“The three great essentials to achieve anything worth while are, first, hard work; second, stick-to-itiveness; third, common sense.”

-Thomas Edison

University of Alberta

Sedimentology of the Charlie Lake Formation

by

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For my family:

I would like to thank you for your unending love and support throughout the (many) years of university. Mom and Dad, you can always see the “bigger picture” and it was my conversations with you that allowed me to work through the most difficult and seemingly endless portions of the project. Your generosity throughout my life has given rise to many opportunities that I am so grateful for. I cannot thank you enough for everything you have done for me, but I am truly appreciative. Kirsten and Jarod: thank you for your support and friendship. We have transcended the boundaries of sibling-ship and I am happy to call you two of my dearest friends. Kenton, you are my rock; words cannot express my gratitude for you. I love you all.

Abstract

The Carnian Charlie Lake Formation is a hydrocarbon bearing formation found predominantly in northeastern British Columbia, Canada. Aeolian sand bodies are present in both the subsurface and outcrop occurrences, and in fields like Brassey, are the primary hydrocarbon reservoir. For this study, 2 outcrop occurrences of Charlie Lake Formation in its entirety (Brown Hill and Schooler Creek) and a case study on the Artex member sandstone involving 15 cores from Brassey Field were evaluated. Although non-correlatable, the relationships between the outcrop and subsurface Charlie Lake Formation were assessed and, show similar preservation of the coastal dune bodies, related to deposition in shore-parallel depressions that were initiated as lagoons or lakes. Consequently, it is proposed that preserved aeolian dune thickness is directly related to lagoon / lake depth, which in turn is likely related to local tidal regime.

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My deepest thanks go out to my colleagues that I have had the opportunity to work with and alongside throughout the past few years. I would like to acknowledge and thank the many IRGers who have offered their friendship, advice, and insight including: Jesse, Andrew, Ryan L., Curtis, Ryan K., Edwin, Camillo, Carolyn, Tomonori, Robynn, and Tiffany (just to name just a few!) I have shared great moments with all of you, and I have treasured memories of my time at the U of A. I would also like to extend a sincere thanks to those that came into the field to gather the data for this thesis with me. Greg Baniak, Jenna Phillips, and Luke McHugh, without your tireless efforts, companionship, friendship, and help in and out of the field, I would not have been able to complete this feat. Additionally, Luke your exceptional work and help with the geochemical data has been phenomenal, and I really enjoyed working with you. I extend a very heartfelt thank-you to Jenna Phillips, whose friendship has been particularly special to me throughout this journey. I consider myself very lucky to have met you, and I am not sure that without our morning work outs, coffee breaks, and vent sessions if I would have reached 'the end'. I am glad that we could go through this journey together.

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Thank you.

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LIST OF SYMBOLS AND ABBREVIATIONS

MISCELLANEOUS

BI	Bioturbation Index
PPL	Plane polarized Light
XPL	Cross polarized Light
TCS	Trough cross stratified
HCS	Hummocky cross stratified
ppm	parts per million
mD	millidarcy

CHAPTER I

WCSB	Western Canada Sedimentary Basin
BCOGC	British Columbia Oil and Gas Commission

CHAPTER 2

BCOGC	British Columbia Oil and Gas Commission
MFS	Maximum flooding surface
(FA-1)	Facies Association 1
(FA-2)	Facies Association 2
(FA-3)	Facies Association 3
(FA-4)	Facies Association 4
(FA-5)	Facies Association 5
(FA-6)	Facies Association 6
(FA-7)	Facies Association 7
(FA-8)	Facies Association 8

(FA)	Facies A	(FB)	Facies B
(FBi)	Facies Bi	(FC)	Facies C
(FD)	Facies D	(FE)	Facies E

(FF)	Facies F	(FG)	Facies G
(FH)	Facies H	(FI)	Facies I
(FJ)	Facies J	(FK)	Facies K
(FL)	Facies L	(FM)	Facies M
(FN)	Facies N	(FO)	Facies O
(FP)	Facies P	(FQ)	Facies Q
(FR)	Facies R	(FS)	Facies S
(FT)	Facies T		

CHAPTER 3

BCOGC British Columbia Oil and Gas Commission

(FA-1) Facies Association 1

(FA-2) Facies Association 2

(FA-3) Facies Association 3

(F1)	Facies 1	(F1A)	Facies 1 A
(F2A)	Facies 2A	(F2B)	Facies 2B
(F3)	Facies 3	(F4)	Facies 4
(F5)	Facies 5	(F6)	Facies 6
(F7)	Facies 7	(F8)	Facies 8
(F9)	Facies 9	(F10)	Facies 10

This following thesis is arranged in a paper format. Consequently, some portions of text and concepts are reiterated throughout the subsequent chapters. To facilitate reading of this thesis, a short summary of each chapter is provided below.

CHAPTER 1 – Provides an introduction to the thesis and includes a general history of the Charlie Lake Formation and previous studies. This chapter provides research context for the following chapter(s).

CHAPTER 2 – Presents a facies classification scheme and interpretation for 2 outcrops locations of Charlie Lake strata (Brown Hill and Schooler Creek) and discusses mode of preservation of dune facies.

CHAPTER 3 – Case study on a subsurface member (Artex) of the Charlie Lake Formation. Facies classification and interpretation are discussed.

CHAPTER 4 – Provides a detailed summary and comprehensive discussion of the results and of the main concepts generated and discussed in Chapters 2 and 3.

CHAPTER I - INTRODUCTION

This study focuses on the detailed sedimentology and stratigraphic architecture of the Upper Triassic (Carnian) Charlie Lake Formation in British Columbia, utilizing both subsurface and outcrop data. The first section (Chapter 2) provides an analysis of the Charlie Lake Formation at two atypically well-exposed outcrop successions in the Peace River Foothills area. The distribution of lithofacies and lithofacies associations, including well-sorted sandstone beds interpreted as aeolian dune successions is discussed. The second part (Chapter 3) provides a case study of a hydrocarbon field (Brassey Field) that produces from an aeolian sandstone body (the Artex Member) in the Lower Charlie Lake Formation. This study examines the sedimentologic framework and the economic importance of this unit, and investigates the potential for discovery of other, similar plays.

CHARLIE LAKE FORMATION THICKNESS AND DISTRIBUTION

The Charlie Lake Formation occurs throughout much of the subsurface of northeastern British Columbia as well as in the Peace River embayment area of north central Alberta (Figure 1.1). It is present (in the subsurface) throughout the Peace River plains, as far east as Grand Prairie, and to the west is found in the foothills exposures between the Muskwa and Sukunka Rivers. (Glass, 1990). Surfacially, the Charlie Lake Formation attains a maximum thickness of ~405 metres north of Williston Lake, near the headwaters of Schooler Creek (Glass, 1990; Gibson and Edwards, 1990a).

In the subsurface (Figure 1.2), the Charlie Lake Formation varies from an erosional zero edge on its eastern and northern margins to over 550 m adjacent to the foothills south of the Peace River. The north and eastward thinning of the unit is attributed to both erosive causes (unconformities and later Jurassic erosion), and depositional effects (Gibson and Edwards, 1990 a, b).

CHARLIE LAKE FORMATION STRATIGRAPHY AND LITHOLOGY

Despite the economic importance of the Charlie Lake Formation, the stratigraphic framework and depositional evolution of the Triassic succession

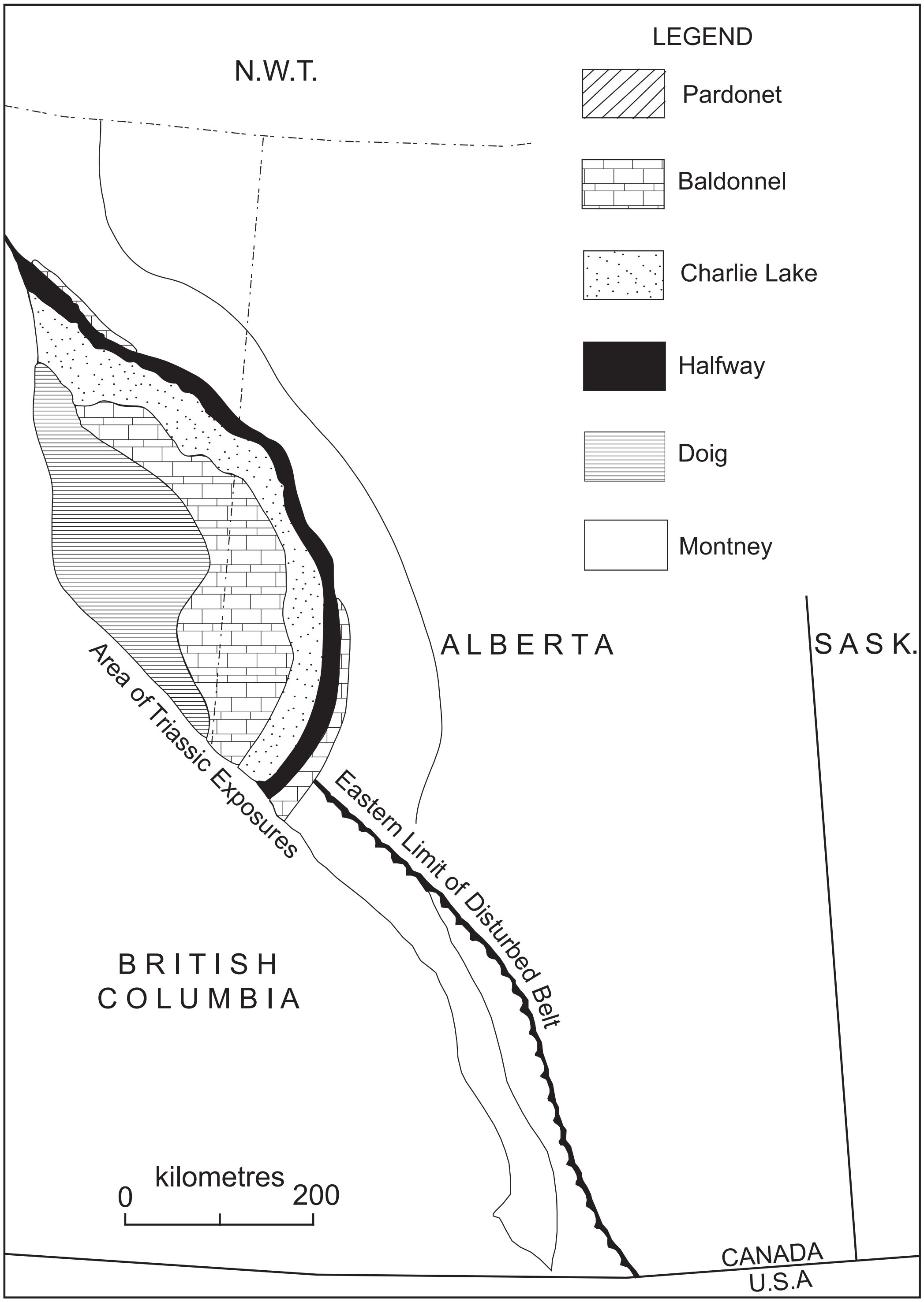


Figure 1.1: The distribution of Triassic strata throughout British Columbia and Alberta. The Charlie Lake Formation is found predominantly in northeastern British Columbia and sub-crops in northwestern Alberta. Modified after Arnold, 1994.

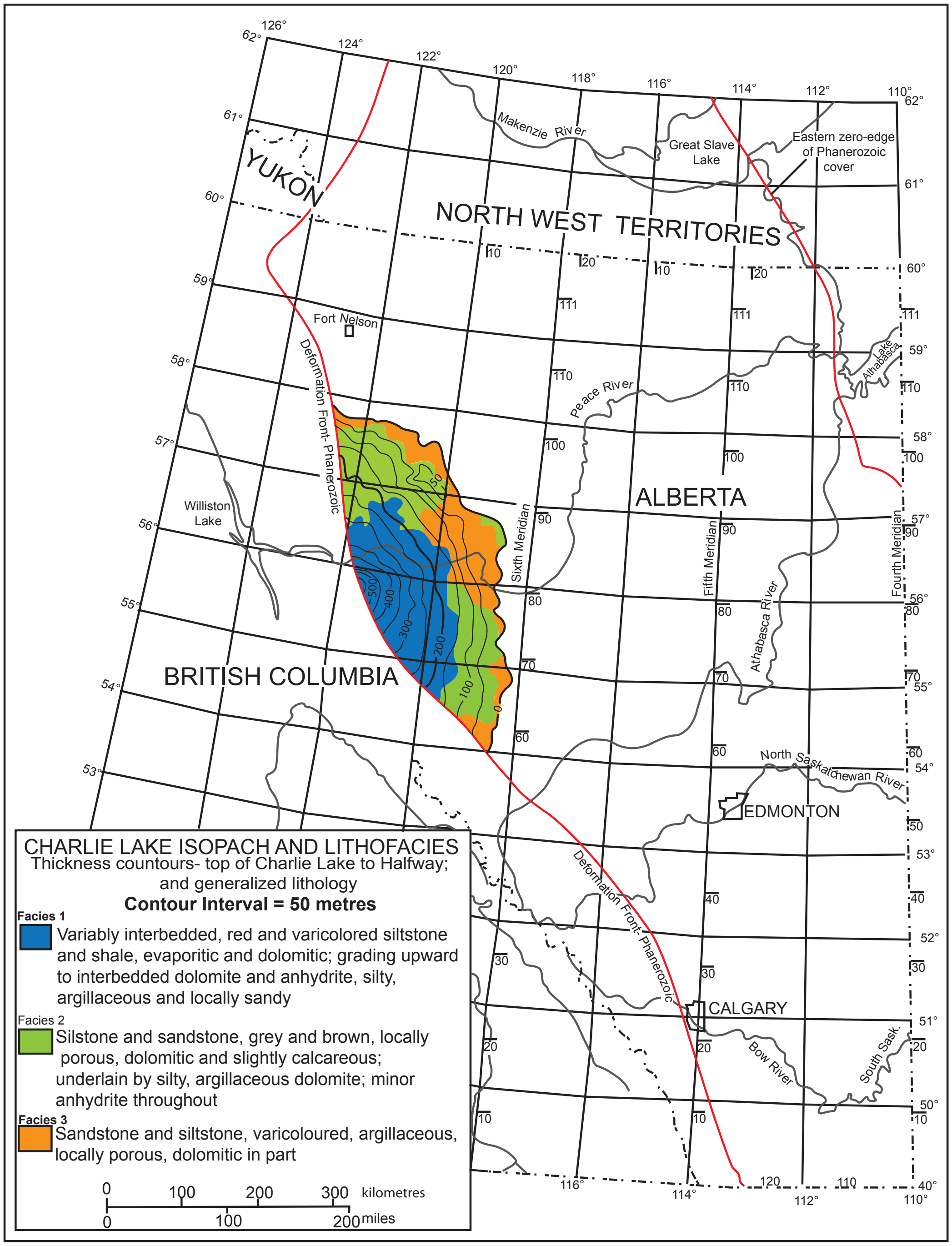


Figure 1.2: Charlie Lake Isopach and generalized lithofacies distribution. In the subsurface, presence of the Charlie Lake Formation varies from zero in the extreme east and north to over 550 m (1804 feet) adjacent to the foothills south of Peace River. The Charlie Lake has been subdived into 3 major lithofacies including. Modified from Edwards et al, 1994.

is among the least well understood of any Paleozoic or Mesozoic interval in western Canada. Upper Triassic strata, particularly the mixed siliciclastic-carbonate-evaporite Charlie Lake Formation, are especially poorly represented in the geological literature. The stratigraphy of the Charlie

Lake Formation is particularly ill understood, due in part to difficulties in interpretation of this inherently complex stratigraphic interval, to its recessive nature (and concomitantly few adequate outcrop exposures) and to the paucity of core through much of this interval. The Charlie Lake Formation itself is geologically unique in the Western Canada Sedimentary Basin (WCSB), comprised of siliciclastic, evaporite, and carbonates rocks, although few thorough studies exist on the entirety of the Charlie Lake Formation. Arnold (1994) provided a framework for future studies, however, details on depositional mechanisms are lacking and, in light of new, as yet unpublished, biostratigraphic and chemostratigraphic data, contains a number of stratigraphic inaccuracies that this thesis hopes to correct. As well, abundant new data have become available in the 15 years since the Arnold study was completed allowing for more detailed and precise depositional models.

The adjoining formations (Figure 1.3) to the Charlie Lake, the older Middle Triassic Halfway Formation, and the subsequently deposited younger Baldonnel Formation, both have distinctive lithologies and contacts with the Charlie Lake Formation, which may be advantageous when attempting to decipher the sequence stratigraphy of the unit. The Halfway has been described as a time-equivalent, locally fossiliferous marine sandstone unit deposited in a general shoreface to foreshore depositional setting, with the transition to the Charlie Lake Formation representing an overall marine to non-marine regression (Caplan and Moslow, 1997, 1999; Willis, 1992; Zonneveld et al, 1997) The general consensus is that contact between the Halfway Formation and the Charlie Lake Formation is conformable (Armitage, 1962; Barclay and Leckie, 1986; Cant, 1986; Gibson and Edwards, 1990b; Arnold, 1994).

The unit overlying the Charlie Lake Formation, the Baldonnel Formation, also conformable, consists of fossiliferous fine to microcrystalline dolomite (Arnold, 1994). The Charlie Lake formation itself is an overall transgressive unit.

Internally, the Coplin unconformity separates the Charlie Lake into ‘upper’ and ‘lower’ units. The majority of the members comprising the Charlie Lake are informal members, with only 3 recognized formal members

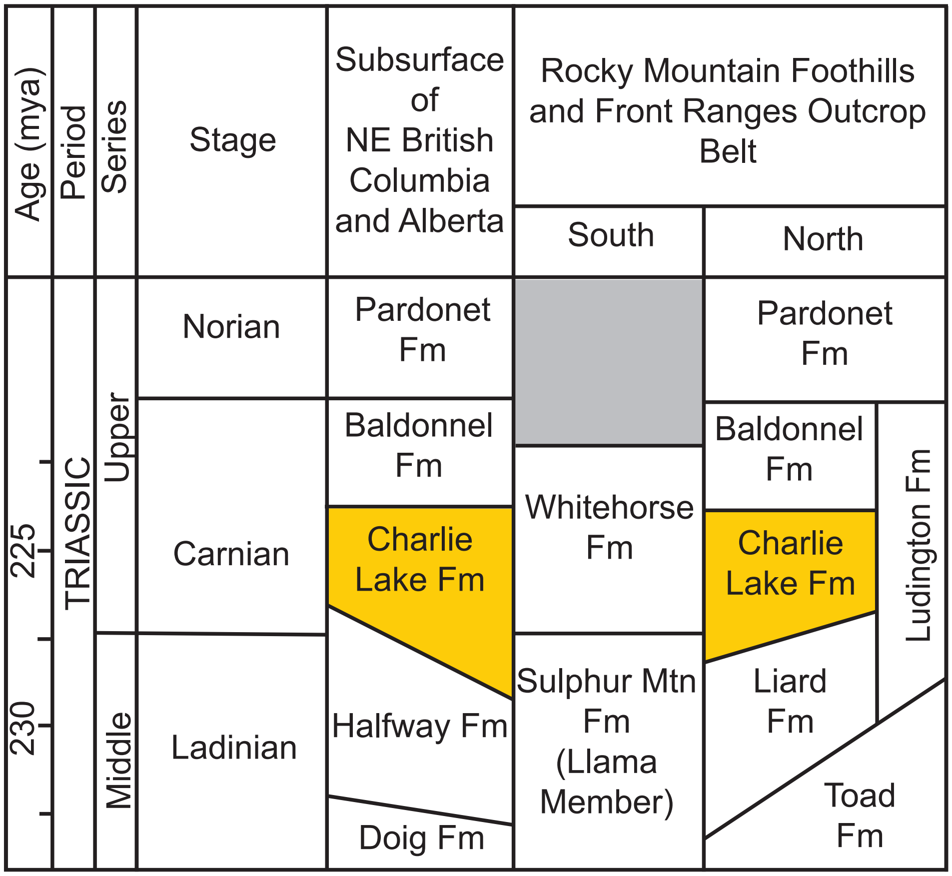


Figure 1.3: Stratigraphic Column showing Middle and Upper Triassic, specifically the Triassic Carnian Charlie Lake Formation and its equivalent units. Modified from Arnold, 1994.

(Inga, Coplin and Boundary). The members that comprise the lower Charlie Lake Formation are, in ascending order: Artex, Cutbank, North Pine, Inga (formal member), Farrell, Blueberry, A Marker, Valhalla, Braeburn. Above the Coplin unconformity there are four formal members which are (ascending): Coplin (formal), Boundary (formal), Nancy, Cecil and Siphon. The Artex, North Pine, Inga, Farrell, Blueberry are known siliciclastic hydrocarbon producers, while the Boundary, Nancy, Cecil and Siphon are carbonate in nature.

Lithologically, the diverse assemblage of generally unfossiliferous mixed siliciclastic, carbonate, and evaporitic rocks of the Charlie Lake have, historically, been interpreted to represent sabhka and/or back barrier depositional environments (Arnold, 1994).

UNCONFORMITIES WITHIN THE CHARLIE LAKE FORMATION

The internally complex stratigraphy, at both the core and outcrop scale, can be attributed in part to the many internal, regionally-extensive unconformities (Gibson and Edwards, 1990 a,b; Davies, 1997; Hess, 1968; Zonneveld et al., 2004). The most significant of these unconformities occur in the Upper Charlie Lake Formation. Of these, the Coplin Unconformity is the most regionally widespread and extensive unconformity in Triassic strata (Figure 1.4). It occurs throughout northeastern British Columbia and western Alberta where, moving eastward, it overlies progressively older Triassic strata (Gibson and Edwards, 1990 a,b; Davies, 1997). Indeed, whilst it cuts through Charlie Lake strata in the west, it erodes through the entire Lower Charlie Lake Formation, the Halfway Formation and into the Doig Formation in the east, indicating erosional removal of 10s to hundreds of metres of section. The angular nature of the unconformity indicates that it is tectonic in origin (Davies, 1997) rather than related to global sea level fluctuations as has been postulated elsewhere (Embry, 1997). Other, more local (less regional) unconformities within the Charlie Lake Formation are the Boundary Unconformity and the Siphon Disconformity. Both of which are occur above the Coplin Unconformity, and eventually merge with the Coplin unconformity at their eastern termini. It has been proposed by Cant (1986) that these smaller unconformities were caused by sea level fluctuations and perhaps local tectonism as opposed to major, regional-scale uplift and erosion. According to Gibson and Edwards (1990a) these unconformities are not observed in outcrop, while Zonneveld et al. (2004) stated that the outcrop equivalence of all of these unconformities remains conjectural in the absence of a regional-scale sequence biostratigraphic framework.

Both the upper and lower contacts of the Charlie Lake Formation have been subject to speculation of erosion. The conformable facies interpretation, where the upper Doig facies is interpreted to be offshore and/or transitional lower shoreface beds, gradationally succeeded by shoreface deposits of the Halfway Formation, in turn overlain by lagoonal to sabkha deposits of the lower Charlie Lake Formation, has been supported by most authors (Barclay and Leckie, 1986; Cant, 1986; Gibson and Barclay, 1989; Caplan and Moslow, 1997, Qi, 1995; Spence and Evoy, 1998.) However, several workers have postulated, based on variations in interpretation of the stratigraphic relationships between the Middle to lowermost Upper Triassic, that the Halfway-Charlie Lake contact comprises a regional unconformity

(Campbell et al., 1989; Dixon, 2005, 2008).

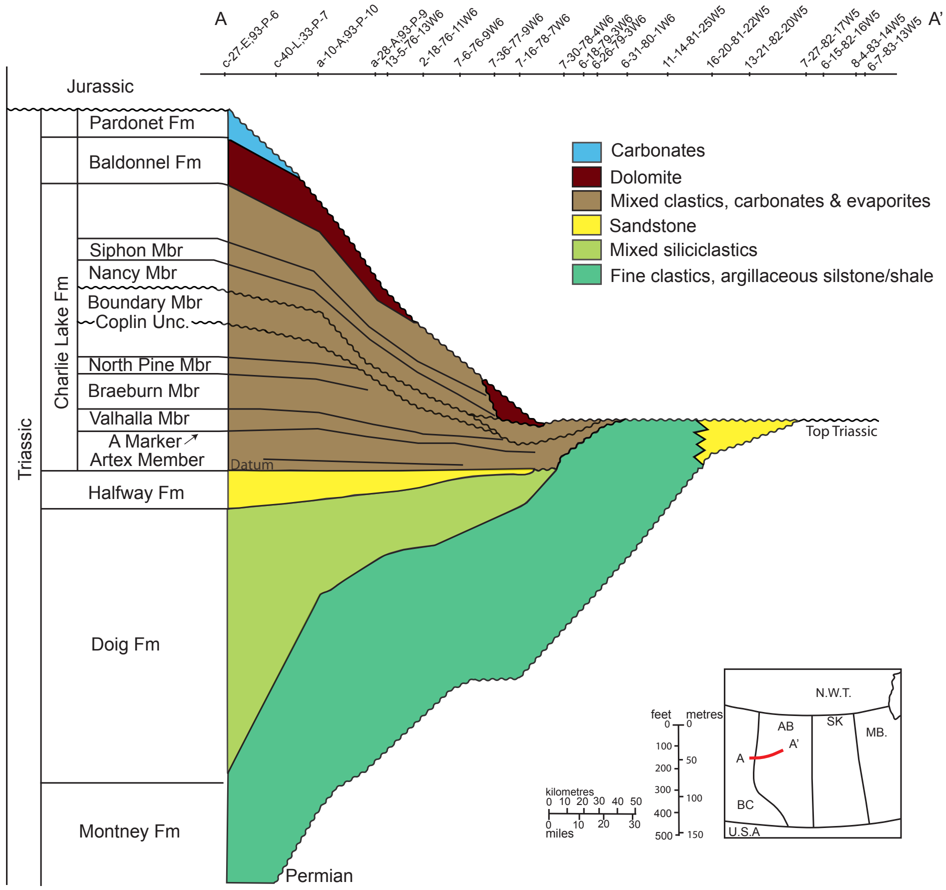


Figure 1.4: Cross section A-A' across the Peace River embayment showing the complex stratigraphic relationships in the Charlie Lake Formation. Two different datum's have been assigned; in the west the top of the Halfway, and in the east the sub-Jurassic unconformity. The figure shows a generalized West to East distribution of Triassic strata, and gives an indication of the special configuration of some of the members in the Charlie Lake Formation as well as the Coplin Unconformity. Modified from Edwards et al, 1994.

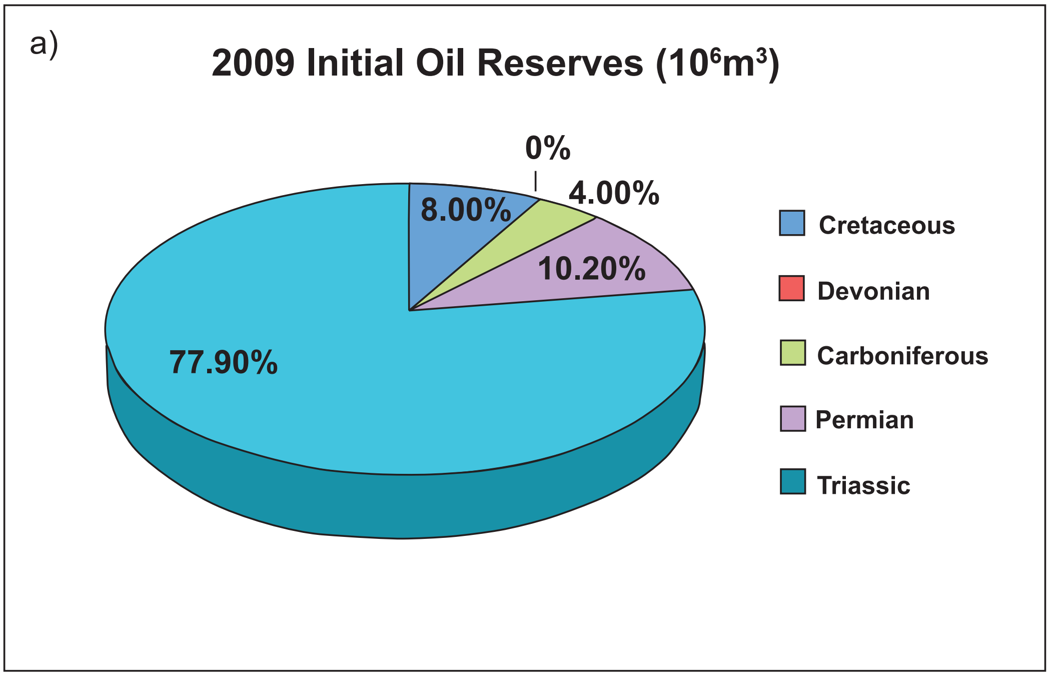
IMPORTANCE OF THE CHARLIE LAKE FORMATION

The Charlie Lake Formation serves as an interesting and relevant topic of research for several reasons. Firstly the Charlie Lake is of significant geologic importance as it represents and records a unique time in the Earth's history where globally arid conditions resulted in an atypical depositional system consisting of mixed siliciclastic and carbonate rocks (Zonneveld et al, 2001; Chumakov and Zharkov, 2003). Detailed stratigraphic analyses of the Charlie Lake Formation are essential to better determine regional paleogeography during the Triassic and to help constrain the timing of tectonic / orogenic events. Second, the Charlie Lake has been identified an important hydrocarbon reservoir in British Columbia, hosting hydrocarbons in both clastic and carbonate reservoir types.

Triassic strata have long been identified as " the most important geological interval for hydrocarbon production in British Columbia," (Janicki, 2008). Currently, Triassic oil production accounts for approximately 4.1% of total production in the Alberta portion of the WCSB (AGS, 2008), while Triassic potential accounts for at least 4.5% of total oil and gas reserves for the Alberta portion of the WCSB (AGS, 2008). The hydrocarbon production and potential of strata in British Columbia alone, (Figure 1.5, A & B), is staggering. According to the British Columbia Oil and Gas Commission's (BCOGC) most recent reports (2010), there is a total of about 131.2 million cubic metres of initial oil reserves in British Columbia and of these, Triassic strata comprises approximately 77.9% of the total. As of December 31st, 2009, initial raw gas reserves in British Columbia, show a total of 1412.0 billion cubic metres of gas (BCOGC, 2010). Triassic Strata makes up approximately 46.6% of the initial raw gas reserves (BCOGC, 2010).

A by-formation breakdown of the initial recoverable oil and raw gas reserves in Triassic Strata in British Columbia (Figure 1.6, A & B) shows that the Charlie Lake Formation houses a substantial amount of hydrocarbons. Of a total of approximately 102.167 million cubic metres of initial recoverable oil reserves in Triassic strata in British Columbia, the Charlie Lake Formation comprises more than any other Triassic formation, with approximately 57.157 million cubic metres of initial recoverable oil reserves (BCOGC, 2010). In regards to the initial recoverable initial raw gas reserves, a total of 658.047 billion cubic metres of initial recoverable initial raw gas reserves exists in Triassic Strata, with the Baldonnel Formation housing the majority with approximately 225 billion cubic metres (BCOGC, 2010). The Charlie Lake has the second most with approximately 34 billion cubic metres of initial raw gas reserves (BCOGC, 2010). In addition to housing substantial amounts of hydrocarbons, the Charlie Lake formation, specifically the evaporates, serve as an important lower seal to the overlying Pardonet and Baldonnel reservoirs (Barss and Montandon, 1981).

The Charlie Lake Formation contains some of the only known hydrocarbon producing aeolian reservoirs in western Canada, yet, apart from



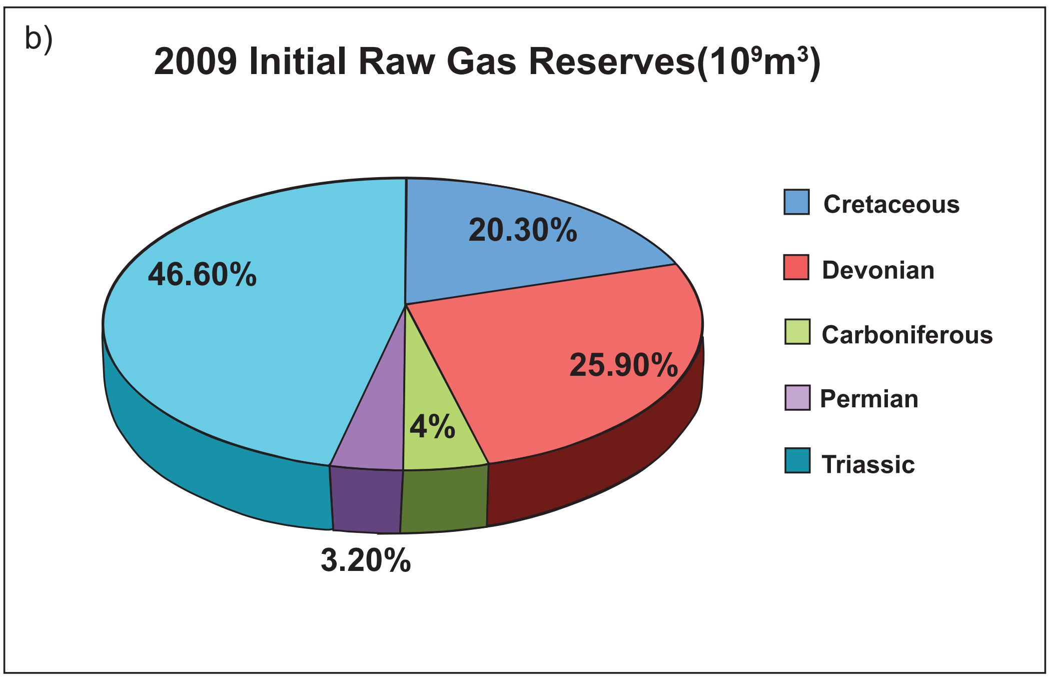


Figure 1.5: Initial Reserves in British Columbia, Canada by Geological Period

a) Pie chart showing the initial oil reserves as of December 31st, 2009 in British Columbia. There is a total of 131.2 million cubic metres, and Triassic strata comprises approximately 77.9% of the initial oil reserves, BCOGC, 2010.

b) Pie chart showing the initial raw gas reserves as of December 31st, 2009 in British Columbia. There is a total of 1412.0 billion cubic metres. Triassic Strata makes up approximately 46.6% of the initial raw gas reserves, BCOGC, 2010.

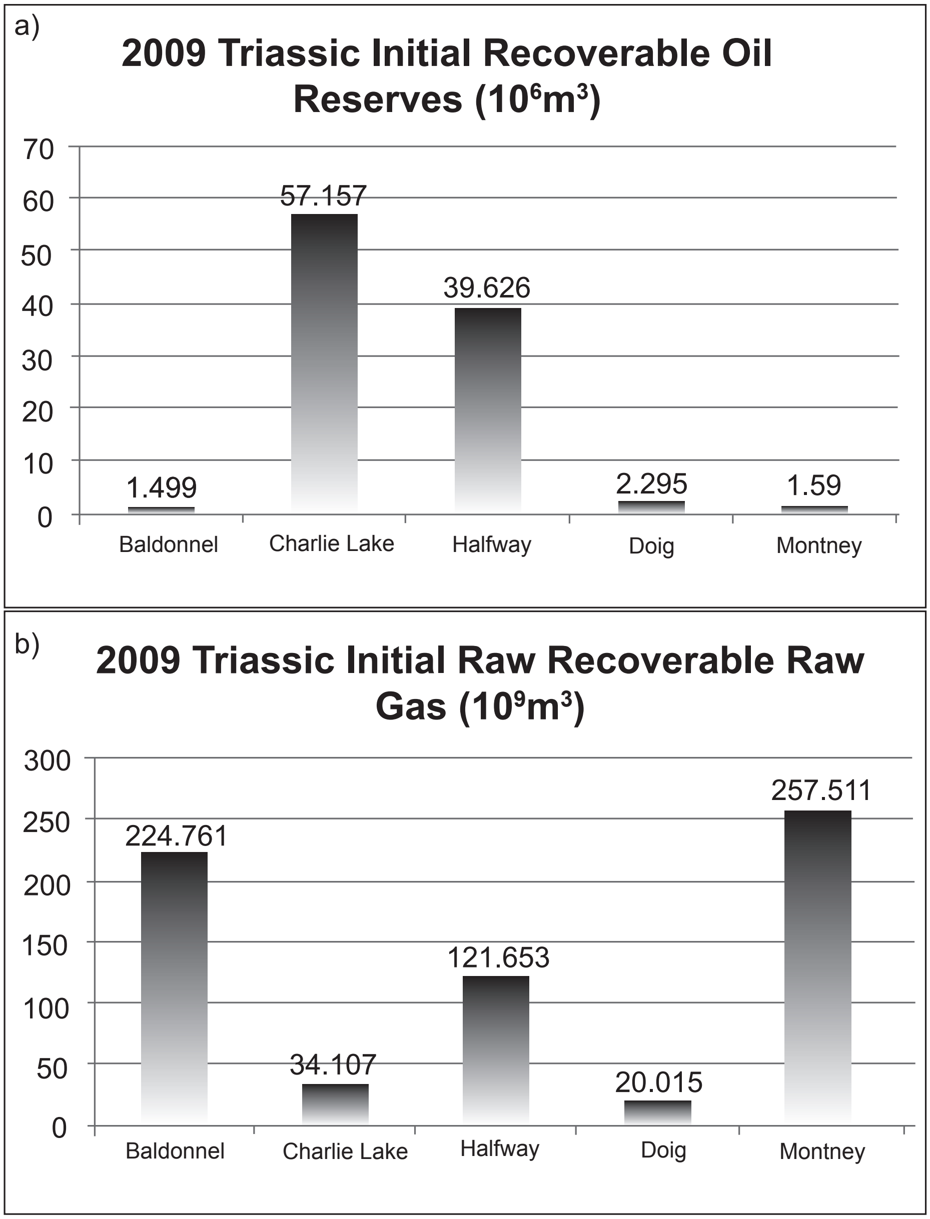


Figure 1.6: Initial Recoverable Oil and Raw Gas Reserves in Triassic Strata in British Columbia, Canada

a) Histogram showing the 2009 Triassic initial recoverable oil reserves in 106m3 subdivided by formation. There are a total of 102.167 million cubic metres of initial recoverable oil reserves in Triassic strata in British Columbia. Of this, the Charlie Lake Formation has the most, with approximately 57.157 million cubic metres of initial recoverable oil reserves, BCOGC, 2010.

b) Histogram showing the 2009 Triassic initial recoverable initial raw gas reserves as of December 31st, 2009 in British Columbia. The figures reported are in 109m3 and subdivided by formation. There are a total of 658.047 billion cubic metres of initial recoverable initial raw gas reserves in Triassic Strata. The Baldonnel Formation houses the majority, with approximately 225 billion cubic metres. The Charlie Lake has the second most with approximately 34 billion cubic metres of initial raw gas reserves, BCOGC, 2010.

some petrophysical and engineering aspects the attributes (i.e. stratigraphy, sedimentology, whole rock geochemistry) of these strata in most areas remain largely undescribed. This research on the Charlie Lake formation will provide a geologic model of how the economic hydrocarbon potential of these reservoirs may be exploited, and will provide valuable information on the preservation constraints and predictability of dune structures, of which little research exists.

