Ophiomorpha annulata* (Figure 7). The tops of these burrows have been removed, indicating that erosion was associated with the transgression, and the transition from transgressive systems tract to highstand systems tract.

Conclusions

Sedimentary facies within the upper Liard Formation at Williston Lake comprise five distinct facies associations. Lithofacies association I consists of a coarsening upwards, mixed siliciclastic-carbonate shoreface to foreshore succession characterized by a low diversity *Skolithos* assemblage. Physical sedimentary structures within lithofacies association II, interpreted as washover fan/lagoonal are consistent with deposition in a less energetic setting than the underlying units.

Lithfacies association III (intertidal flats) is characterized by a diverse array of dwelling, feeding, and crawling traces attributable to a variety of crustaceans, polychaetes, bivalves, and gastropods. The upper intertidal zone in the Liard Formation contains 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 availabilty and may be useful indicators of sedimentation rate. Bioclastic sandsstone beds, interpreted as intertidally emplaced storm washover deposits, contain a robust assemblage of post-event opportunistic colonizers imported from seaward in conjunction with storm-transported sediments.

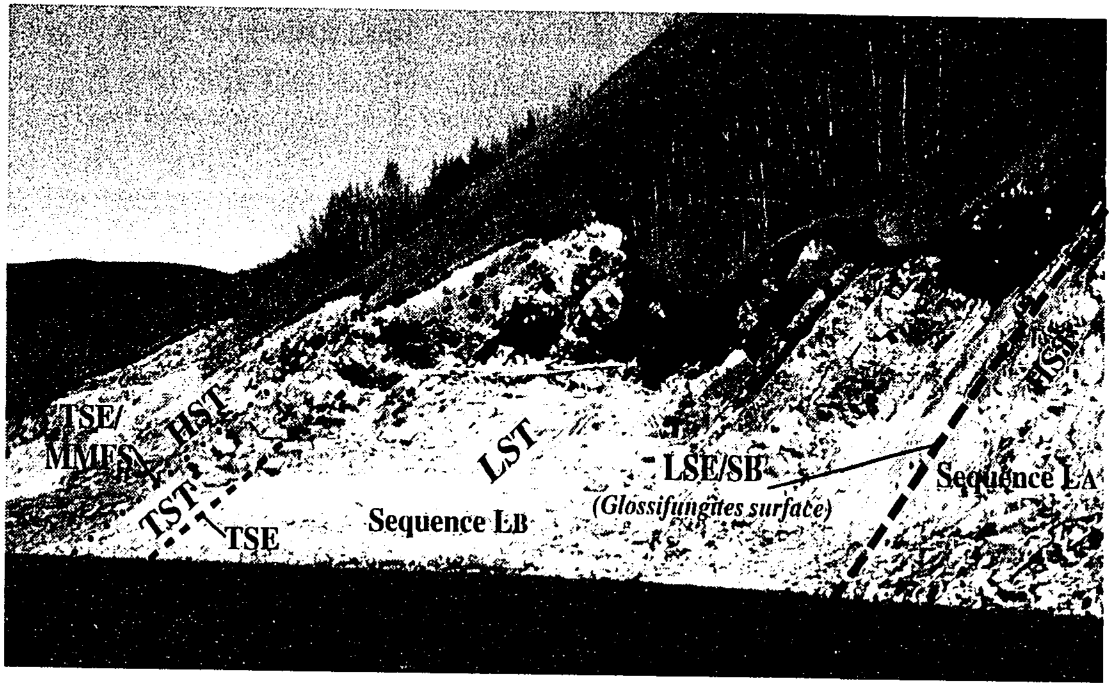


Figure 14. Outcrop photograph of the study interval at Beattie Ledge. Sediments to the right (southeast) of the lowstand surface of erosion/ sequence boundary (LSE/SB) consist of shoreface sandstone and comprise the top units of the sequence LA highstand systems tract (HST). This sequence boundary occurs as a *Glossifungites* surface at Beattie Ledge (Figure 13). Sediments to the left of the lowstand surface of erosion/ sequence boundary (LSE/SB) consist of the Beattie Ledge marginal marine succession and comprise the sequence LB lowstand systems tract (LST). The thin sequence LB transgressive systems tract (TST) overlies the initial transgressive surface of erosion (TSE). The sequence LB highstand systems tract (HST) is initiaited by the transgressive surface of erosion/maximum marine flooding surface (TSE/MMFS) and is characterized by offshore transition shale, siltstone and sandstone.

Coastal sabkha/salina deposits (lithofacies association IV) are characterized by dolomitic siltstone/mudstone and solution collapse breccias (lithofacies G) composed of silty dolomitic and calcareous mudstone and algal-laminated wackestone. The latter lithofacies is formed by the dissolution of evaporite layers (gypsum and anhydrite) and provides evidence of periodic cycles of desiccation and subsequent rejuvenation. 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.

Deltaic deposits have not yet been reported within the Middle Triassic of northern British Columbia, likely due, at least in part, to difficulties inherent in recognizing deltaic deposits associated with ephemeral rivers in arid environments. Siliciclastic sediment within the study area was likely derived from aeolian transport and longshore currents from depocentres outside the study area. Nonsiliciclastic sediments within the study interval were derived primarily from marine biogenic sources and are dominated by bioclastic sand and silt. Controls governing and promoting mixed siliciclastic-carbonate deposition within 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

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CHAPTER 4.

LITHOFACIES ASSOCIATIONS AND DEPOSITIONAL FRAMEWORK OF THE GRAYLING, TOAD AND LIARD FORMATIONS (LOWER TO MIDDLE TRIASSIC), WILLISTON LAKE, NORTHEASTERN BRITISH COLUMBIA

"Eventually all things merge into one, and a river runs through it. The river was cut by the world's great flood and runs over rocks from the basement of time. On some of the rocks are timeless raindrops. Under the rocks are the words, and some of the words are theirs. I am haunted by waters."

Norman F. Maclean, 1976

INTRODUCTION

The Grayling, Toad and Liard Formations of northeastern British Columbia provide one of the most complete records of deposition on the western margin of the Pangean supercontinent during the Lower to Middle Triassic. Previous work documented several vertically extensive and well-exposed Triassic outcrops along the margins of the Peace River and subsequently, after construction of the W.A.C Bennett dam in 1967, along Williston Lake (MacLearn, 1941a & b; Gibson and Edwards, 1990; Pelletier, 1964). These early investigations concentrated primarily on regional lithostratigraphic mapping, paleontology and ammonoid biostratigraphy.

This chapter constitutes the third contribution of a continuing regional study assessing the depositional and sequence biostratigraphic framework of the Grayling, Toad and Liard Formations (Table 1) within the Williston Lake area, northeastern British Columbia (Figure 1). Previous papers concentrated on lithofacies associations and depositional environments of the upper Liard Formation at Glacier Spur and Brown Hill (Zonneveld *et al.*, 1997b), and discussed depositional controls and trace fossil assemblages of arid marginal marine successions in the Liard Formation (Zonneveld and Gingras, *in press*).

This chapter, based on research by the author during late May and early June of 1995 through 1998, presents a detailed description and interpretation of marine and marginal marine strata deposited within an arid, mixed siliciclastic-carbonate depositional system. It expands, both regionally and stratigraphically, upon ideas introduced in previous contributions (Zonneveld *et al.*, 1997; Zonneveld and Gingras, in press; chapters 2 and 3), and introduces new concepts to explain the unique amalgamation of siliciclastic, carbonate and evaporitic sediments that comprise the Grayling-Toad-Liard interval in the Williston Lake Region. Lithofacies associations discussed in this paper provide the building blocks for the sequence biostratigraphic analysis discussed in chapter 5.

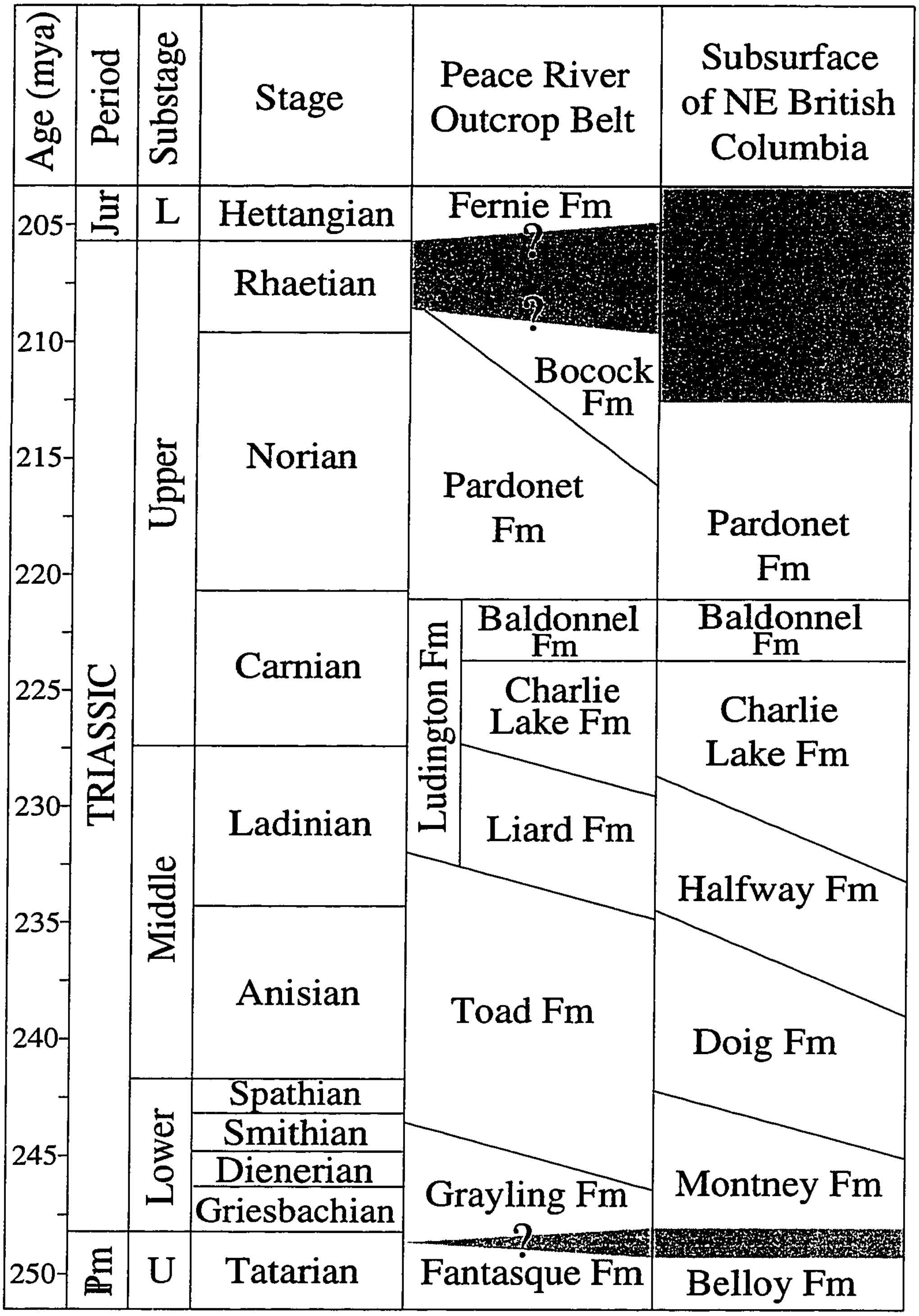


Table 1. Triassic stratigraphic nomenclature, subsurface and outcrop, northeastern British Columbia (adapted from Gradstein et al., 1994; Tozer, 1994). Contacts between Lower and Middle Triassic formations are drawn to reflect their diachronous nature.

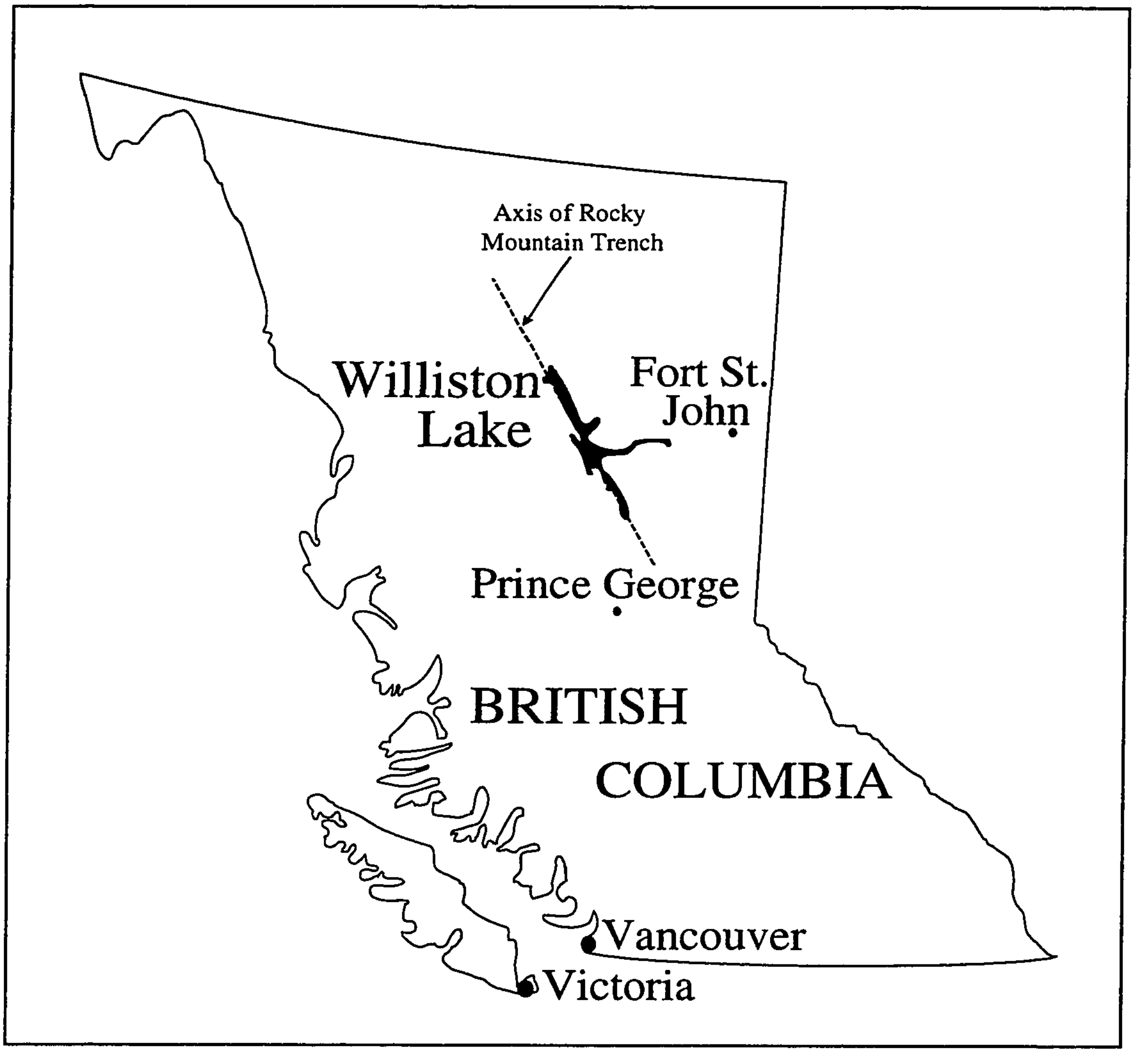


Figure 1. Map showing location of Williston Lake in northeastern British Columbia, Canada.

STUDY AREA

Williston Lake is located approximately 80km west of Fort St. John, British Columbia (Figure 1), along the upper Peace River, and expanding into the Rocky Mountain Trench. This study concentrates upon lower and middle Triassic exposures at five localities along the Peace Reach of Williston Lake (Figure 2). Detailed sections were measured at Ursula Creek, Brown Hill, Glacier Spur, Beattie Ledge, and Aylard Creek to describe sedimentary facies and to assess vertical and lateral lithofacies variability (Figures 3 through 7) . These five outcrop sections comprise a 35-40km dip-oriented succession along the northern margin of the late Paleozoic/early Mesozoic Peace River embayment. The Grayling, Toad and Liard Formations (Table 1) at these sites preserve a continuum of deep basinal through marginal marine and continental strata deposited within a mixed siliciclastic-carbonate depositional system on the western margin of Pangea (Figure 8).

REGIONAL GEOLOGY AND STRATIGRAPHIC SETTING

Triassic strata in the Western Canada Sedimentary Basin comprise a westward thickening succession of marine and marginal marine siliciclastics, carbonates and minor evaporites deposited on the western margin of the North American craton (Gibson and Barclay, 1989). As observed in this study, Lower and Middle Triassic outcrop within the Peace River foothills region consist of an overall shallowing upward succession of mixed siliciclastic-carbonate offshore to shoreface and marginal marine parasequences.

Although they are lithostratigraphic units, the Grayling, Toad and Liard Formations comprise distinct environmental components of a single depositional system. Lithologic differences between these units reflect an environmental gradation from black shales deposited within a deep-marine setting (Grayling Formation) through interbedded shale, siltstone and very fine-grained sandstone deposited in a shelf/slope setting (Toad Formation), to a heterolithic package of shale, siltstone, sandstone, bioclastic rudstone/grainstone, dolomitic mudstone/wackestone and fenestral-laminated limestone deposited within a shoreface to marginal marine setting (Liard Formation). The Charlie Lake Formation comprises the marginal to nonmarine end-member in this succession. Exposure of this unit within the study area was described in detail by Arnold (1994) and is not discussed here.

Grayling Formation

The Grayling Formation comprises a variably thick sequence of dolomitic siltstones and shales, fine-grained sandstones, silty micrites and silty dolomicrites (Kindle, 1944; Gordey *et al.*, 1991), outcropping in a thin belt extending along the Rocky Mountain Front from the British Columbia-Alberta border to the British Columbia-Yukon Border. The Grayling is the temporal equivalent of the Toad Formation in eastern outcrop exposures, the lower Montney in the subsurface to the east, and the Phroso Siltstone Member of the Sulphur Mountain Formation in the outcrop belt along the Rocky Mountain Front of southwestern

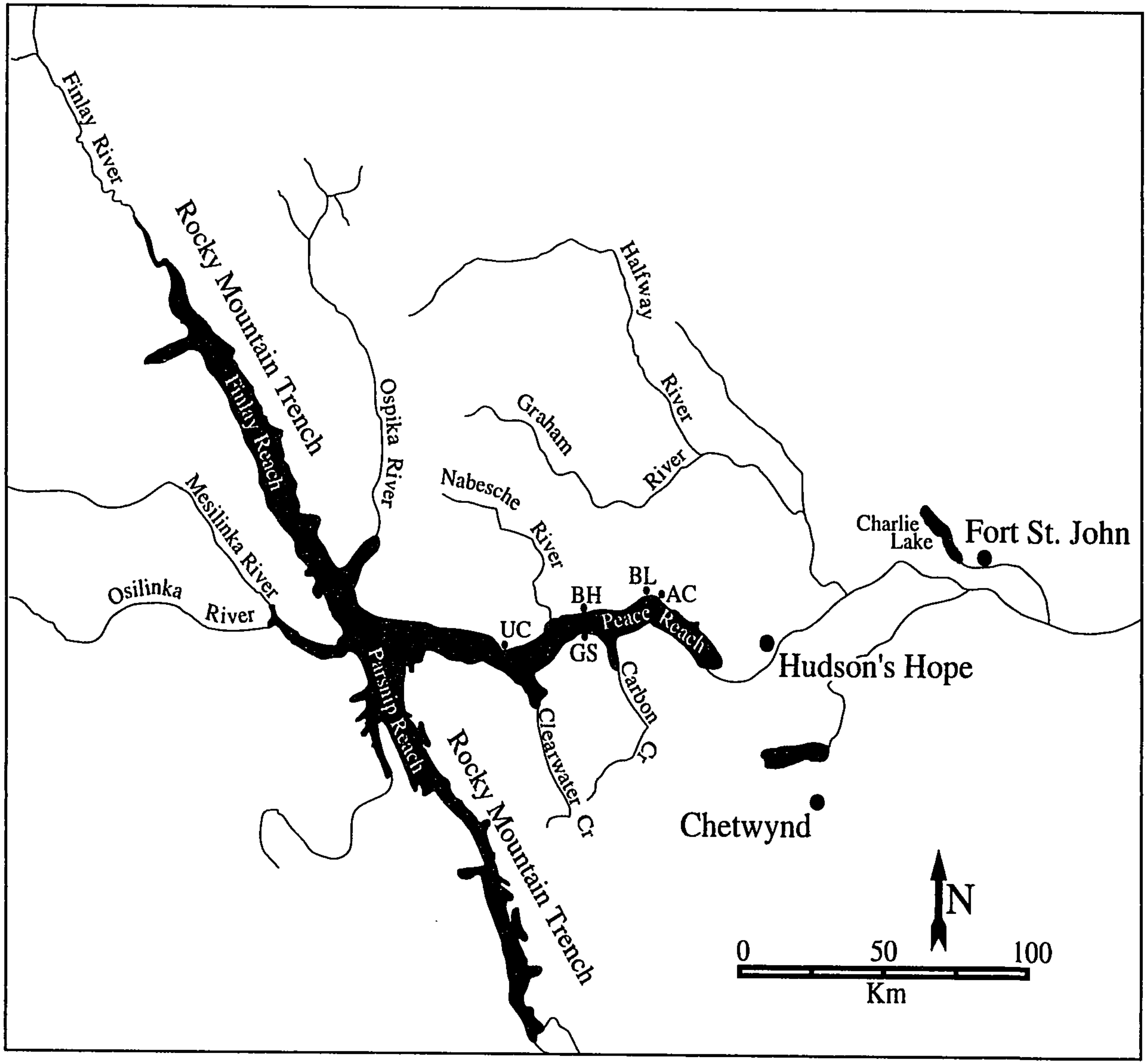


Figure 2. Location map of the study area at the headwaters of the Peace River, Williston Lake, northeastern British Columbia. The localities discussed in this report are denoted by the letters UC (Ursula Creek), BH (Brown Hill), GS (Glacier Spur), BL (Beattie Ledge) and AC, (Aylard Creek).

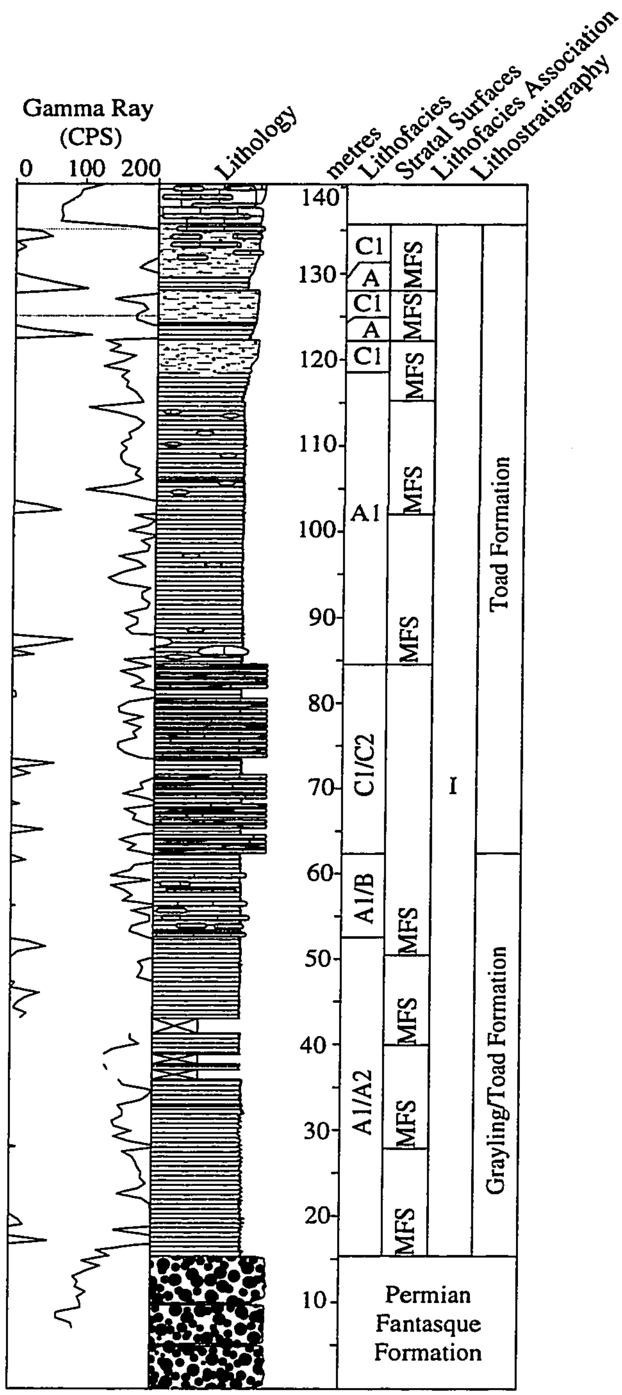


Figure 3. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the upper Grayling and Toad formations at Ursula Creek. Outcrop gamma readings are measured in counts per second (CPS) using a Scintrex BGS-4 scintillometer. Lithofacies designators are summarized in Table 2. Stratal surface acronyms include: FS= flooding surface; MFS= maximum flooding surface; RS= ravinement surface; LSE= lowstand surface of erosion (sequence boundary); TSE= transgressive surface of erosion; CFS= correlative flooding surface. Lithofacies association designators are the same as those used in the text.

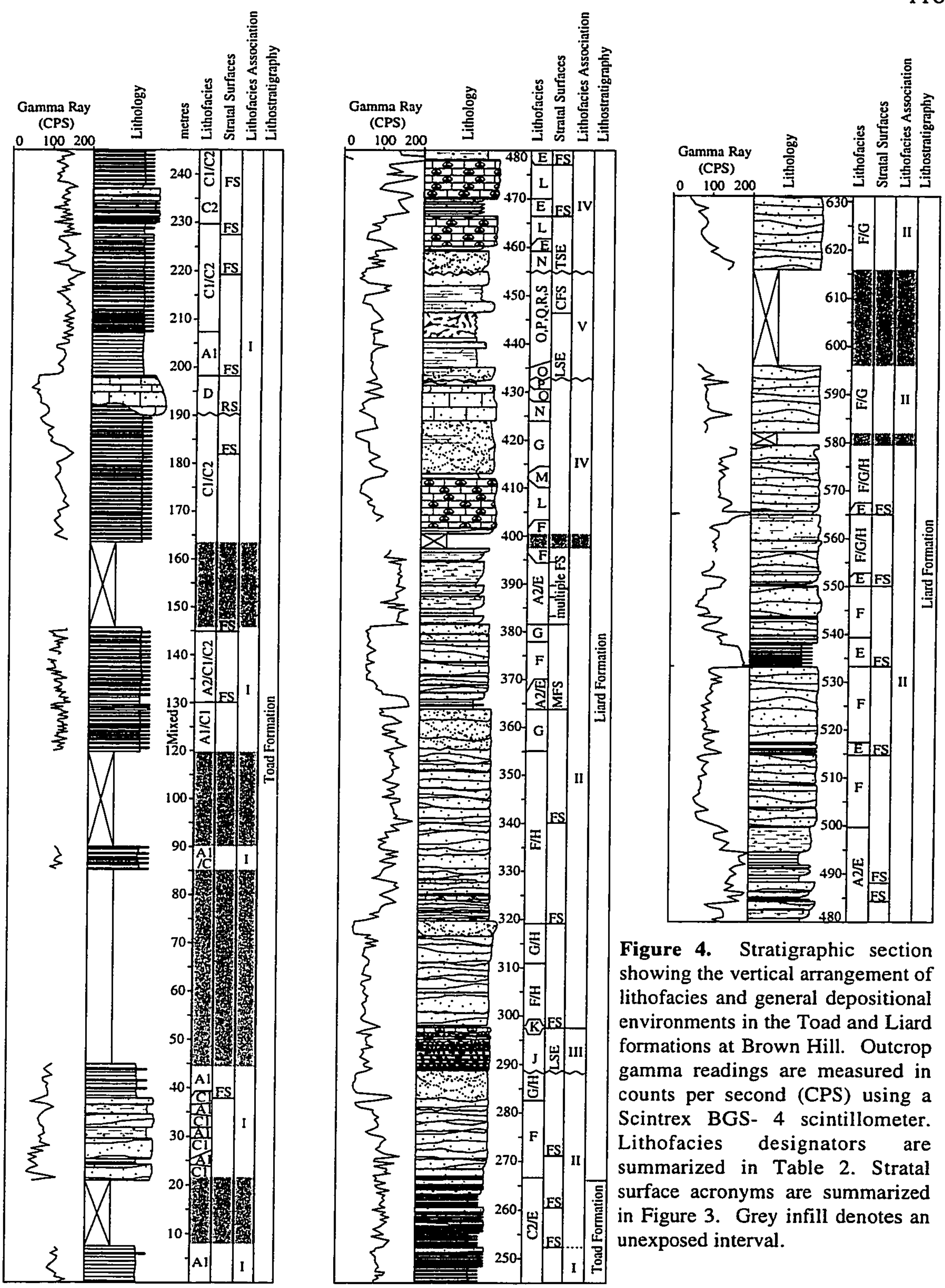


Figure 4. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard formations at Brown Hill. Outcrop gamma readings are measured in counts per second (CPS) using a Scintrex BGS- 4 scintillometer. Lithofacies designators are summarized in Table 2. Stratal surface acronyms are summarized in Figure 3. Grey infill denotes an unexposed interval.

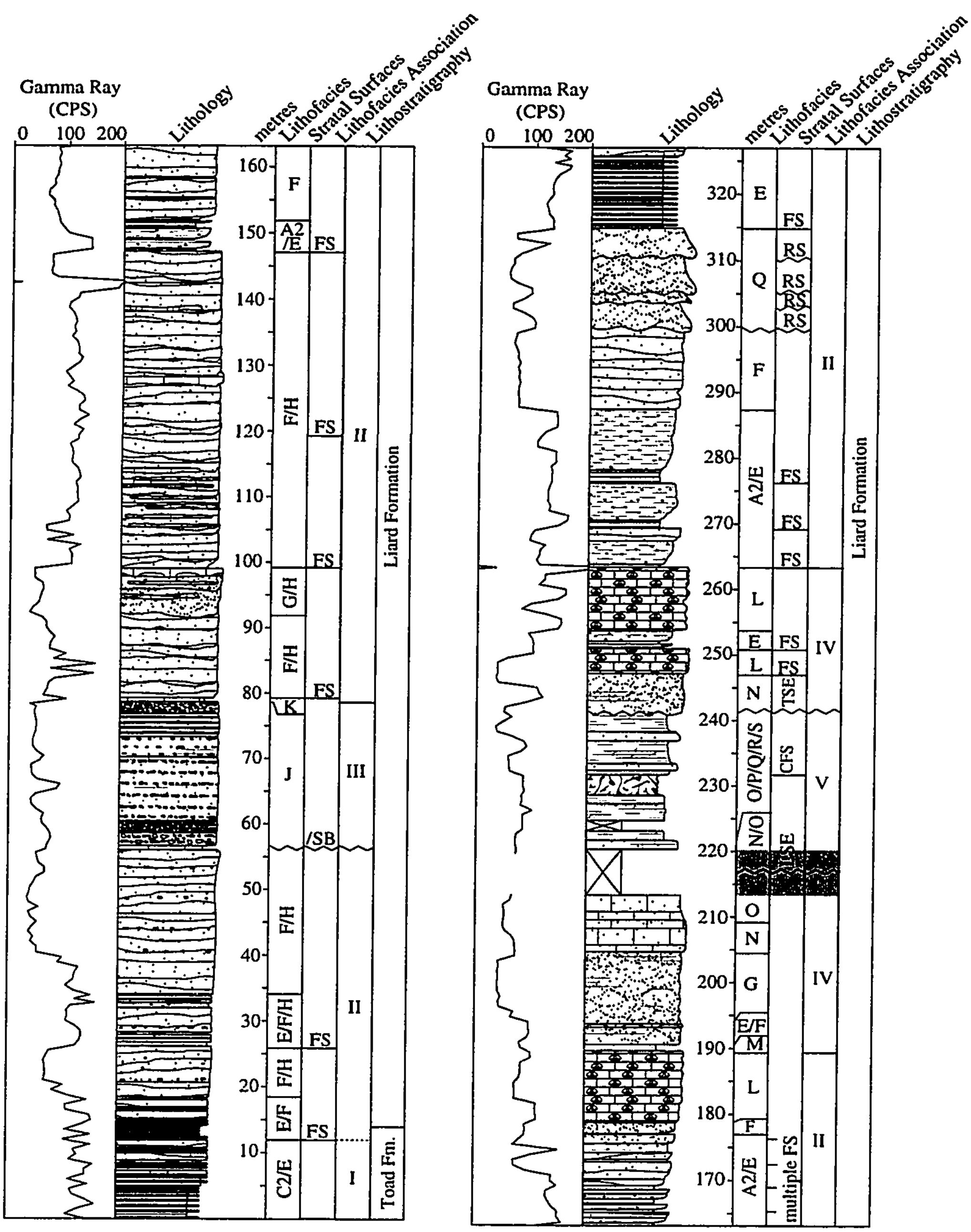


Figure 5. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard formations at Glacier Spur. Outcrop gamma readings are measured in counts per second (CPS) using a Scintrex BGS- 4 scintillometer. Lithofacies designators are summarized in Table 2. Stratal surface acronyms include: FS= flooding surface; MFS= maximum flooding surface; RS= ravinement surface; LSE= lowstand surface of erosion (sequence boundary); TSE= transgressive surface of erosion; CFS= correlative flooding surface. Lithofacies association designators are the same as those used in the text. Grey infill denotes an unexposed interval.

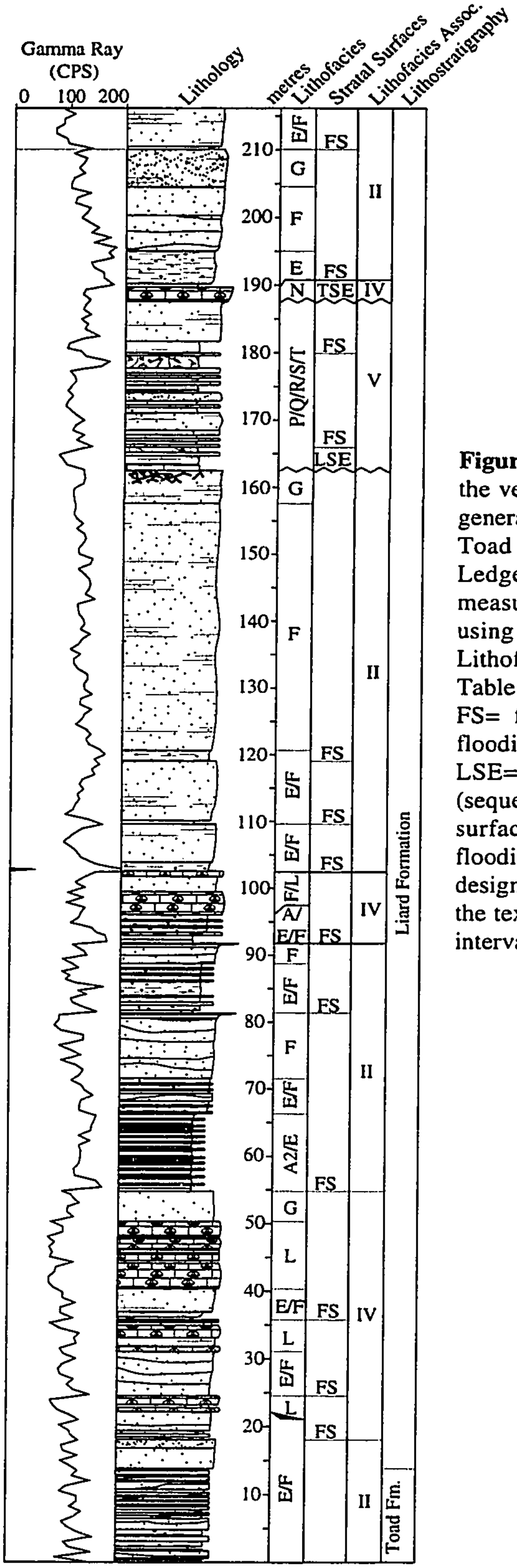


Figure 6. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard formations at Beattie Ledge. Outcrop gamma readings are measured in counts per second (CPS) using a Scintrex BGS- 4 scintillometer. Lithofacies designators are summarized in Table 2. Stratal surface acronyms include: FS= flooding surface; MFS= maximum flooding surface; RS= ravinement surface; LSE= lowstand surface of erosion (sequence boundary); TSE= transgressive surface of erosion; CFS= correlative flooding surface. Lithofacies association designators are the same as those used in the text. Grey infill denotes an unexposed interval.

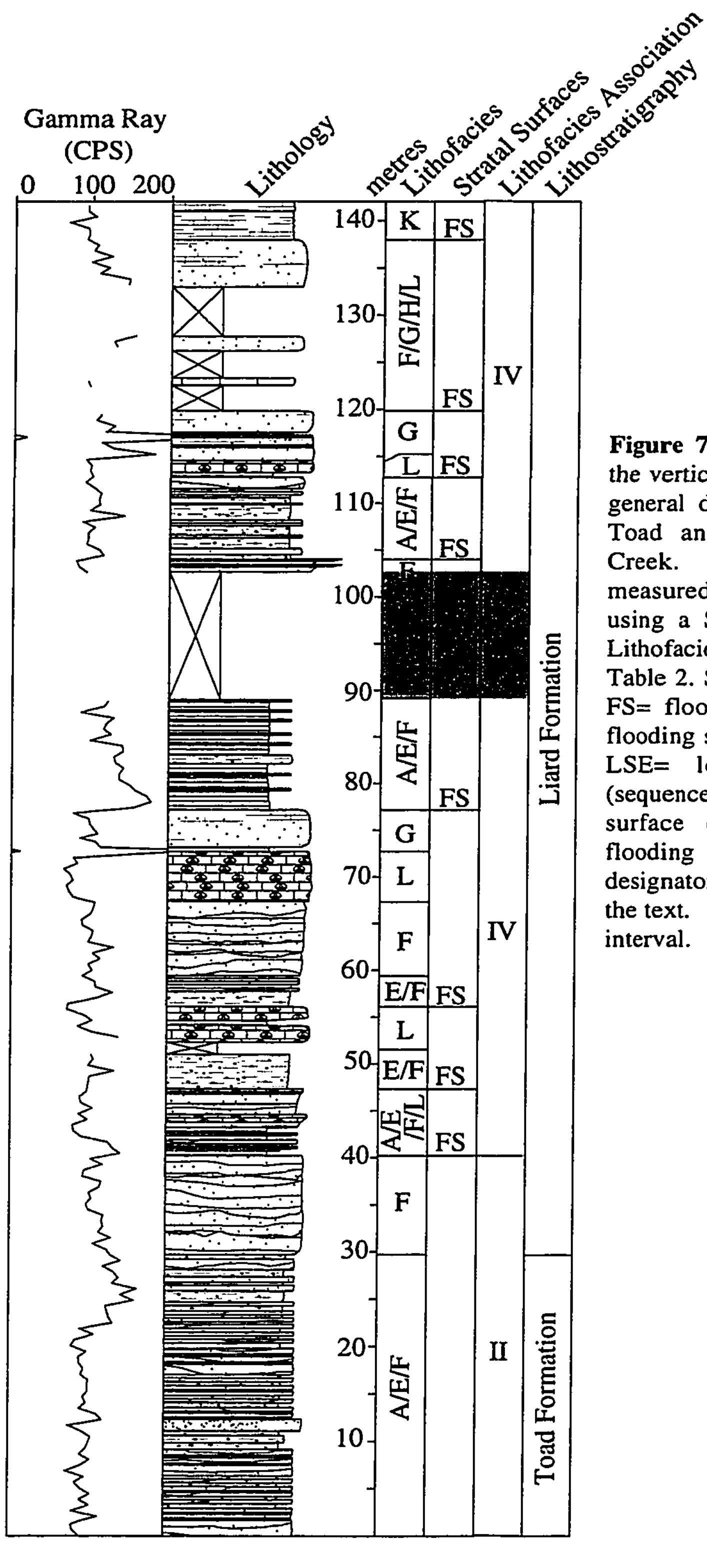


Figure 7. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard formations at Aylard Creek. Outcrop gamma readings are measured in counts per second (CPS) using a Scintrex BGS- 4 scintillometer. Lithofacies designators are summarized in Table 2. Stratal surface acronyms include: FS= flooding surface; MFS= maximum flooding surface; RS= ravinement surface; LSE= lowstand surface of erosion (sequence boundary); TSE= transgressive surface of erosion; CFS= correlative flooding surface. Lithofacies association designators are the same as those used in the text. Grey infill denotes an unexposed interval.

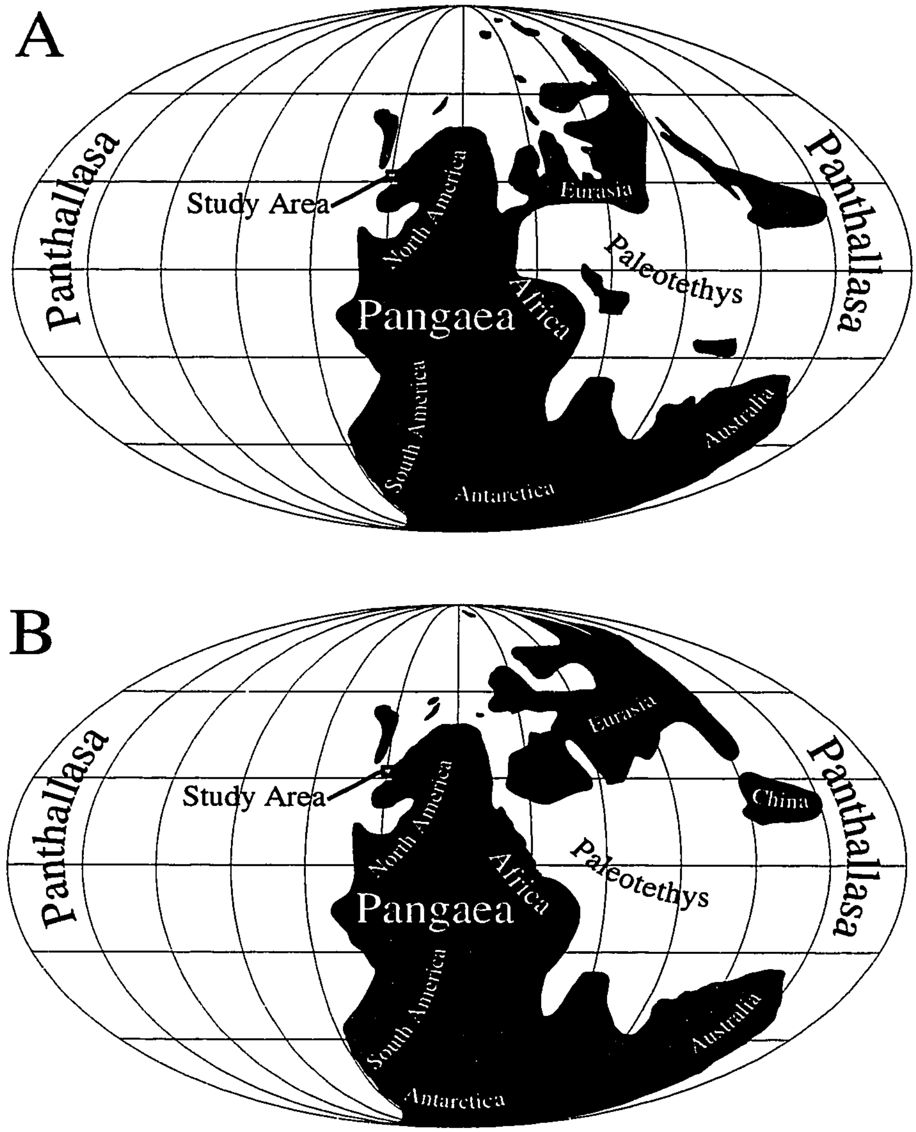


Figure 8. Schematic palaeogeographic reconstructions of Pangaea during the Early (Greisbachian; Figure 8a.), and Middle Triassic (Ladinian; Figure 8b). Adapted from Smith et al. (1994).

Alberta (Table 1). With the exception of rare ammonoid and bivalve impressions, the Grayling Formation produced few fossils within the study area.

North of the study area, the contact between the Grayling and the overlying Toad Formation has been picked above a zone of dark grey to black, siliceous phosphate nodules (Gibson and Edwards, 1992; Jones *et al.*, 1997). However, this marker bed is not observed within the study area. Within the study area, the Grayling is particularly thin and is gradational with the overlying Toad Formation (Figure 3).

Throughout most of northeastern British Columbia the Toad Formation unconformably overlies the Permian Fantasque Formation. At Ursula Creek, the most distal locality within the study area the Fantasque-Toad contact is abrupt but conformable and is interpreted here as a maximum marine flooding surface (Figure 3). Strata immediately overlying the lithostratigraphic contact are characterized by high gamma ray radiation and are interpreted as a condensed interval (Figure 3). Recent interpretations indicate that the Permian-Triassic boundary may actually occur a few centimetres to a few metres above the base of the Grayling Formation rather than at the lithostratigraphic contact as has been previously reported (Henderson, 1997).

Toad Formation

The Toad Formation consists of a series of dark grey argillaceous to calcareous siltstones, silty shales, silty limestones, silty dolomites, and fine-grained sandstones (Kindle, 1944). It thickens from 160 metres in the Williston Lake region to approximately 825 metres near the Halfway River to the north (Gibson and Edwards, 1990; 1992; Gordey *et al.*, 1991). The Toad is the equivalent of the upper Montney and lower Doig in the subsurface to the east and to the Sulphur Mountain Formation in the southern Rocky Mountain foothills outcrop belt (Table 1). Within the study area, the unit conformably overlies the Grayling Formation and is conformably overlain by the Liard and Ludington Formations. Although not as fossiliferous as the overlying Liard Formation, the Toad contains a variety of brachiopod, ammonoid, bivalve and fragmentary fish fossils, as well as a wide variety of trace fossils.

Liard Formation

The Liard Formation consists primarily of hard grey calcareous to dolomitic, fine to coarse grained sandstones, calcareous to dolomitic siltstones, and sandy to silty dolomites and limestones (Gibson and Edwards, 1990; 1992). The Liard is considered equivalent to the Halfway and upper Doig Formations in the subsurface to the east, and to the Llama Member of the Sulphur Mountain Formation in the Rocky Mountain Foothills belt of Alberta (Table 1). Within the study area, the Liard Formation conformably overlies the Toad Formation. The contact between the Liard Formation and the carbonates and evaporites of the Charlie Lake Formation is not exposed within the study area, but has been interpreted as conformable elsewhere in British Columbia (Gibson and Edwards, 1992).

The Liard Formation is one of the most fossiliferous horizons within the field area.

Invertebrate fossils collected during the course of field work associated with this study include abundant ammonoids, gastropods, numerous bivalve genera (including pteriids, trigonids, pectenids), brachiopods (lingulids, acrotretids, spiriferids, and terebratulids), a variety of echinoderms (echinoids, crinoids and brittle stars), crustaceans (decapods and phyllocarids), foraminifera, bryozoans and possible corals. Skeletal elements of marine reptiles (thallattosaurs and ichthyosaurs) and fish have also been collected. Trace fossils are diverse (~40 ichnogenera) numerous, and contain several forms not normally associated with Triassic deposition (Zonneveld *et al.*, 1997a; Zonneveld *et al.*, 1998b). These fossils have been invaluable in interpreting depositional environments of the Liard Formation at Williston Lake and are discussed, where pertinent, in this chapter, as well as in chapers 2 and 3.

LITHOFACIES ASSOCIATIONS

Twenty lithofacies have been recognized in the Grayling, Toad, and Liard Formations within the study area, identified on the basis of lithology, bounding surfaces, primary physical and biogenic sedimentary structures, and bioclastic or fossil composition. These lithofacies are summarized in Table 2. Sedimentary facies within the study area occur within five recurring lithofacies associations. These facies associations are: I) shelf/ramp turbidites; II) clastic offshore/shoreface; III) transgressive shoreface; IV) mixed siliciclastic-carbonate shoreface; V) brachiopod-echinoderm biostrome, and VI) mixed siliciclastic-carbonate marginal marine.

The Carboniferous through Triassic periods within the Western Canada Sedimentary Basin comprise a mixed siliclastic-carbonate transitional succession between dominantly carbonate early-middle Paleozoic units and siliciclastic-dominated deposition during the later Mesozoic and Tertiary. Although lithofacies associations within the study area were deposited under a wide range of depositional parameters, all contain a significant carbonate component. In describing and interpreting these lithofacies associations, special attention is therefore given to the nature and derivation of this carbonate material.

Trace fossils were particularly valuable in indentifying lithofacies and assessing parameters governing their deposition. Trace fossil assemblages characteristic of each lithofacies association are discussed below. In each case, trace fossil assemblages are named for dominant or characteristic forms (i.e. *Cruziana-Lingulichnus* assemblage), and are discussed briefly in terms of depositional significance.

LITHOFACIES ASSOCIATION I: Distal Shelf/Ramp Turbidites

Description- Lithofacies association I (Figures 3 and 9), consisting of six sedimentary facies (A1, A2, B, C1, C2 and D; Table 2) is characteristic of the Grayling and Toad Formations within the study area. This lithofacies association is characterized by numerous, normally-graded, centimetre to decimetre scale, very fine-grained sandstone, to siltstone/silty shale beds. Basal bounding surfaces of individual beds are sharp, and often characterized by flute marks and load casts. Sandstone beds range from massive appearing to ripple and parallel laminated to convolute-bedded (Figures 10a, 10c). Micro-faults and mudclasts often

FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	FOSSILS	DEPOSITIONAL ENVIRONMENT
A1	Laminated Black Shale	Plane parallel laminae, rare silt and sand lam, rare carbonate &/or phosphate concretions.	None observed	None observed	Distal Shelf /Slope
A2	Laminated Black silty shale	Plane parallel laminae, discontinuous normally graded sand/silt laminae, rare HCS and current ripple laminae,	Pa,He,Hl, Ph,Sc,Ch	*Lingula*, rare fish and ammonoids	Distal Shelf /Slope
B	Silty Bioclastic Packstone	Lense or pod shaped beds of normally graded fine-grained bioclasts.	None observed	Thin-shelled pelagic bivalve fragments.	Distal Shelf/Slope /Turbidite Lobe
C1	Interbedded shale, siltstone & vf sandstone	Soft-sediment deformation, convoluted & distorted laminae, micro-faults, ripple and parallel lamination.	He, Hl, Ph, Ch	fish scales and bivalves, normally graded bioclastic hash layers.	Turbidite Levee /Overbank ("CCC Turbidites")
C2	Interbedded vf sandstone, siltstone and shale	normally graded beds, amalgamated Bouma B-C-D-E, B-C-D, & C-D-E.	He, Hl, Ph	fish scales & bivalves, bioclastic hash layers	Turbidite Lobe
D	Bioclastic rudstone/grainstone (100% fragmentary clasts)	Obscured by weathering, normally graded.	None Observed	~75% fragmentary bioclastic hash	Turbidite Channel
E(B)	Interlaminated HCS Siltstone & Sandstone	Plane parallel laminae, flow ripples, HCS, rare oscillation ripples.	Sl,He,Hl, Ph,Th,Sb, Sp,Lk,Li,Pa,Pl,Cr,Sc	whole lingulids, bones, bioclastic hash layers	Offshore/Shoreface Transition
F(C)	HCS Sandstone (very fine)	Amalgamated HCS beds, planar bedding, current and oscillation ripples.	As,Be,Di,Sk,Th,Pa,Cy, Li Te,Ro,Si,Lk,Ar,Pl,Rh	ling. brachs, bivalves, fish, brittle stars.	Lower Shoreface
G(F)	Calcareous sandstone (very fine to fine)	Predominantly TCS, rare HCS (SCS?), rare oscillation ripples	Di,Sk, Pa, Pl	scattered brachiopod & echinoderm debris	Distal Upper Shoreface
H	Pebbly/sandy bioclastic grainstone (laterally restricted)	Scoured base, normally graded, possible TCS, pebble/granule lags.	None Observed	abraded brach., bivalve & echinoderm debris	Rip-Tidal Channel
I(M)	Calcareous sandstone (fine to medium)	Predominantly TCS grading up into current ripple laminae, mudclast lags	None observed	Rare bivalve shell lags.	Tidal Inlet Channel
J	Nodular Bioclastic Silty/Sandy Packstone	Nodular bioclastic packstone/grainstone clasts (1-40cm) within a siliciclastic matrix, abdt. chert peb.	None Observed	bioclastic hash, brachs, bivalves, ammonoids, gastropods, ammonoids	Transgressive Shoreface
K	Terebratulid/spiriferid grainstone	None Observed.	None Observed	whole, unabraded spiriferids & terebratulids	Lower Shoreface

Table 2a. Summary of sedimentary facies characteristics in the Grayling, Toad, Liard, and Charlie Lake formations, Williston Lake, northeastern British Columbia. Ar = *Arenicolites;* As = *Asterosoma;* Be = *Bergauria;* Ch = *Chondrites;* Co = *Conichnus;* Cr = *Cruziana;* Cy = *Cylindrichnus;* Di = *Diplocraterion;* Gy = *Gyrochorte;* Hl = *Helminthoida;* He = *Helminthopsis;* Li = *Lingulichnus;* Lk = *Lockeia;* Mo = *Monocraterion;* Op = *Ophiomorpha;* Pa = *Palaeophycus;* Ph = *Phycosiphon;* Pl = *Planolites;* Rh = *Rhizocorallium;* Ro = *Rosselia;* Sc = *Scalarituba;* Sb = *Schaubcylindrichnus;* Sl = *Scolicia;* Si = *Siphonites;* Sk = *Skolithos;* Sp = *Spongelliomorpha;* Te = *Teichichnus;* Th = *Thalassinoides;* Tr = *Treptichnus;* BAT = bivalve adjustment trace; BRT = Bivalve resting trace; Pit = feeding pit.

FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	FOSSILS	DEPOSITIONAL ENVIRONMENT
L1(D)	Sandy Bioclastic Grainstone	Low-angle stratification, random orientation to grains, grading not observed.	As, Cy, Pa, Ro	crinoid ossicles, echinoid, brachiopods	Reef Mound/ Biostrome Fringe
L2(D)	Bioclastic rudstone/grainstone (<50% of clasts fragmentary)	Obscured by abundant bioclasts. Beds thicken upwards (30 to 60cm). Grading not observed. Abrupt bounding surfaces.	None observed	terebratulid brachs echinoids, & crinoids, rare acrotretid brach.s	Reef Mound/ Biostrome
M(E)	Bioclastic floatstone/mudstone	low-angle planar laminae, thinly bedded, normally graded?	Pl	echin., crin., brachs, fish, decapods,bivalves	Back Reef
N(G)	Bioclastic sandy packstone (fine to medium)	Trough to planar cross-stratification at base, grading up into planar-tabular laminae. Inversely graded, abundant chert pebbles).	Op, Pl	bioclastic debris, brachs, bivalves, rare ichthyosaur bones	Proximal Upper Shoreface/Foreshore
O(H)	Calcareous sandstone	Appears massive, planar lam. to TCS, beds thicken upwards (5-10 to 30cm).	Sk, Pa, Pl, Gy, BRT	rare *Lingula* and bioclastic debris	Backshore/ Washover Fan
P1(I)	Fenestral laminated dolomite	fenestral laminae, bird's eye structure	Algal laminae	None observed	Lagoonal/ Intertidal Flat
P2(K)	Dolomitic mudstone	Planar laminae, syneresis cracks	Cy, Gy, Tr	rare lingulids, bivalves, and gastropods	Lagoonal/Lacustrine
Q(J)	Planar cross-stratified sandstone	low-angle planar cross-stratification, oscillation ripple lamination.	Sk, Pa, Gy,	None observed	Shoreface/ Washover Fan
R1(K)	Dolomitic siltstone	Planar laminations, current and oscillation ripples, heterolithic wavy laminae, polygonal mudcracks	Ar,Cy,Co,Di,Gy, Lk,Pa,Pl,Rh,Sk, Th, feeding pits	*Lingula*, bivalve frags, gastropods	Intertidal Flats/ Marginal lagoonal
R2(K)	Dolomitic sandstone	Heterolithic wavy laminae, flaser bedding, symmetrical ripples, dessication cracks, rill marks	Cy,Gy,La,Pa,Pl, Rh,Sk,Si,Te,Th, biv. adjust. tr.	bivalves, gastropods, lingulid fragments	Intertidal Flats
S(L)	Solution collapse breccia	Solution collaspse of other lithofacies.	None observed	None noted	Supratidal
T	Ripple-laminated dolomitic siltstone/mudstone	Wavy to ripple laminated, adhesion ripples	Cy, Mo, Op, Pa, root traces	None Observed	Supratidal Lacustrine
U	High-angle cross-stratified sandstone	Planar cross-bedding, tabular to wedge-planar bedsets, inversely graded laminae	None observed	None Observed	Aeolian Sand Dunes

Table 2b. Summary of sedimentary facies characteristics in the Grayling, Toad, Liard, and Charlie Lake formations, Williston Lake, northeastern British Columbia. Ar = *Arenicolites;* As = *Asterosoma;* Be = *Bergauria;* Ch = *Chondrites;* Co = *Conichnus;* Cr = *Cruziana;* Cy = *Cylindrichnus;* Di = *Diplocraterion;* Gy = *Gyrochorte;* Hl = *Helminthoida;* He = *Helminthopsis;* Li = *Lingulichnus;* Lk = *Lockeia;* Mo = *Monocraterion;* Op = *Ophiomorpha;* Pa = *Palaeophycus;* Ph = *Phycosiphon;* Pl = *Planolites;* Rh = *Rhizocorallium;* Ro = *Rosselia;* Sc = *Scalarituba;* Sb = *Schaubcylindrichnus;* Sl = *Scolicia;* Si = *Siphonites;* Sk = *Skolithos;* Sp = *Spongelliomorpha;* Te = *Teichichnus;* Th = *Thalassinoides;* Tr = *Treptichnus;* BAT = bivalve adjustment trace; BRT = Bivalve resting trace; Pit = feeding pit.

characterize convolute-laminated units (Figure 10b).

In a typical lithofacies association I parasequence, laminated, black, silty shale (lithofacies A) grades upwards into numerous, sharp-based, normally-graded siltstone to very fine-grained sandstone beds (Figures 10d, 10e). Although comprised of numerous normally and inversely graded sediment packages, ranging in scale from laminae and lamina-sets to parasequences and parasequence-sets, this lithofacies association comprises an overall "cleaning" upwards succession (decreasing shale component/increasing sand component upwards).

Normally-graded, sharp-based, planar laminated, bioclastic beds (lithofacies B) commonly occur interbedded with black laminated silty shales (lithofacies A; Figure 10f) and with normally graded siliciclastic sandstone/siltstone beds (lithofacies C). Bioclasts within lithofacies B consist primarily of thin bivalve shells but also include possible foraminifera, ammonoids and rare vertebrate fragments. A single, 3-5m thick, laterally restricted lens of sandy bioclastic rudstone/grainstone (lithofacies D) incises through a succession of normally graded sandstone/siltstone beds at Brown Hill (Figure 10g). Bioclasts within lithofacies D consisted of disarticulated and fragmentary bivalve, gastropod, echinoderm and brachiopod detritus. With the exception of bioclastic debris within lithofacies B and D, body fossils were rare within lithofacies association I, consisting of isolated fish skeletal elements and ammonoid impressions on bedding planes within lithofacies C.

Although trace fossils are relatively rare in lithofacies association I, two distinct trace fossil assemblages have been observed to occur. These trace fossil assemblages were not observed at Ursula Creek and are limited to exposure of lithofacies association I at Brown Hill and Glacier Spur. The *Didymaulichnus-Chondrites* assemblage, consisting of isolated occurences of *Chondrites, Didymaulichnus, Helminthopsis/Helminthoida* and rare *Scalarituba* occurs primarily on bedding planes within lithofacies A (black shale) and shale laminae within lithofacies C. The *Spongelliomorpha-Palaeophycus striatus* assemblage consisting of *Skolithos*, *Spongelliomorpha* (Figure 10h), *Palaeophycus* (var. *striatus*) and *Anconichnus* is relatively rare, occuring primarily within several normally graded siltstone and silty sandstone packages (lithofacies C) within the Toad Formation at Brown Hill and Glacier Spur.

Interpretation- Lithofacies association I is interpreted to have been deposited in a shelf to slope-fan turbidite setting (Figure 11). Normally-graded sandstone to siltstone/shale beds (Figures 10d, 10e) are interpreted as Bouma sequences. These beds exhibit a gradation from massively bedded sandstone (Bouma A) through planar laminated sandstone (Bouma B; upper flow regime), ripple laminated sandstone (Bouma C; lower flow regime) and finally planar laminated siltstone and silty shale (Bouma D and E; dominantly suspension deposition; Bouma, 1962; Middleton, 1993).