This thesis provides new analyses into the sedimentology, stratigraphy and geochemistry of the Charlie Lake Formation. It includes the first detailed analysis of the sand bodies of the Charlie Lake Formation and thus has potential applications and relevance in other arid coastal depositional systems areas worldwide. This project provides the first detailed integrated sedimentologic / stratigraphic model on the occurrence of aeolian sandstone bodies in the Charlie Lake Formation and will facilitate new discoveries in this interval.

HISTORY AND PREVIOUS WORK

The history and nomenclature of the Charlie Lake Formation was summarized by Arnold (1994). Triassic strata in western Canada were first identified by Selwyn (1877) during the 1872 expedition by the Geologic Survey of Canada to the Peace River Foothills foothills. Although Dawson (1881) and McConnell (1891) conducted reconnaissance scale analyses in the area, Triassic strata were not analyzed in detail until McLearn's field work in 1917-1920 (McLearn, 1940, 1953; McLearn and Kindle, 1950). McLearn and his successors established the stratigraphic and biostratigraphic nomenclature as it currently stands in northeastern British Columbia (i.e. Warren, 1945; McLearn, 1953; McLearn and Kindle, 1950; Hunt and Ratcliffe, 1959; Pelletier, 1960; Tozer, 1961, 1981; Siberling and Tozer, 1968; Barss et al., 1964; McAdam, 1979; Stewart, 1984; Gibson and Barclay, 1989; Gibson and Edwards, 1990a,b;).

The name 'Charlie Lake' was first applied to the study interval, by L.M. Clark in May of 1954, during an address to the Canadian Institute of Mining and Metallurgy (Arnold, 1994). He suggested that because of the close proximity to the town of Charlie Lake, the evaporitic rocks of the Upper Triassic in the Fort St. John area of British Columbia be assigned the name

‘Charlie Lake’.

In further studies by Hunt and Ratcliffe in 1959, in addition to formally proposing the name ‘Charlie Lake Formation’ and designating a type section (Pacific Fort St. John well No.16 in 2-18-84-19 W 6th Meridian) an attempt was made to correlate Triassic outcrop sections in the Rocky mountains to subsurface strata (Glass, 1990). Additionally, Hunt and Ratcliffe further subdivided the Triassic into (ascending) the Toad, Grayling, Halfway, Charlie Lake, Baldonnel and Pardonet Formations (Arnold, 1994). This study also outlined other stratigraphic implications for the Charlie Lake Formation, including the assignment of the Halfway, Charlie Lake, Baldonnel and Pardonet Formations into the Schooler Creek Group, and interpreted the contacts of the Charlie Lake as being conformable (Hunt and Ratcliffe, 1959).

The Montney and Doig Formation assignments are a product of Armitage’s 1962 study in which the two new formations replaced the Grayling and Toad (respectively) in the subsurface. Armitage (1962) noted the occurrence of hydrocarbon production from thin sandstones, encased in carbonate rocks, within the Charlie Lake formation. He identified and proposed the Boundary Lake Member as the first official member of the Charlie Lake Formation. He described the Boundary Member as being composed of skeletal limestone and deposited in a local zone of subsidence possibly caused by the reactivation of Paleozoic faults. Subsequent studies by Barss et al. (1964) interpreted the evaporitic portion of the Charlie Lake Formation as being deposited in a shallow, lagoonal sea.

The first observations of the sedimentary structures of sandstones within the mixed evaporitic-carbonate- siliciclastic Charlie Lake Formation were made by Pelletier in 1965. After observing the cross-bedded nature of the sands, Pelletier interpreted the sands as offshore sandbars (Pelletier, 1965). Additionally, by observing the directional trends of the crossbeds and the progressive fining of sediment, he inferred a sediment transport direction to the southwest (Pelletier, 1965). Two years later, sparked by the discovery of the Inga Oil field in 1966, Fitzgerald and Peterson conducted a preliminary study on the Inga oil field in which the Inga and Upper Coplin sand bodies were recognized as formal stratigraphic members in the Charlie Lake Formation (Fitzgerald and Peterson, 1967). Once again the sands were deemed to be of marine origin, although no sedimentological data was given for this reasoning.

Another, more thorough study was conducted on the subsurface Charlie Lake by Roy in 1972. Again, this study focused on the hydrocarbon bearing Boundary Lake Member. Roy described the Boundary member as a "cyclic stromatolite-pelmicrite-micrite complex" and presented some preliminary interpretations regarding configuration of the limestone that overlies an anhydritic package and is overlain by silt. The lateral facies relationships were interpreted to have been deposited in an environment in which the anhydrite was deposited within a large standing water body, with possible subaerial exposure, capped by intertital/lagoonal carbonates, and the siltstones as coastal plain tidal flats or sabhka deposits (Roy, 1972). Also of note, Roy observed a rippled, heterolithic sandstone body 2 -5 ft in thickness, which he used as a datum, with distinctive grain frosting. No interpretation or conclusions were made on the origin(s) of the frosted grains. Stratigraphically, Roy observed that the Boundary Member appeared to be preserved in a paleostructural low.

The discovery of the Brassey oil pool in 1987 by Canadian Hunter Exploration sparked renewed interest in the Charlie Lake Formation, particularly in the hydrocarbon bearing zone- one of the sandy bodies in the Charlie Lake Formation, informally coined the Artex member (Stewart, 1984). A series of studies on the Artex member followed in the next several years (Klein and Woofter, 1989; Higgs, 1990; Woofter and MacGillvray, 1990), building evidence for the aeolian interpretation for the productive sand body. Gibson and Barclay (1989) also suggest the aeolian deposition and shorefaces sands as a possible interpretation for their observations. The Artex continues to be an area of interest for current research (Fefchak and Zonneveld, 2010). The most thorough analysis of the Charlie Lake Formation to date is an unpublished M.Sc. thesis (Arnold, 1994), which provides a mixed outcrop-subsurface study on strata in northeastern British Columbia. Arnold (1994) reiterated the aeolian interpretations of previous studies for some of the sands in Charlie Lake for both the Brown Hill outcrop and subsurface Inga field. Arnold proposed that the aeolian dunes observed in Charlie Lake strata could be compared to the modern coastal ergs of the Namibian desert. Arnold (1994) also suggested correlation between the interpreted aeolian sands at

Brown Hill and the lower interpreted aeolian sands observed in subsurface Charlie Lake. However, it has been noted that members of the Charlie Lake Formation have not/can not be recognized in outcrop with any degree of confidence (Glass, 1990).

This study focuses on the Upper Triassic (Carnian) Charlie Lake Formation in British Columbia (Canada), and is distinguished from earlier studies by its incorporation of extensive sampling, detailed photography, outcrop gamma spectrometry, thin-section analyses, geochemical analysies and detailed sedimentological analysis of two outcrop sections (which span the entirety of the Charlie Lake Formation) as discussed in Chapter 2, and a case study, focused on the lower Charlie Lake Formation Artex Member, as presented in Chapter 3. Additionally, the Schooler Creek section, discussed in Chapter 2, is a previously undescribed outcrop of Charlie Lake Formation. Prior studies have focused on the regional extent and stratigraphy of Charlie Lake Formation sandstone bodies and the relationship of the Charlie Lake Formation to underlying strata (Higgs, 1990; Young, 1997; Dixon, 2007) however detailed sedimentary descriptions have not been provided. This thesis aims to remediate this by establishing consistent facies descriptions and interpretations for the Charlie Lake Formation both in outcrop and core. Furthermore, the relationships between the occurring facies in subsurface and outcrop were observed and discussed.

The Charlie Lake Formation stratum observed in this study are interpreted to represent deposition in an arid, coastal mixed carbonate-silciliclastic regime. Aeolian coastal dune deposits are present in both outcrop and subsurface. The interpretation of both the outcrop and subsurface stratum indicate that coastal dune preservation is related to deposition in shore-parallel depressions that were initiated as lagoons or lakes. These aeolian units are subsequently overlain by intertidal and other continental deposits. Thus it is proposed that preserved aeolian dune thickness is directly related to lagoon/lake depth, which in turn is likely related to local tidal regime. These conclusions serve to improve the understanding of the occurrence and mode of preservation of coastal dune deposits, Triassic (Carnian) deposition in general, and the stratigraphic and sedimentological relationships related to these conclusions.

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CHAPTER II – SEDIMENTOLOGY OF THE CHARLIE LAKE FORMATION

Abstract

It is estimated that the Carnian aged Charlie Lake Formation houses 57.157 million cubic metres of initial recoverable oil reserves (BCOGC, 2010). Much of the productive Charlie Lake oil occurs in cyclically occurring aeolian sand bodies that are encased in intertidal and supratidal deposits. Outcropping Charlie Lake strata in North Eastern British Columbia, also displays regularly occurring aeolian sand bodies. Although the sand bodies are believed to not directly correlate to those in the subsurface, nonetheless they too have a repetitive and cyclic nature and partial predictability that may serve useful in subsurface studies.

The interpreted depositional environments of the two outcrops observed in this study (Charlie Lake Formation outcrops at Brown Hill and Schooler Creek) are indicative of an arid mixed carbonate siliciclastic system. 21 distinctive facies and 7 facies associations have been identified. Relationships between the facies associations, specifically presence and placement of dolomitized lacustrine and ephemeral sediments, are similar to those observed in the Coorong region of Australia. A series of 13 "cycles" occur in the Brown Hill section, with 7 aeolian sands. The increased thickening of the deposits at Schooler Creek in addition to the presence of fully marine strata within the Charlie Lake Formation signals the mostly westward occurrence of Charlie Lake strata, and is interpreted to represent the depositional margin.

Introduction

The Middle–Upper Triassic (Late Ladinian to Carnian) Charlie Lake Formation occurs most extensively in northeastern British Columbia. It is a lithologically diverse succession of primarily unfossiliferous mixed siliciclastic, carbonaceous, and evaporitic rocks. Historically, these rocks have been interpreted to represent a sabhka or back-barrier depositional environment (Arnold, 1994; Higgs, 1990). Adjacent formations (Figure 2.1) consist of the older (underlying) Middle Triassic (Ladinian) Liard Formation (outcrop equivalent of the subsurface Halfway Formation), and the younger (overlying) Upper Triassic (Carnian) Baldonnel Formation. These units are composed of rock types that are lithologically distinct from the Charlie Lake Formation and thus formation contacts are easily distinguished in the subsurface using drillcore and petrophysical logs.

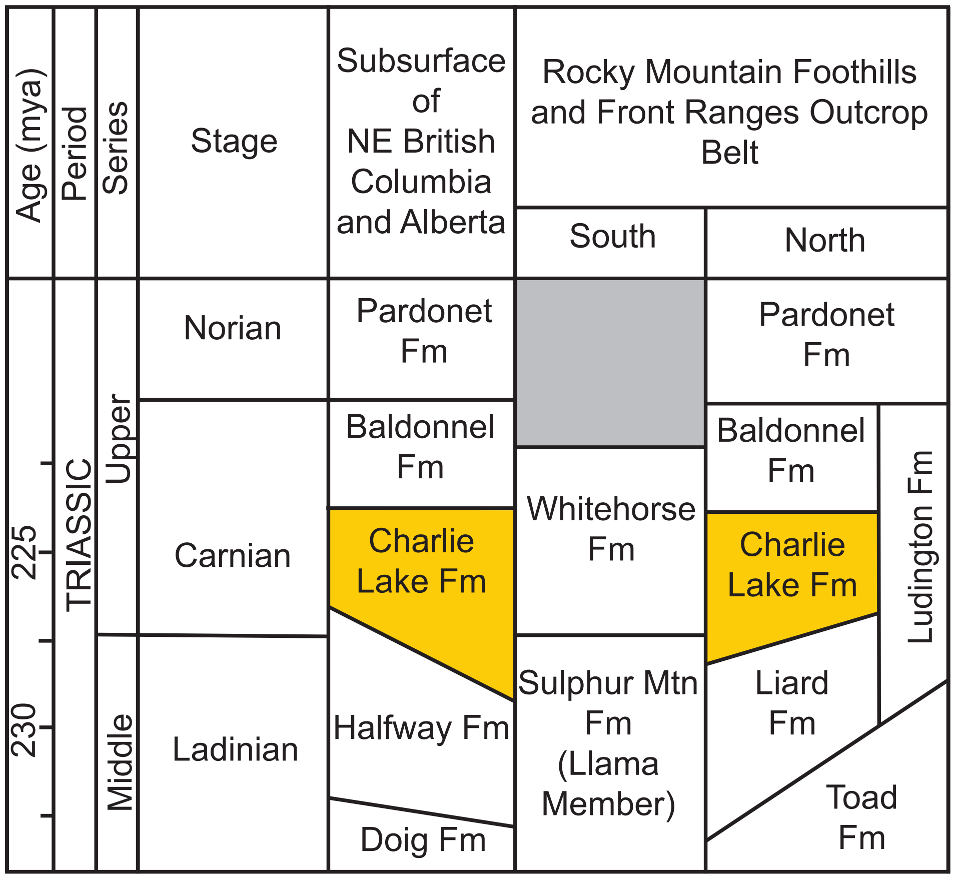

Figure 1.2: Stratigraphic Column showing Middle and Upper Triassic, specifically the Triassic Carnian Charlie Lake Formation and its equivalent units. Modified from Arnold, 1994.

The Charlie Lake Formation and the Liard Formation (Halfway Formation in subsurface) are lateral, temporal equivalents (Arnold, 1994; Caplan and Moslow, 1997; Zonneveld et al., 1997; 2001). The Liard and Halfway formations are locally fossiliferous marine sandstone and limestone successions that were deposited in shallow marine / shoreface environments (Gibson, 1971; Gibson and Edwards, 1990). Consequently, the transition between the Halfway / Liard and Charlie Lake formations within any one area represents a marine-nonmarine regression. This transition is gradational in many parts of the basin, but sharp and unconformable in other areas (Caplan and Moslow, 1997; Willis and Wittenberg, 2000; Dixon, 2008; Zonneveld., 2008). In the study area, the Liard-Charlie Lake contact is clearly conformable

(Arnold, 1994; Zonneveld et al., 2001; Zonneveld, 2008).

The overlying Charlie Lake–Baldonnel Formation contact consists of an abrupt shift to fossiliferous limestone and dolomite (Zonneveld and Orchard, 2002; Zonneveld et al., 2004). This contact is both gradational and conformable in many parts of the basin but is demarcated by an abrupt erosional surface in others (Davies, 1997a; Zonneveld and Orchard, 2002; Zonneveld et al., 2004).

These formations are inferred to represent a temporally equivalent succession that records a initial westward progradation of a dominantly clastic shallow shelf succession (Doig / Lower Liard formations) laterally adjacent to a barrier island / tidal inlet succession (Halfway / Upper Liard Formations), capped by the sabkhas, hypersaline lagoons, subaerial dunes, tidal flats, and playas of the Charlie Lake Formation (Gibson and Edwards, 1990; Caplan and Moslow, 1997; 1999; Zonneveld et al., 1997; 2001). This Middle Triassic (Anisian-Ladinian) progradational succession is overlain by an Upper Triassic (Carnian) retrogradational succession in which the marginal marine and continental strata of the Charlie Lake Formation segue upwards and westwards into the shallow carbonate shelf deposits of the Baldonnel Formation (Zonneveld et al., 2004).

Triassic strata account for approximately 40% of oil reserves in British Columbia, making this unit both of economic and academic interest (BCOGC, 2001). Although exploration interest has focused on conventional plays such as the Halfway Formation sandstone or Baldonnel Formation carbonates and unconventional plays in the Doig and Montney siltstone successions, considerable reserves occur within the Charlie Lake Formation as well. These include dolomitic-siltstone hosted reservoirs in the medial Charlie Lake Formation and several sand-dominated, members in the lower Charlie Lake Formation (e.g., the Siphon, Blueberry and Artex members). Despite the economic importance of this interval it has received minimal attention in the published literature. Although partially addressed in one unpublished thesis (Arnold, 1994), detailed facies descriptions and assessments of facies associations remains lacking. One problem is that core datasets are sparse, limited primarily to horizons of economic interest with most of the formation represented by minimal or no core coverage. Excellent outcrop exposures occur in several places in the Rocky Mountain Foothills and Front Ranges (Zonneveld, 2008). For this study, the outcrop were described with the intent of developing detailed depositional models for the Charlie Lake succession that will provide the basis for future comparison with equivalent successions in the subsurface to the east

Geologic Setting

Deposition of Middle to Late Triassic sediments in the Western Canada Sedimentary basin occurred along a westward facing continental shelf on the margin of the topographically low North American craton (Davies, 1997a). Sediments accumulated in a westward-thickening wedge in along the northwestern margin of the supercontinent Pangaea on the coast of the Panthalassa Sea / proto-Pacific ocean (Gibson and Barclay, 1989; Davies, 1997a).

The outcrop locations for this study are located in the Williston Lake area of British Columbia, Canada. Paleographically, this is situated immediately north of the Peace River embayment, a major tectonic downwarp initiated by the collapse of the Paleozoic Peace River Arch (Zonneveld et al, 2001). The role tectonism played during Triassic deposition is still under debate; however, abrupt changes in stratal thicknesses and the presense of several thick convolute bedded intervals in Middle and Upper Triassic strata suggest that tectonic influences were at times significant. It is estimated that the latitude at time of deposition was around 32°-34° (Habicht, 1979; Irving et al, 1985). Paleocurrent measurements of aeolian sandstone beds indicate a dominant northeast to southwest oriented wind direction (Pelletier, 1965; Arnold, 1994). Extensive evaporite deposits, usually observed in drill core, suggests that arid conditions were prevalent during deposition of the Charlie Lake Formation (Gibson and Barclay, 1989; Zonneveld et al., 1997).

Study area

This paper focuses on sedimentological description and interpretation of several Charlie Lake Formation outcrops in the Peace River Foothills area of northeastern British Columbia. In the Summer and Fall of 2009, two main outcrop locations (Brown Hill and Schooler Creek, respectively) were assessed (Figure 2.2). Although the Charlie Lake Formation is typically a recessive interval, these two sites exhibit continuous or nearly continuous outcrop exposure through the study interval. The Brown Hill section occurs on the north shore of the Peace Reach of Williston Lake (Figure 2.3). This site is scoured by wave action during annual inundation below the waters of Williston Lake. The Schooler Creek section is a cliff section at the headwaters of Schooler Creek with near continuous exposure. Although augmentary data were obtained from other localities along the lake, these two sites comprise the best known exposure of the Charlie Lake Formation and thus, this paper focuses on these sites. These outcrop locations were selected on the basis of quality of outcrop exposure, and ease of access to the Charlie Lake Formation. Additionally, the outcrops are relevant to and provide additional context to previous and ongoing studies and current research by Zonneveld and his graduate students.

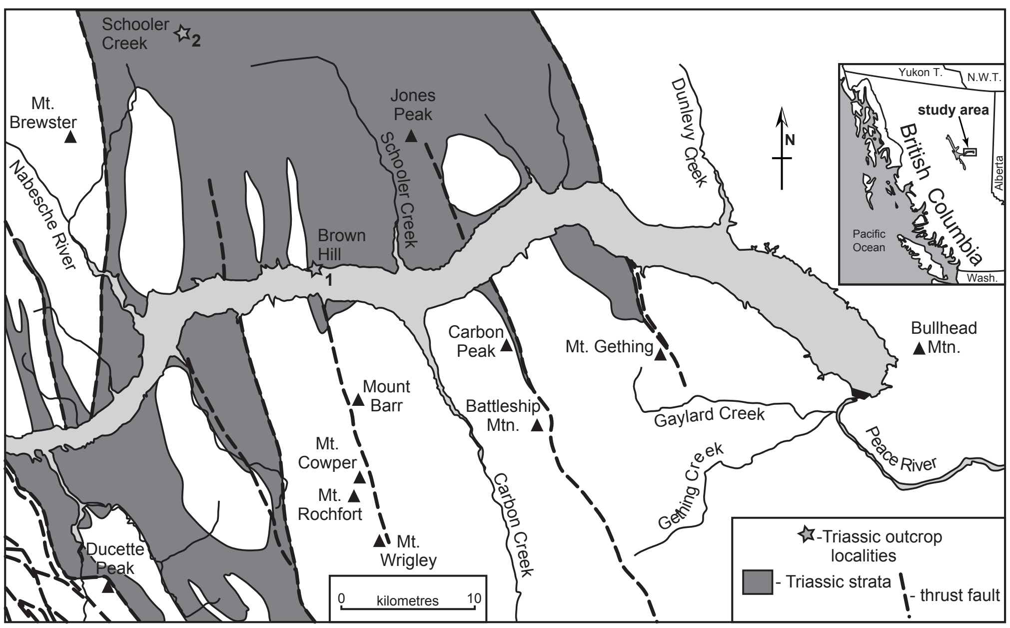

Figure 2.2: Location of outcrop (#1- Brown Hill; #2- Schooler Creek) in British Columbia. Modified from Zonneveld, 2008

The Brown Hill outcrop is the designated surface reference location for the Charlie Lake Formation and occurs at NTS 11-E/ 94-B-2 (56.11404 °N 122.81905°W (Colquhoun, 1962, Glass, 1990). The W.A.C. Bennett Dam, constructed in 1967, provides hydroelectric power to the Peace district and the province of British Columbia. Although earlier observations of the Brown

Hill outcrop have been made (McLearn, 1953) at that time, portions of the outcrop were permanently submerged beneath the lake. Since construction of the W.A.C. Bennett Dam, more extensive exposure was created higher on the hill and these portions of outcrop are part of the focus of this paper. Access to this locale is by boat, and fieldwork is most effective in early Spring when water levels are at their lowest levels, providing maximum outcrop exposure. The annual variation in Williston water levels (the result of controlled water release at the dam) is advantageous as it keeps outcrops fresh and free of talus and vegetation. The Charlie Lake Formation at Brown Hill is a continuous, nearly undeformed section with a total thickness of 103m of strata, and stratigraphic dip of about 72° to the SSE with a strike of 170° (consistent with Arnold, 1994). Lateral exposure of this outcrop section is ~ 20 metres (depending on water depth) and is bounded by the waters of Williston Lake and the tree line. The contact of the Charlie Lake with the Middle to Upper Triassic Liard Formation occurs within a ~20 metre covered interval, however the contact with the overlying Baldonnel formation is well exposed.

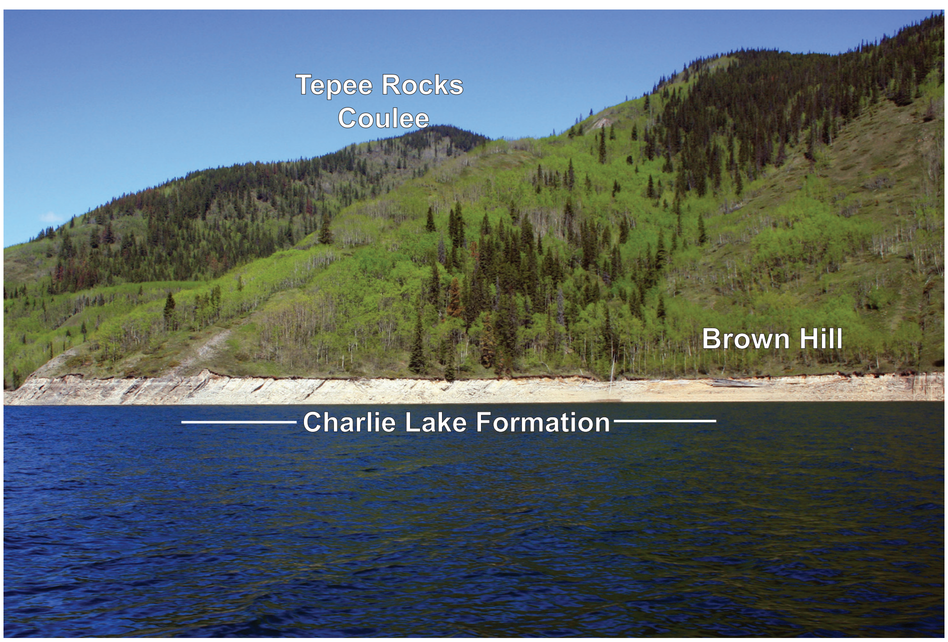

Figure 2.3: Brown Hill outcrop section. Photo Credit: J.P. Zonneveld

The second outcrop section (Figure 2.4) in the study is an unnamed peak, approximately 22 km northwest of Brown Hill at NTS 11-E/ 94-B-6 (56°16'22.79"N 123° 0'33.50"W) and near the headwaters of Schooler Creek.

The section is a steep, east-facing cliff forming unit of outcrop that features a steep exposure of late Middle and Upper Triassic units. The treacherous (falling rocks) and steep nature of the outcrop provided some limitations in data recovery, resulting in limited lateral assessment. 3 sections were measured and combined to create the Schooler Creek strip log, found in the appendix. Although, the exposed rocks are extensively weathered and vegetation-covered in areas, the outcrop provides nearly a kilometer of lateral section exposure, and with proper equipment advanced, data recovery may be possible. The described section was measured 94 meters up from the base of the Charlie Lake Formation. The lower contact with the underlying Liard formation is talus covered. The top contact with the Baldonnel Formation was not reached, and it is estimated from photos that 94m is approximately one third to half the thickness of the Charlie Lake Formation at this locality. The strata dip at approximately 43° to the SSW, with a strike of approximately 133°.

Figure 2.4: Schooler Creek outcrop section showing exposed Liard, Charlie Lake, and Baldonnel Formations. The Liard/Charlie Lake contact is covered. Photo Credit: Filippo Ferri.

PREVIOUS WORK

Previous studies focused primarily on stratigraphic observations of the Brown Hill outcrop (Colquhoun, 1962; Arnold, 1994; Zonneveld et al., 2004). Arnold (1994) focused on the sandstone intervals and confirmed the interpretation that these are primarily aeolian dune successions. At Brown

Hill after observing two distinct sets of aeolian cross beds, Arnold interpreted the stratigraphically lower (and thinner) occurring cross-bedded sand bodies as being obliquely migrating crescentic (barchan) dune forms. The observation of stratigraphically higher (and commonly distinctively thicker) occurring aeolian bodies, were interpreted as obliquely-oriented transverse dune forms (Arnold, 1994). Arnold further proposed that the aeolian dunes observed in Charlie Lake strata are comparable to the modern coastal ergs of the Namibian desert (Arnold, 1994). More recent descriptions, supplement Arnold's observations and summarize the Charlie Lake outcrop at Brown Hill as a "combination of grey to yellow dolomitic to calcareous sandstone, siltstone, and sandy limestone or dolostone"(Zonneveld et al., 2004). Subordinate amounts of cyanobacterially-laminated dolostone and evaporite deposits are also observed to be present. In outcrop, evaporitic beds are not observed, likely due to a combination of early post-depositional dissolution as well as to their recessive nature in the rare instances in which they experienced long-term preservation. The occurrence of variably thick solution collapse breccia beds is interpreted to reflect early post-depositional dissolution of evaporite deposits (Zonneveld et al., 2004). In subsurface, the Charlie Lake Formation has been subdivided into numerous members (Glass, 1990). Although Arnold (1994) correlated many of these with outcrop units at Brown Hill, this was done largely on the basis of wireline log correlations. These correlations are herein considered suspect. The Charlie Lake Formation is a highly diachronous unit and these members cannot be recognized in outcrop with any degree of confidence.

Based on comparison with locality information in Gibson's 1971 study of Triassic Stratigraphy in the Sikanni Chief River- Pine Pass region, the second section discussed herein is identical to, or is similiar to, the "Schooler Creek" measured section discussed in that study. Gibson (1971) indicated that this is the thickest Charlie Lake outcrop known, having a reported estimated thickness of ~405m. Based on the measurements made in this study of the outcrop, the thickness of the formation appears to be much less thin (between 200-300m thick). Lack of precision is due to the inaccessible nature of the steeper portions of the outcrop section. Outcrop descriptions in Gibson (1971) are brief and imprecise as they were intended to augment lithostratigraphic mapping and not for sedimentological analyses.

Methods

The entire Charlie Lake section at Brown Hill, and roughly the lowermost ~100 meters at Schooler Creek were described, photographed, sampled for thin section examination and geochemical analysis (sample interval: 0.5m), and a gamma spectrometer (sample interval: 0.5 metre and 1 metre, respectively) was used to detect the radioactivity of the rocks. This paper is based on the sedimentological descriptions and interpretations of the Brown Hill and Schooler Creek outcrops.

Sedimentological analysis focused on the documentation of grain-size (visual estimation), lithology, texture, primary and secondary sedimentary structures, formation and bedding contacts. The Wentworth scale (1922) was used to assess grain size. To describe and evaluate bioturbated strata, bioturbation indices (BI) were assessed following the protocol outlined in Taylor and Goldring (1993). This system assigns a relative number grade (1-6) to bioturbated sediment to quantify the relative degree of syn- and post-depositional biogenic reworking.

Textural components often used to describe and interpret aeolian environments are typically more visible in outcrop than in drill core because natural weathering can highlight seminal criteria such as grain-size variations in the laminae. A portable hand- held radiation spectrometer was used to measure the natural gamma radiation from the outcrop locations. A RS-230 Super-Spec made by Radiation Solutions was used. Like all gamma spectrometers the unit is accurate but lacks precision. The instrument obtains its reading from a circular swatch of outcrop approximately 1 metre in diameter. Thus, gamma readings of beds thinner than 1 metre may be affected by emissions from adjacent strata. Considering this level of precision and following outcrop gamma protocol established by Slatt et al. (1992), individual and total radiation measurements were taken at 0.5 metre intervals for the Brown Hill section, and 1 metre (due to time constraints) intervals at the Schooler Creek section. The handheld gamma measured the radioactivity for a total of 2 minutes at each sample position. Each spot was measured only one time. Outcrop gamma radiation measurements are an important tool when evaluating lithological composition, and are particularly useful when used for correlation between outcrop sections. These logs can also be used to correlate between outcrop sections and subsurface wells (Zonneveld et al, 2004).

TABLE 2.1 Chapter II Facies Table

LITHO• FACIES	LITHOLOGY	PHYSICAL AND BIOGENETIC SEDIMENTARY STRUCTURES	FOSSILS/ TRACE FOSSILS	DEPOSITIONAL ENVIRONMENT
A	Hummocky silt to very fine sand	• hummocky silt to very fine sand • hummocks have even lamination with dip angles and truncation angles of < 15° • erosive basal contact	none observed	marine environment
B	Rippled fine to medium sand	• light grey to brown fine to medium grained sandstone with abundant ripples • bi-directional, oscillatory ripples, combined flow ripples	none observed	marine environment
Bi	Planar laminated fine to medium sand	• light grey to brown fine to medium grained sandstone • planar laminated sand that is normally graded • rare pebble lags demarcates a new bedset • variable coloration	none observed	marine environment
C	Massive, lightly bioturbated grey sandstone	• massive grey sandstone • very fine to fine grained, with up to medium grained sandstone • rare normal grading • not dolomitized, as it is unreactive with HCL acid.	*Planolites* *Chondrites*	marine environment
D	Massive carbonate mudstone	• recessive, massive carbonate mudstone with 3-6 cm anhydritic nodules • common granule to pebble- sized vugs • pervasive stylolites • common interbedded fissile shale at top of the beds, or at contacts • gradational to erosive upper contact can be gradational • conformable, non-erosive basal contact	none observed	lagoon
E	Fine to medium grained sandstone with abundant mudclasts	• lenticular sand and silt with planar and ripple laminae • sharp to erosival basal contact • common mudclats • can be associated with a granule-pebble lag	• dissolved or recrystallized clam/bivalve fragments.	ephemeral fluvial or tidal channel
F	inclined, sandy to silty mudstone	• inclined lenticular sand and silt • planar and ripple laminae • erosional basal contact • fining upward trend •occasionally capped by paleosol (Facies 0)	none observed	ephemeral fluvial or tidal channel /tidal point bar
G	Wavy bedded fine dolomitized sand with abundant silt and/or carbonate mud laminae	• heterolithic (tan to orange and black) dolomitized fine sand with silt and/or carbonate mud wave interbeds • common ripples • common mudcast • chert common • calcite lined vugs	*Arenicolites*	intertidal flat
H	Yellow dolomitized silt to very fine sand	• massive very fine sandstone to lenticular bedded sand with mud interbeds • common current ripples	intertidal flat	intertidal flat

I	Dolomitized algal siltstone	• dolomitized silt • fenestrate porosity (birdseye texture) • pebble sized vugs • planar algal laminae • common current ripple laminae	none observed	intertidal flat
J	Microbial laminated mudstone	• alternating layers of light grey to white mud and darker light brown mud to silt laminae • from crinkled to gentle undulatory subtle mounds • rare desiccation cracks • carbonate mud interbeds • rare pebble sized calcite filled vugs	none observed	supratidal flat
K	Intraclast breccia	• irregular, predominately matrix supported breccia composed of other lithofacies • common mud clasts with rip up clasts and high angled cross-stratified sands • clasts are fragmented and range in size • exhibit slumping, micro faulting, etc. • variable thickness	none observed	sabhka
L	Crossbedded (?) fine to medium grained sand and organic (pellets?) mud.	• silty fine to medium grained sandstone • interbedded with irregular, discontinuous white carbonate mud • carbonate mud has been subjected to various sqeezing, contortion, and deformation • mud appears to be pelleted • may be subtly crossbedded.	none observed	supratidal marsh/storm deposits
M	Massive white calcareous siltstone	• massive white calcareous undifferentiated siltstone • subtle fining upward trend • characteristic horizontal lamination • occasionally up to pebble sized granules can be dispersed in this unit • rare fine grained sandstone ripples.	none observed	lacustrine
N	Planar to wave rippled laminated sandstone	• very fine to fine grained planar to wave ripple laminated sandstone • variable thickness; ranging between .5m to over 10m • sharp but conformable lower contact • upper contact is gradational to incised/ erosive.	rare *Arenicolites*	lacustrine
O	Rust red, yellow, black claystone to siltsone	• pedogenically altered yellow to rusted red, and occasionally black (carbonaceous) rooted siltstone. • massive to blocky fracture • rhizoliths are common and can be observed especially well in the carbonaceous sample.	none observed	paleosol
P	Trough cross-stratified fine to medium grained sandstone	• high angled, trough cross-stratified fine to medium grained sandstone • evidence for early cementation of anhydrite • inversely graded laminae • forsets have average inclinations of ~20–30° +	none observed	aeolian dune (grain flow deposit/ grain fall)
Q	Low-angle to planar fine to medium grained sandstone	• fine to medium grained sandstone • foresets have inclinations of typically 20°-30° • commonly observed to interfinger with sandflow laminae	none observed	aeolian dune (predominantly grain fall deposition)

R	Fine to medium grained convolute sandstone	• fine to medium grained convolute sandstone • composed of lithofacies (FP, FQ, and/or FS) that has been highly pre-diagenetically deformed and contorted.	none observed	inundated/ flooded aeolian dune
S	Ripple cross stratified fine to medium grained sandstone	• thin planar to low angle (<10°) • low relief, translatent ripples, inverse grading • pin strip laminae	none observed	aeolian dune (translatent and/or wind ripple deposit)
T	Fissile shale	• fissile grey shale • sharp planar contacts between each laminae set. • basal contact is erosive, with granule, shelly, and phosphate lag	•*Glossifungites*- demarcated discontinuity surface •cf. *Planolites* •*Skolithos* •*Thalassinoides*	Flooding surface

Lithologs showing detailed descriptions of sedimentological, ichnological, and stratigraphical observations as well as supplementary gamma readings (provided in ppm) are provided in the Appendix. In addition, Table 2.1 summarizes the characteristics of individual lithofacies, including sedimentological, ichnological, and stratigraphical data, and organized by interpreted depositional environment.

Sedimentary Lithofacies and Facies Associations

Twenty distinct sedimentary lithofacies were observed in the Charlie Lake outcrop at Brown Hill and Schooler Creek. These facies are organized in seven facies associations. A comprehensive table describing individual lithofacies characteristics and interpretations, facies associations and interpreted depositional environments are provided in the appendix.

FACIES ASSOCIATION 1: SHOREFACE / STORM DEPOSITS/ WASHOVER FAN

Description

Facies association 1 (FA-1) consists of 3 lithofacies and a single sub-facies: A (Hummocky cross stratified siltstone to very fine-grained sandstone), B (rippled, fine to medium sand), subfacies Bi (Planar laminated fine to medium sand) and C (Massive, lightly bioturbated, grey fine-grained sandstone).

Lithofacies A is composed of very fine to fine grained sandstone with predominately quartz grains. The dominant bedding form is hummocky cross stratified (HSC) sand (Figure 2.5, e), where the base of the unit has a sharp and sometimes erosive basal contact. The bedsets forms up to 3 m thick successions and have swales with even lamination showing dip angles and truncation angles of < 15°. Rare horizons of trough cross- stratified (TCS) sand of less than 1 m occur intermittently amongst the HCS. Neither trace fossils nor body fossils were observed in this lithofacies.

Lithofacies B and Bi are lithologically identical, but differ in preserved sedimentary structures. Lithofacies B is a light grey to brown, fine- to medium-grained sandstone with abundant ripples. Ripple morphology is usually bi-directional, oscillatory ripples, but in several occurrences these were observed to amalgamate into combined flow ripples capped by oscillatory ripples (Figure 2.5, h). Bi is characterized by planar laminated sand that is normally graded. In rare instances a coarse pebble lag was observed to demarcate the base of a new bedset (around 70m in the Schooler Creek section). A variation in coloring is common in the subfacies, with alternating lighter and darker beds. Neither trace fossils nor body fossils were observed in either subfacies in this lithofacies.

Facies C is a massive grey sandstone characterized by very fine- to-fine grained (up to medium-grained) sandstone. Common mud lenses and drapes occur intermittently. This facies is characterized by the presence of distinct unlined trace fossils that lack spreiten (Figure 2.5 f ,g). A predominantly horizontal trace, *Macaronichnus,* occurs concurrently with (but less frequently) than the dominant inclined trace, *Planolites*. The *Planolites*, traces are approximately 1-2 cm in burrow length depth, and 1-3 mm in diameter. They do not appear to branch. The burrow length of the *Macaronichnus* trace is <1cm to 2 cm, and has an average burrow diameter of 2-4 mm. The infill of the both the *Macaronichnus* and *Planolites* traces (white in color) strongly contrasts with that of the surrounding grey sediment. Although the diversity of the traces is low, the degree of sediment churning is moderate (BI Index 3-4); discrete traces with rare overlap of the individual traces. It appears that the pervasiveness of traces dissipates moving towards the top of the sandy package. This facies has rare normal grading. Of note, this facies does not react when tested with HCL.

Interpretation

Lithofacies A, B, Bi, and C are interpreted to be fully marine deposits with varying marine depositional environments ranging from distal upper-shoreface storm deposits, to foreshore deposits, to washover fan deposits.

Lithofacies A is primarily composed of HSC beds, with TCS interbeds. The presence of hummocky cross-stratified sandstones suggests reworking of sediments by possible storm-generated currents (Southard et al., 1990). These types of deposits are found throughout the shoreface (Hamblin and Walker, 1979).

Lithofacies B and subfacies Bi ard C interpreted to have been deposited in a foreshore to wash-over fan environment. Sedimentologically,

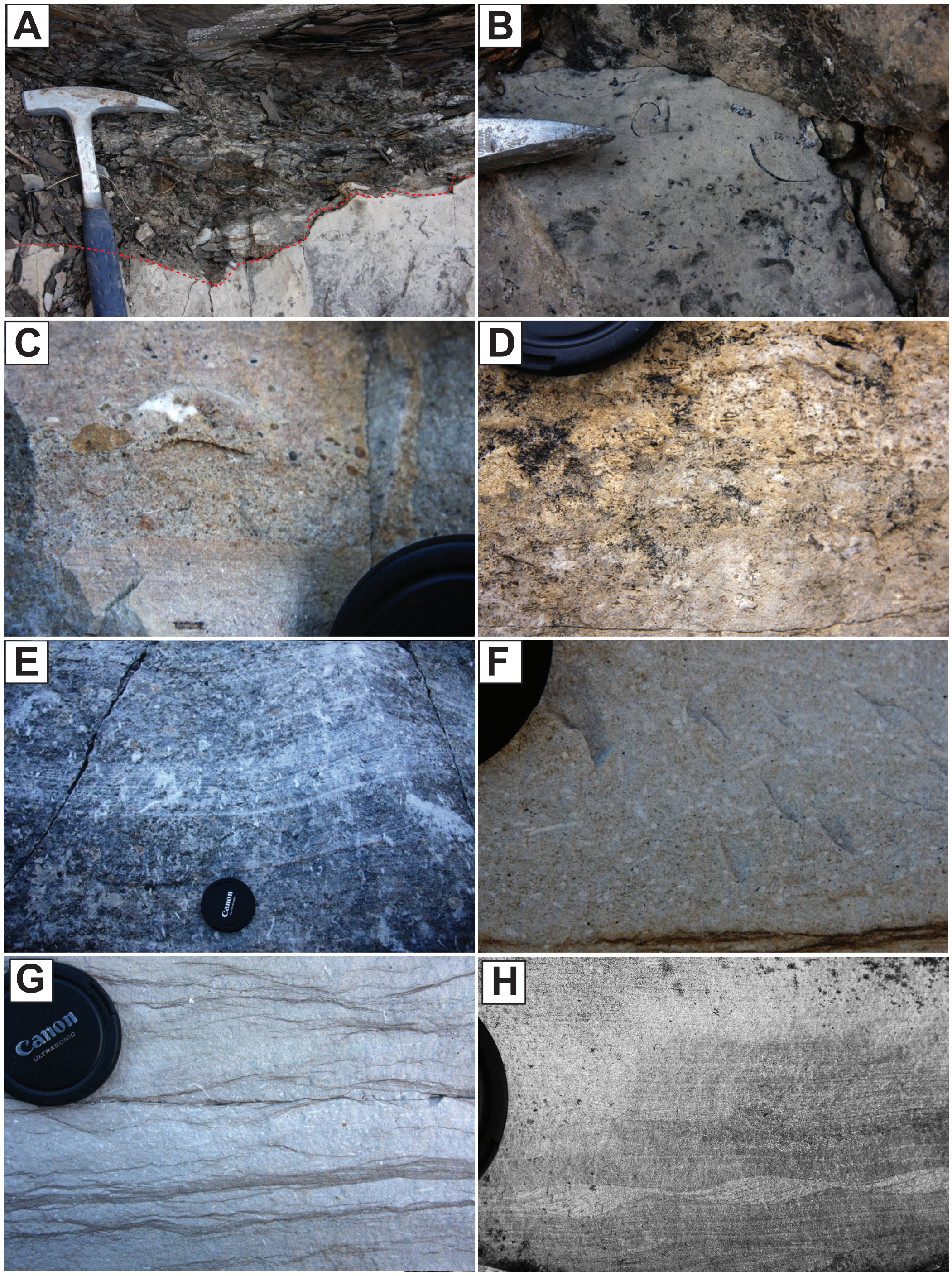

Figure 2.5: Lens Cap for Scale
A) Erosive phosphate lag at Charlie Lake/Baldonnel contact, Brown Hill, 103m.
B) Recrystallized shell fragments, Brown Hill, 103m
C) Lithofacies M granule to pebble lag, Schooler Creek , 38m, lens cap for scale.
D) Lithofacies M; dissolved bivalve and ooid fragments with gradational contact with underlying facies, Schooler Creek , 15m. Lens Cap for scale.
E) Lithofacies A, hummocky cross stratified (HSC) sand, Schooler Creek , 42m.
F & G) Abundant *Planoloites* and *Chondrites,* lithofacies C, Schooler Creek, 40 m.
H) Combined flow ripples in FB, 64m, Schooler Creek.

the planar stratification (lithofacies B) grading to oscillatory ripples (subfacies Bi) represents the transition of upper shoreface to foreshore and washover fan deposition. Additionally, this facies contains strata that are characterized by the presence of unlined, unspreitenated trace fossils. *Macaronichnus* and *Planolites* are traces that are consistent with mobile-deposit feeding behaviors. Additionally *Macaronichnus* is a trace fossil that is commonly associated with deposition in shallow, marginal marine sedimentary environments (Gingras et al, 2002). Its presence can be representative of a specialized adaptation to a specific environment, often high energy foreshore to proximal upper shoreface environments (Saunders and Pemberton, 1986). The *Planolites* are unlined, unbranched to rarely branching burrows, infilled with a different matrix then the surrounding sediment.

FACIES ASSOCIATION 2: SUBTIDAL LAGOON

Description

Facies Association 2 (FA-2) consists of a single lithofacies, Facies D (massive carbonate mudstone). It is characterized by a recessive, massive carbonate mudstone with 3-6 cm anhydritic nodules. Common granule to pebble- sized crystal -lined vugs and stylolites are pervasive and reiterate the carbonate nature of the mud. Fecal pellets are observed in this unit. Interbedded fissile shale is common near the tops of the beds, or at contacts. Lithofacies D is found interbedded to several lithofacies (E, G, H, I). The lower contact is typically sharp but conformable, with no evidence of erosion, however, the upper contact can be either gradational or erosionally by the overlying unit. The thickness of lithofacies D is variable, and ranges from 10cm to 70cm. Commonly, as observed in Figure 2.6, lithofacies D tends to have a depositional signature that shows a thicker bed (~40-50cm) interbedded with several thinner beds (~10-20 cm).

Interpretation

Facies Association 2 (FA-2) was deposited in a restricted lagoonal setting laterally adjacent to tidal flat deposits (FA-4, 5). Protection from a distant barrier (unobserved), created a sheltered environment where carbonate mud was produced and accumulated. Fecal pellets are present,

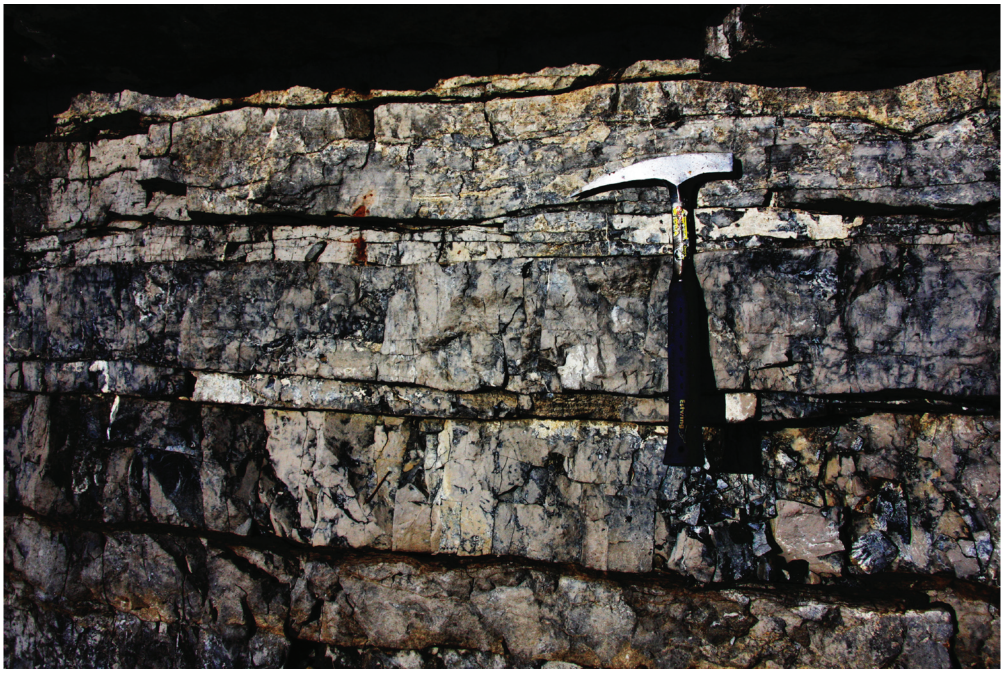

Figure 2.6: Lithofacies D- massive carbonate mudstone

but bioturbation of sediment is surprisingly low, possibly reflecting highly stressed environmental conditions. Likely the lack of bioturbation can be attributed to stressed lagoonal conditions such as increased salinities. Invertebrate faunas in hypersaline settings (salinity in excess of 45%) are characterized by extremely low specific diversity (de-Gibert and Ekdale, 1999). Other potential lagoonal stressors resulting in low to absent ichnotaxonomic diversity can result from the transition from lagoon to ephemeral lagoon. In the Coorong region of Australia, ephemeral lagoons are connected to the main lagoon during winter, but become disconnected and evaporate during summer months (Von der Borch, 1976; Von der Borch and Lock, 1979). Alternatively, the mud may be thoroughly bioturbated resulting in the massive appearance. The lagoonal muds tend to be found encased in intertidal deposits (lithofacies E, G, H, I).

FACIES ASSOCIATION 3: EPHEMERAL FLUVIAL/TIDAL CHANNEL

Description

Facies association 3 (FA-3) is composed of lithofacies E (fine to medium grained sandstone with abundant dissolved allochems) and/or lithofacies F (inclined, sandy to silty mudstone) and/or lithofacies O (rust red, yellow, black claystone to siltstone).

Lithofacies E is defined by the presence fine to medium grained sand with dissolved or recrystallized clam/bivalve fragments. Lithofacies E occurs in other facies associations. Lithofacies F is characterized by lenticular sandstone and siltstone with planar and ripple laminae (Figure 2.7, d). This stratum is dominated by normally graded inclined sandy cross beds. Mudstone intraclasts are common, this unit tends to comprise the majority of tidal channels.

This unit incises into other facies associations including FA- 2 (lagoon), FA-6 (coastal aeolian dune). It is periodically capped with lithofacies O, but can also fine up to and by capped by a thin (0.5cm) fissile shale bed.

The channels appear to be very laterally restrictive and greatly vary in width from less than 1 to several metres in width. Additionally, the height of the channels appears to be quite variable, with some under .50 metre, and some interpreted channel deposits reaching ~1 metre in height. When lithofacies F comprises the channel often it gradual grades into lithofacies I (FA-intertidal flat).

The basal contact is irregular and slightly erosional in places. Steep walls are often observed (with relief up to 20 cm) This facies exhibits a fining upward trend, includesmintraclasts, and is occasionally capped by paleosols (lithofacies O). There is a subtle fining upwards trend in lithofacies F. This facies association is normally graded, erosionally based and laterally restricted. It has a variable thickness dependent on facies occurrence, but tends to be around 50 cm in thickness. This facies was observed to cut through FA- 2 (lagoonal), FA- D, G, H, I and J, which are interpreted as intertidal and supratidal flats (discussed below).

Interpretation

When the basal contact of lithofacies E or F is sharp and erosive it is interpreted have been deposited in a tidal channel. The scouring surface and granule to pebble lag associated with these facies are indicative of the erosive nature of tidal channels. The above facies are interpreted to represent

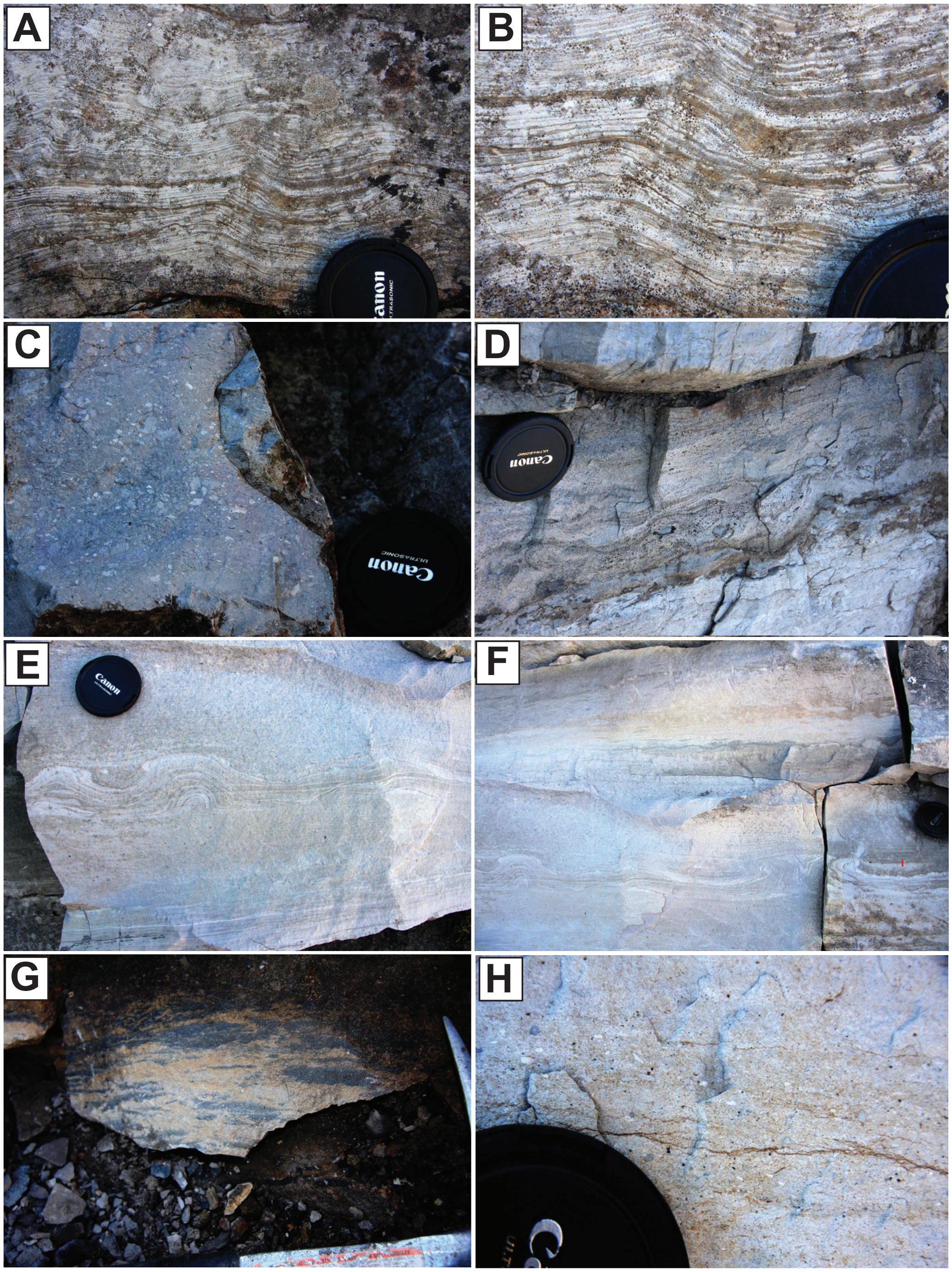

Figure 2.7: Lens/Hammer for scale
A & B) Facies J, domal- type microbial laminated mudstone, Schooler Creek, 83.5m
C) Facies K- lime mud rip up clasts within silty to sandy matrix. Schooler Creek, 57m
D) Lithofacies F; lenticular sandstone and siltstone with planar and ripple laminae Schooler Creek, 58m.
E & F) differential compaction of semi-unconsolidated sand leads to contorted bedding and fluid escape structures (photo F) in fine sand, Schooler Creek, 64.5 m. Lens Cap for scale.
G) Heterolithic muddy/silty dolomitic sandstone, lithofacies E, Schooler Creek, 83m
H) Lithofacies M; massive, white, calcareous siltstone with a subtle fining upward trend with granule to pebble-sized intraclasts occur in several horizons. Schooler Creek, 92 m.

a channel-fill succession that cuts through both intertidal and supratidal flat deposits. The erosive base, low-angle cross-bedded nature, laterally-restricted nature of the FA and sand-dominated grain size distribution is consistent with both tidal flat channels (Terwindt, 1988). Intertidal flats, particularly those in mesotidal or macrotidal settings, contain common small but steep channels that drain them during low tide conditions (Terwindt, 1988). Lags consisting of shell debris and intraclasts (including laminated mudclasts) are common characteristic of tidal channels (Terwindt, 1988). Fossil deposits in the tidal channels are likely derived from residents of the intertidal flats or from other deposits the channels cut through. Tidal channels redistribute much of the sand transported landward by wave-action (Shinn, 1983). When capped by lithofacies 0, it is interpreted as a tidal point bar with paleosol development.

FACIES ASSOCIATION 4: INTERTIDAL & SUPRATIDAL FLAT DEPOSITS

Description

Facies Association 4 (FA-4) is composed of 3 lithofacies: lithofacies G (wavy bedded, fine-grained dolomitized sandstone with abundant silt and/or carbonate mud laminae), lithofacies H (yellow dolomitized silt to very fine-grained sandstone) and lithofacies I (dolomitized algal siltstone).

Facies G (Figure 2.7, g) is characterized by tan, to orange and black, highly dolomitized siltstone and sandstone. This facies is wavy to flaser bedded with carbonate mud composing the swale-fill in the flaser bedding. Symmetrical wave ripples, asymmetrical current ripples and mudclasts lags are also common. Rare *Arenicolites* are found at the top contact, sometimes contributing to low diversity *Glossifungites* surfaces.

Lithofacies H consists of yellow dolomitized siltstone to very fine-grained sandstone. Lenticular bedded sandstone with mudstone interbeds are dominant and are characterized by common current ripples. This lithofacies is commonly interbedded with shale. The base can be slightly erosive, and the package tends to fine upwards slightly. It has a maximum thickness of < 1m. Rare *Arenicolites* are found at the top contact (Figure 2.8, a, b).

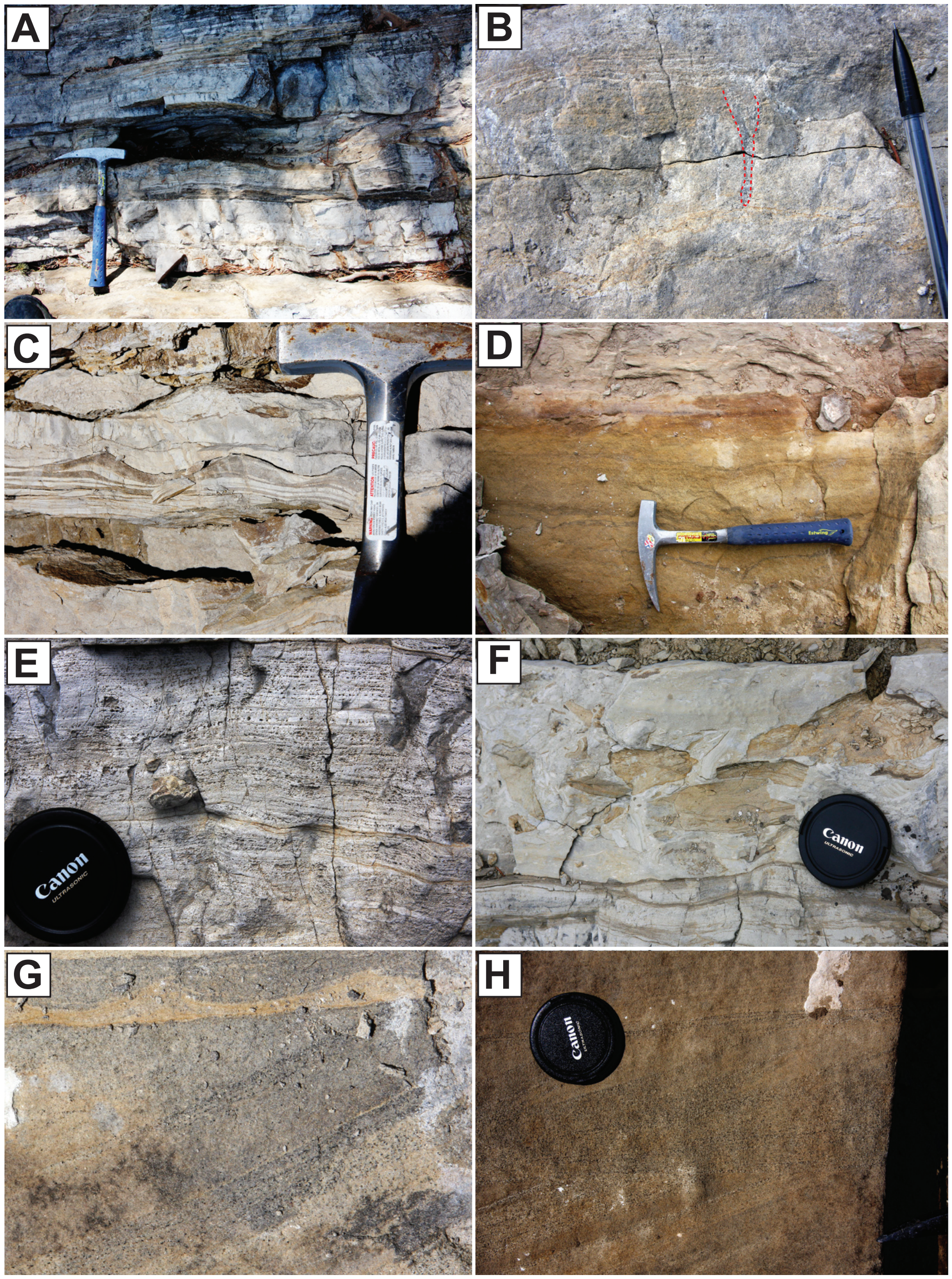

Figure 2.8:

A)Lithofacies E; wavy bedded fine sand with abundant silt and/or carbonate mud laminae, Brown Hill, ~15 m. Hammer for scale.

B) Lithofacies H; dolomitization makes it difficult to differentiate ichonological traces; *Skolithos cf* or *Arenicolites cf* forming a *Glossifunigites* surface, Brown Hill, 15.2m.

C) Lithofacies N; oscillatory wave ripples, Brown Hill, 33.2m.

D) Lithofacies I (lacustrine) grades into the red pedogenically altered, rhizolith abundant lithofacies A (palaeosol), Brown Hill, 50m. Hammer for scale.

E) Lithofacies J;Domal microbial laminated mudstone with fenestrate texture with common mud laminae. Brown Hill, 55m. Lens cap for scale.

F) Facies K, intraclast breccia., matrix supported and clast composition is predominantly lithofacies H, Brown Hill, 58m.

G) Lithofacies P; Inverse grading in sand dunes, capped by wave ripples, Brown Hill. 73m

H) aeolian bounding surfaces, Brown Hill, 73m, lens cap for scale.

Lithofacies I is characterized by dolomitized very fine-grained sandstone with common fenestral porosity (i.e. birdseye texture), pin-point to pebble sized vugs and planar to crinkly laminae (Figure 2.9, a & b). Starved current ripples are common. This facies is commonly encased in other lithofacies interpreted to reflect intertidal / supratidal deposition (i.e. lithofacies D, E, G, K, L).

Spatially, the lithofacies comprising FA-4, may occur together, or individually, interbedded with lithofacies characteristic of other facies associations, particularly those characteristic of intertidal deposition (i.e FA-1 (shoreface/washover fan deposits) FA-2 (lagoonal deposits), FA-5 (supratidal flat/sabkha/lacustrine), FA-6 (coastal aeolian dune succession).

Interpretation

Facies Association 4 is interpreted to record deposition in a mixed siliciclastic-carbonate intertidal flat environment. The intertidal zone undergoes alternating intervals of subaqueous flooding and subaerial exposure. This is recorded in the interbedded lenticular and flaser-bedded heterolithic siltstone and sandstone of lithofacies G and H. The rippled sandstone records wave-mediated deposition during intervals of advancing or retreating tides. Slackwater high tide intervals allow for suspension deposition of carbonate mud on the ripple surfaces.

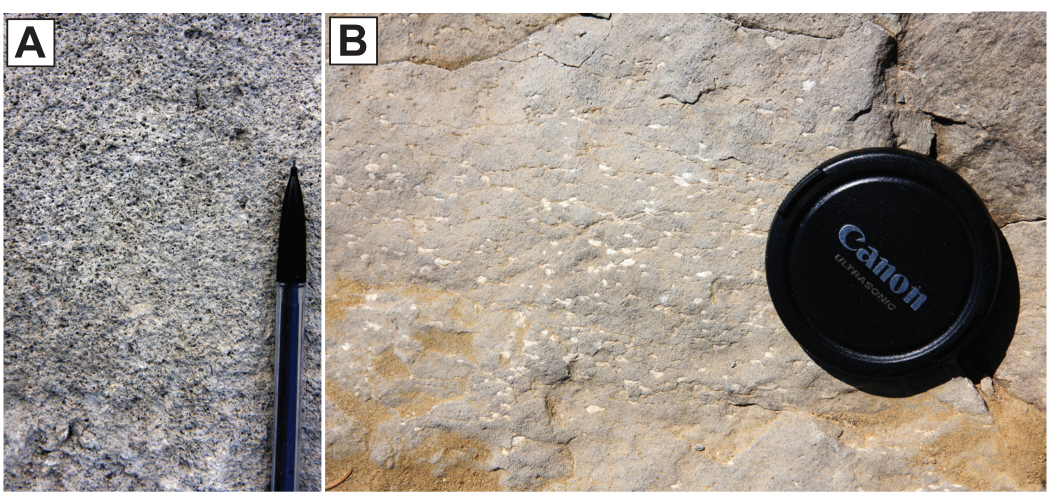

Figure 2.9: Lithofacies I: dolomitized algal siltstone.
a) Pin point porosity in Brown Hill out crop 19m, pencil for scale.
b) Vug-sized, calcite filled birds eye texture, Brown Hill, 8.5m

As discussed above, trace fossils in this facies association consist of monotypic associations of *Arenicolites* in lithofacies G and H. *Arenicolites* is an unlined, non- spreitenate, U shaped burrow. Most likely this structure served as a permanent or semi-permanent dwelling for a suspension feeding organism, possibly a polychaete or amphipod (Fischer and MacGinitie, 1928; Häntzschel, 1939). Although not restricted solely to any one depositional environment, *Arenicolites* is most common in shallow and marginal marine depositional settings (Pemberton & Wightman, 1992; Pemberton et al., 1992; Gingras et al., 1999; Mángano and Buatois; 2004). They are common in intertidal flat settings and their occurrence in monotypic assemblages supports the interpretation of a depositional setting prone to common environmental stresses (Pemberton et al., 1992; Gingras et al., 1999). In several examples, this trace comprised low-diversity *Glossifungites* surfaces (Figure 2.8, a), wherein the infill material of the burrow is distinct from the composition of the bioturbated horizon. This indicates that there was periodic exposure of the tidal flats.

At both Brown Hill and Schooler Creek, mixed siliciclastic/carbonate intertidal flat successions (lithofacies G and H) are commonly blanketed with planar to crinkly laminated dolomitic siltstone beds with abundant pinprick to pebble-sized fenestral voids (lithofacies I). These beds are interpreted to represent stromatolitic layers (cyanobacterially-laminated beds). This facies is similar to the microbially laminated mudstone (stromatolites) (lithofacies J) of the supratidal zone (discussed below) but is sandier and more interbedded with other lithofacies. Cyanobacterial laminites / stromatolites are most commonly preserved in supratidal settings but can occur in intertidal and subtidal settings as well (Playford, and Cockbain, 1976). The common exclusion of stromatolitic beds from these latter settings is related to the presence of common grazers in areas with normal or near-normal salinities. The upper intertidal and supratidal are subaerially exposed for longer intervals and thus are characterized by higher exposure and hypersalinity stresses (Shinn, 1983; Nichols, 1999). The commonly gradational transition from lithofacies I to lithofacies J is herein interpreted to represent the transition from the intertidal zone to the supratidal zone.

The overall low abundance of traces is interesting to note, as tidal flats and adjacent lagoons can be very hospitable for many species of organisms resulting in abundant bioturbation of sediment (Tucker and Wright, 2009). Their absence in the Charlie Lake intertidal successions is interpreted to reflect high salinity stress on the tidal flats due to high net evaporation in an arid coastal setting (Zonneveld et al., 2001). The diminished organismal activity thus allowed the cyanobacterial mats of Facies I and J to flourish. Cyanobacterial mats are characteristic of the intertidal zone (Belperio et al, 1988). Although common in many modern environments, preservation of algal mats in the rock record is relatively low. The distribution of algal mats in modern tidal enviroments are controlled by factors that include grazing by invertebrate organisms such as gastropods (Tucker and Wright, 2009). Shrinkage, gas escape, or air escape during flood of the algal mats results in fenestrate / birds-eye textures (Shinn, 1968). Birdseye structure is preserved often because of its occurrence in an active diagenetic environment, with common early lithofaction (Shinn, 1983). Voids are often filled with cement, surrounding sediment, or evaporites that possibly form penecontemporaneously with deposition (Shinn, 1983). These types of microbial mats are not exclusive to intertidal deposition; they can form in protected subtidal intertidal and supratidal settings. However they are most commonly preserved on intertidal flats (Hagan and Logan, 1975).

FACIES ASSOCIATION 5: SUPRATIDAL FLAT/SABKHA/LACUSTRINE

Description

Facies association 5 (FA-5) is a heterolithic succession containing several lithofacies including laminated mudstone (lithofacies J), intraclast breccia (lithofacies K), fine- to medium-grained sandstone (lithofacies L), massive calcareous siltstone (lithofacies M), planar to wave-rippled sandstone (lithofacies N, and variegated siltstone (lithofacies O).

Lithofacies J is a laminated mudstone (Figure 2.7 a,b) comprised of alternating layers of light grey to white mud and darker light brown mud to silt laminae, which vary in form from crinkled to gentle, undulatory mounds. Sedimentary structures observed within this facies include desiccation cracks, carbonate mud interbeds and rare pebble sized calcite filled vugs. Texturally, fenestrate or birds eye texture is common. The beds can be thick, and at Schooler Creek reach a maximum thickness of > 2m, with the thickest observed deposits reaching almost 5 m. Lithofacies J commonly occurs encased in other facies interpreted to represent intertidal/supratidal or lagoonal deposition (most commonly lithofacies G, H, or K).

Lithofacies K is an intraclast breccia characterized by irregularly-shaped, predominately matrix-supported (rarely clast-supported) clasts composed of a variety of lithofacies (most commonly lithofacies I, J and L through S). Mudstone intraclasts are also common (Figure 2.7, c). Clasts are fragmented and range in size from a few centimeters to over 1 meter in diameter. Often the upper surface of the breccia exhibits slumping and micro-faulting. The bed thickness is variable almost 5 metres.

Lithofacies L consists of silty, fine- to medium-grained sandstone interbedded with irregular, discontinuous white carbonate mud lenses. The carbonate mud shows numerous evidences of distortion, including convolute, overturned bedding and micro-faulting. The mud commonly has a strong pelleted appearance (Figure 2.7 e, f).

Lithofacies M consists of massive, white, calcareous siltstone with a subtle fining upwards trend. This lithofacies exhibits characteristic horizontal lamination. Rippled fine-grained sandstone laminae and granule to pebble-sized intraclasts occur in several horizons (Figure 2.7, h).

Lithofacies N consists of planar laminated- to-wave rippled very fine-grained to fine-grained sandstone (Figure 2.8, c). The thickness of this unit is variable, ranging from 0.50 m to over 10 m. Lithofacies N and M occasionally occur together with Facies N usually occurring beneath Facies M with a gradational contact. These facies also occur singularly, and have variable relationships with its adjoining units. The lower contact is typically sharp but conformable and overlies FA-4 (intertidal flat) or FA-6 (coastal aeolian dune succession). The upper contact tends to be gradational and is commonly overlain by Lithofacies 0 (pedogenically altered siltstone) or Facies K (intraclast breccia).

Lithofacies 0 is a pedogenically altered, yellow to rust-red, and occasionally black (carbonaceous), siltstone. Rhizoliths are common, as are pedogenic slickensides. This lithofacies occurs either underlying or overlying lithofacies F (sandy to silty mudstone / tidal channel) or lithofacies M and N (massive siltstone to rippled sandstone / lacustrine).

The constituents of FA-5 tend to occur together as a package (Figure 2.8, d). The lower contact of FA-5 is typically sharp but conformable and overlies FA-4 (intertidal flat) or FA-6 (coastal aeolian dune succession). The upper contact is gradational with FA-4 (intertidal flat) or FA-6 (coastal aeolian dune succession).

Interpretation

FA-5 is interpreted to represent deposition within a coast-proximal supratidal / sabhka environment adjacent to a low gradient shoreline, which allowed for development of restricted topographic lows characterized by extensive microbial / cyanobacterial mats. The supratidal/sabhka depositional zone in this succession lies just above the mean high tide mark and experienced inundation by seawater during rare storm and spring tide conditions (Shin, 1983).

Lithofacies J is interpreted as microbially / cyanobacterially laminated mudstone (laminar stromatolites) that formed in the supratidal zone. Shrinkage during desiccation and gas escape caused by the rotting of buried organic mats resulted in the fenestrate and birds-eye textures observed in this facies (Figure 2.8, e). Supratidal birdseye structure is preserved often because of it occurrence in an active diagenetic environment, with common early lithofaction (Shin, 1983). Voids are often filled with cement, surrounding sediment, or evaporites that possible forms penecontemporaneously with deposition (Shin, 1983). Larger vugs may have resulted from dissolution of evaporite nodules, similar to those that characterize modern cyanobacterial mat successions (Shin, 1983; Belperio et al, 1988).

Cyanobacterial laminae in arid areas can result both from alternating flooding and deposition of marine sediment and cyanobacterial mat growth or alternating aeolian deposition and cyanobacterial growth (Shin, 1983).