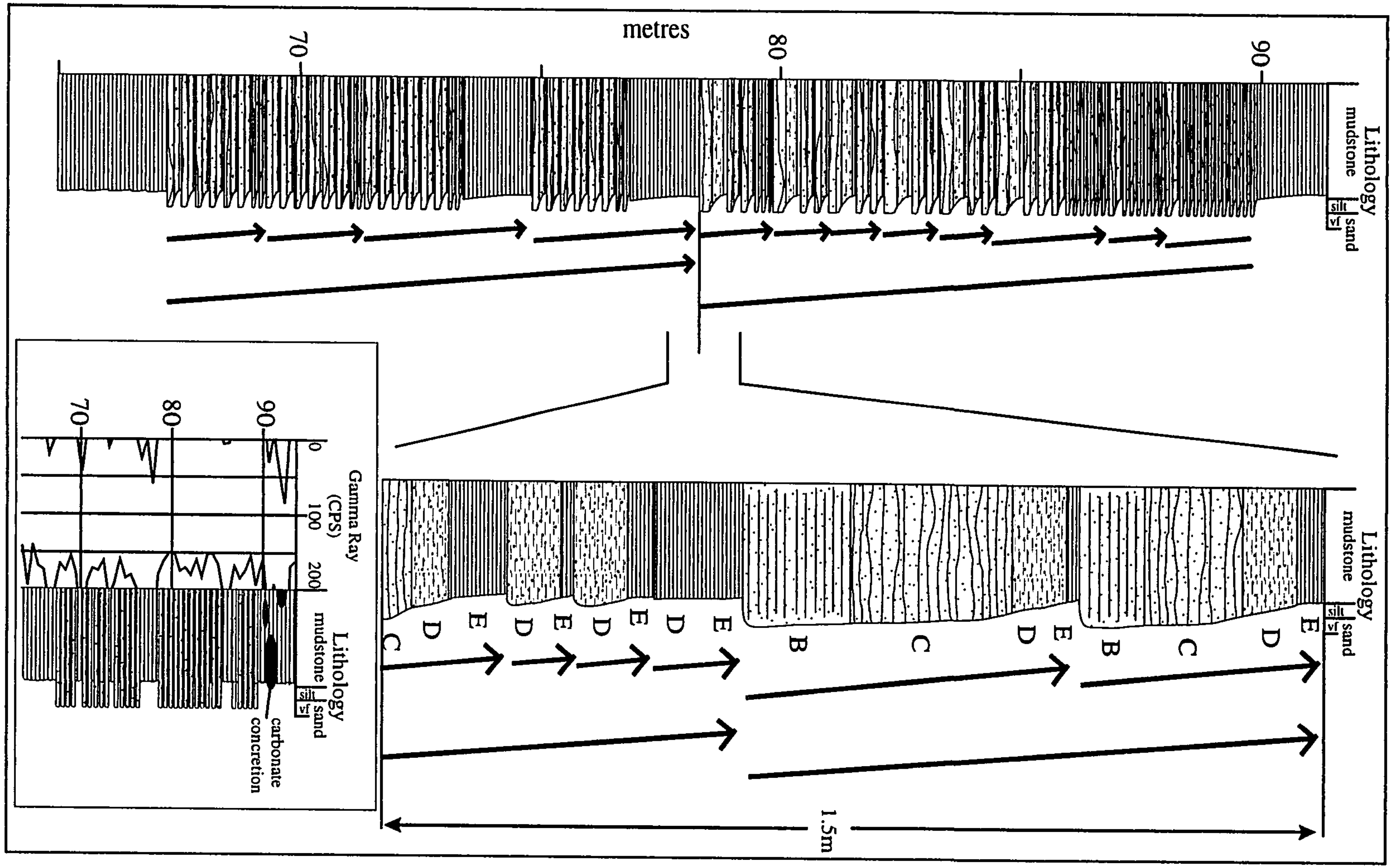
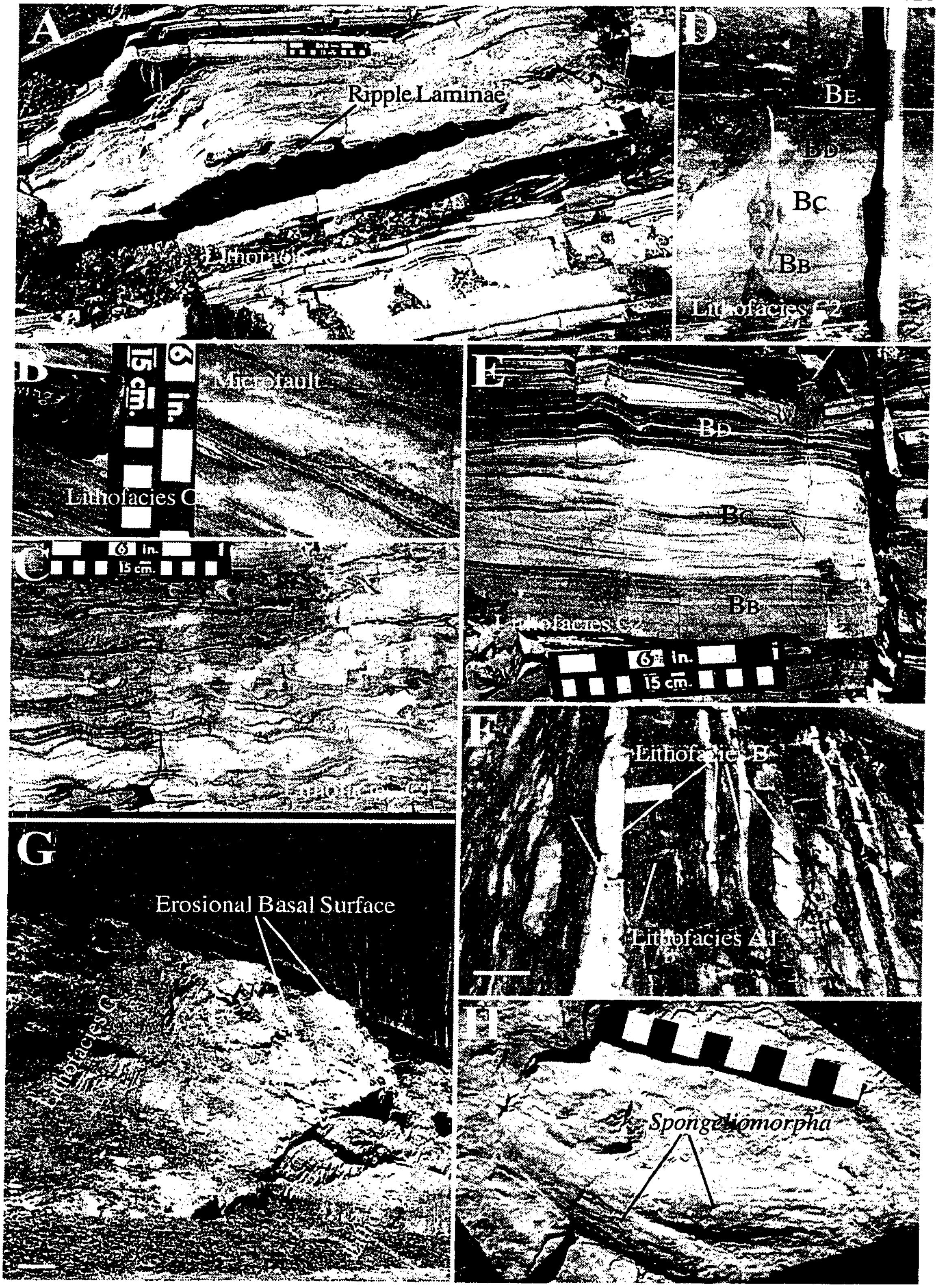


Figure 9. Stratigraphic section showing the vertical arrangement of sedimentary facies in a typical Lithofacies Association I succession (Toad Formation, Ursula Creek). Inset at bottom right shows the gamma pattern of this interval. Arrows denote normally graded successions. The column on the right shows detail of six individual parasequences. Letters on the right side of this column denote Bouma subdivisions of individual turbidites.

Figure 10. Outcrop photographs of lithofacies C1 (turbidite levee/overbank), C2 (distal shelf/slope/turbidite lobe) and D (turbidite channel). **Figure 10a, 10c.** Very fine-grained sandstone exhibiting a gradation of soft-sediment deformation features such as convolute and distorted lamination as well as ripple and parallel lamination (lithofacies C1; turbidite levee/overbank; "CCC" turbidites), Toad Formation, Brown Hill (165m). **Figure 10b.** Very fine-grained sandstone laminae offset by micro-faulting (lithofacies C1; turbidite levee/overbank; "CCC" turbidites), Toad Formation, Brown Hill (165.5m). **Figure 10d.** Succession of normally graded, very fine-grained sandstone beds, (lithofacies c2; distal shelf/slope/turbidite lobe), Toad Formation, Ursula Creek (75m). Bouma subdivisions B_B (upper flow regime planar lamination), B_C (lower flow regime current ripple lamination), B_D (suspension deposition), and B_E (suspension sedimentation) are labeled. **Figure 10e.** Succession of normally graded, very fine-grained sandstone beds, (lithofacies c2; distal shelf/slope/turbidite lobe), Toad Formation, Brown Hill (220m). Bouma subdivisions B_B (upper flow regime planar lamination), B_C (lower flow regime current ripple lamination), and B_D (suspension deposition) are labled. **Figure 10f.** Interbedded black shale (lithofacies A; distal shelf/slope) and silty bioclastic packstone (lithofacies B; distal shelf/slope/turbidite lobe), Grayling/Toad Formation, Ursula Creek, (55m). **Figure 10g.** Thick, normally graded, bioclastic rudstone/grainstone (lithofacies D; turbidite channel) incising deeply into underlying strata (lithofacies C, Toad Formation, Brown (Hill, 186-202m). **Figure 10h.** *Spongelliomorpha* on the sole of sharp-based, normally graded sandstone package (lithofacies C2;distal shelf/slope/turbidite lobe), Toad Formation, Brown Hill, 220m).


A
Ripple Laminae
D
BE
BD
BC
BB
Lithofacies C2
B
Microfault
Lithofacies C
E
BD
BC
BB
Lithofacies C2
C
F
Lithofacies B
Lithofacies A1
G
Erosional Basal Surface
Lithofacies C
H
Spongeliomorpha

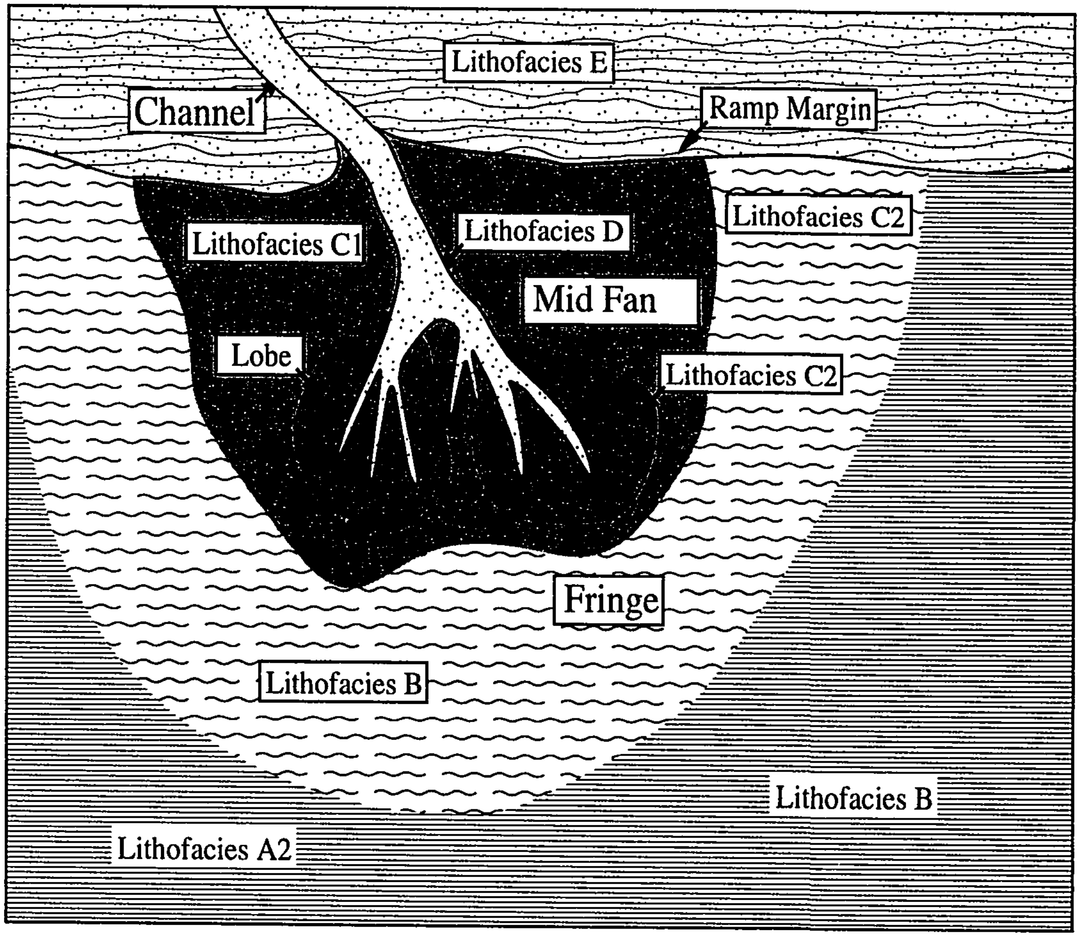


Figure 11. Simplified schematic model showing the proposed paleoenvironmental distribution of individual sedimentary facies within lithofacies association I.

Lithofacies C, a thick succession of amalgamated turbidites, comprises the bulk of lithofacies association I (Figure 3: 65-85m, 115-135m; Figure 4: 0-250m; Figure 5: 0-15m and Figure 9) . Sediments of this lithofacies comprise two distinct subdivsions. Lithofacies C1 exhibits a variety of soft-sediment deformation features such as convoluted and distorted lamination, and micro-faulting as well as current and climbing ripple and parallel lamination (Figures 10a, 10b and 10c). Sediments deposited by turbidity currents and characterized by these features are referred to as "CCC turbidites (Walker, 1985). The presence of convolute laminae, mudclasts, syndepositional micro-faults and climbing ripple laminae suggest high rates of deposition. These sedimentary characteristics are consistent with deposition in a turbidite channel margin or levee setting (Moslow and Davies, 1997; Walker, 1985; 1992). Lithofacies C2 is characterized by numerous complete to partially complete Bouma successions (Figures 10d, 10e). The sedimentary characteristics of this lithofacies suggest deposition via turbidity currents. The rarity of soft-sediment deformation features such as convolute laminae and microfaults, and absence of climbing ripple laminae suggest greater distance from the turbidite channel than that inferred for lithofacies C1. Lithofacies C2 is interpreted to have been deposited within a succession of turbidite fan lobes.

Bioclastic grainstone lenses (lithofacies B) at Ursula Creek (Figure 3: 53-60m) consist primarily of thin bivalve shells as well as ammonoids, foraminifera and rare vertebrate bones. These bioclasts consist of an assemblage of pelagic and planktonic marine organisms and are consistent with deposition in a distal marine setting. Concentration of this bioclastic material as sharp-based, normally-graded units within black, organic-rich shales in distal locales such as Ursula Creek (figure 10f), or interbedded with normally graded sandstone units (lithofacies C) in more proximal locales such as Brown Hill and Glacier Spur is consistent with turbidity current deposition.

Exposure of lithofacies D was limited to a single occurrence within the Toad Formation at Brown Hill (Figure 4: 190-197m). This bioclastic rudstone/grainstone consists of disarticulated and highly fragmentary bioclastic detritus and incises deeply into underlying strata (lithofacies C) and is abruptly but conformably overlain by lithofacies A1 (Figure 4, 190-197m; Figure 10g). This unit consists of numerous 30-50cm thick beds and comprises an overall normally graded succession. Numerous normally graded beds and the nature of its association with subjacent and overlying lithologies is consistent with deposition as a turbidite channel.

The *Didymaulichnus-Chondrites* assemblage is dominanted by horizontal to subhorizontal deposit-feeders. *Chondrites*, a notable exception to this, occurs primarily within thin shale laminae between turbidite-generated sandstone beds (lithofacies C). The *Chondrites* ethology is particularly useful adaptation in environmental settings characterized by event deposits (Vossler and Pemberton, 1984; 1989). This deep, probing behavior allows penetration of Bouma A-D subdivisions in individual beds, permiting the organism to access buried nutrients.

The *Spongelliomorpha-Palaeophycus striatus* assemblage is limited to the soles of several sandstone beds in the Brown Hill and Glacier Spur sections. *Spongeliomorpha* are thick, cylindrical to subcylindrical, branching, horizontal to subhorizontal burrow systems (Figure 10h). Although similar in some respects to *Thalassinoides, Spongelliomorpha* differs by the presence of abundant, prominent transverse striae or scratch marks (Häntzschel, 1975; Metz, 1993; 1995). Both *Thalassinoides* and *Spongeliomorpha* are interpreted to represent dwelling structures of burrowing arthropods (Fürisch, 1973; Häntzschel, 1975). *Palaeophycus striatus,* a variety of *Palaeophycus* characterized by lined burrows walls with abundant, continuous longitudinal striations, are common within this assemblage and may also be arthropod derived. The rarity and nature of beds characterized by the *Spongelliomorpha-Palaeophycus striatus* assemblage may (or may not) reflect organisms transported from a more proximal setting by turbidity currents. These organisms likely prefered a more proximal environmental setting such as the lower shoreface or offshore transition, but subsisted, at least temporarily, in this more distal ramp setting.

LITHOFACIES ASSOCIATION II: Clastic Offshore-Shoreface

Description- Lithofacies association II (Figure 12), consisting of six sedimentary facies (A, E,F, G, H and I; Table 2) is characteristic of the upper Toad and lower Liard Formations within the study area (Figures 4, 5, 6 and 7). In a typical lithofacies association II parasequence (Figure 12), black silty shale (lithofacies A) with thin planar to ripple laminated and hummocky cross-stratified siltstone and sandstone beds (lithofacies E; Figure 13a) grade upwards through thick, amalgamated, hummocky cross-stratified sandstone beds (lithofacies F), into thick, trough and planar cross-stratified bioclastic sandstone beds (lithofacies G). Sand beds are variable in thickness, from 0.5 to 10.0 centimetres where interbedded with black silty shale, 15.0 to 40.0 centimetres where hummocky cross-stratified, to over 75.0 centimetres where trough cross-stratified.

Bioclastic detritus is common at the base of several hummocky cross-stratified sandstone beds (Figures 13c, 13d) and in trough cross-stratified sandstone intervals at the top of most lithofacies association II parasequences (Figure 4, 5 and 12). Sandstone beds within lithofacies association I are locally incised by laterally constricted, normally graded, sandy, bioclastic grainstones with abundant chert pebbles (lithofacies H; Figure 13b) and calcareous sandstone lenses with basal mudclast lags (lithofacies I).

Identifiable body fossils include numerous bivalve steinkerns, rare ammonoids in shalier horizons, scattered lingulid brachiopods (*Lingula* cf. *L. selwyni*, Figure 13g) within interbedded shale/sandstone horizons and hummocky cross-stratified sandstone intervals, rare terebratulid brachiopods (*Aulacothyroides liardensis, A. silvana* and *A. petriana*) throughout and abundant spiriferid brachiopods (*Spiriferina borealis*) within trough cross-stratified sandstone beds.

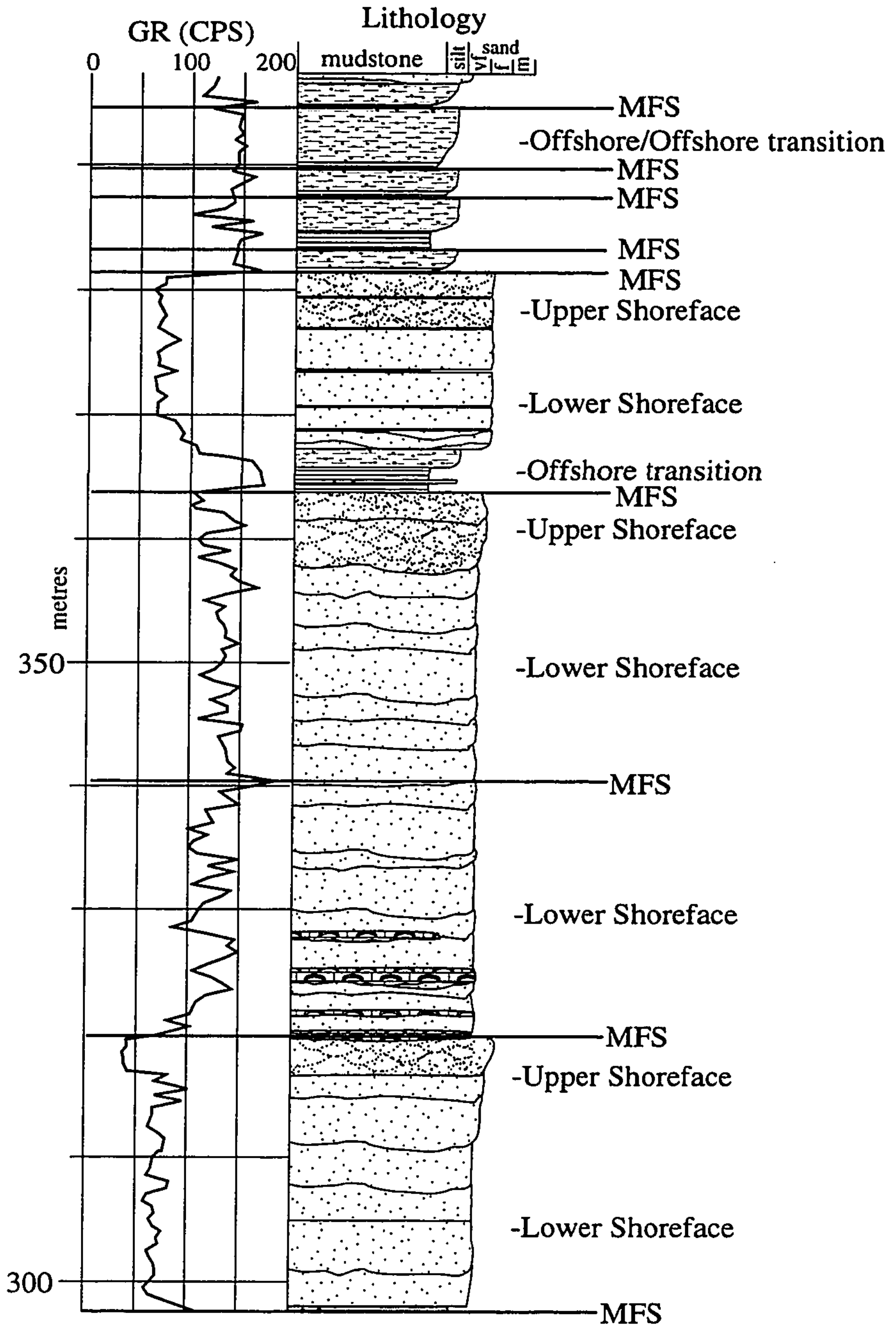
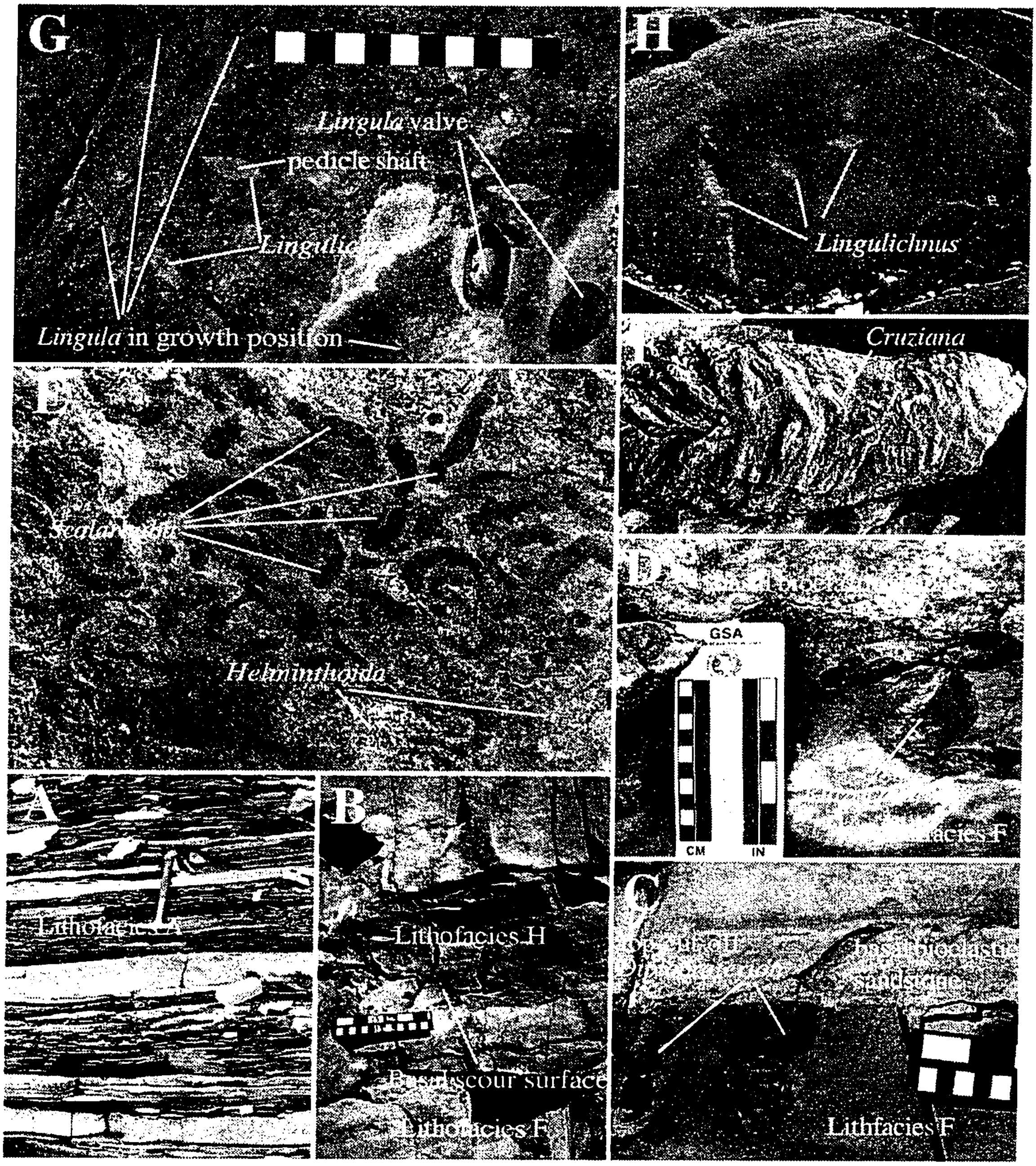


Figure 12. Detailed stratigraphic section showing the vertical arrangement of sedimentary facies in a typical Lithofacies Association II succession (Liard Formation, Brown Hill). The "spiky" pattern to the gamma profile between 320 and 362m is attributed to abundant organic detritus and intense bioturbation rather than to muddiness of the sediment. MFS= marine flooding surface.

Figure 13a. Black silty shale/siltstone (lithofacies A/E; offshore; offshore transition) with thin, sharp-based, normally-graded, hummocky cross-stratified sand beds (lithofacies E: offshore transition), Liard Formation, Beattie Ledge (60m). **Figure 13b.** Laterally restricted, bioclastic, calcareous sandstone lense (lithofacies H; rip-tide channel) incising hummocky cross-stratified fine-grained sandstone (Lithofacies F; lower shoreface), Liard Formation, Brown Hill (280m). **Figure 13c.** Hummocky cross-stratified, very fine-grained sandstone exhibiting a large, slightly obliquely oriented, *Diplocraterion*, erosionally overlain by a normally graded, bioclastic sandstone (Lithofacies F; lower shoreface), Brown Hill, Liard Formation (320m) **13d.** Hummocky cross-stratified, very fine-grained sandstone exhibiting a large, slightly obliquely oriented, *Diplocraterion*, erosionally overlain by a normally graded, bioclastic sandstone (Lithofacies F; lower shoreface), Aylard Creek, Liard Formation (44m). **Figure 13e.** Co-occurence of the trace fossils *Phycosiphon/Helminthoida* and *Scalarituba* on silty sandstone bedding plane (lithofacies E; offshore transition), Toad/Liard Formation, Aylard Creek (18m). **Figure 13f.** Large, robust *Cruziana* on basal silty sandstone bedding plane (lithofacies E; offshore transition), Toad/Liard Formation, Beattie Ledge (10m). **Figure 13g, 13h.** Co-occurence of the lingulid brachiopod *Lingula* on bedding plane and in growth position, and the lingulid-generated trace fossil *Lingulichnus* on bedding plane of silty, hummocky cross-stratified, very fine-grained sandstone (lithofacies E; offshore transition), Liard Formation, Brown Hill (466m).


G
Lingula valve
pedicle shaft
Lingulichnus
Lingula in growth position
H
Lingulichnus
Cruziana
E
Helminthoida
D
GSA
CM
IN
A
B
Lithofacies H
Basal scour surface
C
Lithfacies F

Lithofacies association II is characterized by a suite of trace fossils reflecting a gradation from suspension deposition to active, current-dominated transport. Trace fossils within lithofacies association II peak in diversity in the offshore transition to lower shoreface. The *Phycosiphon-Scalarituba assemblage*, consisting of *Palaeophycus*, *Helminthopsis*, *Phycosiphon* (Figure 13e), *Scalarituba* (Figure 13e) and *Chondrites* occurs within thin-bedded, planar laminated, black, silty shale containing thin normally graded layers of silt and very-fine grained sand (lithofacies A and E).

The *Cruziana-Lingulichnus* assemblage consisting of *Anconichnus, Chondrites, Cruziana* (Figure 13f), *Diplocraterion, Lingulichnus* (Figures 13g, 13h), *Lockeia, Palaeophycus, Phycosiphon, Planolites, Rusophycus, Scalarituba, Scolicia, Spongelliomorpha, Teichichnus, Treptichnus,* and *Thalassinoides* co-occur within interlaminated muddy siltstone, silty mudstone and muddy very fine-grained sandstone (lithofacies E).

The *Diplocraterion-Rosselia* assemblage is an exceptionally diverse assemblage consisting of *Anconichnus, Arenicolites, Asteriacites, Asterosoma, Bergaueria, Cylindrichnus, Diplocraterion* (Figure 13e), *Lockeia, Monocraterion, Palaeophycus, Planolites, Rhizocorallium, Rosselia, Schaubcylindrichus, Skolithos, Teichichnus, "Terebellina"* sp., *Thalassinoides,* bivalve adjustment traces, an as yet undescribed pelleted structure, and numerous escape traces occurs within very fine- to fine-grained quartzose sandstone (lithofacies F) with thin sandy mudstone interbeds.

Interpretation- Lithofacies association II is interpreted as a proximal offshore through upper shoreface succession characterized by numerous indications of storm-influenced deposition. The paucity of coarser allochthonous sediment and the textural maturity of sands within lithofacies association II reflects both storm winnowing and a texturally mature sediment supply (Zonneveld *et al.* 1997b). In a typical lithofacies association II parasequence, black silty shale deposited within the proximal offshore with thin distal tempestites or dilute turbidites (Figure 13a) grades upwards through thick, amalgamated, storm-deposited, hummocky cross-stratified sandstone beds, into thick, trough and planar cross-stratified bioclastic sandstone beds deposited within an upper shoreface setting. Shoreface sands are locally incised by tidal inlet channels comprised primarily of fine- to medium-grained sand, with basal lags of dolomitic mud-clasts (lithofacies I).

Although lithofacies association II has been designated the clastic offshore-shoreface assocition, like all intervals within the Liard Formation, it contains a significant proportion of bioclastic material. Laterally restricted (rarely wider than 4 metres), normally graded, sandy, bioclastic grainstones (lithofacies H) with abundant chert, composed primarily of bioclastic detritus (bivalve, echinoderm and brachiopod) are interpreted as rip-tidal channels (Figure 13b). Rip currents are strongest immediately after storms (Gruszczyński *et al.*, 1993). Rapid, post-storm decline in flow resulted in sudden deposition of massive, non-graded to crudely cross-stratified beds (Gruszczyński *et al.*, 1993). These coarse lags reflect basinward transport and the removal of fine-grained material during strong post-storm seaward flow (Aigner, 1982; 1985; Gruszczyński *et al.*, 1993).

Thin, normally graded, bioclastic lenses within lithofacies E (interbedded siltstone and hummocky cross-stratified sandstone) are interpreted as bioclastic tempestites deposited within the transition zone between the shoreface and the offshore (Figures 13c, 13d and 14). In a shoreward direction, these bioclastic beds thicken and develop erosional bases. Hummocky cross-stratified sandstone beds (lithofacies F) containing robust *Diplocraterion* and *Skolithos* are commonly erosionally overlain by planar cross-stratified bioclastic sandstone beds (Figure 14). The bioclastic component of these sandstone beds decreases rapidly upwards, gradationally giving way to hummocky cross-stratified sandstone. This relationship was observed within tempestites at several outcrop sections within the study area. These siliciclastic-carbonate couplets are similar in structure and derivation to limestone-quartzite couplets interpreted as storm deposits from the Lower Carboniferous of Morocco (Kelling and Mullin, 1975). Although quartz (SiO_2) has a higher specific gravity than calcite or aragonite ($CaCO_3$), quartz sand within the study area is primarily very fine- to fine-grained. The bioclastic component at the base of individual storm couplets ranges from granule- to sand-sized clasts. Mobilization and deposition of this coarse-grained material occured during peaks in storm intensity. Gradation from coarse-grained bioclastic to fine-grained quartz sand reflects waning storm conditions.

Upper shoreface sediments (trough cross-stratified very fine-fine grained sandstone; lithofacies G) within lithofacies association II contain abundant bioclasts. Carbonate detritus generally comprises a minor (8-20%) albeit persistent component of upper shoreface sediments within lithofacies association II. Reworked, fragmentary, highly abraded (and thus unidentifiable) bioclastic detritus comprises much of the bioclastic fraction. Siliciclastic and bioclastic grains display an inverse relationship within the Liard shoreface (Zonneveld and Gingras, *in press*), due primarily to cross-shore transport of coarse and fine-grained sediment fractions (Bowen, 1980; Nummedal, 1991). It is assumed that coarse bioclastic detritus in excess of the equilibrium grain size was preferentially transported shoreward, while finer grained siliciclastic sediments were preferentially transported basinward (chapter 3; Figure 15).

The most visible bioclastic component within the Liard upper shoreface consists of whole and relatively unabraded spiriferid brachiopods (*Spiriferina borealis*). The lack of abrasion or fragmentation of these corrugated thick-shelled brachiopods suggests that these brachiopods endured minimal transport and may have been infaunal constituents of the upper shoreface.

The *Phycosiphon-Scalarituba* assemblage, dominated by horizontal deposit-feeders, characterizes proximal offshore successions within the study area. The traces *Helminthopsis*, *Helminthoida* and *Phycosiphon* (Figure 13e) are interpreted to represent a continuum in the grazing/foraging activity of a single genus of tracemaker responding to changes in

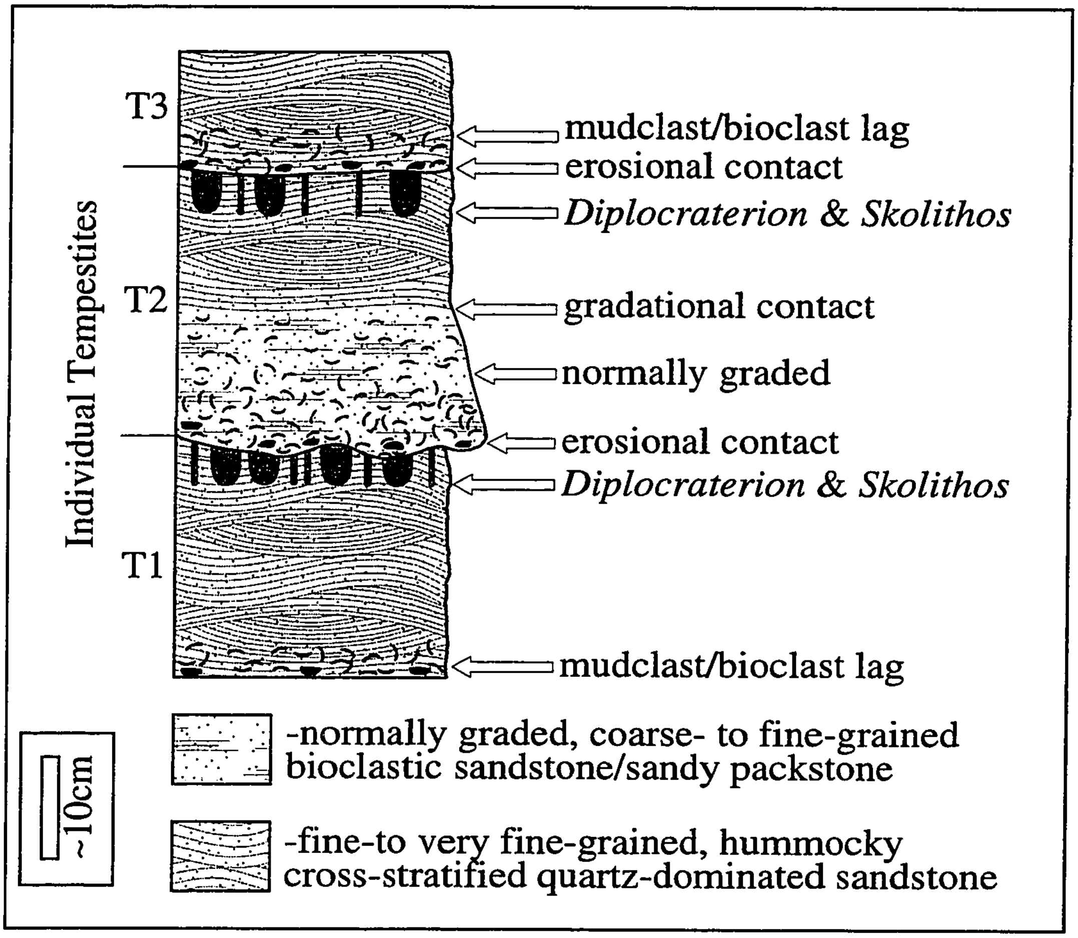


Figure 14. Schematic model of a mixed siliciclastic-carbonate tempestite (lithofacies F). Hummocky cross-stratified sandstone beds containing robust *Diplocraterion* and *Skolithos* are erosionally overlain by planar cross-stratified bioclastic sandstone beds. The bioclastic component of these sandstone beds decreases rapidly upwards, gradationally giving way to hummocky cross-stratified sandstone. The bioclastic component at the base of individual storm couplets ranges from granule- to sand-sized clasts. Mobilization and deposition of this coarse-grained material occurred during peaks in storm intensity. Gradation from coarse- grained bioclastic to fine-grained quartz sand reflects waning storm conditions.

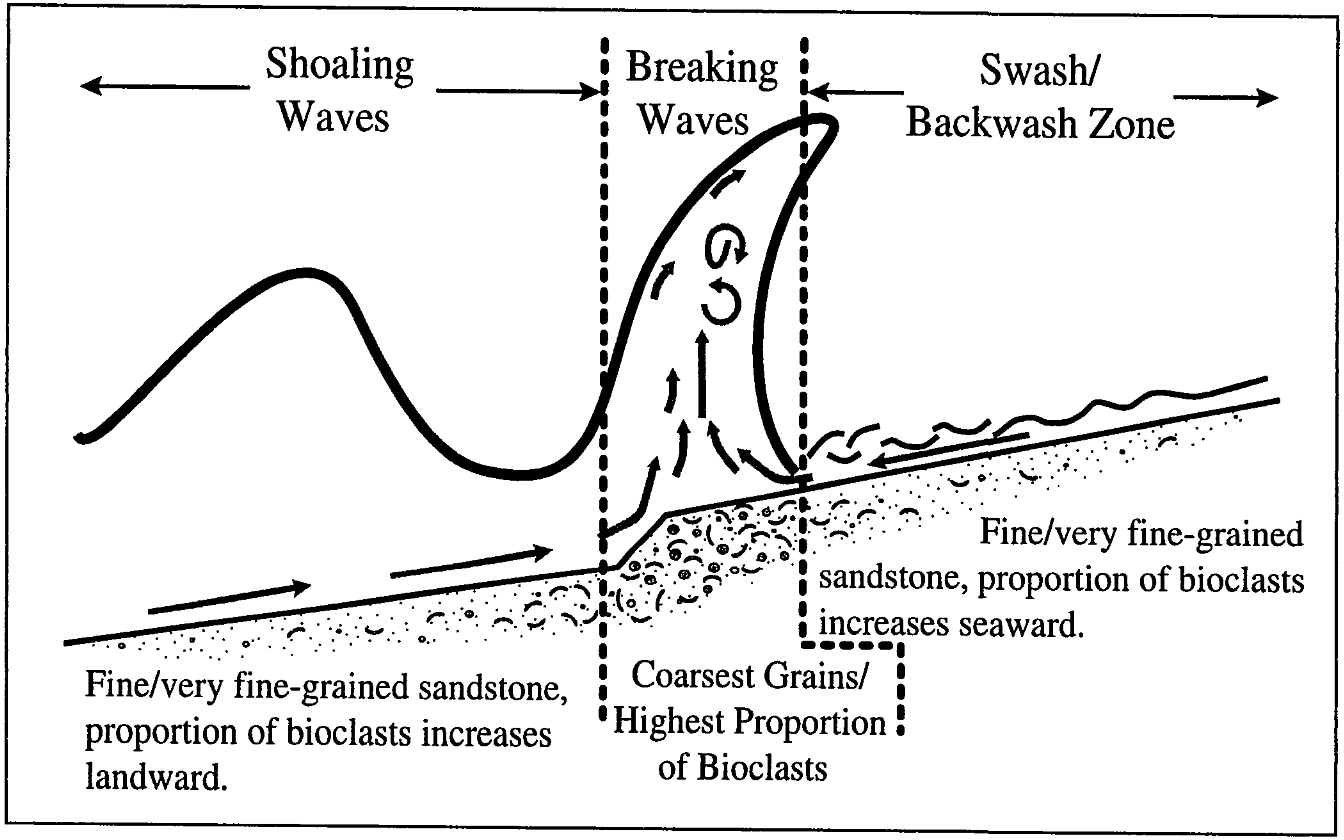


Figure 15. Net sediment movement within the Liard proximal upper shoreface/foreshore (after Miller and Ziegler, 1958). The increase of bioclastic detritus towards the breaker zone is a reflection of the overall fine-grained nature of quartz sand and coarse-grained nature of bioclastic material within the Liard shoreface. Arrows indicate net sediment movement during wave break.

sedimentation rate, substrate composition and food availability. *Helminthopsis* represents the random, irregularly meandering movement of a worm-like organism grazing or searching for food. As mentioned above, *Helminthoida* and *Phycosiphon* represent end members in a behavioral spectrum. The regular meanders of *Helminthoida* reflects normal, feeding behaviour, while the spreitenate meanders of *Phycosiphon* are interpreted here as an adaptation to systematically harvest a particularly organic-rich horizon. A recurrent association of *Helminthopsis* and *Phycosiphon* cross-cut by *Scalarituba* reflects exploitation of nutrient-rich sediments by a low-diversity, high-abundance infauna.

The *Cruziana-Lingulichnus* assemblage, dominated by deposit feeding traces is consistent with the distal *Cruziana* ichnofacies and is characteristic of the transitional zone between the lower shoreface and offshore within the study area. The presence of large, robust *Cruziana* (Figure 13f), an ichnotaxon otherwise limited to the Paleozoic, makes this assemblage unique among Mesozoic marine successions world wide. Several subsets, which appear to reflect bathymetrically controlled biotic zonation, occur within this assemblage at Beattie Ledge and Aylard Creek. The first, and correspondingly deepest assemblage, consists of *Chondrites,* atypically large robust *Diplocraterion, Anconichnus, Planolites, Scalarituba,* and *Teichichnus*. The second subset consists of *Anconichnus, Cruziana* (Figure 13d), *Palaeophycus, Planolites, Rusophycus* and *Thalassinoides.* The infill within many specimens of *Cruziana* is completely reworked by *Anconichnus.* The third, and correspondingly shallowest, assemblage consists of diminutive *Cruziana, Palaeophycus* (var. *striatus*) , *Spongelliomorpha, Teichichnus, Thalassinoides* and *Treptichnus.*

At Brown Hill, abundant *Lingulichnus* occur within thin (5-20 cm) beds of silty, very fine-grained, hummocky cross-stratified sandstone (Figure 13g, 13h), often in association with abundant *Cylindrichnus* and rare *Asterosoma, Chondrites, Helminthopsis* and *Palaeophycus*. Many of the burrows contain specimens of *Lingula* cf. *L. selwyni*, either vertically within growth position (Figure 13 g) or lying on the bedding planes beside the burrow (Figure 13g). This association represents populations of *Lingula* exhumed be storm processes, and redeposited within the offshore transition. Many individuals survived the journey and subsequent burial unscathed, and were able to reorient themselves into vertical dwelling positions. Others survived transport but were unable to re-exhume themselves, as evinced by burrows which terminate prior to reaching bedding planes (figure 13h), and paired *Lingula* valves buried within beds rather than at bed or bedset contacts (Figure 13g). The presence of *Lingula* preserved within growth position at contacts between individual storm deposits suggests that many specimens were killed by subsequent events (Figure 13g).

The *Diplocraterion-Rosselia* assemblage is consistent with the proximal *Cruziana* ichnofacies, comprises an unique mix of horizontal deposit feeders and vertical/horizontal suspension feeders. A subset of this assemblage consisting of abundant *Asteriacites, Anconichnus, Asterosoma, Cylindrichnus, Monocraterion, Palaeophycus, Rhizocorallium, Rosselia, Schaubcylindrichus, Teichichnus,* and unique pelleted structures occurs together in thick silty sandstone beds containing abundant faecal material at Aylard Creek. These ichnogenera in this occurrence indicate prolonged periods of stability and a diverse infauna taking advantage of a substrate rich in organic resources. Both *Asteriacites* and well-preserved ophiuroid body fossils occur in this assemblage. *Rosselia rotatus*, an unusual form of this ichnogenus appears to be an adaptation to take advantage of an anomalously organic-rich substrate (McCarthy, 1979).

A second subset, consisting of low diversity assemblages of *Arenicolites, Cylindrichnus, Diplocraterion, Rhizocorallium* and *Skolithos*, occurs within amalgamated, well sorted, hummocky cross-stratified sandstone beds. The tops of these traces are often missing reflecting reworking of the upper portion of each bed. This vertical burrow-dominated assemblage within storm generated deposits may reflect post-event colonization by a comparably low diversity opportunistic fauna during a period of higher than normal storm frequency.

LITHOFACIES ASSOCIATION III: Transgressive Shoreface

Description- Lithofacies association III (Figure 4: 288-297m; Figure 5: 56-79m; Figure 16) is limited to the lower Liard Formation at Brown Hill and Glacier Spur. Although comprised of only two lithofacies, and limited in exposure to a single horizon at Brown Hill and Glacier Spur, this lithofacies association is unique in both composition and inferred derivation within the study area. Two sedimentary facies (J and K; Table 2) are interpreted to have resulted from processes reflecting an interplay of fluvial-deltaic and shoreface processes. In this lithofacies association, matrix-supported, nodular, bioclastic, silty packstone with interlaminated silty, siliciclastic, very fine-grained sandstone laminae (lithofacies J; Figure 17a) is overlain by a brachiopod grainstone dominated by whole and unabraded terebratulid and spiriferid brachiopods (lithofacies K).

Lithofacies J, comprising the bulk of lithofacies association III, is one of the most enigmatic lithofacies within the study area. The bioclastic component includes fragmented and abraded terebratulid and spirifirid brachiopods, crinoid columnals, echinoid skeletal debris, bivalves, and foraminifera. Lithofacies J is dominantly sandy towards the base and incises into trough cross-stratified sandstones of lithofacies G (upper shoreface; Figure 17b). The top of this unit comprises a thin, laterally persistent limestone layer (lithofacies K) containing abundant, complete and unabraded terebratulid and spiriferid brachiopods which in turn is conformably overlain by hummocky cross-stratified sandstones of lithofacies F (lower shoreface). Lithofacies association II is highly variable in thickness, doubling in thickness from Brown Hill to Glacier Spur, a distance of under three kilometres. The carbonate clasts/nodules are smaller, more highly rounded and deposited concurrent to cross-stratifiaction at Glacier Spur (Figure 17c).

Few individual trace fossils were identified within lithofacies association III. Differential weathering and diagenetic alteration of the carbonate component have rendered primary physical and biogenic structures of the original sediments essentially unidentifiable. Thin-section and polished sections have revealed the presence of unlined and lightly lined

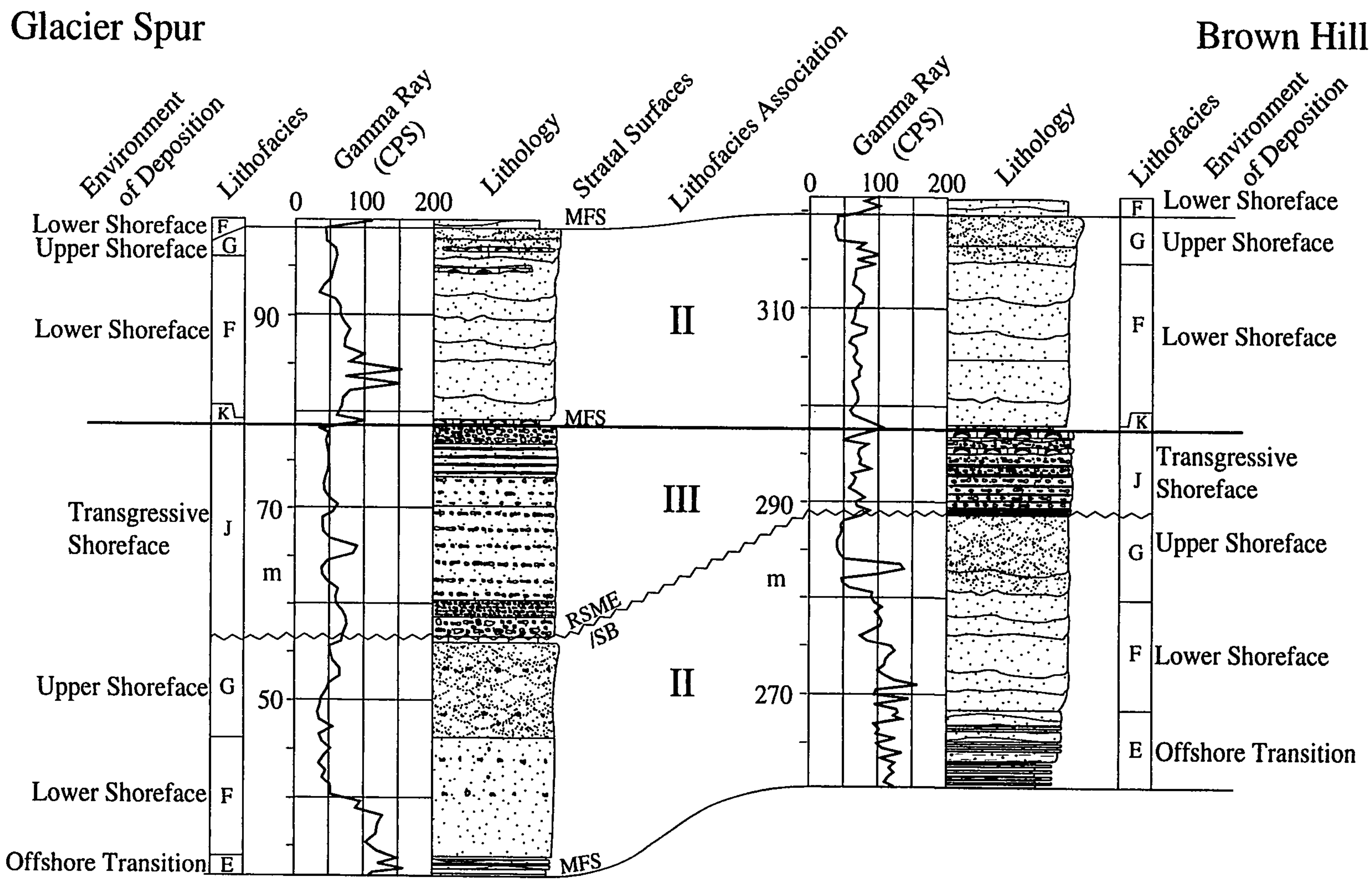


Figure 16. Detailed stratigraphic section showing vertical and lateral lithofacies relationships within Lithofacies Association III (Liard Formation, Glacier Spur and Brown Hill). MFS= marine flooding surface; RSME/SB= regressive surface of marine erosion/ sequence boundary.

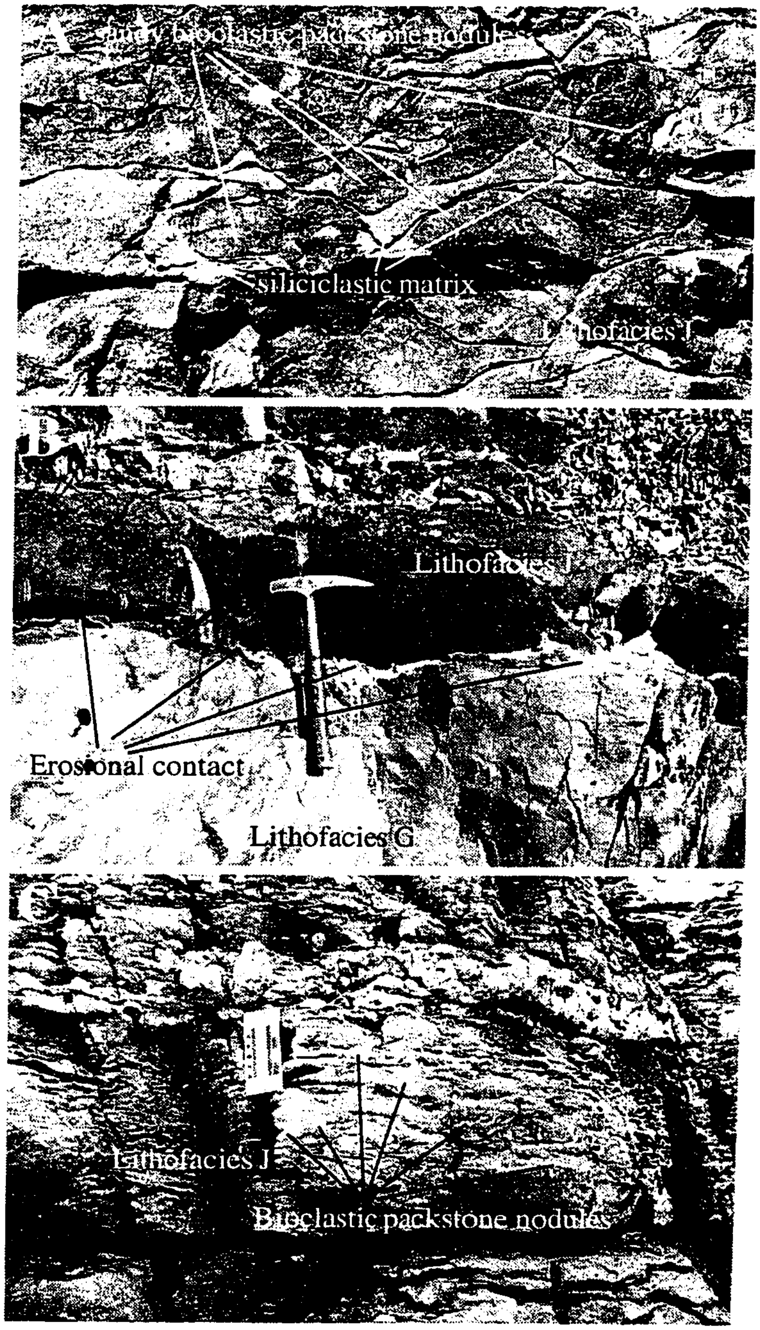


Figure 17a. Large silty bioclastic packstone clasts within a silty sandstone matrix (lithofacies J; transgressive shoreface), Brown Hill, Liard Formation (295m). **Figure 17b.** Silty/sandy packstone (lithofacies J; transgressive shoreface), erosionally overlying trough cross-stratified fine-grained sandstone (lithofacies G; upper shoreface), Brown Hill, Liard Formation (288m). **Figure 17c.** Small, rounded silty bioclastic packstone clasts deposited concurrent with bedding (lithofacies J; transgressive shoreface), Glacier Spur, Liard Formation (70m).

burrows however specific forms were not identified. Small rounded to subrounded pits eroded into individual breccia clasts and blocks are interpreted as invertebrate borings.

Interpretation- This association is interpreted to have been deposited during early transgression along a wave-dominated coastline characterized by numerous occurrences of beachrock. Coarse-grained bioclastic detritus was concentrated in the upper shoreface and foreshore by wave activity during sea-level highstand (Figure 18a) a common occurrence in the Liard Formation (Zonneveld *et al.*, 1997; chapter 2). Early cementation of this bioclastic detritus, via the dissolution of unstable shell material and reprecipitation of calcite, likely occurred both prior to subaerial exposure, and later as sea-levels fell, welding the bioclasts into a lithified packstone. Rocky shores commonly develop on carbonate and mixed siliciclastic carbonate coasts, since carbonates are prone to early lithification (Semeniuk and Johnson, 1985; Semeniuk and Searle, 1987).

Rising sea-levels resulted in marine erosion as these lithified sediments once again passed into the zone of wave reworking (Figure 18b). This situation was likely exacerbated by undercutting of the lithified unit as subjacent unconsolidated sands were reworked by wave activity. Marine bioeroders likely had a significant effect on the destruction of this lithified substrate. Small pits eroded into individual breccia clasts are interpreted as a low-diversity *Trypanites* assemblage. Residents of the Liard shoreface responsible for these borings may include bivalves, echinoids, bryozoans, sponges and possibly polychaetes (Figure 18b). The *Trypanites* ichnofacies is charcteristic of fully lithified marine substrates such as the rocky coastline described here (Pemberton and MacEachern, 1995). Marine transgression often results in erosion of newly lithified carbonate rocks (Semeniuk and Johnson, 1985).

As sea-levels continued to rise, the residual breccia passed beneath the zone of effective wave reworking and the larger blocks were colonized by hardground-preferring epifaunal organisms (Figure 18c). Terebratulid brachiopods (*Aulacothyroides liardensis*), the dominate organism within this assemblage, are common residents within hardground communities within the study area (Zonneveld *et al.*, 1997b). The thin, brachiopod grainstone (lithofacies K) comprised of whole, articulated, unabraded, randomly oriented terebratulid and spiriferid brachiopods within a siltstone matrix is interpreted to reflect reworking of these brachiopods during continuing transgression.

Although distinct primary biogenic and physical sedimentary structures were not identified, the composition of individual breccia clasts/nodules is consistent with upper shoreface sediments observed elsewhere in the study area. The paucity of trace fossils within individual clasts is attributed to preservational constraints rather than the absence of trace-making organisms within the original, uneroded substrate.

LITHOFACIES ASSOCIATION IV: Mixed Siliciclastic-Carbonate Shoreface
Description- Occurrence of this lithofacies association at the Brown Hill and Glacier Spur

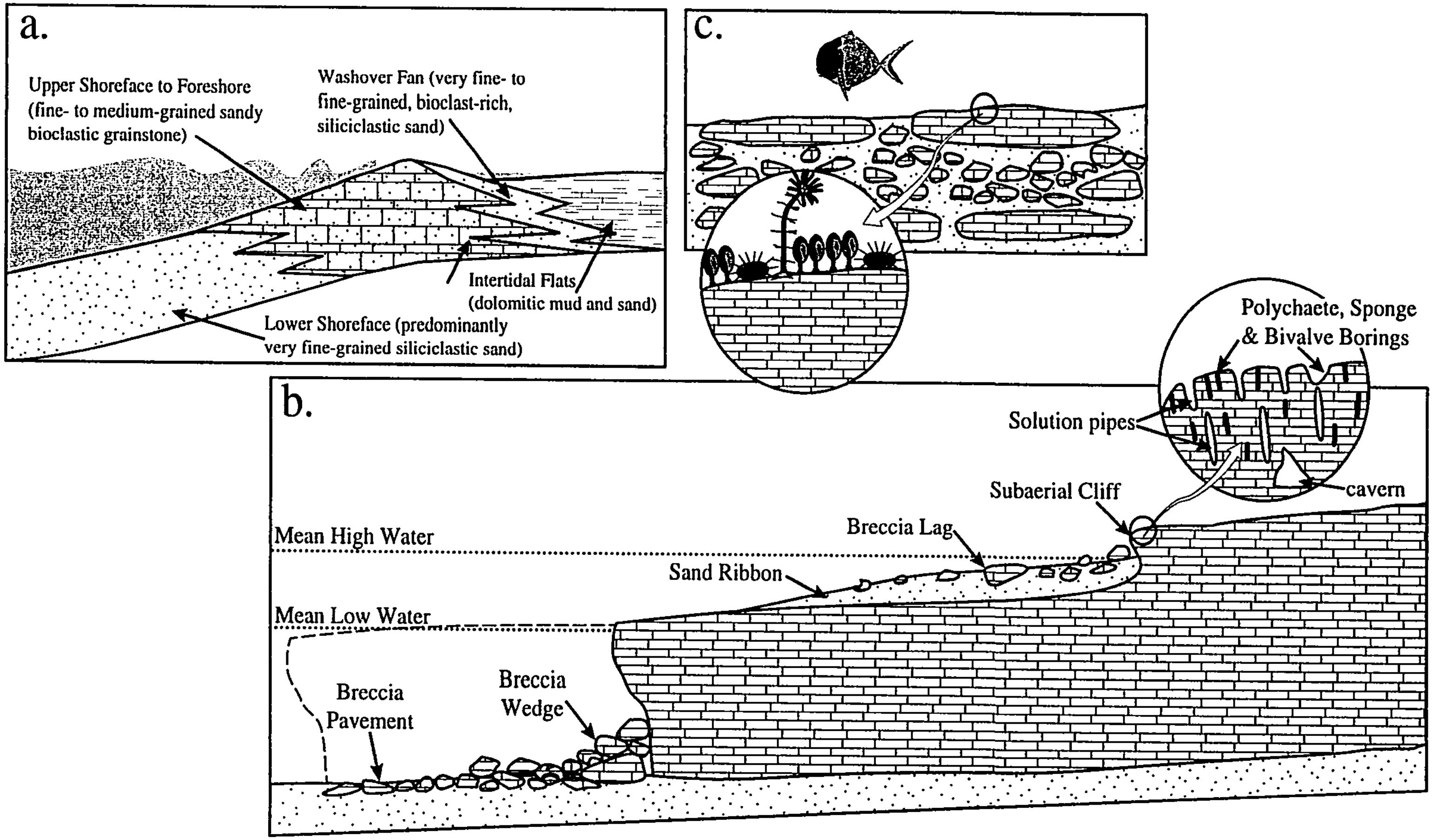


Figure 18. Development of siliciclastic sand-supported, nodular bioclastic grainstone breccia in the Liard shoreface. Figure 18a. Coarse-grained bioclastic detritus is concentrated in the upper shoreface and foreshore by wave activity during transgression. **Figure 18b.** During transgression bioclastic shoreface sediments were quickly cemented via the dissolution of unstable shell material and reprecipitation of calcite, welding the bioclasts into a lithified packstone. As transgression accelerated, marine erosion of these lithified sediments resulted in erosion of a rocky shoreline producing a carbonate breccia lag (adapted from Semeniuk and Johnson, 1985). **Figure 18c.** When the residual breccia passes beneath the zone of effective wave reworking, the larger blocks were colonized by hardground-preferring epifaunal organisms. Terebratulid brachiopods, the dominate organism within this assemblage, are common residents within hardground communities within the study area (see figure 19). A thin, brachiopod grainstone comprised of whole, articulated, unabraded, randomly oriented terebratulid and spiriferid brachiopods within a siltstone matrix is interpreted to reflect reworking of these brachiopods during continuing transgression.

localities was discussed in detail by Zonneveld *et al.* (1997b; Chapter 2). It is modified here, incorporating new field observations at eastern outcrop exposures.