The brecciated clasts of lithofacies K are composed of lithologies characteristic of adjacent lithofacies, indicating that deposition of these lithologies and primary cementation had occurred prior to development of the breccia (Figure 2.8, f). These breccias are interpreted as solution collapse breccias (Arnold 1994, Zonneveld et al, 2004) that indicate the prior presence of now-dissolved evaporite deposits, rendering this not a true deposited lithofacies but a diagenetic lithofacies. Thus, this lithofacies provides evidence for a lithology that is no-longer present in the study interval (Zonneveld et al., 2001). The evaporite minerals were derived from two sources. First, periodic / aperiodic flooding of coastal depressions, possibly during atypically high spring tides, or high tides that coincided with storms, introduced marine waters into these areas. Second, evaporation in the supratidal zone resulted in saline water being drawn up through the coastal sediments and, concomitantly resulted in precipitation of evaporite minerals within and on the sediment surface (Fisk, 1959). This tends to form continuous lenses and beds of evaporite (Fisk, 1959) In arid coastal settings, supersaline waters can evaporate and created thick deposits of evaporate sediment, most commonly anhydrite, gypsum or halite. These deposits have a high tendency for dissolution when in contact with water, and their dissolution is believed to have formed the collapse beds. This dissolution was likely early post-depositional as overlying beds commonly have distorted / convolute bedding (i.e. dissolution occurred prior to lithification of these beds). Thus it is believed that the dissolution is a result of local fluctuations in sea-level and changing positions of the water table.

Lithofacies L, M and N are interpreted to be reflective of deposition in a supratidal body of water, likely either a supratidal lagoon or lake. The laminated to massive and convolute bedded mud in lithofacies L and M represent deposition from suspension in the quiet, protected waters of a lake / lagoon. Abundant faecal pellets in this unit indicates abundant biotic activity. Rare wave –rippled beds indicate wave reworking of coarser components (very fine- to fine-grained sand). Granule to pebble-sized intraclasts (Figure 2.5 c, d) resulted form early, surficial lithification and reworking, likely during rare storms. The massive to contorted nature of many of the mudstone siltstone intervals may indicate complete biogenic reworking in this environment, despite the fact that no distinct ichnogenera could be differentiated. Similar beds occur in the Coorong lakes and lagoons in southeastern Australia (von der Borch, 1976).

The predominant structures preserved within lithofacies N indicates a relatively undisturbed, low energy setting in which wind blown sand settled in the lakes forming planar laminae. Wave reworking resulted in the formation of low-relief symmetrical ripples in this facies. This facies commonly occurs adjacent to (typically overlying) aeolian dune successions (lithofacies P and Q) underscoring the aeolian source of this sediment.

Facies O, which is found predominantly above lithofacies N consists of pedogenically altered calcareous and dolomitic clay-rich siltstone. The source of the sediment is probably similar to that described for lithofacies L and M above. This lithofacies is representative of the drying of the possible ephemeral lake. Pedogenic slickensides result from the wetting and drying of clay-rich sediments (Gray and Nickleson, 1989). Pedogenic slickensides and root traces provide clear evidence for soil forming processes. This lithofacies has been observed in Charlie Lake Formation outcrop elsewhere (Zonneveld et al., 2004), where pedogenic slickensides and roots were also common.

FACIES ASSOCIATION 6: COASTAL AEOLIAN DUNE SUCCESSION

Description

Facies association 6 (FA-6) consists of lithofacies P (trough cross-stratified to planar wedge, fine to medium grained sandstone), lithofacies Q (low-angle to planar fine to medium grained sandstone), lithofacies R (fine to medium grained convolute sandstone), and lithofacies S (ripple cross stratified fine to medium grained sandstone).

Lithofacies P (Figure 2.8, g) is a well-sorted, fine- to medium-grained, orange-yellow to tan, sandstone, with very well rounded grains. The bedding consists of high-angle trough and wedge cross stratification, with foreset inclinations averaging ~20-25° (up to 34°), which have tangential beds. The lithofacies consists of numerous, smaller-scale, inversely graded bedsets (Figure 2.10, a). The bedset thickness is variable, with the thinnest being the asymptotic bottom bedset, 2-5 cm in thickness. The thickness of the unit is variable but on average the thickness ranges from 1-3m. The contacts between the cross-beds are angular (Figure 2.10 b, c, d, e).

Lithofacies Q is a low-angle cross-bedded to planar-bedded, fine- to medium-grained sandstone. Thin, planar to low-angle (<10°) cross-beds dominate (Figure 2.10, f). Beds are inversely graded with common oscillatory ripples. This facies occurs interbedded with lithofacies P, and also commonly occurs above this lithofacies. The contacts between lithofacies Q and adjacent lithofacies are typically sharp but nonerosional. The thickness of this lithofacies, like lithofacies A, is variable but ranges from 50 cm to 1.5 m. Both lithofacies P and Q show evidence for early cementation as indicated in the pin-strip laminae and the darker bands in the lower portion of each new bed set.

Lithofacies R is compositionally similar to lithofacies P and Q but is characterized by moderate-scale convolute and overturned bedding (Figure 2.10 g, h). This lithofacies tends to be observed less frequently than lithofacies P or Q, but commonly occurs adjacent to them. It is most common at the base of an aeolian dune succession (typical above lithofacies K) but can also occur above lithofacies P and Q.

Lithofacies S is a ripple cross-laminated fine- to- medium grained sand with low-relief, translatent ripples, commonly with faintly preserved foresets. This lithofacies occurs most commonly interbedded with lithofacies P and Q.

Interpretation

Facies Association 6, consisting of lithofacies P (trough cross-stratified fine- to medium-grained sandstone), lithofacies Q (low-angle to planar fine- to medium-grained sandstone), lithofacies R (fine- to medium-grained convolute-bedded sandstone) and lithofacies S (ripple cross-stratified fine- to medium-grained sandstone) is interpreted as an aeolian dune succession deposited within an arid coastal environment. Primary sedimentological characteristics in lithofacies P, Q, and S have textures and sedimentary structures consistent with aeolian processes. Textural components often used to describe and interpret aeolian environments are typically more visible in outcrop than in subsurface core because natural weathering can highlight seminal criteria such as grain-size variations in the laminae, as is the case with these outcrop locales, and because beds can be walked out laterally for several metres to several 10s of metres. Criteria used to identify aeolian strata within the study interval includes the overall excellent sorting, the well-rounded, commonly frosted sand grains, and bedforms preserved in lithofacies P, Q, and S at both Brown Hill and Schooler Creek.

Two major sedimentary processes create high-angle cross-stratified

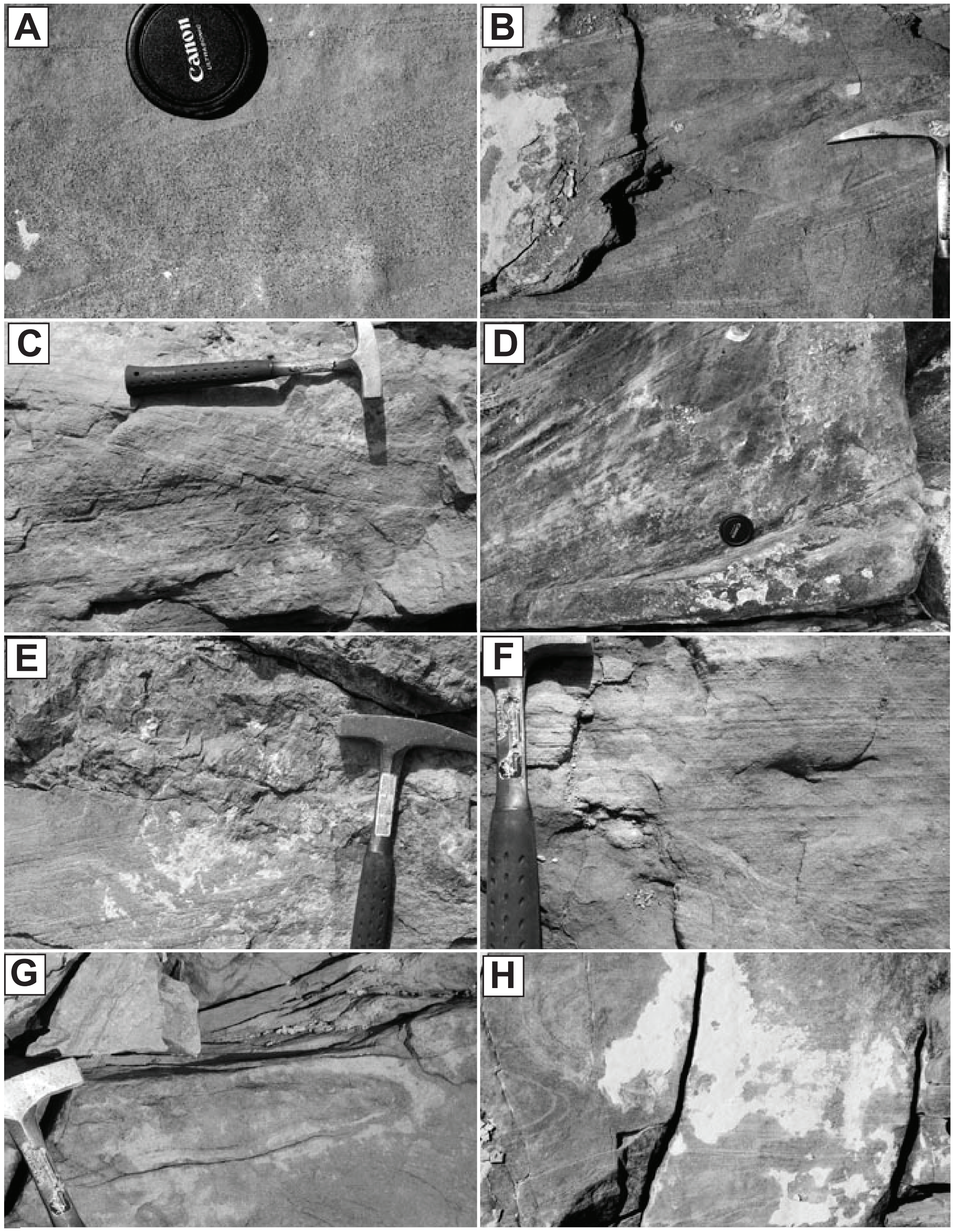

Figure 2.10:
A) Lithofacies P, inversely graded bedsets. Lense cap for scale. Brown Hill ~
B-E) Various examplars of Lithofacies P- planar cross-stratified sand in aeolian dunes. Hammer for scale, Brown Hill 10.5m
F) Lithofacies Q: low angled crossbeds
G-H) Lithofacies Q: convolute and overturned bedding. Examples from Brown Hill.

deposits with abnormally high angles of inclination on the lee side of sand dunes: grainfall and grain flow (Pye and Tsoar, 1990). The sedimentary process resulting in the texture observed in Facies P is mostly likely due to the grainflow of sand grains. These deposits were created in dry sand, by sand grains avalanching over the slip face of the dune, resulting in dominantly inversely graded lamina sets and stratification angles of 32°-34° on average (Pye and Tsoar, 1990). The resultant bedform is known as sandflow cross-stratification. It is characterized by thicker deposits- than typical grainfall deposition, and as a result of the open packing of sand grains has a higher porosity compared to other aeolian stratification types. Foresets in grainfall strata (lithofacies Q) have slightly lower dip angles (typically 20°-30°) and are characterized by lamination with less well-sorted grains and less apparent grading (Brookfield, 1992). These deposits tend to have intermediate packing of sand grains resulting in slightly lower porosity deposits compared to grainflow deposits. The spatial location of the grainfall laminae depends on the morphology of the dune. Typically, grainfall strata accumulate on the lee side of the dune, just over the crest. Once the accumulation meets and exceeds the angle of repose, grains cascade down the steep duneface and create the erosionally-based 2-5 cm thick grainflow deposits (Pye and Tsoar, 1990). Within the study area grainfall strata were commonly observed to interfinger with sandflow laminae, a phenomenon consistent with many other aeolian depositional successions (Brookfield, 1992). The inversely graded laminae observed in Lithofacies P, Q, R, and S, when used in association with other criteria, are strongly indicative of aeolian deposition (Fryberger and Schenk, 1988).

The planar to slightly inclined nature of sandstone beds in lithofacies Q is interpreted to represent tractional processes resulting in wind-ripple laminae deposited on the aeolian dune surface. These bedforms are dependent on variable wind speeds during dune deposition. When wind speed increased and became too strong for ripple development and propagation, tightly packed, inversely graded planar laminasets were formed. Likewise, with a decrease in wind speed it is possible to create climbing-ripple laminae. Unlike subaqueous climbing ripples, foresets in aeolian climbing ripples are commonly difficult to distinguish due to their low relief (Brookfield, 1992). In addition, the stoss and the crest are commonly eroded during migration of the ripple, preserving only planar-laminated beds (Brookfield, 1992). It is herein interpreted that the planar bed lamination and climbing ripples are wind-ripple deposits formed either at the crest of the dune or near the dune apron (i.e., the basal portion of the lee side of the dune).

Another observed criterion, pin-stripe laminae (Figure 2.11), is also a distinctive feature of both modern and ancient aeolian strata (Fryberger and Schenk, 1988). This texture is especially useful in the outcrop studies (such as the study interval), wherein advanced weathering of exposed outcrop can enhance this textural feature.

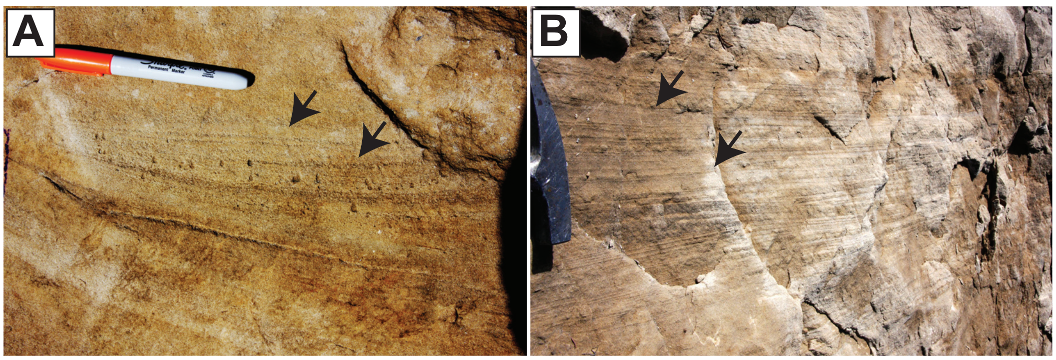

Figure 2.11: Pin-stripe laminae in Brown Hill aeolian strata.

Pin-striping can be produced during the small-scale processes of grainfall, avalanche, and ripple sedimentation, however in the case of lithofacies Q, it is most likely the result of migrating wind ripples. These bedforms likely produced an inverted grading of sand grains wherein coarser sand grains aggraded at ripple crests and finer sand grain settled in the ripple troughs (Figure 2.12). The coarser sand grains moved via saltation and were blown over the troughs of the ripples, allowing for the finer grained sediments to fall out and to be sheltered from the larger salting grains and settle in the troughs where they were not disturbed by eddies (Fryberger and Schenk, 1988). Fryberger and Schenk (1988) also suggest that electrostatic effects play a role in the accumulation of finer grained material in the ripple troughs. Preferential cementation of the finer grained material in the troughs produced the observed 'pin stripe' fabric. Subsequent differential weathering of outcrop surfaces increased the visibility of pin-striping because early carbonate cementation of finer grained sand increased the resistance to weathering, thus producing a relative surface of relief surrounding the pin-striping. Pin-striping of aeolian strata aids in identifying bounding surfaces (Figure 2.8, h) between aeolian deposits and is associated with first order bounding surfaces (Fryberger, 1993). Grainflow, grainfall, and wind rippled strata are sedimentary structures that are consistent with an aeolian interpretation for these lithofacies.

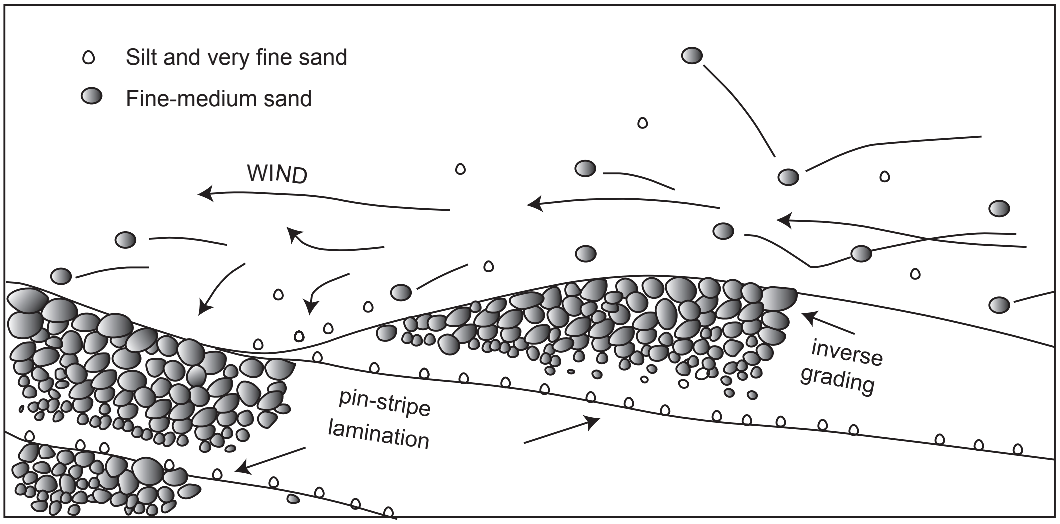

Figure 2.12: Schematic cross section of a wind ripple showing 'pin stripe laminae', a distinctive feature when interpreting aeolian strata. Inverse grading is the result of coarser grained material aggrading at the crests of ripples, while finer grained silts settle at the troughs. As the ripple migrates this creates an inverse grading of grains. Preferential cementation of the finer grained material in the troughs produces 'pin stripe' fabric. Modified from Fryberger and Schenk (1988).

While the structures observed in lithofacies P, Q, and S are primary in origin, the structures and textures observed in lithofacies R are secondary and are interpreted to be both syn-depositional and early post-depositional. Formation of contorted bedding in dunes can be attributed to slumping of weakly coherent sand blocks, flowage of saturated sand, pressure loading due to sediment overburden, and scour and fill by wind or water (Pye and Tsoar, 1990).

Aeolian interpretations for beds within the Charlie Lake Formation at Williston Lake have been discussed by several authors (Arnold, 1994; Gibson and Edwards, 1990; Zonneveld et al., 2001, Zonneveld et al, 2004). Aeolian deposits have also been reported from Middle and Upper Triassic strata in the Trutch Region of British Columbia, north of the present study area (Zonneveld et al., 2004) and in a number of areas in the subsurface east of the present study area (Klein and Woofter, 1989; Higgs, 1990; Jackson, 1990; Arnold, 1994; Davies, 1997b). These latter occur primarily in elongate shore parallel trends, and are significant hydrocarbon producers in the lower Charlie Lake Formation in a variety of fields (Klein and Woofter, 1989; Higgs, 1990; Jackson, 1990; Arnold, 1994; Davies, 1997b). Their origin and preservation is discussed in Chapter 3.

The aeolian sequences at Brown Hill are commonly encased in lacustrine or intertidal deposits, and are commonly associated with supratidal deposits including solution collapse breccias. Similar facies association relationships were observed in the Charlie Lake Formation in the Trutch Region (Zonneveld et al, 2004). Coastal dunes are affected by changes in wind strength, rainfall, and evaporation rates, as well changes in sea level (Pye and Tsoar, 1990).

FACIES ASSOCIATION 7: MEDIAL CARBONATE SHELF

Description

Facies association 7 (FA-7) is composed of only a single lithofacies (lithofacies T- fissile calcareous silty shale). It is found capping the Charlie Lake deposits at Brown Hill, and is characterized by dark grey, planar laminated, fissile calcareous silty shale. Sharp, planar but conformable contacts occur between each lamina-set. The basal contact is erosive and incises into the underlying silty sand stone deposits. It is associated with granule lag with abundant shell debris (Figure 2.5, b) and phosphatic detritus that grades into a phosphatic lag that is up to 5 cm in thickness. A low-diversity *Glossifungites*-demarcated discontinuity surface, characterized by small tubes (cf. *Planolites*), *Skolithos* and *Thalassinoides* demarcates the base of the unit (Figure 2.5, a). This unit has been observed to contain marine fossils including conodonts, fish teeth and probable ichthyosaur bone (Zonneveld and Orchard, 2002).

Interpretation

Facies association 7 (FA-7) is a fissile grey shale and is the most distal marine facies observed in the study areas. Facies association 7 is interpreted to be a marine flooding surface that demarcates the base of the Baldonnel Formation, and signifies transition from restricted marine deposits of the Charlie Lake to the open shelf environment of the Baldonnel Formation. This succession has elsewhere been interpreted to be a medial carbonate shelf succession (Zonneveld and Orchard, 2002). The base of the Baldonnel marks the beginning of an overall deepening upwards event and heralds a return to marine deposition in the Williston Lake Triassic.

Discussion and Depositional Model

The mid-latitudinal location of the supercontinent Pangaea at the time of Charlie Lake deposition resulted in an arid to semi-arid climactic regime. Decreased fluvial occurrence, and predominance of aeolian sediments are hallmarks of arid coastal succession.

The extensive distribution of evaporite minerals in the Charlie Lake Formation in the subsurface suggests arid conditions during the Triassic (Gibson and Barclay, 1989; Zonneveld et al., 1997). The presence of a solution collapse breccia in outcrop suggests that dissolution of this facies occurred. Mixed siliciclastic-carbonate sedimentation, like that observed at Schooler Creek and Brown Hill, occurs primarily within arid settings characterized by low input of clastic sediment to the shoreface (Gostin et al., 1984; Flessa and Ekdale, 1987; Belperio et al., 1988, Zonneveld et al, 2001). It has been suggested that input of siliciclastic sand to the shoreface was likely derived from three sources including: aeolian input from land, fluvial input, and longshore drift, likely from the north (Zonneveld et al, 2004).

Although Brown Hill and Schooler Creek are composed of many of the same lithofacies and facies associations representing an overall arid coastal setting, there are several significant differences between the 2 outcrops that places the Brown Hill sediments at a much more distal position in the depositional model, and Schooler Creek more proximal to the shoreface (Figure 2.13).

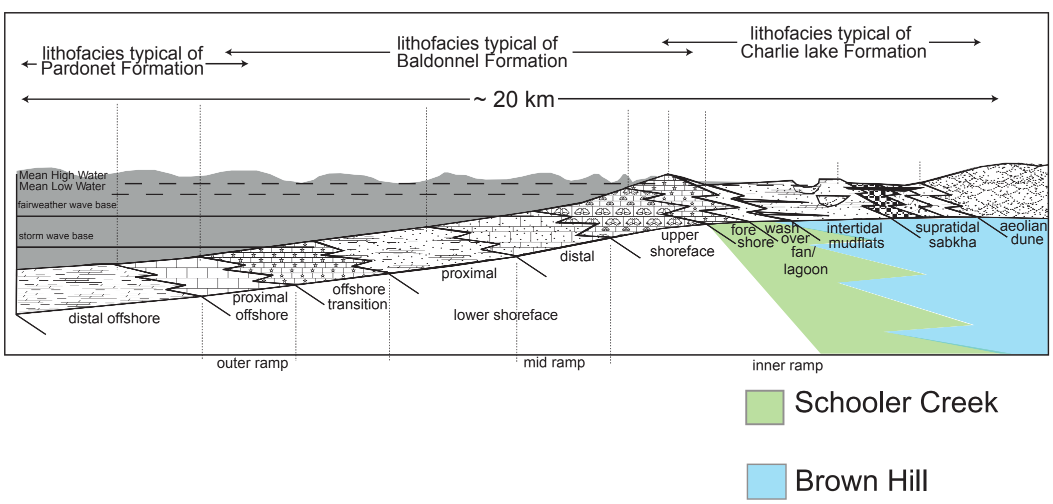

Figure 2.13: Depositional model for Upper Triassic strata (Charlie Lake, Baldonnel and Pardonet formations) in northeastern British Columbia. Brown Hill strata is deposited at a more landward position than the sediments at Schooler Creek; modified from Zonneveld (2008).

Brown Hill, the more southeastern location, has facies associations that place it in the intertidal to sabkha region of the inner ramp. At Brown Hill, lagoonal deposits indicate a barrier was present, with less tidal influence, and a mixed siliciclastic regime in which lacustrine, lagoonal, aeolian, and intertidal deposits are interbedded, and form 13 progradational packages. Brown Hill facies associations are primarily marginal marine and continental deposits. At Schooler Creek, a significant shift is observed with facies associations generally being decidedly more basin proximal than those observed at Brown Hill. At Schooler Creek the presence of shoreface/ washover fan deposits encased in intertidal and supratidal deposits, suggests that this area was not restricted as observed to the intertidal and supratidal facies of Brown Hill. Furthermore, the absence of a lagoonal facies suggests moreover the absence of a barrier to the north. A particular section of strata at Schooler Creek shows a conformable sediment package thatwas interpreted as a shoreface-washover fan deposit, showing unidirectional climbing ripples, grading into bi-directional oscillatory ripples, topped by planer laminated sand. The orientation of the ripple foresets indicates a near parallel slice through the ripple, in which a northerly current flow direction can be inferred. It appears that a temporary increase in sediment and/or energy occurs briefly before a decrease in energy occurs, an return to bi- directional current flow, and a final drop in energy results in laminar flow of sand. Combined flow ripples (Figure 2.14) are indicative of increased sedimentation rates, and in addition to contorted bedding and changing flow regimes (indicated by changing bed morphologies) further cements the notion that there is no barrier at Schooler Creek.

In addition to having no lagoonal facies, Schooler Creek also shows no sign of lithofacies K- the intraclast breccia (interpreted as a solution collapse breccia). The absence of breccias to the west has been noted in previous studies (Pelletier, 1965) and there it was suggested the most of the Charlie Lake Formation is evaporitic and is found on the land sand of offshore bars. A decreased level of ephemeral lacustrine activity may be partially responsible for the absence of this facies; at Brown Hill lacustrine facies are sometimes found adjacent to (and younger) than breccia deposits. These lacustrine deposits may provide a reservoir in which the water can become supersaturated and result in thick evaporate deposits. The lack of playas may be attributed to the diminished dune prevalence at Schooler Creek. In modern environments, like the Coorong region in Australia, migration of aeolian dunes can block tidal channels and channels and leads to the development of coastal saline lakes where evaporation is the dominant process (Belperio et al, 1988).

Further evidence to support the distal position of the Schooler Creek Charlie Lake deposits can be found by examining the lamination thickness of lithofacies J at Schooler Creek and Brown Hill. At Schooler Creek, lithofacies J not only displays substantially thicker deposits than lithofacies J at Brown Hill, but those that are more thinly and frequently interbedded. This increase in lamination frequency in tidal sediments can be relatively indicative of proximity to shore, as the laminae generally result from spring or storm tide deposition (Shinn, 1983). Thicker laminated deposits are found more landward than thinly laminated tidal sediment (Shinn, 1983). This again reiterates that the tidal deposits at Schooler Creeks sits at a more marine-proximal position, than Brown Hill. The thickness variation in the tidal deposits between Schooler Creek and Brown Hill can be attributed to climatic factors; distribution of algal mats is determined largely by ecological factors, as even a subtle difference in climate can dramatically change the composition or morphology of an algal mat (Golubic, 1976).

The postulated depositional environment of the Charlie Lake sediments at Brown Hill and Schooler Creek is a tidal influenced arid sabhka-like environment, each outcrop showing a series of progradational or regressive event packages. Brown Hill is inferred to have 13 progradational shoaling up sequences, while School Creek has a total of 15 progradational cyles.

IMPLICATIONS OF PRESERVATION OF THE CHARLIE LAKE FORMATION

Both the Liard and Baldonnel formations represent fully marine depositional conditions. The entirety of the Charlie Lake is comprised of mostly non-marine strata, which by nature tends to have a lesser affinity for preservation. Preservation of a thick package of marginal and non-marine facies in a western geographic setting implies the abrupt creation of accommodation space in a setting that should have low accommodation. Although evidence in this study is not conclusive, preservation of the

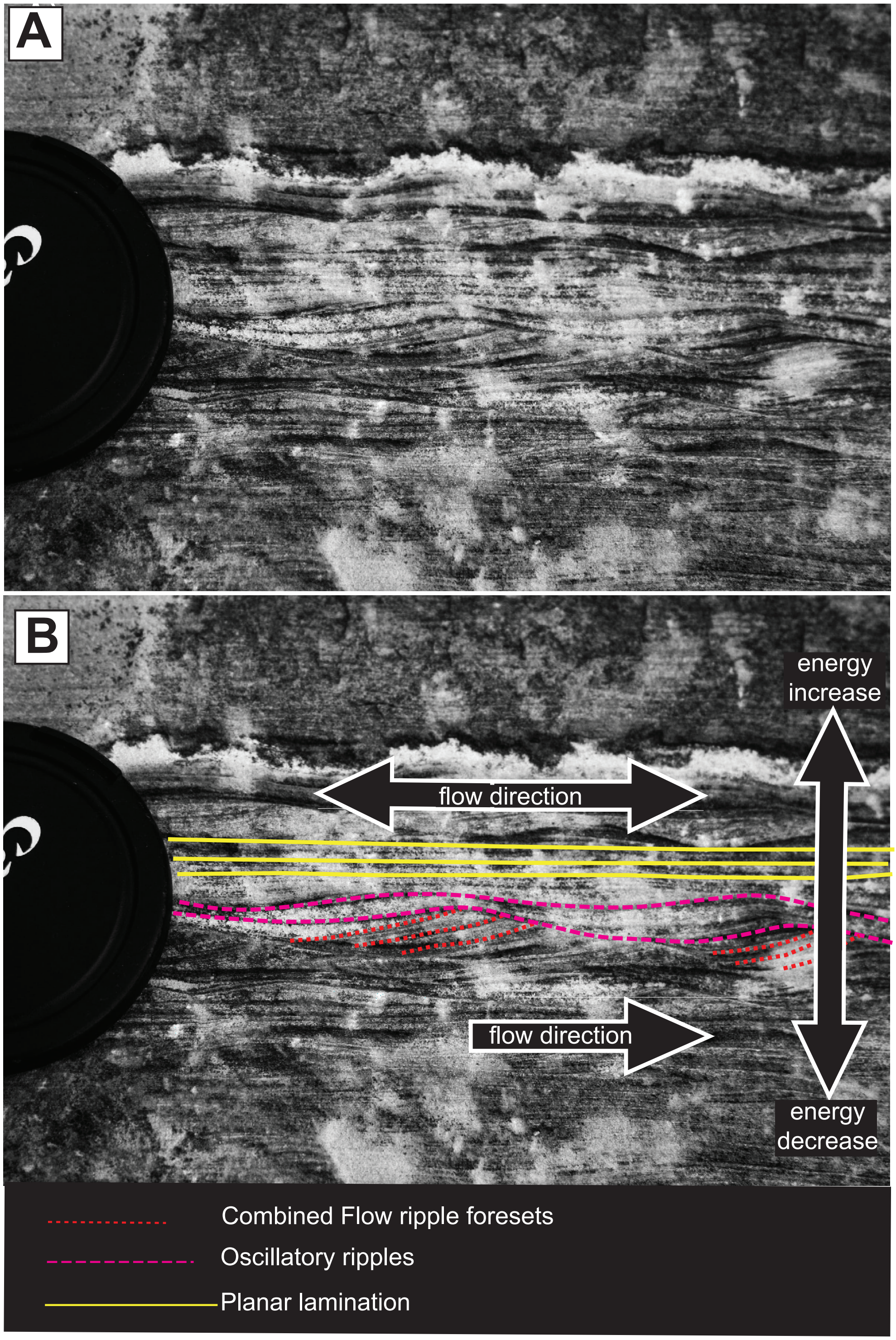

Figure 2.14:
a) Original Photo, ~65 metres Schooler Creek
b) This conformable sediment package shows unidirectional combined flow ripples, grading into bi-directional oscillatory ripples, topped by planar laminated sand. The orientation of the ripple foresets indicates a near parallel slice through the ripple, in which a northerly current flow direction can be inferred. It appears that a temporary increase in sediment and/or energy occurs briefly before a decrease in energy occurs, a return to bi- directional current flow, and a final drop in energy results in laminar flow of sand.

succession here, and the presence of an angular unconformity to the east, clearly suggests a tectonic influence in the creation of the accommodation space that allowed the preservation of the unit.

The Coplin unconformity is a tectonically induced angular unconformity. Paleontological dating of the Upper Liard at Brown Hill identifies it as medial to upper Carnian in age (Zonneveld, 2011, personal communication). The basal Baldonnel at Brown Hill is Middle-Upper is Upper Carnian to Lowermost Norian, and has been dated from conodonts (Zonneveld and Orchard, 2002).

Tectonism did not play a role in Early Triassic sedimentation (Zonneveld et al, 2010), but it appears that by the Carnian, tectonic forces were in affect that allowed for preservation of a thick package of strata, with typically low preservation potential.

Conclusion and Summary

The Brown Hill and Schooler Creek outcrop were rigorously evaluated and analyzed. The postulated depositional environment of the Charlie Lake sediments at Brown Hill and Schooler Creek is tidally influenced arid sabhka-like environment. Both outcrop have a series of progradational or regressive event packages. Brown Hill is inferred to have 13 progradational shoaling up sequences, while Schooler Creek has a total of 15 shoaling up sequences. Although Brown Hill and Schooler Creek are composed of many of the same lithofacies and facies associations representing an overall arid coastal setting, significant observations made between the 2 outcrop indicates that the Brown Hill strata are at a more landward position than Schooler Creek in the depositional model.

Sedimentological indicators such as pin-stripe lamination, high angled bedding, and inversely graded laminae aided in identification and interpretation of aeolian deposits. Detailed observations of the two outcrop in this study lend itself to several conclusion regarding the aeolian sand bodies:

1. The presence of aeolian sand bodies decrease both in size and frequency to the north and the to the west (7 aeolian occurrences at Brown Hill vs. 4 at Schooler Creek). Aeolian sands occur more distal to the shoreface and are found amongst predominately supratidal and lacustrine deposits. The depositional edge of the Charlie Lake Formation occurs the northwest of Brown Hill, as indicated by the increased inter-fingering of fully marine strata at School Creek.

2. When they occur, the aeolian sand bodies are usually the last deposited unit in a progradational package or are subsequently overlain by a solution collapse breccia or lacustrine deposit.

3. An aeolian deposit is not always a portion of a progradational package.

4. Aeolian preservation seems to be related to migration of dune over playas, or solution collapse deposit.

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CHAPTER III – SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CHARLIE LAKE FORMATION, BRASSEY FIELD (ARTEX RESERVOIR), NORTHEAST BRITISH COLUMBIA, CANADA.

Abstract

Hydrocarbon production from the Lower Charlie Lake Formation (Upper Triassic) of northeastern British Columbia occurs primarily from sandstone units such as the Artex Member. Brassey Field has proven to be one of the most prolific fields producing from the Artex Member. At Brassey Field, the Artex Member comprises an aeolian sand dune succession encased in an anhydritic and dolomitic interdune/supratidal sabhka package. Despite the economic importance of this member, few studies have focused on the sedimentology of this interval; consequently, the facies relationships, geological history and depositional controls of this member remain poorly constrained.

Detailed core analysis and petrography, augmented with wireline log correlations, has aided in the development of a preliminary facies model for the Artex Member at Brassey Field. Ten lithofacies, grouped into three facies associations, have been identified. These facies associations are interpreted to record deposition in aeolian sand dune, interdune/supratidal sabhka, lagoon and lake, and transgressive shoreface environments. Reservoir quality lithofacies are limited to a ~1-4 metre thick sandstone interval interpreted as an aeolian dune succession. Net reservoir thickness is a function of total sandstone thickness minus the proportion of sandstone with pervasive porosity-occluding cements (primarily anhydrite). These cements are interpreted to be early post-depositional and are related to dissolution of gypsum and anhydrite interbeds that interfinger with other rock types in the interdune/supratidal flat successions and consequent re-precipitation within the sandstone intervals. The Artex Member in Brassey Field is preserved within a local topographic depression preserved on the surface of the underlying Halfway Formation. Recognition of these depressions is critical to aid in the development of predictable models for the Artex Member sand.

Introduction

The Middle–Upper Triassic (Late Ladinian to Carnian) Charlie Lake Formation occurs extensively in both outcrop and subsurface of northeastern British Columbia. It is a lithologically diverse succession of primarily non-fossiliferous mixed siliciclastic, carbonate and evaporitic rocks. These rocks have been interpreted to represent deposition in sabhka or arid back-barrier depositional settings (Arnold, 1994; Higgs, 1990). Adjacent formations consist of the older (underlying) Middle Triassic (Ladinian) Halfway Formation and the younger (overlying) Upper Triassic (Carnian) Baldonnel Formation. These units are composed of rock types that are easily distinguished from the Charlie Lake Formation and thus formation contacts are easily distinguished in drill core and on petrophysical logs. The Halfway Formation has been described as a fossiliferous marine sandstone succession that is a lateral, temporal equivalent to the Charlie Lake Formation (Arnold, 1994; Caplan and Moslow, 1997). Consequently, the transition from the Halfway to the Charlie Lake Formation represents a marine-continental regression that is gradational in some areas of the basin but appears to be sharp and abrupt in others. The contact between the Halfway Formation and the Charlie Lake Formation is conformable in many areas (Arnold, 1994) including the study area, although it has been argued to be unconformable in other areas (Caplan and Moslow, 1997; Zonneveld et al., 1997; Young, 1997; Dixon, 2005). The overlying Charlie Lake–Baldonnel Formation contact consists of a shift to fossiliferous limestone and dolomite (Zonneveld and Orchard, 2002). This contact is conformable and gradational in many parts of the basin but is demarcated by an abrupt erosional surface in others (Davies, 1997a; Zonneveld and Orchard, 2002; Zonneveld et al., 2004).

Triassic strata account for approximately 40% of oil reserves and 25% of natural gas reserves in British Columbia, making this unit both of economic and academic interest (BCOGC, 2001). Several sand-dominated, commonly hydrocarbon-bearing members of the Charlie Lake Formation occur above the thick Halfway Formation sandstone succession (e.g., the Siphon, Inga and Artex members). As recognized by several authors (e.g., Dixon, 2007), facies descriptions in the Charlie Lake Formation have been lacking, due in part to the fact that the majority of cored intervals are sparse and in many areas are limited to the basal units of the Charlie Lake Formation below the 'A' marker, a locally fossiliferous limestone of marine derivation. Several studies have focused on the regional extent and stratigraphy of Charlie Lake Formation sandstone bodies and the relationship of the Charlie Lake Formation to underlying strata (Higgs, 1990; Young, 1997; Dixon, 2007) however detailed sedimentary descriptions have not been provided.

The best known of these sandstone intervals consists of the Artex Member, which occurs in the basal beds of the Charlie Lake Formation. The Artex Member produces hydrocarbons in several of parts of the basin in British Columbia. It has most commonly been exploited as a secondary target encountered in Halfway Formation exploration and development wells. An exception to this is the Brassey Field (Figure 3.1), the focus of the present study, where production occurs primarily from the Artex Member.

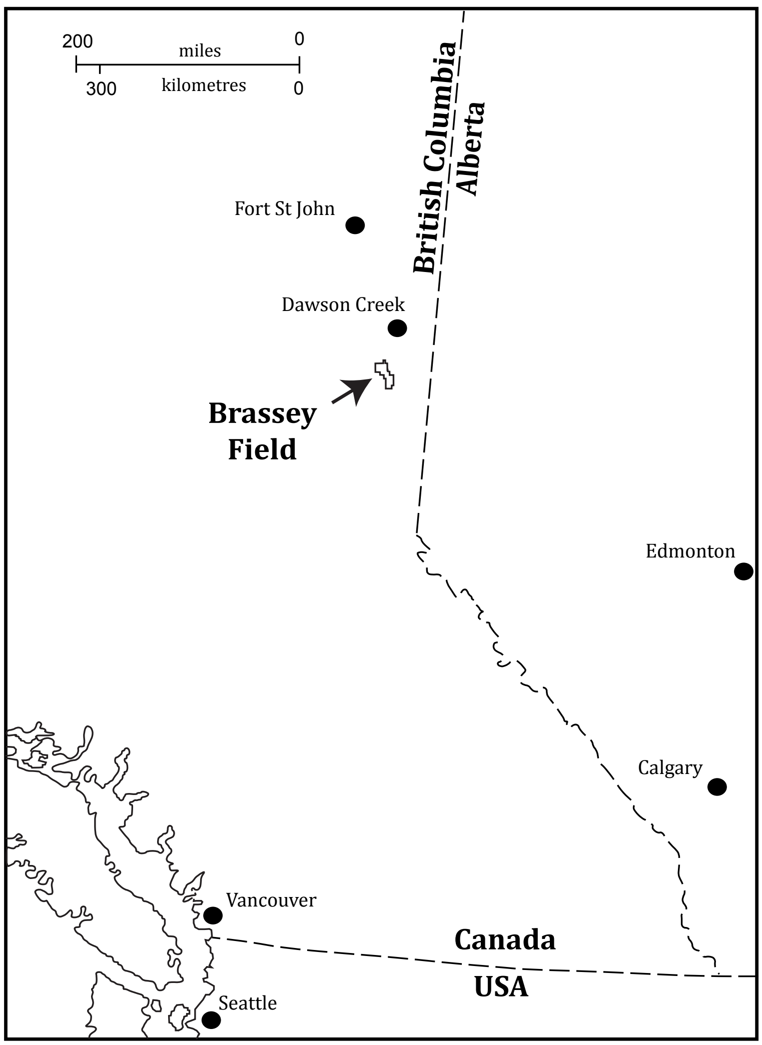

Figure 3.1: Location of the Brassey Field, northeastern British Columbia; modified from Woofter and MacGillivray (1990).

The discovery of the Brassey oil pool in 1987 by Canadian Hunter Exploration Limited sparked renewed economic interest in the Charlie Lake Formation, particularly in hydrocarbon bearing sandstone beds such as the Artex Member in the lower Charlie Lake Formation (Stewart, 1984). The name Artex (an anagram of the word 'extra'), was first published by Stewart in 1984 to describe a distinctively cross-bedded sandstone interval in the lower Charlie Lake Formation (Higgs, 1990). Although the name forgoes traditional stratigraphic nomenclature protocol (usually references a geographic locale) formal member status for the zone was proposed and eventually granted (Higgs, 1990). The Artex Member has excellent reservoir parameters, including: an average porosity of 16%, average permeability of 152 mD, and 57° API oil (Woofter and MacGillivray, 1990). The Brassey Field has produced over 13 MMBLS or 2176.1 E^3m^3 to date (Accumap, 2011).

The Artex Member in Brassey Field has been the focus of several investigations since its discovery (e.g. Klein and Woofter, 1989; Higgs, 1990; Woofter and MacGillivray, 1990). Previous studies have focused mainly on stratigraphic, engineering and development aspects (e.g., Higgs, 1990; Woofter and MacGillivray, 1990). The aeolian interpretation, first postulated by Klein and Woofter (1989), and accepted by all subsequent workers, is consistent with the dominance of high-angle cross-bedded sandstone beds within an interval dominated by dolostone anhydrite and dolomitic siltstone (Arnold, 1994). Higgs (1990) suggested that the sandstone 'thicks' represent aeolian dunes whereas the sandstone 'thins' represent associated interdune areas. The presence of an adjacent dolomitic mudstone facies prompted Higgs to infer a coastal setting for the dunes deposits (Arnold, 1994).

Woofter and MacGillivray's 1990 study focused mainly on the development of a miscible flood program for enhancing hydrocarbon production in Brassey field, but also discussed some of the unique sedimentological characteristics of the sandstone interval; in particular the high-angle cross-beds interpreted as grain flows, high to low-angle wind-ripple laminae, and massive to contorted sandstone beds. They inferred that the prevalence of wind-ripple lamination over grain-flow cross stratification resulted from bi-directional wind currents. Excellent core control, and some limited oriented-core data within the field supports the hypothesis that the primary wind direction was from the north-northeast with a secondary wind direction from the northwest causing the aeolian dunes to migrate in an orientation oblique to the primary wind direction (Woofter and MacGillivray, 1990).

The present investigation focuses on the process sedimentology and petrography of reservoir and host rock intervals within the study area and tests the premise that the Artex Member at Brassey Field consists of a buried aeolian dune succession. A clearer understanding of the sedimentary framework of this unit is essential for petroleum exploration and development. To date, predictive facies models are lacking for this reservoir interval despite its economic importance and the potential for other analogous successions in the thick Charlie Lake Formation.

Study Area Description

Brassey Field, the focus of the present investigation, is located in northeastern British Columbia, approximately 60 kilometres southwest of the town of Dawson, Creek (Figure 3.1). The field is oriented approximately northwest-southeast, and straddles the northern part of the 93-P-10 NTS block and the southern boundary of the Peace River township block in the area of Township 77, Range 19, West of the 6th Meridian. Brassey Field consists of 5 pools (A-E) that vary in size, but consist of elongate bodies oriented in a northwest-southeast direction (Figure 3.2).

Geological Setting

Deposition of Triassic sediments in the Western Canada Sedimentary Basin occurred along a westward-facing continental shelf on the western margin of the topographically low North American craton (Zonneveld et al., 2001). Accumulation occurred in an extensional basin along the northwestern margin of Pangaea on the eastern shore of the Panthalassa Sea or proto-Pacific ocean (Arnold, 1994; Davies, 1997 a, b). Triassic strata form a wedge-like deposit that is thickest in the west-southwest and thins to the east-northeast where it is truncated by Jurassic and Cretaceous erosional unconformities. The resultant northwest-southeast oriented belt of preserved sediment stretches from the Yukon to southern Alberta (Arnold, 1994). In the subsurface, the Charlie Lake Formation varies in thickness from

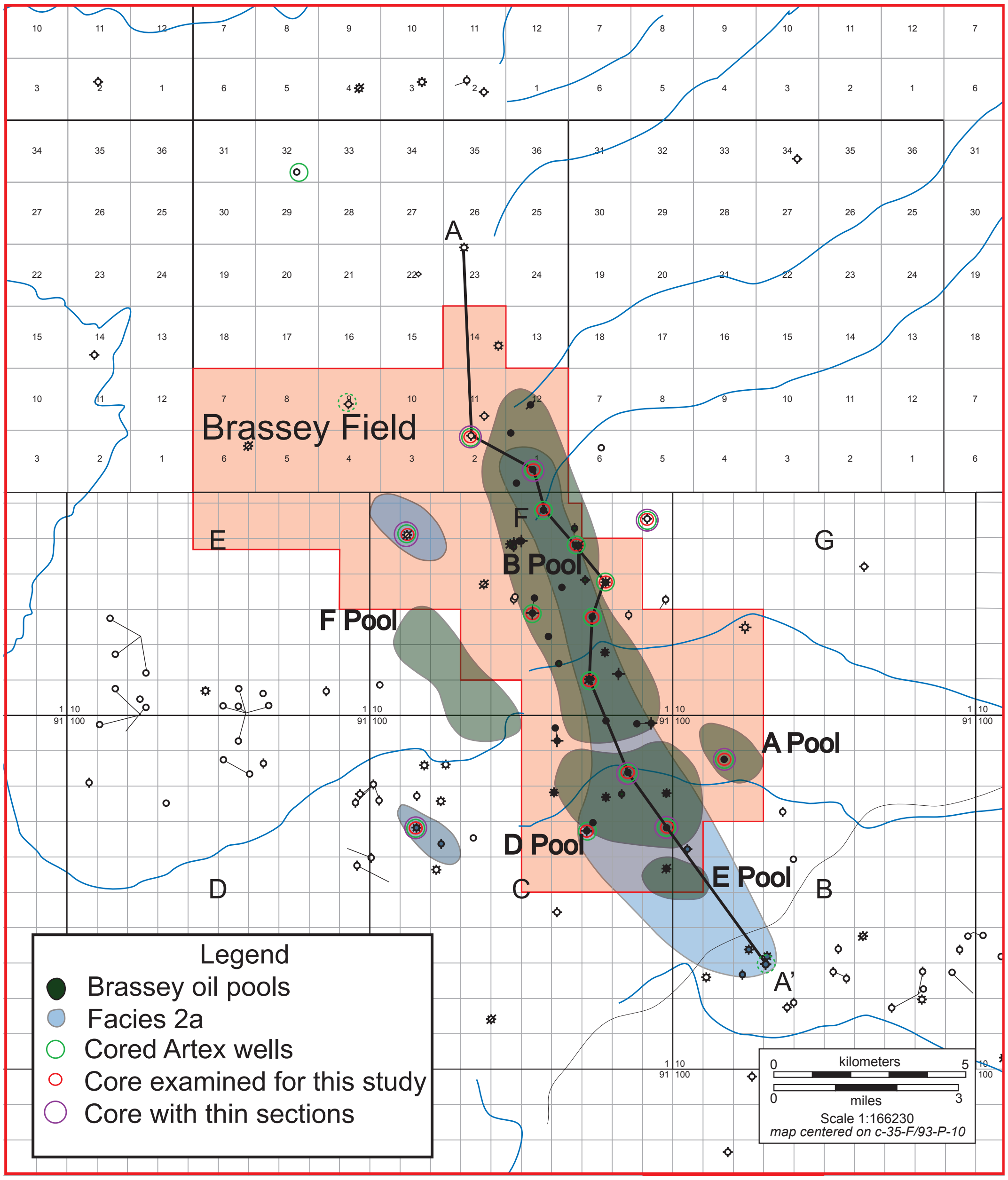

Figure 3.2: Facies and oil pool map of the Brassey Field.

zero in the extreme east and north to over 550 m (1804 feet) adjacent to the foothills south of Peace River (Glass, 1990). The north and eastward thinning of the unit is attributed to both erosional factors (unconformities and later Jurassic erosion), and depositional effects (Gibson and Edwards, 1990 a, b). The subcrop edge tracks southeast through northern British Columbia into west-central Alberta, resulting in the majority of economically viable Charlie Lake formation lying within the province of British Columbia (Figure 3.3).

It is estimated that the latitude at time of deposition was around 32°-34° north of the equator (Habicht, 1979; Irving et al, 1985). Extensive evaporite mineral deposits within the Charlie Lake Formation, usually observed in drill core, suggest that arid conditions prevailed during deposition (Gibson and Barclay, 1989; Zonneveld et al., 1997). The Charlie Lake Formation in the study area is restricted to marginal marine and continental sedimentation, with deposits accumulating in environments such as aeolian sand dunes, interdune/supratidal sabhka, lagoonal and lacustrine / paludal, with a single thin interval interpreted as transgressive shoreface deposits at the top of the succession (Fefchak and Zonneveld, 2010). Supplemental paleocurrent

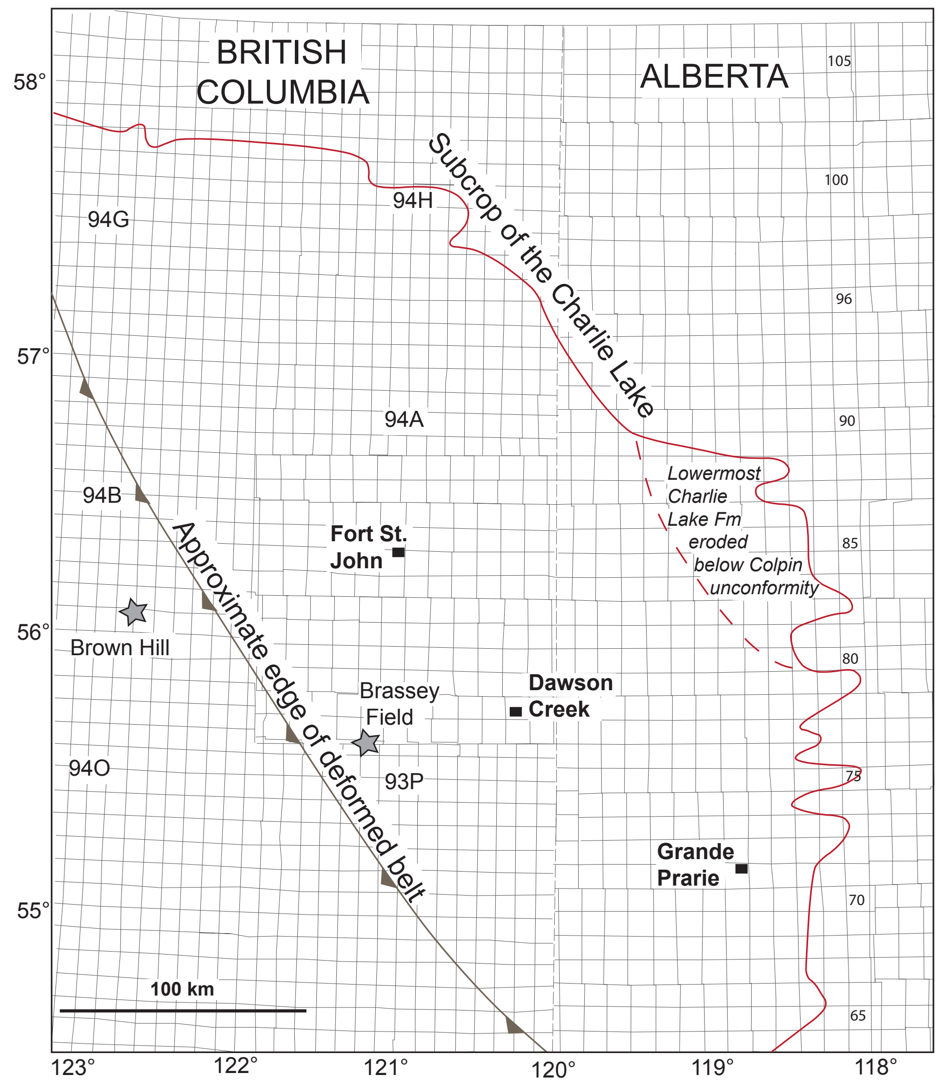

Figure 3.3: Extent and subcrop of subsurface Charlie Lake Formation throughout British Columbia and Alberta; modified from Dixon (2007). Brassey Field and Brown Hill (Chapter 2) denoted.

measurements of aeolian sandstone beds, both from the Brassey Field as well as in outcrop indicate a dominant northeast to southwest oriented wind direction (Pelletier, 1965; Arnold, 1994).

TECTONIC ACTIVITY DURING DEPOSITION

In the western Cordillera of North America, widespread Triassic igneous and carbonate rocks have been interpreted as island arc volcanics and reefs which accreted on the North American Craton during subduction of the Panthalassan ocean (Monger et al, 1982; Tozer, 1981; Monger, 1989). Some researchers believe that tectonic influence were absent during the Triassic (Tozer, 1981; Gibson and Barclay, 1989) however a growing body of research suggests that tectonics played an active role (Richards, 1989; Barclay et al., 1990; Ferri and Zonneveld, 2008). Most workers have suggested that docking of the accreted terranes that comprise the British Columbia Cordillera occurred during the late Jurassic and Cretaceous and thus had no bearing on Triassic deposition (Coney et al, 1980; Tozer 1981). Although many researchers have suggested that the lower Triassic Charlie Lake formation was deposited during an interval in which tectonic influences were relatively minor (Tozer, 1981; Dixon, 2005) the presence of major unconformities, including major angular unconformities such as the Coplin Unconformity, bifurcate the Charlie Lake Formation across the entire basin and can only be attributed to Triassic tectonic influences. As well, a variety of pre-existing geological structures, particularly the Peace River arch, strongly influenced Triassic sedimentation in western Canada (Richards, 1989; Henderson, 1989; Barclay et al, 1990; O'Connell et al 1990).

Methods

CORE AND THIN SECTION ANALYSIS

Fifteen drill core from within and around the Brassey Field were examined, described in detail and sampled for petrographic analyses. Although the drill core varied in length, they provided representation of all lithofacies in, and around, the primary reservoir unit. Ten distinct facies and subfacies (summarized below) were identified. Drill core used in this study were chosen to represent intervals both within the primary reservoir pools as well as those outside the pools to aid in developing criteria for establishing proximity indicators and constructing a predictive facies model.

Drill core analyses focused on the documentation of grain-size, lithology, texture, primary and secondary sedimentary structures, cement composition and pervasiveness, and ichnology, in addition to bedding contacts and other observable characteristics in the rock. Additionally, several of the drill core were calibrated to attain correct positioning with wireline log. 45 samples were taken for further visual thin section analyses and were observed using a Zeiss Axio Imager A1 Transmitted Light petrographic compound microscope. The Wentworth scale (Wentworth, 1922) was used to assess grain size. To describe and evaluate bioturbated strata, bioturbation indices (BI) were assessed following the protocol outlined in Taylor and Goldring (1993). This system assigns a relative number grade (1-6) to bioturbated sediment to quantify the relative degree of syn- and post-depositional biogenic reworking.

Textural components often used to describe and interpret aeolian environments are typically less visible in drill core than in outcrop because natural weathering can highlight diagnostic criteria such as grain-size variations in the laminae and because drill core are limited in lateral extent (rarely wider than 8-10 cm) and large scale bed forms can not be viewed in their entirety. In addition, intense internal heterogeneities, due in part to advanced post-depositional diagenesis, has affected reservoir quality and has likely destroyed or obscured some of the textures and structures useful for interpretation. Despite this, it is apparent that lithofacies distribution remains the primary control on the extent, shape and quality of the reservoir.

A detailed summary of the sedimentological observations, gamma ray profile, facies information, and thin section samples from the observed drill cores (compiled into strip logs) is located in the Appendix. In addition, a comprehensive table (Table 3.1) summarizes the individual lithofacies, and is arranged by facies association.

TABLE 3.1- Chapter III Facies Table

LITHO-FACIES	LITHOLOGY	PHYSICAL AND BIOGENETIC SEDIMENTARY STRUCTURES	OTHER CHARACTERISTICS	FOSSILS/ TRACE FOSSILS	DEPOSIT-IONAL ENVIRON-MENT
F1	Dolomitic bioturbated siltstone	• dolomitic bioturbated siltstone with common very fine grained sand laminae • oscillatory ripples (visible within lightly mottled intervals) • interbedded with both light and dark mud beds, 3–6 cm thick. • rare vuggy intervals (0.4 to 1.0 cm); most commonly filled with calcite or anhydrite cement, but unfilled examples were also observed	• traces are dominated by relatively simple forms, with variable orientations including horizontal, vertical and inclined • bioturbation index ranges from light to moderate (BI 1–BI 5). • moderate porosity characterize this subfacies; however, permeability is lacking.	• *Skolithos, Trichichnus, Scoyenia*	ephemeral lagoon
F1A	Dolomitic bioturbated siltstone with vugs	• same characteristics as F1 but with vuggy porosity • vugs range in size from 0.4 to 1.0 cm • occur most commonly filled with calcite or anhydrite cement, but unfilled examples were also observed • patches of moderate porosity characterize this subfacies • permeability is lacking.	• see above	• see above	ephemeral lagoon
F2A	Trough cross-stratified sandstone	• very fine to medium-grained sandstone • abundant patchy anhydrite and/or calcite • anhydrite nodule morphology varies with diameters ranging from <1 cm to >3 cm • average foreset inclinations of ~20–25° • low-angle (<10°) cross-strata (with identical grain-size, oil staining and porosity) occurs intermittently interbedded with the steeper beds • common oscillatory ripples	• porosity is dominantly dependent on the degree of anhydrite cementation • porosity ranges from nearly zero to relatively high (>15% from a visual estimation of thin sections) • often stained with micrinite bitumen, as noted by Klein and Woofter (1989) • erosive contact with the underlying facies • average thickness is variable, but is usually approximately 1–3 m	none observed	aeolian dune (grain flow deposit)
F2B	Massive well-sorted fine- to medium-grained sandstone	• fine- to medium-grained sandstone, generally massive in occurrence • moderately- poorly sorted sand with a bimodal nature. • rare convolute bedding, distinguished by faint, distorted laminae • oscillatory ripples • pervasive anhydrite and/or calcite cementation	• poor porosity and minimal permeability •convolute, load-casted basal contacts to this facies	none observed	aeolian dune transported into interdune areas
F3	Dolomitic anhydrite sitstone	• dolomitic siltstone with abundant calcite-replaced anhydrite nodules • nodules are relatively small (<0.5 cm) and are circular to subcircular • devoid of sedimentary and biogenic structures	• low porosity and virtually no permeability • predominantly light grey in colour but was observed to have a reddish hue in some samples	none observed	Sabkha/ supratidal

F4	Planar to low-angle fine-grained sandstone	• very fine to fine-grained sandstone • planar laminated to low-angle crossbeds (<8°) •faint coarsening-upward trends are visible •nodular (<1 cm) anhydrite cement •rare to common coarser laminae (up to medium grained)	• gradational, nonerosional contacts with the adjoining facies • average thickness is about 20 cm (F2 is considerably thicker)	none observed	aeolian dune (wind ripple deposit)
F5	Planar to convolute laminated dolomitic mudstone	• very fine to fine-grained sandstone • planar laminae and low-angle crossbeds (<8°) • rare, faint coarsening-upward trends • rare to common coarser laminae (up to medium grained) • common anhydrite cement in the form of nodules (<1 cm)	• gradational, nonerosional contacts with the adjoining facies • average thickness of this facies is about 20 cm	none observed	intertidal/ supratidal
F6	Laminated dolomitic mudstone and siltstone	• parallel laminated siltstone with alternating mudstone laminae • lens-like appearance of the silt. • faint oscillatory ripples are common	• upper surface of this facies where ripples are truncated by subsequently deposited erosive facies.	none observed	interdune
F7	Planar bedded anhydrite	• low-angle (8–12°) crossbeds • small-scale unidirectional ripples common • lacks biogenic structure(s)	• nonerosional contacts with the adjoining facies • average thickness of this facies is about 10-15 cm • very low porosity and permeability, acts as fluid barrier within the reservoir	none observed	aeolian dune/ dry interdune area
F8	Dolomitic siltstone with convolute-bedded nodules	• interbedded crystalline calcite (replacing anhydrite) and dolomitic siltstone • planar anhydrite beds that underwent subsequent disturbances resulting incontorted layers of calcite-replaced anhydrite	• thickness varies, but most commonly ranges between 9 and 12 cm in thickness • usually above subfacies F2b (fine-grained convolute-bedded sandstone)	none observed	Sabkha
F9	Massive undifferentiated siltstone	• characterized by massive dolomitized siltstone • lacks discernible bedding or internal structure • rare mud drapes and common pyrite occurrences • rare, very fine grained sandstone laminae	• non erosional contacts with the adjoining facies	none observed	ephemeral lagoon
F10	Calcareous siltstone-limestone	• fossiliferous, dolomitic bioclastic wackestone, packstone and rarely grainstone consisting of poorly sorted silt- and clay-sized grains • recrystallizedfossil debris (echinoderms, brachiopods, bivalves and gastropods) and framework grains of calcite are most visible in microscopic analysis.	• characterized by an erosive base and is commonly situated on convolute-bedded mudstone (F5) • Dolomitized mudstone rip-up clasts are common	• echinoderms, brachiopods, bivalves, gastropods • *Thalassinoides, Planolites*, *Teichichnus* • *Glossifungites*-demarcated surface	regional marine incursion

Facies Descriptions

FACIES 1: DOLOMITIC BIOTURBATED SILTSTONE (F1)

Facies 1 is a dolomitic bioturbated siltstone with common silt or very fine-grained sand laminae. This facies is characterized by a mottled or clotted texture (Figure 3.4 a,b, 3.5, c).

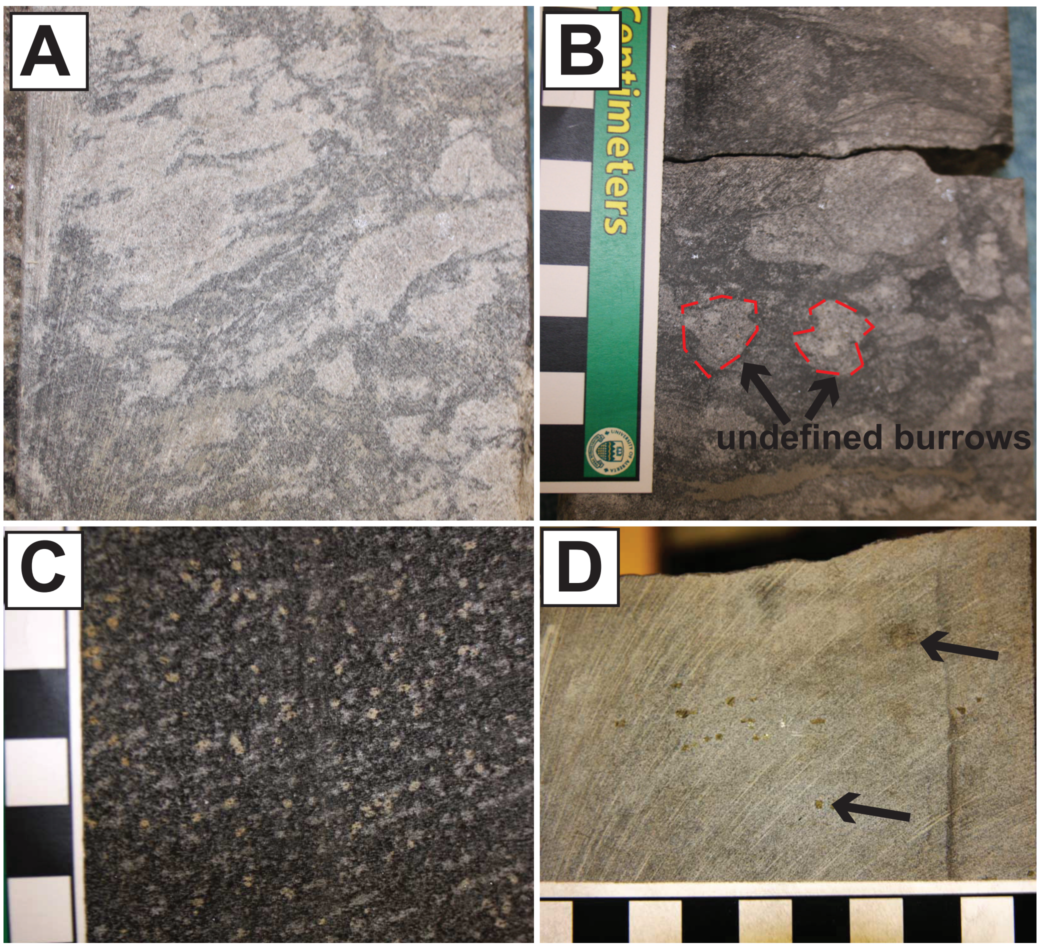

Figure 3.4:
a, b) Facies 1 (dolomitic bioturbated siltstone) exhibiting mottled or clotted texture. B shows moderate bioturbation (BI 2-3) and display undifned, predominately simple inclined and horizontal tubes (c.f. *Planolites*). From (a) 14-2-19W6, (b) A-82-C/93-P-10
c) Subfacies 2a; primarily fine- to medium-grained, trough cross-stratified sand, with foreset inclinations of ~20–25°. From A-82-C/93-P-10
d) Pyrite occurring in F9; C-63-C-93-P-10.

The 'mottling' is a result of variable syndepositional bioturbation (Zonneveld et al., 2001). The traces are dominated by relatively simple forms with variable orientations including horizontal, vertical and inclined (such as *Planolites* and *Skolithos / Trichichnus*). More rarely meniscate, back-filled traces (cf. *Scoyenia*) were also observed. The bioturbation index ranges from low to moderate (BI 1-BI 3), although rare examples attain BIs of ~6. Sedimentary structures (visible within lightly mottled intervals) include oscillation ripples (Figure 3.5 a, b). Facies 1 is commonly interbedded with both light and dark mud beds, 3-6 cm thick. A single subfacies (F1A) was identified to further describe a variant of this lithofacies characterized by vuggy porosity. The vugs range in size from 0.4 to 1.0 cm. They occur most commonly with either calcite or anhydrite cement fills, but unfilled examples were also observed. Patches of moderate porosity characterize this subfacies; however, permeability is lacking.

FACIES 2: WELL-SORTED FINE- TO MEDIUM-GRAINED SANDSTONE (F2)

Facies 2 is characterized by very fine- to medium-grained sand. The cement consists primarily of patchy anhydrite and/or calcite. Cementation is the primary porosity inhibitor (Figure 3.5 d,e,f) within this reservoir subfacies, and ranges from nearly zero to relatively high (>15% from a visual estimation of thin sections).

The pervasiveness of the anhydrite cement ranges from light to heavy. Significant variation occurs in patch morphology with diameters ranging from <1 cm to >3 cm. In this facies, porosity depends primarily on the degree of anhydrite cementation. The Artex Member consists solely of this facies and thus it is the primary reservoir unit in the Brassey Field. Variability in the Artex Member sandstone has resulted in differentiation of two subfacies within this facies.

Subfacies 2a (Figure 3.4 c, 3.6 c) consists primarily of fine- to medium-grained, moderately-sorted to well-sorted, trough cross-stratified sandstone, with average foreset inclinations of ~20-25°. Thin beds of subfacies 2a with angles of ~30° occur rarely, and are at most 10 cm in thickness. Lower-angled (<10°) cross-strata (with identical grain-size, oil staining and porosity) occur intermittently interbedded with the steeper beds. Other sedimentary structures include common oscillation ripples. This unit is often stained with micrinite bitumen, an inert hydrocarbon resulting from thermal cracking of oil, as noted by Klein and Woofter (1989). This distinction between bitumen and micrinite is important as bitumen may severely plug a conventional

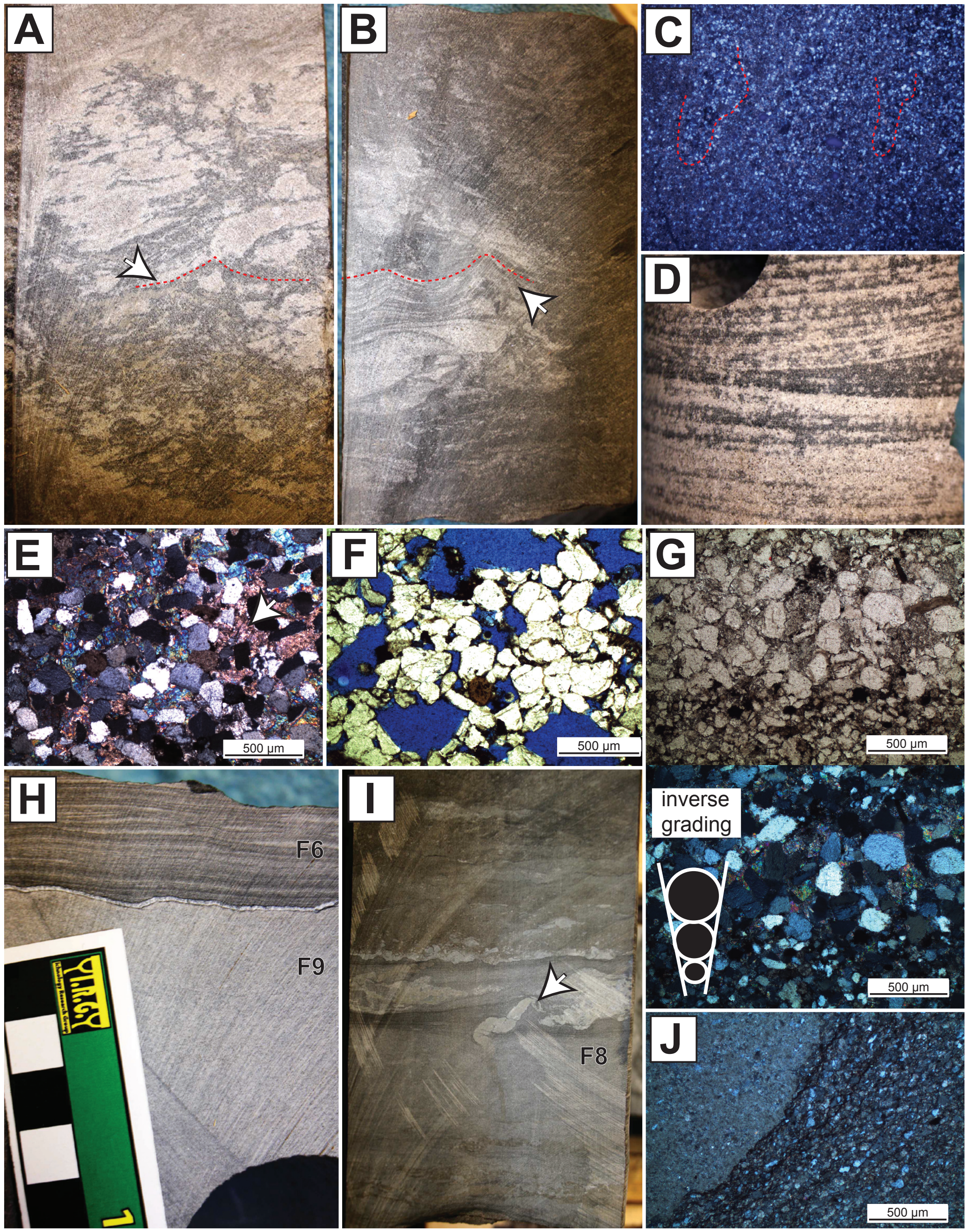

Figure 3.5:
a)F1 from 6-1-77-19W6, fine silt with visible sand laminae, faint oscillatory ripples, denoted by arrow.
b)F1 from B-59-F-93-P-10, fine silt with oscillatory ripples, denoted by arrow.
c)F1; #2 from 6-1-77-2 (XPL), 2857.2m. Possible biogenic grain sorting (outline in red).
d)F2a from D-69-C-93-P-10 showing toe-set of coastal dune. Note abundant anhydrite cementation. Scale ~5cm.
e)Porosity occlusion from anhydrite cementation in F2a. From #16, D-69-C-93-P-10 @ 3185m, XPL, 10x. Arrow indicates anhydrite cement.
f)Excellent reservoir porosity in F2a, # 7-1 from A-82-C-7-93-P-10 @ 3038m, PPL. Blue epoxy represents porosity.
g)Faint coarsening-upward trends (inverse grading) in F4; #4 from C-51-F-93-P-10 @ 2959m, PPL (upper) and XPL (lower).
h)Facies contact between F9 and F6. A thin calcite contact separates the facies in D-69-C-93-P-10.
i)F8; A-82-C-93-P-10, dewatering structure
j)F8; #3 A-82-C-93-P-10 @3041m, dewatering/soft sediment deformation structure from (i) in thin section. Fluid mud (left hand side) has a thin black contact with the siltstone of F8.

reservoir, while micrinite tends to reduce porosity and permeability only slightly (Woofter and MacGillivray, 1990). Additionally, subfacies F2A has a sharp and irregular contact with the underlying facies. The average thickness of this unit is variable, but in most occurrences ranges from 1-3 m. This subfacies comprises the primary reservoir rock type in the Artex Member at the Brassey Field.