Lithofacies association IV (Figure 19) is characteristic of the upper Liard Formation within the study area. It consists of a conformable, coarsening-upwards succession of six sedimentary facies (A, E, F, G, N and O; Table 2). The basal part of this succession (lithofacies A, E, F and G) is common to lithofacies association II and is thus not discussed in detail here.

Parasequences within this lithofacies association are generally characterized by a strong upwards increase in the proportion of bioclastic detritus and correspondingly a decrease in the proportion of siliciclastic detritus (Figure 5: 190-215m; Figure 6: 18-50m; 92-103m; Figure 7: 40-74m; Figure 19). Within a typical lithofacies association IV parasequence, black, laminated silty shales (lithofacies A) interbedded with abundant, normally graded very fine grained sandstone (lithofacies E) grades rapidly up into amalgamated beds of hummocky cross-stratified quartz-dominated sandstone (lithofacies F; Figure 19). This primarily siliciclastic succession is conformably overlain by a bioclastic sandstone/sandy bioclastic packstone characterized by trough to planar cross-stratification and planar-tabular laminae (lithofacies G and N), which in turn is overlain by calcareous sandstone characterized by horizontal to subhorizontal laminations (lithofacies O; Figure 19). Chert granules and pebbles are locally abundant in planar cross-stratified to lanar tabular laminated bioclastic packstones (lithofacies N Figures 20a, 20b)

Beds within lithofacies association II exhibit an overall thickening-upwards trend. They range in thickness from millimetre to centimetre scale within lithofacies A and E, decimetre to several decimetres in lithofacies F, several decimetres to tens of decimetres in lithofacies G and N, and centimetre to decimetre scale in lithofacies O. Bedset contacts range from sharp to strongly erosive, within lithofacies E, F, and N, and are sharp but conformable in lithofacies A and O.

Although many of the body fossils within this association are fragmentary and highly abraded, rendering them unidentifiable, others are more complete. Identifiable body fossils include bivalves, scattered lingulid brachiopods (*Lingula* cf. *L. selwyni*) within hummocky cross-stratified sandstone intervals (lithofacies F) and laminated calcareous sandstone (lithofacies O), rare terebratulid brachiopods (*Aulacothyroides* sp.) throughout, abundant spiriferid brachiopods (*Spiriferina borealis*) within trough cross-stratified sandstone/sandy packstone beds (lithofacies G and N) and isolated ichthyosaur bones on bedding planes throughout the succession.

Although trace fossils are less common within lithofacies association IV than within lithofacies association II (clastic offshore-shoreface) several assemblages were observed. Isolated *Skolithos*, *Diplocraterion* and *Teichichnus* are common within hummocky cross-stratified sandstone (lithofacies F). The *Ophiomorpha-Skolithos* assemblage, consisting of

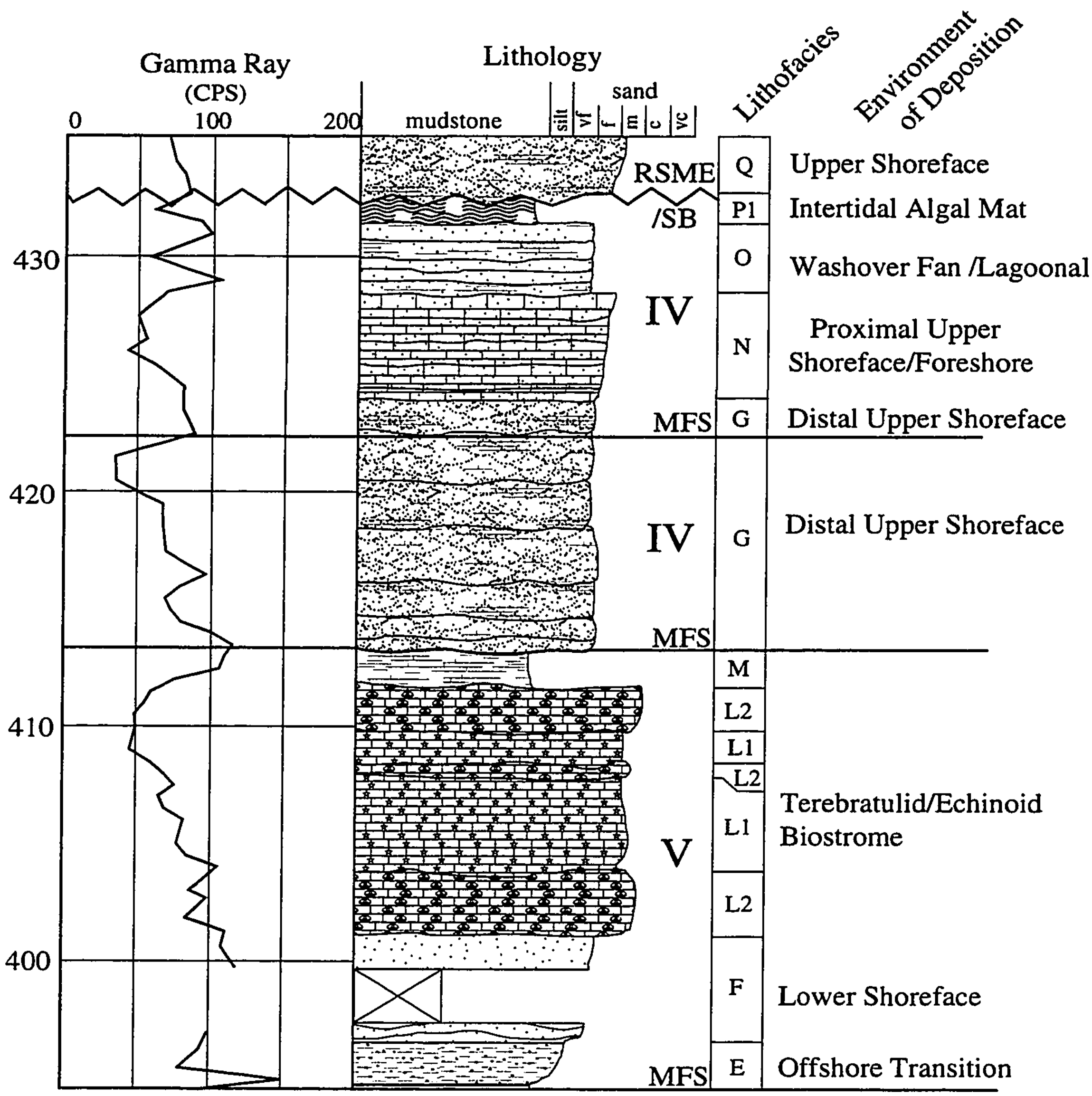


Figure 19. Detailed stratigraphic section showing the vertical arrangement of sedimentary facies in typical Lithofacies Association IV and V parasequences (upper Liard Formation, Brown Hill). Roman numerals to the right of the lithology column denote the lithofacies association designation. Lithofacies are summarized in Table 2. RSME/SB= regressive surface of marine erosion; MFS= marine flooding surface.

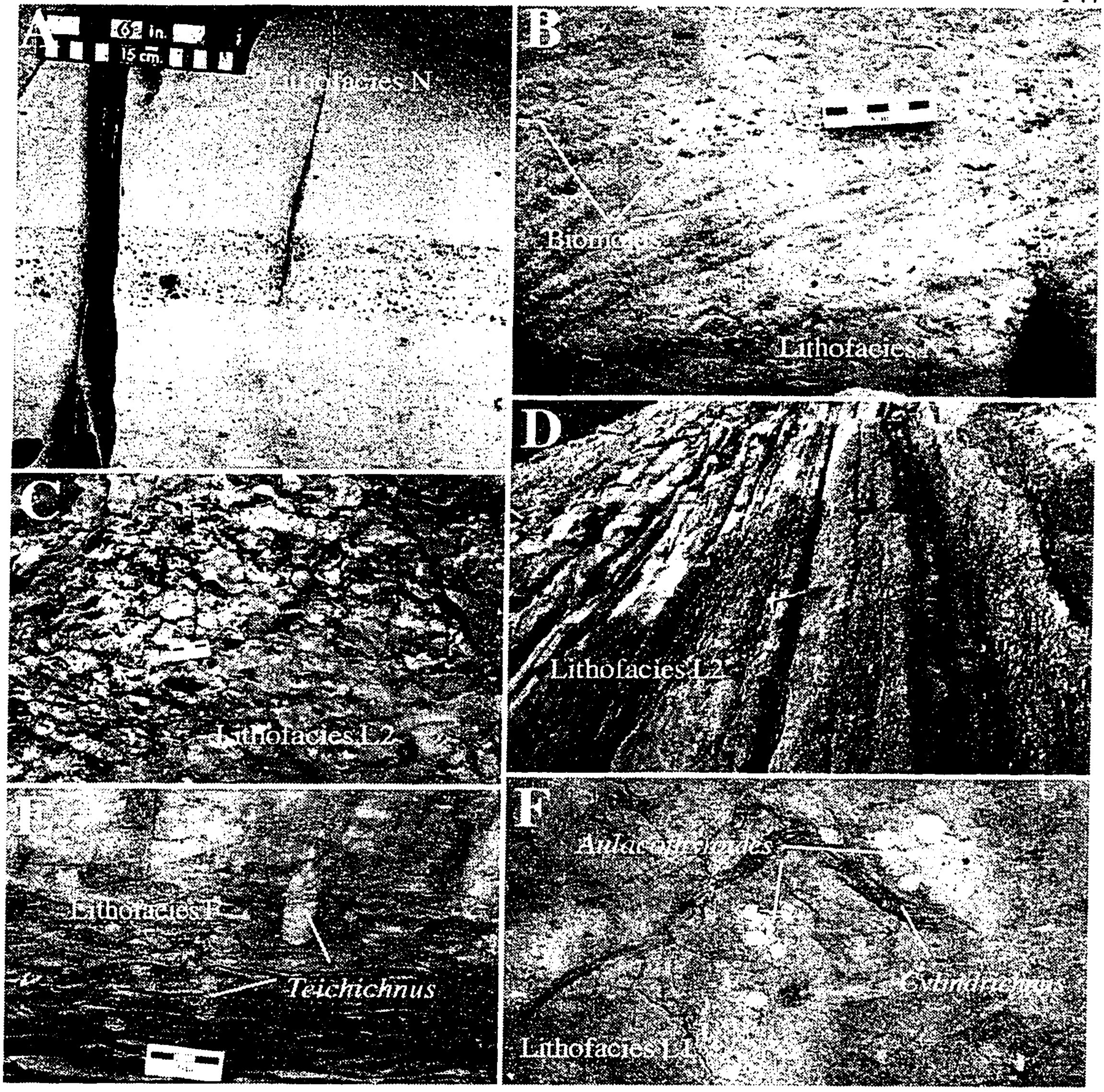


Figure 20a. Bioclastic silty packstone with abundant chert pebbles and a chert pebble-rich bed (8cm thick) running concurrent to cross-stratification (lithofacies N; upper shoreface), Glacier Spur, Liard Formation (245m). **Figure 20b.** Trough cross-stratified bioclastic silty packstone with abundant chert pebbles and bioclast molds (lithofacies N; upper shoreface), Glacier Spur, Liard Formation (245.5m). **Figure 20c.** Dense accumulation of terebratulid brachiopods (lithofacies L2; reef mound/biostrome), Glacier Spur, Liard Formation (185m). **Figure 20d.** Biostrome composed primarily of terebratulid brachiopods (lithofacies L2; reef mound/biostrome), Glacier Spur, Liard Formation, 182-186m). **Figure 20e.** Robust *Teichichnus* at flooding surface above brachiopod-echinoderm biostrome zone (lithofacies F; lower shoreface), Glacier Spur, Liard Formation (192m). **Figure 20f.** Pods of the terebratulid brachiopod *Aulacothyroides liardensis* with abundant infaunal burrows such as *Cylindrichnus*, (lithofacies F; lower shoreface), Liard Formation, Aylard Creek (56m).

Diplocraterion, Ophiomorpha, Palaeophycus, Planolites, Skolithos and *Thalassinoides* occurs within trough to planar cross-stratified fine-grained bioclastic sandstone/sandy packstone (lithofacies G). Rare *Planolites* and localy abundant *Ophiomorpha* were noted within cross-stratified sandy packstone (lithofacies N). The *Gyrochorte*-BRT assemblage, consisting of *Skolithos, Palaeophycus, Gyrochorte*, and an as yet undescribed type of bivalve resting trace (BRT) occurs within low-angle cross-stratified calcareous sandstone (lithofacies O).

Interpretation- Lithofacies association IV is interpreted as a mixed siliciclastic-carbonate shoreface succession. The carbonate component of this association is dominantly detrital, and is thus governed by the same depositional parameters (grain size, shoreface slope angle, wave energy, tidal range, etc...) as the silicilastic component. The proportion of bioclastic material increases significantly and that of siliciclastic material decreases significantly from bottom to top in a typical lithofacies association IV parasequence, a phenomenon attributed to the cross-shore transport of coarse bioclastic detritus and fine-grained sands (Figure 15).

Trace fossils within lithofacies association IV are consistent with deposition in an active shoreface setting. *Skolithos, Diplocraterion* and *Teichichnus* within hummocky cross-stratified sandstone (lithofacies F) are suggestive of lower shoreface deposition.

The *Ophiomorpha-Skolithos* assemblage is dominated by vertically-oriented burrows, characteristic of the *Skolithos* ichnofacies. This trace fossil association, as well as abundant scour surfaces, trough to planar cross-stratification, abundant chert pebbles and the highly abraded nature of the bioclasts are suggestive of deposition in a moderate to high-energy setting. Although most of these ichnogenera occurred within beds interpreted as distal upper shoreface (lithofacies G), *Ophiomorpha* and *Planolites* were also observed within units interpreted as proximal upper shoreface (lithofacies N). Quartz sand (fine- to medium-grained) and chert pebbles within lithofacies N comprise the coarsest non-bioclastic sediment observed within the study area (Figures 20a and 20b). Planar cross-laminated bioclastic deposits in the upper part of lithofacies N are charactersitic of swash zone or foreshore deposition.

The trace fossil assemblage (*Gyrochorte*-BRT) and physical sedimentary structures within lithofacies O are consistent with deposition in a quieter setting than lithofacies N. Facies N is interpreted as a backshore/lagoonal deposit (Zonneveld and Gingras, in press). Individual sharp-based sandstone beds are interpreted to be a product of storm washover events (Zonneveld and Gingras, in press).

LITHOFACIES ASSOCIATION V: Brachiopod-Echinoderm Biostrome

Description- Occurrence of this lithofacies association at the Brown Hill and Glacier Spur localities was discussed in detail by Zonneveld *et al.* (1997). It is modified here, incorporating new field observations at eastern outcrop exposures.

Lithofacies association V (Figure 19), consisting of four sedimentary facies (F, L1, L2 and M; Table 2) is characteristic of the Liard Formation within the study area (Figures 4,5,6 and 7). Lithofacies F is common to lithofacies associations II and IV. A typical lithofacies V parasequence consists of bioclastic hummocky cross-stratified sandstone (lithofacies F) grading up into a sandy, crinoid ossicle-dominated bioclastic grainstone (lithofacies L1) and finally into a sandy, terebratulid brachiopod-dominated bioclastic rudstone/grainstone (lithofacies L2). Fossil debris is predominantly deposited concordant to bedding. Although distinct physical sedimentary structures were not observed, beds (15-60cm thick) and bedsets are arranged in a series of amalgamated lenses (Figure 20d).

Lithofacies association V is characterized by a diverse array of body fossils. Within this succession, lithofacies F is characterized by scattered brachiopods (articulate and inarticulate) as well as bioclastic debris. Whole and unabraded terebratulid Brachiopods (*Aulacothyroides liardensis, A. silvana* and *A. petriana*) are the most common fossils within this succession (Figure 20c). These brachiopods were previously referred to the genus *Coenothyris* (Zonneveld et al., 1997). This genus has however recently been emended (Sandy, 1995) and is now incorporated into the genus *Aulacothyroides*. These brachiopods as well as disarticulated, unabraded cidaroid echinoid elements (*Miocidaris* sp.) and disarticulated, unabraded articulate crinoids (*Holocrinus* sp.) comprise the bulk of lithofacies L. Rare, compressed but articulated crinoid and echinoid specimens were also collected.

Two subfacies have been distinguished within lithofacies L (Figure 19) based on a predominance of echinoderm elements (lithofacies L1) or terebratulid brachiopods (lithofacies L2). Other bioclasts within this lithofacies include acrotretid brachiopods (cf. *Discinisca* sp.), bivalves, rare spiriferid brachiopods (*Spiriferina borealis*), bryozoans, and possibly corals. Lithofacies M is characterized by a wide variety of unabraded body fossils, including crustaceans (decapods and phyllocarids), terebratulid brachiopods (*A. liardensis, A. silvana* and *A. petriana*), acrotretid brachiopods (cf. *Discinisca* sp.), echinoid elements (*Miocidaris* sp.) and several types of bivalves. Fish skeletal debris (including the palaeonisciform *Bobasatrania*) and marine reptile bones (ichthyosaurs and thalattosaurs) occur throughout lithofacies V.

The *Cylindrichnus-Palaeophycus* assemblage, consisting of *Asterosoma, Cylindrichnus* (Figure 20f), *Palaeophycus,* and *Rosselia* occurs within bioclastic sandstone (Lithofacies F) adjacent to thick bioclastic rudstone/grainstone accumulations (lithofacies L). Numerous, densely-packed, large, robust *Teichichnus* occured within very fine-grained, quartz-dominated sandstone (lithofacies F) within this lithofacies association at Glacier Spur (Figure 20e).

Numerous terebratulid brachiopods within lithofacies L2 display groupings of microscopic dissolution pits, interpreted as the trace fossil *Podichnus* (Zonneveld *et al.*, 1997). The size and geometry of these pit concentrations is inconsistent with traces made by sponges or other benthic boring organisms, but are consistent with the shape and size of the distal end of a terebratulid brachiopod pedicle. They are interpreted to be the result of dissolution via chemicals secreted from brachiopod pedicles (Bromley and Surlyk, 1973; Zonneveld *et al.*, 1997).

Interpretation- Lithofacies association V, interpreted as reef mounds or biostromes composed primarily of whole and unabraded terebratulid brachiopods, articulate crinoid elements and cidaroid echinoid spines and interambulacral plates accumulated within the Liard shoreface during periods of comparably low siliciclastic input (Zonneveld *et al.*, 1997). The terebratulid-echinoderm reef mounds were initiated by a process referred to as allogenic taphonomic feedback (Kidwell and Jablonski, 1983; Kidwell, 1991). Storm-generated skeletal concentrations provided "islands" of comparably stable substrate (Figures 21, 21b). These islands provided a locus for colonization by stable substrate-preferring organisms (Figure 21c) such as the terebratulid brachiopods *Aulacothyroides liardensis, A. silvana* and *A. petriana*, cidaroid echinoids (*Miocidaris* sp.), articulate crinoids (*Holocrinus* sp.), bryozoans, and rare spiriferid brachiopods (*Spiriferina borealis*). These biostromes likely underwent numerous cycles of colonization, storm burial, re-exhumation and recolonization (Figures 21d through 21f).

The protected back reef environment provided a haven for an abundance of organisms, including crustaceans (decapods and phyllocarids) acrotretid brachiopods (cf. *Discinisca* sp.), a variety of bivalves (including *Modiolus* sp.), echinoids (*Miocidaris* sp.). Fish (including the palaeonisciform *Bobasatrania*) and marine reptiles (ichthyosaurs and thalattosaurs) frequented the biostromes, likely feeding on brachiopods and echinoids (and possibly each other).

Trace fossils (*i.e. Asterosoma, Cylindrichnus, Palaeophycus, Rosselia* and *Teichichnus*) within quartz-dominated sand layers and lenses which interdigitate with sandy bioclastic grainstone/rudstone layers suggests continuous turnover of infaunal and epifaunal communities at the edges of the Liard brachiopod-echinoderm biostromes. These trace fossils reflect a mixed popultion of horizontal (*i.e. Asterosoma, Teichichnus*) and vertical (*i.e. Cylindrichnus, Rosselia*) deposit feeding organisms, consistent with deposition in a lower shoreface environmental setting.

LITHOFACIES ASSOCIATION VI: Silicilastic-Carbonate Marginal Marine

Summary- Occurrence of this lithofacies association at the Brown Hill and Glacier Spur localities was discussed briefly by Zonneveld *et al.* (1997) and in detail by Zonneveld and Gingras (in press) and is summarized briefly here.

Lithofacies association VI (Figure 22) is a heterolithic amalgamation of seven sedimentary facies (I, O, P1, P2, Q, R1, R2, S T and U; Table 2), and occurs as a thin horizon within the upper Liard Formation at Beattie Ledge (Figure 6), Glacier Spur (Figure 5) and Brown Hill (Figure 4). Marginal marine deposits within the Liard Formation were subdivided by Zonneveld and Gingras (in press; Chapter 2) into four lithofacies successions:

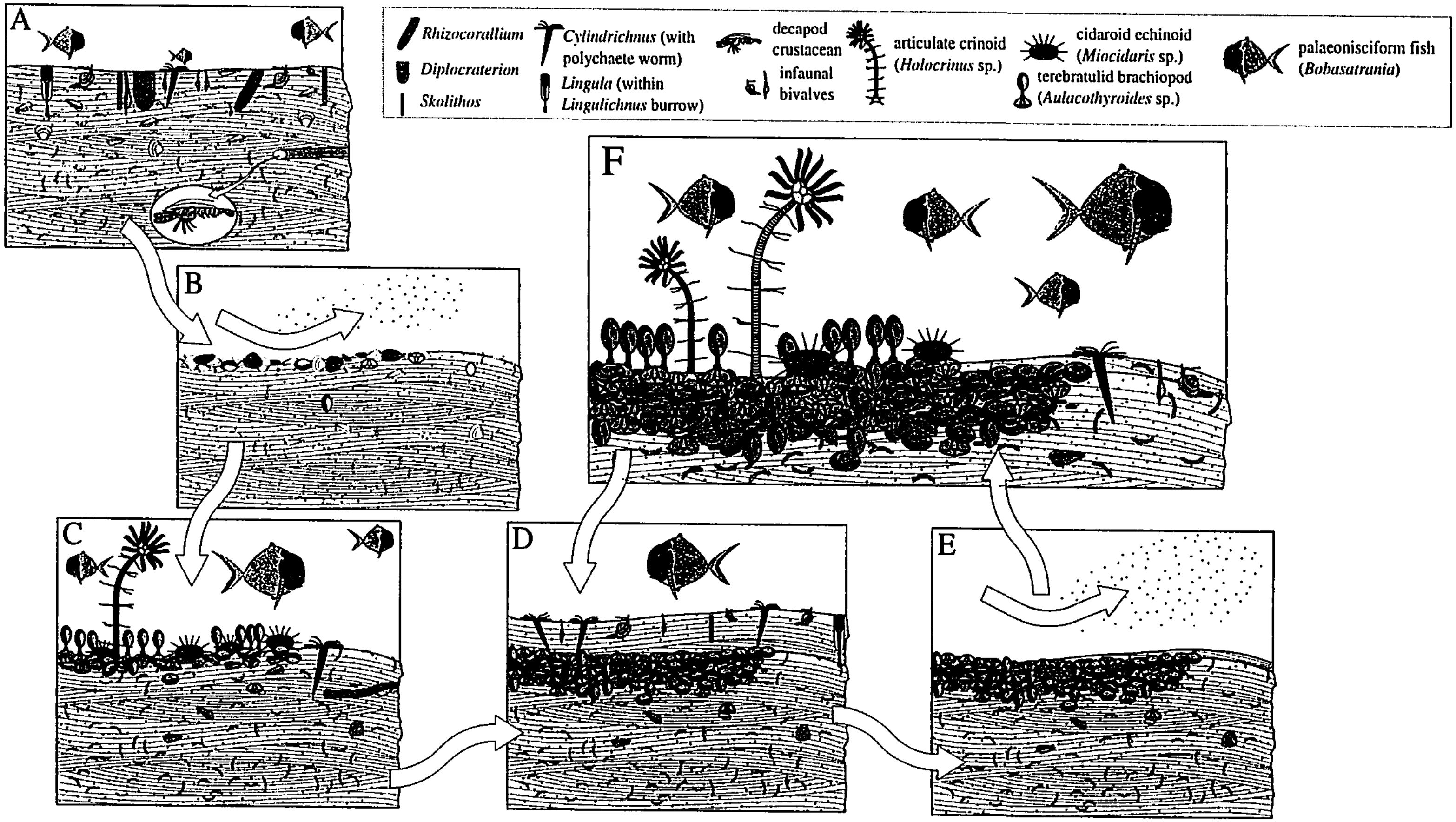


Figure 21. Development of brachiopod-echinoderm dominated biostromes in the Liard shoreface. The lower shoreface is normally populated by a diverse infaunal assemblage dominated by burrowing bivalves, lingulid brachiopods, arthropods and polychaetes (**Figure 21a**). Winnowing of very-fine grained sand by storm-generated currents leaves a lag of bioclastic detritus at the sediment/water interface (**Figure 20b**). This comparably stable substrate is quickly colonized by hardground-preferring epifaunal organisms such as articulate crinoids, terebratulid brachiopods, and cidaroid echinoids (**Figure 20c**). Storm currents, as well as normal shoreface currents, frequently bury part or all of the biostrome in siliciciclastic sand which is recolonized by infaunal organisms (**Figure 20d**). Storm- generated currents re-exhume the bioclastic hardground (Figure 20e) which is subsequently recolonized by epifaunal organisms (**Figure 20f**). Abundant quartz- dominated sand layers and lenses between whole-bioclast dominated grainstone layers suggests continuous turnover of infaunal and epifaunal communities at the edges of the Liard brachiopod-echinoderm biostromes.

(1) washover fan/lagoonal; (2) intertidal mudflat (Figures 23a, 23c, 23d); (3) supratidal sabkha (Figure 23b); and (4) aeolian dune; which are grouped here into the mixed siliciclastic-carbonate lithofacies association.

Washover fan/lagoonal deposits (lithofacies O, P, and Q) are characterized by a low diversity assemblage of trace fossils consisting of *Gyrochorte*, *Palaeophycus*, *Planolites*, *Skolithos* and an as yet undescribed type of bivalve resting trace. Traces within lagoonal settings (lithofacies P2) including *Cylindrichnus*, *Gyrolithes* and *Trichichnus*, are generally diminutive, consistent with growth in a stressed environment.

Intertidal mudflat deposits (lithofacies P2, R1 and R2) are characterized by *Arenicolites, Cylindrichnus* (Figure 23a), *Conichnus, Diplocraterion, Gyrolithes, Laevicyclus, Lockeia, Skolithos*(Figure 23a), *Palaeophycus, Planolites, Rhizocorallium, Siphonites, Skolithos, Taenidium, Teichichnus, Thalassinoides* as well as bivalve adjustment traces, ray (?) feeding pits and escape traces ((Figure 23c). Sandy layers, interpreted as intertidal tempestites, contain a robust assemblage of post-event, opportunistic colonizers imported from seaward in conjunction with storm-transported sediments. Bedforms such as flaser (Figure 23c) and wavy bedding, typical of tidally influenced deposits, are difficult to discern in the Liard formation due to low variability in sediment grain sizes (Zonneveld and Gingras, in press). The presence of abundant minor channel sands and starved current ripples in the mudflat facies indicates ebb-dominated flow in an intertidal setting and possibly the presence of back-barrier tidal creeks (Zonneveld et al., 1997).

Supratidal sabkha deposits (lithofacies P2, R2, S and T) are characterized by wavy to ripple laminated dolomitic siltstone and solution (Figure 23b), collapse breccia and by a low-diversity trace fossil assemblage consisting of *Cylindrichnus, Monocraterion, Ophiomorpha* and *Palaeophycus*. Solution collapse breccia and root traces overprint primary physical sedimentary structures as well trace fossils, suggesting cycles of dessication and rejuvenation of the lakes (Zonneveld and Gingras, in press). Similar to lakes and lagoons within the Coorong region of Australia, dolomite forms within lagoonal/intertidal mudflat settings and in supratidal sabkhas within the Liard Formation (Zonneveld and Gingras, in press). The dolomite formed by primary precipitation during annual evaporitic concentration of groundwater, and by periodic mixing of comparably low-salinity continental groundwater with marine-derived groundwater (von der Borch *et al.*, 1975; von der Borch and Lock, 1979). Coorong style dolomitization implies seasonality in precipitation, and correspondingly in recharge of shore proximal lakes, along the northwest coast of Pangea.

Aeolian dune deposits (lithofacies U) are characterized by well-sorted, fine-grained sandstone exhibiting well-defined lamination within large-scale, planar cross-beds. Bedsets are tabular to wedge-planar, varying in thickness from 10 to 120 centimetres in thickness. Lower bounding surfaces are coplanar with internal bedding. Individual laminae and laminasets are inversely graded, steepen upwards within beds, and are generally concave upward. Neither trace fossils nor body fossils were observed in lithofacies I.

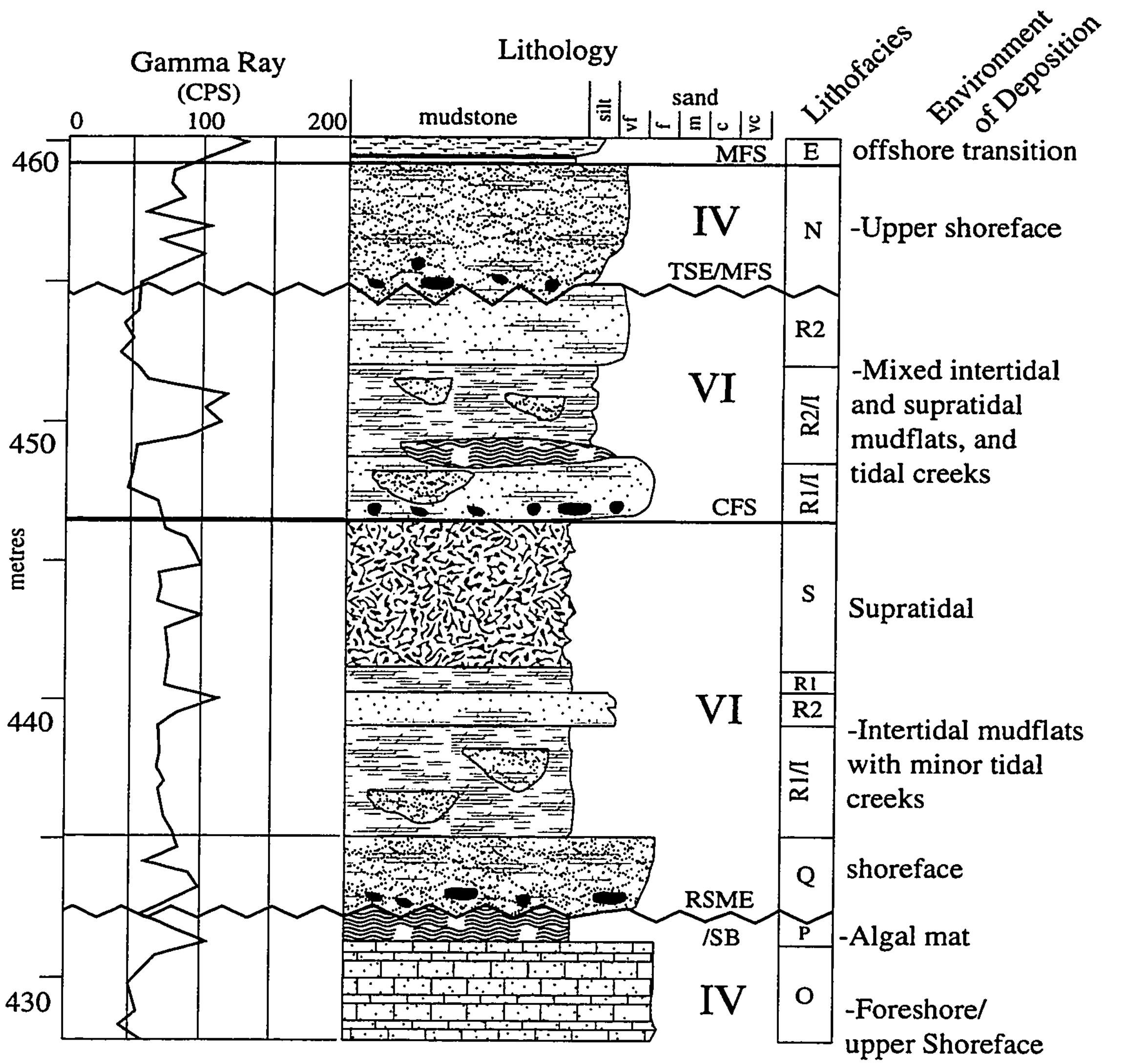


Figure 22. Detailed stratigraphic section showing the vertical arrangement of sedimentary facies in typical Lithofacies Association VI parasequences (upper Liard Formation, Brown Hill). Roman numerals to the right of the lithology column denote the lithofacies association designation. Lithofacies are summarized in Table 2. RSME/SB= regressive surface of marine erosion; MFS= marine flooding surface; CFS= correlative flooding surface; TSE/MFS= transgressive surface of erosion/marine flooding surface.

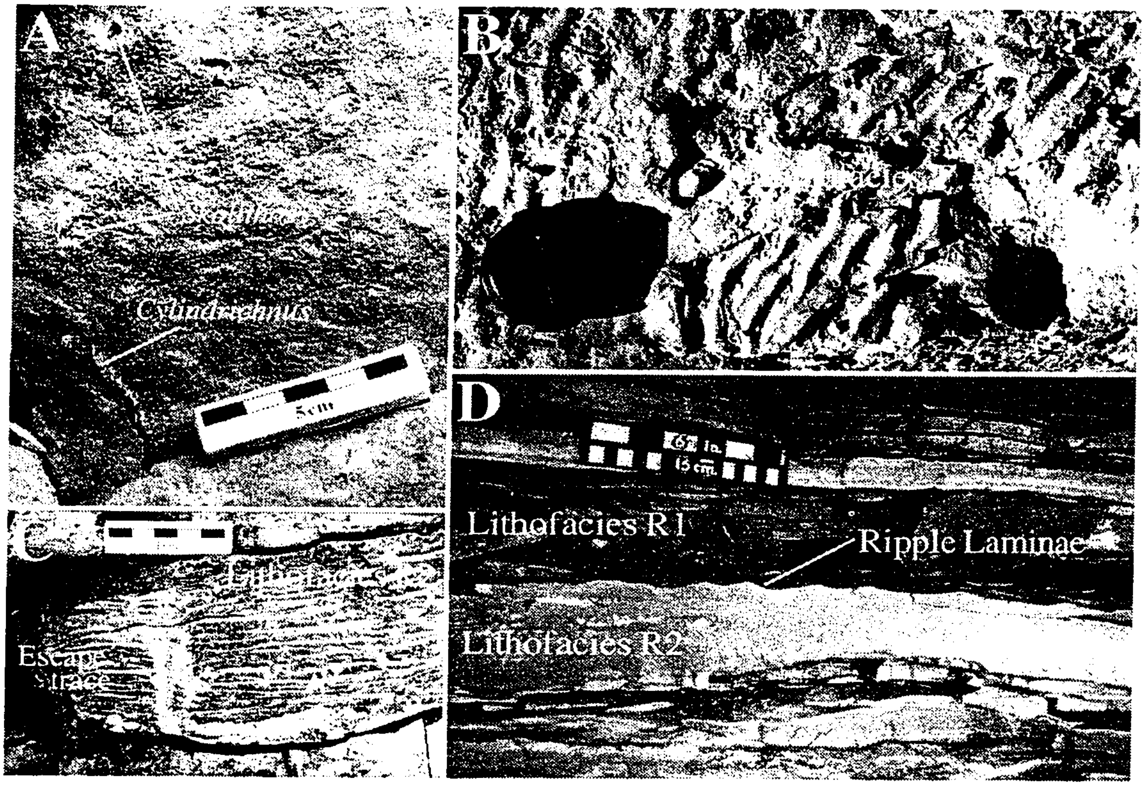


Figure 23a. Dolomitic sandstone with abundant trace fossils including *Cylindrichnus* and *Skolithos* deposited within an intertidal flat setting (lithofacies R2; intertidal flat), Brown Hill, Liard Formation (440m). **Figure 23b.** Oscillation ripple-laminated dolomitic mudstone deposited within a supratidal lacustrine setting (lithofacies T; supratidal sabkha), Beattie Ledge, Liard Formation (175m). **Figure 23c.** Flaser bedded dolomitic sandstone with escape traces deposited within (lithofacies R2; intertidal flat), Brown Hill, Liard Formation (436m). **Figure 23d.** Interbedded dolomitic siltstone (lithofacies R1; intertidal flat) and ripple-laminated dolomitic sandstone (lithofacies R2; intertidal flat) Brown Hill, Liard Formation (450m).

Although sandstone interpreted as aeolian dunes are common within the overlying Charlie Lake Formation (Arnold, 1994), within the Liard Formation they occur only at Beattie Ledge, interbedded with pedogenically altered carbonate siltstones (lithofacies S and T; Zonneveld and Gingras, in press).

CONTROLS ON SEDIMENT COMPOSITION

Descriptions of Recent and Holocene arid coastlines have primarily emphasized carbonate depositional systems. Although many examples of Recent carbonate deposition exhibit transition with siliciclastic-dominated systems (Shark Bay, Australia; Belize Reef Tract; Persian Gulf), this aspect has been largely overlooked (Roberts, 1987). This trend has reversed itself in recent years with excellent descriptions of several Recent/Holocene, mixed siliciclastic-carbonate, coastal depositional systems (*i.e.* Belparrio *et al.*, 1988; Choi and Ginsberg, 1990; Early and Goodell, 1990; Frey and Pinet, 1990; Fuller *et al.*, 1994; Maxwell and Swinchatt, 1990; Purser *et al.,* 1990; Roberts, 1987; Semeniuk, 1993; 1996 Shinn, 1990). Mixed siliciclastic-carbonate deposition generally occurs along coastlines with limited siliciclastic input or exceptionally low seaward gradients (Selley, 1970). Although not restricted to mid-latidudes, mixed siliciclastic-carbonate coastal deposition within Recent and Holocene systems is most prevalent between ~25-40° north and south of the equator.

Mixed siliciclastic-carbonate deposits occur as a result of either spacial variability in lithofacies, or temporal variability in sedimentation patterns (Budd and Harris, 1990). The transition of deposition between carbonate and siliciclastic sediments is largely controlled by climate, tectonic setting (Roberts, 1987), and fluctuations in sea-level. Mixed siliciclastic-carbonate deposition within the Grayling, Toad and Liard Formations is due to several factors, including a unique tectonic setting, an arid climate, and biological constraints (including but not limited to patterns in faunal recovery in the aftermath of the Permian-Triassic crisis).

Geomorphic and Tectonic Influence

The textural and mineralogical maturity of siliciclastic sediments within the study area were, in part, governed by topographic relief and compositional parameters of antecedent strata. Low relief of the coastal plain and in the sediment source area severely constrained the nature of sediment available for transport to the coastal zone. Samarium-Neodymium (Sm-Nd) isotopic analysis of zircons derived from whole rock shale and sandstone samples from the Liard Formation along the Liard River north of the study area suggest that some of the siliciclastic sediment that comprises the Liard Formation is reworked from the Innuitian (Precambrian; Ellesmerian) clastic wedge that may have covered the Canadian shield northeast of the study area (Ross *et al.*, 1997). Coarse (*i.e.* >sand) siliciclastic sediment within the study area consists slmost solely of chert granules and pebbles. This material is similar in composition to samples from the underlying Fantasque Formation (upper Paleozoic), suggesting that late Paleozoic strata may, at least locally, have supplied a portion of siliciclastic sediment within the Liard Formation.

Although it has been suggested that tectonism had minimal effect on deposition in the Triassic of western Canada (Gibson & Barclay, 1989; Gibson & Edwards, 1990; O'Connell *et al.*, 1990), an increasing body of evidence suggests this may not be true (Henderson and Zonneveld, 1998; Qi, 1995; Wittenberg, 1992). During the late Permian and early Triassic, subduction along the western margin of Pangaea resulted in collision of a series of island arcs with the western cratonic margin (Davies, 1997a). By the mid-Triassic, extensional breakup had resulted in a narrow seaway separating east and west Pangea (Smith *et al.*, 1994). This tectonic activity, as well as reactivation of local horst-graben complexes may have generated tectono-eustatic sealevel changes which effected sedimentation within the study area.

Climatic Constraints

Although there is minimal substantiated evidence as to the nature of the climate of northwestern Pangaea during the middle Triassic, solution collapse breccias (likely generated by the dissolution of evaporite minerals) in the upper Liard Formation, and the presence of thick solution collapse breccias and evaporite accumulations in the overlying Charlie Lake Formation suggests an arid, or at least seasonally arid depositional setting during the later Triassic (late Ladinian-Rhaetian). Paleocurrent measurements on aeolian sandstones within the Charlie lake Formation indicate a dominant wind direction from the northeast Arnold, (1994).

Climate plays a significant part in coastal processes in arid settings. High evaporation rates, limited rainfall, cyclonic storms, strong winds and severely constrained sediment delivery to the coastal zone combine to produce a unique amalgamation of silicilcastic, bioclastic and chemical sediments (Semeniuk, 1996). Aridity on the northwestern coast of Pangea played a significant role in coastal processes, and thus directly influenced sediment composition within the study area. Factors promoting arid coastal conditions within the study area include seasonal, onshore, cold water, oceanic upwelling (Kristan-Tollman and Tollman, 1982; Davies, 1997), offshore-oriented, northeast to southwest dominated wind direction (Arnold, 1994; Davies, 1997), and geographic position (on the coast of an immense, globe-spanning supercontinent; Figures 8, 24).

Rainfall in arid regions is typically seasonal and often intense (Semeniuk, 1996). During these infrequent rain storms in arid regions, runoff is sudden and intense (*i.e.* flash floods), and may carry an atypically high sediment load (Roberts, 1987), due in part to sparse vegetation in sediment source areas. Within the study area, fluvial transport of terrigenous sediment to the shore zone was ephemeral, likely limited primarily to flash floods associated with cyclonic storms.

While fluvial influx of siliciclastic sediment to the coast was intermittent, aeolian transport of silt and very fine-grained sand likely occured year round. Aeolian transport is an important mechanism in delivering disseminated terrigenous sediments to marine settings downwind of arid regions (Windom and Chamberlain, 1978). Disseminated sand and silt in

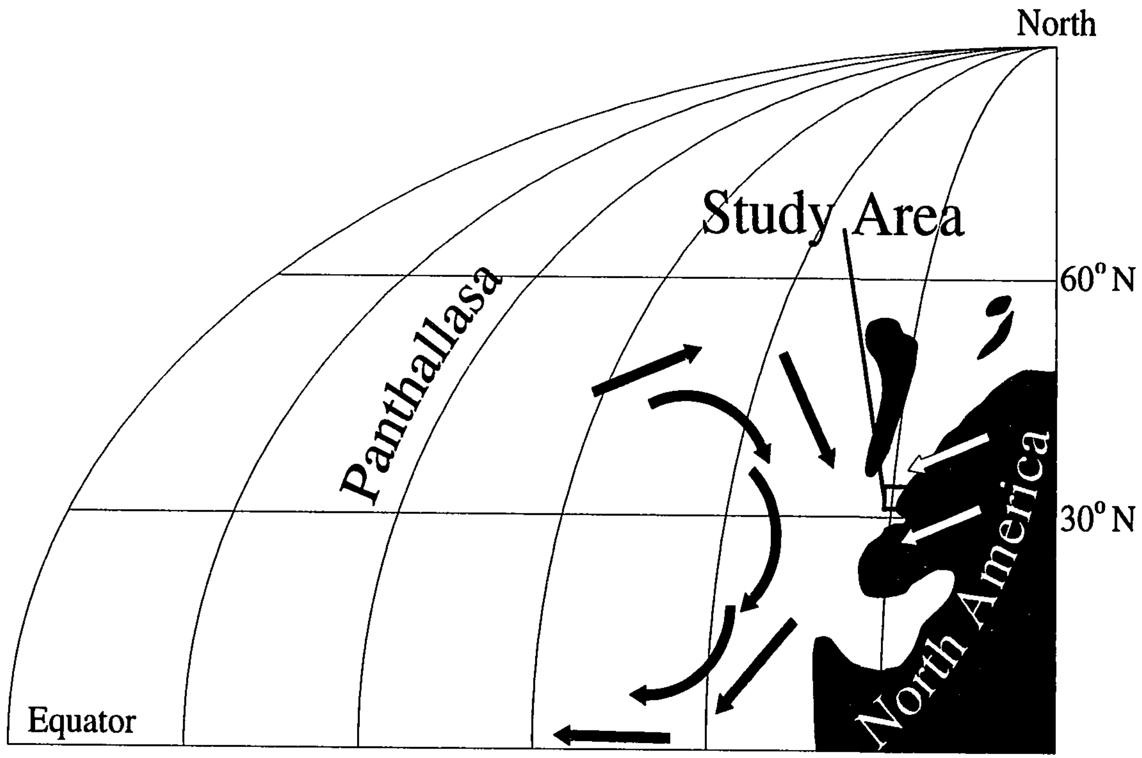


Figure 24. Generalized Early to Middle Triassic summer paleocirculation patterns in the northwestern quarter of the globe. Arid coastal conditions within the study area were promoted by seasonal, onshore, cold water, oceanic upwelling caused by marine circulation cells (black arrows) and offshore-oriented, northeast to southwest dominated wind direction (white arrows) Adapted from Kristan-Tollman and Tollman (1982), Davies (1997) and Arnold, (1994). During the winter (not shown), offshore barometric highs would have moved south towards the equator and western Canada would have been dominated by onshore cyclic storm winds (Davies, 1997).

black, offshore shales (lithofacies A) and within dolomitic mudstone/siltstone and cyanobacterially laminated mudstone (lithofacies P, R and T; intertidal/supratidal flats/shore proximal lacustrine) may have been sourced by aeolian transport from contemporaneous continental environment. Although the provenance cannot be unambiguously ascertained, well rounded, fine grained quartz and chert sand in Middle Triassic shoreface sandstones may also be attributed to aeolian processes (Davies, 1997).

Arid climatic conditions within the study area likely resulted in high evaporation rates in intertidal and supratidal settings, and in embayments along the coastline (Burne *et al.*, 1980; Flessa and Ekdale, 1987; Gostin *et al.*, 1984). High evaporation rates facilitated precipitation of carbonate minerals in the Liard intertidal/supratidal zone (Zonneveld and Gingras, 1997). Restricted embayments, lagoons and shore proximal lakes were likely seasonally hypersaline, resulting in deposition of evaporite minerals.

Proximity to a Siliciclastic Point Source

The fine-grained nature of shoreface sediments is due, at least in part, to low clastic input to the Liard shoreface. Low clastic input in the study area has been attributed to low-relief and thus low sediment availability in the source area and to minimal or intermittent fluvial input to the shoreline (Davies, 1997; Zonneveld and Gingras, *in press*). Sediment textural maturity within the study area has previously been interpreted as evidence of distance from a point-source of clastic sediment (Zonneveld *et al.* 1997). However several lines of evidence suggest otherwise. Granule to pebble-sized chert clasts are locally abundant within sediments interpreted as turbidite channels (lithofacies D), rip-tidal channels (lithofacies H), transgressive shoreface (lithofacies J) and proximal upper shoreface/foreshore (lithofacies N). Medium and coarse-grained sand infill desiccation cracks and burrows within intertidal deposits, likely as a result of storm transport and deposition. The lower Carboniferous conodont (*Siphonodella*, Gibson, 1996) was identified from transgressive shoreface deposits (lithofacies J). Although equivocal, these factors provide strong evidence of a local siliciclastic sediment source, either within or in a location proximal to the study area.

The nature of lithofacies association III varies significantly between Brown Hill and Glacier Spur, where the carbonate clasts/nodules are smaller, more highly rounded and deposited concurrent to cross-stratifiaction. It has previously been proposed that lithofacies association III was deposited along an arid-system, ephemeral deltaic coastline (Zonneveld *et al.*, 1998). Carbonate clasts eroded from partially lithified highstand shoreface deposits were redeposited in transgressive shoreface sediments and in the mouths of wave-dominated ephemeral deltas. The low clastic content of these deposits is attributed to low-relief and thus low sediment availability in the source area and to ephemeral/seasonal fluvial input. Siliciclastic sediments transported to the shoreface via seasonal fluvial input were transported laterally by strong longshore currents and disseminated throughout the shoreface by normal wave action and by storm processes. Deltas of this type experience continuous cycles of short term delta construction in the aftermath of severe inland rain storms and longer term delta destruction and sediment redistribution by longshore processes between episodes of fluvial discharge (Semeniuk and Searle, 1987; Semeniuk, 1996).

The morphology of these features may vacillate from positive features (shoreface protuberances) after substantial sediment influx, to negative features (shallow embayments) during the delta destruction phase. Evaporative water loss from embayments in arid settings may produce a net influx of water and suspended sediment (Furisch *et al.*, 1991; Flessa and Ekdale,), resulting in the silt to very fine-grained sand matrix surrounding the bioclastic nodules.

Arid system deltaic deposits associated with ephemeral fluvial input are difficult to distinguish from normal, shoreface deposits. The deposits described here are similar in many respects to present-day eroding ephemeral deltas along the Pilbara coast of northwestern Australia (Semeniuk and Searle, 1987; Semeniuk, 1996). These 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). One of the most characteristic features of these "relic" deltas are pavements of eroded carbonate beachrock (Semeniuk and Searle, 1987; Semeniuk, 1996).

Biological Constraints

One of the primary differences between carbonate and siliciclastic depositional systems is that carbonate systems generate sediments *in situ*. For a mixed system to develop, it is not enough to simply limit siliclastic input, there must also be a significant and persistent source of carbonate sediment. Framework reefs, primary sources of detrital carbonate through the Paleozoic and later Mesozoic, are globally unknown from the early Triassic (Flügel, 1994). The first true patch reefs on the west coast of Pangea occur in Upper Triassic accretionary terranes (Reid and Ginsberg, 1986; Stanley, 1989).

Within the study interval, the primary sources of carbonate sediment are thick brachiopod-echinoderm dominated biostromes located within the lower shoreface. Initiation, growth and composition of these authigenic bioclastic accumulations was constrained by several ecological and environmental parameters including water turbidity, sedimentation rates, substrate stability and resource availability. The model envisioned here involves allogenic taphonomic feedback (Kidwell and Jablonski, 1983; Kidwell, 1991); colonization of patches of comparably stable substrate by an epifauna dominated by terebratulid brachiopods cidaroid echinoids and articulate crinoids (Zonneveld *et al.*, 1997), and to a lesser extent, spiriferid brachiopods, bryozoans, acrotretid brachiopods and possibly corals. High carbonate productivity, consisting primarily of infaunal bivalve, also occurred in intertidal flat deposits,

Taxononmic composition of these biostromes was significantly affected by recovery patterns in the aftermath of the Permian-Triassic crisis. Characteristic reef taxa such as tabulate and rugose corals were eliminated during the extinction while others were severely impacted (Erwin, 1993). Echinoderms were particularly hard hit. Echinoids and crinoids, both significant components of the Liard biostromes, were reduced to a few genera (Erwin, 1993). Brachiopods are arguably the most abundant and diverse Permian fossils (Erwin, 1993). Although spiriferid brachiopod diversity was considerably reduced by the extinction, terebratulids were essentially unaffected. Spiriferids rebounded rapidly, and by the late Middle Triassic had attained pre-extinction diversity levels (Tasch, 1973). Terebratulid diversity gradually increases through the Triassic (Tasch, 1973).

It is postulated that the composition of the Liard biostromes reflects opportunistic niche expansion of terebratulid brachiopods due in part to the demise of competitors as well as population expansion due to the demise of traditional predators during the Permian-Triassic extinction event. In the absence of reefs, the Liard biostromes provided an ideal situation for opportunistic colonization by articulate crinoids, cidaroid echinoids and bryozoans, taxa which prefer stable substrates (Zonneveld *et al.*, 1997).

Within the study area these biostromes attain thickness ranging from 2 to 12 metres. Brachiopods, living and fossil alike, require well-oxygenated water and minimal turbidity. Since the brachiopods and crinoids were sessile (i.e. permanently attached to the substrate), high sedimentation rates would quickly have suffocated the biostromes. An annual influx of sediment in excess of a decimetre, or a blanket of sand several centimetres in thickness deposited within a single storm may have been enough to smother these epifaunal residents. A decrease or cessation in siliciclastic input to the shoreface was neccessary therefore to allow the biostromes to attain appreciable thicknesses. Numerous hiatal surfaces, some overlain by thin, quartz-dominated sand layers occur within each biostrome suggesting that they were periodically buried by shifting sands, reexhumed during periods of low siliciclastic input, and subsequently recolonized. This model is consistent with deposition along an arid coast characterized by infrequent and ephemeral influx of fluvially-derived terrigenous sediment.

DISTRIBUTION OF BIOCLASTIC SEDIMENT

As discussed above, carbonate sediment within the Grayling, Toad and Liard interval is predominantly biogenic in origin and was derived from two distinct sources: 1) intertidal and subtidal production from bivalves, gastropods, and brachiopods, and 2) shoreward transport of subtidally produced (primarily within lower shoreface biostromes) brachiopod, bivalve, echinoid and crinoid skeletal debris. From these sources, carbonate sediment is redistributed throughout the offshore, shoreface, and intertidal zones. All six lithofacies associations discussed in this paper contain a significant carbonate component.

Siliciclastic and bioclastic grains display an inverse relationship within the Liard shoreface, due in part to cross-shore transport of coarse and fine-grained sediment fractions (Chapter 3). Beach face slope and grain size is governed by the asymmetry of swash intensity and the asymmetry of onshore-offshore sand transport (Komar, 1976). Percolation of water through sand and friction of the return flow result in weaker backwash than shoreward uprush (Komar, 1976). Sediment transport will be predominantly shoreward and the slope of the beach face will increase until an angle is reached at which an equivalent amount of material is being transported in each direction and the slope is in dynamic equilibrium (Komar, 1976). Although the amount of material transported is roughly equal, grain-sizes transported in each direction differ. Coarser fractions are transported onshore while finer fractions are transported offshore (Bowen, 1980; Nummedal, 1991).

Grain size is only one factor effecting sediment segregation however. Although the specific gravities of quartz and shell-forming minerals (calcite and aragonite) are not remarkably different, quartz sand and bioclastic detritus are not hydraulic equivalents. Wrack-line shell accumulations along the coasts of Georgia (Frey and Dörges, 1988; Frey and Pinet, 1978) and Padre Island, Texas (Watson, 1971) are governed primarily by longshore drift and tend to accumulate within beach concavities. Shells and coarse sand accumulate in protected zones of longshore current convergence, and are concentrated by aeolian deflation of fine-grained sediment (Watson, 1971). Although these authors primarily discussed whole bioclasts, the hydraulic behavior of abraded sand to gravel sized bioclastic sediment is likely governed by the same mechanisms. Factors controlling the accumulation of bioclastic material in the Liard upper shoreface and foreshore include grain size, shape and density.

During severe storms sediments were redistributed through the entire succession. Storm loading would have produced higher sea levels along the coast (Seilacher and Aigner, 1991), driving waves and suspended sediment far inland, as observed within lithofacies association VI. During peak storm intensity, the effective wave base is greatly increased due to increased wave-length of surface waves, and to storm-wave generated turbulence (Aigner, 1982). Differing water levels in the coastal zone and offshore generated obliquely-oriented basinward bottom flow (Aigner, 1985), which existed as long as the pressure gradient persisted (*i.e.* the length of the storm). This flow distributed bioclastic detritus to the lower shoreface and offshore and is responsible for bioclastic tempestites and turbidites emplaced within the lower shoreface, offshore transition and proximal offshore (lithofacies association II). Strong storm-generated rip currents also moved bioclastic detritus in an offshore direction. Rip currents are particularly strong immediately after severe storms (Gruszczyński *et al.*, 1993). Coarse, crudely cross-stratified bioclastic lags incising shoreface sands are attributed to basinward transport during strong post-storm seaward flow (Aigner, 1985; Gruszczyński *et al.*, 1993).

The Williston Lake turbidite succession (lithofacies association I) differs from most siliciclastic examples in the literature by the presence of a significant detrital carbonate component. While carbonate turbidites are themselves not particularly rare, mixed clastic-carbonate turbidite successions are poorly documented. Two types of bioclastic accumulations have been identified within lithofacies association I: a) normally graded, fine-grained, bioclastic grainstone lenses (lithofacies B) interbedded with laminated black shale (lithofacies A; figure 4c) or siltstone/sandstone beds (lithofacies C); and b): laterally restricted sandy bioclastic rudstone/grainstone incising through a succession of normally graded siltstone/sandstone beds (lithofacies D; figure 4d). The presence of bioclastic turbidites (lithofacies B) in an otherwise siliciclastic depositional system implies a cessation or interruption in clastic sediment supply to the slope or episodic basinward transport of shore-proximal bioclastic sediment. These punctuations in siliciclastic input may be driven by either climatic, eustatic or autocyclic forces.

During transgressive and highstand conditions, the distal shelf and slope are starved of siliciclastic sediments. Pelagically-derived skeletal debris comprises a higher proportion of the sediment and is the dominant coarse-fraction constituent at these times. Bioclastic debris thus comprises the basal component of each mixed carbonate-siliciclastic Bouma succession (A, B), grading upwards into mixed clastic-carbonate silt (C and D) and finally pelagic shale (E).

Alternatively, these bioclastic turbidites may result from climatic fluctuations. During prolonged periods of drought, clastic input to the shoreface effectively ceases and carbonate sediments predominate. Redistribution of these sediments to the offshore, most likely via slope instability, sediment loading or seismicity, may have resulted in bioclastic turbidites.

Lithofacies D, a thick bioclastic rudstone/grainstone composed of abraded, fragmentary brachiopods (terebratulid and spiriferid), bivalve and echinoderm detritus, interpreted as a submarine turbidite channel, incises deeply into underlying strata. Within the study area, *in situ* accumulations of terebratulid brachiopods, spirifirid brachiopods, crinoids and echinoids are restricted to mixed siliciclastic-carbonate shoreface sediments (lithofacies association IV) within the Liard Formation. Basinward transport of coarse bioclastic material characteristic of a proximal depositional setting through a channel incising fine-grained clastic sediments is interpreted as evidence for a relative lowstand in sea level.

CONCLUSIONS

The early-middle Triassic (Griesbachian-Ladinian) Grayling, Toad, and Liard Formations outcrop extensively along the shores of Williston Lake. These units preserve a continuum of basinal through marginal and non-marine strata deposited within mixed siliciclastic-carbonate depositional systems on the northwestern margin of Pangea. These Formations are characterized by twenty-one lithofacies within six distinct lithofacies associations: I) shelf/ramp turbidites; II) clastic offshore/shoreface; III) transgressive shoreface; IV) mixed siliciclastic-carbonate shoreface; V) brachiopod-echinoderm biostrome, and VI) mixed siliciclastic-carbonate marginal marine.