Subfacies 2b (F2B) consists of fine- to medium-grained sandstone, generally massive in occurrence. Rare examples of convolute bedding, distinguished by faint, distorted laminae occur, commonly overlain by oscillatory ripples. Microscopic analysis reveals that F2B is characterized by poorly sorted sand with a bimodal grain size distribution. Qualitative assessment shows anhydrite and calcite cementation are more pervasive in this unit, resulting in decreased porosity and poor permeability. The anhydrite sometimes forms a thick heavily cemented horizon 5 cm in height. The facies above and below the anhydrite layer is consistent. Subfacies 2b occurs primarily interbedded with subfacies 2a and tends to have a sharp contact. Where subfacies 2a is not present, this unit sometimes sits above dolomitic siltstone (F6/F9). The contact is between (F2B) and the underlying facies (F6/F9) is coalescent, and appears to have a 'mixed' appearance.

FACIES 3: DOLOMITIC ANHYDRITE SILTSTONE (F3)

Facies 3 consists primarily of massive dolomitic siltstone with abundant calcite-replaced anhydrite nodules. The nodules are relatively small (<0.5 cm) and are roughly circular to subcircular. This facies is characterized by low porosity and virtually no permeability. It is devoid of sedimentary and biogenic structures. It is predominantly light grey in colour but was observed to have a reddish hue in some samples.

FACIES 4: PLANAR TO LOW-ANGLE FINE-GRAINED SANDSTONE (F4)

Facies 4 is characterized by very fine- to fine-grained sandstone. The bedding in this facies consists of planar laminae and low-angle cross-beds (<8°). Although difficult to discern, faint coarsening-upward trends (Figure 3.4, g) are common. Anhydrite cement in the form of nodules (<1 cm) is also common. Rare to common coarser laminae (up to medium-grained) occur

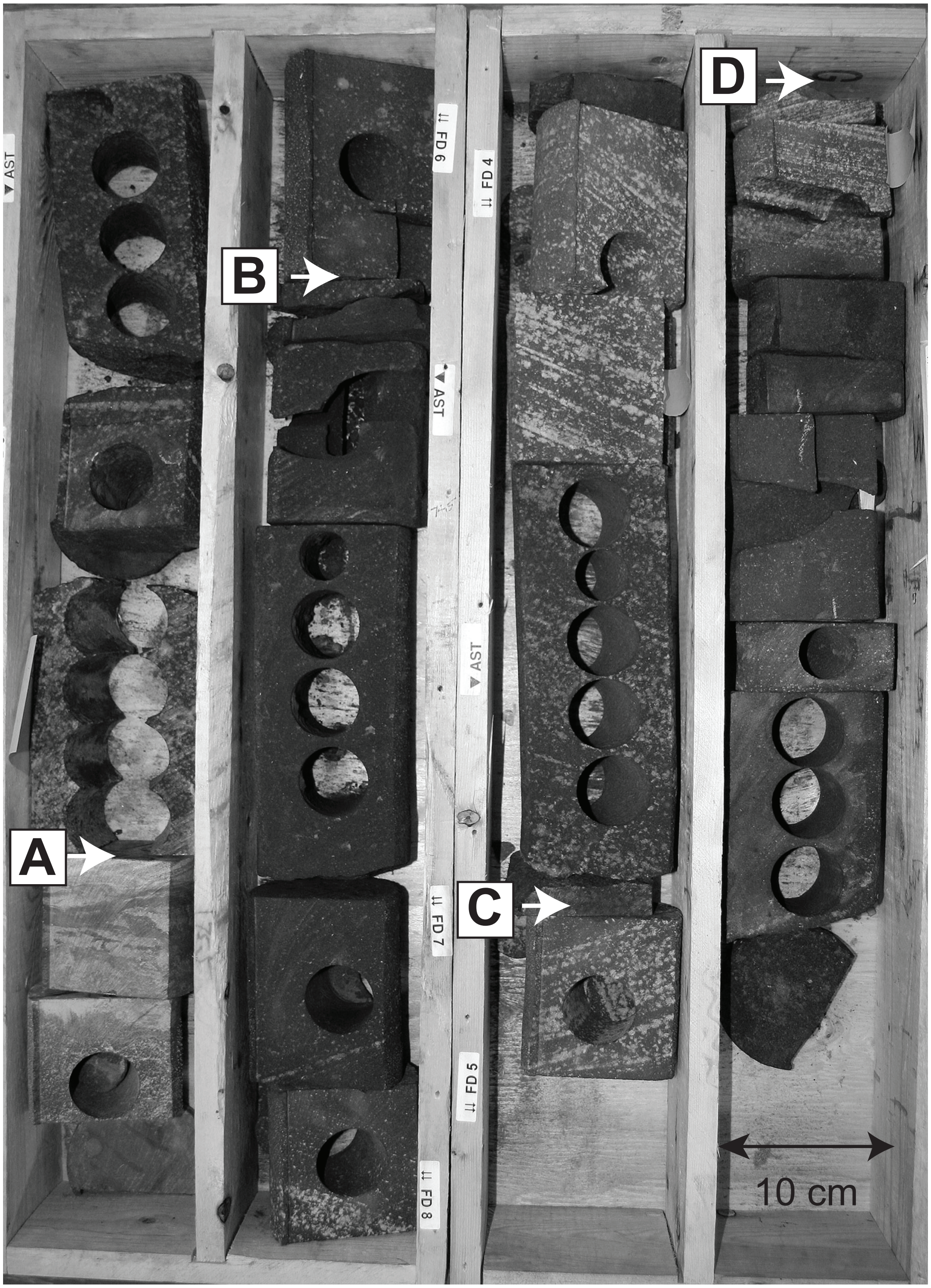

Figure 3.6: Drillcore from 6-1-77-19W6 showing various sedimentological features:
A) Contact between the interdune/dune; interdune F1, bioturbated silt/sand; reservoir subfacies F2a sits above F1;
B) F2b, massive sand;
C) third-order sequence boundary, reactivation surface; possibly due to wind direction variation;
D) wind- ripple laminae, F4.

within this facies. The average thickness of this facies is approximately 20 cm (F2 is considerably thicker). It typically exhibits gradational, nonerosionive contacts with adjoining lithofacies.

FACIES 5: PLANAR TO CONVOLUTE-LAMINATED DOLOMITIC MUDSTONE (F5)

Facies 5 is composed of grey, laminated, dolomitic mudstone. This facies is commonly characterized by soft sediment deformation structures, including highly convolute bedding. Dewatering structures, resulting from fluidized mudstone subjected to sudden loading resulting in a sinuous and tapered morphology, are also common. Thin-section analysis shows that microscopic dissolution seams (microstylolites) characterized by organic matter residue are common in this facies (Figure 3.7a). This mudstone also exhibits intervals dominated by planar bedding with minimal deformation. In many examples, a thin (0.25 cm), dark, organic-rich band occurs at the upper contact of this facies. The dolomitic mudstone intervals are relatively thin (10-20 cm) and commonly overlie an erosional surface that truncates subjacent facies.

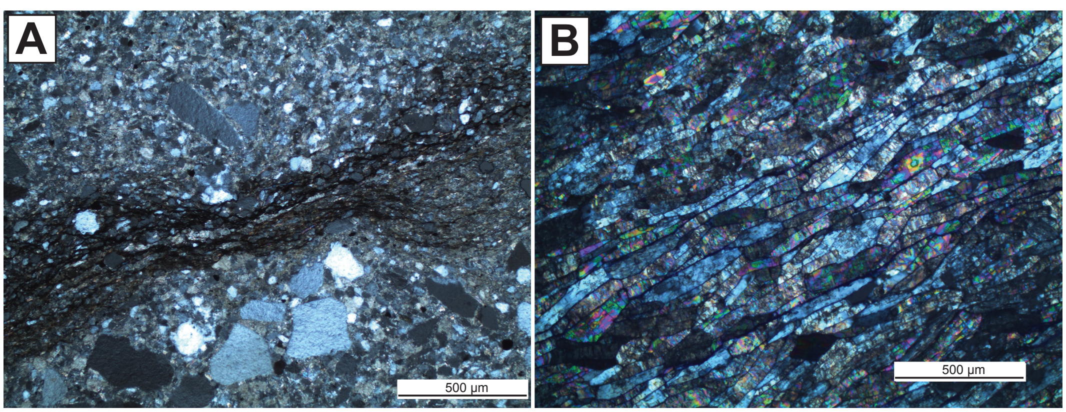

Figure 3.7:
a)Photomicrograph shows that microscopic dissolution seams characterized by organic residue (microstylolites) are common in this facies. Slide B-59-F-2a from B-59-F/ 93-P-10 @ depth 2952m, XPL.
b)Planar-bedded anhydrite of F7. Slide D-89-B-5a from D-89-B/93-P-10 2854, XPL.

FACIES 6: HETEROLITHIC INTERLAMINATED DOLOMITIC MUDSTONE AND SILTSTONE (F6)

This facies consists of planar-bedded siltstone with common mudstone interbeds. The siltstone is commonly rippled and lacks evidence of bioturbation. The planar-laminated mudstone commonly drapes the crest of the ripples, indicating differential compaction within this heterolithic facies. Overall, this facies appears flaser to lenticular bedded and lacks biogenic structures. The upper surface of this facies commonly exhibits evidence of erosion with truncation of ripples by subsequently deposited facies.

FACIES 7: PLANAR-BEDDED ANHYDRITE (F7)

Facies 7 consists of planar-bedded anhydrite. It is a relatively thin facies, commonly 10-15 cm in total thickness. Thin-section analysis (Figure 3.7b) reveals that the anhydrite is dominantly planar bedded, with no biogenic structures visible. Small-scale unidirectional ripples are also common and low-angle (8-12°) crossbeds have been observed. This facies is devoid of both porosity and permeability, and likely acts as a barrier to any fluid flow within the reservoir. In core this facies is easily distinguished by its reflective sheen. Contacts with the adjoining formations are nonerosive and range from planar to contorted. When overlain by facies F1A the contact is planar, with a thin (<1 cm) dark band separating the two facies.

FACIES 8: DOLOMITIC SILTSTONE WITH CONVOLUTE-BEDDED NODULES (F8)

This facies is composed of interbedded crystalline calcite (replacing anhydrite) and dolomitic siltstone. The anhydrite appears to have been deposited initially as horizontal beds that underwent subsequent disturbances resulting in contorted layers of calcite-replaced anhydrite. The facies thickness varies, but most commonly ranges between 9 and 12 cm. It is usually found above subfacies F2B (fine-grained convolute-bedded sandstone).

FACIES 9: MASSIVE UNDIFFERENTIATED SILTSTONE (F9)

This facies consists of massive dolomitized siltstone. The siltstone exhibits virtually no discernible bedding or internal structures. Variations in the lithology include rare mud lenses and common patchy (<.5 cm) pyrite occurrences (Figure 3.4, d), with rare, poorly sorted, very fine-grained sandstone laminae. Unlike F1, the sand laminae do not appear to be biogenically sorted (bioturbated), but rather occur as discrete, planar, structureless lenses. The contacts with the subsequently deposited facies are conformable.

FACIES 10: CALCAREOUS SILTSTONE/LIMESTONE (F10)

This facies is characterized by fossiliferous, dolomitic, bioclastic wackestone, packstone and rarely grainstone consisting of primarily of poorly sorted silt- and clay-sized grains with larger grains (generally bioclastic detritus) floating within. Recrystallized fossil debris (echinoderms, brachiopods, bivalves and gastropods) are most easily visible in microscopic analysis (Figure 3.8 a,b). Trace fossils, including *Thalassinoides, Planolites* and *Teichichnus* also occur. Dolomitized mudstone rip-up clasts are common, particularly at the base of this facies. Facies 10 invariably has an erosive base, typically characterized by a low-diversity *Glossifungites*-demarcated discontinuity surface. It is commonly situated on convolute-bedded mudstone (F5).

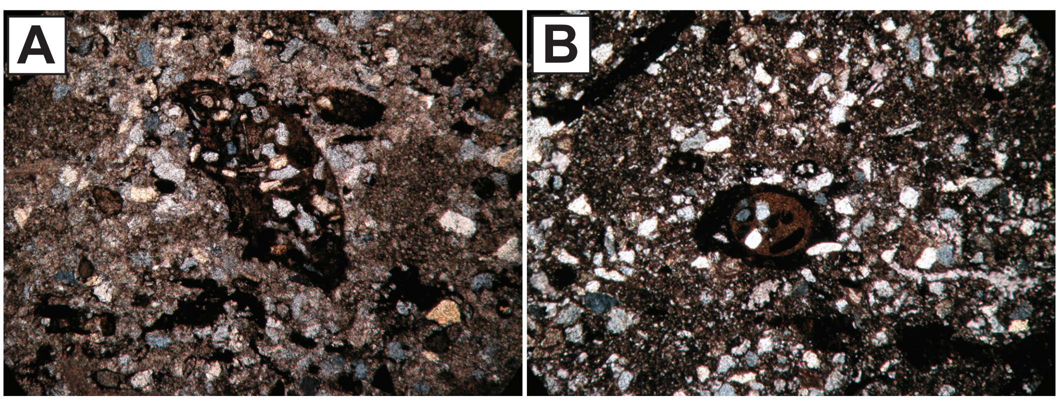

Figure 3.8:
A and B) F10: silty limestone incursion with recrystalization occurring within a fragmented shell/gastropod; both #15 from D-69-6-93-P-10 @3187m (10X, XPL)

Facies Associations

FACIES ASSOCIATION I (FA-I)

Facies association I (consisting of F2A and F4) is interpreted as an aeolian dune succession deposited within an arid coastal environment. The Artex Member, in common with several other intervals within the Charlie

Lake Formation, exhibits depositional characteristics consistent with deposition in an aeolian dune setting (Higgs, 1990; Arnold, 1994; Zonneveld and Gingras, 2002; Zonneveld et al., 2004). Specific textures and sedimentary structures within aeolian dunes facilitate identification of the location on the dune where individual facies were most likely deposited. Subfacies 2a (high-angle cross-stratified sand) provides the strongest evidence for an aeolian interpretation for this facies association. The high angled beds have been interpreted as planar and wedge tabular cross-stratification. These cross-stratified bedforms are typical of aeolian environments (Ahlbrandt and Fryberger, 1982; Blakey and Middleton, 1983). Other key criteria indicating aeolian influence include the overall excellent sorting and well-rounded grains (Figure 3.9a), mainly the result of grain-grain interaction during saltation (Whalley and Marshall, 1986; Pye and Tsoar, 1990). As well, anhydrite cements mimicking primary bedding orientation is similar to cementation trends in other ancient aeolian successions (Fryberger, 1993).

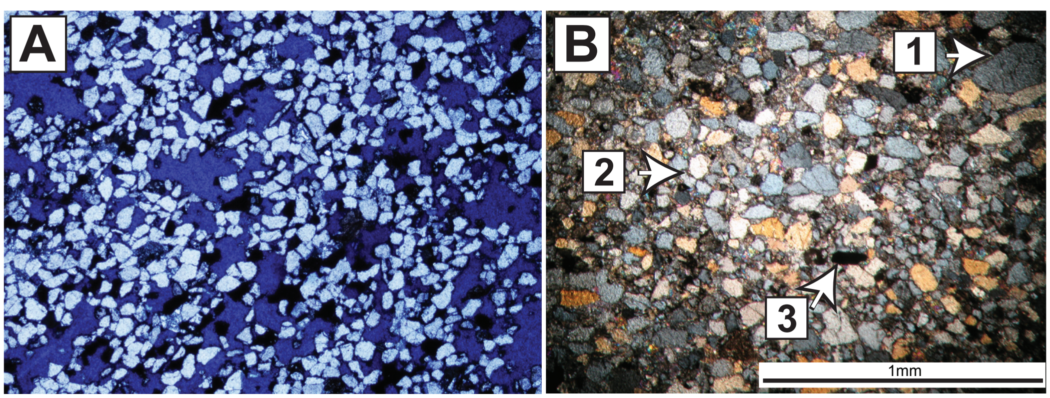

Figure 3.9: Photomicrographs from the Artex Member at the Brassey a) thin-section taken from F2a, grading difficult to see but heavy minerals are at an inclined angle; post depositional diagenesis has improved porosity; 6-1-77-19W6, 50x plane-polarized light; b) thin section from FA 2B (interdune) showing the poorly sorted, bimodal nature of the interdune area (1, 2) and the presence of heavy minerals (3).

Two major sedimentary processes create high-angle deposits on the lee side of sand dunes: grainfall laminae and sandflow (also known as avalanche cross-bedding), which both have the ability to form cross-stratified deposits with abnormally high inclinations (Pye and Tsoar, 1990). Lithofacies F2A is interpreted to have resulted from primarily from the grainfall of sand grains. These deposits were created by winds picking up sand grains on the stoss side of the dune form and dropping from the air on the protected lee side of the dunes (Pye and Tsoar, 1990). This type of lamination is characterized by unsorted grains with rare grading (Brookfield, 1992). Packing is typically loose, with an average primary depositional porosity of approximately 40%. Sandflow laminae, resulting from grainflow deposition, are characterized by thicker, slightly steeper, but more irregular deposits, and have a slightly higher porosity (Pye and Tsoar, 1990). Another distinguishing factor between these two processes are the angles at which the strata are deposited. In grainfall lamination, the angle of deposition is 28° or less. In sandflow deposits, oversteepened beds are common, with angles of deposition up to ~35° (Pye and Tsoar, 1990). Based on the drillcore examined at the Brassey Field, the majority of inclined strata have dips averaging between 20° and 25°, supporting the hypothesis that the most likely process of deposition was grainfall (Figure 3.6).

The spatial location of the grainfall laminae depends on the morphology of the dune. Typically, grainfall strata accumulate on the lee side of the dune just over the crest. Once the accumulation meets, and exceeds, the angle of repose, grains cascade down the steep dune and create an erosionally based 2-5 cm thick sandflow deposit (Pye and Tsoar, 1990). Grainfall strata commonly interfinger with sandflow laminae (Brookfield, 1992). The rarely occurring, more steeply inclined beds (~30°) of subfacies 2a have been interpreted as the avalanching sandflow laminae, that occur as grainflow strata becomes oversteepened.

The planar to slightly inclined nature of sandstone beds in F4 (Figure 3.6, d) are interpreted to be dominantly wind-ripple laminae and translatent strata deposited on the aeolian dune surface, caused by tractional processes. Tractional deposition occurs when the carrying capcitiy of wind is dimished and saltating grains are deposited, usually on the lee sides of ripples (Hunter, 1977). Each lamina is created by the migration of a single ripple moving under translational movement (Pye and Tsoar, 1990).

These bedforms are dependent on variable wind speeds during dune deposition. Translatent strata are produced when wind speeds increase and are too strong for ripple creation and migration, and tightly-packed, normal or inversely-graded plane bed laminated packages are formed on a smooth surface (Hunter, 1977; Swezey, 1998). Likewise, on a rippled surface, with a decrease in wind speed, it is possible to create climbing-ripple laminae. These commonly laterally extensive deposits tend to consist of closely-packed, inversely graded strata (Hunter, 1997; Kocurek and Dott, 1981). Unlike subaqueous climbing ripples, foresets in aeolian climbing ripples are difficult to distinguish because of their low relief (Brookfield, 1992). The planar laminated beds and climbing ripples observed in F4 are interpreted as wind-ripple deposits that were formed either at the crest of the dune (exemplars from within and at the top of this facies) or near the dune apron (i.e., the basal portion of the lee side of the dune; exemplars from within and at the base of this facies). The identification of wind-ripple strata is an excellent method for distinguishing aeolian strata from subaqueous deposits (Swezey, 1998).

FACIES ASSOCIATION II (FA-II)

Facies association II consists of nine facies (F1, F2B, F3 and F5–F9). This facies association is herein interpreted as interdune deposits. The interdune area is the area where the water table directly interacts seasonally with the environment/sediment-air interface (Brookfield, 1992). Two interdune end members have been recognized; depositional and deflationary or non-depositional (Ahlbrandt and Fryberger, 1982). The nature of the facies indicates that periodic hydration, resulting in development of numerous shallow ephemeral lakes and lagoons, was commonplace (Zonneveld et al., 2004) and yields the interpretation of a depositional type interdune. The Lower Charlie Lake interdune area was a highly variable environment, with multiple controls on lateral lithological variability. It is proposed that the Artex sands were deposited in a sand-limited desert. These deserts typically have interdune areas that are characterized by numerous small dunes, deflation lags and coarse sand sheets (Brookfield, 1992). In the study interval the Artex Member comprises the sole sandstone unit attributed to aeolian processes. In the outcrop belt in the Peace River foothills (Chapter 2), sandstone beds interpreted as aeolian successions are numerous although proportionally they comprise much less of the outcrop succession than do interdune successions and other facies associations.

Lancaster (1995) recognized three types of depositional interdune: dry, damp, and wet. Two facies (F1 and F9) are interpreted to be interdune deposits deposited in subaqueous settings (i.e., ephemeral lagoon, playa, paludal), yielding a wet interdune interpretation. Locally pervasive bioturbation interpreted to be syndepositional in nature, and abundant oscillatory (wave) ripples, are consistent with subaqueous deposits (Higgs, 1990). The presence of burrows in F1 and the lack of biogenic structures in F9 is attributed herein to water chemistry in the ephemeral lakes and lagoons (Zonneveld et al., 2004). Within F1, bioturbation became prevalent after a very short lag time wherein burrowing organisms were first established and, consequently, pervasive burrowing ensued. This is similar to seasonally rejuvenated ephemeral lagoons and lakes in the Coorong region of Australia (Warren, 1988). The unbioturbated mud and silt of F9 reflects deposits in which chemical conditions were simply too harsh (likely too saline, acidic or anoxic) for the development and proliferation of infaunal populations. Locally abundant pyrite observed within F9 is consistent with sulphate-rich waters in this facies and with dysoxic to anoxic waters in an evaporating ephemeral lake or lagoon environment (Higgs, 1990). In the Coorong region, increased salinity associated with seasonal evaporation results in annual decimation of infaunal populations and the lagoons and lakes become devoid of invertebrate life within the months after the last rainfall event (Warren, 1988). The mud drapes on ripples in F9 also supports interpretation of an overall low-energy environment such as a lagoon.

Facies 2b has been interpreted as slump deposits that originated on the dunes and were subsequently transported into interdune areas. The poorly sorted, massive nature of the sands is consistent with slumping, most likely after the dune had been saturated with rain, although we recognize that other atmospheric (wind storms) or seismic phenomena could have also initiated the slumps. The bimodal nature of this facies (Figure 3.9b) is consistent with interdune deposits, consistent with observations made by Lancaster and Teller (1998) on modern aeolian and interdune deposits in the Namib Sand Sea of southwestern Africa. Convolute, load-casted basal contacts to this facies are also consistent with sudden sediment movement onto soupy, unconsolidated substrata, likely ephemeral lagoon or lake deposits.

Sabkha deposits in the study area are represented by F3 and F8. These sabhka deposits develop in the interdune area during seasonal drying of ephemeral water bodies. The nodular morphology of anhydrite in F3 suggests that it was deposited as subsequent drying of the interdune occurred. Local red coloration (Figure 3.10) of F3 (also noted by Arnold, 1994; Zonneveld et al., 2001 and Dixon, 2007) may be due to incipient soil development within these areas, as has been observed in Charlie Lake Formation outcrop elsewhere (Zonneveld et al., 2004). The fluidized appearance of the recrystallized anhydrite observed in F8 (Figure 3.5 i, j) is likely a result of periodic influxes of groundwater likely due to rain during an overall dry interval.

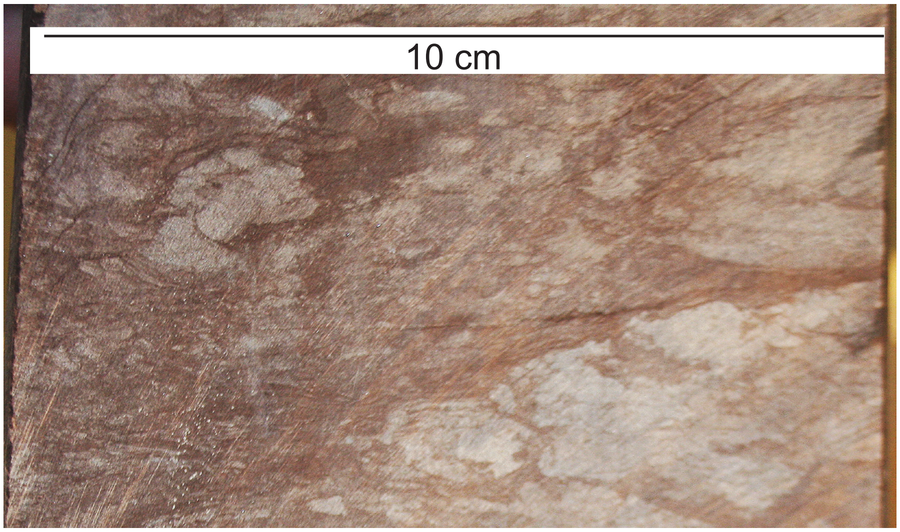

Figure 3.10: Local red coloration of F3 suggests that it was deposited as subsequent drying of the interdune occurred; 14-2-77-19W6.

Mudstone and siltstone (F5 and F6) were deposited within interdune areas during intervals in which the interdune lagoons and lakes were infilled with water. Laminated mudstone included within F6 was deposited under primarily quiescent conditions (Figure 3.5, h). Heterolithic, flaser- to lenticular-bedded, interlaminated mudstone/siltstone reflect fluctuating energy conditions, possibly within intertidal flats on the margins of a tidally influenced lagoon. Lancaster and Teller (1998) observed the occurrence of extensive sabhka cross cutting dunes, and noted that flooding of these sabkhas occurred when spring tides were high. The convolute-bedded mudstone included within F5 is the result of the sudden burial of water-saturated sediment. Soft sediment deformation is regularly observed in modern interdune deposits (Fryberger et al, 1983; Lancaster and Teller, 1988).

Seasonal desiccation of the lagoons and lakes resulted in the deposition of laminar anhydrite beds (F7). The horizontal nature of the delicate anhydrite crystals in most examples suggests that this facies was deposited during a time of seasonal dryness, when the ephemeral water body was shrinking or absent. An unusual aspect of anhydrite deposits in the study interval is the occurrence of ripples and low-angle cross-beds in this facies, which suggests post-depositional, likely aeolian reworking and redeposition. Although aeolian reworking of anhydrite is unusual and rarely preserved, precedence does occur in the Pleistocene to Modern dune complexes at White Sands, New Mexico (Ewing and Kocurek, 2010).

FACIES ASSOCIATION III (FA-III)

Facies association III consists of a single facies (F10). This facies was observed within a single horizon, near the top of the study interval, and has been informally referred to as the A-marker member of the Charlie Lake Formation (Dixon, 2005). The presence of marine fossils (echinoderms and brachiopods) in association with fossils of facies-crossing organisms (bivalves and gastropods) provides clear evidence of a marine transgression within the study area (Zonneveld and Gingras, 2002). The A-marker member occurs throughout the subsurface of northeastern British Columbia (Zonneveld, 1999). It is invariably thin throughout (rarely exceeding 2-7 m in thickness) and both overlies and underlies sedimentary successions deposited in marginal marine and continental depositional settings, underscoring the short-lived nature of this regional marine incursion as well as the overall low accommodation space that characterized this interval.

Discussion

AEOLIAN FACIES MODELS

Aeolian facies models were among the last clastic models to be developed (Brookfield, 1992). This is due in part to the nature of climatic variations and controls in aeolian systems and to difficulties in assessing the sedimentary structures and bedforms in present-day dune systems. However, research offered in the past few decades has allowed a predictive framework to be developed for identification and interpretation of aeolian systems (Hunter, 1977; Pye and Tsoar, 1990). Brookfield (1992) identified several fundamental observations necessary for an aeolian dune interpretation, including the identification of sedimentological processes that produce larger-scale bedforms found in aeolian strata. Most aeolian deposition is tractional or gravity driven in nature, resulting in typically translatent and/or wind ripple laminae and or grainflow/grainfall deposits, respectively (Swezey, 1998). It is the migration and amalgamation of these smaller, variable-sized bedforms that create the larger bedforms observed in aeolian environments (ie. dunes, draas, etc.). The boundaries of these bedforms (grainfall, grainflow and ripple lamination) form unique facies and can be assessed to deduce the nature and possibly infer the morphology of the dunes.

Three distinct types of bounding surfaces have been identified within aeolian successions (Figure 3.11) (Brookfield, 1992). The formation of first-order bounding surfaces is attributed to the migration of draas (the largest-scale bedform identified), which varies from 10 to 450 m in height (Brookfield, 1992). The boundary of the draa is usually identified as being between interdune and dune deposits, demarcated by the contact of two dunes.

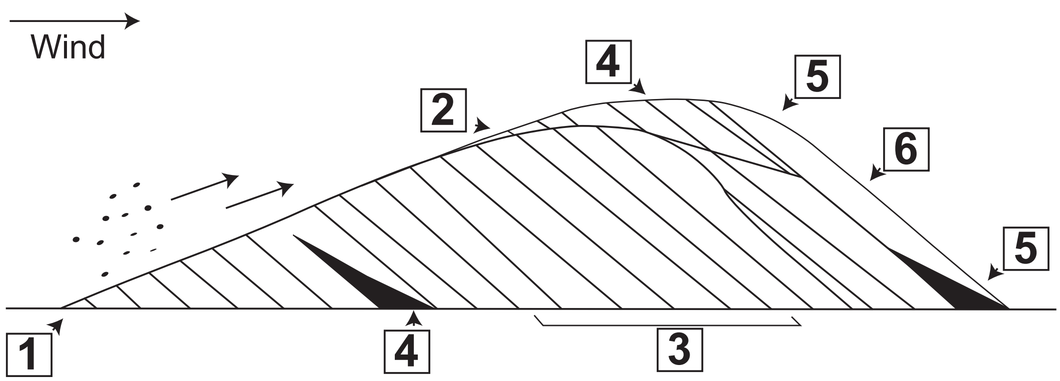

Figure 3.11: Simplified aeolian dune showing depositional and architectural features. The dune depicted in this schematic has undergone migration on the draa with unidirectional wind influence: 1) First-order bounding surface; showing a draa-interdune contact; 2) second-order bounding surface; dune-dune; 3) third-order bounding surfaces are aeolian laminations; 4) wind-influenced strata-spatial location of wind ripple or planar strata, found at the crest or apron of subsequent dunes, where wind influence is at its strongest; 5) location of grainfall laminae; 6) location of sandflow laminae.

Second-order bounding surfaces are formed by migration of the dune on the draa surface. Dunes are characterized by being larger than ripples but smaller than the draa on which they formed. Heights vary from 0.1 to 100 m. Second-order bounding surfaces usually form on the lee, or downward, side of the draa. Third-order bounding surfaces represent aeolian lamination and are often reactivation surfaces. The aeolian lamination will often consist of bundles of laminae (lamina sets) formed by the erosion and subsequent reactivation of the cross-bed (Brookfield, 1992).

Mapping of the second- and third-order sequences is affected by well density and distance and, as pointed out by Woofter and MacGillivray (1990), is therefore not mappable in some fields. Because of the considerable size of draas, first-order bounding sequences should be mappable on a larger (regional) scale. The Brassey Artex dune succession is part of a small-scale coastal dune succession. Thus, the highest order bounding surfaces of this system are picked at the base of the dune succession. Interdune intervals in the Charlie Lake Formation are much thicker (commonly by > 1 order of magnitude) than the dune intervals themselves (Arnold, 1994; Chapter 2). In the Brassey Field, the dune-interdune contact is distinct in both drill core and on well logs (Figures 3.6) Identification of lower-order bounding surfaces has been accomplished in parts of the Brassey Field however, these correlations are less definitive due to well spacing. Work is ongoing to substantiate the veracity of these correlations and assess their role in reservoir compartmentalization.

Deserts are characterized and influenced by a variety of depositional constraints, including sediment supply, wind strength and direction, and basin morphology. Within erg systems, several types of dunes commonly coexist, depending on local and regional wind patterns. The morphology of the dunes is related to the wind direction / directions (Brookfield, 1992). Previous research showing sand thickness in the area around the Brassey Field has interpolated a substantial erg system within which the Artex sandstone at Brassey Field was deposited (Higgs, 1990). The size and areal extent of this dune field remains conjectural (Higgs, 1990; Arnold, 1992) however the preserved thickness is generally under 4 metres in thickness. Previous interpretations of a major Artex erg system of which only a minor component is preserved due to limited accommodation space are not supported by observations in the present study.

Dominantly unidirectional wind orientation often results in the formation of transverse and barchanoid dunes, whereas longitudinal and star dunes are more likely to form under variable wind conditions (Brookfield, 1992). Conflicting studies have postulated that the wind directions during the deposition of Charlie Lake Formation sands to have been both northeasterly (in the northern portion of British Columbia) and westerly (Arnold, 1994). Observation of the facies distribution (Figure 3.2, 3.12) in combination with oriented drillcore data (Woofter and MacGillivray, 1990) suggest that the predominant wind direction forming the dunes at the Brassey Field was from the northeast. This suggests that the dunes are preserved at an oblique angle to the dominant wind direction (Woofter and MacGillivray, 1990).

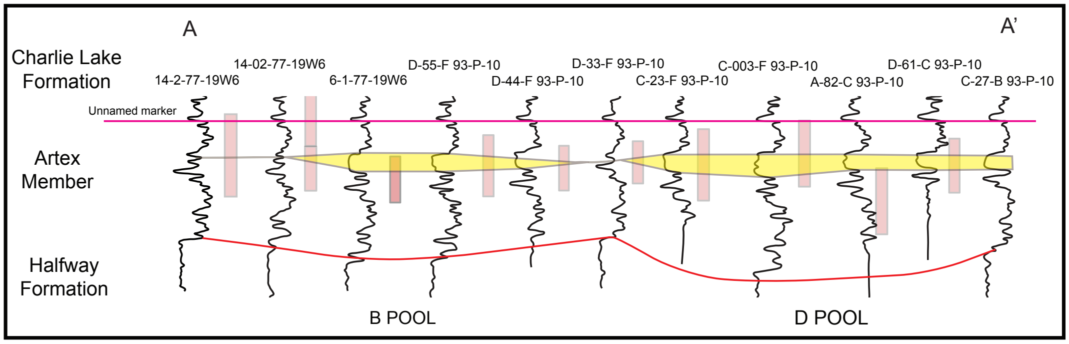

Figure 3.12: Northeast-southwest cross section through pools B and D of the Brassey Field. An unnamed field-wide marker is used as a stratigraphic datum (indicated by a pink line). The marker corresponds to a slightly sandier silt bed within facies F1.

Facies mapping of the reservoir superimposed on the pool locations shows that reservoir facies F2 presence is consistent with the producing oil pools, substantiating the prior evidence (high porosity and permeability in thin section) that indicated that this is indeed the primary reservoir facies. Analysis of the northeast-southwest cross-section through 2 of the pools in the Brassey Field (Figure 3.2) shows the lateral variability of the reservoir facies (Artex sands) throughout the study area. Utilization of a field wide stratigraphic datum at a horizon above the Artex Member clearly illustrates that thinning of immediately adjacent overlying and underlying strata does not occur however it is apparent that a local topographic depression does occur. In these correlations the top of the Artex sands remains planar, whereas the basal contact gradually deepens towards the centre of the pool where the Artex is thickest. The local topographic depression within which the Artex sands are preserved at Brassey, was formed by local thinning of the underlying Halfway Formation. Intermediate strata drape this depression showing no signs of thickening or thinning; however, Artex deposition filled in this low and is overlain by horizontally emplaced fine-grained strata. Thus, paleotopography played a critical role in the preservation of the reservoir facies and development of a seal overtop of the Artex interval. Arnold (1994) also noted the preservation of the Inga aeolian sand in localized depressions, but the depressions were attributed the to formation of structural basins associated with the Fort St. John Graben Complex. Observations made in this study propose an alternate hypothesis of dune preservation related to paleotopography and the presence and orientation of lagoons and /or lakes.

Apart from the Brassey field, other aeolian type reservoirs are found in the lower Charlie Lake formation, which form elongate shore parallel trends (Klein and Woofter, 1989; Higgs, 1990; Jackson, 1990; Arnold, 1994; Davies, 1997b). In fact, at least eight stratigraphically distinct dune successions have been identified in the Charlie Lake subsurface (Higgs, 1990; Arnold, 1994); however, only the Artex is currently productive. Outcrop analyses in the Peace River foothills and Trutch region (Arnold, 1994; Zonneveld et al., 2001; 2004) indicate that Triassic aeolian sandstone units in northeastern British Columbia are distributed regionally and most commonly oriented in a northwest-southeast orientation, parallel to regional shoreline trends in the underlying Halfway Formation. Considering these observations, and the observations made in this study, we hypothesis that coastal dune preservation is related to lagoon orientation, which too was shore parallel. Preservation of the aeolian bodies occurs when the aeolian dunes migrate over topographic lows, and are subsequently covered with marginal marine and continental successions. If migration of the dunes over lagoonal successions is the primary preservation mode of dunes in the Charlie Lake Formation it stands to reason that sandstone thickness is a direct function of lagoon depth (i.e. available accommodation space). Previous research has postulated that tidal regimes along the Middle-Upper Triassic coastline ranged from microtidal to mesotidal (Willis and Moslow, 1994a, b; Caplan and Moslow, 1997; 1999) and thus back-barrier lagoons were likely under 5 metres in thickness. Preserved thicknesses of Charlie Lake aeolian sandstone beds in outcrop and of ~ 1 to 4 metres subsurface (Higgs, 1990; Arnold, 1994; Zonneveld et al., 2001; 2004) are consistent with these interpretations.