Lithofacies Association I (slope fan turbidites) consists of a thick succession of normally graded, interbedded units of very-fine-grained sandstone, siltstone and shale. These units are interpreted to have been deposited by turbidity current processes in turbidite fan lobes in a medial shelf to ramp setting. A thick, laterally dicontinuous bioclastic rudstone/grainstone incises these deposits in the basal portion of the Brown Hill section and is interpreted as a turbidite channel.

Lithofacies Association II (clastic offshore through upper shoreface) was deposited on a storm-dominated, prograding barrier island shoreline. In a typical lithofacies association B parasequence, thin distal tempestites grade upwards through hummocky and trough cross-stratified sandstone. These progradational parasequences are locally incised by tidal inlet channels and show many indications of storm-influenced deposition (Zonneveld *et al.*, 1997).

Lihofacies association III (transgressive shoreface) is interpreted to have been deposited during early transgression along a wave-dominated coastline characterized by abundant partially lithified beachrock. Coarse-grained bioclastic detritus was concentrated in the upper shoreface and foreshore by wave activity during sea-level highstand. Bioclastic shoreface sediments were subaerially exposed and quickly cemented welding the bioclasts into a lithified packstone. This likely occured during a period of relatively low sea-level. Transgression resulted in marine erosion of these lithified sediments resulting in a carbonate breccia lag eroding from a rocky shoreline. During late transgression, the residual breccia passed beneath the zone of effective wave reworking and the larger blocks were colonized by hardground-preferring epifaunal organisms. A thin, brachiopod grainstone comprised of whole, articulated, unabraded, randomly oriented terebratulid and spiriferid brachiopods within a siltstone matrix is interpreted to reflect reworking of these epifaunal hardground colonizers during transgression.

Lithofacies association IV (mixed siliciclastic-carbonate shoreface) consists of a coarsening upwards, mixed siliciclastic-carbonate, shoreface succession. In a typical lithofacies association IV parasequence, the proportion of bioclastic material increases significantly and that of siliciclastic material decreases significantly from bottom to top, a phenomenon attributed to the cross-shore transport of coarse bioclastic detritus and fine-grained sands.

Lithofacies association V (brachiopod-echinoderm biostrome) was the dominant source of carbonate sediment within the Liard shoreface. This unique biogenic association consists of brachiopods (terebratulids, spiriferids, lingulids and acrotretids) echinoderms (cidaroid echinoids and articulate crinoids), bivalves, arthropods (decapods and phyllocarids). bryozoans and possible corals. These accumulations were initiated by allogenic taphonomic feedback. The lower shoreface was normally populated by a diverse infaunal assemblage dominated by burrowing bivalves, lingulid brachiopods, arthropods and polychaetes. Winnowing of very-fine grained sand by storm-generated currents left lags of bioclastic detritus which were quickly colonized by hardground-preferring epifaunal organisms such as articulate crinoids, terebratulid brachiopods, and cidaroid echinoids. Storm currents, as well as normal shoreface currents, frequently buried part or all of the biostrome in siliciciclastic sand which was subsequently recolonized by infaunal organisms.

Storm-generated currents frequently re-exhumed the bioclastic hardground which was subsequently recolonized by epifaunal organisms. Quartz-dominated sand layers and lenses between bioclastic grainstone layers suggest a continuous turnover of infaunal and epifaunal communities at the edges of the Liard brachiopod-echinoderm biostromes.

Lithofacies association VI represents the shallowest deposition within the study interval and is a complex succession of siliciclastic and carbonate sediments deposited within washover fans, backbarrier lagoons, intertidal mudflats, minor tidal channels, aeolian dunes and supratidal sabkhas.

Significant factors promoting mixed deposition within the upper Liard Formation include an arid climate, fluctuations in sediment supply, variability in sedimentation style and source, a significant source of biogenic carbonate sediment and lateral shifts in lithofacies. The overall fine-grained and well-sorted nature of these sediments reflects both hydrodynamic winnowing and a texturally mature (recycled) sediment supply. Siliciclastic sediment within the study area was derived from aeolian transport, longshore drift from depocentres, both outside and within the study area, and episodic fluvial input to the shoreface. The low clastic content of the Liard deltaic deposits is attributed to low precipitation, low-relief and thus low sediment availability in the source area and to ephemeral/seasonal fluvial input. Siliciclastic sediments transported to the shoreface via seasonal fluvial input were transported laterally by strong longshore currents and disseminated throughout the shoreface by normal wave action and by storm processes.

Carbonate sediment within the study interval was derived primarily from marine biogenic sources and is dominated by bioclastic sand. Siliciclastic and bioclastic grains display an inverse relationship within the Liard shoreface, due primarily to cross-shore transport of coarse and fine-grained sediment fractions. Coarse bioclastic detritus in excess of the equilibrium grain size was preferentially transported shoreward, while finer grained siliciclastic sediments were preferentially transported basinward.

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CHAPTER 5.

SEQUENCE BIOSTRATIGRAPHIC FRAMEWORK OF A MIXED SILICICLASTIC-CARBONATE DEPOSITIONAL SYSTEM: MIDDLE TRIASSIC, PEACE RIVER FOOTHILLS, NORTHEASTERN BRITISH COLUMBIA

"During intervening periods, the space may either remain unaltered, or suffer what is termed denudation, *in which case a superior set of strata are removed by the power of running water, and the subjacent beds are laid bare, as happens wherever a sea encroaches upon a line of coast. By such means, it is obvious that the discordance in age of rocks in contact must often be greatly increased.*

The frequent unconformability in the stratification of the inferior and overlying Formationis another phenomenon in their arrangement, which may be considered as a natural consequence of those movements that accompany the gradual conversion of part of an ocean into land; for by such convulsions the older set of strata may become rent, shattered, inclined, and contorted to any amount."

Charles Lyell, 1833

INTRODUCTION

Since the advent of modern sequence stratigraphy in the early 1980's, emphasis has been placed on analyzing the Middle Triassic of the Western Canada Sedimentary Basin (WCSB) within a chronostratigraphic framework (*i.e.* Arnold, 1994; Caplan, 1992; Caplan and Moslow, 1997; Evoy, 1995, 1997; Evoy and Moslow, 1996; Willis, 1992; Wittenberg, 1992 and Young, 1997). With the exception of Arnold's (1994) analysis of the Charlie Lake Formation, these studies have been limited to relatively discrete subsurface regions, generally as part of a reservoir-centred analysis of oil/gas fields or groups of oil/gas fields east of the Foothills outcrop belt.

Previous studies of the Grayling, Toad and Liard Formations (Table 1) of northeastern British Columbia have concentrated primarily on ammonoid biostratigraphy and Formation delineation (MacLearn, 1930; 1940a; 1940b; Pelletier, 1964; Gibson, 1971; 1975; Gibson & Edwards, 1990; 1992; Tozer, 1967; 1994) and to a lesser extent on sedimentary facies analysis (Zonneveld *et al.*, 1997a & b; Zonneveld and Gingras, in press).

In order to understand the stratigraphic relationships between proximal and distal sedimentary sections it is neccessary to interpret these units within a detailed chronostratigraphic framework. Understanding these relationships is particularly important in the Triassic of the Western Canada Sedimentary Basin. Many important reservoir units, such as the Valhalla-La Glace turbidite facies (Moslow and Davies, 1997), bioclastic shoreface sandstone units in the Sturgeon Lake region (Mederos, 1995; Markhasin, 1997), and transgressive bioclastic shoreface deposits in the Tommy Lakes region (chapter 6) are associated with key sequence boundaries.

In the absence of adequate magnetostratigraphic data or radiometrically datable rocks, chronostratigraphic analysis is best achieved through biostratigraphic correlation. Although the Triassic biostratigraphic zonation of the Western Canada Sedimentary Basin has been discussed in numerous papers (Tozer, 1963; 1965; 1967; 1994; Orchard and Tozer, 1997), biostratigraphic data discussed in association with sedimentologic and sequence stratigraphic data has been lacking.

This study concentrates on outcrop within the vicinity of Williston Lake, British Columbia (Figure 1) and comprises the first sequence stratigraphic analysis of Middle Triassic outcrop in the Western Canada Sedimentary Basin. In addition, this treatise provides a preliminary sequence biostratigraphic framework for the Middle Triassic within the Williston Lake region and correlates significant events with surfaces recognized in other Triassic successions.

Study Area

Triassic strata in the Williston Lake (formerly Peace River) region were deposited within the "Peace River Basin" (Davies, 1997), on the northern margin of the Peace River embayment (Figure 2). The late Paleozoic/early Mesozoic Peace River embayment developed during the Mississippian as a result of the collapse of the earlier Palaeozoic Peace River Arch (Barss *et al.*, 1964; Cant, 1988; Gibson and Barclay, 1989, Barclay *et al.*, 1990).

This paper concentrates on five main outcrop sections, comprising a 35-40km dip-oriented cross-section through the northwestern portion of the Peace River embayment. Ursula Creek, the westernmost, and correspondingly most distal section of Triassic outcrop in the Peace River Foothills (Figures 1 and 3), comprises approximately 20 metres of upper Paleozoic and over 200 metres of Early through Upper Triassic strata interpreted as distal shelf and slope deposits. This site is interpreted to be the most chronologically complete section in the study area. In the absence of evidence of either subaerial or submarine erosion it is possible that this site contains a continuous succession from the latest Paleozoic into the Upper Triassic (Carnian/Norian).

Brown Hill, 20 kilometres to the east consists of over 600 metres of Middle Triassic (?Anisian-upper Ladinian) offshore, shoreface and marginal-marine deposits, as well as approximately 300 metres of Upper Triassic strata not discussed in this report (Figures 1 and 4). Glacier Spur, Beattie Ledge, and Aylard Creek have been dated as Middle Triassic (Ladinian). Glacier Spur (Ladinian), approximately 1.7km south of Brown Hill consists of 320m of proximal offshore to marginal marine deposits (Figures 1 and 5). Beattie Ledge and Aylard Creek (upper Ladinian; 250m and 140m respectively) comprise the easternmost and correspondingly most landward sites in the study area, consisting primarily of Middle Triassic (Ladinian) shoreface and marginal marine deposits (Figures 1, 6 and 7).

Methods

Detailed stratigraphic sections were measured at each locality using outcrop logging

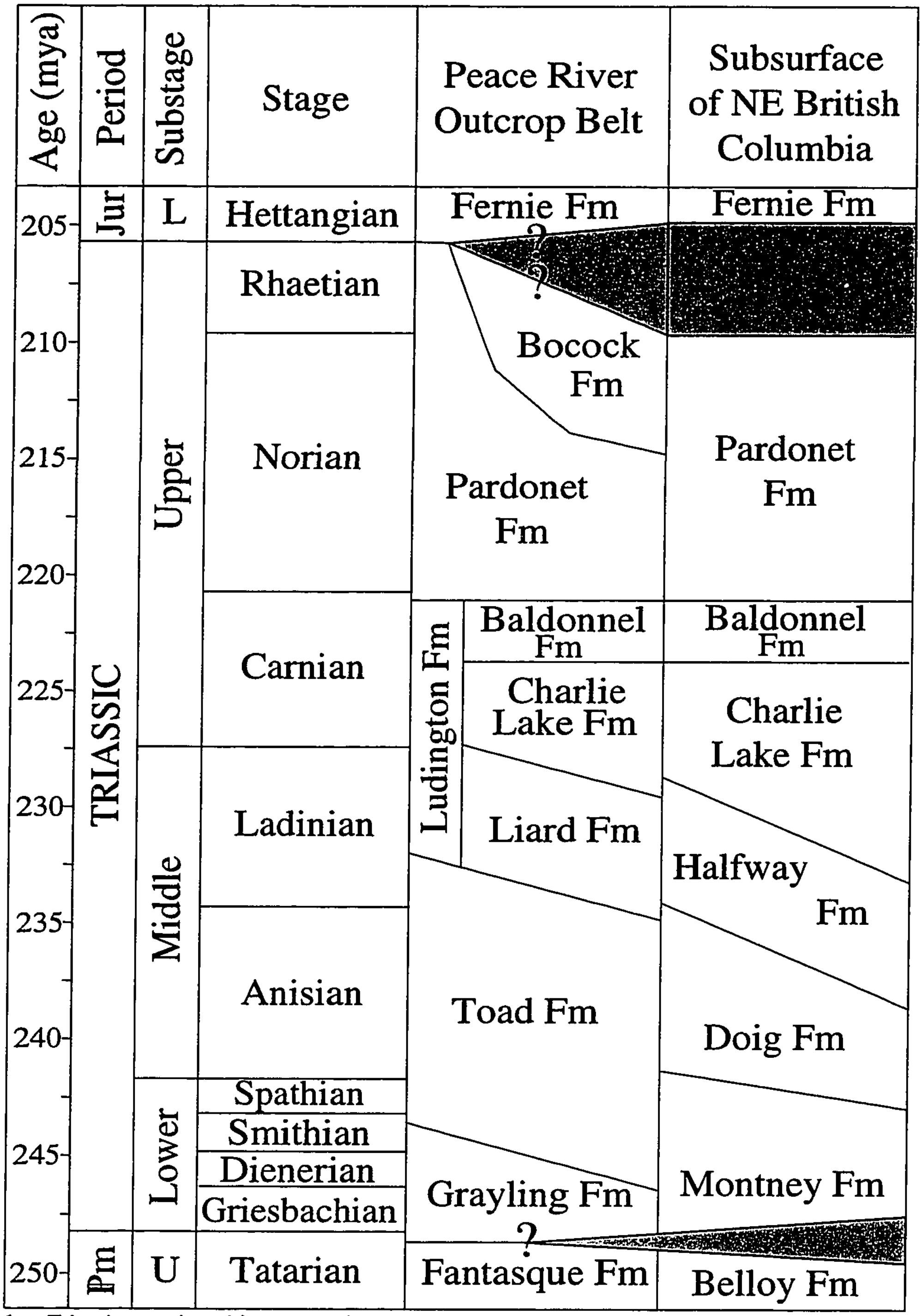


Table 1. Triassic stratigraphic nomenclature, subsurface and outcrop, northeastern British Columbia (adapted from Gradstein et al., 1994; Tozer, 1994). Contacts between Lower and Middle Triassic formations are drawn to reflect their diachronous nature, and are not absolute. Numerous intraformational unconformities occur within the Triassic of Western Canada although they are not shown here. Triassic chronostratigraphy utilized here follows the recommendations of the IUGS Subcommision on Triassic Stratigraphy (Gradstein *et al.*, 1994) in retaining the Rhaetian as a valid stage.

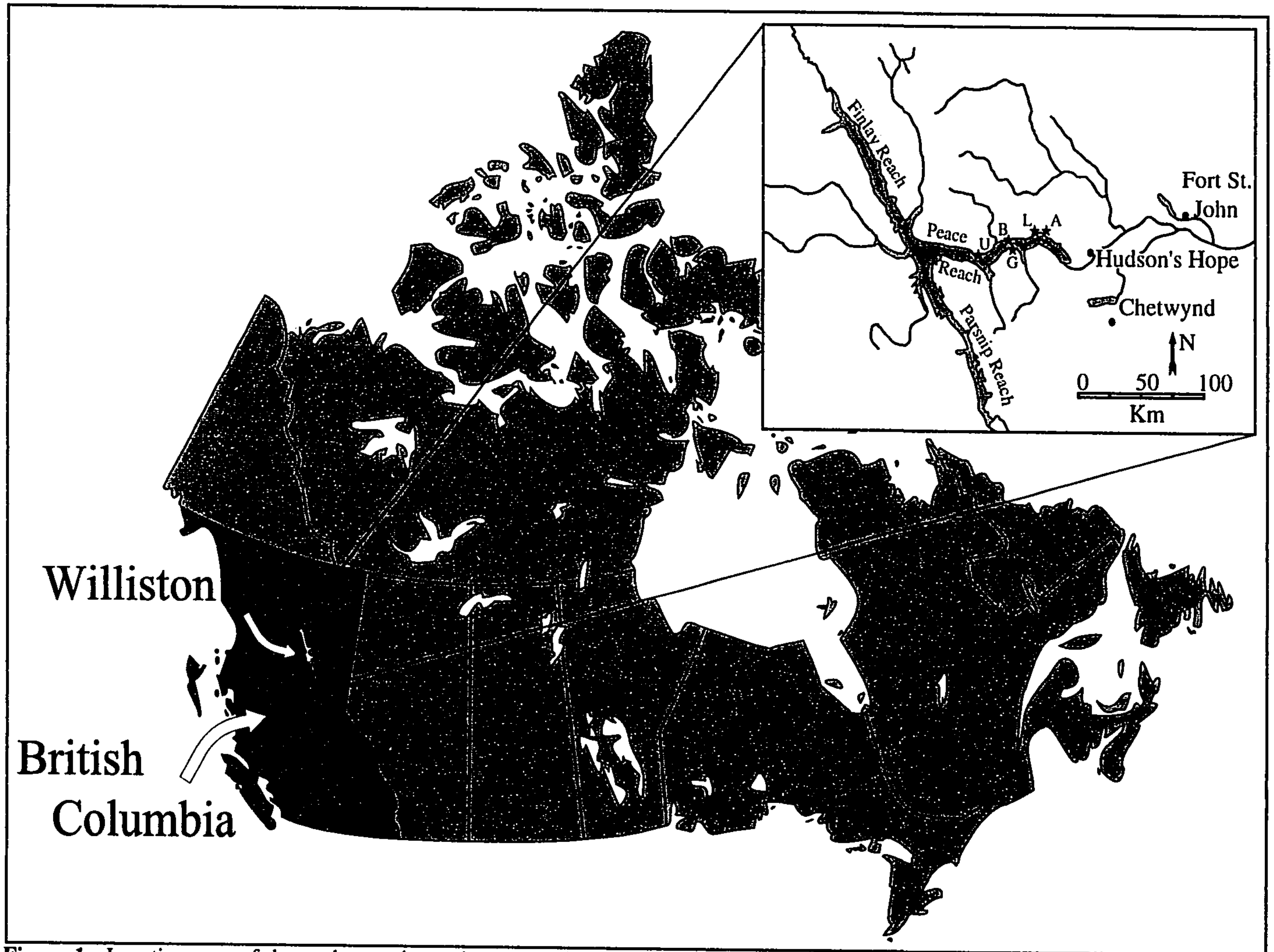


Figure 1. Location map of the study area in northeastern British Columbia, Canada. Inset map shows the location of localities along the Peace Reach of Williston Lake discussed in this report. These localities include Ursula Creek (U), Glacier Spur (G), Brown Hill (B), Beattie Ledge (L) and Aylard Creek (A).

forms to ensure consistency and accuracy. Attention was paid to lithology, bounding surfaces, primary physical and biogenic sedimentary structures, and fossil composition. In addition to macrofossils, samples were obtained of all shale and carbonate horizons and analyzed for conodonts. All conodont samples were processed in the laboratories of the Applied Stratigraphy Research Group at the University of Calgary. Data concerning conodont identification, distribution and abundances was obtained from several unpublished reports (Henderson, 1996; 1998). Biostratigraphic analysis has facilitated placing the study interval into a preliminary biostratigraphic framework (Figures 8 and 9). Further biostratigraphic analysis of outcrop and subsurface samples, collected within a tight sedimentological and stratigraphic framework, is needed before a biostratigraphic framework can be presented for the Middle Triassic interval of western Canada.

Outcrop gamma scans using a portable scintillometer (Scintrex BGS-4) were obtained at all outcrop sections to aid in correlation between distal and proximal localities and to facilitate delineation of significant bounding surfaces. Five radiation count readings of ten seconds each were obtained at 0.50m intervals following the methodology of Slatt *et al.* (1992). The highest and lowest values were discarded and the remaining three averaged to obtain the value for each horizon. In total, 1450m of section and 2900 gamma-ray intervals were measured. The gamma-ray profiles generated through this study have proven invaluable in facilitating better understanding of subsurface well log signatures and correlations.

Lithofacies were described both vertically and horizontally to assess lateral and vertical variability in lithofacies relationships and sediment composition, and were grouped into six recurrent lithofacies associations: I) ramp turbidites; II) clastic offshore/shoreface; III) transgressive shoreface; IV) mixed siliciclastic-carbonate shoreface; V) brachiopod-echinoderm biostrome, and VI) mixed siliciclastic-carbonate marginal marine (Table 2; Chapter 4). A synopsis of lithofacies and lithofacies associations encountered during the course of this study is provided in Tables 2 and 3. Detailed descriptions and analysis of these lithofacies and lithofacies associations are available in previous papers (Zonneveld *et al.*, 1997, Zonneveld and Gingras, *in press*; Chapters 2, 3 and 4) and are thus, not repeated here.

Lithostratigraphy

The Grayling Formation (Table 1) comprises a thick succession of dolomitic siltstone and shale, fine-grained sandstone and silty micrite and dolomicrite (Kindle, 1944), outcropping in a thin belt extending along the Rocky Mountain Front from the British Columbia-Alberta border to the British Columbia-Yukon Border (Gibson, 1971; 1975). The Grayling is the temporal equivalent of the lower part of the Montney Formation in the subsurface to the east, the Phroso Siltstone Member of the Sulphur Mountain Formation (Table 1) in the outcrop belt along the Rocky Mountain Front of southwestern Alberta, and the Toad Formationin the eastern portion of the outcrop belt. Exposure of the Grayling Formationalong Williston Lake is limited to the basal part of the Ursula Creek section. Fossils were not observed within the Grayling Formation within the study area.

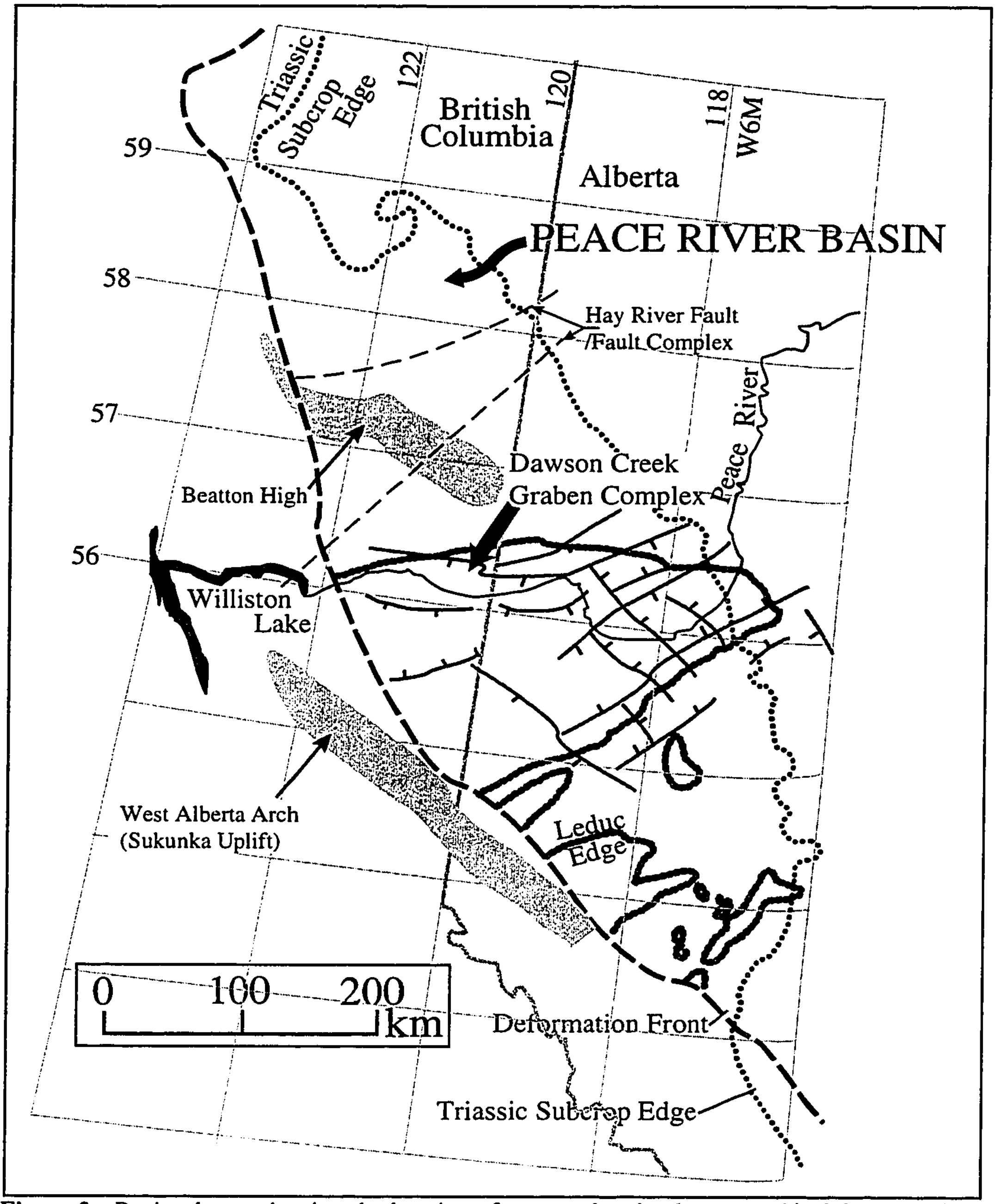


Figure 2. Regional map showing the location of structural and paleogeographical features which may have affected Triassic deposition in the Western Canada Sedimentary Basin (adapted from Davies, 1997). The Triassic Peace River Basin is centred on the late Paleozoic Peace River embayment. The erosional subcrop edge of Triassic sediments is indicated by the dotted line. The eastern limit of Laramide deformation is shown by the heavy dashed line. The West Alberta Arch (Sukunka Uplift, Richards, 1989) and Beatton High (Henderson et al., 1994) are late Paleozoic structural elements which may have affected Triassic deposition within the study area. Faults within the Dawson Creek Graben Complex have been shown to have had a pronounced effect on Triassic deposition within the Peace River Basin.

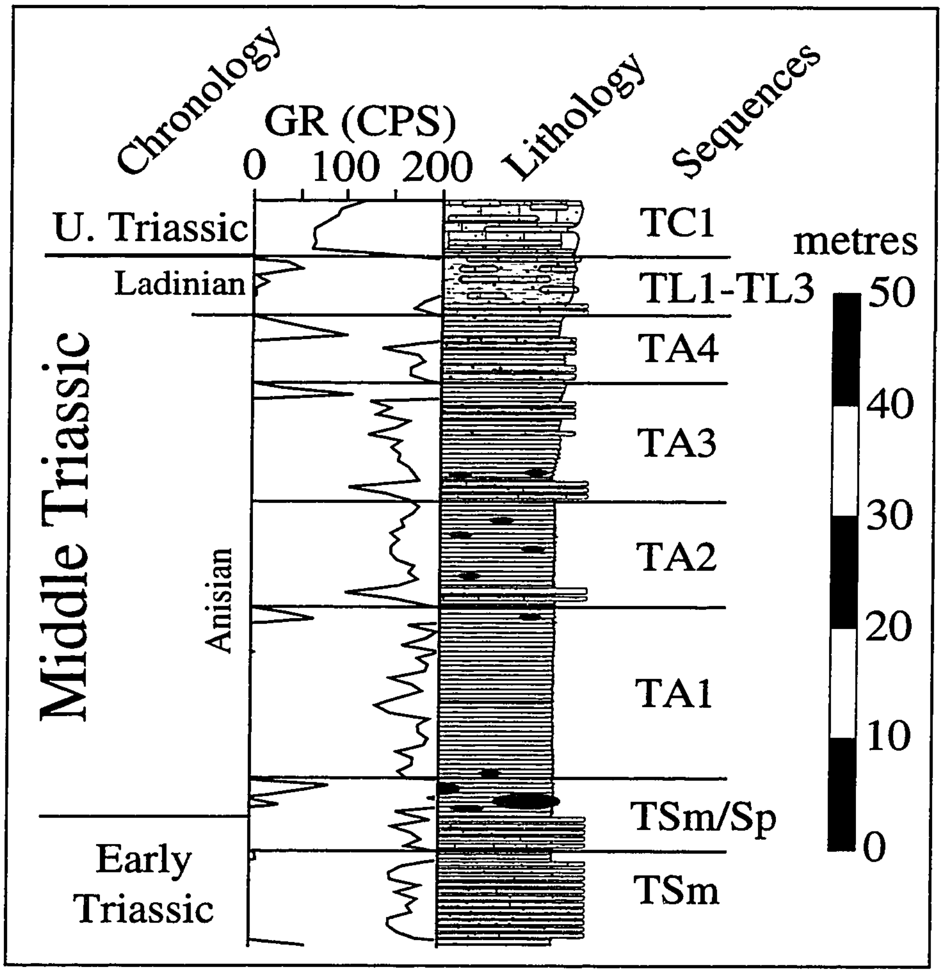


Figure 3. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and basal Ludington formations at Ursula Creek. Acronyms are defined in text (p. 193-194).

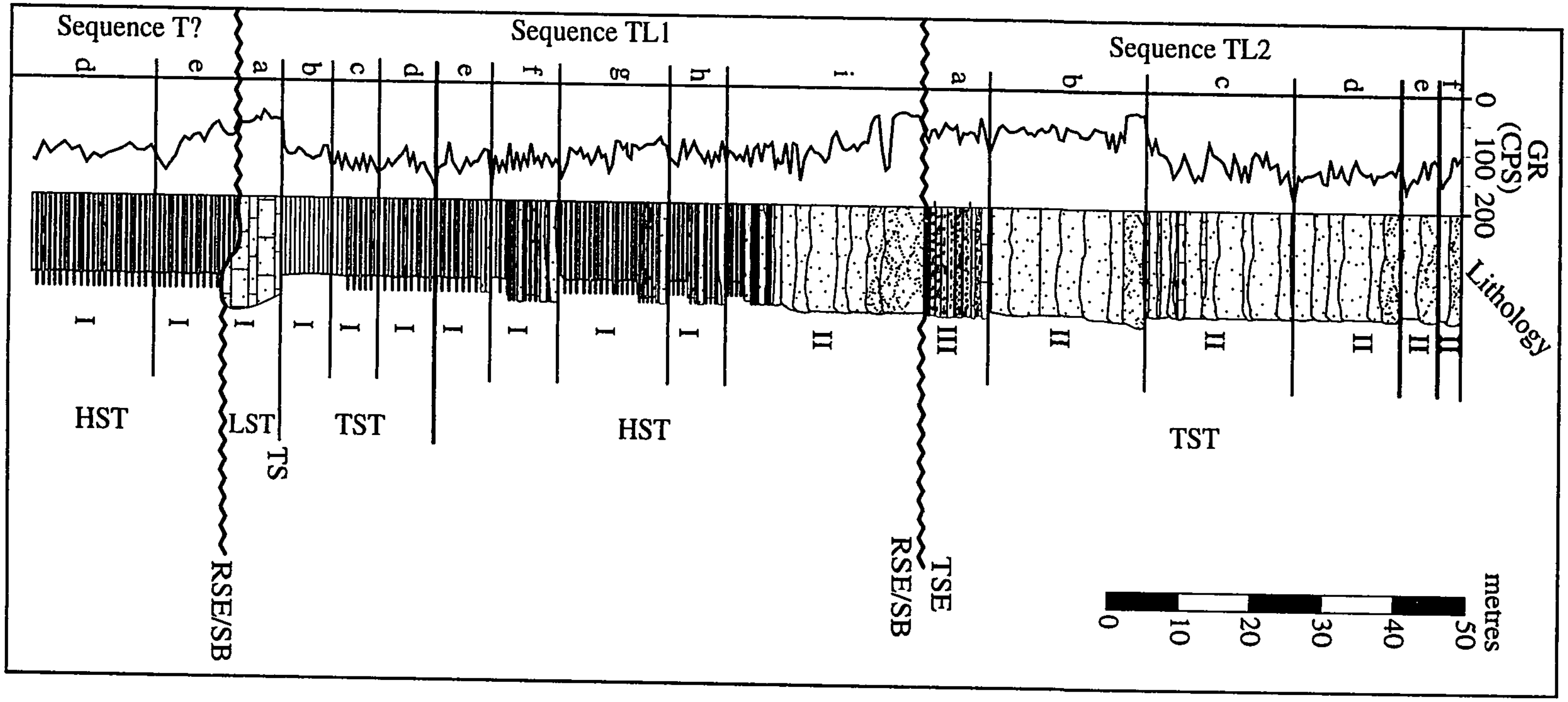


Figure 4a. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard Formations at Brown Hill. Acronyms are defined in text (p. 193-194).

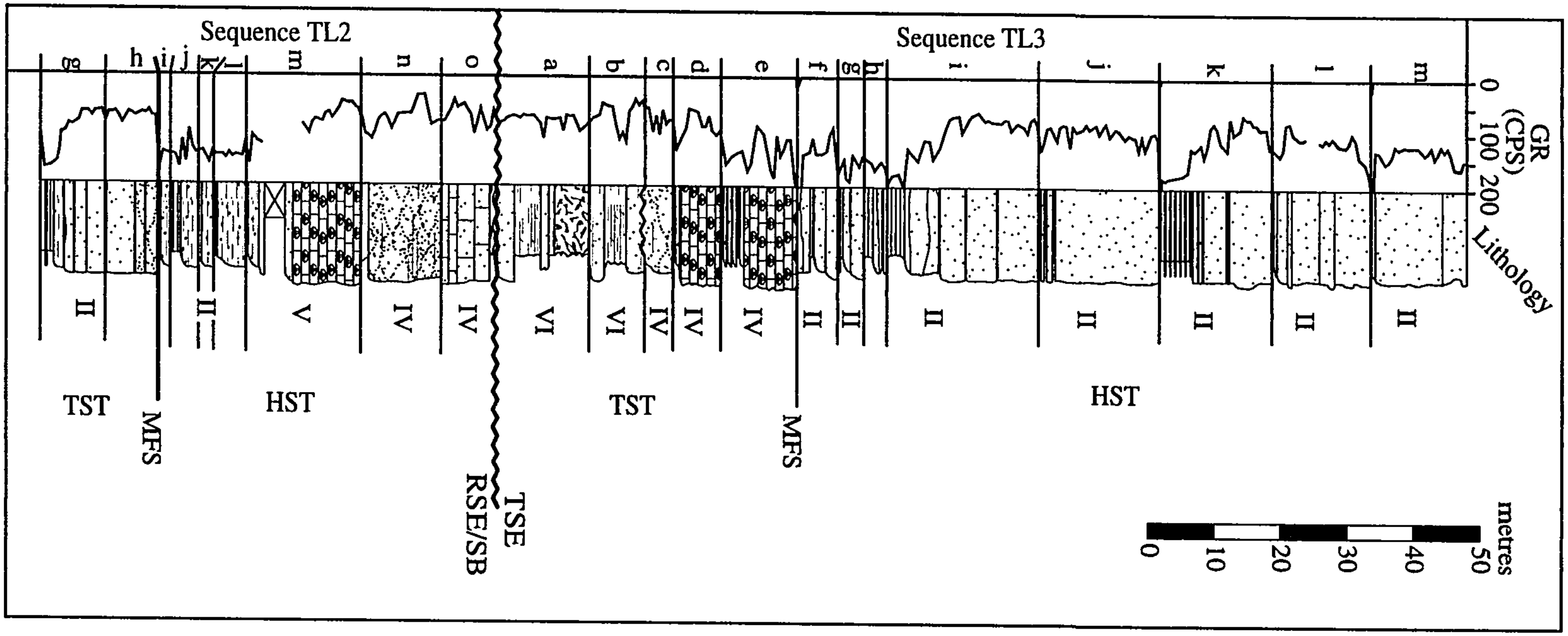


Figure 4b. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard Formations at Brown Hill. Acronyms are defined in text (p. 193-194).

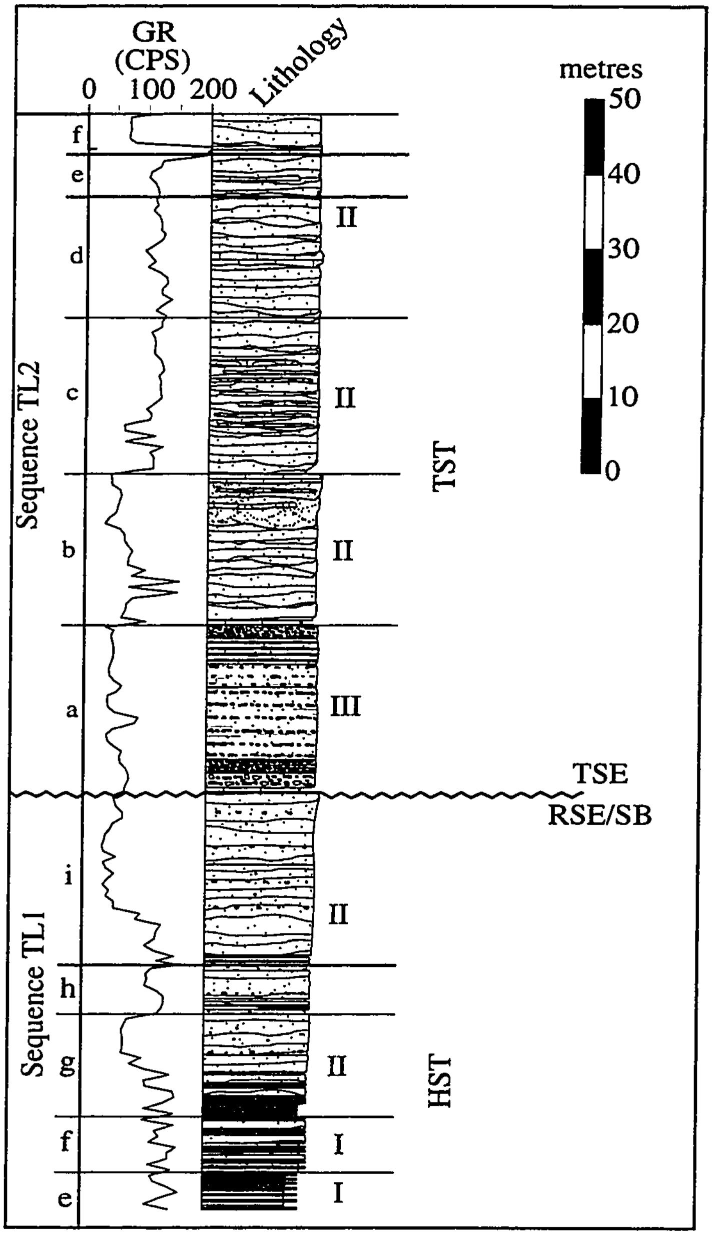


Figure 5a. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard Formations at Glacier Spur. Acronyms are defined in text (p. 193-194).

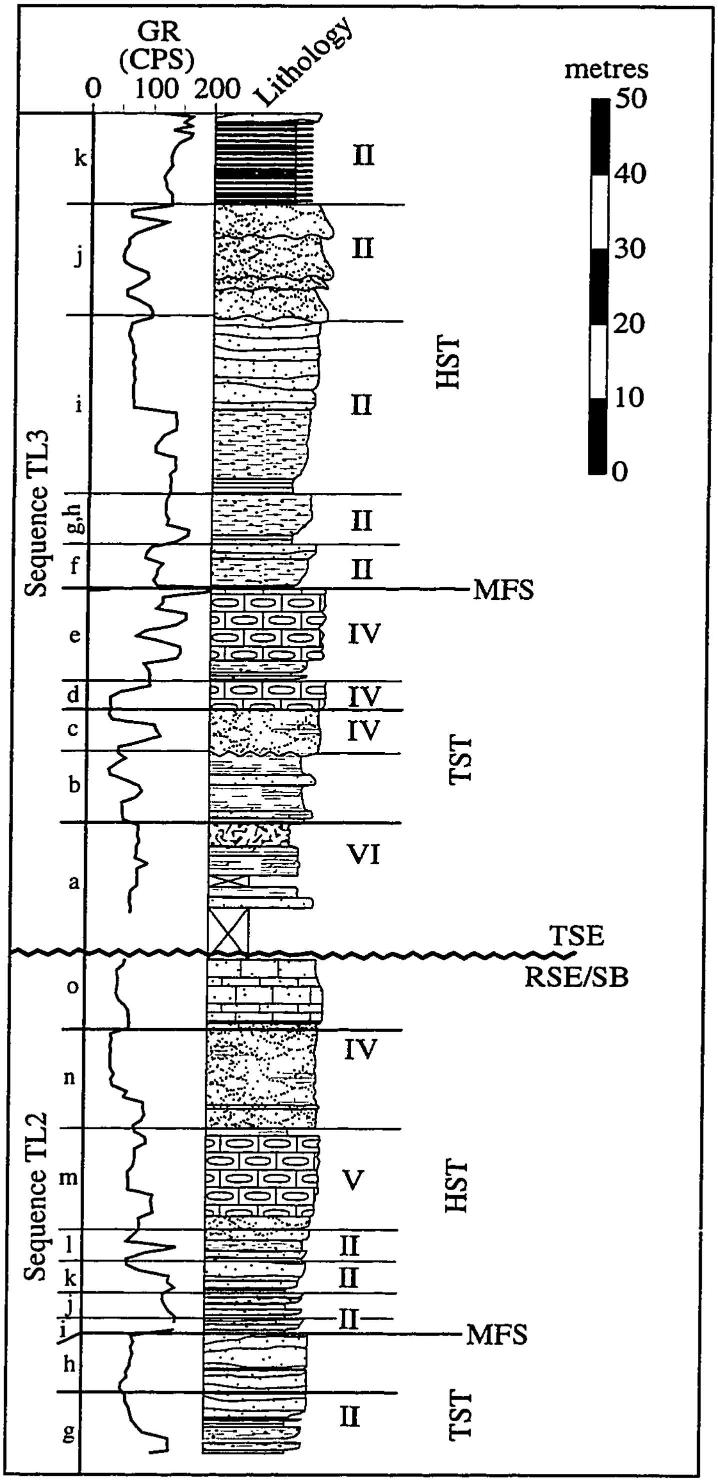


Figure 5b. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard Formations at Glacier Spur. Acronyms are defined in text (p. 193-194).

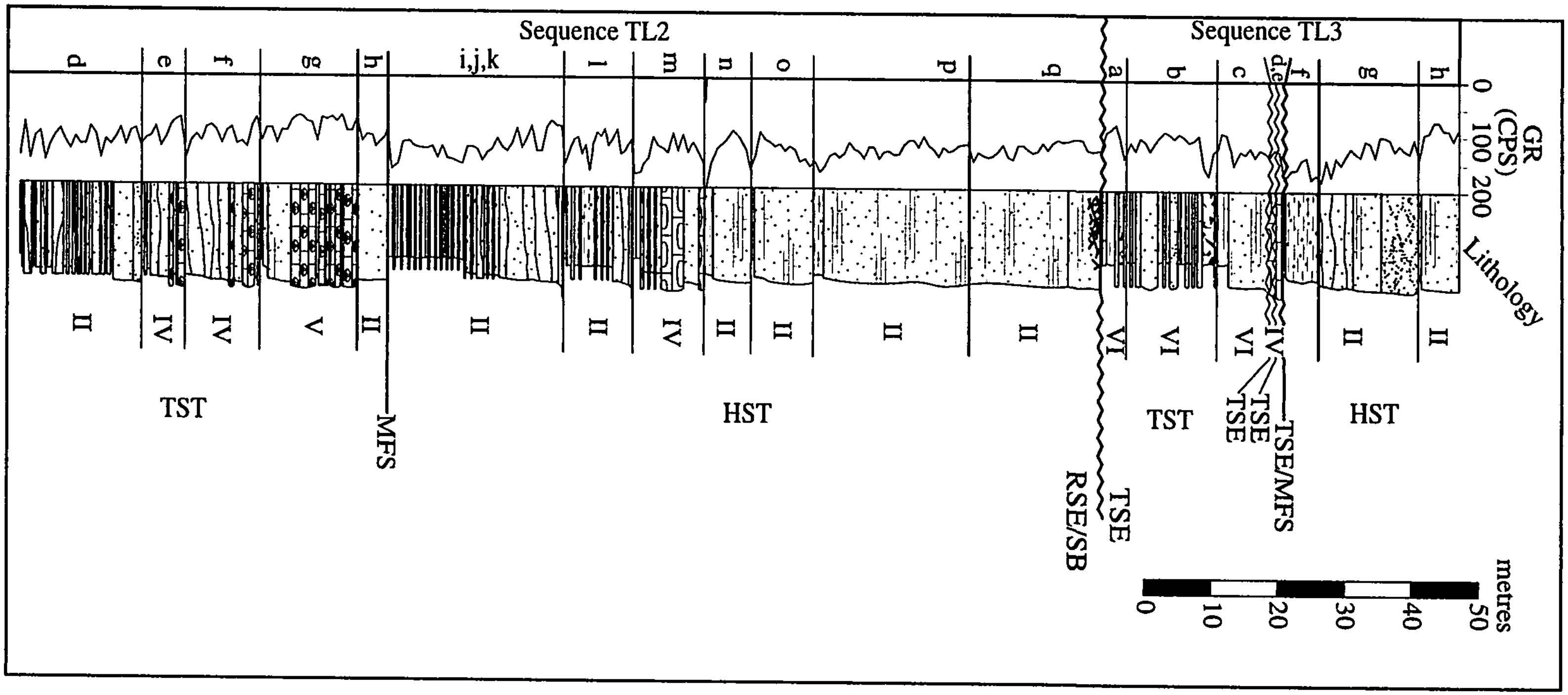


Figure 6. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard Formations at Beattie Ledge. Acronyms are defined in text (p. 193-194).

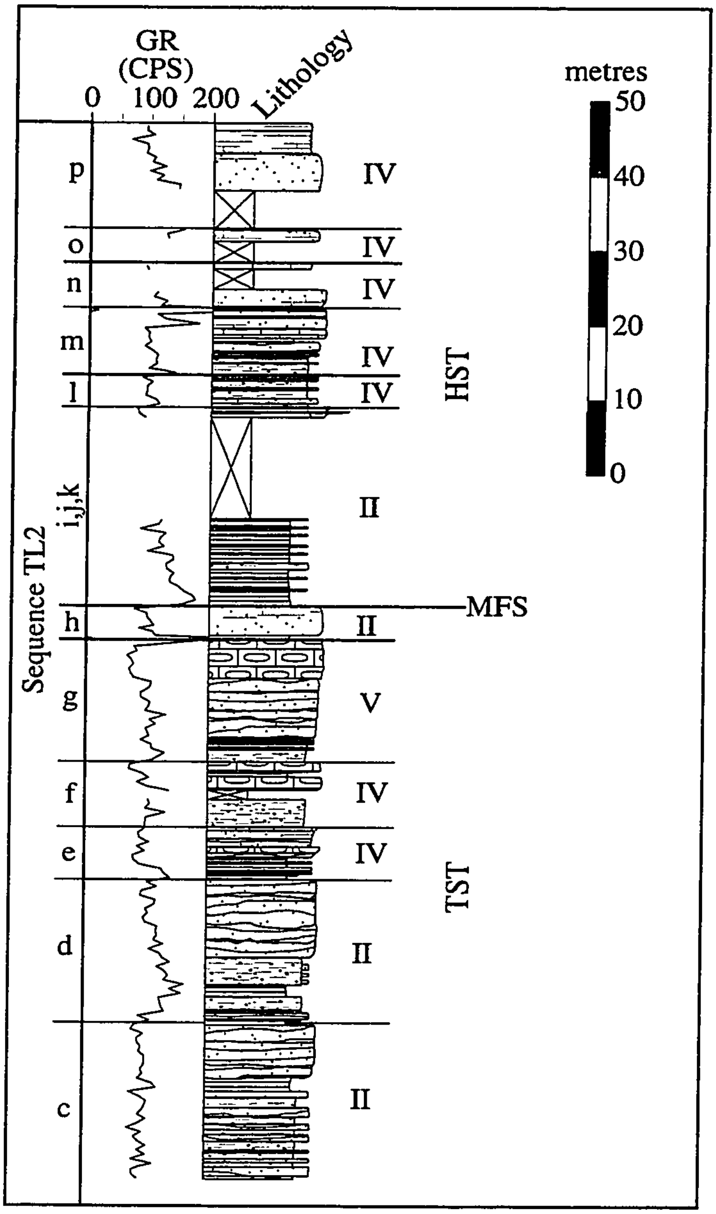


Figure 7. Stratigraphic section showing the vertical arrangement of lithofacies and general depositional environments in the Toad and Liard Formations at Aylard Creek. Acronyms are defined in text (p. 193-194).

Within the study area, the Grayling Formation abruptly but conformably overlies the Permian Fantasque Formation (Table 1). In the absence of evidence suggesting subaerial exposure or erosion, this contact is interpreted here to be conformable, representing a maximum marine flooding surface and a significant landward shift in sedimentary facies. High gamma radiation and total organic carbon (TOC) levels in the basal Grayling Formationare consistent with severely condensed sedimentation during late transgressive and early highstand conditions (Henderson *et al.*, 1997; Zonneveld *et al.*, 1998).

In the absence of biostratigraphic evidence, previous researchers have assumed that the Permian-Triassic chronostratigraphic boundary coincides with the Fantasque-Grayling lithostratigraphic contact (Gibson and Edwards, 1992; Wang et al., 1994). Recent evidence however has suggested that the actual chronostratigraphic boundary actually occurs several decimetres to metres above the lithostratigraphic contact (Henderson, 1997). The basal Grayling Formation is thus likely uppermost Permian within the study area. Within the study area, the Grayling Formation is conformably overlain by primarily coarser sediments of the Toad Formation.

The Toad Formation (Table 1) is composed of a series of dark grey argillaceous to calcareous siltstone, silty shale, silty limestone and dolostone, and fine-grained sandstone (Kindle, 1944). It varies significantly in thickness from approximately 120-240 metres in the Williston Lake region (this study) to over 800 metres near the Halfway River to the north (Gibson, 1971). The Toad is the chronologic equivalent of the upper Montney and lower Doig in the subsurface to the east and to the Sulphur Mountain Formation in the southern Rocky Mountain foothills outcrop belt. Within the study area, the unit is conformably overlain by the Liard or Ludington Formations. Although fossils were not common within the Toad Formation at Williston Lake, the presence of palaeoniscid fish scales, ammonoids, bivalves, and brachiopods were integral in biostratigraphic and paleoenvironmental analysis.

The Liard Formation (Kindle, 1944) conformably overlies the Toad Formation (Table 1). Within the Williston Lake region, the Liard Formation is a mixed siliciclastic-carbonate unit composed of shale, siltstone, quartz dominated sandstone and bioclastic packstone-grainstone (Gibson and Edwards, 1990; 1992; Zonneveld *et al.*, 1997). The Liard is considered equivalent to the Halfway and upper Doig Formations in the subsurface to the east, and to the Llama Member of the Sulphur Mountain Formation in the Rocky Mountain Foothills belt of Alberta (Table 1). Within the study area, the Liard Formation conformably overlies the Toad Formation and is overlain, after a thin covered interval, by mixed siliciclastic, carbonate and evaporite sediment of the Charlie Lake Formation (Table 1).

The Liard Formation is one of the most fossiliferous horizons within the field area. Fossils include at least 10 bivalve genera, four brachiopod genera, as well as gastropods, ammonoids, decapod and phyllocarid crustaceans, a variety of echinoderms (echinoids, crinoids and brittle stars), fish, and marine reptiles (ichthyosaurs and thallatosaurs). These fossils have proven invaluable in establishing depositional environments and biostratigraphic

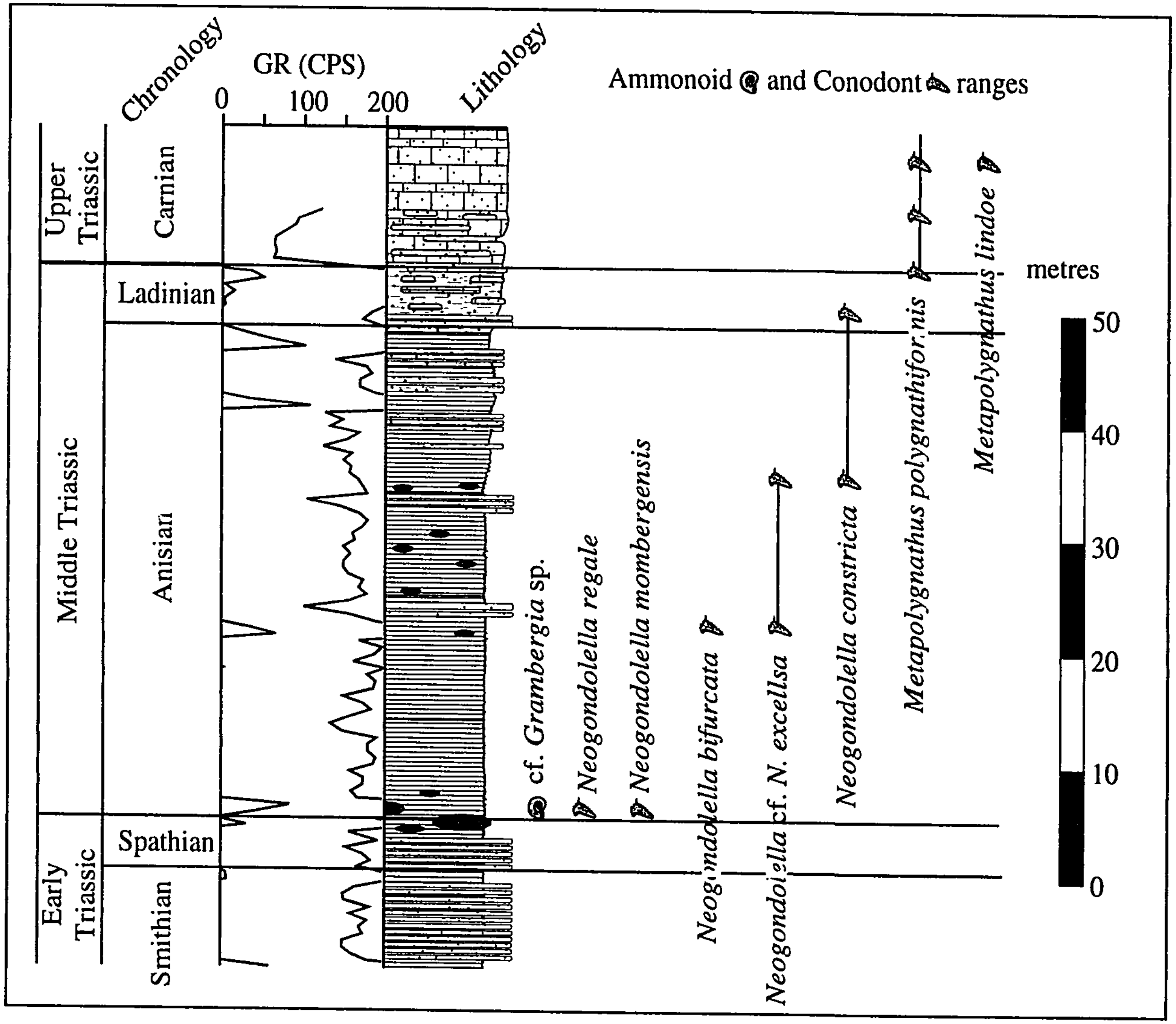
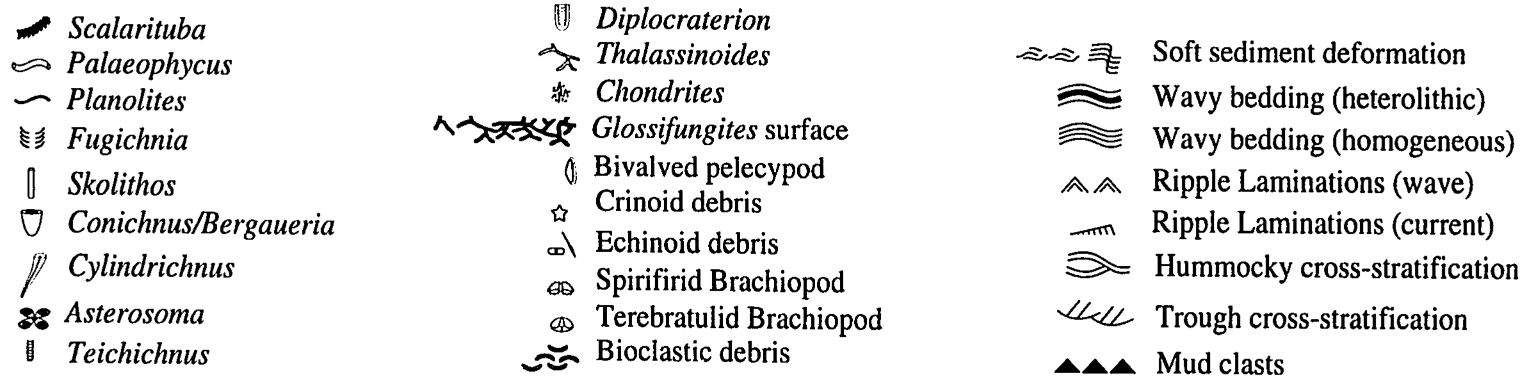


Figure 8. Middle Triassic Biostratigraphic framework, Ursula Creek, northeastern British Columbia.

Lithofacies Association	Lithofacies	Interpretation
I	A1, A2, B, C1, C2 and D	Distal Ramp Turbidites
II	A, E, F, G, H and I	Clastic Offshore-Shoreface
III	J and K	Transgressive Shoreface
IV	A, E, F, G, N and O	Mixed Siliciclastic-Carbonate Shoreface
V	F, L1, L2 and M	Brachiopod-Echinoderm Biostrome
VI	I, O, P1, P2, Q, R1, R2, S, T and U	Mixed Siliciclastic-Carbonate Shoreface
VII	convolute bedded bioclastic packstone	Distal Ramp

Table 2a. Summary of Lithofacies associations within the Grayling, Toad and Liard formations, Williston Lake, northeastern British Columbia. Individual lithofacies are discussed in chapter 4 and summarized in Tables 2b and 2c. Trace fossil abbreviations used in Table 2b and 2c include: Ar= *Arenicolites*; Bi= Bivalve resting trace (not *Lockeia* isp.); As = *Asterosoma*; Be = *Bergaueria*; Ch = *Chondrites;* Co = *Conichnus;* Cr = *Cruziana;* Cy= *Cylindrichnus*; Di= *Diplocraterion*; Gy = *Gyrochorte;* He= *Helminthopsis*; Is= *Isopodichnus; La=Laevicyclus*; Li= *Lingulichnus;* Lk= *Lockeia* Mo = *Monocraterion;* Pa= *Palaeophycu*; Ph= *Phycosiphon;* Pl= *Planolites* Rh= *Rhizocorallium;* Ro = *Rosselia;* Sc= *Scalarituba*; Sb = *Schaubcylindrichnus;* Si= *Siphonichnus;* Sk= *Skolithos;* Sp= *Spongelliomorpha;* Te= *Teichichnus;* Th= *Thalassinoides;* Tr = *Treptichnus;* BAT = bivalve adjustment trace; BRT = Bivalve resting trace; Pit = feeding pit. FS= Marine Flooding Surface; MFS = Maximum Marine Flooding Surface; CFS = Correlative Flooding Surface; TSE= Transgressive Surface of Erosion; RS= Ravinement Surface; RSME/SB = Regressive Surface of Marine Erosion/Sequence Boundary. Symbols used in Figure 13 are shown below.



FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	FOSSILS	DEPOSITIONAL ENVIRONMENT
A1	Laminated Black Shale	Plane parallel laminae, rare silt and sand lam, rare carbonate &/or phosphate concretions.	None observed	None observed	Distal Shelf /Slope
A2	Laminated Black silty shale	Plane parallel laminae, discontinuous normally graded sand/silt laminae, rare HCS and current ripple laminae,	Pa,He,Hl, Ph,Sc,Ch	*Lingula*, rare fish and ammonoids	Distal Shelf /Slope
B	Silty Bioclastic Packstone	Lense or pod shaped beds of normally graded fine-grained bioclasts.	None observed	Thin-shelled pelagic bivalve fragments.	Distal Shelf/Slope /Turbidite Lobe
C1	Interbedded shale, siltstone & vf sandstone	Soft-sediment deformation, convoluted & distorted laminae, micro-faults, ripple and parallel lamination.	He, Hl, Ph, Ch	fish scales and bivalves, normally graded bioclastic hash layers.	Turbidite Levee /Overbank ("CCC Turbidites")
C2	Interbedded vf sandstone, siltstone and shale	normally graded beds, amalgamated Bouma B-C-D-E, B-C-D, & C-D-E.	He, Hl, Ph	fish scales & bivalves, bioclastic hash layers	Turbidite Lobe
D	Bioclastic rudstone/grainstone (100% fragmentary clasts)	Obscured by weathering, normally graded.	None Observed	~75% fragmentary bioclastic hash	Turbidite Channel
E(B)	Interlaminated HCS Siltstone & Sandstone	Plane parallel laminae, flow ripples, HCS, rare oscillation ripples.	Sl,He,Hl, Ph,Th,Sb, Sp,Lk,Li,Pa,Pl,Cr,Sc	whole lingulids, bones, bioclastic hash layers	Offshore/Shoreface Transition
F(C)	HCS Sandstone (very fine)	Amalgamated HCS beds, planar bedding, current and oscillation ripples.	As,Be,Di,Sk,Th,Pa,Cy, Li Te,Ro,Si,Lk,Ar,Pl,Rh	ling. brachs, bivalves, fish, brittle stars.	Lower Shoreface
G(F)	Calcareous sandstone (very fine to fine)	Predominantly TCS, rare HCS (SCS?), rare oscillation ripples	Di,Sk, Pa, Pl	scattered brachiopods & echinoderm debris	Distal Upper Shoreface
H	Pebbly/sandy bioclastic grainstone (laterally restricted)	Scoured base, normally graded, possible TCS, pebble/granule lags.	None Observed	abraded brach., bivalve & echinoderm debris	Rip-Tidal Channel
I(M)	Calcareous sandstone (fine to medium)	Predominantly TCS grading up into current ripple laminae, mudclast lags	None observed	Rare bivalve shell lags.	Tidal Inlet Channel
J	Nodular Bioclastic Silty/Sandy Packstone	Nodular bioclastic packstone/grainstone clasts (1-40cm) within a siliciclastic matrix, abdt. chert peb.	None Observed	bioclastic hash, brachs, bivalves, ammonoids, gastropods, ammonoids	Transgressive Shoreface
K	Terebratulid/spiriferid grainstone	None Observed.	None Observed	whole, unabraded spiriferids & terebratulids	Lower Shoreface

Table 2b. Summary of sedimentary facies characteristics in the Grayling, Toad, Liard, and Charlie Lake formations, Williston Lake, northeastern British Columbia. Trace fossil abbreviations are summarized in Table 2a.

FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	FOSSILS	DEPOSITIONAL ENVIRONMENT
L1(D)	Sandy Bioclastic Grainstone	Low-angle stratification, random orientation to grains, grading not observed.	As, Cy, Pa, Ro	crinoid ossicles, echinoid, brachiopods	Reef Mound/ Biostrome Fringe
L2(D)	Bioclastic rudstone/grainstone (<50% of clasts fragmentary)	Obscured by abundant bioclasts. Beds thicken upwards (30 to 60cm). Grading not observed. Abrupt bounding surfaces.	None observed	terebratulid brachs echinoids, & crinoids, rare acrotretid brach.s	Reef Mound/ Biostrome
M(E)	Bioclastic floatstone/mudstone	low-angle planar laminae, thinly bedded, normally graded?	Pl	echin., crin., brachs, fish, decapods,bivalves	Back Reef
N(G)	Bioclastic sandy packstone (fine to medium)	Trough to planar cross-stratification at base, grading up into planar-tabular laminae. Inversely graded, abundant chert pebbles).	Op, Pl	bioclastic debris, brachs, bivalves, rare ichthyosaur bones	Proximal Upper Shoreface/Foreshore
O(H)	Calcareous sandstone	Appears massive, planar lam. to TCS, beds thicken upwards (5-10 to 30cm).	Sk, Pa, Pl, Gy, BRT	rare *Lingula* and bioclastic debris	Backshore/ Washover Fan
P1(I)	Fenestral laminated dolomite	fenestral laminae, bird's eye structure	Algal laminae	None observed	Lagoonal/ Intertidal Flat
P2(K)	Dolomitic mudstone	Planar laminae, syneresis cracks	Cy, Gy, Tr	rare lingulids, bivalves, and gastropods	Lagoonal/Lacustrine
Q(J)	Planar cross-stratified sandstone	low-angle planar cross-stratification, oscillation ripple lamination.	Sk, Pa, Gy,	None observed	Shoreface/ Washover Fan
R1(K)	Dolomitic siltstone	Planar laminations, current and oscillation ripples, heterolithic wavy laminae, polygonal mudcracks	Ar,Cy,Co,Di,Gy, Lk,Pa,Pl,Rh,Sk, Th, feeding pits	*Lingula*, bivalve frags, gastropods	Intertidal Flats/ Marginal lagoonal
R2(K)	Dolomitic sandstone	Heterolithic wavy laminae, flaser bedding, symmetrical ripples, dessication cracks, rill marks	Cy,Gy,La,Pa,Pl, Rh,Sk,Si,Te,Th, biv. adjust. tr.	bivalves, gastropods, lingulid fragments	Intertidal Flats
S(L)	Solution collapse breccia	Solution collaspse of other lithofacies.	None observed	None noted	Supratidal
T	Ripple-laminated dolomitic siltstone/mudstone	Wavy to ripple laminated, adhesion ripples	Cy, Mo, Op, Pa, root traces	None Observed	Supratidal Lacustrine
U	High-angle cross-stratified sandstone	Planar cross-bedding, tabular to wedge-planar bedsets, inversely graded laminae	None observed	None Observed	Aeolian Sand Dunes

Table 2c. Summary of sedimentary facies characteristics in the Grayling, Toad, Liard, and Charlie Lake formations, Williston Lake, northeastern British Columbia. Trace fossil abbreviations are summarized in Table 2a.

STAGE		AMMONOID ZONE	CONODONT FAUNAS/ZONE	
CARNIAN	L	*Sirenites nanseni*	*Metapolygnathus polygnathiformis*	*Paragondolella inclinata*
		Austrotrachyceras obesum		
		Trachyceras desatoyense		
LADINIAN		*Frankites sutherlandi*	*Budrovignathus mungoensis*	
		Maclearnoceras maclearni	*Budrovignathus hungaricus*	*Paragondolella foliata*
		Meginoceras meginae		
		Tuchodiceras poseidon	*Neogondolella aldae*	
		Eoprotrachyceras matutinum		*Paragondolella* ex. gr. *excelsa*
ANISIAN	U	*Frechites chischa*		
		Eogymnotoceras deleeni	*Neogondolella constricta*	
	M	*Holandites minor*		*Paragondolella bulgarica*
			Neogondolella shoshonensis	*Neogondolella regale*
		Tetsaoceras hayesi		
		Buddhaites hagei		
	L	*Lenotropites caurus*	*Neogondolella mombergensis*	
		Siberlingites mulleri		
			Chiosella timorensis	

Table 3. Middle Triassic biochronology showing intercalibration of ammonoid and conodont zones and faunas (after Orchard and Tozer, 1997).

relationships within the Liard Formation at Williston lake.

Sequence Stratigraphy: General Concepts

This study utilizes a revised form of the basic sequence stratigraphic framework outlined by Jervey (1988), Van Wagoner (1985) and Van Wagoner *et al.* (1988; 1990). Sequence stratigraphic terminology has evolved rapidly during the past several years. To alleviate confusion, pertinent terms and concepts are summarized here. Acronyms utilized in figures 3 through 7 are shown in parentheses.

Sequences consist of packages of genetically related strata bounded by regionally extensive subaerial unconformities and their correlative conformities (Van Wagoner *et al.*, 1990). The basic building blocks of sequences are parasequences. Parasequences are conformable successions of genetically related beds or bedsets bounded by marine flooding surfaces (Van Wagoner *et al.*, 1988; 1990). Marine flooding surfaces (FS) are surfaces which separate older, underlying strata from younger, overlying strata, across which there is evidence of an upward increase in water depth (Van Wagoner *et al.*, 1988; 1990; Myers and Milton, 1996). Progradational packages of sediments within marginal marine and nonmarine sections are informally referred to by some researchers as terrasequences (Bartels and Zonneveld, 1997). Each terrasequence, interpreted as the nonmarine analogue of a parasequence, is characterized by a conformable succession of genetically related strata (Bartels and Zonneveld, 1997; Zonneveld *et al.*, 1997; 1998). As in their marine counterparts, terrasequence boundaries reflect a landward shift in sedimentary facies and are referred to here as correlative flooding surfaces (CFS). An example of a correlative flooding surface from the study interval is the sequence TL3 parasequence a/b flooding surface (Figures 4b, 5b, and 6).

Sequences are often subdivided into a succession of systems tracts, defined by Brown and Fisher (1977) as linkages of contemporaneous depositional systems. Parasequences within systems tracts collectively display a similar response to sea-level fluctuations. From base to top, the basic Exxon sequence model consists of the lowstand systems tract (or shelf margin systems tract), transgressive systems tract and highstand systems tract (Van Wagoner *et al.*, 1990). Subsequently, various authors have recognized other possible systems tracts such as the forced regressive systems tract and falling-stage systems tract (Hunt and Tucker, 1992; Myers and Milton, 1996; Miall, 1997).

The lowstand systems tract (LST) consists of two parts, a lowstand fan deposited during relative sea-level fall (and possibly during intitial sea-level rise) and the lowstand prograding wedge deposited during accelerating sea level rise (Van Wagoner *et al.*, 1990; Myers and Milton, 1996). It has recently been suggested that the lowstand fan (basin floor fan and slope fan) and the lowstand prograding wedge are, at least in some successions, deposited simultaneously (Ito, 1998). Further study is needed before it can be assumed that this is part of a recurrent pattern.

The shelf margin systems tract (SMST) occurs in sequences in which the drop in sea-level at the depositional-shoreline break is imperceptible (Van Wagoner *et al.*, 1990). This systems tract is equivalent in relative position to the lowstand systems tract. The top of the shelf margin systems tract and correspondingly, the base of the transgressive systems tract is referred to as the transgressive surface (TS).

Transition from the lowstand to transgressive systems tract (TST) is marked by the surface of maximum progradation or transgressive surface (TS). Where minor erosion occurs during transgression, this surface is referred to as the transgressive surface of erosion (TSE). The transgressive systems tract is characterized by an aggradational to retrogradational succession of parasequences deposited during a period of relative sea-level rise (Myers and Milton, 1996).

The top of the transgressive systems tract and base of the highstand systems tract (HST) is marked by the maximum marine flooding surface (MFS) and is characterized by a sudden landward shift in sedimentary facies and consequently by an abrupt increase in gamma radiation in both proximal and distal settings. The highstand systems tract is characterized by a strongly progradational package of parasequences. During deposition of the highstand systems tract, sediment supply exceeds the creation of accommodation space and sea-level rise decelerates. At the basin margin, the highstand systems tract is capped by the regressive surface of erosion/sequence boundary (RSE/SB), signifying falling sea-level.

Williston Lake Sequence Stratigraphy

Triassic strata in the Western Canada Sedimentary Basin have been subdivided into three lithofacies assemblages reflecting large scale cycles in regional sea levels (Gibson and Barclay, 1989). The study interval spans an interval beginning in the latest early Triassic (late Spathian) and ending in the early Upper Triassic (early Carnian) corresponding to Assemblage II of Gibson and Barclay (1989).

Stratigraphic sections are presented for the five localities discussed in this report (Figures 3 through 7). Correlation of these measured sections (Figure 10) reflects the complex depositional history of the study area. Depositional sequences within the study area are assigned alpha-numeric designators corresponding to their ages. This paper discusses four Anisian (TA1-TA3) and three Ladinian (TL1-TL2) depositional sequences bound by subaerial unconformities and their basinward correlative conformities (Figures 3 through 7). Strata exposed at the base of the Brown Hill section have thus far failed to yield biostratigraphically diagnostic fossils and are referred to as T? reflecting their uncertain stage assignation (Figurs 4 and 9). Parasequences are designated sequentially from the base of each sequence by lower case letters placed after the sequence designator (i.e. TL1b refers to sequence TL1, parasequence b).

Definitively Anisian sediments are limited in outcrop exposure to the Ursula Creek section within the study area (Figures 3 and 8). Middle Triassic sequences at Ursula Creek show an overall thinning-upwards trend, from over fifteen metres thick in the early Anisian (sequence TA1) to less than two metres in the Ladinian (sequences TL2 and TL3; Figure 3).

Ladinian sediments, particularly upper Ladinian sediments crop out at all localities discussed in this paper (Ursula Creek, Brown Hill, Glacier Spur, Beattie Ledge and Aylard Creek; Figures 3 through 7). The Ladinian succession is particularly condensed at Ursula Creek. Although three Ladinian sequences have been identified elsewhere in the study area, sequence separation proved impossible at Ursula Creek.

Anisian Sequences (TA1-TA4)

Distal settings: Ursula Creek

Exposure of Anisian sequences (TA1 through TA4) within the study area are limited primarily to Ursula Creek (Figure 3 and 8). Although the dangers of delineating sequences on the basis of a single, basinal locality are recognized, preliminary correlation with wells in the subsurface east of the study area (*i.e.* a-40-L/94-B-1) suggests that these sequences are correlatable through at least the western portion of the Western Canada Sedimentary Basin.

Each Anisian sequence consists of a thin (10-15m) package of shale, siltstone and silty very-fine-grained sandstone (lithofacies association I; Table 2). Each sequence is initiated by a thin bed of comparably coarse sediment (silty very-fine grained sandstone), characterized by relatively low levels of gamma radiation and interpreted as the lowstand systems tract. In each sequence, the transgressive systems tract is characterized by an overall fining-upwards succession of sandy siltstone to silty mudstone (Figure 3). The sharp gamma ray spike capping each sequence (Figure 3) is interpreted as the late transgressive systems tract and highstand systems tract. This thin, radioactive interval constitutes a condensed section reflecting a period of relative sediment starvation in more distal parts of the basin. In most sequences, these intervals were characterized by abundant phosphate nodules.

The conodonts *Neogondolella regale* and *N.* sp. aff. *mombergensis*, collected from the highly radioactive zone underlying sequence TA1 (Figure 8) are consistent with early Anisian deposition (Orchard and Tozer, 1997). The ammonoid genus cf. *Grambergia* sp. collected from the same interval (Figure 8) provides additional support for a lower Anisian age assignment (Tozer, 1994). *N. bifurcata* and *N.* cf. *N. excelsa* from the upper phosphatic interval in sequence TA1 are characteristic of Middle Anisian deposition (Orchard and Tozer, 1997). Co-occurence of the conodonts *N.* cf. *N. excelsa* and *N. constricta* from the base of sequence TA3 (Figure 8) is indicative of late Anisian deposition (Orchard and Tozer, 1997). The age of sequence TA4 is less well constrained than subjacent sequences. A monospecific assemblage of *N. constricta* collected from overlying strata (Figure 8) is suggestive of deposition within the late Anisian to early Ladinian. Further analysis is needed to constrain the age of this interval more precisely.

The highly radioactive horizon subjacent to sequence TA1 (Figures 3 and 8) is the outcrop equivalent of the base of the Doig phosphate zone, a regionally correlatable marker horizon commonly utilized as a datum in Triassic subsurface studies in the Western Canada Sedimentary Basin. The sequence TA1 basal boundary lies several metres above the Spathian-Anisian boundary. A "near Spathian-Anisian" boundary has been recognized in numerous Triassic successions world wide (i.e. Germany, Italy, Himalayas, Siberia, Sverdrup Basin, Barents Sea) and is interpreted to be a globally correlatable second-order sequence boundary (Embry, 1997). Additional analysis is needed before the sequence TA1 basal boundary can be confirmed or refuted as the globally correlatable "near Spathian-Anisian" boundary.

The upper part of the Doig phosphate zone likely includes the entire Anisian succession at Ursula Creek (Figure 3). These sediments are fine-grained (primarily shale and silty shale), contain abundant phosphate nodules, and are characterized by fairly high gamma radiation levels. Comparably coarse sediments (silty, very fine-grained sand) within this interval may comprise the distal portions of Anisian (TA1 through TA4) lowstand systems tracts (Figure 3), however additional analysis is needed before the regional extent (and thus veracity) of these sequences can be assessed.

Ladinian Sequences

Distal settings: Ursula Creek

As mentioned earlier, Middle Triassic sequences at Ursula Creek display an overall "thinning-upwards" trend (Figure 3). This phenomonon is particularly apparent in the upper part of the Middle Triassic package. Ladinian sediments at Ursula Creek are limited to a thin package (~5 metres) of sediments wedged between sequence TA4 and a thick succession of Carnian strata. Similar to Anisian sequences, Ladinian strata at Ursula Creek consist of a thin zone of silty very-fine grained sandstone beds overlain by black, phosphatic silty shale (lithofacies association I; Table 2). Correlation with other localities in the study area however suggests the presence of at least three Ladinian sequences within this interval.

The Ursula Creek Ladinian package is also characterized by an increasing proportion of carbonate beds and lenses upwards (Figure 3). The Ladinian-Carnian contact at this locality is coeval with the lithostratigraphic Toad-Ludington contact reflecting a shift from dominantly siliciclastic (lithofacies I; Table 2) to carbonate (lithofacies VII; Table 2) deposition.

Diagnostic Ladinian conodonts were not collected at Ursula Creek. The Ladinian succession is limited to at most 5 metres. Conodont sampling density rarely exceeded one bulk sample every 5 to 10 metres. Thus, the absence of Ladinian conodonts may be an artifact of sample density rather than a lack of Ladinian sediments. A sample collected within the Ladinian succession yielded *Neogondolella constricta*, suggestive of late Anisian to early Ladinian deposition (Figure 8). The next sample collected in the Ursula Creek section (from four metres above the *N. constricta* sample; Figure 8) contained

Metapolygnathus polygnathiformis, a characteristic Lower Carnian form. Additional sampling and more detailed gamma ray analysis is needed to establish the presence and nature of Ladinian sequences at Ursula Creek. These samples restrict the total upper Ladinian succession to a maximum of four metres.

Sequence T?: The Abiotic Zone

Proximal settings: Brown Hill

A thick (albeit intermittently exposed) succession of normally graded silty very fine-grained sandstone to silty mudstone packages at the base of the Brown Hill section (Figure 4a) is interpreted as amalgamated turbidites deposited in a ramp setting (lithofacies association I; Table 2). Despite careful outcrop analysis and intensive conodont sampling this interval has yielded neither ammonoids nor conodonts. Scant biostratigraphic data from the overlying sequence (sequence TL1) further compounds the problem of placing these strata within a sequence biostratigraphic framework (Figure 9). Preliminary correlation between Brown Hill and wells in the subsurface east of the study area (*i.e.* a-40-L/94-B-1) places this interval above the Doig phosphate zone and thus within the Middle Triassic (Anisian or early Ladinian).

Few uppermost Anisian and lowermost Ladinian conodont collections are known within the Western Canada Sedimentary Basin (Orchard and Tozer, 1997). This absence, despite intensive sampling through strata likely deposited within these intervals may reflect a regional (northwestern pangean) mid to late Anisian conodont extinction event (Henderson, pers. comm.). The complete absence of conodonts in numerous samples collected from the basal part of the Brown Hill section may be a reflection of diminished conodont faunas in the aftermath of this extinction. Utilizing an absence of faunal evidence as evidence of faunal absence is however counter intuitive. Until biostratigraphic data becomes available, this "abiotic" zone is referred to here as Middle Triassic (Sequence T?).

Intermittent exposure of these sediments has made it difficult to separate this succession into systems tracts. Parasequences T?d and T?e (Figure 4a) are tentatively interpreted as the sequence T? highstand systems tract, based primarily on their strongly progradational nature and their position below the T?/TL1 sequence boundary.

Ladinian Sequence TL1

Proximal settings: Brown Hill & Glacier Spur

At Brown Hill and Glacier Spur (Figures 4a and 5a) sequence TL1 consists of an overall progradational package of offshore to shoreface parasequences. The basal sequence boundary, at Brown Hill consists of a thick bioclastic rudstone/grainstone, interpreted as a turbidite channel, incising deeply into the underlying strata (parasequence T?e). This unit (parasequence TL1a) is normally graded, and composed primarily of bioclastic detritus and siliciclastic sand (lithofacies D, lithofacies association I; Table 2). The bioclastic component consists of abraded brachiopod (terebratulid and spiriferid), bivalve, gastropod, and echinoderm (crinoid and echinoid) fragments. Parasequence TL1a comprises the entire TL1 lowstand systems tract at Brown Hill. Terebratulid brachiopods, crinoids and echinoids are common components of sediment within the lower shoreface and offshore transition within the Liard Formation, and are generally restricted to these zones. Although progradational below parasequence TL1a and retrogradational above, most parasequences within this part oft the Brown Hill succession consist of fine-grained siliciclastic sediment. Basinward transport of bioclastic material generally restricted to a relatively proximal depositional setting within a deeply incisional channel provides additional evidence for a relative lowstand in sea level within the study area.

At Brown Hill (Figure 4a) the transgressive systems tract consists of a back-stepping (retrogradational) package of thin, progradational parasequences (TL1b, TL1c and TL1d) interpreted as turbidites (possibly tempestites), deposited in a ramp setting (lithofacies association I; Table 2). The maximum marine flooding surface signifying the transition from transgressive to highstand conditions is characterized by a sudden increase in gamma radiation at both proximal and distal sites (Figures 3, 4a and 10), consistent with sediment starvation and a higher proportion of organic detritus within basinward sediments.

The sequence TL1 highstand systems tract at Brown Hill and Glacier Spur (parasequences TL1e through TL1i) is characterized by a strongly progradational succession of proximal offshore to shoreface parasequences (Figures 4a and 5a). Channelized sand bodies and bioclastic sand filled gutter casts commonly bisect hummocky cross-stratified sandstone units within the uppermost parasequence in sequence TL1 and are interpreted as incision and infill associated with tidal inlet channels and storm-generated rip-currents (lithofacies association II; Table 2). The Toad/Liard formational boundary is gradational and occurs within the TL1 highstand systems tract at Brown Hill and Glacier Spur. The Formation boundary is picked near the base of parasequence TL1i, where the overall proportion of shale diminishes, and that of sandstone greatly increases (Figures 7a and 8a).

Although numerous samples from sequence TL1 have been analyzed for conodonts from this interval, none have produced diagnostic fossils. Gibson and Edwards (1992) report the presence of "*Nathorstites*" impressions from this interval, suggesting possible Ladinian deposition.

Ladinian Sequence TL2

Proximal settings I: Brown Hill & Glacier Spur

At Brown Hill and Glacier Spur the TL1/TL2 sequence boundary is characterized by a relatively minor shift in lithofacies (Figures 4a and 5a). Shoreface sandstone units within parasequence TL1i (lithofacies association II; Table 2) are incised by parasequence TL2a consisting of intercalated nodular bioclastic silty packstone and silty very fine-grained sandstone layers (lithofacies association III; Table 2). Parasequence TL2a has been interpreted as a transgressive shoreface succession (Chapter 4) and comprises the sequence TL2 early transgressive systems tract (Figures 4a and 5a). A thin, laterally persistent, brachiopod-rich limestone layer at the top of parasequence TL2a is interpreted as a flooding surface and a parasequence boundary. Sequence TL2 is interpreted to be a type II sequence following the terminology of Van Waggoner *et al.* (1990), in part because although there is significant erosion, there is minimal apparent fall in relative sea level associated with the sequence boundary at Brown Hill.

The medial portion of the transgressive systems tract (parasequences TL2b through TL2f; Figures 4a and 5a) consists of an aggradational package of parasequences, each of which coarsen upwards from very fine-grained, hummocky cross-stratified to fine-grained low-angle trough cross-stratified bioclastic sandstone (lithofacies association II; Table 2). The presence of granule to pebble-sized chert clasts within channelized sand/bioclast bodies bisecting shoreface sandstone units (tidal channels or rip-current scour fill) suggests close proximity to a siliciclastic point source (Zonneveld *et al.*, in press). A prominent flooding surface at the base of parasequence TL2g reflects the inability of sediment input to keep pace with increasing water depths (Figures 4b and 5b). Parasequences TL2g and TL2h comprise the upper part of the sequence TL2 transgressive systems tract. Transition from transgressive to highstand deposition occurs at abrupt maximum marine flooding surface overlying parasequence TL2h (Figures 4b and 5b).

Parasequences TL2i-TL2k, comprise the most distal (i.e. deepest water) deposits within the Liard Formation. These units, deposited within the offshore to offshore transition, consist of an aggradational to slightly progradational succession of parasequences and comprise the basal portion of the highstand systems tract (Figures 4b and 5b).

Parasequences TL2m, TL2n and TL2o comprise one of the most unique units within the study area (Figures 4b and 5b). This interval consists of a relatively heterolithic, coarsening upwards, mixed siliciclastic-carbonate, shoreface succession (lithofacies associations IV and V; Table 2). Thick ungraded accumulations of unabraded brachiopods, echinoid and crinoid elements at the base of parasequence TL2m are interpreted as lower shoreface emplaced terebratulid-echinoid dominated biostromes (lithofacies associations V; Table 2). Although the terebratulid-echinoid biostromes vary in thickness and composition between Brown Hill and Glacier Spur, a distance of approximately 2km, similar deposits have been observed in shoreface parasequences throughout the study area (*i.e.* Beattie Ledge and Aylard Creek, Figures 6, 7 and 10). Subsurface equivalents have not previously been recognized, but when identified will likely comprise significant potential hydrocarbon reservoir units. Parasequences TL2n and TL2o consist of a coarsening upwards succession of sandy bioclastic packstone/calcareous sandstone conformably overlain by a thick cryptalgal laminite (lithofacies association IV and VI. These parasequences, deposited within a barrier island shoreface, foreshore and backshore/lagoonal setting (chapter 2) comprise the top of sequence TL2 (Figures 4b and 5b).

The age of sequence TL2 is well-constrained as upper Ladinian *(maclearni-sutherlandi* Zones) by the presence of conodonts within several parasequences at Brown Hill and Glacier Spur. The co-occurence of several conodont taxa; *Paragondolella* cf. *P. foliata*, *Budurovignathus mungoensis* and *Budurovignathus diebeli*, indicate an upper Ladinian *maclearni* zone designation for the sequence TL2 shelf margin and transgressive systems tracts, and possibly the base of the highstand systems tract (Figure 9; Mosher, 1973). Co-occurrence of the conodonts *Paragondolella inclinata* and *Budurovignathus mungoensis* within the upper highstand systems tract indicate deposition within the upper Ladinian *sutherlandi* zone (Figure 9; Mosher, 1973; Zonneveld *et al.*, 1997).

Proximal Settings II: Beattie Ledge and Aylard Creek

The base of the Middle Triassic successions at Beattie Ledge and Aylard Creek (Figures 6 and 7) begins within the transgressive systems tract of sequence TL2. These parasequences (TL2c-TL2H) consist of an aggradational to moderately progradational succession of offshore through lower shoreface sediments. Rather than dominantly siliciclastic sediment such as that observed within the TL2 transgressive systems tract at Brown Hill and Glacier Spur, this package consists of a mix of siliciclastic and bioclastic sediment (lithofacies associations II and IV; Table 2). Similar to the upper transgressive systems tract at Brown Hill and Glacier Spur (Figures 4b and 5b), a prominent flooding surface occurs at the base of parasequence TL2g, prior to the maximum marine flooding surface at the base of parasequence TL2i (Figures 6, 7 and 10).

The highstand systems tract at Beattie Ledge and Aylard Creek consists of an overall progradational succession of dominantly siliciclastic parasequences deposited primarily within the offshore transition and lower shoreface (lithofacies associations II and IV; Table 2). Lithofacies within the sequence TL2 highstand systems tract, in particular parasequences TL2n and TL2o (Figures 6 and 7), reflect deposition in a slightly deeper depositional setting than their counterparts at Brown Hill and Glacier Spur (Figure 4b and 5b). Preservation of hummocky cross-stratification, ichnofossils consistent with the *Cruziana* ichnofossil assemblage and the presence of *in situ* infaunal lingulid brachiopods suggests deposition with the lower shoreface (Zonneveld *et al.*, 1997; chapters 2 and 4). Two additional parasequences (TL2p and TL2q) occur within this succession at Beattie Ledge and Aylard Creek (Figure 4b and 5b) which have been erosionally removed from Brown Hill and Glacier Spur (Figures 6 and 7) at the TL2/TL3 sequence boundary (Figure 10).

Ladinian Sequence TL3

Proximal Settings I: Brown Hill and Glacier Spur

Parasequence TL3a consists of an amalgamation of shoreface, foreshore, washover fan, intertidal flat and supratidal flat deposits (lithofacies association VI; Table 2). The basal surface incises deeply into the underlying cyanobacterial laminite at the top of parasequence TL2m (Figures 4b and 5b). This surface is correlatable to Beattie Ledge (Figures 6 and 10) and has been observed in wells in the subsurface west of the study area (*i.e.* well a-83-A/94-

B-8; Figure 13). Parasequences TL3a and TL3b consist of a succession of dolomitic sandy/silty mudstone to wackestone interbedded with cyanobacterial laminae and mounds as well as minor calcareous channel sandstones (lithofacies association VI; Table 2). Parasequences TL3a and TL3b represent either the sequence TL3 lowstand systems tract, or perhaps more likely, the early transgressive systems tract. These units, deposited within an environment oscillating between supratidal and intertidal conditions, represent a significant basinward shift in facies. Sequence TL3 is interpreted as a type I sequence (*sensu* Van Waggoner *et al.*, 1988; 1990), likely deposited in a ramp margin setting (Zonneveld *et al.*, 1997).

The base of parasequence TL3c comprises a transgressive surface of erosion/ravinement surface (Figures 4b and 5b). This surface is the first significant flooding surface above the TL2/TL3 sequence boundary. Correspondingly this surface may be the initial transgressive surface and the base of the transgressive systems tract, or alternatively is a parasequence boundary separating earlier and later stages of the transgressive systems tract. Parasequence TL3c, composed of bioclastic sandstone, incises into the intertidal deposits of parasequence TL3b (Figures 4b and 5b). Parasequences TL3a through TL3e comprise an aggradational to retrogradational package capped by an abrupt basinward shift in lithofacies, and are interpreted as the sequence TL3 transgressive systems tract (Figures 4b and 5b). Parasequences TL3c through TL3e contain thick accumulations of bioclastic debris including abraded, disarticulated and whole terebratulid and spiriferid brachiopods, echinoderm detritus and bivalve fragments. These units are interpreted to have been deposited within a transgressive shoreface setting.

The anomalously high gamma radiation spike at the base of parasequence TL3f (Figures 4b and 5b) is attributed to large quantities of phosphatic vertebrate skeletal elements within the basal transgressive lag. Units TL3f through TL3j consist of an overall aggradational to retrogradational succession of progradational offshore transition to shoreface parasequences (Figures 4b and 5b). A series of erosive-based, normally graded sandstone bodies at Glacier Spur, characterized by basal dolomitic mudclast lags, are interpreted as tidal inlet channels (Figure 5b; Zonneveld *et al.*, 1997).

A second major flooding surface, exposed only at Brown Hill and Glacier Spur, occurs at the base of parasequence TL3k (Figures 4b and 5b). Similar to the basal lag at the base parasequence TL3f, (the maximum marine flooding surface), this flooding surface is characterized by a thin pebble lag containing appreciable amounts of vertebrate skeletal material. Parasequences above this (TL3k, TL3l, TL3m) comprise an overall aggradational package (Figure 4b). These units comprise the top of the Liard Formationwithin the study area and correspondingly the top of the study interval. The contact with the overlying Charlie Lake Formationis buried within the study area.

Abundant ammonoids and conodonts within sequence TL3 tightly constrain this interval as uppermost Ladinian *(sutherlandi* zone), to possibly lowermost Carnian in the upper part of the sequence *(desatoyense* zone?). Ammonoids collected from the top of parasequence TL3e *(Nathorstites macconnelli, Daxatina canadensis, Muenesterites glaciensis* and *Lobites ellipticus*), are diagnostic of the *sutherlandi* Zone (Figure 9; Tozer, 1994; Zonneveld *et al.*, 1997). Conodonts collected from this same horizon (*Paragondolella inclinata* and *Budurovignathus mungoensis*) confirm this age diagnosis (Mosher, 1973; Orchard and Tozer, 1997). Numerous ammonoid impressions collected from parasequences TL3g and TL3h (Figure 9), referred to *Frankites* cf. *F. sutherlandi*, support an interpretation of uppermost Ladinian *(sutherlandi* zone) deposition.

Although *Budurovignathus mungoensis* is unknown from above parasequence TL3e, the conodont *Paragondolella inclinata* occurs as high as parasequence TL3l (Figure 9). *P. inclinata* ranges from the uppermost Ladinian *(sutherlandi* zone) to the top of the lower Carnian *(nanseni* zone). The presence of abundant representatives of this taxon in the absence of *B. mungoensis* may reflect lowermost Carnian deposition. Additional biostratigraphic evidence is needed to clarify the age of the upper part of this succession as either uppermost Ladinian or lowermost Carnian.

Proximal Settings II: Beattie Ledge

The TL2/TL3 sequence boundary at Beattie Ledge (Figures 6 and 10) is characterized by a high-density, low-diversity *Glossifungites* assemblage consisting of sharp-walled, unlined *Thalassinoides* (Figure 13). The *Glossifungites* ichnofacies consists of an assemblage of trace fossils which penetrate firm, unlithified substrates, specifically those which have been subaerially exposed or buried and subsequently re-exhumed (Pemberton and MacEachern, 1995). The burrows penetrate a well-sorted, very-fine grained, calcareous sandstone interpreted as lower to distal upper shoreface (Zonneveld and Gingras, *in press*). The burrows are infilled with a poorly sorted, sandy bioclastic packstone, a lithofacies absent in ovelying strata implying a sequence of events consisting of deposition and burial of lithofacies TL2q, reexhumation and burrowing, burial by a sandy bioclastic packstone, reexhumation, and finally deposition of sequence TL3a.

Similar to the succession observed at Brown Hill and Glacier Spur (Figures 4b and 5b), the sequence TL3 lowstand/early transgressive systems tract (parasequences TL3a and TL3b) at Beattie Ledge (Figure 6) consists of a succession of dolomitic sandy mudstone to wackestone, minor channel sandstones, cyanobacterial laminae and mounds and aeolian sand dunes (lithofacies association VI; Table 2). The top of this succession is erosionally overlain by a ravinement surface signifying the passing of the shoreline at this location and a shift back to fully marine conditions (Figures 6 and 10).

The upper part of the transgressive systems tract consists of a retrogradational package of three parasequences (parasequences TL3c TL3d and TL3e). Parasequence TL3c consists of calcareous sandstone with scattered vertebrate skeletal debris and lingulid fragments. The upper two of these parasequences contain a diverse array of poorly sorted, highly abraded to (rarely) unabraded bioclastic detritus. All three parasequences within the sequence TL3 upper transgressive systems tract are erosively based (Figures 6 and 10). Correlation with Brown Hill and Glacier Spur shows that these parasequences are significantly thinner at Beattie Ledge than in western localities, possibly due to erosional removal of transgressive sediments (Figure 10).

The maximum flooding surface observed at the base of parasequence TL3f at Brown Hill and Glacier Spur (Figures 4b and 5b) is also apparent at Beattie Ledge (Figures 6 and 10). This surface, also comprises the upper bounding surface of the transgressive systems tract and is pock-marked with abundant *Ophiomorpha annulata* burrows. The tops of these burrows have been eroded away indicating that erosion was associated with the deepening event signifying the transition from transgressive to highstand conditions (Zonneveld and Gingras, 1997). The highstand systems tract at Beattie Ledge, consists of three strongly progradational offshore transition to lower shoreface parasequences (Figure 6).

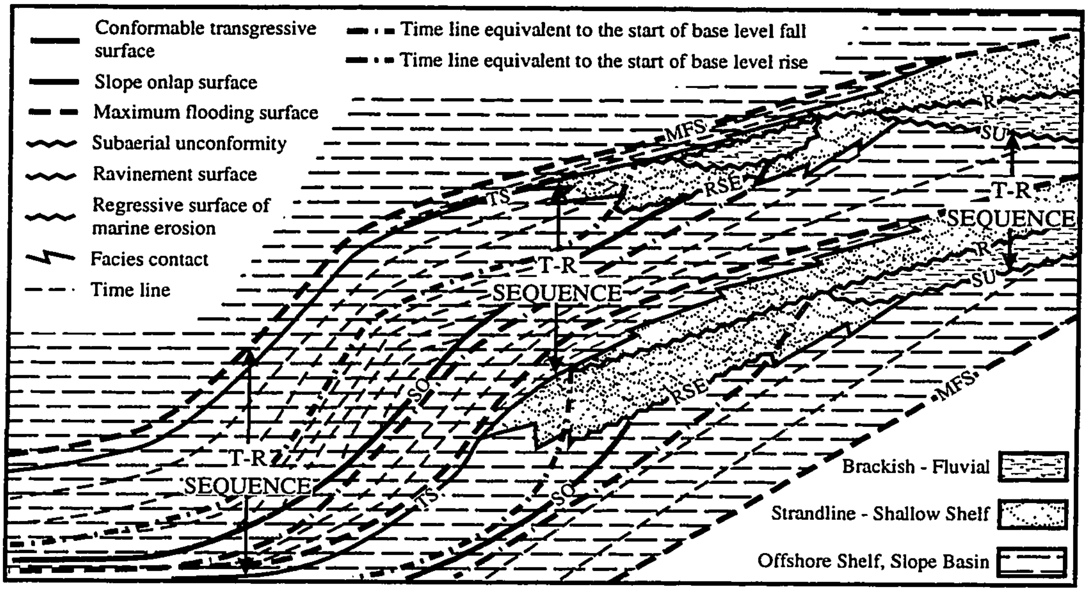
DISCUSSION

Depositional Sequences vs. T-R sequences

Over the past several decades, numerous methods have been proposed to analyze packages of sedimentary strata within a genetic or chronostratigraphic framework. Most of these methodologies employ subaerial unconformities to delineate stratigraphic packages. An alternative system has been proposed, utilizing sediment packages bounded by regional maximum marine flooding surfaces (Galloway, 1989; Xue and Galloway, 1995). Although this system has several advantages, particularly the ease with which this surface may be picked on well logs and seismic sections, subaerial unconformities are often incorporated within these "genetic sequences" creating inherently diachronous sediment packages.

Sloss (1963) recognized the presence of large scale sequences, bounded by interregional unconformities and correlatable across the North American craton. Evolution of concepts discussed in Sloss (1963) and continued development of the concepts of seismic stratigraphy (Vail *et al.*, 1977) resulted in the eventual development of the discipline of depositional sequence stratigraphy (Jervey, 1988; Van Wagoner, 1985; Van Wagoner *et al.*, 1988; 1990; Vail *et al.*, 1977). Within this framework, sequences are composed of conformable successions of genetically related strata bounded by regionally extensive unconformities and their basinward correlative conformities (Figure 11a).

Although the basic Exxon sequence stratigraphic framework has been widely accepted by stratigraphers, it has become apparent that there are significant problems in defining the basinal correlative of the sequence boundary and therefore the position of sediments comprising the lowstand systems tract. Sequence boundaries were originally defined as regionally extensive subaerial unconformities which form during relative lowstands in sea level and their basinward correlative conformities which form at the initiation of sea level fall (Vail *et al.*, 1977; Van Wagoner *et al.*, 1988; 1990). The phrase "correlative conformity" implies the presence of a discrete surface, basinward and equivalent



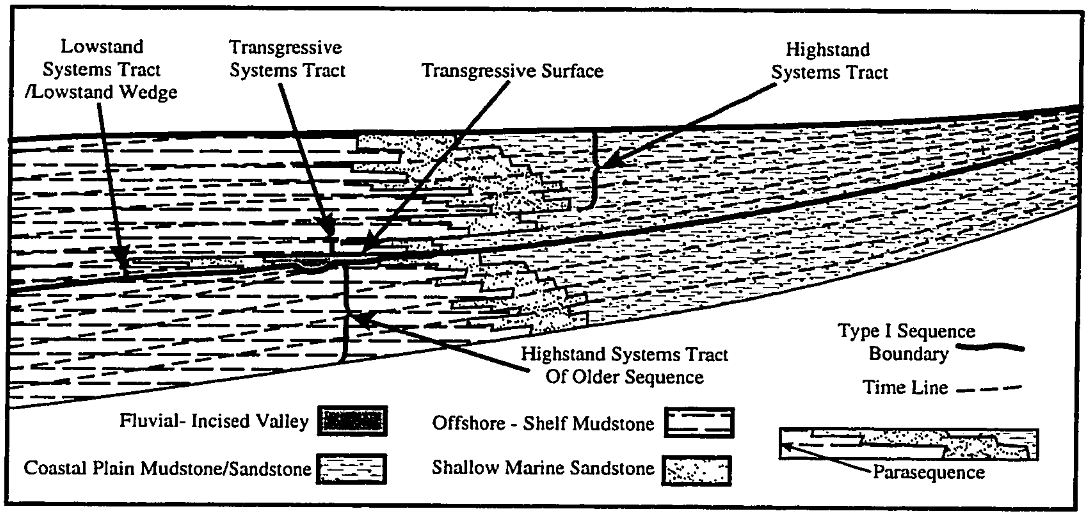


Figure 11a. Schematic model of a transgressive-regressive sequence (after Embry, 1997). Transgressive-regressive sequences boundaries consist of subaerial unconformities (or ravinement surfaces which have replaced them) and correlative transgressive surfaces. **Figure 11b.** Schematic model of a type I depositional sequence in a basin with a ramp margin (after Van Wagoner et al., 1990). Depositional sequence boundaries consist of regionally extensive subaerial unconformities and their correlative conformities, which form during relative lowstands in sea level.

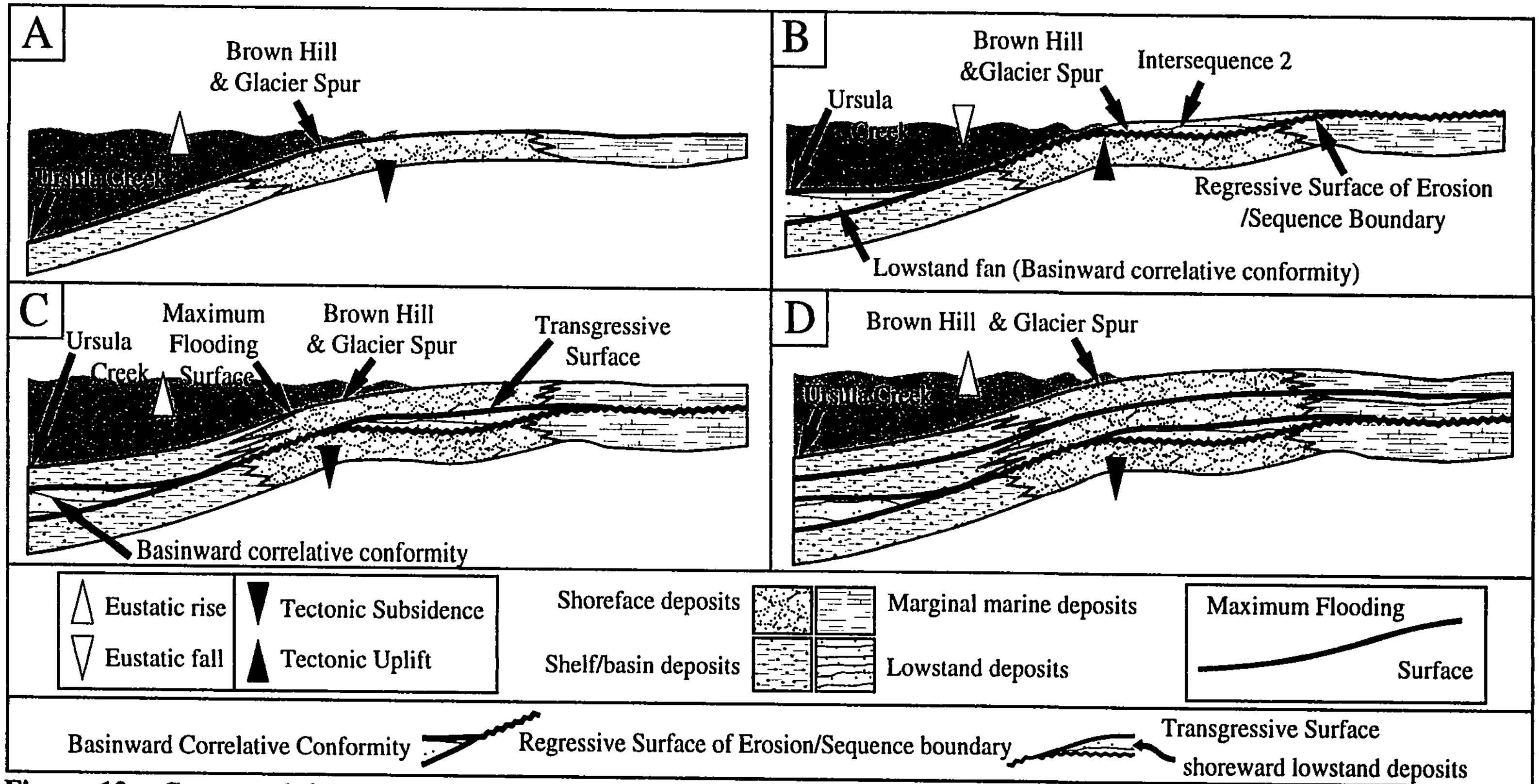


Figure 12. Conceptual framework for the development of the TL1/TL2 sequence boundary. **Figure 12a.** Sequence TL1 highstand deposition. Sedimentation outpaces the creation of accomodation space resulting in relative sea-level fall. **Figure 12b.** Sea-level fall continues to accelerate and the shore zone is exposed and eroded. Sediments eroded from proximal settings during sea-level fall and initial sea-level rise bypass the shelf and are redeposited in the lowstand fan. Accelerating sea-level rise results in deposition of the lowstand prograding wedge (not exposed within the study area). Erosion of cemented shoreface sediments (transgressive shoreface) results in deposition of the sequence TL2 early transgressive systems tract. **Figure 12c.** Relatively rapid sea-level rise results in deposition of the upper transgressive systems tract. **Figure 12d.** A decrease in the creation of accomodation space and/or a relative slow down in sea-level rise results in progradation and deposition of the sequence TL2 highstand systems tract. Relative sea-level fluctuations are likely the result of a mix of eustatic and tectonic forces.

to the subaerial unconformity.

In reality, the basinward equivalent to the sequence boundary logically consists of a package of sediments deposited during the period in which more proximal locations were subaerially exposed (*i.e.* the late stages of sea-level fall and the early stages of sea-level rise). This package of sediments, which includes at least part of the lowstand systems tract, is thus chronologically equivalent to time missing at the sequence boundary. Picking the base (or the top) of the lowstand systems tract as the correlative conformity of the subaerial unconformity thus creates an inherently diachronous surface.

Rather than Exxon-style sequence boundaries (*sensu* Van Wagoner *et al.*, 1988; 1990), stratigraphic correlations of Triassic strata within the Canadian Arctic Archipelago have utilized transgressive-regressive (T-R) sequence boundaries (Embry, 1993; 1995; 1997; Embry and Gibson, 1995). Transgressive-regressive sequences are packages of sedimentary rocks deposited during the interval between one deepening event and the beginning of the next (Figure 11b). Transgressive-regressive sequence boundaries consist of subaerial unconformities (or ravinement surfaces which have replaced them) and correlative transgressive surfaces (Johnson *et al.,* 1985; Embry, 1997). Picking the basinal sequence boundary at the transgressive surface separates sequences into sedimentary packages deposited during the interval between the top of a preceeding lowstand in sea level through a subsequent highstand and terminating at the top of the succeeding lowstand. The surface generally referred to as the transgressive surface however does not reflect the point at which sea-level begins to rise. While it is easily identified due to an abrupt change in lithofacies, this surface is in actuality the surface of maximum transgression rather than the surface of initial transgression. Utilizing this surface places the sequence boundary after the point of maximum lowstand.

Embry (1997) suggests that the unconformity within T-R sequences is part of the boundary rather than included within the sequence. The fact remains however that the basinward equivalent of the subaerial unconformity comprises a package of sediment rather than a surface. Inclusion of these strata within either sequence inevitably results with a significantly diachronous sequence boundary. Thus, neither depositional sequences (*sensu* Van Wagoner et al., 1990), nor transgressive regressive (T-R) sequences (*sensu* Embry, 1995; 1997) offer a satisfactory solution to this quandry.

Satisfactory resolution of this dilemma may lie in the recognition of "intersequences", packages of sediments deposited synchronously with the formation of subaerial unconformities (Figure 12). These units are chronologically distinct from either the preceeding or succeeding sequence and logically, should be considered separate from them. This diachroneity is rarely a concern in shallow settings, but is particularly significant where proximal and distal successions are correlated.

Debating the comparative virtues of depositional sequence stratigraphy and transgressive-regressive sequence stratigraphy boils down to situational semantics. As suggested above, the two methodologies are equally accurate from a chronostratigraphic viewpoint. The question should therefore perhaps focus on the conditions under which each methodology is most appropriately applied.

The majority of described sequences are bounded by Type I boundaries (*sensu* Van Wagoner *et al.*, 1988; 1990) in which sea-level lowstand occurs below, or basinward of, the shelf edge (Miller and West, 1998). With the exception of incised valley systems, lowstand deposits associated with these systems (lowstand deltaic systems, lowstand fans) also occur primarily basinward of the shelf edge (Miller and West, 1998). In this situation, depositional sequence stratigraphy provides an excellent framework for stratigraphic analysis.

In other situations transgressive-regressive sequence stratigraphy provides a more user-friendly framework. Carboniferous and Permian strata in the midwestern United States have traditionally been separated into cyclothems. The term "cyclothem" was introduced during the early part of the century to describe strata characterized by cyclic facies patterns in the Carboniferous of the Illinois Basin (Wanless and Weller, 1932). Most cyclothems consist of a stratigraphic succession of marine (shale, limestone) and continental (coal, sandstone, shale, often pedogenically altered) deposits. Application of depositional sequence stratigraphy has proven problematic, due primarily to difficulties in isolating sequence boundaries among numerous, often closely stacked, exposure surfaces (Miller and West, 1998). Marine flooding surfaces overlying continental successions are however generally prominent. Thus, the use of transgressive surfaces to delineate sequence boundaries has proven more practical than utilizing lowstand surfaces of erosion (Miller and West, 1998).

Transgressive-regressive sequence stratigraphy also facilitates characterization of the Middle to Upper Triassic Charlie Lake Formationin the Western Canada Sedimentary Basin. This unit, in both outcrop and core, is characterized by numerous paleosols, solution collapse breccias and erosion surfaces. Surfaces representing subaerial exposure predominate. Isolating regionally significant sequence boundaries within this cacophonous amalgamation of surfaces is essentially impossible. Rare bioclastic sandstone beds occur intermittently throughout this unit. These units comprise transgressive surfaces and provide a means for chronostratigraphic correlation.

Systems tracts within the Middle Triassic succession at Williston Lake have been placed within a relatively conventional sequence stratigraphic framework. The inherent caveats in demarcating sequence boundaries in distal settings are recognized however and it is acknowledged that transgressive-regressive sequences could serve equally well.

The Driving Forces Behind Sequences: Tectonics and Eustasy

During recent years, the driving forces behind sea-level fluctuations and sequence boundary generation have come under increasing scrutiny. Historically, widespread (global) relative sea-level fluctuations were considered to be a primarily eustatic phenomenon (Haq et al., 1987;1988). Tectonism is the primary controlling mechanism on the creation and destruction of accommodation space and thus, at least within individual basins, may be the primary driving mechanism behind the genesis of sequence boundaries (Myers and Milton, 1996).

It has recently been proposed that major plate reorganizations may also be implicated in driving global relative sea-level changes (Cloetingh *et al.*, 1985; Embry, 1997). Episodic changes in the direction or rate of movement of one or more plates theoretically results in alteration of the horizontal stress regimes of all plates (Cloetingh *et al.*, 1985; Embry, 1997). Preferential subsidence of the oceanic portions and uplift of the continental portions of all of the plates (basin margins) results in relative global sea-level fall (due to an increase in total oceanic basins volume), and thus in a globally correlatable unconformity (Embry, 1997). When stresses relax, the oceanic portions of the plates rebound upwards and basin margins subside, resulting in relative sea-level rise (Embry, 1997). These effects would theoretically be locally reversed (or exacerbated) in tectonically active areas such as the various horst-graben complexes within the Peace River Embayment. This could potentially produce localized trangressive successions during regional or global lowstands, or localized subaerial unconformities during regional or global highstands.

Middle Triassic Biostratigraphy

Detailed Triassic biostratigraphic zonations for the Western Canada Sedimentary Basin have been presented in several papers (Tozer, 1994; Orchard and Tozer, 1997). Biostratigraphic data discussed in association with sedimentologic and sequence stratigraphic data have been lacking however. Although these papers refer to localities from which the specimens were collected, measured stratigraphic sections are not provided. Knowing precisely where organisms occur within a section is equally as important as knowing their position relative to each other (Holland, 1995; Brett, 1998). Biostratigraphic data utilized without isolating maximum marine flooding surfaces and potentially chronologically extensive subaerial unconformities provides limited, possibly misleading information (Brett, 1995; 1998; Holland, 1995).

Rather than occurring continuously through a stratigraphic succession, ammonoids generally occur in thin beds, separated from each other by thick successions of unfossiliferous sediments. At several localities within the study area, beds containing ammonoids often occur as lags at maximum flooding surfaces. Ammonoids at Brown Hill were limited to three thin (<0.25m) beds within approximately 600 metres of measured section. The upper two of these were associated with the sequence TL3 maximum marine flooding surface and early highstand systems tract. Ammonoids within the Ursula Creek section were limited to a single bed with particularly high gamma readings, interpreted as the late transgressive systems tract/early highstand systems tract immediately preceeding sequence TA1.

Ammonoids are similarly sporadically preserved in other stratigraphic units.

Ammonoids within the Permian Belcher Channel Formation(=Nansen Formation) of the Sverdrup basin were observed within a single, thin (10cm) bed, 235m above the base of a 806m section (Nassichuk and Henderson, 1986). This is the only locality containing ammonoids identified within the section described (Nassichuk and Henderson, 1986; Henderson *et al.*, 1995). Other Upper Carboniferous through Lower Triassic ammonoid localities in the Sverdrup Basin occur in discrete, widely spaced beds (Henderson, pers. comm., 1998).

Rather than reflect this sporadic distribution however, biostratigraphic standards are drawn as a continuous succession of ammonoid zones (*i.e.* Table 1, Tozer, 1994; Figures 3-8, Orchard and Tozer, 1997), indiscrimanately crossing stratigraphically significant surfaces. This practise promotes a false impression of the abundance and distribution of ammonoids in a given interval. Accurate depiction of ammonoid occurences plotted against detailed stratigraphic sections would alleviate many of these problems.

Over the past several decades, biostratigraphers have begun to stress the utility of conodonts as biostratigraphic indices for the Triassic of the Western Canada Sedimentary Basin (Mosher, 1968; 1973; Henderson, 1997; Orchard and Tozer, 1997). Conodonts tend to occur more regularly throughout stratigraphic successions, however, conodont sampling has often been limited to sediment obtained from ammonoid producing horizons (Orchard and Tozer, 1997), and has thus been of limited use in understanding the sequence biostratigraphic framework of the Triassic of western Canada.

Although ammonoids are extremely rare, excellent recovery of conodonts from the Ursula Creek section has permitted emplacement of Middle Triassic strata within a tight biostratigraphic framework. Due to an absence of diagnostic biostratigraphic indicators, correlation of the lower parts of the Brown Hill and Glacier Spur successions (?upper Anisian to ?lower Ladinian) remains tenuous. Conodont analysis has however permitted correlation of upper Ladinian sediments throughout the study area. Additional sampling is needed to confirm the nature of the Ladinian succession at Ursula Creek and the presence of the Ladinian-Carnian boundary in the upper Liard Formationat Brown Hill.

Orchard and Tozer (1997) provide an excellent summary of current ammonoid and conodont zonations in the Western Canada Sedimentary Basin, however their reliance on numerous undescribed conodont taxa compound difficulties in the utilization of this biostratigraphic framework. A revised version of this summary is presented in table 3. As exemplified by this study, considerable work is still needed to resolve the Middle Triassic biostratigraphic framework of western Canada.

Triassic Sequence Boundaries: Global Distribution

As the discipline of sequence stratigraphy has evolved and matured, various authors have attempted to construct a framework of globally correlatable sequence boundaries (Embry, 1984, 1988, 1997; Haq *et al.*, 1987; 1988). Triassic global sea-level curves are particularly problematic due to a paucity of chronostratigraphically (*i.e.* biostratigraphically, magnetostratigraphically or isotopically) controlled sequence stratigraphic studies. Nevertheless, over the past several years several global trends in Triassic sea-level have become apparent.

Embry (1997) summarized sequence stratigraphic data from eight localities worldwide, including Arctic Canada (Sverdrup Basin), Russia (East Siberia), Norway (Svalbard and Barents sea), Germany, Italy, China (northern Himalayas), southwestern United States, and western Canada (Western Canada Sedimentary Basin). The data available from these sites ranged from excellent (*i.e.* the Italian Alps) to marginal (much of the German Triassic; Embry, 1997).

Embry (1997) recognized 12 globally correlatable second- and third-order sequence boundaries within the Triassic. Global sequence boundaries pertinent to this study include the near Spathian-Anisian boundary (second-order), the near Anisian-Ladinian boundary (third-order), and the near Ladinian-Carnian boundary (second order; Embry, 1997). While these trends do appear globally correlatable, the stratigraphic framework from many of the sites is based on poor biostratigraphic data. Imprecision in dating and correlation methods are also a significant problem. Mørk (1994) considered transgressions to be simultaneous if they occured within a time span of two million years or less. While it is acknowledged that the biostratigraphic scale is an imprecise tool, this level of imprecision will likely promote correlation of non-related events. Continued sequence stratigraphic analysis in combination with detailed biostratigraphy is needed to construct an accurate and detailed global tectono-eustatic chart for the Triassic.

Middle Triassic sequence boundaries at Williston Lake

The Middle Triassic at Williston Lake is characterized by four Anisian (TA1-TA4) and three Ladinian (TL1-TL3) depositional sequences. Overall, Middle Triassic sequence boundaries discussed here support the general occurrence and timing of global sea-level correlations discussed in Embry (1997).

Anisian sequence boundaries

Anisian sequences are limited in outcrop exposure to Ursula Creek, the westernmost and correspondingly most distally emplaced section. The age of Anisian sequence boundaries at Ursula Creek are moderately well-constrained by conodont biostratigraphy (Figures 3 and 8).

The basal Anisian sequence boundary at Ursula Creek (*i.e.* the Smithian-TA1 boundary) occurs slightly above the base of the Anisian, as evidenced by the presence of earliest Anisian conodonts from the condensed horizon immediately subjacent to sequence TA1 (Figure 8). Although some authors have indicated that the Spathian-Anisian sequence boundary (2nd order) is a latest Spathian phenomenon (Aigner and Bachmann, 1992; Rüffer and Zühlke, 1995), emplacement of this sequence boundary slightly above stage boundary in the study area is consistent with global correlations presented in Embry (1997). Discrepency with interpretations of the German Trias is perhaps unsurprising, particularly in light of an absence of Early and earliest Middle Triassic marine units in this area.

Three internal Anisian sequence boundaries, TA1\TA2 (medial Anisian) and TA2\TA3 (late Anisian), and TA3\TA4 (late Anisian) have been identified within the Ursula Creek section (Figure 8). Although internal Anisian sequence boundaries are known from Italy (Rüffer and Zühlke, 1995) and Germany (Aigner and Bachmann, 1992; Rüffer and Zühlke, 1995), biostratigraphic evidence is insufficient to suggest that these sequence boundaries are globally correlatable.

An Anisian-Ladinian sequence boundary (3rd order) is present in most regions in which strata through this interval are preserved (Embry, 1997). Good biostratigraphic control in the Italian and German sections place the boundary in the latest Anisian (Embry, 1997; Rüffer and Zühlke, 1995). This boundary is currently rather poorly constrained within the study area. Conodont faunas characteristic of the late Anisian to early Ladinian occur within sequences TA3 and TL1 (Figure 8). Sequences within this part of the section range in thickness from six to less than two metres. More intensive conodont sampling than has previously been achieved is needed to establish the nature and timing of the Anisian-Ladinian sequence boundary within the study area.

Ladinian sequences boundaries

The Ladinian succession at Williston Lake is exposed at all five sites discussed in this report. Ladinian sequences are bound by subaerial unconformities in proximal sections such as Aylard Creek, Beattie Ledge, Brown Hill and Glacier Spur, and their basinward correlative conformable sediment packages at Ursula Creek. The presence of late Anisian to early Ladinian conodonts from the base of the interval and Carnian conodonts from the Ludington Formationimmediately overlying the study interval constrains the Ladinian succession to a maximum of five metres of section at Ursula Creek (Figure 8) although it is possible that the Ladinian is unrepresented at this site. Until more intensive conodont sampling of this interval is completed, the presence and thickness of the three Ladinian sequences at Ursula Creek can not be definitively established.