DIAGENESIS AND ANHYDRITE FORMATION

The precipitation of the dolomite and anhydrite within the aeolian sands was closely related to the hydrologic regime (Figure 3.13) in the coastal region at the time of deposition. In sabhka environments, high salinities and temperatures combine to facilitate the precipitation of anhydrite at or beneath the water table (McKenzie et al, 1980).

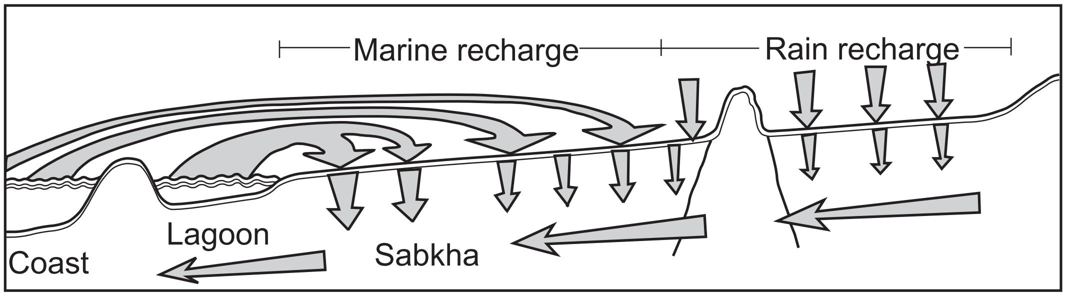

Figure 3.13: Hydrologic regime of sabhkas showing the water movement during times of recharge sabhka environments, high salinities and temperatures combine to facilitate the precipitation of anhydrite at or beneath the water table; McKenzie et al, 1980.

Dolomitic and anhydrite cemented aeolian deposits similar to those in the study interval occur in the Teapot Dome Tensleep sandstones in Wyoming (Yin et al, 2005). There it was postulated that marine water and rainfall charged the aeolian sands during flooding seasons, while the salinity of intergranular solution was increasing during evaporation, leading the precipitation of dolomite and anhydrite (Yin et al, 2005). Likewise, the precipitation of dolomite crystals likely was caused when the hypersaline solution saturated the fine-grained laminae, while capillary pressure differential caused deferred flowage of the solution into coarser-grained laminae to remain uncemented (Yin et al, 2005). Thus, likely the mechanism of anhydrite cementation resulted from inundation with a supersaturated solution after burial of the migrated sand body into the topographic depression.

RESERVOIR LITHOLOGIES AND POROSITY DISTRIBUTION

The anhydrite cementation in the Charlie Lake Formation is complex and warrants more extensive investigation than was part of this study. However, observations in the present study allow for several preliminary conclusions about the Brassey Artex cementation regime. The primary reservoir facies (Facies 2a) is pervasively covered with patchy but consistently dispersed anhydrite cement. More prolific anhydrite cementation occurs at the basal and upper contact of the reservoir facies. This is likely related to the interaction with complex lagoon and/or sabhka interaction as the dune migrates into the lagoon, and is subsequently covered. Unlike other portions of the Artex, where sands are saturated with thick bands of anhydrite cement (Facies 2b), the patchy nodular type does not inhibit porosity or permeability. Although the cementation greatly reduces primary porosity within this reservoir subfacies, overall porosity still reaches >15% (from a visual estimation of thin sections). The pervasiveness of the patchy anhydrite cement is quite variable, and significant size variation occurs in patch morphology with diameters ranging from <1 cm to >3 cm.

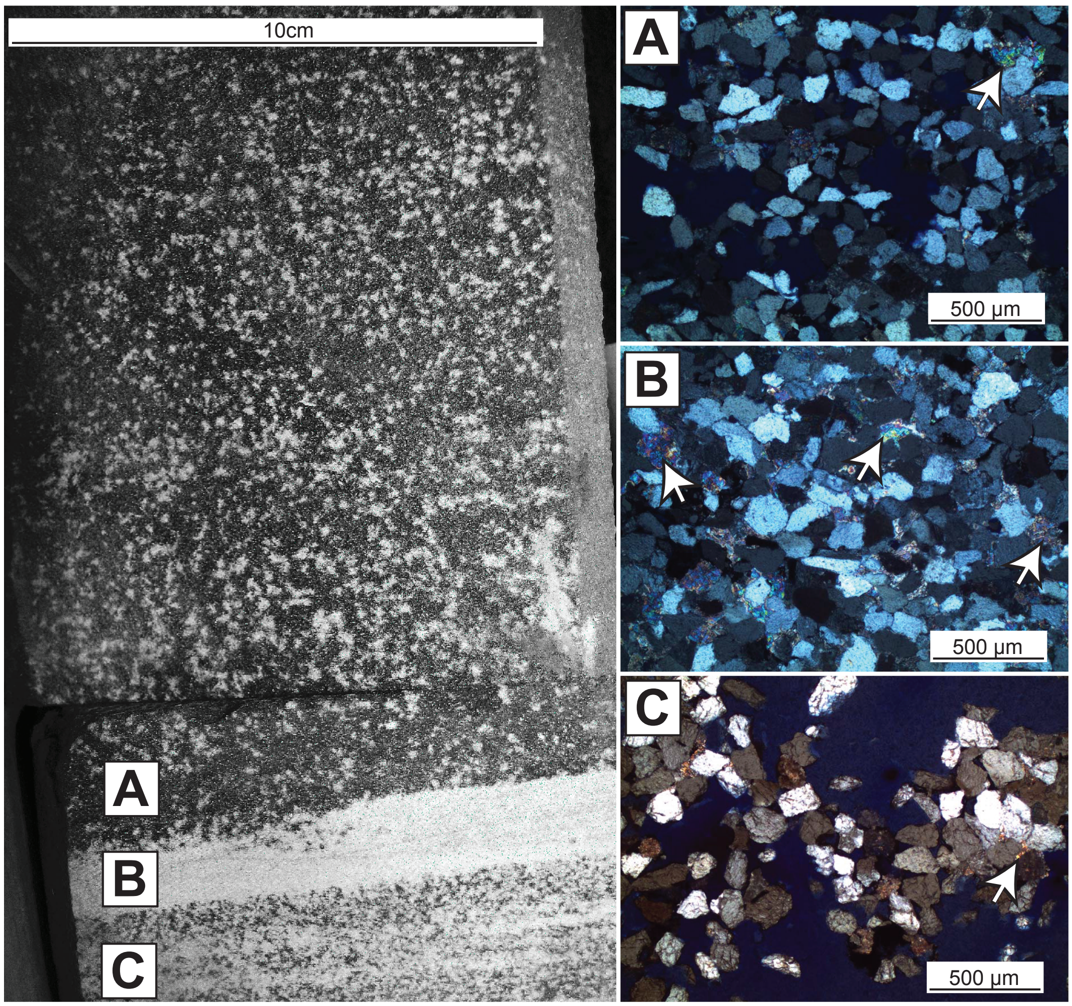

Figure 3.14: Variation in the pervasiveness of the anhydrite cement observed in D-89-B/93-P-10 (2850.1m). Core sample on left with thin section locations (A,B,C) denoted on core. Thin sections on right; anhydrite cement denoted with arrow. Anhydrite cement is distinguished by its high interference colors. Dark blue epoxy represents porosity. All slides in XPL.
(a) moderate cementation by anhydrite, distinguishable by its high interference colors.
(b) complete cementation of the dolomitized sand by anhydrite. Porosity and permeability are significantly reduced. This anhydrites cemented layer is a possible hydrocarbon flow barrier; (c) Significantly reduced anhydrite cementation resulting in high permeability and porosity

Although the majority of porosity-occluding anhydrite cementation occurs at the top and bottom of the reservoir unit, it has been observed that anhydrite cement is present in other facies (F2A, F2B) where it forms thick (up to 10 cm) horizons of tightly anhydrite-cemented strata (Figure 3.14). This increase in cementation appears to be a preserved water table(s) or alternatively bounding surfaces.

Conclusion and Summary

The strata in and around the Artex sands of the Charlie Lake Formation have been carefully assessed and have been assigned to ten lithofacies that are grouped into three recurrent facies associations. These facies associations are interpreted to record deposition in aeolian sand dune, interdune/supratidal sabhka, lagoon and/or lake, and transgressive shoreface environments.

The Artex sandstone is separated into 2 main reservoir facies; the primary facies F2A and minor facies F4 have both been interpreted to have resulted from aeolian sedimentation. From a process sedimentological stance, aeolian deposition is tractional or gravity driven in nature. The resulting bedforms are observed in the reservoir facies: F2A (grainflow/grainfall deposits) and F4 (translatent and/or wind ripple laminae) are consistent with the coastal dune interpretation. Facies mapping of the Brassey Field shows that reservoir subfacies F2A coincides with the pools within in the field. As proposed by Woofter and MacGillivray (1990), the primary wind direction is southwesterly and the resulting dunes formed at an oblique angle to the wind. Associated facies (F1, F2B, F3 and F5–F9) interpreted as lagoonal/sabhka/lake/tidal simplified as interdune facies, encase the primary reservoir unit with a predictable facies assemblage. The interdune zone was mostly likely a periodically wet or ephemeral system, as suggested by some of the structures observed (i.e. dewatering structures).

A northeast-southwest cross-section through the pools of the Brassey Field suggests that the primary control on deposition and preservation of these sand units were topographic depressions that were present at the time of deposition. The use of a field-wide datum as a stratigraphic marker clearly shows that no thinning of the adjacent strata occurs above or below the Artex sand reservoir facies. This indicates that reservoir predictability is dependent on paleotopography of the Halfway Formation. Previous studies (Arnold, 1994) also noted the occurrence of aeolian sand bodies in the Charlie Lake Formation (at the Inga Field, Northeastern British Columbia, Canada) persevered in topographic depressions. However, in Arnold's study, the depressions were interpreted as artifacts related to structural basins associated with the Fort St. John Graben Complex.

The extensive presence of anhydrite indicates an arid environment at the time of deposition. The aeolian sand bodies have been interpreted as coastal dunes primary by their association with a lagoonal facies, as first noted by Higgs (1990). Additionally the presence of a fully marine transgressive shoreface unit (FA-III) provides evidence of nearby marine proximity. The preserved height of the dunes (up to 5m) are believed to be more representative of the depth of lagoon in which the dune migrated over, as opposed to the height of the actual dunes that characterized this area. Furthermore, we can infer that the tidal regime in the Halfway-Charlie Lake area resulted in lagoons that ranged from 1-5 metres in thickness.

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CHAPTER IV – CONCLUSIONS

This study focused on the Upper Triassic (Carnian) Charlie Lake Formation in British Columbia, and has incorporated both subsurface and outcrop data. Two outcrop sections, that span the entirety of the Charlie Lake Formation are discussed in Chapter 2, while a case study focused on the lower Charlie Lake Formation Artex Member examined the process sedimentology, mode of preservation and reservoir attributes at Brassey Field southeast of Dawson Creek is presented in Chapter 3. The entire Charlie Lake exposure at Brown Hill and the accessible portion of the Schooler Creek exposure were described in detail. Extensive sampling, detailed photography, outcrop gamma spectrometry, thin-section analyses, and geochemical analysies were conducted. Lithologs (provided in the Appendix) were compiled and illustrate detailed descriptions of sedimentological, ichnological, and stratigraphical observations as well as supplementary gamma readings (provided in ppm). Individual lithofacies, with sedimentological, ichnological, and stratigraphical details are summarized in Table 2.1.

Fifteen drillcore from within and around the Brassey Field were examined, described in detail, sampled for petrographic analyses and calibrated to petrophysical well logs. Individual drill-core varied in length, from 8 to 25 metres. A total of 194 metres were described and provide a representative sampling of all lithofacies in and around the primary reservoir unit (i.e. the Artex Member). A detailed summary of sedimentological observations, gamma ray profile, facies information, and thin section samples from the observed drill cores were compiled into strip logs. Ten distinct facies and subfacies were identified.

Drill core analyses focused on the documentation of grain-size, lithology, texture, primary and secondary sedimentary structures, cement composition and pervasiveness, and ichnology, in addition to bedding contacts and other observable characteristics in the rock. 45 Samples were taken for further visual thin section analyses were observed under a Zeiss Axio Imager A1 Transmitted Light petrographic compound microscope.

The Charlie Lake Formation strata at the two outcrops observed in this study (Brown Hill and Schooler Creek) are herein interpreted to represent deposition in an arid, coastal mixed carbonate-silciliclastic regime. The regionally extensive Charlie Lake Formation in outcrop and subsurface is highly diachronous in nature, and thus the two studies areas are not lateral equivalents to each other; however, depositional patterns are correlative and the outcrop sections provide excellent analogues for subsurface sections.

In outcrop, The Charlie Lake Formation was separated into 21 distinct lithofacies, which comprise 7 recurrent facies. Relationships between the facies associations, specifically the presence and emplacement of dolomitized ephemeral and perennial lacustrine sediments, are similar to those observed in the Coorong region of Australia (Von der Borch, 1976; Warren, 1988). A series of 13 "cycles" occur in the Brown Hill section, with 7 aeolian sands. Increased thickening of the deposits at Schooler Creek, in addition to the presence of fully marine strata interfingering with 'normal' Charlie Lake facies reflect the westward pinchout of continental and marginal marine strata of the Charlie Lake Formation on the western margin of the North American craton. The Schooler Creek section is the westernmost section of the Charlie Lake Formation identified thus far.

At Brassey Field, ten lithofacies, grouped into three facies associations, were identified. These facies associations are interpreted to record deposition in aeolian sand dune, interdune/supratidal sabhka, lagoon and lake, and transgressive shoreface environments. Reservoir quality lithofacies are limited to an approximately 1-4 metre-thick aeolian sandstone interval referred to the Artex Member. The Artex Member, which occurs in the basal beds of the Charlie Lake Formation, produces hydrocarbons in several parts of the basin, and has been most commonly exploited as a secondary target encountered in Halfway Formation exploration and development wells. Brassey Field is an exception as the Artex Member is the primary reservoir target in this area. The Artex Member has excellent reservoir parameters, including: an average porosity of 16%, permeability of 152 mD, and 57° API oil (Woofter and MacGillivray, 1990).

The Charlie Lake Formation at both outcrop locales and subsurface location was found to reflect a series of shallowing up cycles. Additionally, both the outcrop and subsurface study showcase aeolian sandstone bodies encased in arid coastal deposits. Sedimentological indicators such as pin-strip lamination, high angled bedding, and inversely graded laminae aided in identification and interpretation of aeolian deposits. The preserved height of the aeolian deposits are similar (around 4.5 metres) for both the outcrop and subsurface study. At Brassey the preserved aeolian package (up to 5m) are believed to be more representative of the depth of the depression (likely a lagoon or shore-proximal lake) that the dunes migrated over, as opposed to the height of the actual dunes that characterized this area. At Brassey Field, lagoonal or interdune facies encase the primary reservoir unit with a predictable facies assemblage (Chapter 3). The interdune zone was mostly likely a periodically wet or ephemeral system, as suggested by some of the structures observed (i.e., dewatering structures). With the aid of wire-line correlations, northeast-southwest oriented cross-sections through the pools of the Brassey Field indicate that the primary control on the deposition of these sands appears to be depressions in the topography at the time of deposition. The use of a field-wide datum as a stratigraphic marker clearly shows that no thinning of the adjacent strata occurs above or below the Artex sand reservoir facies. This indicates that reservoir predictability is dependent on paleotopography of the Halfway Formation. Recognition of these hollows is critical to aid in the development of predictable models for the Artex Member sand.

Similarly, the outcrop study provides evidence that preservation of aeolian sand bodies is related to the migration of aeolian dunes over topographic depressions in the coastal plain environment. The majority of the aeolian sand bodies are deposited following deposition of lithofacies K, an intraclast solution collapse breccia that provides evidence for lithologies that are no longer present (i.e. dissolution of evaporite minerals) (Chapter 2). Periodic flooding (possibly during atypically high spring tides, or high tides that coincided with storms) of coastal depressions filled by interbedded carbonate mudstone/siltstone and evaporites brought marine waters into these depressions. Subsequent evaporation resulted first in supersaturated, hypersaline waters within the depression and eventually resulted in the formation of bedded evaporite minerals. Subsequently, coastal dunes migrated over this facies. Dissolution of the evaporite minerals, likely by meteoric waters resulted in formation of the solution collapse breccias. In several examples cross-bedded sandstone beds directly overlie the solution collapse breccias suggesting that breccia formation occurred prior to dune migration. In other exemplars, cross-bedded sandstone beds are separated from the solution collapse breccias by convolute-bedded sandstone intervals indicating that the solution collapse occurred after initial dune migration. Results from this study indicate when aeolian facies do not overlie the brecciated facies, and instead are subsequently deposited on lacustrine (Facies M or N) deposits the topographic depression creating the lake is still the primary mode of preservation (Chapter 2). Presumably, the lake sediments were still damp or dry (and did not leave an evaporite layer) when the dunes migrated over the depression.

Lastly, the implications of the preservation of the entire Charlie Lake Formation were briefly discussed (Chapter 2). In short, both the Liard and Baldonnel formations represent fully marine depositional conditions, while the entirety of the Charlie Lake Formation is comprised of mostly non-marine/continental strata. These types of deposits accumulate in areas with low accommodation potential and thus they are typically thin in coastal successions. Preservation of a thick package of marginal and non-marine facies in a western geographic setting on the coast of Middle / Upper Pangaea implies a relatively abrupt increase in accommodation space in a setting that should have low accommodation. It is suggested that tectonic forces were in affect at the time of Charlie Lake deposition, which allowed for preservation of a thick package of strata, with typically low preservation potential.

This study concludes that coastal dune preservation is related to deposition in shore-parallel depressions that were initiated as lagoons or lakes (Chapter 2, Chapter 3). Thus it is proposed that preserved aeolian dune thickness is directly related to lagoon / lake depth, which in turn is likely related to local tidal regime. These conclusions serve to improve the understanding of the occurrence and mode of preservation of coastal dune deposits, Triassic (Carnian) deposition in general, and the stratigraphic and sedimentological relationships related to these conclusions.

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Warren, J.K., 1988, Sedimentology of Coorong dolomite in the Salt Creek region, South Australia: Carbonates and Evaporites, Volume 3, pages 175-199.

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APPENDIX

SYMBOLS: CORE/OUTCROP LOGGING FORMS

Ichnofossil Symbols

- Root Traces
- *Scalarituba*
- *Gyrochorte*
- tubular tidalite
- *Planolites*
- *Treptichnus*
- *Gyrolithes*
- *Trichichnus*
- *Fugichnia*
- *Asteriacites*
- *Chondrites*
- feeding pit
- *Lingulichnus*
- *Cylindrichnus*
- *Asterosoma*
- *Roselia*
- *Zoophycos*
- *Siphonichnus*
- *Lockeia*
- vertical discoidal & plug-shaped burrows
- *Glossifungites* surface
- Undifferentiated Bioturbation
- *Phycosiphon/Anconichnus*
- *Helminthopsis/Helminthoida*
- *Skolithos/Monocraterion*
- *Conichnus/Bergaueria*
- *Rhizocorallium*
- *Teichichnus*
- *Diplocraterion*
- *Arenicolites*
- *Spongelliomorpha*
- *Thalassinoides/Camborygma*
- *Ophiomorpha*
- *Cruziana*
- *Lunulichnos*
- *Palaeophycus*
- *"Terebellina"*
- *Schaubcylindrichnus*
- *Macaronichnus*
- bivalve resting trace
- *Aulichnites*
- *Diplichnites*
- *Monomorphichnus*
- *Phycodes*
- *Scolicia*
- *Halapoa*
- *Fustiglyphus*
- *Macanopsis*
- *Merdelineaus*
- *Psilonichnus*
- *Beaconichnus*

Fossil Symbols

- Conodont
- Ammonoid
- Gastropod
- Nautaloid
- Bivalved pelecypods
- Echinoid/ echinoid debris
- Ophiuroid
- Asteroid
- Crinoid/ crinoid debris
- Spirifirid Brachiopod
- Lingulide Brachiopod
- Terebratulid Brachiopod
- Acrotretid brachiopod
- Atrypid Brachiopod
- Decapod crustacean
- Phyllocarid arthropod
- Foraminifera
- Cryptalgal laminae
- Bioclastic debris
- Vertebrate skeletal elements
- Wood
- Leaves
- Carbonaceous matter
- Carbonaceous laminae

- conformable contact
- marine flooding surface
- erosional surface

Physical Sedimentary Structures

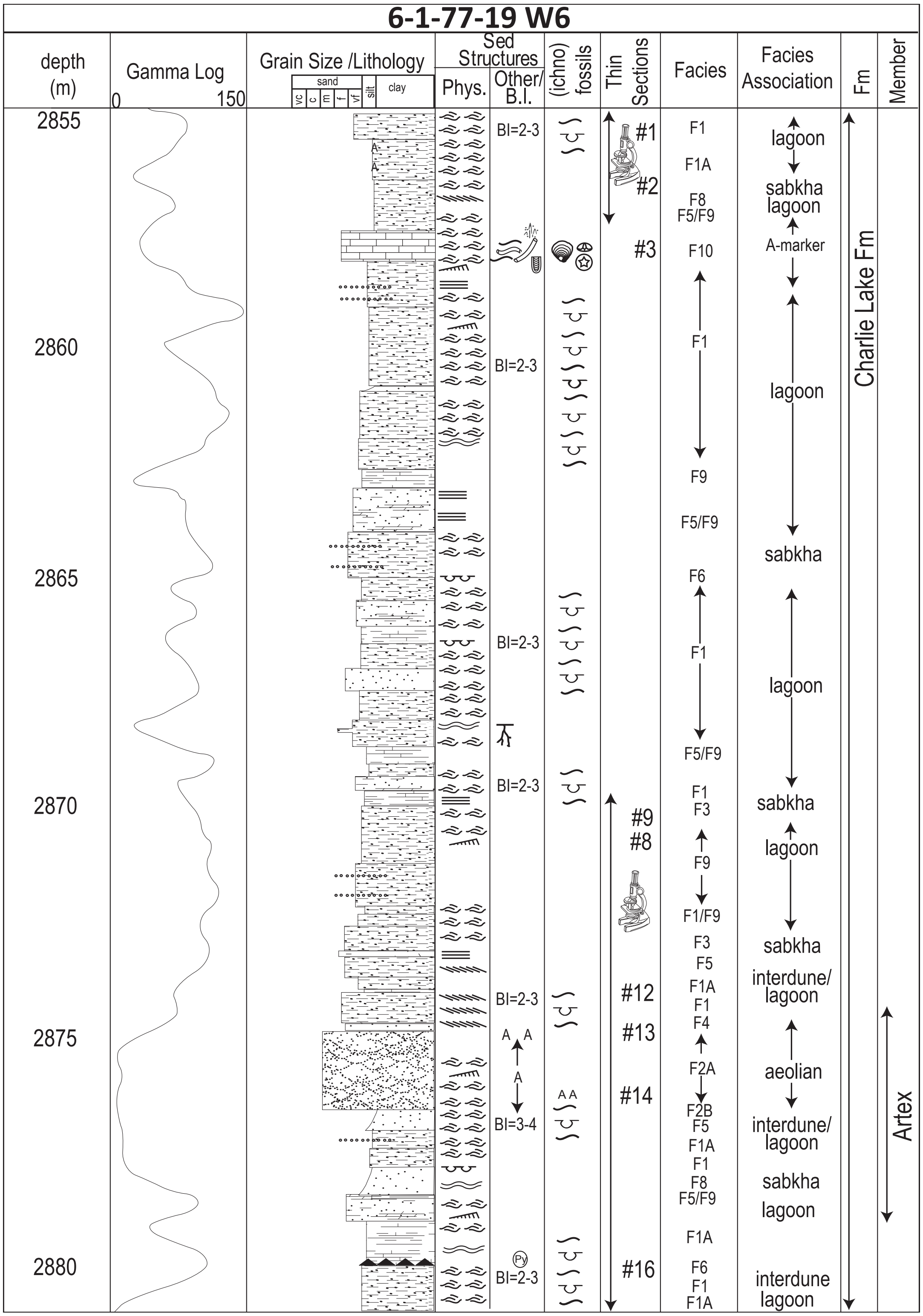
- Flaser Bedding
- Lenticular Bedding
- Tidal Couplets
- Wavy bedding (heterolithic)
- Wavy bedding (homogeneous)
- Ripple Laminae (wave/current)
- Ripple Laminae (bidirectional/starved)
- Climbing Ripples
- Low angle cross-stratification
- Hummocky cross-stratification
- Planar cross-stratification
- Swaley cross-stratification
- Trough cross-stratification
- Over steepened beds
- Evaportitic Minerals
- Shell Fragments
- Mud drapes
- Rip- Up Clasts
- Graded Bedding
- Shrinkage/Dessication cracks
- Planar bedding
- Scour and Fill
- Bird's eye structure
- Tool marks
- Pedogenic slickensides
- Sand laminae
- Silt laminae
- Stylolite
- Load casts
- Synaeresis cracks
- Soft sediment faulting
- Soft sediment deformation
- Dewatering structure
- Convolute lamination

Miscellaneous

- Mud clasts
- Pebble lag
- Shale laminae
- Imbricated clasts
- Photo Available
- Sample collected
- outcrop locality
- subsurface locality
- Ⓢ Siderite
- Ⓖl Glauconite
- Py Pyrite
- Ⓟ Phosphate
- Ⓐ Anhydrite
- Ⓒ Calcite
- A Anhydrite Cement

Schooler Creek Strip Log

Litholog of Brown Hill Outcrop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Sed Structures
Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
2855
2860
2865
2870
2875
2880
BI=2-3
BI=3-4
Py
#1
#2
#3
#9
#8
#12
#13
#14
#16
F1
F1A
F8
F5/F9
F10
F9
F6
F1/F9
F3
F5
F4
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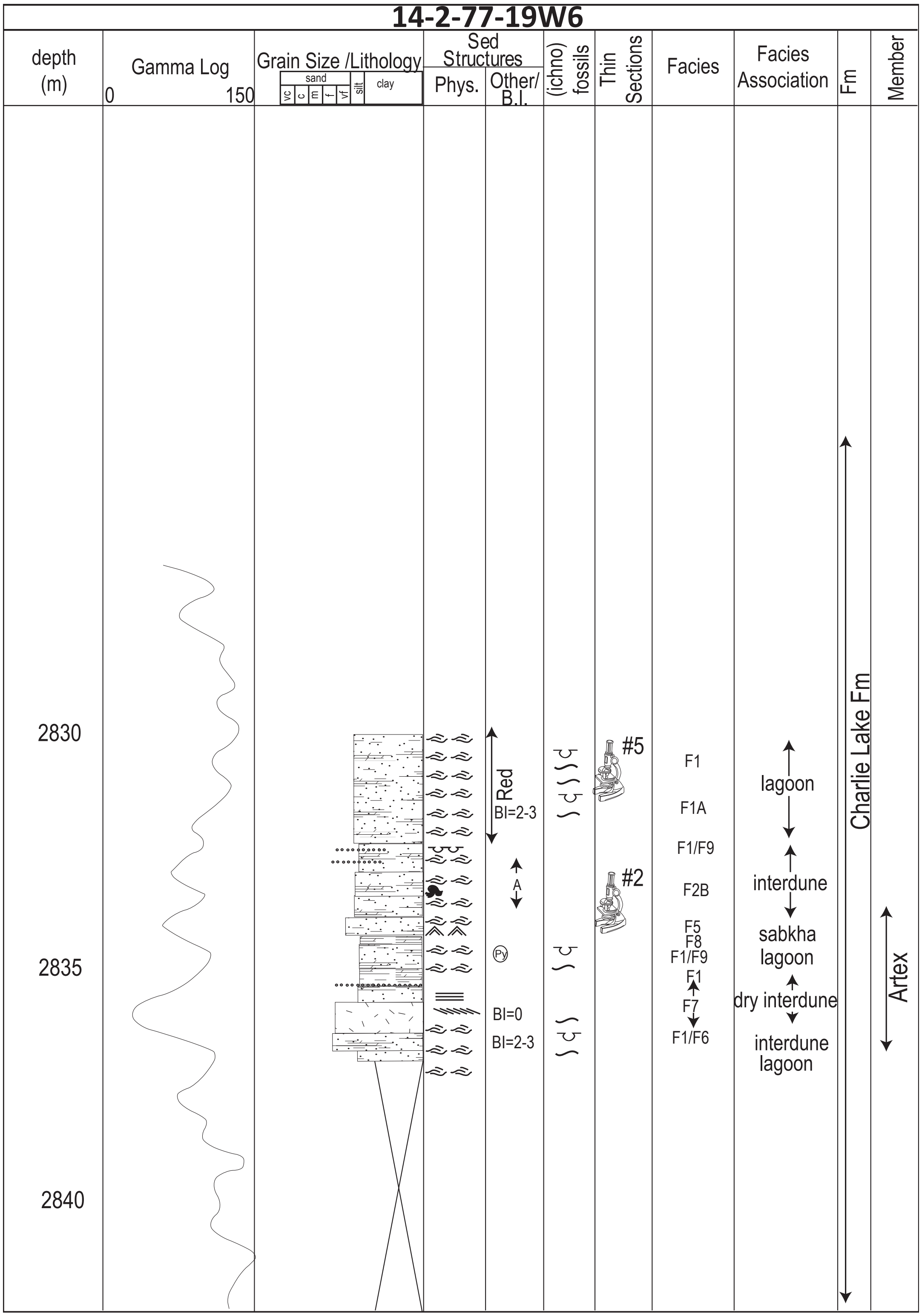
F2B
lagoon
sabkha
A-marker
interdune/ lagoon
aeolian
interdune lagoon
Charlie Lake Fm
Artex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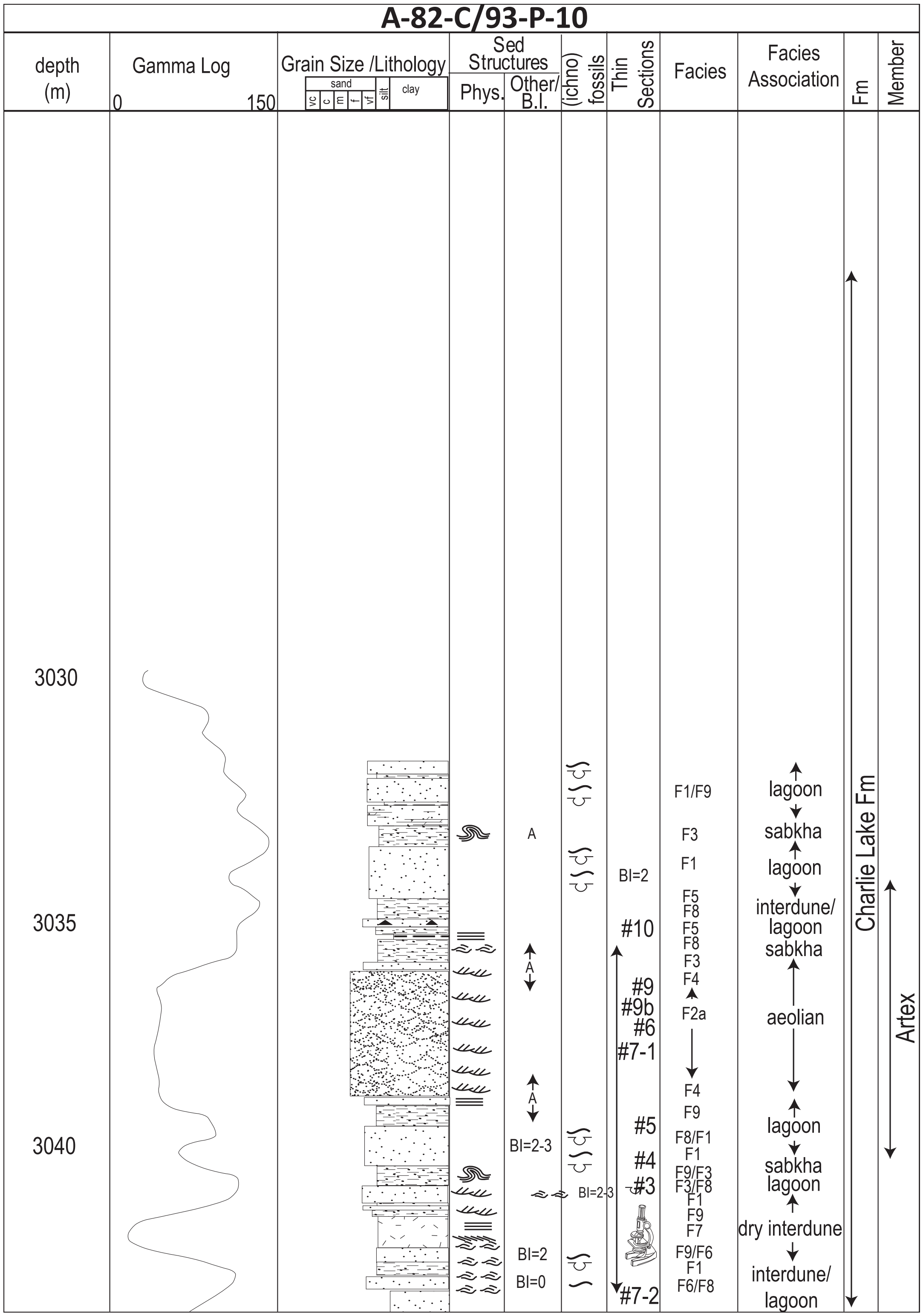
c
m
f
vf
silt
clay
Sed Structures
Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
2830
2835
2840
Red
BI=2-3
A
Py
BI=0
BI=2-3
#5
#2
F1
F1A
F1/F9
F2B
F5
F8
F1/F9
F1
F7
F1/F6
lagoon
interdune
sabkha
lagoon
dry interdune
interdune
lagoon
Charlie Lake Fm
Artex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c
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f
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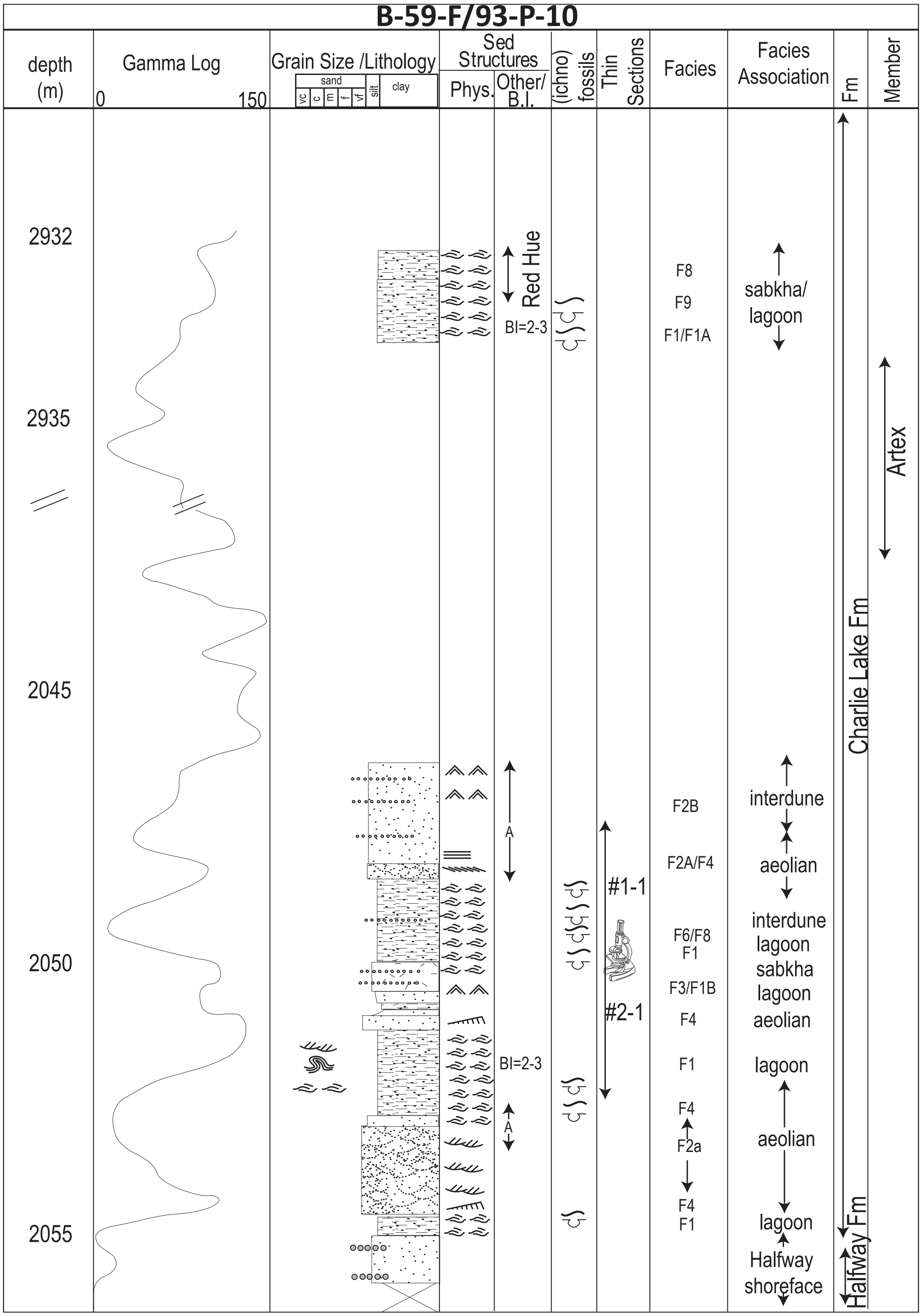
silt
clay
Sed Structures
Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
3030
3035
3040
A
BI=2
#10
#9
#9b
#6
#7-1
#5
BI=2-3
#4
#3
BI=2-3
BI=2
BI=0
#7-2
F1/F9
F3
F1
F5
F8
F5
F8
F3
F4
F2a
F4
F9
F8/F1
F1
F9/F3
F3/F8
F1
F9
F7
F9/F6
F1
F6/F8
lagoon
sabkha
lagoon
interdune/ lagoon
sabkha
aeolian
lagoon
sabkha
lagoon
dry interdune
interdune/ lagoon
Charlie Lake Fm
Artex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f
vf
silt
clay
Sed Structures
Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
2932
2935
2045
2050
2055
Red Hue
BI=2-3
A
#1-1
#2-1
F8
F9
F1/F1A
F2B
F2A/F4
F6/F8
F1
F3/F1B
F4
F1
F4
F2a
F4
F1
sabkha/ lagoon
interdune
aeolian
interdune
lagoon
sabkha
lagoon
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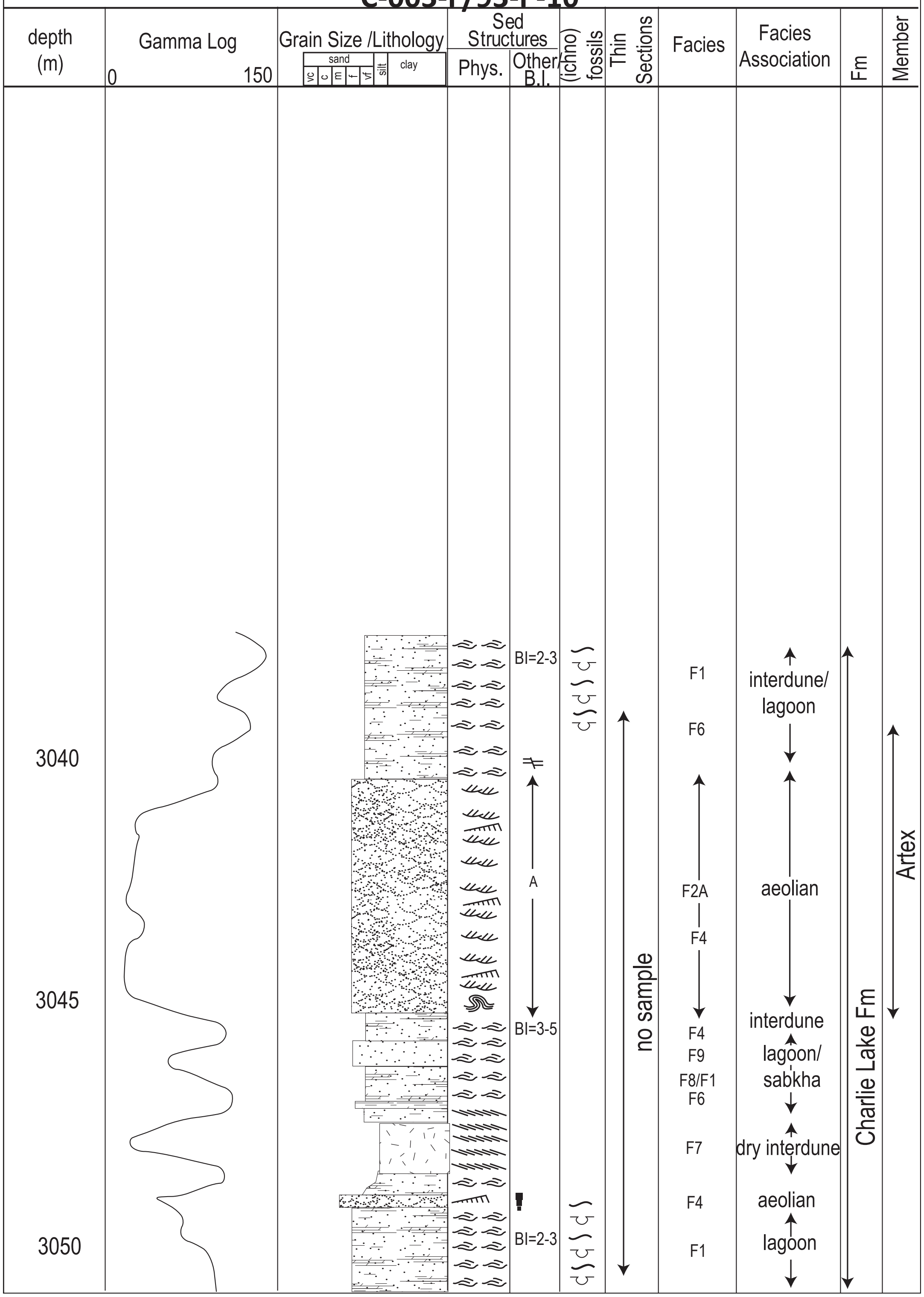
lagoon
aeolian
lagoon
Halfway shoreface
Charlie Lake Fm
Halfway Fm
Artex