Sequences T? (latest Anisian?) and TL1 are limited in outcrop exposure to Brown Hill (Figure 4a). Despite intensive sampling, this succession has yielded few biostratigraphically significant fossils. Additional sampling is essential to place this part of the study interval within a sequence biostratigraphic framework. The TL1\TL2 sequence boundary is exposed at Brown Hill, Glacier Spur and possibly Ursula Creek (Figures 10 and 12). A possible Ladinian ammonoid (cf. *Nathorstites* sp.) from below the sequence boundary, and characteristic Ladinian conodonts from above the boundary (*Paragondolella* cf. *P. foliata*, *Budurovignathus mungoensis* and *Budurovignathus diebeli*) indicate an upper Ladinian *maclearni* zone designation (Figure 9). This sequence boundary is approximately coeval with the La2\La3 sequence boundary in the German and Italian Trias (Rüffer and

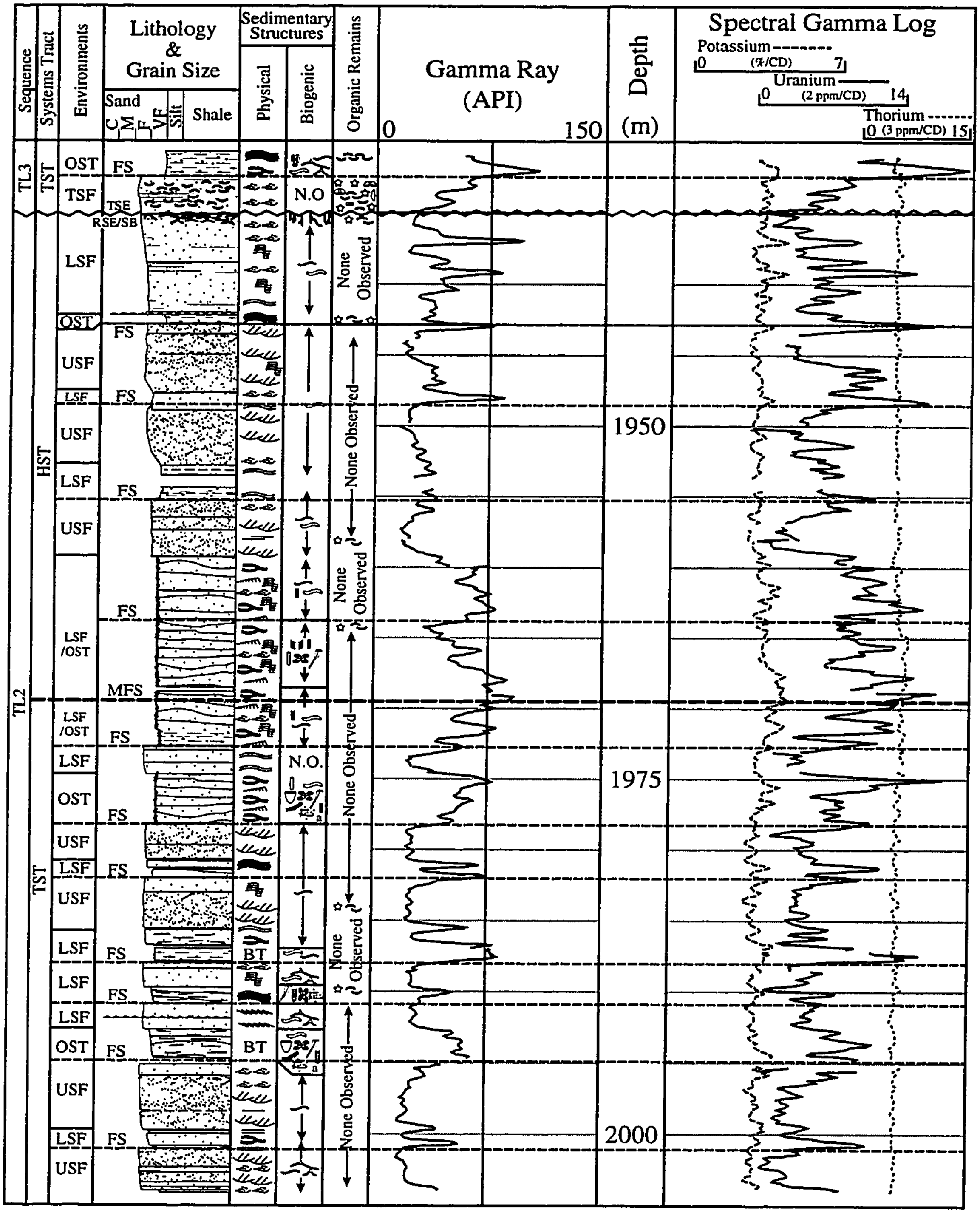


Figure 13. Cored interval within well BCStar PC Altares, a-083-A/094-B-08 (1931.0-2004.0m). Lithofacies designators, sedimentary structure symbols and fossil symbols are summerized in Table 2a.

Zühlke, 1995). It is however, not present within the Sverdrup Basin and east Siberia sections (Embry, 1997) and thus, may not be a globally correlatable event.

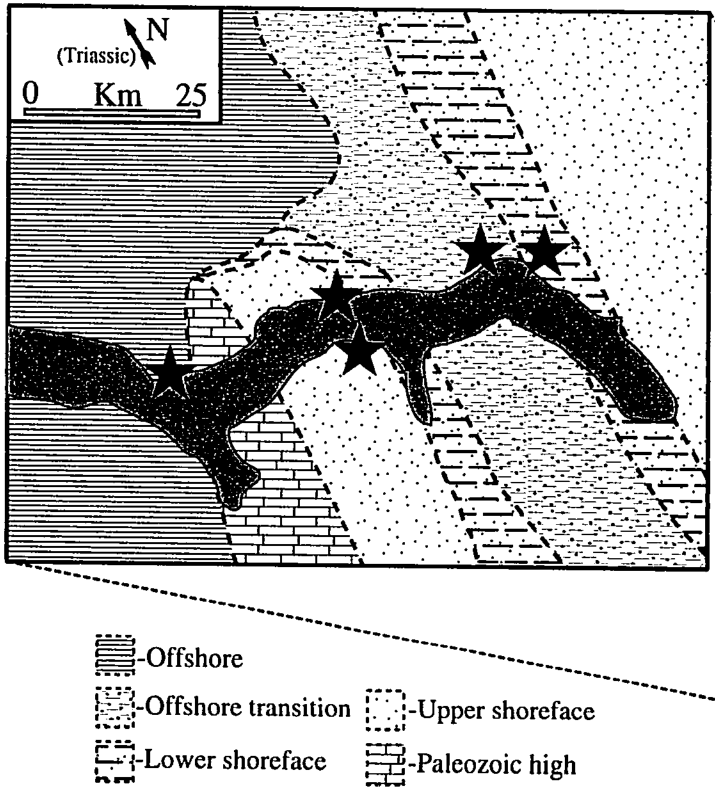
The TL2-TL3 sequence boundary is, with the exception of Ursula Creek, exposed throughout the study area (Figure 10). This subaerial unconformity is conformable at Ursula Creek and unconformable at Glacier Spur, Brown Hill and Beattie Ledge (Figure 10). It is characterized by a well-developed *Glossifungites* surface at Beattie Ledge. *Budurovignathus mungoensis, Paragondolella* cf. *P. foliata* and *Paragondolella inclinata* recovered from below the sequence boundary, and *Budurovignathus mungoensis,* and *Paragondolella inclinata* collected from above the sequence boundary severely constrain the age of this surface to the uppermost Ladinian *sutherlandi* Zone (Figure 9). This sequence boundary is interpreted to correspond to the globally correlatable near Ladinian-Carnian sequence boundary (2nd order) discussed in Embry (1997).

The Charlie Lake Formation in subcrop is characterized by several regionally correlatable subaerial unconformities (Arnold, 1994). Of these, the Coplin Unconformity is the most significant. Although the Charlie Lake Formation is currently characterized by the complete absence of biostratigraphic data, several authors have suggested that this unconformity may be equivalent to the near Ladinian-Carnian second-order sequence boundary (Embry and Gibson, 1995; Embry, 1997; Davies, 1997).

A particularly extensive cored interval through well a-83-A/94-B-8 (Figure 13) contains core throught the "A" marker horizon. Correlation of the TL2-TL3 sequence boundary into the Altares Field in the subsurface east of the outcrop belt (Figure 13) shows that this sequence boundary is equivalent to an erosional unconformity which occurs at the base of the "A" Marker Limestone in this well. The "A" Marker is a regionally extensive marker unit present throughout the northeastern British Columbia portion of the Western Canada Sedimentary Basin. Analysis of core within Wargren Field and Tommy Lakes Field northeast of the study area confirm that an erosional unconformity occurs at, or slightly below (1-15m) the base of the "A" Marker throughout the basin (Chapter 6). This surface is characterized by a thick *Glossifungites* in the Altares Field (Figure 13). The Coplin unconformity occurs approximately 250 metres above the TL2-TL3 sequence boundary in the Altares Field, and is therefore considered to be significantly younger than the uppermost Ladinian/lowermost Carnian.

Paleotopographic Effects

Chronologically equivalent sediment packages generally decrease in thickness in a basinward direction. This is particularly true in arid mixed clastic-carbonate systems where minimal sediment is transported seaward of the shelf/slope break, even during lowstand conditions. A comparison of Middle Triassic sediments at Ursula Creek and Brown Hill (Figure 10) exemplifies this phenomenon. In the absence of evidence of subaerial exposure or submarine erosion, the total thickness of Middle Triassic sediments at Ursula Creek (~45 metres) may represent an essentially continuous section through the Ladinian and Carnian



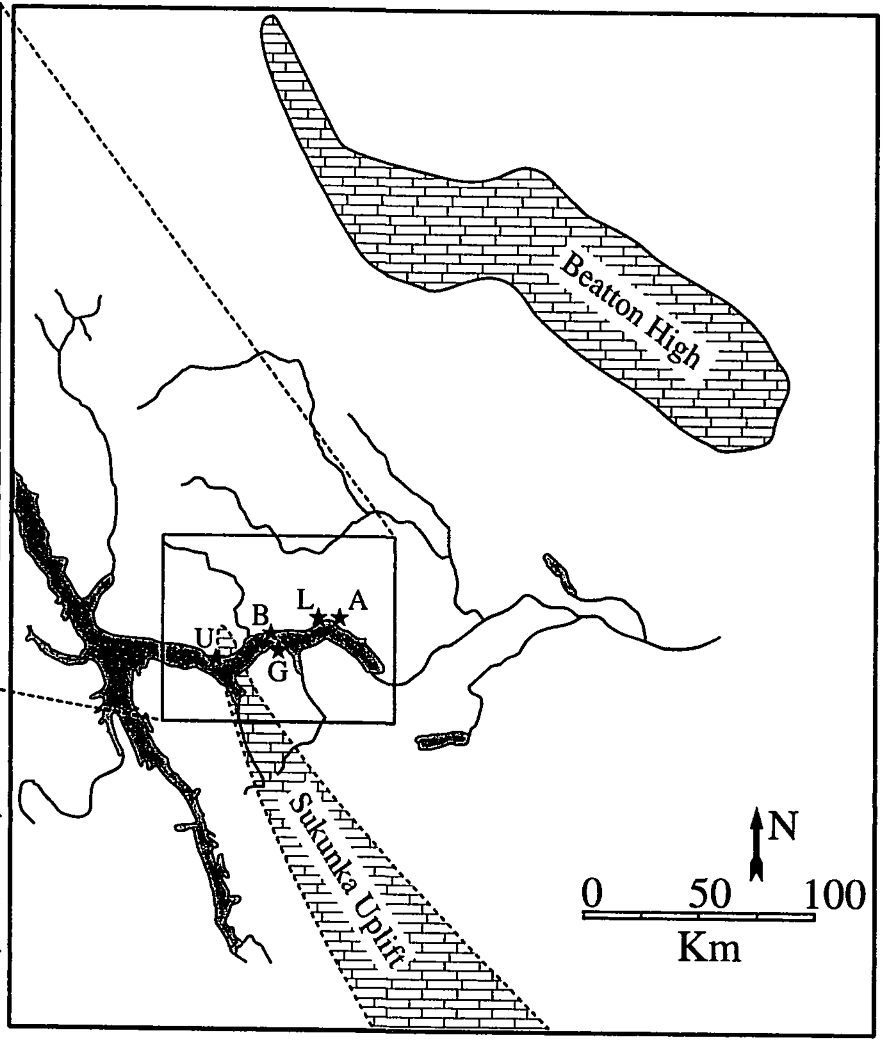


Figure 14. Hypothetical paleogeographic reconstruction of the Williston Lake region during the upper Ladinian (late sequence TL2 highstand systems tract). It is postulated that a paleotopographic high, possibly an extension of the Paleozoic West Alberta Arch/Sukunka Uplift, existed west of Brown Hill and Glacier Spur, in the vicinity of Ursula Creek.

stages in their entirety. The total thickness of Middle Triassic sediments at Brown Hill exceeds 550 metres in thickness, representing deposition in only the Ladinian and possibly the upper Anisian.

Basinward condensation of Ladinian sediments within the study area is particularly dramatic. The upper Ladinian *(meginae* through *sutherlandi* zones) at Brown Hill is characterized by at least 440 metres of section. At Ursula Creek, the Upper Ladinian attains a thickness of between zero and four metres, thus representing thinning of at least two orders of magnitude. It is postulated that this severe thinning resulted from tectono-topographic constraints rather than condensation.

Several lines of evidence suggest the presence of a paleotopographic high located somewhere in the vicinity of Ursula Creek, or between Ursula Creek and Glacier Spur/Brown Hill (Figure 14). These include: a) severe thinning of Ladinian sediments across a relatively short distance (20km today, possibly 10-20% more palinspastically); b) a retrogradational profile (upward thinning and fining) of Middle Triassic sequences at Ursula Creek and a corresponding progradational profile (overall upward thickening and coarsening) of Middle Triassic sequences in more proximal sections; c) an apparent deepening within numerous parasequences from Glacier Spur and Brown Hill "landward" (east) towards Beattie Ledge and Aylard Creek; and d) erosional removal at Brown Hill and Glacier Spur of two parasequences by the TL2\TL3 sequence boundary that are present at Beattie Ledge (a more "landward" locality). While this evidence is not unequivocal, these lines of evidence strongly suggest a more complex coastal morphology than has been previously suggested.

Condensation is perhaps an improper term to use for the thinning of basinal sediments between Brown Hill/Glacier Spur and Ursula Creek. The Ladinian package is characterized by a high gamma spike, consistent with condensed sedimentation. However, this spike is no greater in magnitude or duration than spikes at the top of several other sequences, of considerably less temporal duration, in the Ursula Creek section. Thus, it seems probable that the thin Ladinian package is a result of sediment starvation in addition to true condensation. The study area was characterized by low siliciclastic input due to arid climatic conditions, low precipitation, low-relief and thus low sediment availability in the source area and to ephemeral/seasonal fluvial input (Chapters 3 and 4), conditions ideal for sediment starvation on the shelf and slope. This however is insufficient to explain the inordinate thickness of clastic sediments in proximal locales and thinness in distal sites.

A retrogradational sequence stacking profile at Ursula Creek suggests progressive basinal sediment starvation. The fact that this occurs simultaneously with overall progradation in more proximal sections suggests that rather than sea-level induced sediment starvation, sediment must have been redirected elsewhere in the system. The presence of a paleotopographic high landward (east) of Ursula Creek would have acted as a blockade, effectively rerouting sediment distribution patterns, resulting in sediment starvation in basinal settings.

Correlation between the Brown Hill/Glacier Spur and the Beattie Ledge/Aylard Creek sections is greatly facilitated by the presence of several key stratal surfaces, including the sequence TL2 maximum marine flooding surface, the TL2\TL3 sequence boundary, and the sequence TL3 maximum marine flooding surface (Figure 10). Utilizing this basic framework, it is possible to correlate individual parasequences between the four most proximal sections (figure 10). In most cases, particularly in the sequence TL2 highstand systems tract, parasequences are characterized by finer-grain size and trace fossil associations suggesting more quiescent deposition at Beattie Ledge and Aylard Creek than at Brown Hill and Glacier Spur (Figures 4, 5, 6, 7, and 10). The presence of a topographic high in the region of Glacier Spur and Brown Hill (Figure 14) is perhaps the simplest way to explain why parasequences show progressively deeper water deposition in a landward direction.

Correlation of parasequences between the four more proximal localities has also revealed the presence of two additional parasequences (TL2p and TL2q) at Beattie Ledge that are not present at Brown Hill and Glacier Spur (Figure 10). These parasequences are interpreted to have been erosionally removed from Brown Hill and Glacier Spur. The preservation of these parasequences at Beattie Ledge supports the hypothesis that this part of the study area was topographically lower and thus not subjected to same the degree or duration of subaerial exposure as Brown Hill and Glacier Spur (Figure 10).

This situation reverses itself near the terminus of the sequence TL3 lowstand. Transgressive shoreface parasequences are thicker and better reserved at Brown Hill and Glacier Spur than at Beattie Ledge where they have been reduced by erosion to thin (<1m) bioclastic lags (Figure 10). This implies that the topographic high west of Brown Hill and Glacier Spur and corresponding low in the Beattie Ledge-Aylard Creek area disappeared or was reversed in the latest Ladinian. A sudden, thick influx of coarse, convolute-bedded bioclastic detritus overlying the Ladinian succession at Ursula Creek suggests that the blockade preventing sediment from reaching distal parts of the study area had been removed.

The presence of a paleotopographic high on the western margin of the Western Canada Sedimentary Basin is not a new idea, however it has not previously been recognized as affecting Triassic deposition. The West Alberta Arch/Sukunka Uplift (Figures 2 and 14) was a northwest-southeast trending structural element that significantly affected sedimentation south of the Peace River region during the Paleozoic (Davies, 1997; Richards, 1989). It is hypothesized that a Peace River extension of the West Alberta Arch may have affected Ladinian sedimentation in the study area (Figure 13). It is further postulated that this structural element may have comprised part of a horst-graben system. During the Anisian the Peace River extension of the West Alberta Arch was a low and "normal" basinal deposition prevailed. During the Ladinian, this element became a high, blocking most sediments from reaching basinal settings. Uplift of this element, or subsidence of an associated graben, may have resulted from compressional forces associated with convergence of the basinward island arc system with the cratonic edge. Additional fieldwork, north and south of Williston Lake is needed to establish the presence and nature of this possible Middle

Triassic island/peninsula.

CONCLUSIONS

The Middle Triassic succession at Williston Lake consists of at least five third-order and two second-order sequences deposited within a mixed siliciclastic-carbonate depositional system on the northwestern margin of Pangea.

The section at Ursula Creek comprises the westernmost, and correspondingly the most distal (*i.e.* deepest water) succession within the study area, and exhibits minimal grain size variation. The Fantasque-Grayling formational contact comprises the base of the section at this locality. Biostratigraphically significant fossils associated with major surfaces, which are quite apparent on the outcrop gamma profile, allow correlation with more proximal sections. A phosphatic horizon occurring approximately 90m above the base of the section, is characterized by a pronounced gamma-radiation "kick" and has produced Anisian conodonts. This horizon is interpreted as a condensed section, equivalent to the basal Doig phosphate zone in the subsurface to the east, and to the Early-Middle Triassic sequence boundary in the Sverdrup Basin.

Exposure of Anisian sequences (TA1 through TA4) within the study area are limited primarily to Ursula Creek. The lowstand systems tract in each sequence consists of comparably coarse sediments characterized by relatively low levels of gamma radiation. In each sequence, the transgressive systems tract is characterized by an overall fining/cleaning-upwards succession of sandy siltstone to silty mudstone. The sharp gamma ray spike capping each sequence consitutes a condensed interval and is interpreted as the highstand systems tract, reflecting a period of relative sediment starvation in more distal parts of the basin.

Ladinian sediments at Ursula Creek are limited to a thin package (6-7metres) of sediments wedged between sequence TA4 and a thick succession of Carnian strata. Correlation with other localities in the study area suggests the presence of at least three Ladinian sequences within this interval (TL1 through TL3), however the interval is too compressed to distinguish them at Ursula Creek. The Ursula Creek Ladinian package is also characterized by an increasing proportion of carbonate layers and lenses towards the top. The Ladinian-Carnian contact at this locality is co-occurrent with the lithostratigraphic Toad-Ludington contact.

The Toad and Liard Formations at Brown Hill, Glacier Spur, Beattie Ledge and Aylard Creek comprise four sequences bound by 2nd and 3rd order sequence boundaries (T?, TL1, TL2 and TL3). The earliest of these sequences (sequence T?, late Anisian?) occurs only at Brown Hill and at the base of the Glacier Spur section. The ravinement surface separating this lower sequence from the sequence TL1 is characterized by a relatively minor shift in sedimentary facies and is interpreted as a 3rd order sequence boundary.

The sequence TL1/TL2 sequence boundary at Brown Hill and Glacier Spur is characterized by incision of a nodular bioclastic silty packstone and silty very fine-grained sandstone layers (Parasequence TL2a) into cross-stratified shoreface sands (parasequence TL1i). Parasequence TL2a has been interpreted as a transgressive shoreface and comprises the sequence TL2 early transgressive systems tract. The initial transgressive surface consists of a thin, laterally persistent, brachiopod-rich limestone layer overlying parasequence TL2a. Sequence TL2 is confirmed as upper Ladinian *(maclearni* and *sutherlandi* zones), by abundant diagnostic conodonts trhoughout this succession.

The ravinement surface marking the TL2\TL3 sequence boundary is preserved as an erosional unconformity at Brown Hill and as a *Glossifungites* surface at Beattie Ledge. Parasequences immediately overlying the sequence boundary, comprise an aggradational succession of marginal marine lithofacies associations (early transgressive systems tract) and represent a basinward shift in facies. This erosional unconformity is interpreted as a second order sequence boundary, equivalent to the globally-correlatable near Ladinian-Carnian boundary. Thin transgressive shoreface bioclastic sandstones at the base of parasequence incise into intertidal deposits at the top of parasequence TL3b. A retrogradational package of transgressive bioclastic shoreface deposits (parasequences TL3d-TL3e) comprise the sequence TL3 upper transgressive systems tract and signify a return to less restricted marine deposition within the study area. The tops of robust, thick-walled *Ophiomorpha* burrows within transgressive shoreface deposits have been removed, indicating that erosion was associated with the transgression, and the transition from transgressive to highstand conditions. Parasequence TL3e is overlain by a maximum marine flooding surface, signifying transition to highstand conditions above. This surface separates underlying brachiopod-dominated, bioclastic sandstones (transgressive shoreface) from overlying laminated black shale and siltstone (proximal offshore) at the four more proximal localities. Biostratigraphic evidence (including both ammonoids and conodonts) supports a latest Ladinian *sutherlandi* Zone designation (possibly extending into the earliest Carnian) for sequence TL3.

It is hypothesized that a paleotopographic high (a northern extension of the West Alberta Arch/Sukunka Uplift) existed basinward of Brown Hill in the vicinity or landward of Ursula Creek, creating a landward sub-basin and promoting excessive sediment starvation in basinal locales. Evidence that supports the presence of this paleotopographic high include: a) severe "condensation" of Ladinian sediments in basinward sections; b) a retrogradational profile of Middle Triassic sequences in basinal locales and a corresponding progradational profile of Middle Triassic sequences in more proximal sections; c) an apparent deepening within numerous parasequences in a "landward" direction; d) erosional removal of several parasequences by the TL2\TL3 sequence boundary that are preserved in more "landward" localities and e) the dramatic shifts in depositional patterns in the Carnian.

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Chapter 6.

Evolution of a barred barrier island shoreface succession: Doig, Halfway & basal Charlie Lake Formation (Triassic), Tommy Lakes Field, northeastern British Columbia, Canada

> *"Although the movements of great bodies of water, termed tides and currents, are in general due to very distinct causes, we cannot consider their effects separately, for they produce, by their joint action, those changes which are subject to geological inquiry."*
>
> Charles Lyell, 1830

Background and Objectives:

Triassic strata in the Western Canada Sedimentary Basin (WCSB) have been subdivided into three "facies assemblages" reflecting large scale cycles in regional sea levels; I) Early Triassic (Griesbachian through Spathian), II) Middle Triassic (Anisian through early Carnian) and III) Late Triassic (Carnian through Rhaetian) (Gibson and Barclay, 1989). Assemblage II (Middle Triassic), consisting of the Doig, Halfway and basal Charlie Lake formations in the subsurface (Table 1), is one of the most economically important stratigraphic intervals within the northern Western Canada Sedimentary Basin. Recent estimates suggest that over 50% of total in-place Triassic hydrocarbon reserves in the Western Canada Sedimentary Basin remain undiscovered (Bird *et al.*, 1994). It is postulated that a significant proportion of these reserves are housed in undiscovered Halfway/Doig shelf and shoreline sandstone reservoirs (Bird *et al.*, 1994).

The Halfway Formation was initially described by Hunt and Ratcliffe (1959) as the first gray marine sandstone below the predominantly terrigenous strata of the Charlie Lake Formation. As a result all such sandstones have subsequently been lithostratigraphically correlated as a single regressive sheet sandstone (Hunt and Ratcliffe, 1959; Armitage, 1962). Other middle Triassic units (*i.e.* the Doig and Charlie Lake formations) were similarily lithostratigraphically defined (Armitage, 1962; Hunt and Ratcliffe, 1959). Since the advent of sequence stratigraphy in the early 1980's, emphasis has been placed on analyzing the Middle Triassic of the Western Canada Sedimentary basin within a chronostratigraphic framework (*i.e.* Arnold, 1994; Caplan, 1992; Evoy, 1995; 1997; Evoy and Moslow, 1995; Willis and Moslow, 1994a; 1994b and Wittenberg, 1992).

Recent studies of lateral facies relationships in the Middle Triassic at Wembley (Willis and Moslow, 1994a; 1994b) and Sinclair (Wittenberg, 1992) fields, Alberta, and the Peejay (Caplan, 1992; Caplan and Moslow, 1999) and Buick Creek (Evoy, 1997; Evoy and Moslow, 1995) fields, British Columbia, have shown that the Doig and Halfway formations, and the lower part of the Charlie Lake Formation are chronologically equivalent parts of the same depositional system. Reservoir quality lithologies within the Doig and Halfway formations of northeastern British Columbia occur intermittently (Bird *et al.*, 1994).

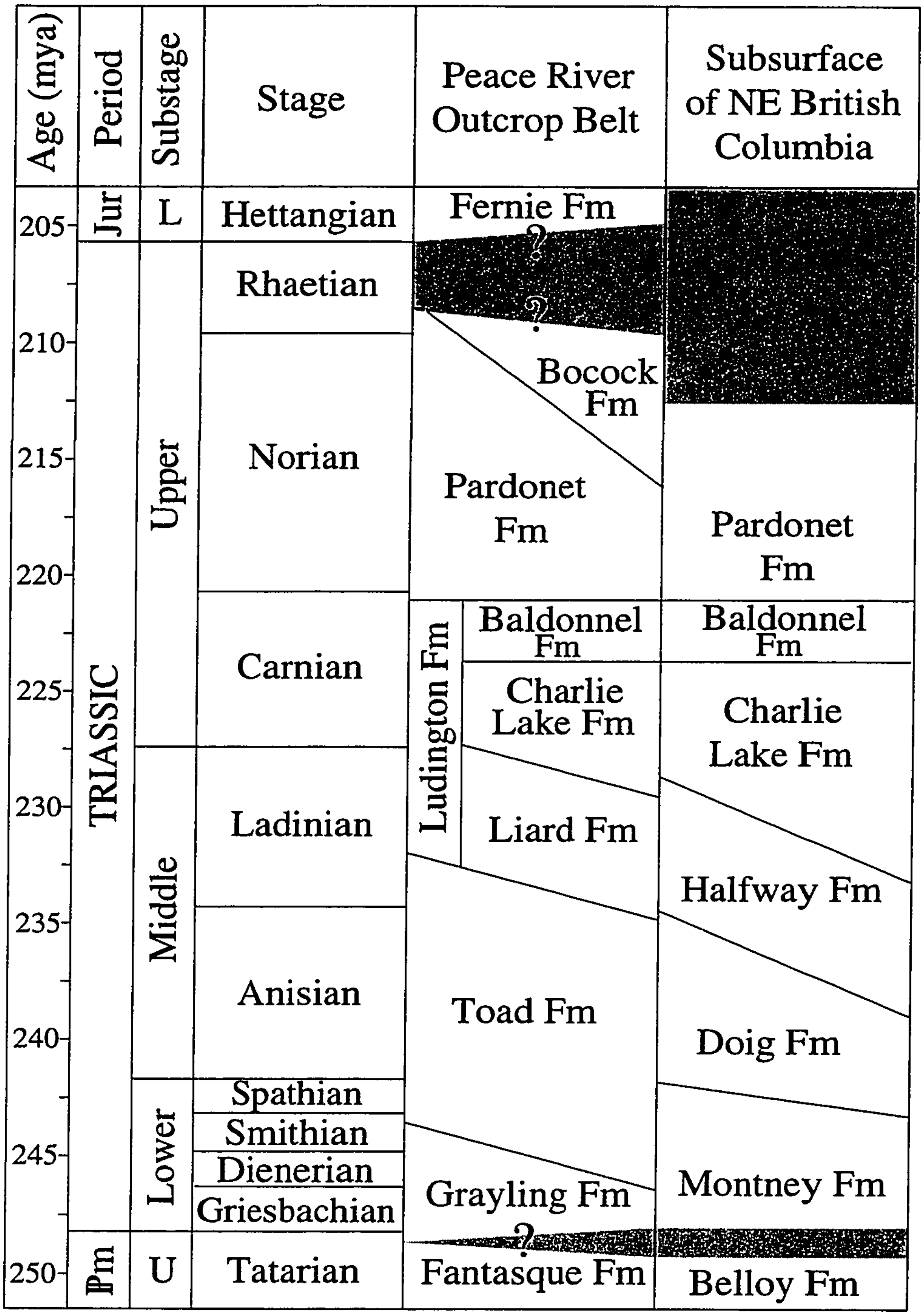

Table 1. Triassic stratigraphic nomenclature, subsurface and outcrop, northeastern British Columbia (adapted from Tozer, 1994). Triassic chronostratigraphy utilized here follows the recommendations of the IUGS Subcommision on Triassic Stratigraphy (Gradstein et al., 1994) in retaining the Rhaetian as a valid stage. Numerous intraformational unconformities occur throughout the Triassic succession but are not shown here.

Lithologic heterogeneity and a paucity of chronostratigraphic data have complicated delineation and regional correlation of genetic stratigraphic units within these formations.

In light of the importance of the Halfway/Doig interval in terms of both discovered and potential hydrocarbon reservoirs a sequence stratigraphic and sedimentologic analysis of the Middle Triassic interval in northeastern British Columbia was initiated. Sequence stratigraphic studies of the Doig-Halfway interval in northeastern British Columbia are limited to three areas south of the present study; Peejay field (Caplan, 1992; Caplan and Moslow), the Fireweed-Buick Creek-Cache Creek-West Stoddart region (Evoy, 1995; 1997; Evoy and Moslow, 1995) and the Umbach-Wargren region (Young, 1997). Tommy Lakes Field, the area chosen for this study constitutes the northernmost Middle Triassic hydrocarbon pool in the Western Canada Sedimentary Basin. The purpose of this study is to provide a detailed description and interpretation of the Middle Triassic interval in the northern portion of the subcrop belt, an area that has previously been largely overlooked. Lithofacies associations and sequence stratigraphic relationships within the Doig-Halfway-Charlie Lake interval at Tommy Lakes field are discussed and compared to chronologically equivalent strata exposed in the Rocky Mountain Foothills outcrop belt southwest of the study area.

Tommy Lakes Field:

The Tommy Lakes field is located in northeastern British Columbia, approximately 250 km northwest of Fort St. John (Figure 1a). The field lies adjacent to the subsurface erosional edge of the Charlie Lake, Halfway and Doig formations (Figure 1b) and thus comprises the northernmost Middle Triassic play in the Western Canada Sedimentary Basin. As presently defined, Tommy Lakes Field is also one of the largest Middle Triassic gas pools within the Western Canada Sedimentary Basin, exceeding 41,000 hectares in size, and containing estimated reserves greater than 19 X $10^9 m^3$ natural gas.

Approximately 120 wells penetrate the Doig-Halfway-Basal Charlie Lake interval within the Tommy Lakes region. Fifty-six of these wells contain core through the study interval. All core available through December, 1998 from the Tommy Lakes region, as well as core from an additional fifty wells outside the immediate Tommy Lakes area were analyzed (~1100m), providing an extensive database with which to analyze lateral and vertical lithofacies relationships and construct a detailed sequence biostratigraphic model.

Hydrocarbons are currently being produced from two main lithofacies at Tommy Lakes field. Shoreface sandstones are characterized by porosities of 7-12% and permeabilities ranging between 4-25md. Actively filled tidal inlet channel bioclastic units are characterized by limited lateral extent and sharp, erosive bases. Porosities within this tidal inlet channels range between 12 and 20% and permeabilities between 15 and 200md.

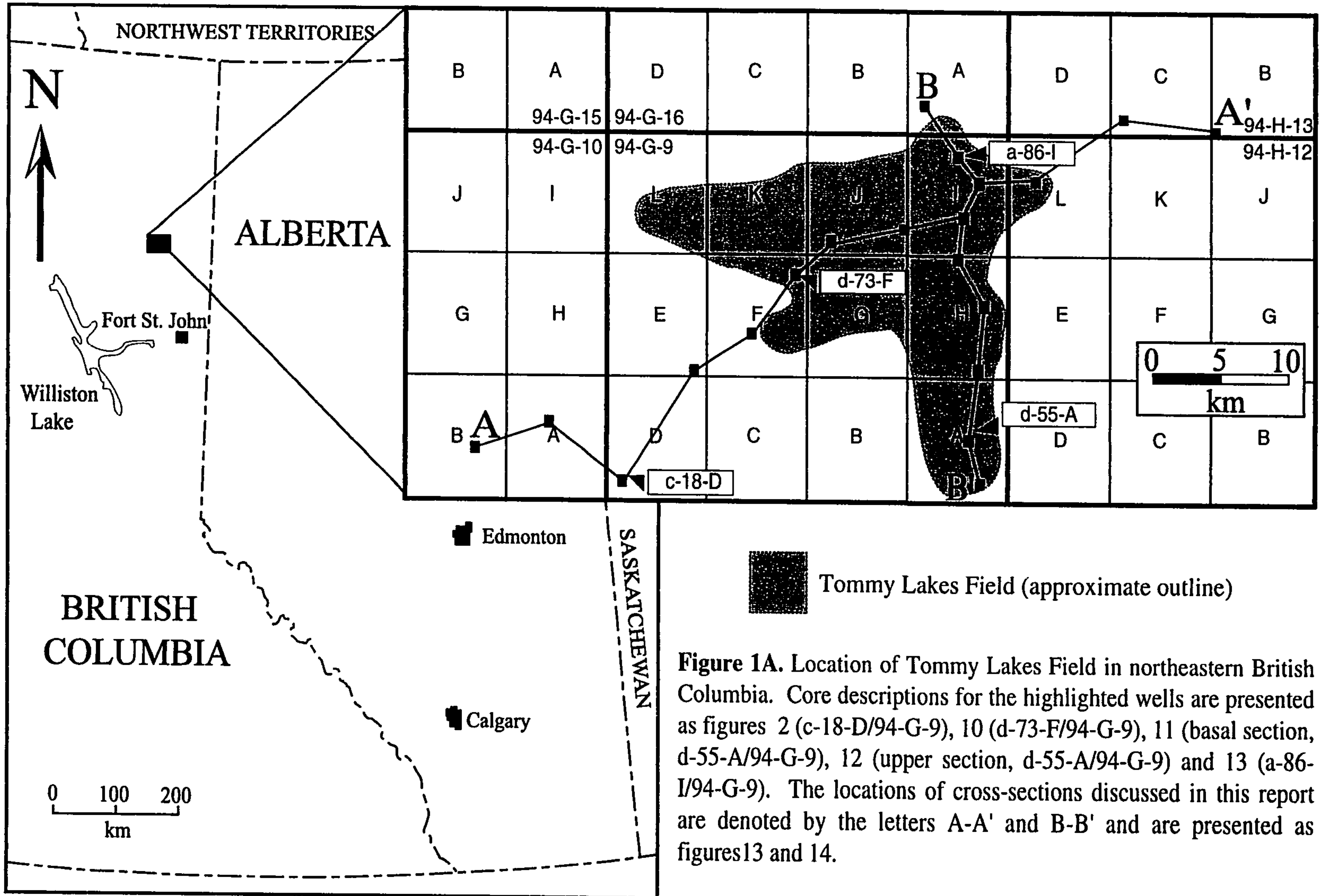

Figure 1A. Location of Tommy Lakes Field in northeastern British Columbia. Core descriptions for the highlighted wells are presented as figures 2 (c-18-D/94-G-9), 10 (d-73-F/94-G-9), 11 (basal section, d-55-A/94-G-9), 12 (upper section, d-55-A/94-G-9) and 13 (a-86-I/94-G-9). The locations of cross-sections discussed in this report are denoted by the letters A-A' and B-B' and are presented as figures13 and 14.

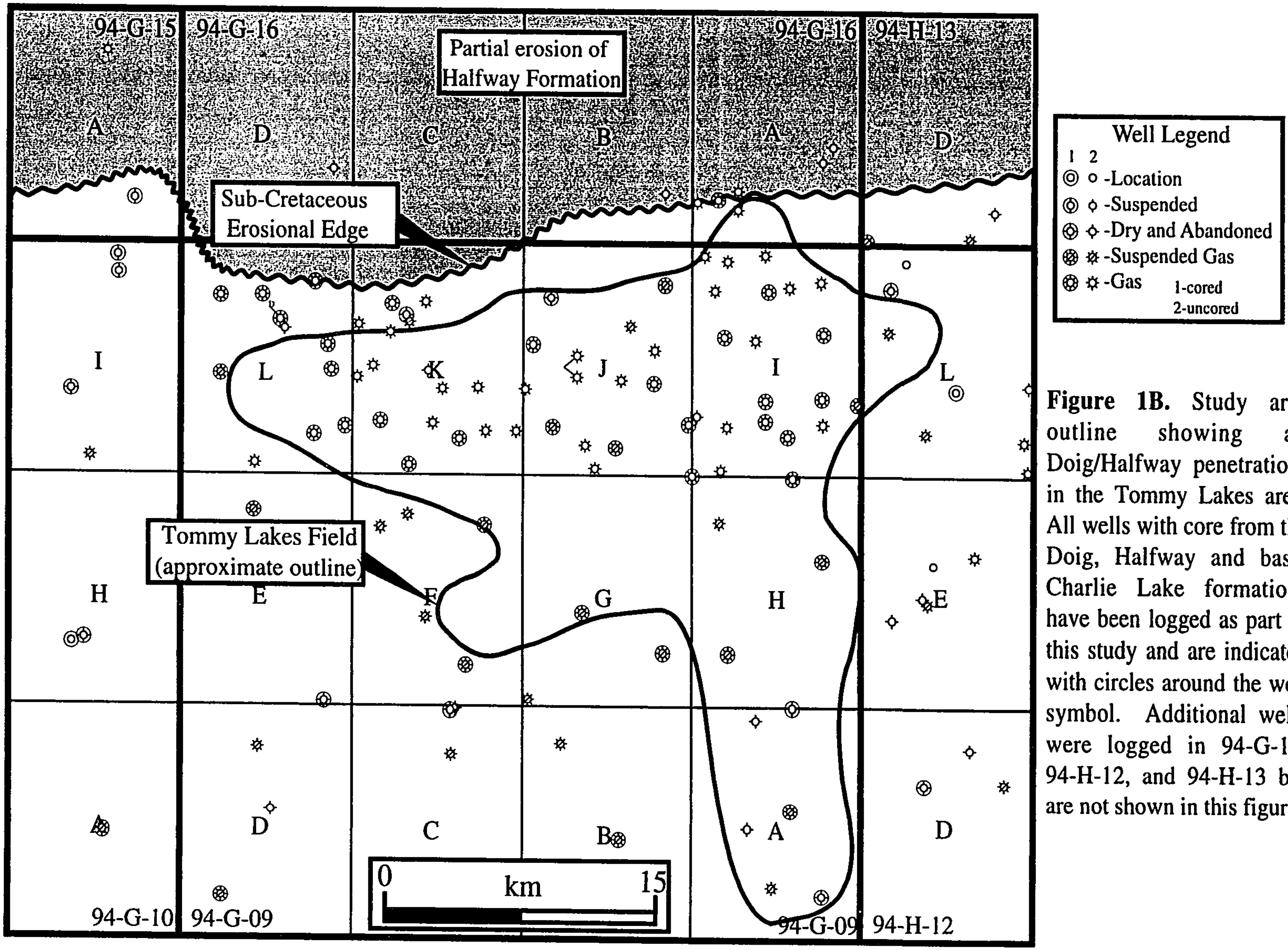

Figure 1B. Study area outline showing all Doig/Halfway penetrations in the Tommy Lakes area. All wells with core from the Doig, Halfway and basal Charlie Lake formations have been logged as part of this study and are indicated with circles around the well symbol. Additional wells were logged in 94-G-10, 94-H-12, and 94-H-13 but are not shown in this figure.

Regional Stratigraphy:

Middle Triassic strata in northeastern British Columbia (Figure 1; Table 1) consist of an overall shallowing upward series of progradational, mixed siliciclastic-carbonate shoreface parasequences deposited on the western margin of a topographically low North American craton. Although earlier studies have made reference to the "Triassic stable craton", an increasing body of evidence suggests that tectonism played an active role in sediment accumulation in western Canada (Wittenberg, 1992; 1993; Qi, 1995; Davies, 1997; Embry, 1997). Subsidence associated with elements of the Peace River Arch and the Dawson Creek Graben Complex has been shown to have had a particularly significant effect on deposition in the northern Western Canada Sedimentary Basin (Cant, 1988; Wittenberg, 1992; 1993; Qi, 1995; Davies, 1997).

In the subsurface of the Western Canada Sedimentary Basin, Middle Triassic (Anisian-Ladinian) strata are subdivided into three lithostratigraphic units: the Doig, Halfway and basal Charlie Lake formations (Table 1). Within the Tommy Lakes region, Middle Triassic strata unconformably overlie the lower Triassic Montney Formation and are unconformably overlain by younger Mesozoic (Jurassic and Cretaceous) strata.

The Doig Formation consists primarily of grey siltstone and dark shale (Armitage, 1962), although within the study area the Doig contains a significant proportion of very fine-grained sandstone. The top of the Doig Formation is defined as the base of the Halfway Formation and is characterized by a sharp decrease in gamma radioactivity (Dawes, 1990). Although the Doig-Halfway contact has been described as a disconformity (Campbell and Horne, 1986; Dawes, 1990; Young, 1997), recent work has shown that it is not a regionally correlatable unconformity (Willis 1994a; Wittenberg, 1992; Evoy, 1995; 1997; Evoy and Moslow, 1995). Within the study area, the Doig-Halfway contact closely approximates an erosional unconformity interpreted to be a third-order sequence boundary (Figure 2).

The Halfway Formation consists of grey, fine to medium-grained, calcareous sandstone (Hunt and Ratcliffe, 1959). Thick, cross-bedded bioclastic accumulations are locally common within both the Halfway and Doig formations (Campbell and Horne, 1986; Barclay and Leckie, 1987; Leckie and Rosenthal, 1987; Willis and Moslow, 1994a & b; Caplan and Moslow, 1997; Zonneveld et al., 1997). Within the study area the Halfway Formation is conformably and gradationally overlain by the dolomitic mudstone/sandstone of the Charlie Lake Formation.

The Halfway and Doig formations and the basal part of the Charlie Lake Formation are chronostratigraphically equivalent to the Toad and Liard formations in the Rocky Mountain Foothills (Table 1; Figure 1). Several sequence boundaries have been identified in outcrop along Williston Lake (Zonneveld *et al.*, 1997; Chapters 2, 3 and 5). It has not yet been established which, if any, of these sequence boundaries is chronologically equivalent to the Tommy Lakes Middle Triassic sequence boundary.

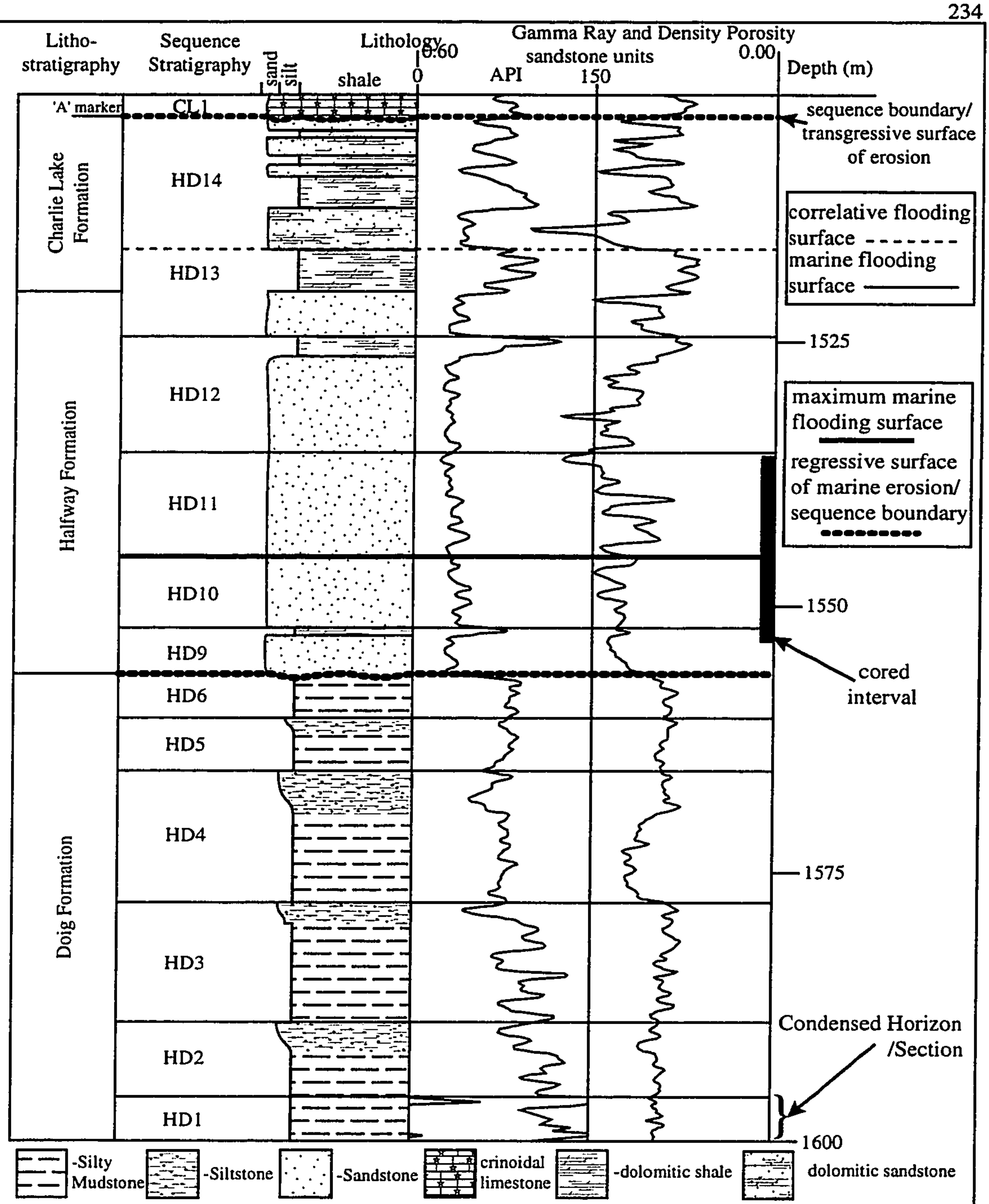

Figure 2. Gamma-ray and density porosity logs and inferred lithology from well c-18-D/94-G-9 through the study interval near the centre of Tommy Lakes Field. Sequence stratigraphic units for the Tommy Lakes Region are shown on the left. A total of fourteen parasequences (HD1-HD14) have been picked within the study area, however no individual well shows all fourteen parasequences. Correlation of these parasequences west of the study area shows that the formational contact occurs well above the sequence boundary. Thus the co-occurrence of a sequence boundary with the Halfway/Doig formational contact (1552m) within Tommy Lakes Field does not imply that this lithostratigraphic contact has regional sequence stratigraphic significance.

Although the Charlie Lake Formation has generally been referred to as an Upper Triassic unit (Dawes, 1990), the Halfway-Charlie Lake contact corresponds with a shift in lithofacies and in inferred depositional environment, and thus is an inherently diachronous contact. The Liard-Charlie Lake contact at Brown Hill, the westernmost outcrop of this contact is likely lower Carnian (Henderson *et al.*, 1997; Zonneveld *et al.*, 1997; Chapter 5). The lithologically equivalent Halfway-Charlie Lake contact is progressively older towards the east. Preliminary biostratigraphic data suggests that the contact may be Ladinian or uppermost Anisian in eastern subcrops.

LITHOFACIES AND LITHOFACIES ASSOCIATIONS

General

Lithofacies were identified on the basis of lithology, bounding surfaces, primary physical and biogenic sedimentary structures, and bioclastic or fossil composition (Table 2). Specific faunal and/or physical parameters can not always be used to define any one depositional environment (Reading and Levell, 1996). Therefore, following the precedent set by Walther (1894), the vertical succession of lithofacies was also utilized in environmental identification. A total of twelve sedimentary facies have been recognized in the Doig, Halfway and Charlie Lake formations within the study area. All of these lithofacies are represented

This study follows the carbonate classification of Embry and Klovan (1971) and utilizes the descriptive terminology of Kidwell and others (1986) and Kidwell and Holland (1991) in the analysis of bioclastic accumulations. The use of ichnofacies and ichnological nomenclature follows Seilacher (1954, 1955, 1985), Frey and others (1990) and Pemberton and MacEachern, (1995). The terminology used to differentiate between sub-environments on the beachface, shoreface and shelf vary widely between studies. This study follows the subdivisions outlined in Reading and Collinson (1996) and follows the framework established for barred nearshore systems by Davidson-Arnott and Greenwood (1976) and Hunter *et al.*, (1979).

Lithofacies A1/A2- Laminated black silty shale and sandy siltstone

Description- Lithofacies A1 consists of thinly bedded, planar laminated black shale to silty shale containing minor amounts of disseminated very fine-grained sand. Lithofacies A2 consists of sandy siltstone and silty shale. Lithofacies A often contains thin (1.0-10.0cm), layers of silt, very-fine grained sand, or bioclasts. These layers are predominantly plane parallel laminated and are normally graded.

Body fossils observed within this unit include rare fish (palaeoniscid) scales, ammonoid impressions on bedding planes, scattered bivalve and brachiopod (*Lingula*) shells as well as thin (1-10cm) bioclastic laminae comprised primarily of bivalve, brachiopod (primarily terebratulid) and echinoderm fragments. Plant debris, including a stem fragment of an early Mesozoic horsetail (cf. *Neocalamites* sp.?; Figure 3a), are also present on bedding planes within lithofacies A. Trace fossils are rare, consisting of isolated specimens of

FACIES	LITHOLOGY	PHYSICAL SEDIMENTARY STRUCTURES	BIOGENIC STRUCTURES	FOSSILS	DEPOSITIONAL ENVIRONMENT
A1	Black silty shale	Plane parallel laminae, Normally graded sand/silt laminae, Heterolithic wavy lam	He, Pa, Pl, Th	pelecypods, *Lingula* ammonoids, fish scales	Distal Offshore
A2	Sandy siltstone/shale	Plane parallel lam., Heterolithic wavy lam.	Ch, Lo, Pa, Pl, Th	rare bivalves, *Lingula*	Proximal Offshore
B	Interlaminated sandstone, siltstone and shale	Wavy bedding, low angle cross-stratification, hummocky cross-stratification.	Be,Cy,He,Pa,Pl, Sc,Th,Tr,Zo,fug	shell fragments, rare terebrat. brachs.	Offshore/Shoreface Transition
C	Muddy/silty very fine-grained sandstone	Hummocky cross-strat., low angle cross-strat., rare current & oscillation ripples	An,Di,Pa,Pl,Sk, Te,Th	rare terebrat. and spiriferid frags.	Lower Shoreface
D	Bioclastic sandstone	Sharp, non-incisive base, low-angle cross-stratification, imbricated bioclasts.	none observed	whole, disarticulated and frag. brachiopods/bivalves/crinoids	Bioclastic Tempestites/ ebb-tidal delta
E1	Cross-stratified fine to medium grained sandstone	Trough to planar cross-stratification, current and oscillation ripple laminae.	Pl, Sk, Op	rare terebratulid, spiriferid and bivalve fragments	Barred Upper Shoreface (longshore bar)
E2	Interbedded fine and coarse pebbly sandstone	Trough to planar cross-stratification,	none observed	rare terebratulid, spiriferid and bivalve fragments	Barred Upper Shoreface (longshore trough)
F	Convolute bedded fine to medium grained sandstone	Chaotic/convolute bedding, possible ripple laminae and trough cross-bedding.	Pa,Pl,Co,Sk, indet. bioturbation	rare terebratulid, spiriferid and bivalve fragments	Barred Upper Shoreface
G	Dolomitic sandy bioclastic grainstone	Basal mud clast lag, erosive base, low angle cross-stratification, imbricated bioclasts	none observed	shell "hash" of echinoderm, brachiopod & bivalve fragments	Tidal Inlet Channel Fill
H	Dolomitic bioclastic sandstone/siltstone	Planar lamination, rare current ripple cross-laminae.	Sk	unidentifiable bioclastic debris	Abandoned Tidal Inlet Channel Fill
I	Silty sandstone w/ mudstone laminae	Planar to rippled laminae, low-angle x-strat. soft sed. def., microfaults, synaeresis cracks.	An,Pl,Sk	rare unidentifiable bioclastic debris	Abandoned Tidal Inlet Channel Fill
J	Dolomitic mudstone	Planar laminations, dessication cracks, convolute bedding.	cryptalgal laminae	None observed.	Intertidal/supratidal flats
K	Dolomitic sandstone/siltstone	low-angle planar cross-stratification, chaotic/swirly/convolute bedding.	cryptalgal laminae	None observed.	Backshore
L	Sandy bioclastic wackestone	low-angle cross-stratification.	None Observed	Crinoid ossicles, brach. frags.	Transgressive Shoreface

Table 2a. Summary of sedimentary facies characteristics and interpretations of depositional environments in the Doig, Halfway and basal Charlie Lake formations, Tommy Lakes Field, northeastern British Columbia.

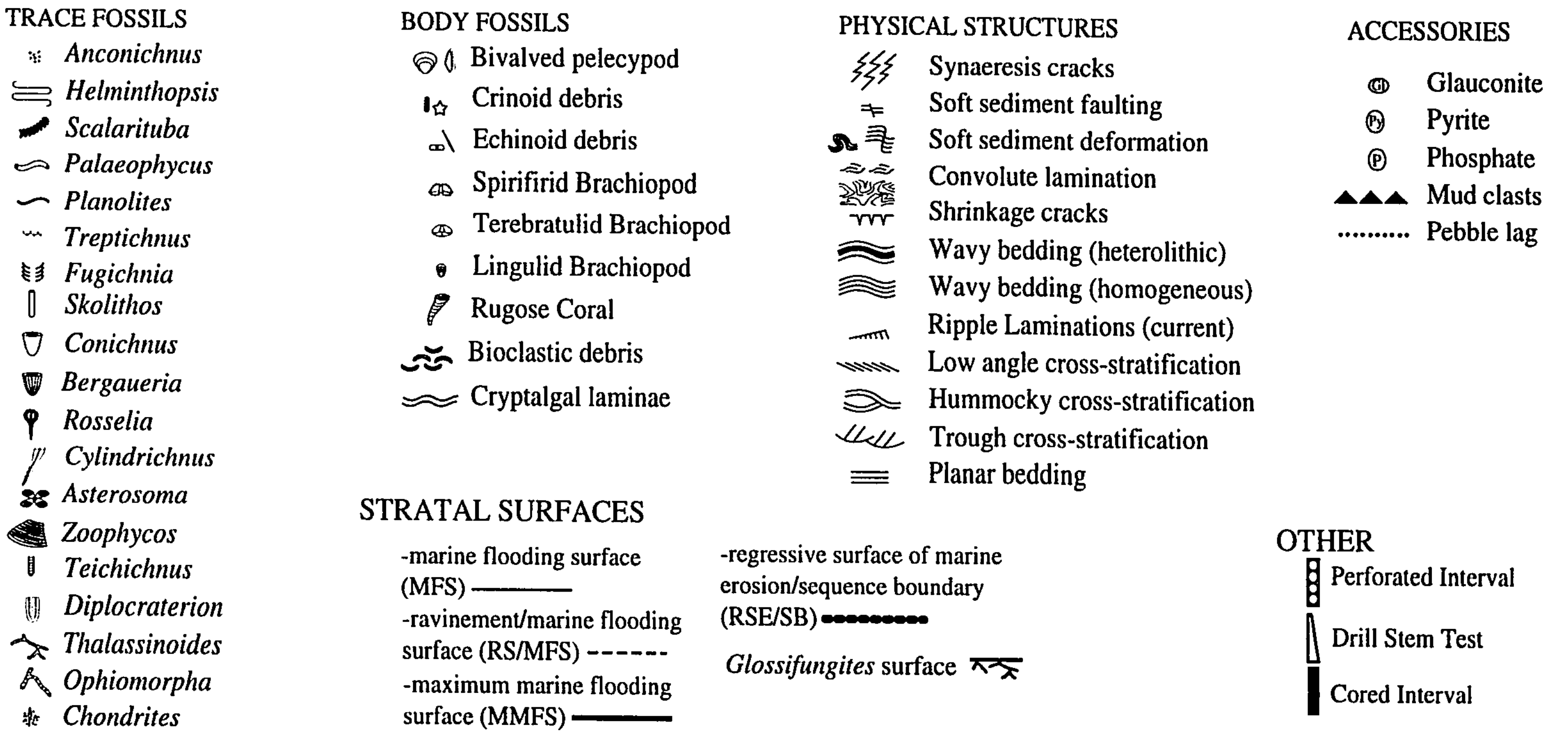

Table 2b. Summary of sedimentary facies characteristics and interpretations of depositional environments in the Doig, Halfway and basal Charlie Lake formations, Tommy Lakes Field, northeastern British Columbia. Acronyms for biogenic structures are as follows: An = *Anconichnus;* Be = *Bergaueria;* Ch = *Chondrites;* Co = *Conichnus;* Cy = *Cylindrichnus;* Di = *Diplocraterion;* fug = *fugichnia;* He = *Helminthopis;* Lo = *Lockeia;* Pa = *Palaeophycus;* Pl = *Planolites;* Op = *Ophiomorpha;* Sc = *Scalarituba;* Th = *Thalassinoides;* Te = *Teichichnus;* Tr = *Treptichnus;* Zo = *Zoophycos.* Symbols used within other figures throughout this study are summarized here.

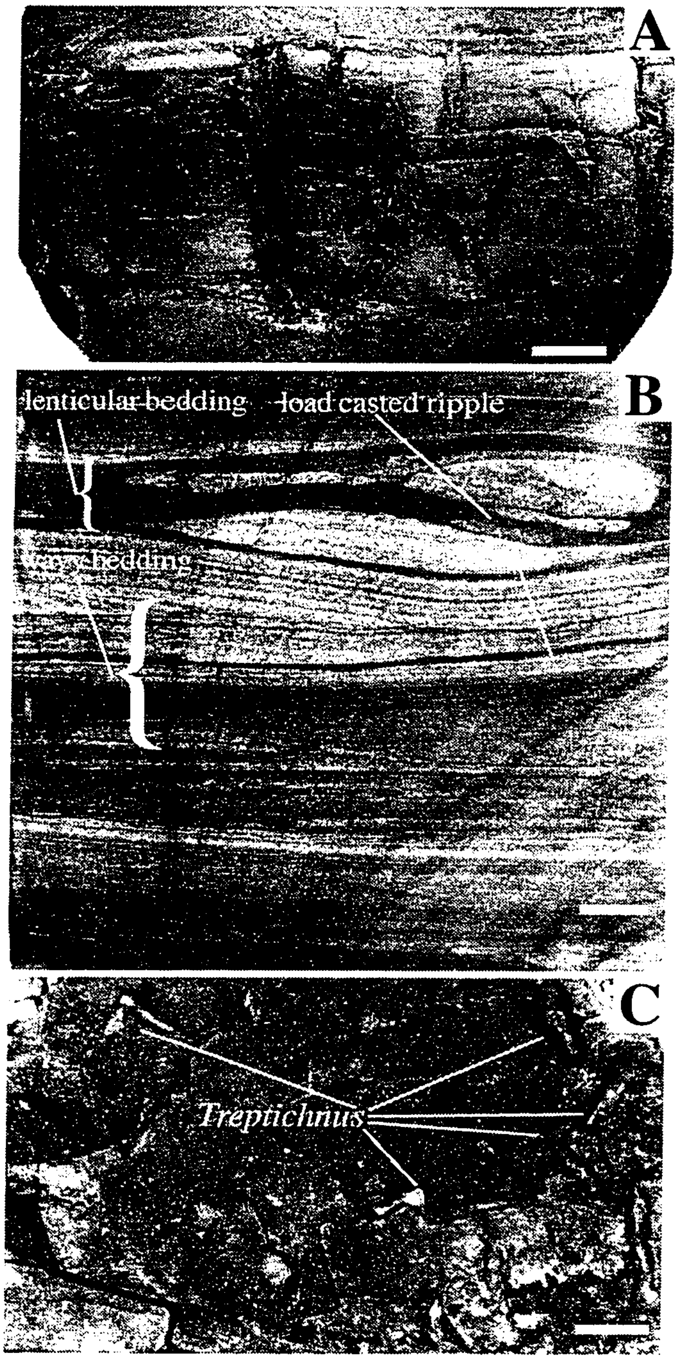

Figure 3. Core photographs of lithofacies A (distal offshore) and B (proximal offshore). Scale bars in lower right corner of each photograph are 1cm. **3A.** Bedding plane surface showing plant stem fragment (cf. *Neocalamites* sp.), within lithofacies A (distal offshore; b-82-J/94-G-9; 1261.0m). This plant material was rafted basinward, possibly during a storm. The presence of plant detritus in marine shales of the Doig Lithofacies has significant implications in the palaeoecologic reconstructions of the Middle Triassic of north-western Pangea. **3B.** Core photograph showing lenticular to wavy bedded and interlaminated very fine-grained sandstone, shaley siltstone and silty mudstone (lithofacies B, proximal offshore; well a-63-H/94-G-9; 1286.40m). **3C.** Bedding plane core photograph of the trace fossil *Treptichnus* (lithofacies B, proximal offshore; well a-43-J/94-G-9; 1007.0m).

Helminthopsis, Palaeophycus, Planolites and *Thalassinoides* within lithofacies A1, and *Chondrites, Lockeia, Palaeophycus, Planolites* and *Thalassinoides* within lithofacies A2.

Interpretation- Lithofacies A was deposited in an offshore setting, well below mean storm-weather wave base. The finely laminated shales are primarily a product of suspension deposition. The disseminated sand and silt was likely transported basinward by aeolian transport from contemporaneous continental environments (Arnold, 1994). Aeolian transport has been shown to be an important mechanism in delivering disseminated terrigenous sediments to ocean basins downwind of arid regions (Windom and Chamberlain, 1978). Thin, normally graded laminae of silt, very-fine grained sand or bioclastic detritus within this facies may be attributed to offshore transport and deposition via storm-generated sediment gravity or geostrophic flows (Nelson, 1982; Zonneveld *et al.*, 1997). The higher proportion of sandstone and siltstone within lithofacies A2 indicates deposition in a more shore proximal setting than lithofacies A1.

The presence of plant detritus in marine shales is attributed to basinward rafting during storms. Although rare, these fossils comprise the only plant material known from the Triassic of northwestern Pangea. Equisetales (horsetails) are common from Triassic Tethyan localities and are usually restricted to deposits interpreted as marginal lagoon or fluvial (Mader, 1990). The presence of a thick (4cm) equisetales stem within lithofacies A (cf. *Neocalamites* sp.?; Figure 3a) may prove useful in paleoecologic reconstuctions.

Lithofacies B- Interlaminated very fine-grained sandstone, shaley siltstone and silty shale.

Description- Lithofacies B, consisting of interlaminated very fine-grained, well sorted sandstone, muddy siltstone and silty shale (Figure 3b), conformably overlies lithofacies A2 (proximal offshore). Sedimentary structures within facies B include plane parallel lamination, heterolithic wavy bedding, and a mix of oscillation and current ripple laminae (Figure 3b). Many of the sandstone beds (10-40cm thick) are sharp based and exhibit low relief hummocky cross-stratification.

Bioturbation is moderately abundant within lithofacies B. Trace fossils consist of *Bergaueria, Cylindrichnus, Helminthopsis, Lockeia, Palaeophycus, Planolites, Schaubcylindrichnus, Teichichnus, Thalassinoides, Treptichnus* (Figure 3c) and *Zoophycos*. "Fugichnia" (escape traces) are locally abundant, usually emanating upwards from the soles of hummocky cross-stratified sandstone intervals.

Interpretation- Lithofacies B was deposited within the transitional zone between the offshore and the shoreface. The presence of hummocky cross stratified beds indicates that this unit was deposited above mean storm weather wave base. With the exception of current ripples and hummocky cross-stratification however, the unit is characterized predominantly by suspension deposition. Trace fossils within lithofacies B comprise a mixed *Cruziana-Zoophycos* assemblage, consistent with deposition within the offshore transition (Pemberton and McEachern, 1995). Trace fossils were more abundant, and trace fossil assemblages were

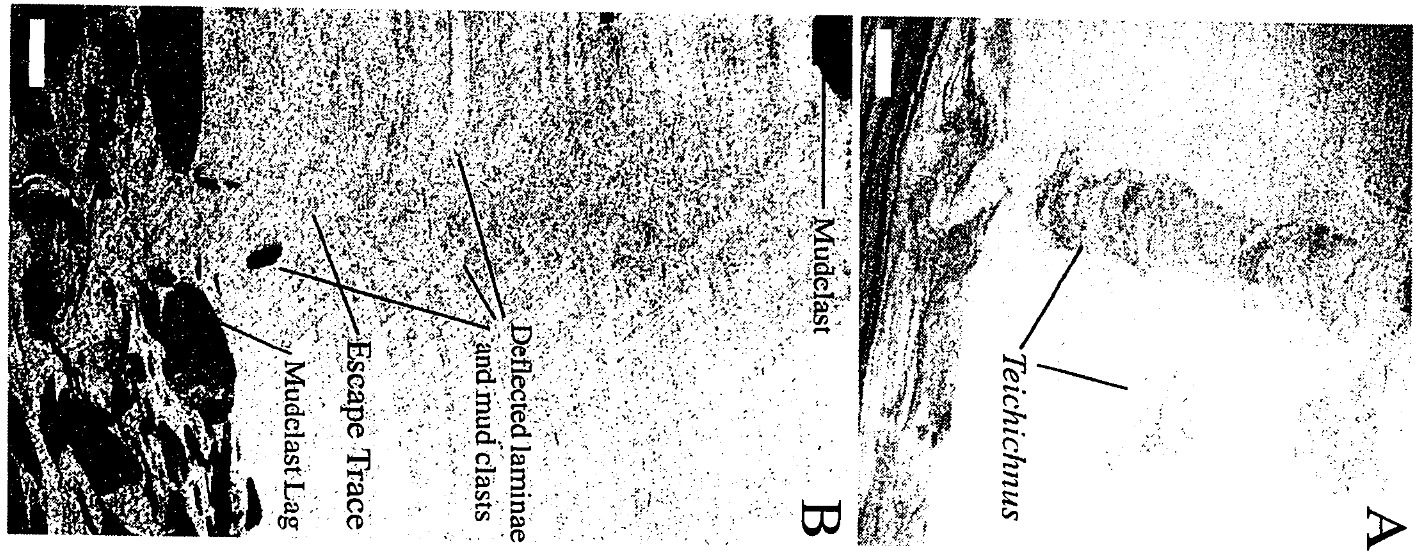

Figure 4. Core photographs of lithofacies C (lower shoreface). Scale bars in lower left corner of each photograph are 1 centimetre. **4A**. Core photograph showing two specimens of the trace fossil *Teichichnus* within hummocky cross-stratified sandstone (d-60-J/94-G-9; 1071.8m). **4B**. Core photograph showing an escape trace emanating from a mudclast lag and deflecting overlying laminae at the base of a storm event deposit (b-28-H/94-G-9; 1345.85m). The trace originates within the mudclast lag, above the base of the event deposit implying that the animal was transported basinward, likely by a geostrophic flow, within the sediment that subsequently buried it

more diverse within lithofacies B than those observed within any other horizon within the study area. The offshore transition provides a relatively protected setting from reworking in all but especially severe storms, while low velocity offshore oriented currents provide a constant influx of nutrients and oxygenated water (Pemberton and McEachern, 1995; 1996).

Lithofacies C- Hummocky cross-stratified, very fine-grained sandstone

Description- Lithofacies C consists of hummocky to low angle cross-stratified, silty, very fine-grained sandstone with rare current or oscillation ripple-laminated beds. Thin lenses of silty shale and muddy siltstone, similar to those of lithofacies A (offshore) and B (offshore/shoreface transition) are common near the base of lithofacies C. Primary physical sedimentary structures within lithofacies C may be overprinted or obscured by biogenic reworking. In several wells, erosive-based hummocky cross-stratified beds alternate with burrowed beds.

Body fossils include scattered brachiopods (spiriferids and terebratulids), and bivalves. Trace fossils consist of a moderately diverse mixed *Cruziana* ichnofacies assemblage consisting of *Anconichnus, Arenicolites, Diplocraterion, Palaeophycus, Planolites, Teichichnus* (Figure 4a) *Skolithos* and *Thalassinoides.* Fugichnia are particularly common (Figure 4b). Trace fossils generally occur as isolated specimens although in rare cases physical sedimentary structures are thoroughly obliterated by biogenic reworking.

Interpretation- Lithofacies C was deposited within a storm-dominated lower shoreface setting. Individual hummocky cross-stratified beds are interpreted as tempestites. Hummocky cross-stratification is most commonly preserved within the lower shoreface to proximal offshore transition (Hamblin and Walker, 1979). *Fugichnia* (escape traces) emanating upwards from the bases of individual beds reflect the episodic nature of sedimentation in lithofacies C. Vertically oriented *Fugichnia* (escape traces) were observed to originate within mudclast-rich horizons several centimetres above the base of the bed (Figure 4b), suggesting that these organisms were transported basinward by geostrophic flows within the sediment which subsequently buried them. Zones of erosive or sharp-based hummocky cross-stratification with decapitated *Diplocraterion* reflect post-event reworking of the upper portions of individual storm deposits (Pemberton and McEachern, 1997).

Facies D- Bioclastic sandstone

Description- Lithofacies D is composed of low angle cross-stratified, calcareous, bioclastic sandstone (Figures 5a and 5b). The sand fraction is quartz-dominated, fine- to medium-grained and moderately well-sorted, while the calcareous bioclasts are highly variable in size (fine-grained sand to gravel sized). The bioclasts consist of a mix of whole, disarticulated and fragmentary brachiopods, bivalves and echinoderms. Preferred orientations were not observed. These accumulations are densely packed at their bases to loosely packed or dispersed at their tops (Figure 5a).

Articulated bivalves and brachiopods, observed within several cores, contained a

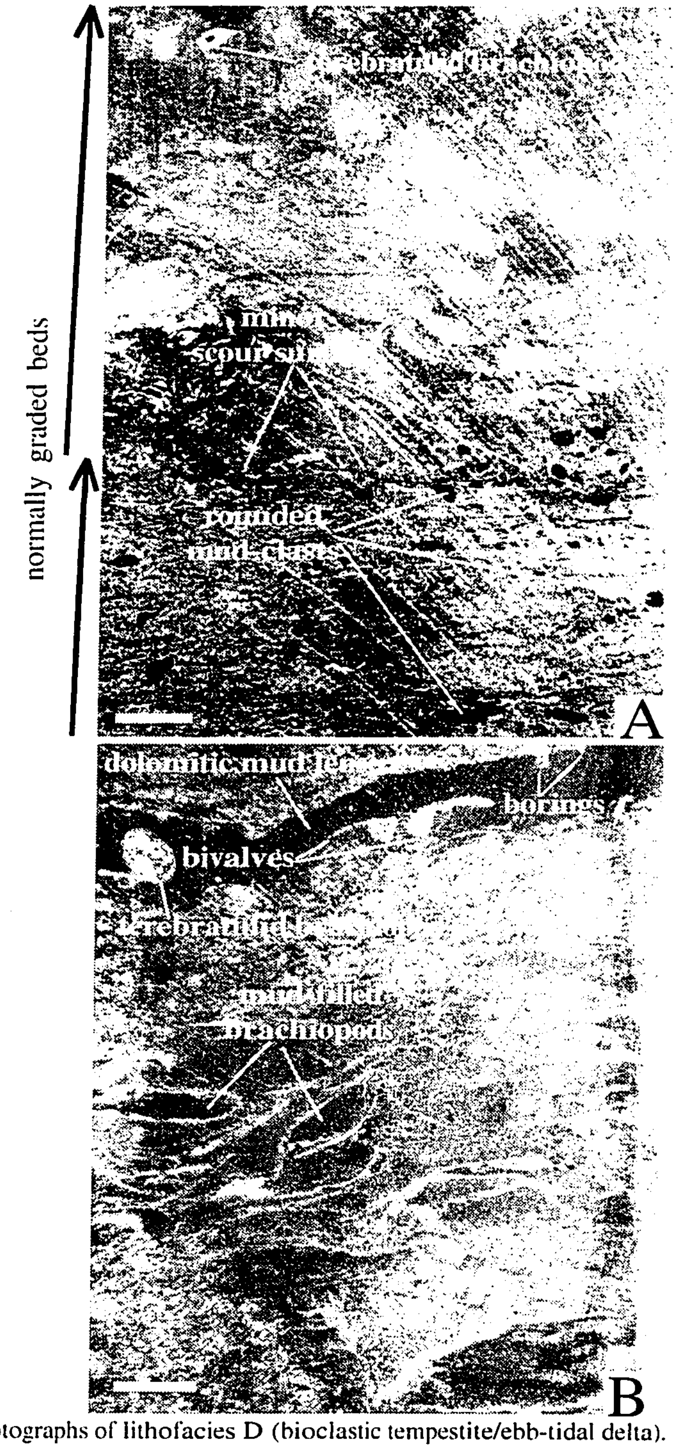

Figure 5. Core photographs of lithofacies D (bioclastic tempestite/ebb-tidal delta). Scale bars in lower left corner of each photograph are 1cm. **5A.** Core photograph showing two normally graded bioclastic sandstone beds (b-28-H/94-G-9; 1340.2m). Lithofacies D contains abundant rounded mudclasts as well as a variety of whole to fragmented and abraded bioclasts. **5B.** Core photograph showing whole and relatively unabraded mudstone-filled bioclasts and large, bored mudclast with a fine- to coarse-grained bioclastic sandstone matrix (a-43-J/94-G-9; 1004.6m).

sediment infilling distinct from the surrounding matrix (Figure 5b). The basal contact is generally sharp, although apparently not necessarily erosive. Lithofacies D is non-graded to normally graded and is low-angle (trough?) cross-stratified although physical sedimentary structures are generally difficult to discern or massive appearing. The tops of these beds are fine to medium-grained and may be characterized by asymmetrical (current) ripples.

Although lithofacies D has been observed at several horizons in numerous wells within the study area, this lithofacies is highly variable in terms of the amount, size and composition of bioclastic and lithoclastic fragments. Lithofacies D grades laterally with shoreface sandstone units (lithofacies C E, or F), and abruptly overlies offshore transition units (lithofacies B) or shoreface sandstone units (lithofacies C or E). Lithofacies D is conformably overlain by either lithofacies C (lower shoreface) or lithofacies E (barred upper shoreface). Trace fossils were not observed within lithofacies D.

Interpretation- Lithofacies D is interpreted as shore parallel tempestites within the lower shoreface and offshore transition. Sharp bases, normal grading (Figure 5a) and mixing of unabraded shells with rounded fragments are all consistent with storm deposition (Aigner, 1985; Seilacher and Aigner, 1991). Similar to bioclastic tempestites observed elsewhere (Seilacher and Aigner, 1991), lithofacies D is comprised of bioclasts similar to faunas in pre- and post-event deposits.

The presence of whole and articulated bioclasts containing infillings which differ from the surrounding sediment matrix (Figure 5b) is particularly significant. After death, the organisms were buried, subsequently re-exhumed, and transported basinward via storm processes or bar migration. Final deposition of the clasts occured within the offshore transition to lower shoreface, below fairweather wave base. Similar to tempestites in other mixed siliciclastic-carbonate systems (Aigner, 1982; 1985), bioclastic storm deposits within the Doig and Halfway formations grade laterally and vertically with quartzose-carbonate sand layers reflecting deposition during waning geostrophic flow conditions.

Alternatively, lithofacies D may represent deposition within a longshore trough/rip channel or rip channel fan (Gruszczyński *et al.*, 1993). Rip currents have been observed to transport a variety of material, from fine sand to cobbles (Gruszczyński *et al.*, 1993) and could easily result in the coarse lags discussed here. Storm rip currents are aqueous gravity currents. Rapid decline in flow and sudden deposition may result in massive, non-graded beds (Gruszczyński *et al.*, 1993). The compositional variability may reflect the presence of numerous interdigitating rip channel and rip channel fan deposits (Gruszczyński *et al.*, 1993; Hunter *et al.*, 1979) rather than a single laterally heterogeneous tempestite. Whether lithofacies D was deposited as tempestites or via rip currents, the coarsest lags likely reflect basinward transport and the winnowing of material during atypically strong seaward flow after heavy storms (Aigner, 1985; Gruszczyński *et al.*, 1993; Seilacher and Aigner, 1991).

Lithofacies E1/E2- Cross-bedded to cross-laminated sandstone

Description- Lithofacies E1 consists of moderately well-sorted trough to planar cross-

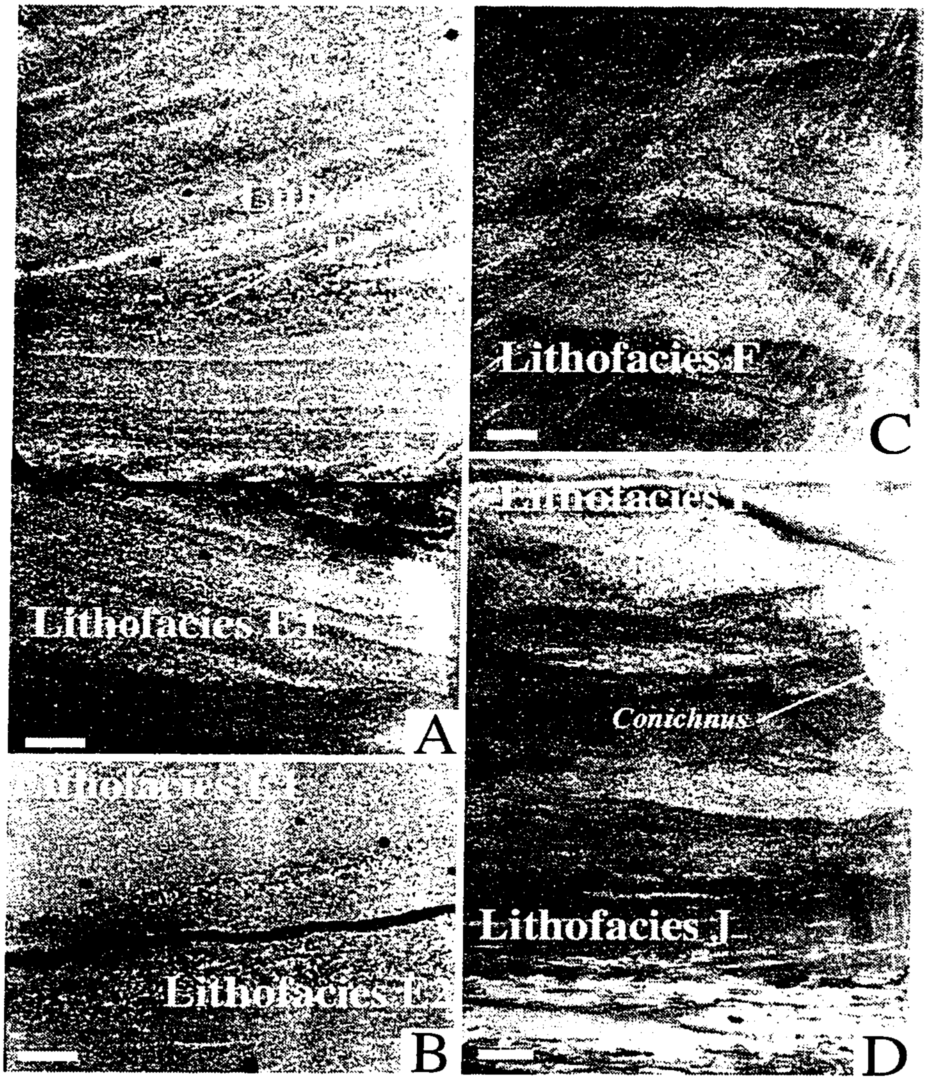

Figure 6. Core photographs of lithofacies E (barred upper shoreface), F (barred upper shoreface) and J (intertidal/supratidal flat). Scale bars in lower left corner of each photograph are 1cm. **6A.** Core photograph showing fine-grained, trough cross-stratified sandstone (Lithofacies E1; barred upper shoreface, longshore bar) with a thin lense of low-angle cross-stratified coarse-grained sandstone (lithofacies E2, barred uppershoreface, longshore trough; a-86-I/94-G-9; 1028.3-1028.5m). Lithofacies E1 has porosities of 8.8% and permeabilities of 0.23md at the top of this photograph. **6B.** Core photograph showing thin lense of planar cross-stratified coarse-grained sandstone (Lithofacies E2, barred uppershoreface, longshore trough) overlain by trough cross-stratified, fine-grained sandstone (lithofacies E1, barred uppershoreface, longshore bar; a-86-I/94-G-9; 1028.0-1028.3m). Lithofacies E1 has porosities of 10.1% and permeabilities of 0.65md. **6C.** Core photograph showing fine-grained, convolute-bedded sandstone. (Lithofacies F, barred upper shoreface; d-55-A/94-G-9; 1358.5m). **6D.** Core photograph showing lithofacies F (barred upper shoreface) conformably overlying lithofacies J (intertidal/supratidal flat; a-86-I/94-G-9; 1029.3m). A large (2cm x 5cm) specimen of the ?anemone dwelling trace *Conichnus* is shown in the top left corner.

stratified, fine- to medium-grained sandstone (Figure 6a). Other physical sedimentary structures include current and oscillation ripple laminae. Beds are twenty to sixty centimetres thick and characterized by abrupt basal bounding surfaces. Bioclastic material consists primarily of highly abraded, well-rounded bivalve, brachiopod and echinoderm fragments. Trace fossils include *Planolites*, *Skolithos* and possibly *Ophiomorpha*.

Lithofacies E2 consists of poorly sorted, planar to trough cross-stratified, fine to medium-grained sandstone with abundant, interbedded, thin (0.5 to 10cm), well-sorted very-coarse sand to fine gravel (granule) beds (Figure 6b). It differs from lithofacies E1 primarily on the basis of grain size and the presence of chert granules (Figures 6a and 6b). Neither trace nor body fossils were observed within lithofacies E2. Lithofacies E1 occurs as 10 to 70 cm beds interbedded with 20 to 60 cm beds of lithofacies F and as 10 to 50cm beds interbedded with 5-20cm beds of lithofacies E2. Within a typical succession, lithofacies E2 abruptly overlies lithofacies E1. In other cases, lithofacies E gradationally overlies lithofacies C (hummocky cross-stratified sandstone), or abruptly overlies lithofacies C (lower shoreface), lithofacies F (upper shoreface), lithofacies G (tidal inlet channel fill), lithofacies H (abandoned tidal inlet channel fill) or lithofacies I (abandoned tidal inlet channel fill).

Interpretation- Lithofacies E is interpreted to have been deposited within a barred shoreface, likely characterized by an obliquely oriented bar/rip channel system. Although vertical sections through barred and non-barred shoreface deposits may produce similar successions of bedforms, lithofacies relationships and the abundance of primarily horizontal internal scour surfaces is more consistent with deposition on a barred coastline (Hunter *et al.*, 1979).

Moderately well-sorted quartz sand, highly abraded bioclasts, and rare trace fossils, are indicative of deposition within a setting characterized by high current velocity transport and wave reworking. The medium-scale trough to planar cross-stratified beds of lithofacies E1 were deposited within a shoreface or longshore bar. The longshore trough is characterized by coarser sediment (medium grained sand to granules). Silt-free sediment was deposited in the longshore trough/proximal rip channel. Interlaminated current and wave ripples are common bedforms within longshore troughs (Hunter *et al.* 1979; Rossetti, 1997; Shipp, 1984). Where overlain by lithofacies E2, the upper contact of lithofacies E1 is characterized by an abrupt (dominantly horizontal) scour surface reflecting lateral migration of the longshore trough and rip-channel. Lithofacies E2 generally grades quickly upwards into lithofacies E1 reflecting lateral migration of the bar over trough sediments. Since the rate of bar migration in most barred systems greatly exceeds the rate of shoreline progradation, progradational barred shoreface accumulations are typically characterized by coarser/finer couplets deposited respectively by longshore troughs and bars (Hunter *et al.*, 1979; Shipp, 1984).

The coarser grained sediment of lithofacies E2, as well as the sand fraction is comprised primarily of chert and quartz. The absence of heavy minerals within these lags attests to the maturity of the sediment, and the predominance of Palaeozoic clastic and carbonate sediments in the source area (Campbell and Horne, 1986).

Lithofacies F- Convolute-bedded to massive appearing sandstone.

Description- Lithofacies F consists of convolute to chaotic bedded sandstone (Figure 6c). It is generally fine to medium-grained and moderately sorted. Lithofacies F contains abundant silt and scattered, disseminated chert pebbles/granules. Dark laminae may reflect a higher organic component in this lithofacies than in adjacent units. Although primary physical sedimentary structures were difficult to identify within this unit, distorted small-scale wave and current ripple laminae and medium-scale cross-stratification (both trough and planar) were present. Rare bioclastic material within lithofacies F consisted primarily of highly abraded, well-rounded bivalve and brachiopod fragments. Although the swirly or convolute nature of the internal bedding gave this lithofacies a highly bioturbated appearance, few specific trace fossil genera were identified. These include *Conichnus* (Figure 6d), *Palaeophycus, Planolites,* and *Skolithos.* Lithofacies F occurs as 10cm to 250cm thick interbeds within lithofacies E1 (barred upper shoreface, longshore bar).

Interpretation- The processes driving the deformation of unconsolidated sand within nearshore accumulations are poorly understood (Owen, 1996). Although primary physical sedimentary structures are largely obscured, remnant small-scale current ripples and possible trough to planar cross-stratification suggests deposition within an environment similar to that interpreted for lithofacies E (barred upper shoreface). The presence of silty/muddy sand intervals suggests deposition within a comparably quiescent setting, possibly within the rip channel mouth bar (Hunter *et al.*, 1979; or "fallout blanket" of Morang and McMaster, 1980).

Rather than thorough biogenic reworking therefore, the chaotic nature of lithofacies F is attributed to sediment liquification and disintegrative failure. This most likely resulted from sand bar migration over an unstable substrate (i.e. unequal surface load) or by storm loading and subsequent release as the storms subsided. Liquefaction and small scale soft-sediment deformation features have been shown to occur as a result of normal fairweather wave activity (Dalrymple, 1979). Schwab and Lee (1988) found that storm-induced cyclic loading events of long duration cause disintegrative failure (extensive internal deformation) in shelf sediments in the Gulf of Alaska, whereas short duration loading events (*i.e.* seismic events) resulted in non-disintegrative failure (slumps of rigid sediment with minimal internal deformation). Cyclic loading may be exacerbated by atypically high storm surges occurring during spring tides. Although storm-induced liquification likely occurs throughout the nearshore, most of this sediment was reworked by normal shoreface hydrodynamic processes. Alternatively, interbedding of "fine" (silt/very fine-grained sand) and "coarse" (fine- to medium-grained sand) material may have produced gravitationally unstable density contrasts and thus contributed to sediment instability (Owen, 1996).

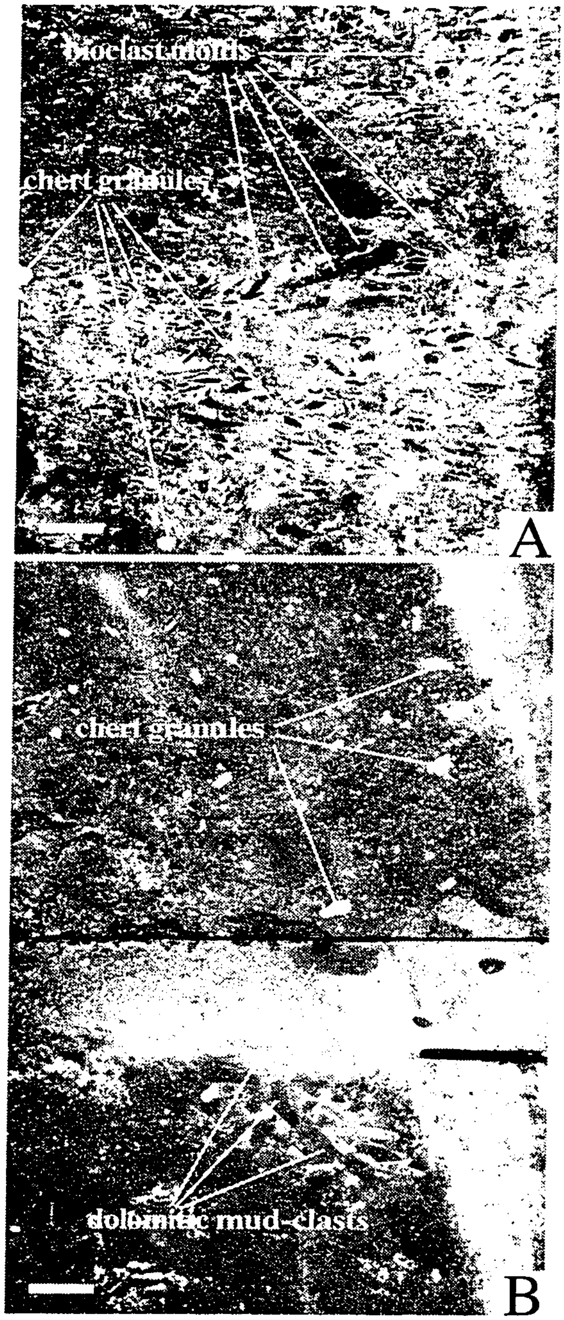

Figure 7. Core photographs of lithofacies G (tidal inlet channel fill). Scale bars in lower left corner of each photograph are 1cm. **7A.** Dolomitic bioclastic sandy grainstone with abundant chert granules (Lithofacies G, tidal inlet channel fill; a-86-I/94-G-9; 1037.6m). Lithofacies G has porosities of 16.2% and permeabilities of 0.22md in the basal half of this photograph. **7B.** Core photograph showing dolomitic mud-clast and chert granule lag within lithofacies G (tidal inlet channel fill; a-86-I/94-G-9; 1036.9). Lithofacies G has porosities of 11.8% and permeabilities of 0.18md in this photograph.

Lithofacies G- Dolomitic sandy bioclastic grainstone

Description- Lithofacies G consists of normally graded, low angle cross-stratified, dolomitic sandy bioclastic grainstone to bioclastic sandstone (Figure 7a and 7b). The lower contact of lithofacies G is erosive into the underlying facies (lithofacies B; offshore transition or C; lower shoreface), and is characterized by a basal lag of dolomitic mudstone or black argillaceous shale clasts (Figure 7b). The clasts range in size from 0.5 cm to 12.0 cm in diameter and occur within a dolomitic sand matrix. Although the degree of abrasion makes identification difficult it appears that bivalve debris comprises ~75-90% of the bioclastic component. Other constituents include highly abraded spiriferid brachiopods, terebratulid brachiopods, rare lingulid brachiopods, gastropods, and rare echinoderm detritus. The bioclasts decrease in size and abundance upwards. They are densely packed, poorly sorted, normally graded and are imbricated or obliquely oriented at the base of each unit. Towards the top of each unit they are loosely packed, bimodaly to well sorted, and oriented concordant with bedding. In many wells the bioclasts have been removed through dissolution and replaced with sandy/silty dolomitic framework. Chert granules and mudclasts (0.25-1.0 cm) are common throughout lithofacies G. Within several wells, 10 to 50 centimetre thick normally graded beds are vertically amalgamated. This lithofacies is laterally restricted and incise into shoreface sandstone units (lithofacies C, D, E and F). Although trace fossils were not observed within lithofacies G, the basal incision is characterized by localized *Glossifungites* surfaces consisting of bioclastic sand infilled *Skolithos* and *Thalassinoides*.

Interpretation- The laterally restricted, poorly sorted sediments included in lithofacies G are interpreted as tidal inlet channel lag and fill. Lithofacies G is very similar to inlet-fill successions described from the Halfway Formation at Peejay Field, northeastern British Columbia (Caplan, 1992; Caplan and Moslow, 1997). Bioclasts within the Doig and Liard formations comprise a significant proportion of the active tidal inlet channel fill within the study interval. A mixture of bioclasts characteristic of both shoreface and intertidal or lagoonal settings predominate. Dolomitic mudclasts were eroded from the intertidal/supratidal zone and transported basinward by ebb tidal currents into the throat of the tidal inlet channels and deposited as lags.

Glossifungites assemblages include trace fossils which penetrate firm, unlithified substrates, specifically those which have been subaerially exposed or buried and subsequently re-exhumed (Pemberton and MacEachern, 1995). Laterally non-correlatable *Glossifungites* surfaces such as those observed at the base of lithofacies G at Tommy Lakes simply imply exhumation of a previously buried substrate, in this case by tidal inlet channel migration. Development of similar autocyclically controlled *Glossifungites* surfaces occur within recent tidal inlet channel successions at Willipa Bay, Washington State (Saunders, pers. comm.; Gingras, pers comm.) and on the Carolina coast (Moslow and Tye, 1985). Autocyclically controlled *Glossifungites* surfaces have also been reported from the Halfway Formation at Wembley Field, Alberta (Willis, 1992; Willis and Moslow, 1994a; 1994b).

Tidal inlet channels incise previously deposited sediments and are characterized by both landward (flood-dominated) and seaward (ebb-dominated) flow. Bioclastic detritus within deposits attributed to tidal inlet channels are therefore characterized by a temporally and environmentally mixed assemblage (Flemming *et al.,* 1992; Henderson and Frey, 1986; Moslow and Heron, 1976). The mixed shoreface/marginal marine assemblage characteristic of lithofacies G is characteristic of tidal inlet channel deposition.

Lithofacies H- Dolomitic bioclastic sandstone/siltstone

Description- Lithofacies H consists of dolomitic, bioclastic, normally graded, medium to very fine-grained, sandstone to siltstone. Bioclastic detritus comprises a significant proportion of lithofacies H, consisting of highly abraded and rounded clasts. Physical sedimentary structures include planar lamination and rare current ripple cross-laminae. Biogenic structures are limited to rare *Skolithos.* Lithofacies H gradationally overlies lithofacies G (tidal inlet channel fill), and is conformably to erosionally overlain by either lithofacies B (offshore/shoerface transition), C (lower shoreface), or G (tidal inlet channel fill).

Interpretation- Lithofacies H is interpreted as active to abandoned tidal inlet channel fill. Tidal inlet channels incising a barrier island shoreface, migrate laterally along the shoreline in response to shifts in physiographic and hydrographic parameters (Tye and Moslow, 1984; Moslow and Tye, 1985; Frey and Henderson, 1986). They are therefore infilled by sediments deposited as a product of both traction and suspension deposition during a tidal cycle. Normally graded sediment, predominance of planar lamination, as well as the stratigraphic relationship with lithofacies G (active tidal inlet channel) are consistent with deposition during waning flow conditions.

Lithofacies I- Silty sandstone with mudstone laminae

Description- Lithofacies I is a heterolithic unit composed primarily of planar to ripple-laminated, low-angle cross-stratified and bioturbated silty sandstone (Figure 8a). Other physical sedimentary structures include tidal couplets (Figure 8a), microfaults (Figure 8c), synaeresis cracks (Figure 8b), soft-sediment deformation (Figure 8c) and alternating laminae of very-fine grained sandstone and siltstone/mudstone laminae (Figure 8a). Bioclastic detritus is rare but scattered throughout. Trace fossils consist of *Fugichnia*, rare *Planolites* and *Skolithos* and locally abundant *Anconichnus.* The latter often occur within 20-30cm horizons of dense, monospecific assemblages interbedded with low-angle cross-stratified beds of equivalent thickness. Lithofacies I is laterally restricted and gradationally overlies lithofacies G (tidal inlet channel fill). It is erosionally overlain by lithofacies E (shoreface sandstone).

Interpretation- Lithofacies I is interpreted as abandoned tidal inlet channel fill. Escape traces, ripple-laminae and low-angle cross-stratification indicate traction deposition from low velocity currents (Figure 8a). Intercalated couplets of very-fine grained sandstone and siltstone/mudstone laminae may reflect alternating flow conditions. Fine grained (siltstone to mudstone) intervals reflect suspension fallout in an abandoned tidal inlet.

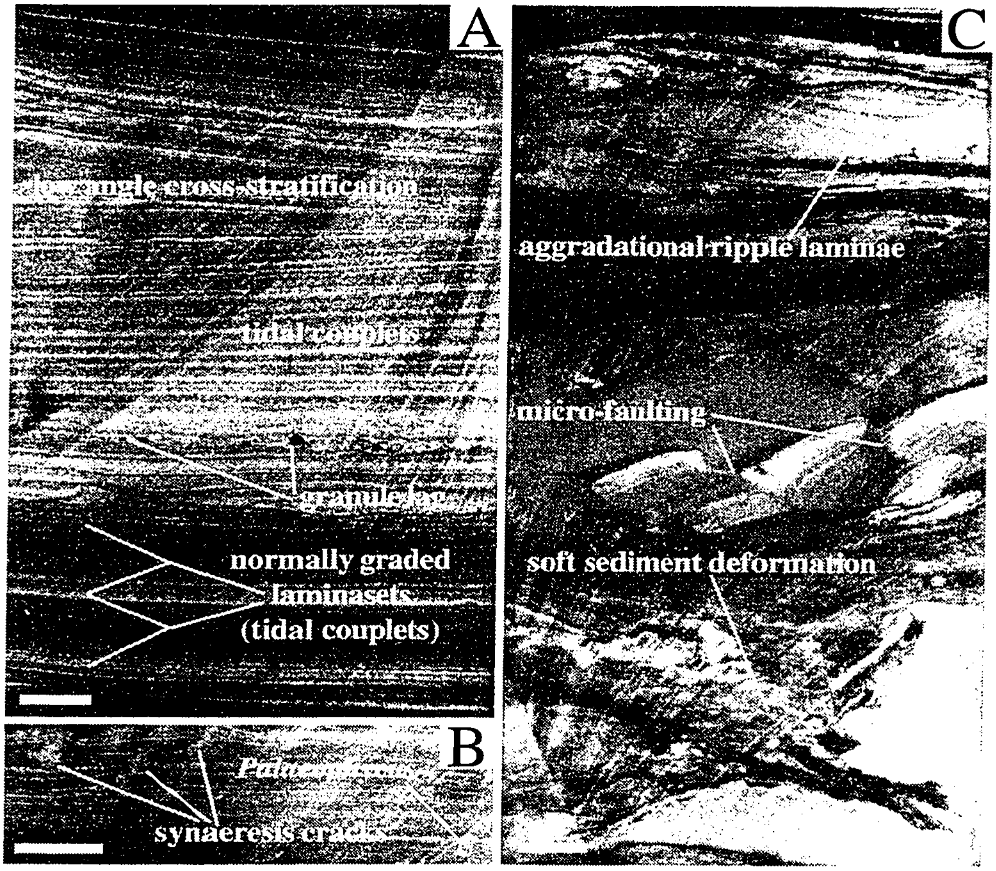

Figure 8. Core photographs of lithofacies I (abandoned tidal inlet channel fill). Scale bars in lower left corner of each photograph are 1cm. **8A.** Normally graded, laminata sets of very fine-grained sandstone and muddy siltstone, overlain by a minor erosion surface characterized by a granule lag. Sediments above this lag are characterized by low angle cross-stratified very fine-grained sandstone (Lithofacies I, abandoned tidal inlet channel fill; d-55-A/94-G-9; 1370.5m. **8B.** Synaeresis cracks and a single *Palaeophycus* within lithofacies I (abandoned tidal inlet channel fill; d-55-A/94-G-9; 1368m). **8C.** Microfaulting, soft-sediment deformation features and aggradational ripples (Lithofacies I, abandoned tidal inlet channel fill; d-55-A/94-G-9; 1367.8m).

Micro-faults and soft-sediment deformation features (Figure 8b and 8c) are common components of modern tidal inlet channel successions and represent failure and collapse of the channel walls (Tye, 1984; Tye and Moslow, 1992). Intercalated low-angle cross-stratified and bioturbated sand intervals probably may be a product of sediment transport by storm surge or spring tide currents and subsequent colonization by infaunal organisms. Monospecific trace fossil assemblages and synaeresis cracks are consistent with a setting characterized by fluctuating salinity levels (Nio and Yang, 1991).

The mix of physical sedimentary structures, laterally restricted nature of these deposits and association with subjacent active tidal inlet fill deposits (lithofacies G) infer that lithofacies I was deposited in a (primarily) abandoned tidal inlet channel.

Lithofacies J- Dolomitic mudstone/wackestone

Lithofacies J consists of laminated to convolute bedded or chaotic sandy yellow/green, grey, or orange dolomitic mudstone/wackestone (Figure 6d). Although identifiable bedforms are rare, synaeresis and desiccation cracks are both common. Anhydrite lenses are common. Planar to undulatory laminated dolomite with tiny fenestrae (birdseye structures) occur within lithofacies J. The unit gradationally overlies and is extensively interbedded with lithofacies E, F and K (Figure 6d). Body fossils and individual trace fossils were not observed within lithofacies J.

Interpretation- Lithofacies J is interpreted to have been deposited within an intertidal to supratidal setting, primarily on their vertical superposition. The convolute or chaotic nature of the bedding may be related either to bioturbation, chemoturbation (disruptive dolomitization or anhydrite dissolution) or a combination of both. Fenestral laminated dolomite layers are interpreted as cyanobacterial laminites (Figure 9a). Cyanobacterial mats are characteristic of protected subtidal intertidal and supratidal settings (Hagan and Logan, 1975).

The apparent paucity or absence of trace fossils within lithofacies J may reflect preservational constraints rather than the absence of trace making organisms. Trace fossils within the stratigraphically equivalent Liard Formation intertidal to supratidal succession at Williston Lake in the outcrop belt to the west often appear to be absent in vertical sections but are abundant and diverse on bedding planes (Zonneveld and Gingras, 1997; 1998).

Lithofacies K- Dolomitic sandstone/siltstone

Description- Lithofacies K consists of moderately sorted, fine-grained dolomitic sandstone/siltstone. Lithofacies K may be normally graded and is characterized by low-angle planar cross-stratification, heterolithic wavy lamination, or chaotic bedding. Synaeresis and desiccation cracks are common, particularly where lithofacies J and K are interbedded. Lithofacies K gradationally overlies lithofacies E and F (barred shoreface sandstones). Interlaminae of yellow/green-grey dolomitic mudstone (lithofacies J) are common. Although the unit may be bioturbated in part, individual trace fossils were not identified. Body fossils

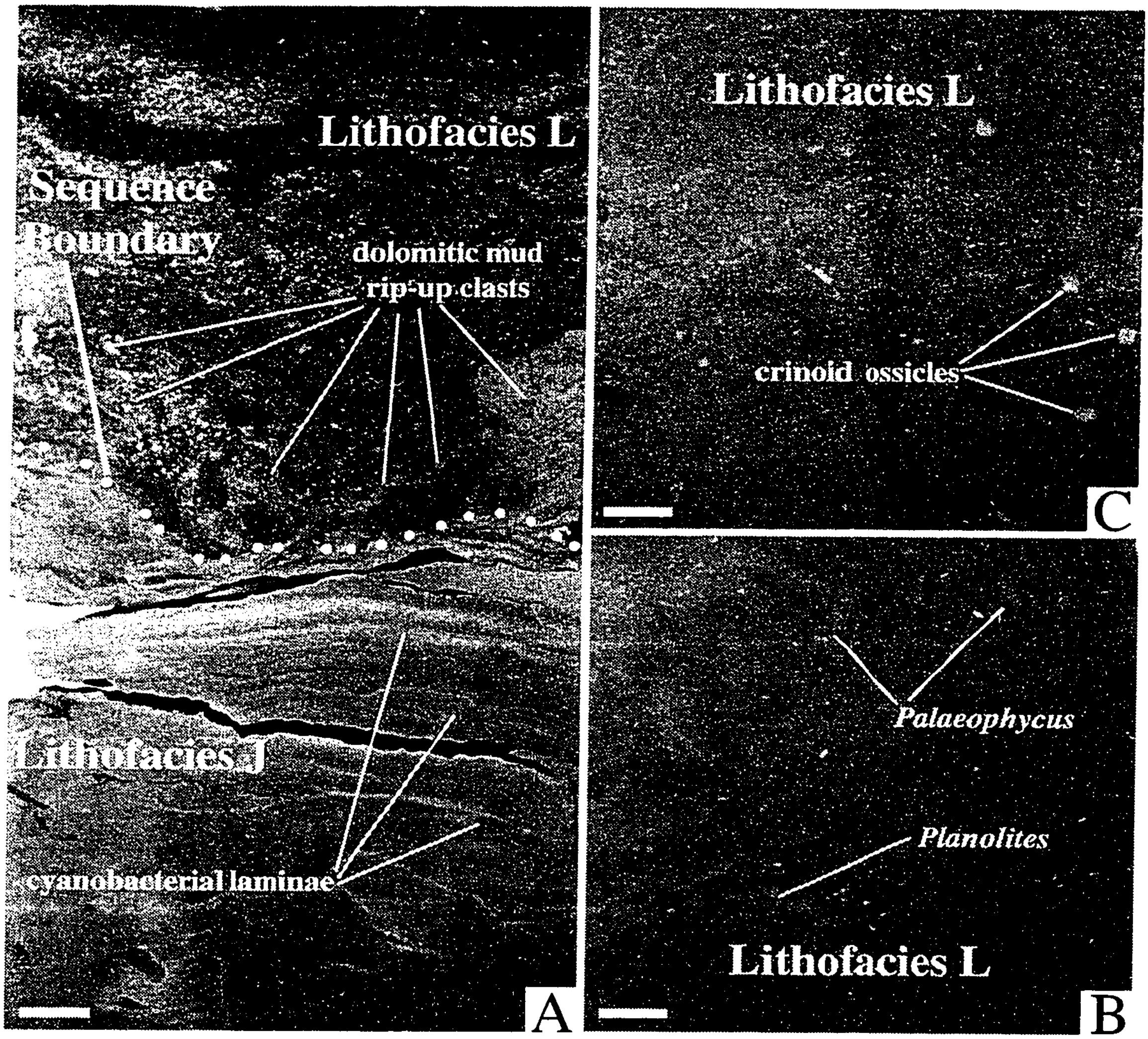

Figure 9. Core photographs of lithofacies J (intertidal/supratidal flat) and L (transgressive shoreface). Scale bars in lower left corner of each photograph are 1 centimetre. **9A.** Cyanobacterial laminae within a dolomitic mudstone (lithofacies J, intertidal/supratidal flat) unconformably overlain by a calcareous, bioclastic sandy wackestone characterized by numerous mudstone rip-up clasts.(Lithofacies L, transgressive shoreface; c-55-A/94-G-10; 1498.0m). **9B.** Bioturbation within lithofacies L (transgressive shoreface). In addition to the trace fossils *Palaeophycus* and *Planolites* (shown) this unit is characterized by rare *Thalassinoides* and *Zoophycos* (c-55-A/94-G-10; 1497.75m). **9C.** Core photograph showing numerous bioclasts within lithofacies L (transgressive shoreface). Crinoid ossicles, by far the dominant form of identifiable bioclast, are shown (c-55-A/94-G-10; 1497.0m).

were extremely rare and consisted of isolated bivalves, gastropods and fragments of lingulid brachiopods.

Interpretation- Lithofacies K is interpreted to have been deposited within a backshore intertidal to wind-tidal flat environment of deposition, on the basis of sedimentary structures and facies relationships. Normal grading, heterolithic wavy laminae and dolomitic interbeds are consistent with deposits interpreted as backshore/lagoonal and intertidal flat in the Liard Formation in the outcrop belt to the west (Zonneveld *et al.*, 1997; Zonneveld and Gingras, 1997; 1998). Wind-tidal flats are a common phenomenon on the barrier shore of Laguna Madre, south Texas, and consist of broad, barren expanses of interbedded sand and algal-rich mud (Morton and McGowen, 1980; Weise and White, 1980; Shideler, 1981). The stratigraphic relationship of lithofacies J with underlying shoreface and foreshore units (lithofacies E and F) is consistent with these interpretations.

Lithofacies L- Sandy bioclastic wackestone

Description- Lithofacies L consists of moderately to poorly sorted, locally vuggy, sandy, bioclastic limestone. Primary physical bedforms are difficult to discern within lithofacies L, consisting primarily of low-angle, possibly trough, cross-stratification. The unit is characterized by a basal mud-clast lag (Figure 9a). The mudclasts are predominantly comprised of dolomitic mudstone (lithofacies J). Bioclastic detritus within lithofacies L is dominated by crinoid ossicles (Figure 9c), but includes brachiopod and bivalve fragments. Trace fossils consist of *Palaeophycus, Planolites*, questionable *Thalassinoides* and *Zoophycos* (Figure 9b). A low-diversity *Glossifungites* assemblage emanates from the base of lithofacies L, penetrating 2-6cm into the subjacent strata in some wells.

Lithofacies L is restricted to a single horizon at the top of the study interval, erosionally overlying either lithofacies J (dolomitic mudstone/siltstone) or lithofacies K (dolomitic sandstone) at the top of parasequence HD-14. This horizon typically occurs approximately 20 meters above productive units within the Tommy Lakes region and thus is rarely cored. The contact between lithofacies L and overlying lithofacies has not yet been observed. Well logs suggest however that this unit is present throughout and beyond the study area.

Interpretation- Lithofacies L is equivalent to the "A-marker" limestone, a commonly utilized lithostratigraphic marker bed within the Western Canada Sedimentary Basin (Moslow and Davies, 1992; Caplan and Moslow, 1997). Due to the paucity of core data, determination of the depositional environment of this enigmatic interval remains somewhat conjectural. The geographical extent of this unit, the presence of abundant marine bioclasts, and the presence of trace fossils characteristic of marine deposition (*i.e. Zoophycos*) suggests a fully marine depositional setting. *Zoophycos* is characteristic of fully marine, offshore deposition (Ekdale, 1977).

This unit was initially interpreted to have been deposited across an extensive, low-relief, coastal plain during an exceptional storm surge or spring tide, however the regional extent of this unit indicates a more stratigraphically significant derivation. The presence of a regionally extensive basal unconformity, as well as a basal *Glossifungites* surface and rip-up clast lag suggest that this unit may have been deposited as a transgressive bioclastic shoreface similar to those described within the Halfway Formation at Wembley Field, Alberta (Willis and Moslow, 1994b) and the Liard Formation at Williston Lake, northeastern British Columbia (Zonneveld *et al.*, 1997).

LITHOFACIES ASSOCIATIONS AND STRATIGRAPHIC RELATIONSHIPS

The lithofacies discussed above occur within four distinct lithofacies associations: I (offshore/offshore transition), II (tidal inlet channel), III (barred shoreface) and IV (mixed siliciclastic-carbonate marginal marine). Figures 10, 11 and 12 show the stratigraphic relationships between these lithofacies associations within two representative cored wells (d-55-A/94-G-9 and a-86-I/94-G9). Sixteen parasequences (HD1 through HD14, CL1 and CL2) within three third (and second?) order sequences have been identified within the study interval. Detailed strike and dip oriented cross-sections (Figures 14 and 15) illustrate lateral lithofacies and sequence stratigraphic relationships within the study area. The cross-sections were constructed, preferentially utilizing wells with core penetrating the Doig-Halfway-Charlie Lake interval to aid in assessing lateral lithofacies variability and genetic stratigraphic relationships. Isopach maps were constructed to furthur illustrate the geographic distribution of lithofacies (Figures 16 and 17).

Lithofacies Association I: Offshore-Lower Shoreface

Lithofacies association I (lithofacies A, B, C and D) comprises an overall coarsening upwards offshore through lower shoreface succession (Figure 10). Similar to stratigraphically and environmentally equivalent outcrop in the Rocky Mountain Foothills, all lithofacies within lithofacies association I show indications of wave-dominated, storm-influenced deposition (Zonneveld *et al.*, 1997; chapter 2). Lithofacies association I parasequences and parasequence sets (HD1 throgh HD 7) are characterized by a coarsening upwards profile (Figure 10), which corresponds to the overall shallowing upwards nature of this association. Within a typical lithofacies association I parasequence, lithofacies A (offshore) grades upwards into lithofacies B (offshore/shoreface transition; 1197-1202m, Figure 10). This succession is frequently gradationally overlain by lithofacies C (lower shoreface). In several wells, lithofacies A (offshore) is erosionally overlain by lithofacies D (bioclastic tempestite) which grades upwards into hummocky cross-stratified sandstone (lithofacies C, lower shoreface; Figure 10) . Occurences of lithofacies D within the study area are laterally restricted (8-10km along strike, 4-5km in a dip-oriented direction). Basal erosion surfaces associated with lithofacies D are associated with storm activity and are not regionally significant unconformities.

Trace fossil assemblages grade upwards from a mixed *Cruziana-Zoophycos* ichnofacies (lithofacies A, offshore; lithofacies B, offshore/shoreface transition) to a mixed *Skolithos-Cruziana* ichnofacies assemblage (lithofacies C, lower shoreface) reflecting an

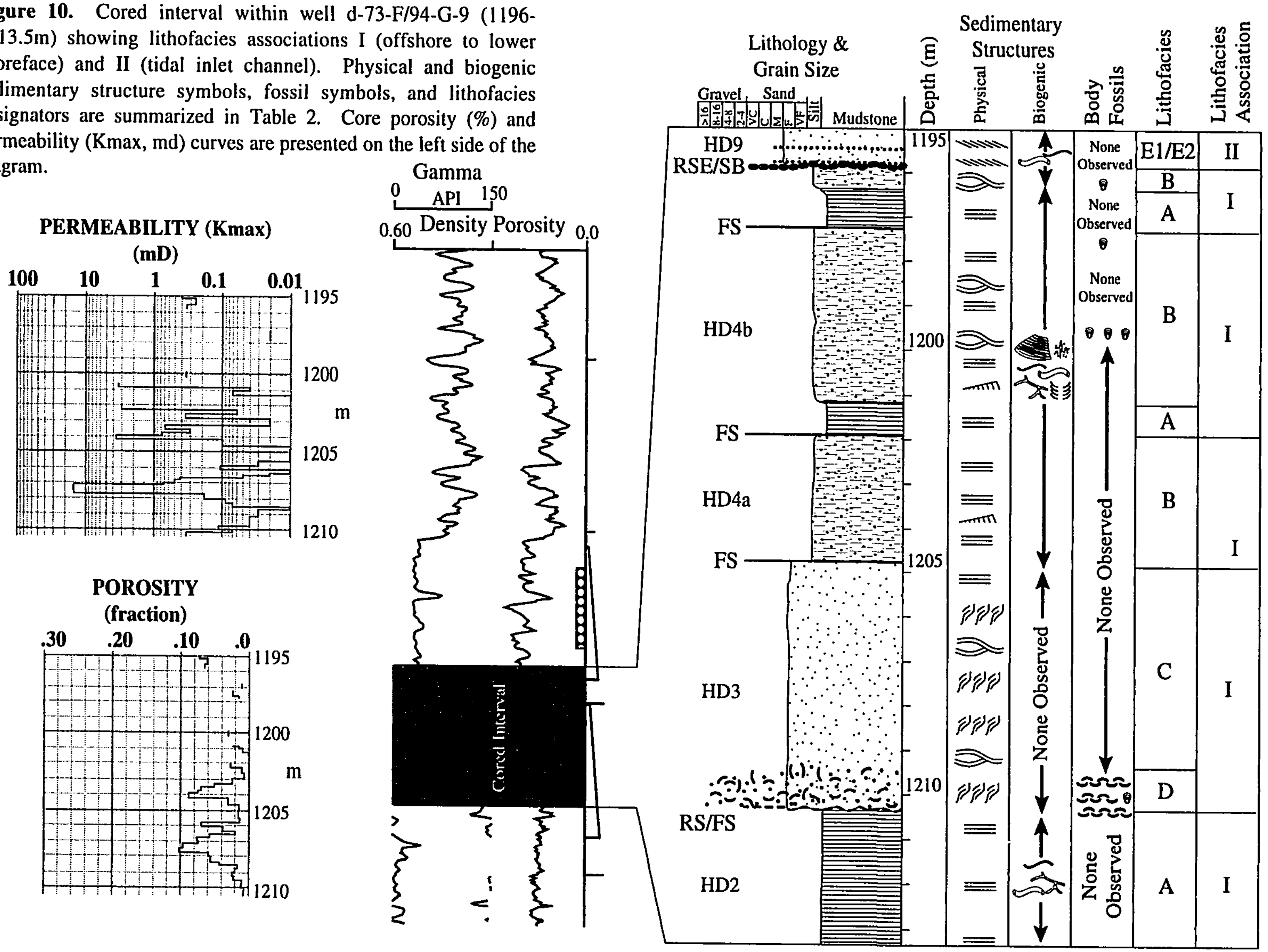

Figure 10. Cored interval within well d-73-F/94-G-9 (1196-1213.5m) showing lithofacies associations I (offshore to lower shoreface) and II (tidal inlet channel). Physical and biogenic sedimentary structure symbols, fossil symbols, and lithofacies designators are summarized in Table 2. Core porosity (%) and permeability (Kmax, md) curves are presented on the left side of the diagram.

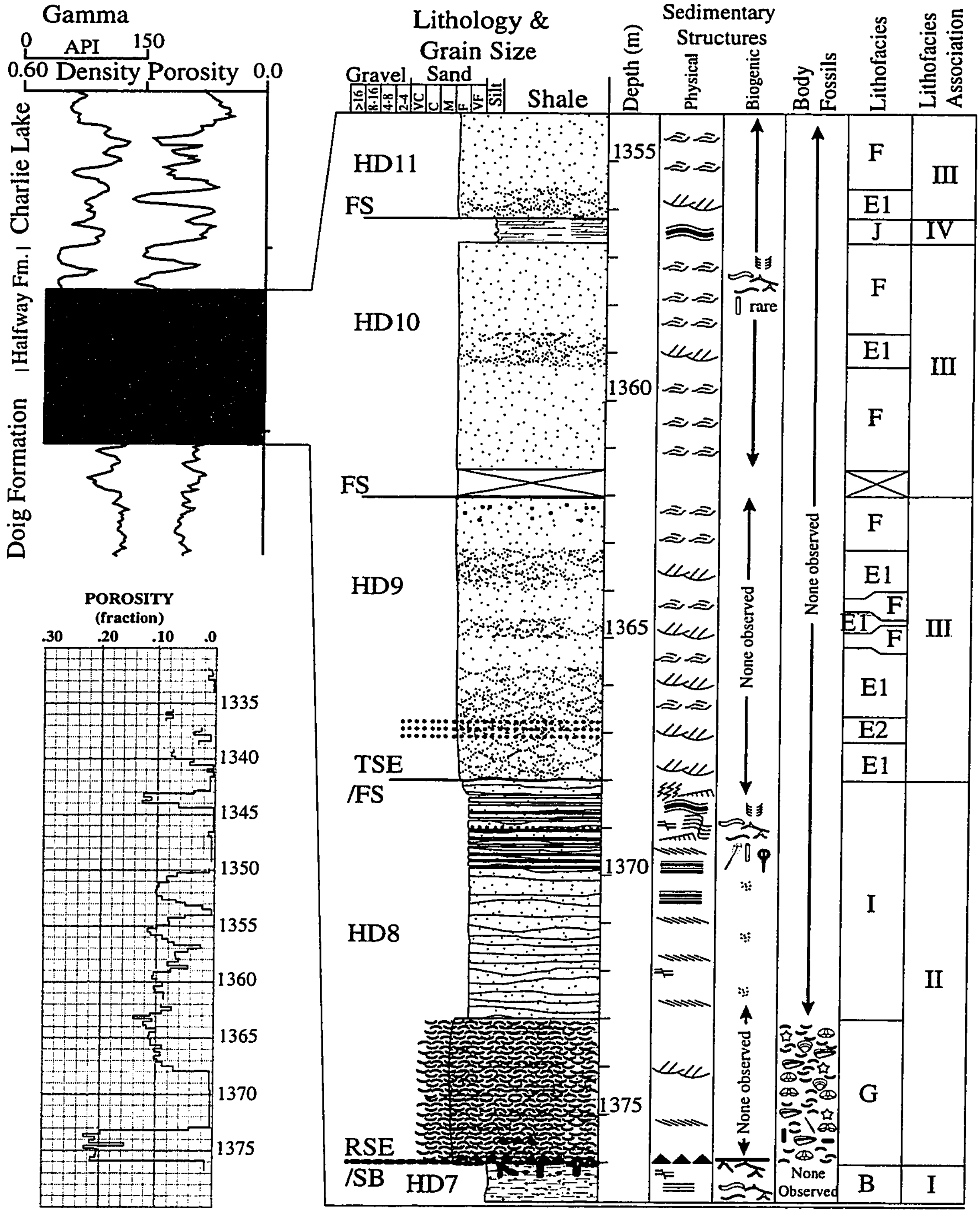

Figure 11. Cored interval within well d-55-A/94-G-9 (1354.0-1376.8m) showing lithofacies associations I (offshore lower shoreface), II (tidal inlet channel), III (barred shoreface) and IV (mixed siliciclastic-carbonate marginal marine). Lithofacies and lithofacies association designators are the same as those discussed in the text and summarized in Table 2. Core porosity, presented in % units, is presented on the left side of the diagram. Permeability for the core interval is shown in figure 12.

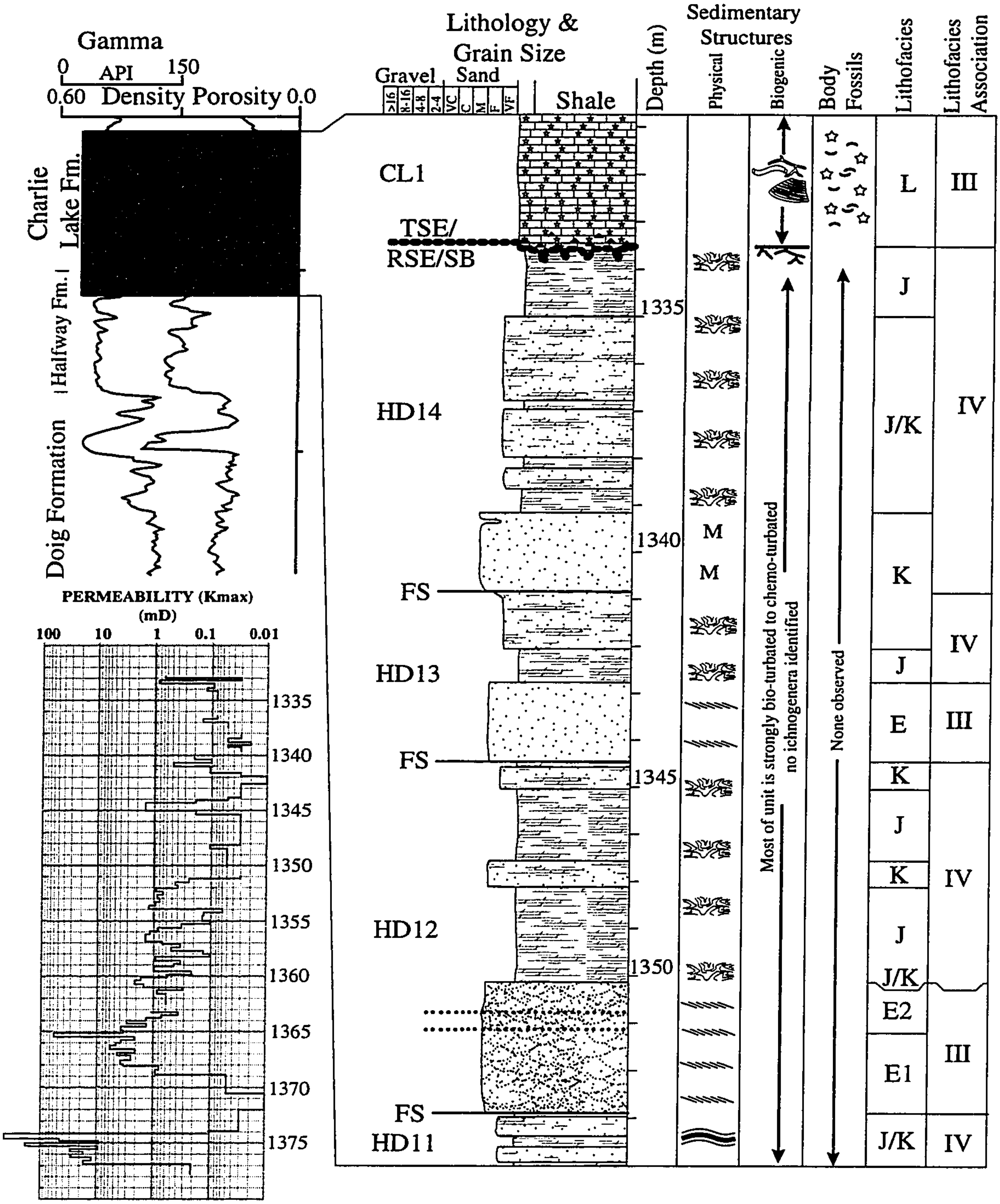

Figure 12. Cored interval within well d-55-A/94-G-9 (1330.7-1354.0m) showing lithofacies associations I (offshore to lower shoerface), II (tidal inlet channel), III (barred shoreface) and IV (mixed siliciclastic-carbonate marginal marine). Lithofacies and lithofacies association designators are the same as those discussed in the text and summarized in Table 2. Permeability (Kmax), is presented on the left side of the diagram. Porosity values for the core interval is shown in figure 11.

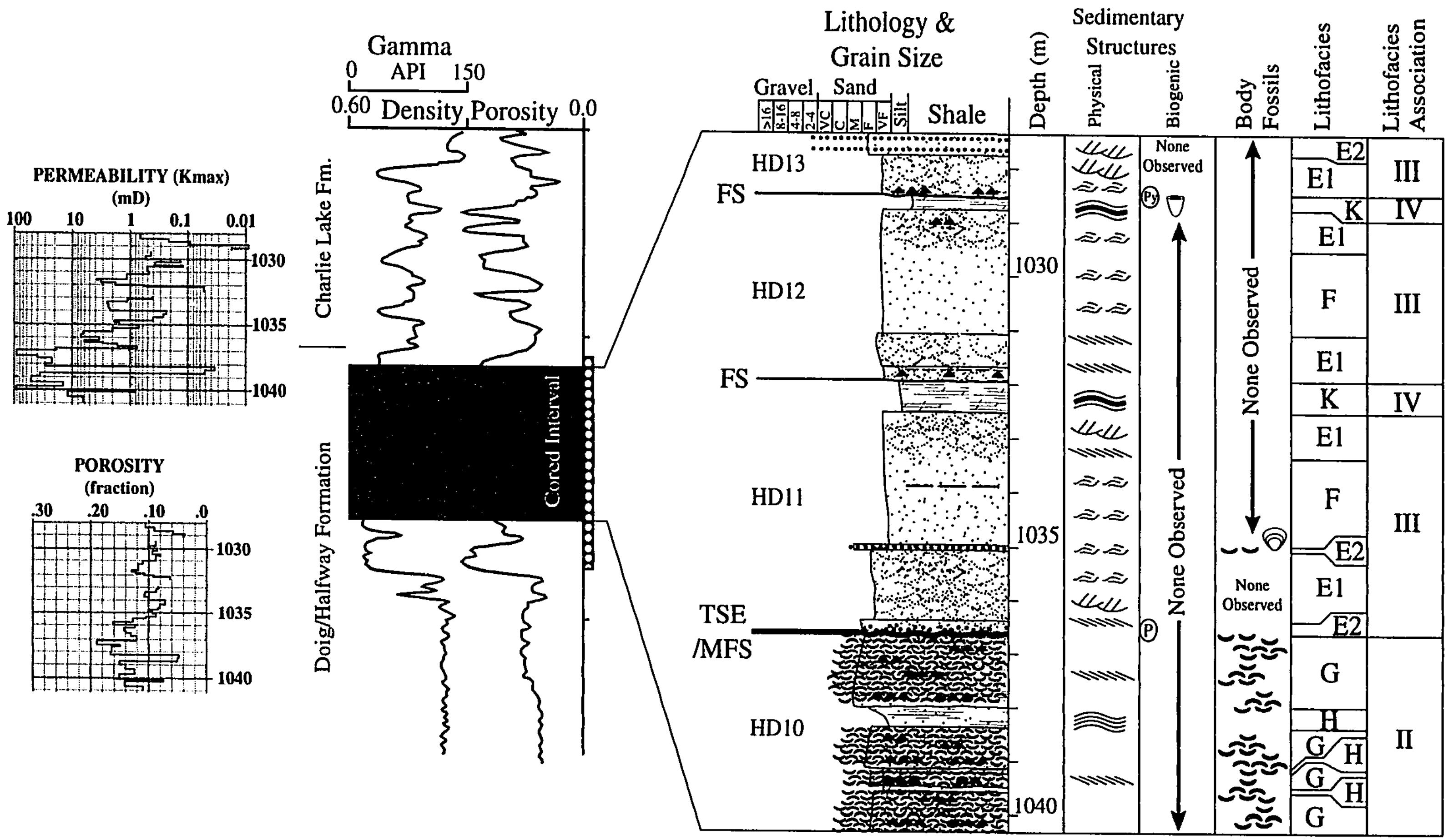

Figure 13. Cored interval within well a-86-I/94-G-9 (1350.7-1354.0m) showing lithofacies associations II (tidal inlet channel), III (barred shoreface) and IV (mixed siliciclastic-carbonate marginal marine). Lithofacies and lithofacies association designators are the same as those discussed in the text. and summarized in Tables 2 and 3. Core porosity (%) and permeability (Kmax, md) curves are presented on the left side of the diagram.

Summary of stratigraphic events, Tommy Lakes Field, British Columbia.	
(7) CLI Transgression	Generation of transgressive surface of erosion, coincident with lowstand surface within study area. Deposition of transgressive shoreface sediments (parasequence CL1)
(6) CLI Lowstand	Net lowstand in sea-level and generation of lowstand surface of erosion. Exposure and erosion of upper HDII parasequences.
(5) HDII Highstand	Deposition of strongly progradational package of barred shoreface to marginal marine parasequences (parasequences HD-11 through HD-14).
(4) HDII Transgression	Generation of transgressive surface of erosion at the base of parasequence HD-9. Deposition of transgressive barrier Island shoreface sediments (parasequences HD-9 and HD-10)
(3) HDII Early Transgression	Incision and deposition of early transgressive tidal inlet channel succession (parasequence HD-8) during a period of relative sea-level fall and possibly initial sea-level rise.
(2) HDI/II Sequence Boundary	Relative drop in sea-level, exposure and erosion of the proximal portions of parasequences HD-1 through HD-7.
(1) HDI Highstand	Deposition of strongly progradational package of offshore to lower shoreface parasequences (HD-1 through HD-7) as shoreface deposition outpaces accomadation creation.

Table 3. Summary of stratigraphic events, Tommy Lakes Field, British Columbia.

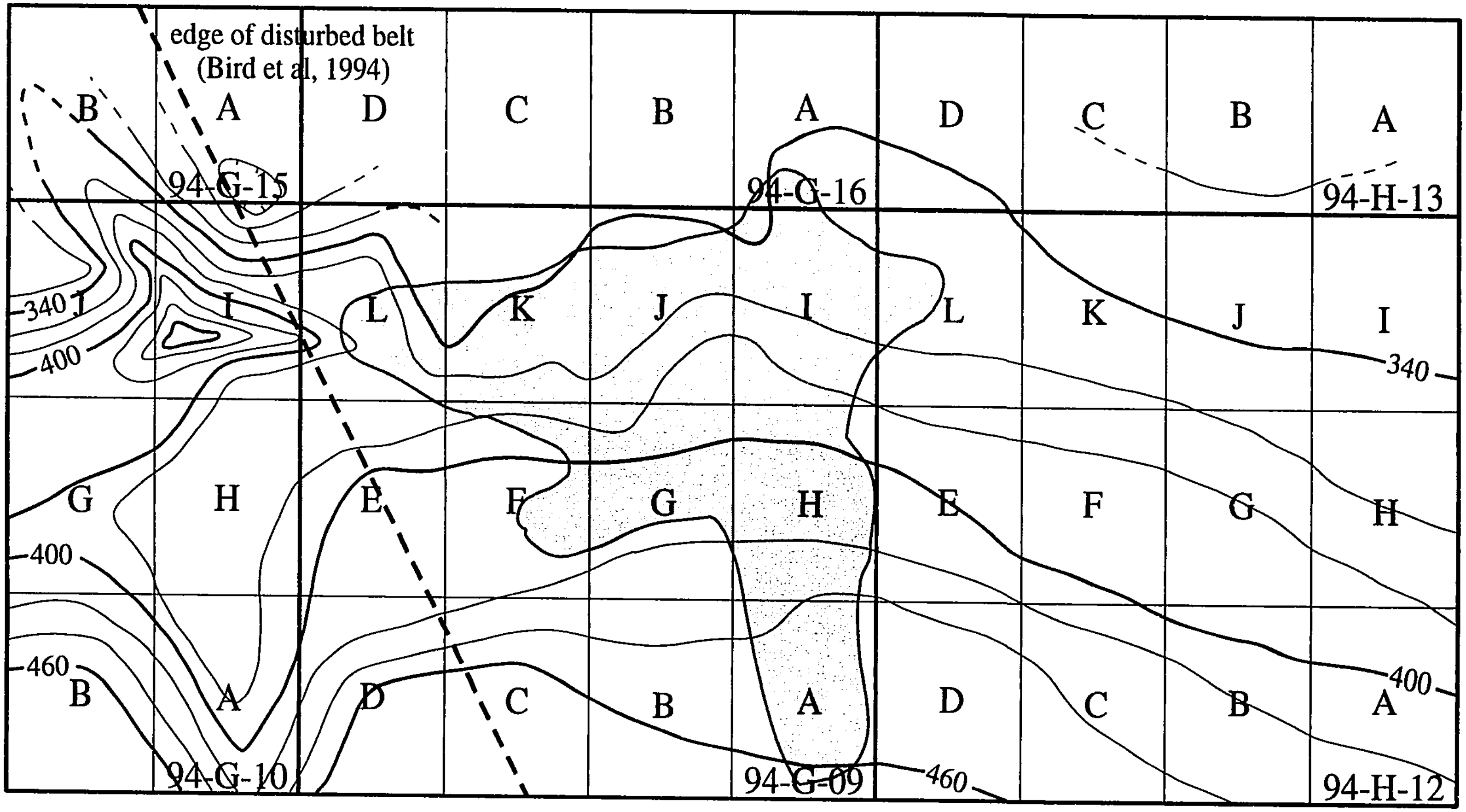

Figure 16. Structure on top of the Halfway Formation at Tommy Lakes field (shaded area). The area at the extreme left demonstrates structural complexity due to Laramide deformation.

Contour Interval: 20m

0 km 15

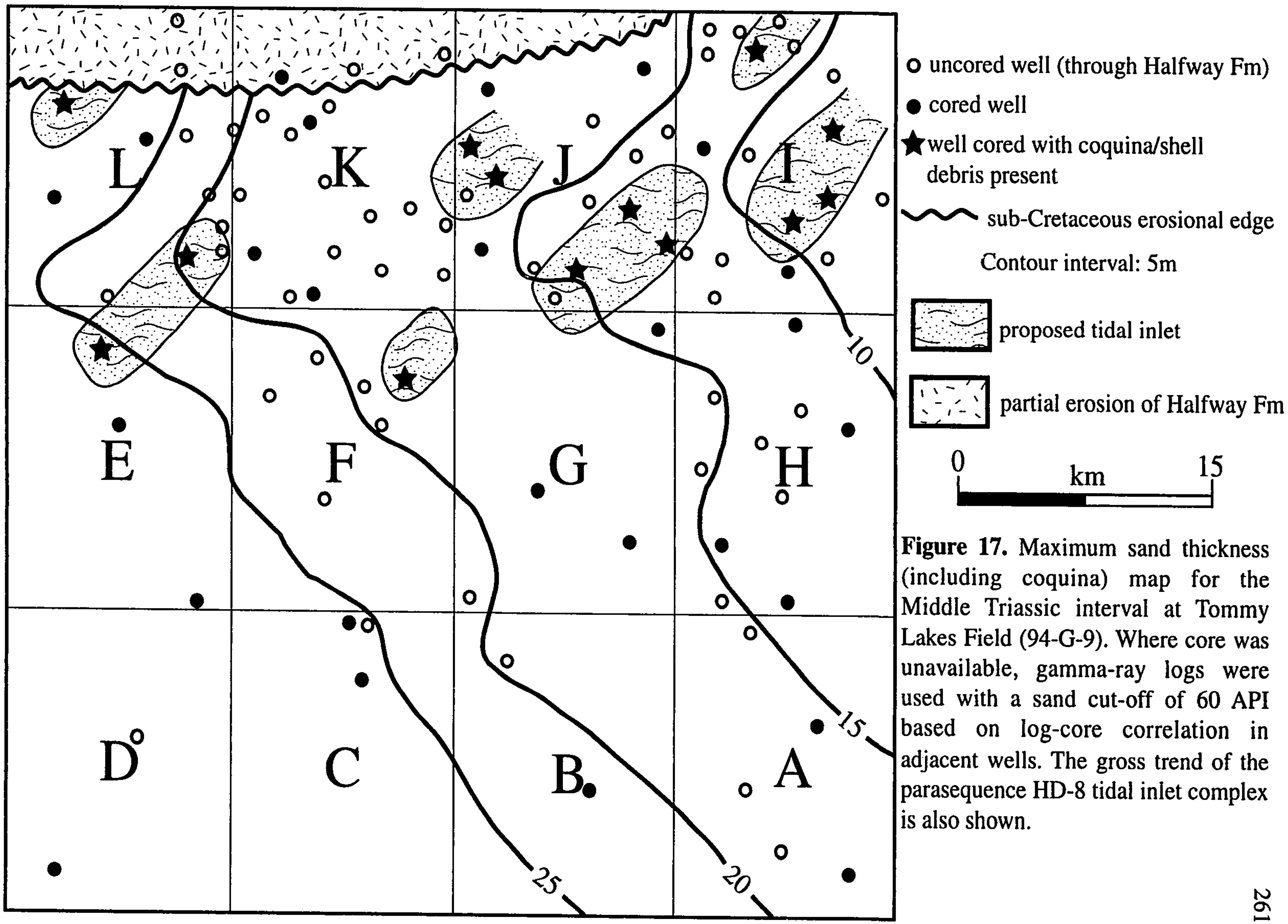

Figure 17. Maximum sand thickness (including coquina) map for the Middle Triassic interval at Tommy Lakes Field (94-G-9). Where core was unavailable, gamma-ray logs were used with a sand cut-off of 60 API based on log-core correlation in adjacent wells. The gross trend of the parasequence HD-8 tidal inlet complex is also shown.

containing *Skolithos, Thalassinoides* and *Fugichnia* with muddy siltstone/silty sandstone layers containing *Planolites, Palaeophycus, Thalassinoides* and *Teichichnus* is common in lithofacies B (offshore/shoreface transition), suggesting a mixture of indigenous infauna and storm-transported, opportunistic colonizers (Pemberton and MacEachern, 1997).

Lithofacies Association II: Tidal Inlet Channel

Lithofacies association II consists of lithofacies D (bioclastic tempestite/ebb-tidal delta), G (active tidal inlet channel fill), H (abandoned tidal inlet channel fill), and I (abandoned tidal inlet channel fill). The tidal inlet channel succession occurs within two thin (3-8m) transgressive parasequences (HD-8 and HD-9) within the study area.

Tidal inlet channels consist of either lithofacies G (active tidal inlet channel fill) and I (abandoned tidal inlet channel fill; Figure 11), or lithofacies G (active tidal inlet channel fill) and H (abandoned tidal inlet channel fill; Figure 13) and are arranged into thick (2-8m) successions of vertically stacked, normally graded units incising laterally adjacent shoreface sediments (lithofacies associations E and F). Both successions are interpreted to be the result of tidal inlet channel incision, migration and abandonment. Deposits associated with ebb- and flood-tidal deltas are rare within the study area. This paucity is interpreted to be due both to difficulties in differentiating these deposits from normal shoreface sediments and to the low preservation potential of such deposits. Normally graded sandstones with abundant bioclasts (lithofacies D) occurring adjacent to, and basinward of, these channels are interpreted as ebb-tidal deltaic deposits. Tidal inlet channels within the study area are laterally restricted (3-5km wide) but are common within the study area (Figure 17), strong evidence for deposition within a tidally influenced mesotidal setting (Tye and Moslow, 1993).

Lithofacies Association III: Barred Shoreface

Lithofacies association III consists of lithofacies D (barred upper shoreface, longshore bar), E (barred upper shoreface, longshore trough), and F (barred upper shoreface) and has been interpreted to represent a barred shoreface. The presence of abrupt horizontal to subhorizontal scour surfaces with pebble lags is unlikely in a non-barred succession and reflects the lateral migration of the longshore trough and rip-channel systems (Davidson-Arnott and Greenwood, 1976; Hunter *et al.*, 1979; Reading and Collinson, 1996).

Barred shorefaces commonly develop where the ratio of wave height to grain size is high (Hunter *et al.*, 1978; Komar, 1976). The Middle Triassic of western Canada was characterized by exceptionally fine-grained sediment, strong north-to-south trending longshore drift and wave-dominated deposition strongly influenced by storm processes (Davies, 1997; Zonneveld *et al.*, 1997), ideal circumstances for the development of a barred coast.

The barred shoreface association is similar in many regards to the clastic offshore/shoreface association in the Middle Triassic at Williston Lake (Chapter 4). Barred

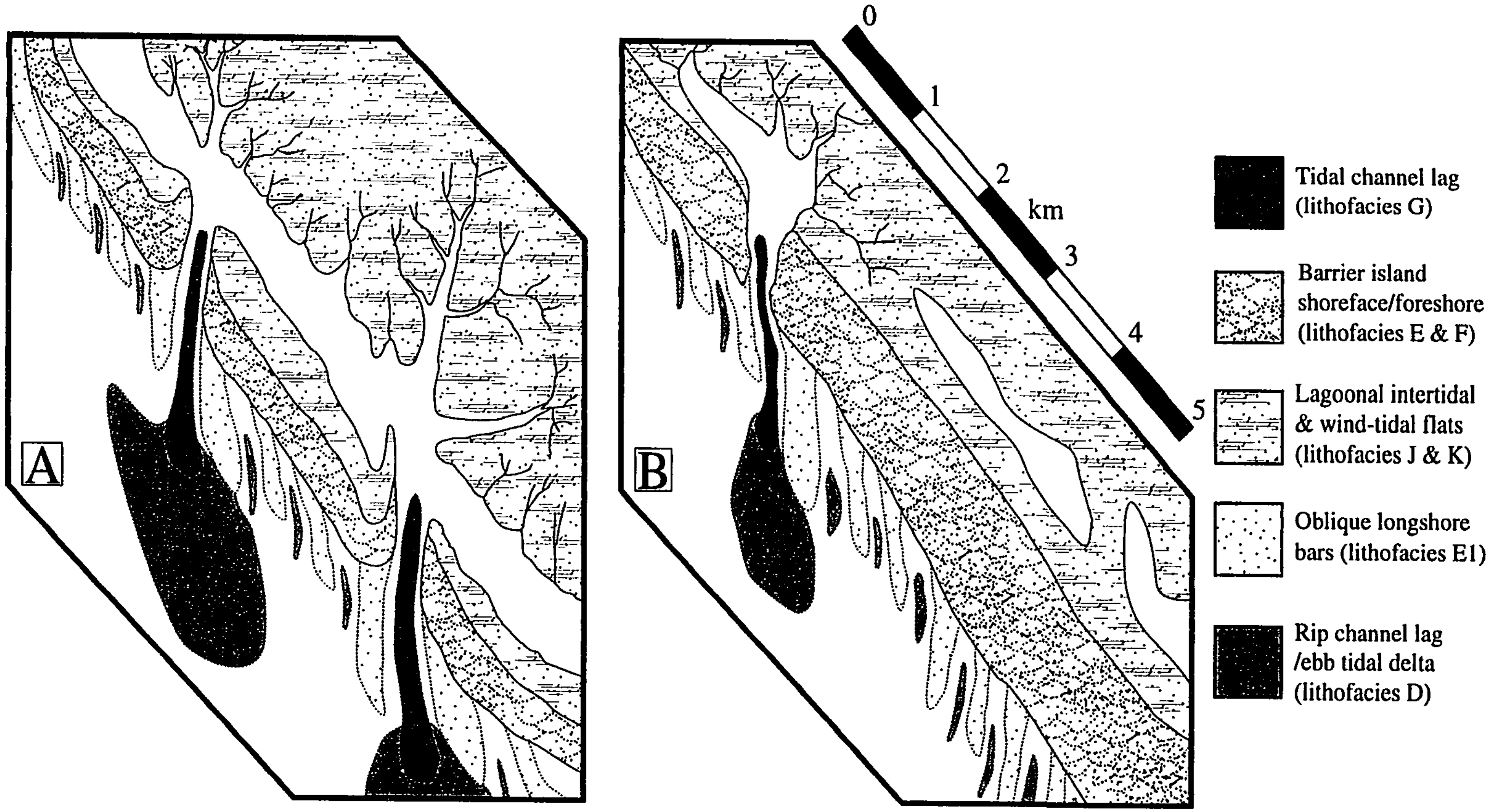

Figure 18. Schematic reconstuction of the Middle Triassic shoreface succession at Tommy Lakes Field. The system evolved from a barred barrier island succession with relatively deep, back-barrier lagoons during transgression (figure 18a), to a low-angle, progradational, barred beach-ridge strandplain succession with abundant minor lagoons and supratidal sabkhas during highstand (figure 18b).

overall increase in wave-energy (Pemberton and McEachern, 1995). Abundant *Fugichnia* emanating from the bases of individual low-angle and hummocky cross-stratified beds in lithofacies B (offshore/shoreface transition) and lithofacies C (lower shoreface) reflect the response of infaunal and epifaunal organisms to sudden burial. Interbedding of sand layers shoreface sediments occur lateral to deposits interpreted as tidal inlet channels (lithofacies association II) in parasequences HD-9 and HD-10 and comprise the main lithofacies association in parasequences HD-11 and 12. Within the study area, the barred shoreface association evolved from a transgressive barred barrier island shoreface succession (parasequences HD-8, HD-9 and HD-10) to a low angle, progradational barred beach-ridge strandplain succcession (parasequences HD11 through HD-14; Figure 18).

Lithofacies Association IV: Mixed Siliciclastic-Carbonate Marginal Marine

Lithofacies Association III consists of lithofacies J, K and possibly L. These lithofacies were deposited within a low-angle intertidal/supratidal setting landward of a barrier island shoreface succession. Interbedding of dolomitic muds and clastic quartz-dominated sand within back-barrier/intertidal sediments at Tommy Lakes may reflect a similar depositional setting to wind-tidal flats described from back barrier settings on the gulf coast of Texas. Wind-tidal flats occur when lagoonal waters flood low angle, back-barrier sand flats as a result of flooding by wind tides (Weise and White, 1980; Shideler, 1981). These flats consist of broad, barren expanses of interbedded sand and lime mud with abundant cryptalgal laminae (Morton and McGowen, 1980; Shideler, 1981). The sand on these flats is deposited as airborne sediment derived from the beach-barrier and as migrating sand dunes (Morton and McGowen, 1980; Weise and White, 1980; Shideler, 1981). The lime mud and algal laminae are deposited during inundation by the lagoon (Hunter et al., 1972; Morton and McGowen, 1980).

As discussed above, the convolute or chaotic nature of the bedding is likely related to extensive bioturbation by infaunal deposit feeders. The predominance of dolomitic sediments within this lithofacies association may be attributed to biogenically mediated authigenic dolomitization in a succession of lagoons and shore proximal lakes in an arid coastal setting (Zonneveld and Gingras, 1997; 1998). Similar dolomitization has been shown to occur in Pleistocene, Holocene and Recent sediments along the Coorong coast of southern Australia (Muir *et al.*, 1980; von der Borch, 1976; von der Borch and Lock, 1979).

SEQUENCE STRATIGRAPHY

The study interval comprises at least fourteen parasequences within two third-order sequences. Sequence and parasequence boundaries may be significant from a reservoir perspective since they are characterized by lateral shifts in lithofacies and may therefore be significant barriers to vertical permeability (Bryant, 1996). The sequence boundary (regressive surface of marine erosion) below parasequence HD-8 (Figure 10, 1210.3m; Figure 11, 1376m) is the base of the Tommy Lakes reservoir zone, due in part to the overall finer-grained nature of subjacent parasequences, but also as a result of porosity occluding calcareous cementation in the subjacent strata.

Sequence HDI Highstand Systems Tract

Within the Tommy Lakes region, parasequences HD-1 through HD-7 consist of a set of individual progradational parasequences comprised of offshore, offshore transition and lower shoreface facies (lithofacies association I). This set offlaps westward (basinward) as shoreface deposition outpaced sea-level rise and the creation of accommodation space. The conodonts *Neogondolella momergensis* and *N. constricta* were recovered from core samples collected from parasequences HD-3 and HD-4 in well a-63-I/94-G-9 (Henderson, 1998). These conodonts are indicative of upper Anisian deposition (Mosher, 1973). Abundant ammonoids and bivalves were also collected from parasequences HD-3 and HD-4 in well a-63-I/94-G-9. Although most of the ammonoids are too poorly preserved for generic identification, several are referred to cf. *Eogymnotoceras* sp., supporting an upper Anisian assignation (Tozer, 1994). The bivalves *Pseudomonotis* sp. and *Anatina* sp. and *Daonella* sp., collected are consistent with Middle Triassic deposition but are too poorly known in the Western Canada Sedimentary Basin for precise age determination.

Sequence HDI/HDII Sequence Boundary

The sequence boundary underlying parasequence HD-9 (and locally HD-8; Figures 10 and 11) is characterized by progressive erosion of the underlying parasequences (Figure 14). In the western part of the study area, parasequence HD-9 erosionally overlies parasequence HD-7, whereas in the east, parasequence HD-9 erosionally overlies parasequence HD-2 (Figure 14). The HDI/HDII sequence boundary is characterized by a moderate basinward shift in sedimentary facies from offshore/offshore transition sediments to upper shoreface sandstone and tidal inlet channel fill. It is thus interpreted to be a type I sequence boundary following the terminology of Van Waggoner *et al.* (1990). The presence of an angular unconformity may suggest tilting of the subjacent strata, implying tectonism in sequence boundary generation. Alternatively, particularly in light of the low angle of the unconformity, an eustatically generated lowstand may have resulted in the erosional removal of the tops of several surfaces resulting in the appearance of tilting. The moderate shift in sedimentary facies and the low angle of unconformity are interpreted to reflect deposition within a ramp margin setting, landward of the depositional-offlap break.

The sequence boundary is usually characterized by an abrupt decrease in gamma radioactivity, however 'clean' sands below the sequence boundary in parts of the study area may make this pick difficult (Figures 10, 11, 14 and 15). The sequence boundary is also characterized by an abrupt increase in density porosity. This shift is interpreted to be related to increased porosity due to the high proportion of detrital dolomite and the predominance of dolomite cement in sediments above the sequence boundary.

Sequence HDII early Transgressive Systems Tract

Tidal inlet channel complex (parasequence HD-8) within the southeastern and northeastern corners of the field (*i.e.* wells d-35-I/94-G-9 and d-55-A/94-G-9, Figures 14 and 15) incise deeply into underlying parasequences. These channels are associated either with lowstand or earliest transgression incision. These channel complexes do not appear to have migrated extensively, although this interpretation is limited by poor well density in the southeastern part of the study area. Similar to inlets within the Barataria Pass region of Louisiana (Levin, 1995), these channels incise offshore transition siltstones and mudstones and lower shoreface sandstones and may have been anchored in place by the fine-grained, cohesive sediments of the channel sidewalls.

The base of the channel preserved in well d-55-A/94-G-9 (Figure 11) is characterized by a moderately low diversity *Glossifungites* assemblage consisting of *Planolites*, *Skolithos* and *Thalassinoides*. The *Glossifungites* ichnofacies includes trace fossils constructed in firm, cohesive substrates and implies a succession of sediment deposition, burial, re-exhumation, and subsequent burrowing (Pemberton and MacEachern, 1995). Although commonly utilized as conclusive evidence of regional sequence boundaries due to implied subaerial exposure and erosion, *Glossifungites* surfaces may form in response to autocyclic as well as allocyclic processes (Pemberton and MacEachern, 1995). Although the example discussed here is associated with early transgression incision, it formed as a response to channel incision and migration, and is not regionally correlatable.

The tidal channel abandonment phase (lithofacies I;) above these lowstand inlet channels is exceptionally thick, particularly in well d-55-A/94-G-9 (~4.2m, Figure 11), reflecting atypically deep incision. The anomalous depth of this tidal channel may be related to incision during a period of relative sea-level fall and abandonment during early sea-level rise within a probable mesotidal setting. The laterally restricted (3-5km along strike) nature of these channels provides strong evidence for mesotidal deposition (Tye and Moslow, (1993).

Sequence HDII Transgressive Systems Tract

In the absence of lowstand deposits throughout most of the Tommy Lakes region, the transgressive surface immediately overlies the HDI/HDII sequence boundary (Figures 14 and 15). The transgressive systems tract consists of a retrogradational package of two parasequences (HD-9 and HD-10; Figures 14 and 15). These parasequences consist of both lithofacies association C (tidal inlet channel) and lithofacies association D (barred shoreface; Figures 10, 11 and 13). Throughout Tommy Lakes Field, this transgressive succession has been subsequently reworked by tidal inlet channel formation and migration.

During transgression, the Tommy Lakes barrier shoreface migrated landward, reworking the top of the previously deposited barrier island succession, leaving a thin (2-6m) relict layer of shoreface sandstone (lithofacies E and F), tidal inlet dolomitic bioclastic grainstone (lithofacies G) and bioclastic sandstone (lithofacies D) deposited in an ebb-tidal deltaic setting (Figures 11 and 13). Similarly, in recent examples, rising sea-levels resulted in destruction of most of the barrier island succession with the exception of a thin basal sheet sandstone (Kraft, 1971), largely comprised of tidal inlet-fill sands (Moslow and Heron, 1978).

Transgression within Tommy Lakes Field progressed from west to east. As a result, parasequences that comprise the transgressive systems tract of sequence HDII (HD-9 and HD-10) progressively thin towards the east. In the eastern end of the field (between wells a-69-L/94-H-12 and a-19-C/94-H-13, Figure 14) parasequence HD-9 reaches it's landward limit, and parasequence HD-10 becomes the basal parasequence in sequence HDII. Parasequence HD-10 is capped by an abrupt but conformable surface consisting of shoreface sandstone (lithofacies E) overlying either lagoonal dolomitic mudstone/siltstone (lithofacies J) or tidal inlet channel coquina (lithofacies G or H). This surface is interpreted as the maximum flooding surface and the top of the transgressive systems tract. This surface is used as the datum in both the strike-oriented and dip-oriented cross-sections (Figures 14 and 15).

Sequence HDII Highstand Systems Tract

The sequence HDII highstand systems tract at Tommy Lakes Field consists of a progradational package of barred shoreface to marginal marine parasequences (parasequences HD-11 through HD-14; Figures 11 through 13). Within the study area, these parasequences become progressively more dominated by marine sandstone to the west (lithofacies C, E and F) and by dolomitic mudstone, siltstone and sandstone (lithofacies J and K) to the east (Figure 14).

The absence of tidal inlet channels within the sequence HDII highstand systems tract within and adjacent to the Tommy Lakes region is interpreted to reflect the evolution of the Tommy Lakes coast from a transgressive barrier island succession with large back-barrier lagoons to a low-angle, progradational, beach-ridge strandplain succession with abundant minor lagoons and shore proximal lakes (Figure 18).

Sequence CL-I Sequence Boundary and Transgressive Systems Tract

The upper bounding surface of the sequence HDII highstand systems tract is placed at the base of the "A" Marker Limestone (Figures 12, 14 and 15). A lack of core within the Charlie Lake Formation above the "A" Marker Limestone at Tommy Lakes Field makes correlations and environmental interpretations tenuous. This higher interval is therefore not discussed here.

The "A" Marker Limestone has been correlated throughout the subsurface of the British Columbia portion of the Western Canada Sedimentary Basin (Moslow and Davies, 1992; Young, 1997). The regional extent and erosive nature of the basal contact of this unit are consistent with a third or possibly second order sequence boundary. An upper Ladinian sequence boundary has been shown to correlate with the unconformity at the base of the "A" Marker Limestone in the Altares Field (Chapter 5). Tight biostratigraphic control on units above and below this sequence boundary in outcrop confirms its age as uppermost Ladinian. This sequence boundary is interpreted to be synchronous with the near Ladinian-Carnian sequence boundary discussed in Embry (1997).

DISCUSSION

Tommy Lakes field is the northernmost Middle Triassic reservoir in the Western Canada Sedimentary Basin and is bound to the north by erosional truncation and removal of Middle Triassic sediments subjacent to the sub-Cretaceous unconformity. The effective limit of Tommy Lakes Field on its western margin occurs where proximally emplaced higher reservoir quality shoreface sandstone grades laterally to finer grained, more distally emplaced silty sandstones. The eastern margin of the field occurs where shoreface sandstone grades laterally to marginal marine dolomitic sandstone and siltstone. The southern limit of the field is less well defined and appears to occur near the southern limit of bioclastic tidal channel migration. This boundary may also be determined in the southern portion of the field by the gas-water contact.

Reservoir Lithologies and Trapping Mechanisms

Figure 16 shows structure on top of the Halfway Formation. Throughout most of the field, well control is insufficient to show small scale structure, however the map does show a strong general structural dip to the south, and extensive deformation within the disturbed belt to the west. A preliminary net sand isopach map of the Doig-Halfway interval within the study area illustrates the geographic distribution of key reservoir lithofacies within the study area (figure 17). Sandstone thickness increases to the southwest, however the highest reservoir quality lithologies occur in the northern part of the field. Core permeability and porosity plots are presented for well d-73-F/94-G-9 (Figure 10), well d-55-A/94-G-9 (Figures 11 and 12) and well a-86-I/94-G-9 (Figure 13).

Hydrocarbons are currently being produced from two main lithofacies types within the Halfway and Doig formations at Tommy Lakes Field. Porosity within shoreface sandstones (lithofacies D, E and F) is primarily attributed to primary intergranular porosity, reduced in part by subsequent quartz and carbonate cements. Lithofacies E (barred shoreface) consists of quartzose, well-sorted, cross-stratified, fine- to medium-grained sandstone, characterized by porosities of 7-12% and permeabilities ranging between 4-25md. Lithofacies E is generally highly interbedded with lithofacies F (convolute bedded sandstone) resulting in high variability in porosity and permeability. This is attributed to variations in cement fabric, density and mineralogy. Poorer sorting and a higher degree of biogenic reworking within lithofacies E also inhibits hydrocarbon flow.

Bioclastic sandstones interpreted as tempestites or ebb-tidal deltas (lithofacies D) are commonly interbedded with other shoreface lithofacies within the study interval. These units are not a significant reservoir facies. Although comprised of similar bioclasts to those observed in tidal inlet channel deposits, early diagenetic alteration of carbonate silt and sand has occluded rather than enhanced porosity within these units.

Porosity within active tidal inlet channel deposits (lithofacies G; sandy, dolomitic, bioclastic grainstone/rudstone) is primarily moldic/vuggy porosity resulting from the dissolution of bivalve and brachiopod fragments. These deposits are characterized by

General	
Location:	-94-G-9, 94-G-16, 94-H-12; 122°10'W, 57°40'N; 250km NW of Fort St. John, British Columbia
Deposition/tectonics:	-Ramp type passive margin -North of Peace River structural embayment -Laramide orogeny provided gentle southwesterly dip of strata
Trap Mechanism:	Combination Trap -Stratigraphic A: dolomitic mudstone/evaporites (Charlie Lake Fm.) -Stratigraphic B: argillaceous shale, sub-Cret. unconf. (Bluesky Fm.) -Structural: gentle dip of strata to the southwest -Diagenetic: localized cementation (dolomite & evaporite)
Source Rock:	-not definitive: presumed to be the Doig phosphate zone

Reservoir Rocks	
Age:	-Anisian-Ladinian
Stratigraphic Units:	-Halfway Formation (shoreface sands & bioclastic tidal inlet channel fill) -Doig Formation (bioclastic tidal inlet channel fill)
Productive lithofacies:	-fine-grained sandstone (lithofacies E & F) -dolomitic sandy bioclastic grainstone (lithofacies G)
Depositional Environments:	-Barred shoreface

Reservoir Characteristics		
Discovery Date:	-February 16, 1960	
Net Pay (thickness):	-13m (based on 60API cutoff)	
Poristy (Range):	-sandstone: 3-12%	bioclastics: 12-19%
Permeability (Range):	-sandstone: 0.1-3.0md	bioclastics: 15-200md
Average depth from surface:	-985m	
Total Area (field):	-41,696Ha	
Estimated Reserves:	-19.25 X 10^9 m^3	

Table 4. Summary of reservoir production characteristics for the Halfway reservoir at Tommy Lakes Field, British Columbia.

moderately limited lateral extent (3-5km) and sharp, erosive-based units. Porosities within lithofacies G range between 12 and 20% and permeabilities between 15 and 200md. Many producing wells penetrate both types of reservoir lithofacies.

In the upper part of the Doig-Halfway succession, bioclastic tidal inlet channels commonly incise shoreface sand accumulations, promoting communication between different reservoir lithofacies. Hydrocarbon movement between these parasequences is enhanced by movement through tidal inlet channels. Fluid and gas movement is further enhanced by the scoured, "sand-on-sand" parasequence contact associated with the transgressive surface of erosion separating parasequences HD-8 and HD-9 and the maximum flooding surface separating parasequences HD-10 and HD-11. Production in the northern part of the field has shown that reservoir facies within the I, J and K blocks of 94-G-9 (Figure 1b) are in reservoir communication even though production comes from distinct parasequences.

Bioclastic tidal inlet channels which incise more deeply (*i.e.* d-55-A/94-G-9), cut into finer grained offshore/offshore transition silts and muds and are capped by tidal inlet channel abandonment phase silty sandstone, preventing communication with lower parasequences. This is fortuitous since these lower parasequences typically contain water rather than hydrocarbons.

Similar to bioclastic tidal channels from the Halfway Formation at Wembley Field, Alberta (Willis and Moslow, 1994) and at Peejay Field, British Columbia (Caplan, 1992; Caplan and Moslow, 1997), hydrocarbon entrapment results from the updip pinch-out of tidal inlet channels and upper shoreface/foreshore sandstones. Tight, marginal marine dolomitic mudstones and evaporites of the Charlie Lake Formation prevented hydrocarbon migration out of the system. An additional seal, particularly significant in the north, is provided by fine-grained sediments of the Bluesky Formation overlying the sub-Cretaceous unconformity.

The source of hydrocarbons in the Tommy Lakes region has not yet been established. The basal Doig phosphate zone has been shown to be the most prolific source rock in the Triassic of northeastern British Columbia (Riediger et al., 1990; Evoy and Moslow, 1995; Riediger, 1997). As well as internal Triassic sources, potential source rocks include organic-rich shales within underlying Devonian and Carboniferous, and overlying Jurassic strata (Bird et al., 1994).

Environmental Parameters of the Tommy Lakes Coastal Zone

Palaeotopographic relief, hydrographic regime (wave height, tidal range, storm strength duration and frequency) and sediment supply (quantity and lithology) have been shown to be to the primary controlling factors on the development, distribution and geometry of tidal inlet channels (Moslow and Heron, 1978; Tye and Moslow, 1992). Although it has been observed by numerous authors (Munroe and Moslow, 1990; Tye and Moslow, 1992;

Willis and Moslow, 1994) that bioclastic tidal inlet channel fills within the Halfway Formation are similar to wave-dominated inlet channels along the coast of North Carolina, these regions differ greatly in terms of geographic setting and sediment supply.

The Halfway and Doig formations were deposited within a mixed siliciclastic-carbonate depositional system along the west coast of Pangea. The textural and mineralogical maturity of sand within the Halfway and Doig formations is reflective of low relief of the coastal plain and a predominance of Palaeozoic sediments within the source area (Campbell and Horne, 1986). An arid climate within the Pangean interior east of the study area, located at approximately 30° north latitude, resulted in intermittent fluvial discharge to the coast. This effectively limited siliciclastic input (Davies, 1997; Zonneveld and Gingras, 1997;1998). By limiting grain size in shoreface sediments, climate played a significant role in the composition of Middle Triassic tidal inlet channels. At present, recent and Holocene analogues of bioclastic tidal inlet channel successions, both in progradational and transgressive systems, are limited primarily to temperate settings such as that found along the present-day shoreline of eastern North America (Tye and Moslow, 1993).

Several lines of evidence support the hypothesis that high microtidal to mesotidal conditions prevailed along the Tommy Lakes coastline during the Middle Triassic, most significantly the limited lateral extent of bioclastic tidal inlet channels in parasequences HD-8 and HD-9. In the absence of evidence to the contrary, it is believed that the Tommy Lakes area was situated in a relatively open coastal setting. Within Recent depositional systems, macrotidal ranges are primarily limited to gulfs and embayments along oceanic coasts (Komar, 1976). The overall geometry and the distribution of tidal inlet channels within the I and J blocks of 94-G-9 are also interpreted to reflect deposition under probable high microtidal to mesotidal conditions. Tidal inlet channels within microtidal settings migrate rapidly along shore and are characterized by large flood-tidal deltas and smaller ebb-tidal deltas. Conversely tidal inlet channels in mesotidal settings tend to develop sizable ebb-tidal deltas and incise deeper into the substrate, thus remaining comparably stationary (Tye and Moslow, 1993).

Tidal inlet channels within the transgressive systems tract (parasequences HD-9 and HD-10) show features characteristic of both microtidal and mesotidal settings, particularly a moderate depth of incision and inlet migration on the scale of several kilometres. The depth of incision and thickness of the tidal channel abandonment phase within parasequence HD-7 likely reflects channel development during falling sea-level and abandonment during transgression.

Bioclastic Tidal Inlet Channel Fill

Wave dominated inlet channels along the microtidal North Carolina coast are characterized by several metres of bioclastic sand (Moslow and Tye, 1985; Tye and Moslow, 1992). This bioclastic material is composed dominantly of highly abraded bivalve fragments (Tye and Moslow, 1992; Tye, 1984). Bioclastic material comprising the active tidal inlet channel fill (lithofacies G) at Tommy Lakes Field is generally highly abraded, making generic identification difficult. Although some of the bioclasts such as terebratulid and spiriferid brachiopods and echinoderm detritus had a fully marine derivation, the origin of bivalve fragments, which comprise most of the bioclastic material, is uncertain. Bivalves and trace fossils attributed to bivalves are particularly common constituents in intertidal flat deposits within the outcrop equivalents of the Halfway and Charlie Lake formations (Zonneveld and Gingras, *in press*). Although bivalves are present, articulate brachiopods and echinoderms predominate within adjacent shoreface successions (Zonneveld *et al.*, 1997).

It is likely that the Tommy Lakes tidal inlet channel fill was derived from both marginal and fully marine sources. Brachiopod, echinoderm and some mollusk debris is interpreted to have accumulated within shoreface sands via normal, shoreward wave transport. This debris was subsequently concentrated as lags within channel thalwegs as the inlets incised into pre-existing shoreface accumulations (*i.e.* earlier parasequences) and migrated laterally along the shore. Much of the mollusk debris originated within the back-barrier/intertidal zone and was transported basinward by ebb-oriented flow.

Henderson and Frey (1986) found that bioclastic accumulations (primarily mollusk shells) within the central scour trough of a tidal inlet channel on Sapelo Island, Georgia were temporally mixed as well as homogenized with respect to original habitat, taxonomy and size. Differential preservation and dissolution of shell material within the Tommy Lakes tidal inlet channels likely reflects similar temporal mixing as the channels simultaneously reworked both underlying deposits and laterally adjacent shoreface sands.

Biostratigraphic Constraints

Determing the age of the Tommy Lakes study interval has been a lesson in the vagaries of biostratigraphic analysis. Although numerous samples have been processed for conodonts, only a few have yielded diagnostic elements. Without exception, productive samples were obtained from core through parasequences HD-3 and HD-4 providing an Upper Anisian age for sequence HDI. An absence of conodonts above these horizons within the study area has made age determination difficult.

Although samples from the "A" Marker Limestone have been processed for conodonts, only non-diagnositic elements have been recovered from it to date (Henderson, 1998). The "A" Marker however is a regionally correlatable unit, interpreted to represent a basin-wide marine transgression (Moslow and Davies, 1992; Young, 1997). Core through the "A" Marker within Tommy Lakes Field revealed a basal erosional unconformity characterized by either a basal *Glossifungites* surface or rip-up clast lag (Figure 9). This surface is regionally correlatable throughout the subsurface of the northeastern British Columbia part of the Western Canada Sedimentary Basin.

Analysis of core through the base of the "A" marker in the Wargren field (well d-57-J/94-H-3) revealed an unconformity characterized by bioclastic fine-grained sandstone incising into cyanobacterially laminated dolomitic mudstone. In the Altares field (well a-83-A/94-B-8), the unconformity is characterized by a vertically extensive *Glossifungites* surface. Correlation of this well with the Williston Lake outcrop belt indicates that this unconformity is equivalent to the upper Ladinian (TL2-TL3) sequence boundary discussed in Chapter 5, and thus may be equivalent to the "near Ladinian-Carnian sequence boundary discussed by Embry (1997).

These age determinations open up as many new questions concerning the timing of Middle Triassic deposition in the Western Canada Sedimentary Basin as they provide answers. The age of sequence HD-1 is confirmed as uppermost Anisian, and that of sequence CLI is inferred to be uppermost Ladinian. Sequence CL1 at Tommy Lakes is inferred to be equivalent with sequence TL3 in the outcrop belt at Williston Lake (Chapter 5). The age of sequence HDII however remains open to conjecture. In outcrop, the Ladinian succession was shown to consist of at least three sequences (TL1, TL2 and TL3) and comprises in eastern exposures (*i.e* those closest to the subsurface of the Western Canada Sedimentary Basin) an inordinately thick succession of strata (at least 350m at Brown Hill; Chapter 5). The Ladinian succession at Tommy Lakes (sequence TLII?) however is much thinner and comprises, at most, two sequences.

CONCLUSIONS

Sedimentary facies within the Doig, Halfway and basal Charlie Lake formations within the Tommy Lakes region of northeastern British Columbia comprise four distinct lithofacies associations: I) offshore/offshore transition/lower shoreface, II) tidal inlet channel, III) barred shoreface and IV) mixed siliciclastic-carbonate marginal marine. The stratigraphic and geographic occurrence of each of these lithofacies associations within the study area is governed primarily by sea-level and thus by position within a sequence stratigraphic framework.

Lithofacies association I, consists of an overall coarsening upwards offshore through lower shoreface succession. This association is unconformably overlain by lithofacies association II, a thin retrogradational package of mixed siliciclastic and bioclastic tidal inlet channel deposits incising siliciclastic shorefacies sediments. Lithofacies association III is a barred shoreface succession which grades upwards and landwards with lithofacies association IV, mixed siliciclastic-carbonate marginal marine.

Hydrocarbon are currently being produced from two main lithofacies at Tommy Lakes field. Shoreface sandstones (lithofacies E and F) are characterized by porosities of 7-12% and permeabilities ranging between 4-25md. Actively filled tidal inlet channel bioclastic units (lithofacies G) are characterized by limited lateral extent and sharp, erosive bases. Porosities within this lithofacies range between 12 and 20% and permeabilities between 15 and 200md.

The stratigraphic succession discussed in this paper comprises fourteen parasequences within two third-order depositional sequences. The basal six parasequences (HD-1 through HD-7) consist of a progradational package (lithofacies association I) comprising the highstand systems tract of sequence HDI. Conodonts and ammonoids collected from parasequences HD-3 and HD-4 indicate that this succession was deposited during the uppermost Anisian.

The HDI/HDII sequence boundary is characterized by a moderate basinward shift in sedimentary facies from offshore/offshore transition sediments to upper shoreface sandstone and tidal inlet channel fill. A tidal inlet channel complex (parasequence HD-8) within the southeastern corner of the field comprises the HDII early transgressive systems tract. This channel complex incised underlying parasequences during sea-level fall and was abandoned early in transgression.

The trangressive surface immediately overlies and approximates the HDI/HDII sequence boundary throughout most of the study area. The transgressive systems tract (lithofacies associations II and III) consists of a retrogradational package of two thin parasequences (HD-9 and HD-10). Moderately rapid transgression resulted in reworking of most of these parasequences and in the preservation of the basal few meters of each.

As the sea-level rise decelerated and sedimentation outpaced the creation of accommodation space, back-barrier lagoons were infilled with sediment . The system evolved from a barrier island succession with relatively deep, back-barrier lagoons during transgression (Parasequences HD-8, HD-9, and HD-10), to a low-angle, progradational, barred beach-ridge strandplain succession with abundant minor lagoons and shore proximal lakes during highstand (parasequences HD-11, HD-12, and HD-13). The sequence HDII highstand systems tract within Tommy Lakes Field consists of lithofacies association III (barred shoreface) grading landwards into lithofacies association IV (mixed siliciclastic-carbonate marginal marine.

The upper bounding surface of the sequence HDII highstand systems tract is placed at an erosional unconformity at the base of the "A" Marker Limestone, a thin (2-5m thick) transgressive shoreface deposit characterized by abundant marine body fossils (crinoid and brachiopod detritus) and trace fossils. Althought his unit has not yielded biostratigraphically significant fossils within Tommy Lakes Field, conodonts collected from the outcrop equivalent of this unit suggest uppermost Ladinian deposition.

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CHAPTER 7.

SUMMARY AND CONCLUSIONS

> *"It must be admitted that the Canadian Triassic is imperfectly known. In only a few areas have systematic investigations been carried on. Elsewhere stratigraphic studies have not been sufficiently detailed, and the search for fossils has not been intensive enough to yield satisfactory results. In some places investigation is hampered by the scarcity and poor preservation of fossils. It follows that the chart and annotations are actually more a record of unsolved problems than of completed studies, and an appropriate title would be* Problems of the Triassic Stratigraphy of Canada*".*
>
> F.H. McLearn, *1953*

The depositional and stratigraphic framework of Middle Triassic strata in outcrop and in subsurface were examined to document variability, both laterally and vertically, the composition and relationships of lithofacies, particularly in regards to siliciclastic and carbonate content, to assess the controls promoting mixed siliciclastic-carbonate deposition on the northwest coast of Pangaea during the Middle Triassic, and to develop an accurate and detailed sequence biostratigraphic framework to facilitate correlation between different parts of the Western Canada Sedimentary basin. To accomplish these goals, this study employed an integrated approach, utilizing ichnology, invertebrate paleontology, lithologic analysis, biostratigraphy, sequence stratigraphy and outcrop gamma ray analysis to investigate Middle Triassic strata in the Peace river outcrop belt along Williston Lake in the Rocky Mountain Foothills, and core from Tommy Lakes Field in the subsurface of the northern portion on the Western Canada Sedimentary Basin.

Peace River Outcrop Belt

The first part of this dissertation (Chapter 2 through Chapter 5) represents a study of the depositional and sequence biostratigraphic framework of the Toad and Liard formations along the shores of Williston Lake in northeastern British Columbia. Five outcrop sections were measured (Ursula Creek, Brown Hill, Glacier Spur, Beattie Ledge, and Aylard Creek), comprising a 40 kilometre long dip oriented cross-section. Each site was analyzed, paying close attention to lithology, physical sedimentary structures, trace and body fossil content, and the nature and type of bounding surfaces. In total, 1,450 metres of section were measured, 2,900 gamma-ray intervals were measured and 250 samples (2-4 kilograms each) were collected and processed for conodonts.

Six recurrent lithofacies associations were identified: I) shelf/ramp turbidites; II) clastic offshore-shoreface; III) wave-dominated transgressive shoreface; IV) mixed siliciclastic-carbonate shoreface; V) brachiopod-echinoderm biostrome; VI) mixed siliciclastic-carbonate marginal marine (intertidal flat, lagoon supratidal sabkha).

Lithofacies association I (shelf/ramp turbidites) consists of a thick succession of normally graded, interbedded fine- to very fine-grained sandstone, siltstone and mudstone beds deposited by turbidity current processes in a medial sheld to ramp setting. A thick (4-8m) laterally restricted sandy bioclastic grainstone incises through these units at Brown Hill and is interpreted as a turbidite channel.

Lithofacies association II (clastic offshore-shoreface) represents deposition on a storm-influenced barrier island shoreline. Numerous laterally restricted sand and bioclastic sand lenses incise through shoreface sand bodies and are interpreted as tidal inlet channels and rip-tidal lags.

Lithofacies association III (wave-dominated transgressive shoreface) represents deposition along a wave-dominated coastline characterized by partially lithified beach rock. This partially lithified beachrock represents bioclastic highstand shoreface deposits, cemented during sea-level lowstand into ridges and blocks of lithified packstone. During transgression these lithified sediments were eroded in rounded nodules and large blocks, by wave erosion, undercutting by the removal of subjacent unlithified sand, and by destruction by marine bioeroders. This material was redeposited as carbonate clasts in a dominantly siliciclastc matrix. As sea-level continued to rise and these clasts passed beneath the zone of wave-reworking, larger blocks were colonized by hard substrate preferring organisms such as terebratulid brachiopods (*Aulacothyroides liardensis*).

Lithofacies association IV (mixed siliciclastic-carbonate shoreface) consists of a progradational succession of siliciclastic sandstone and bioclastic packstone to grainstone. V). Bioclastic sediment increases in proportion, and siliciclastic sediment decrease in proportion, from the base to the top of each lithofacies association IV parasequences. The cross shore transport of bioclastic and siliclastic sediment is attributed to grain size, grain density, and grain shape, and to the absence of coarser allochthonous material.

Lithofacies association V (terebratulid brachiopod-echinoderm biostrome) is unique to the study area within the Middle Triassic of western Pangaea. Storm-generated concentrations of bioclastic debris provided "islands" of stable substrate which wer colonized by hardground-preferring epifaunal organisms. This unique association is dominated by terebratulid brachiopods (*Aulacothyroides liardensis*), articulate crinoids (*Holocrinus* sp.) and cidaroid echinoids (*Miocidaris* sp.). Other occupants of these biostromes include acrotretid brachiopods (cf. *Discinisca*), spiriferid brachiopods (*Spiriferina borealis*), bivalves, bryozoans, and possibly corals. Lingulid brachiopods (*Lingula selwyni*), decapod crustaceans (several new genera and species), and phyllocarid crustaceans (new family? genus and species) inhabited the shifting sandy substrate adjacent to the biostromes. Fish (*Bobasatriana* sp.) and marine reptile fossils (icthyosaurs and thalattosaurs) are also common in these units.

Lithofacies association VI (mixed siliciclastic-carbonate marginal marine; intertidal flat, lagoon supratidal sabkha) represents deposition in a continental setting, along an arid coastline characterized by broad intertidal and supratidal flats, numerous salinas or sabkhas, and aeolian sand dunes. Similar to Recent and Holocene examples from the Corrong coast of Australia, dolomite in the intertidal and supratidal zones formed by primary precipitation during evaporative concentration of groundwater and by mixing of continental and marine-derived groundwater.

Controls governing and promoting mixed siliciclastic-carbonate deposition within marginal marine lithofacies associations in the Toad and Liard formations include an arid climate, fluctuations in sediment supply, variability in sedimentation style and source, a significant and productive source of biogenic carbonate, lateral shifts in lithofacies and a texturally mature sediment source. Siliciclastic sediments within the study area were derived from aeolian transport, longshore drift from depocentres within and outside the study area, and episodic fluvial input to the shoreface. Nonsiliciclastic sediments within the study interval were derived primarily from marine biogenic sources and are dominated by bioclastic sand and silt.

The Middle Triassic Toad and Liard formations at Williston Lake consist of at least seven third-order sequences deposited within two second-order sequences. Outcrop exposure of Anisian sequences (TA1-TA4) are limited primarily to basinward sections (Ursula Creek). Three Ladinian sequences (TL1-TL3) occur within the study area and are preserved at all outcrop sections. Biostratigraphic analysis confirm that sequences TL2 and TL3 are upper most Ladinian in age. The uppermost sequence boundary (TL2\TL3) occurs throughout the study area and has been correlated into the subsurface in the Altares region of northeastern British Columbia. This boundary occurs in the uppermost Ladinian and is overlain by a sedimentary package that grades from uppermost Ladinian to earliest Carnian. It is interpreted to be equivalent to the globally correlatable "near Ladinian-Carnian" sequence boundary. This sequence boundary is overlain by a bioclastic sandstone to packstone informally referred to as the "A" Marker Limestone. This unit is correlatable throughout the northeastern British Columbia portion of the Western Canada Sedimentary Basin providing an excellent marker unit for regional stratigraphic correlation.

It is hypothesized that a paleotopographic high existed within the study area, separating basinward sites (Ursula Creek) from landward sites (Brown Hill, Glacier Spur, Beattie Ledge and Aylard Creek), creating a landward sub-basin and promoting excessive sediment starvation in basinal locales. Evidence supporting the presence of a paleotopographic high include severe thinning of Ladinian sediments in basinward sections, retrogradational profile of Middle Triassic sequences in basinal locales and progradational profiles of Middle Triassic sequences in landward settings, an apparent deepening within numerous parasequences in a "landward" direction, erosional removal of several parasequences by the uppermost Ladinian (TL2\TL3) sequence boundary that are preserved in more "landward" localities finally, the dramatic shift in depositional patterns between the Ladinian and the Carnian.

Doig/Halfway/Basal Charlie Lake Interval in Subcrop

The second part of this dissertation (Chapter 6) represents a study of the depositional and sequence biostratigraphic framework of the Doig, Halfway and basal Charlie Lake formations in the Tommy Lakes Field region of northeastern British Columbia. Core from fifty-six wells within Tommy Lakes Field and an additional fifty wells outside of the Tommy Lakes region were analyzed in a similar manner to that described for the outcrop intervals.

Four recurrent lithofacies associations were identified: I) offshore-lower shoreface; II) tidal inlet channel; III) barred barrier island shoreface and IV) mixed siliciclastic-carbonate marginal marine (intertidal flat, lagoon supratidal sabkha). Lithofacies association I, consists of an overall coarsening upwards offshore through lower shoreface succession. This association is unconformably overlain by lithofacies association II, a thin retrogradational package of mixed siliciclastic and bioclastic tidal inlet channel deposits incising siliciclastic shorefacies sediments. Lithofacies association III is a barred shoreface succession which grades upwards and landwards with lithofacies association IV, mixed siliciclastic-carbonate marginal marine.

The Middle Triassic stratigraphic succession within the Tommy Lakes region comprises at least fourteen parasequences within three third-order depositional sequences (HDI, HDII and CLI). The basal six parasequences consist of a progradational package comprising the highstand systems tract of sequence HDI. Conodonts and ammonoids collected from this interval indicate that this succession was deposited during the uppermost Anisian. The HDI/HDII sequence boundary is characterized by a sharp shift in sedimentary facies from offshore/offshore transition sediments to upper shoreface sandstone and tidal inlet channel fill. Tidal inlet channels characterized the study area during the sequence HDII transgressive systems tract. These channels incise deeply into the underlying sequence in the southeastern corner of the field.

As the sea-level rise decelerated and sedimentation outpaced the creation of accommodation space, back-barrier lagoons were infilled with sediment . The system evolved from a barrier island succession with relatively deep, back-barrier lagoons during transgression, to a low-angle, progradational, barred beach-ridge strandplain succession with abundant minor lagoons and shore proximal lakes during highstand. The upper bounding surface of the sequence HDII highstand systems tract is placed at an erosional unconformity at the base of the "A" Marker Limestone, a thin (2-5m thick) transgressive shoreface deposit characterized by abundant marine body fossils (crinoid and brachiopod detritus) and trace fossils. Althought this unit has not yielded biostratigraphically significant fossils within Tommy Lakes Field, conodonts collected from the outcrop equivalent of this unit at Williston lake indicate uppermost Ladinian deposition. Identification of this unit throughout northeastern British Columbia illustrates its utility as a marker horizon for regional stratigraphic correlation.

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