C-003-F/93-P-10



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clay
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Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
3040
3045
3050
BI=2-3
A
BI=3-5
BI=2-3
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F1
F6
F2A
F4
F4
F9
F8/F1
F6
F7
F4
F1
interdune/ lagoon
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interdune
lagoon/ sabkha
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aeolian
lagoon
Charlie Lake Fm
Artex

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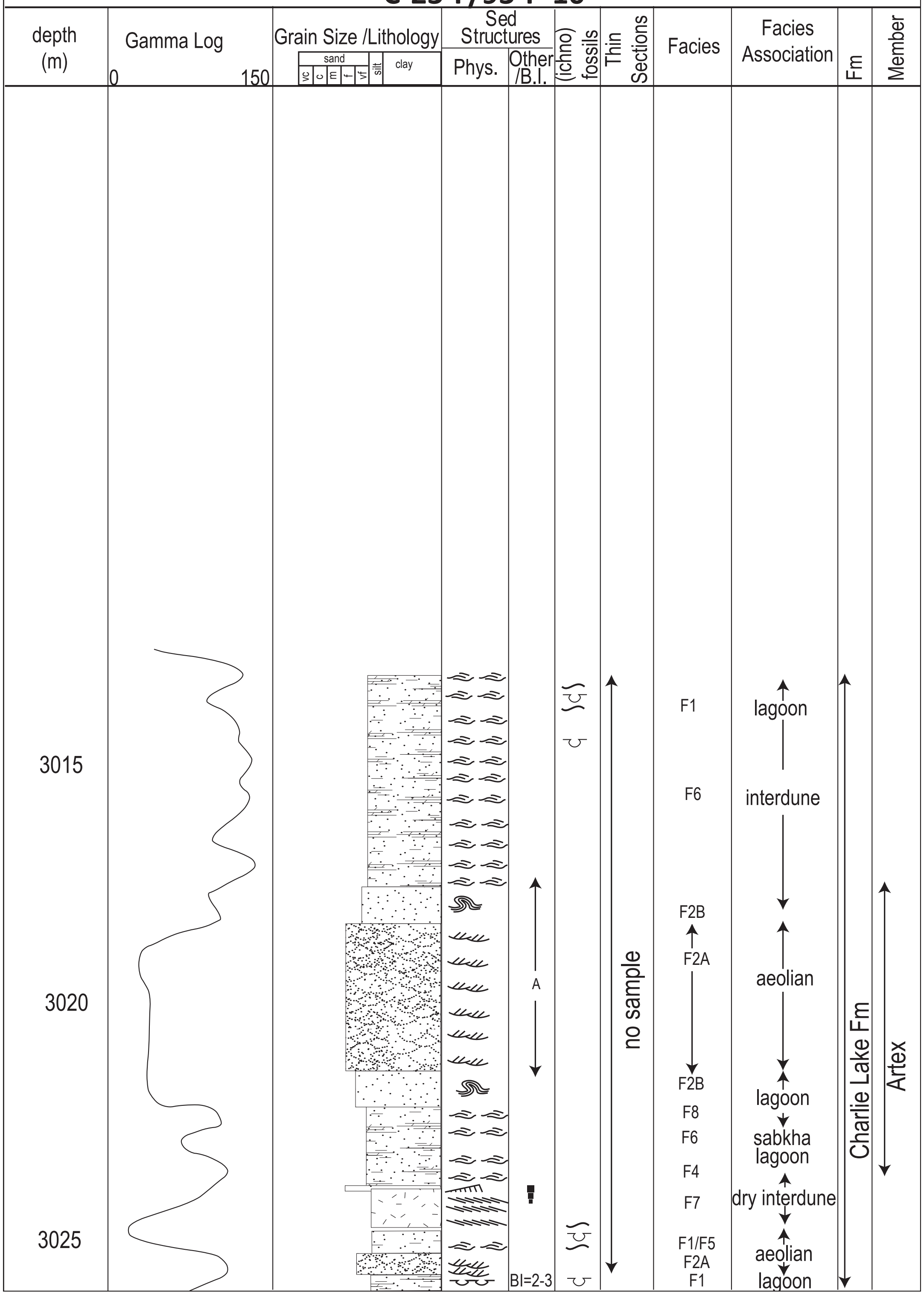

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clay
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Phys.
Other /B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
3015
3020
3025
A
BI=2-3
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F1
F6
F2B
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F6
F4
F7
F1/F5
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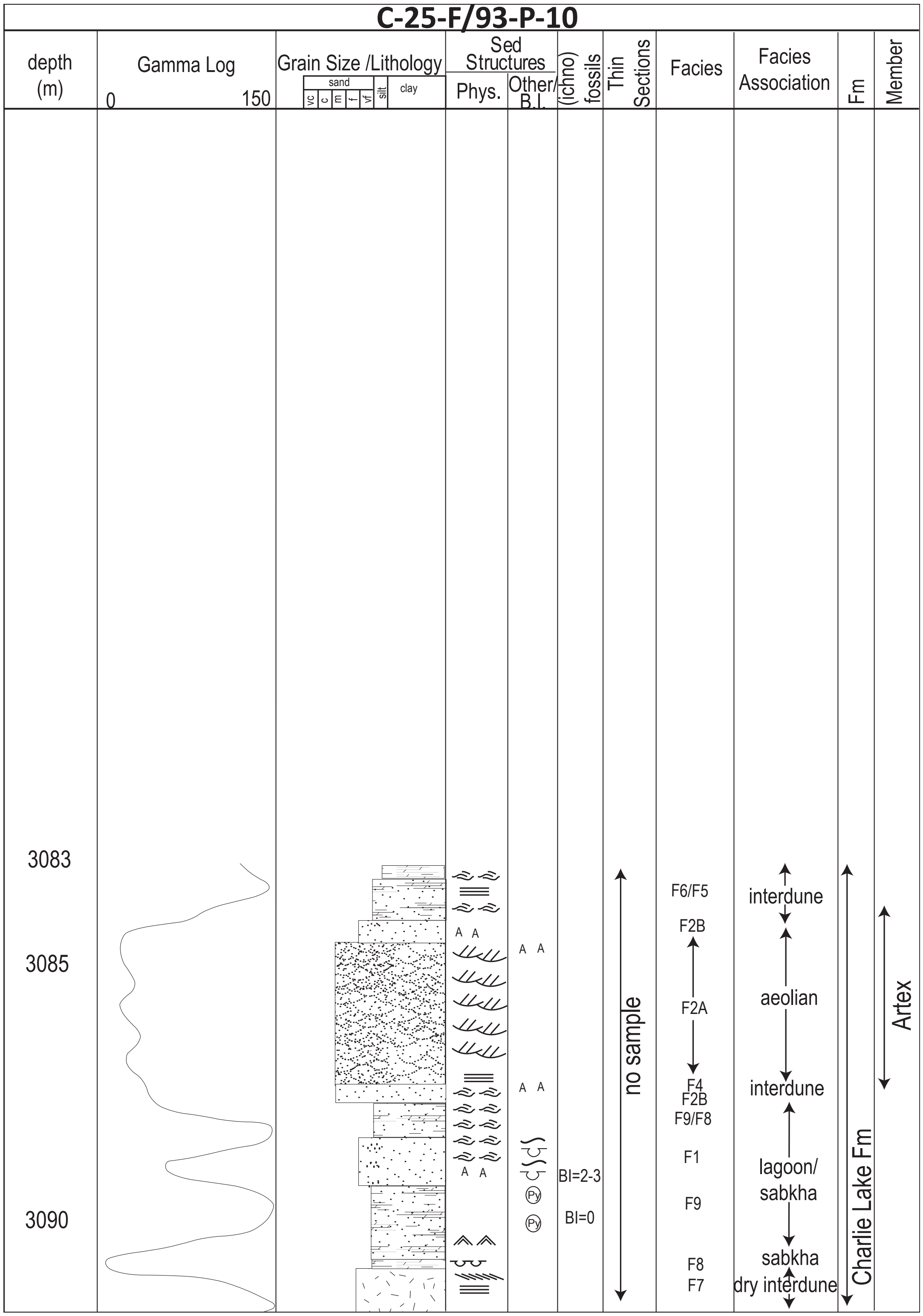
sabkha
lagoon
dry interdune
aeolian
lagoon
Charlie Lake Fm
Artex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Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
3083
3085
3090
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F6/F5
F2B
F2A
F4
F2B
F9/F8
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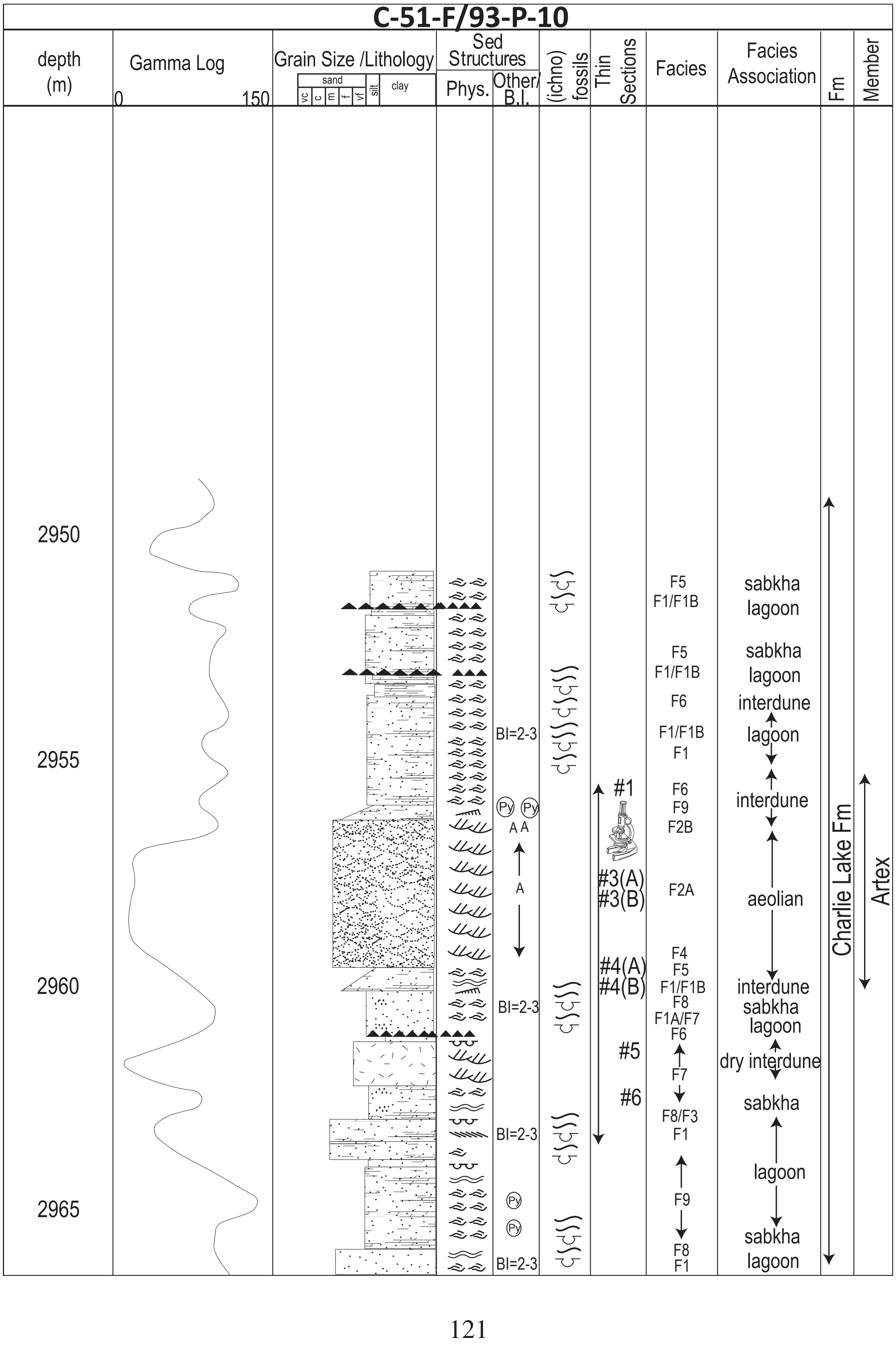
sabkha
dry interdune
Charlie Lake Fm
Artex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Phys.
Other/ B.I.
(ichno) fossils
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Facies
Facies Association
Fm
Member
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2965
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BI=2-3
BI=2-3
Py
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#1
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#3(B)
#4(A)
#4(B)
#5
#6
F5
F1/F1B
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F1/F1B
F6
F1/F1B
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F6
F9
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F2A
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F5
F1/F1B
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F7
F8/F3
F1
F9
F8
F1
sabkha
lagoon
sabkha
lagoon
interdune
lagoon
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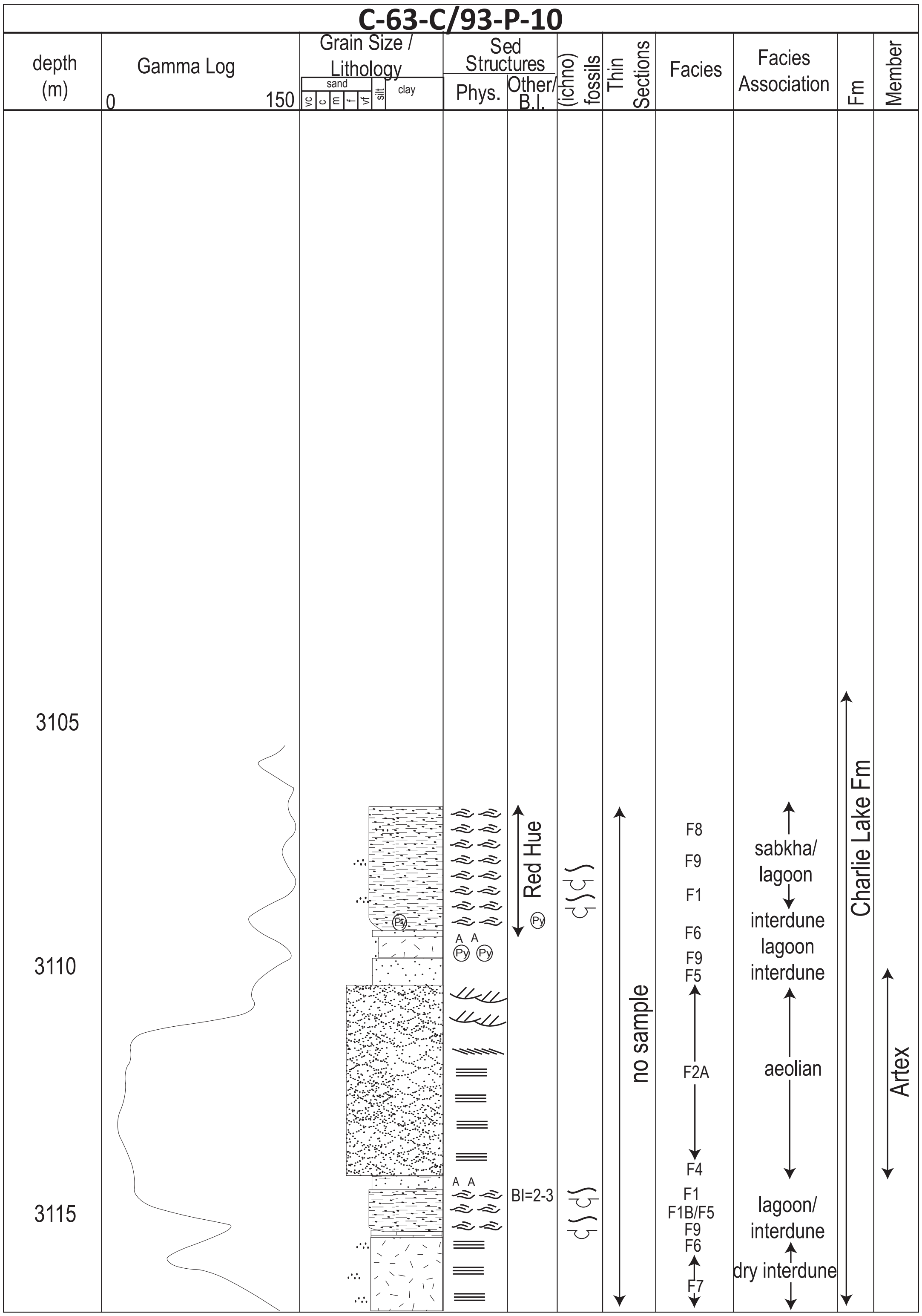
lagoon
sabkha
lagoon
Charlie Lake Fm
Artex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Other/ B.I.
(ichno) fossils
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Facies
Facies Association
Fm
Member
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3110
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BI=2-3
no sample
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F6
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F5
F2A
F4
F1
F1B/F5
F9
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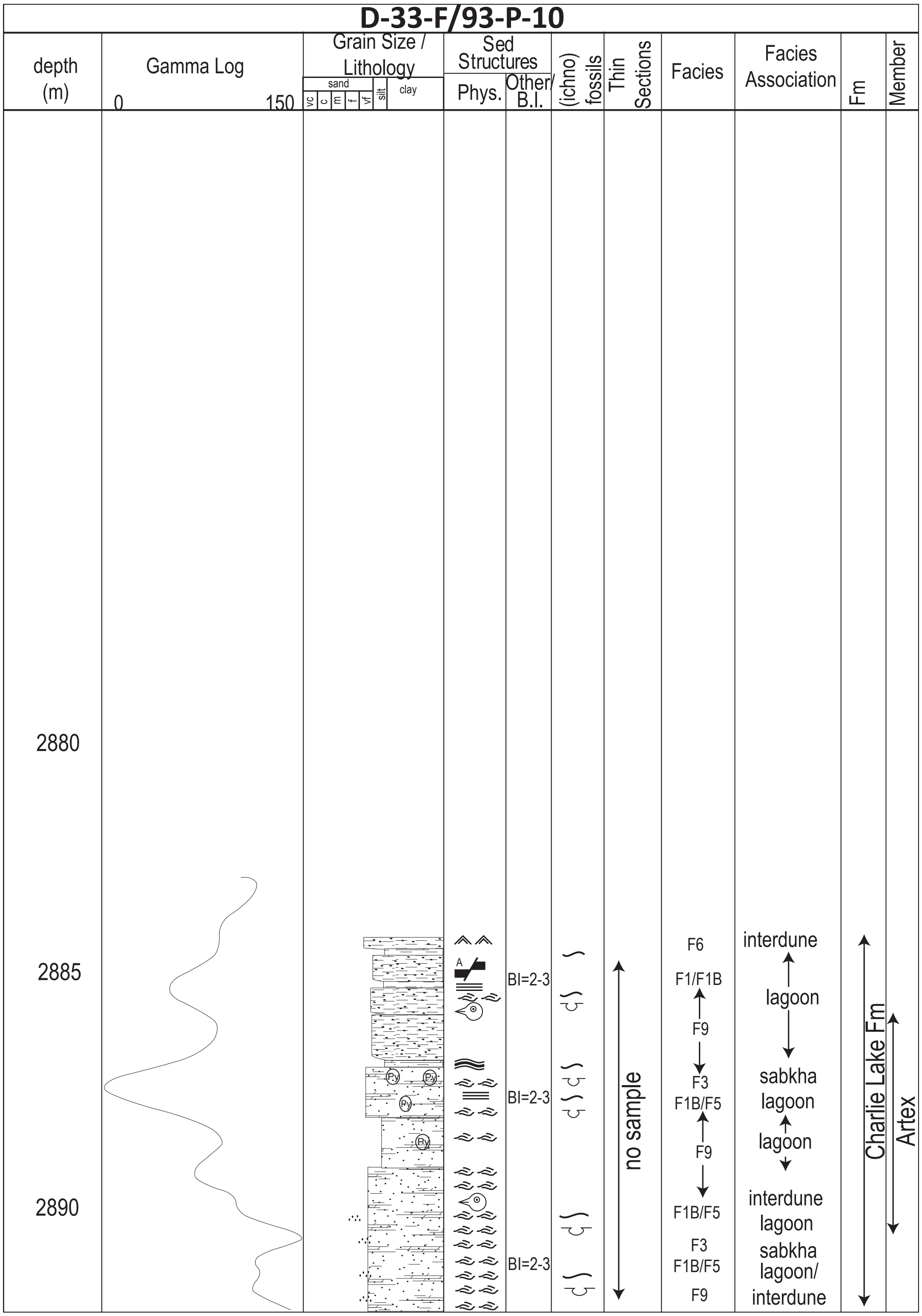
lagoon/ interdune
dry interdune
Charlie Lake Fm
Artex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Phys.
Other/ B.I.
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Thin Sections
Facies
Facies Association
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2885
2890
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Py
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no sample
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F1/F1B
F9
F3
F1B/F5
F9
F1B/F5
F3
F1B/F5
F9
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lagoon
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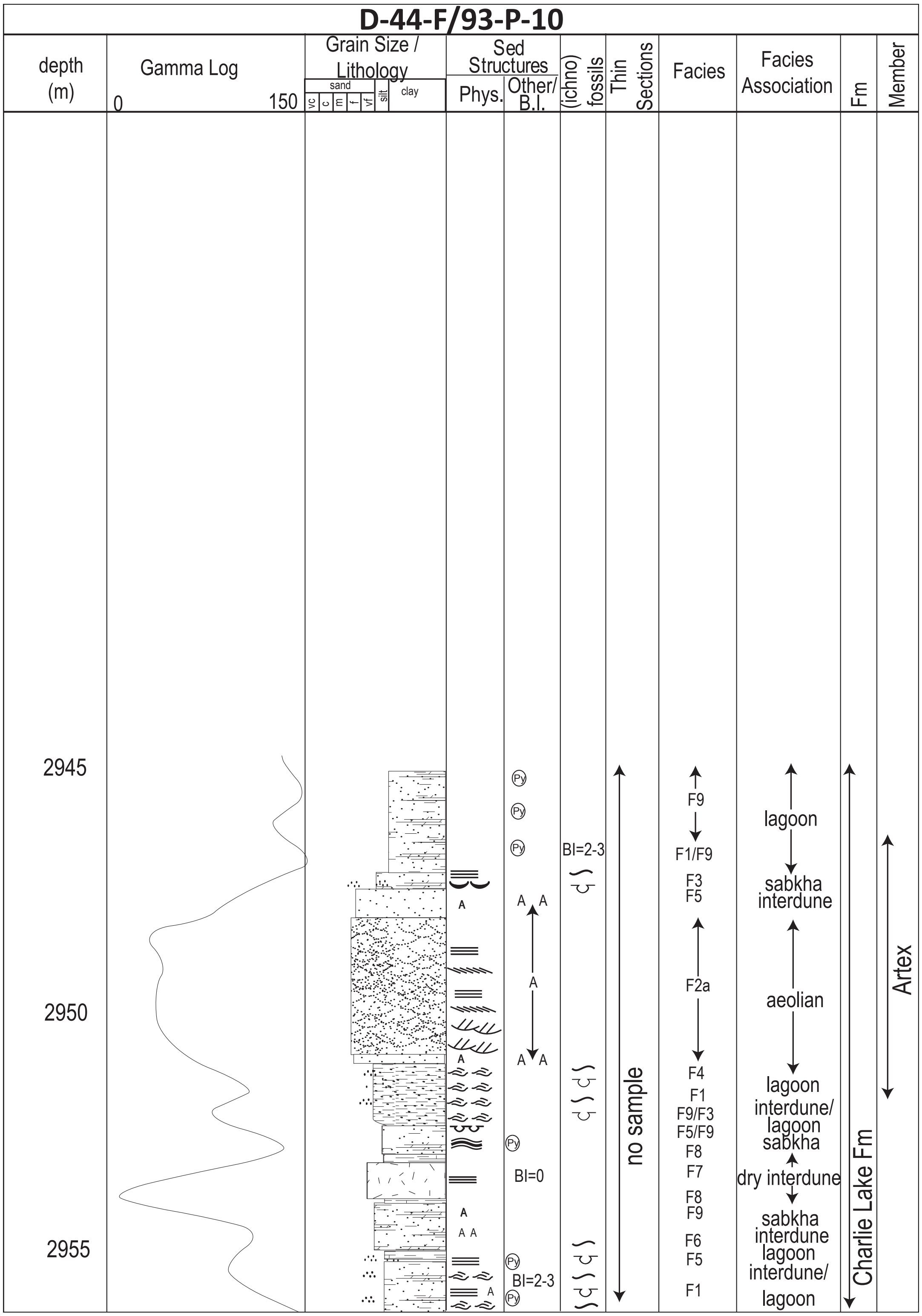
sabkha
lagoon/
interdune
Charlie Lake Fm
Artex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Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
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F4
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F5/F9
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F5
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lagoon
sabkha
interdune
aeolian
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sabkha
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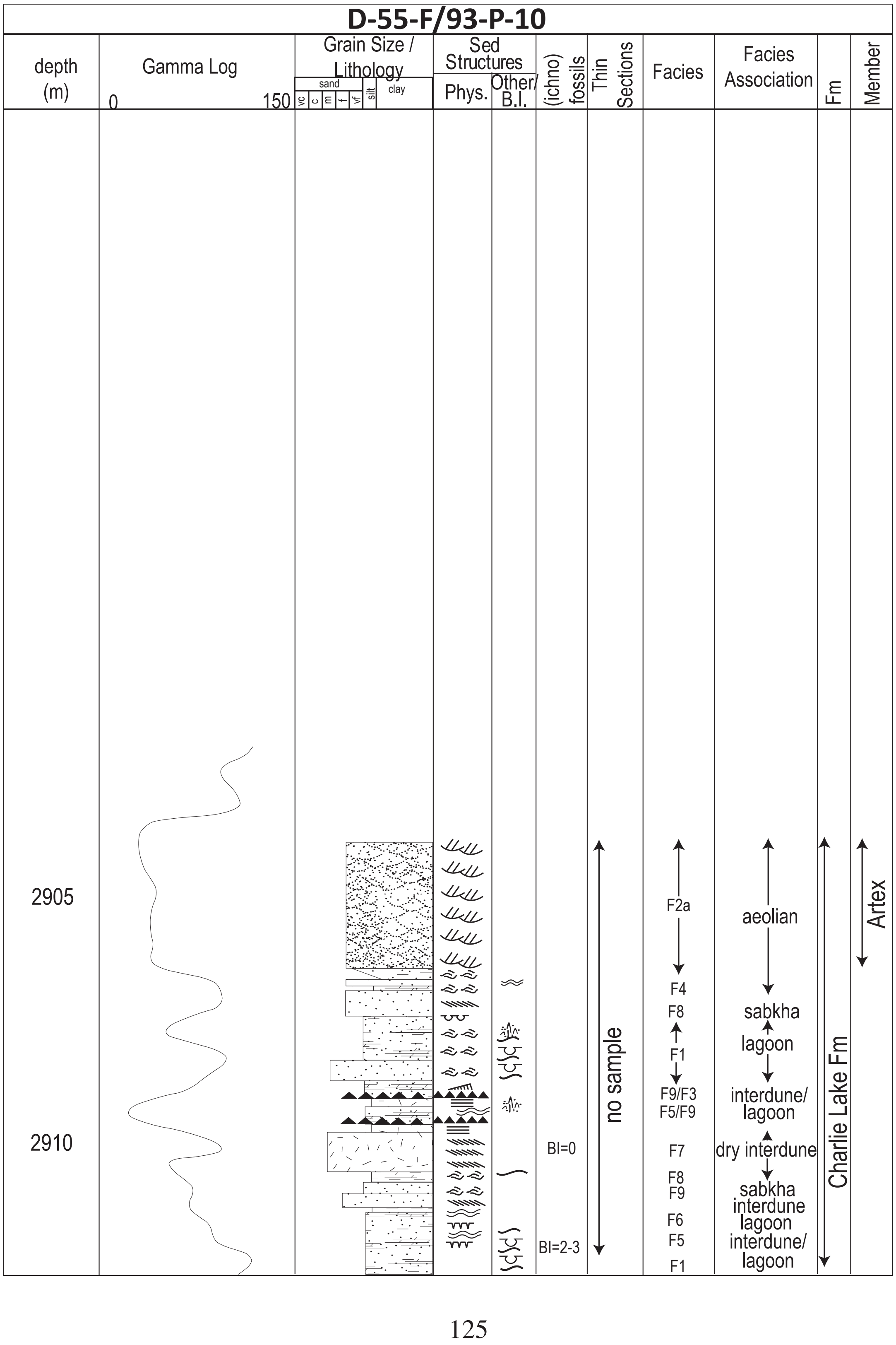
interdune/
lagoon
Charlie Lake Fm
Artex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Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
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2910
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BI=2-3
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F2a
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F1
aeolian
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lagoon
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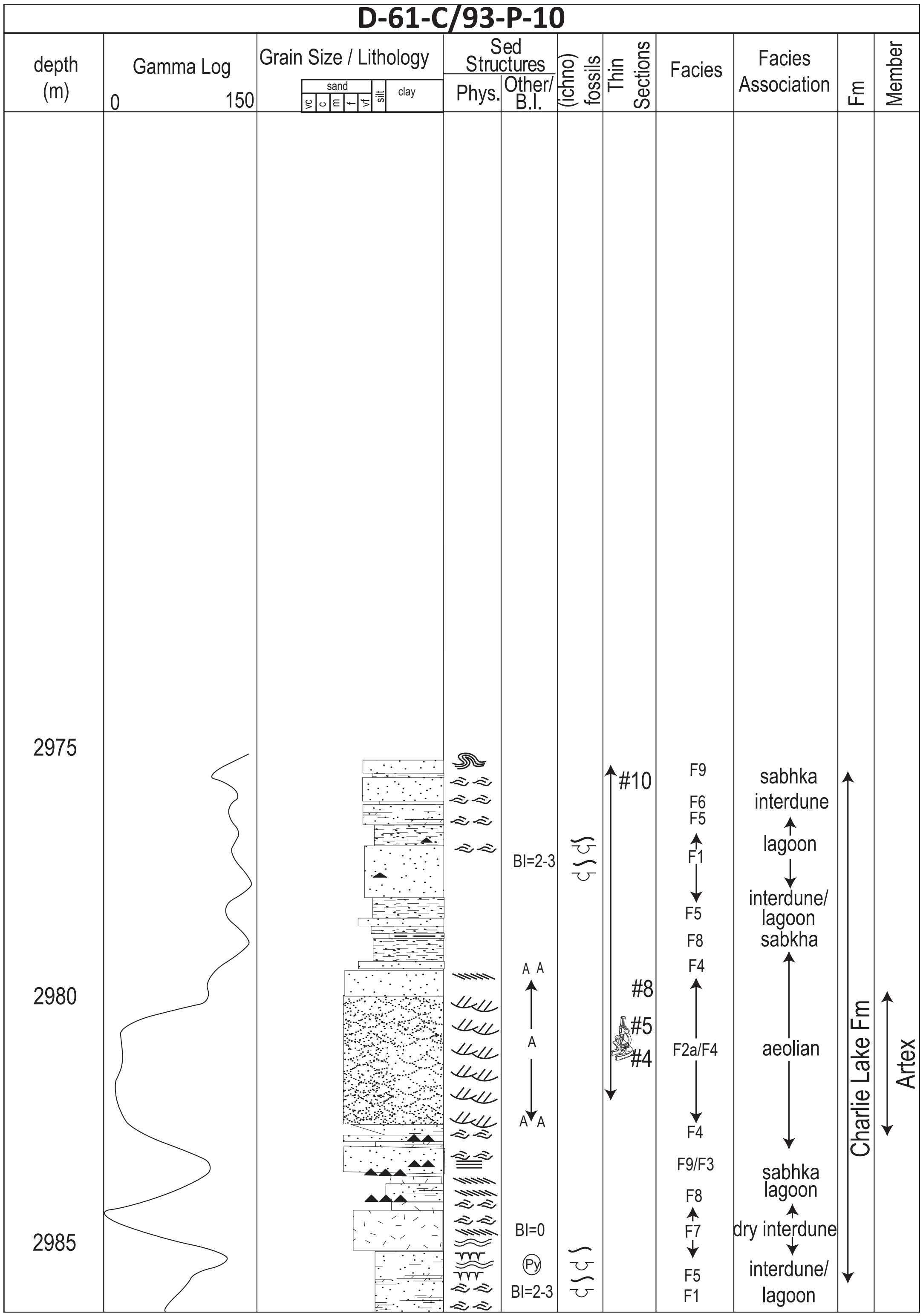
lagoon
interdune/
lagoon
Charlie Lake Fm
Artex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Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
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2980
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#8
#5
#4
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F4
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F1
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lagoon
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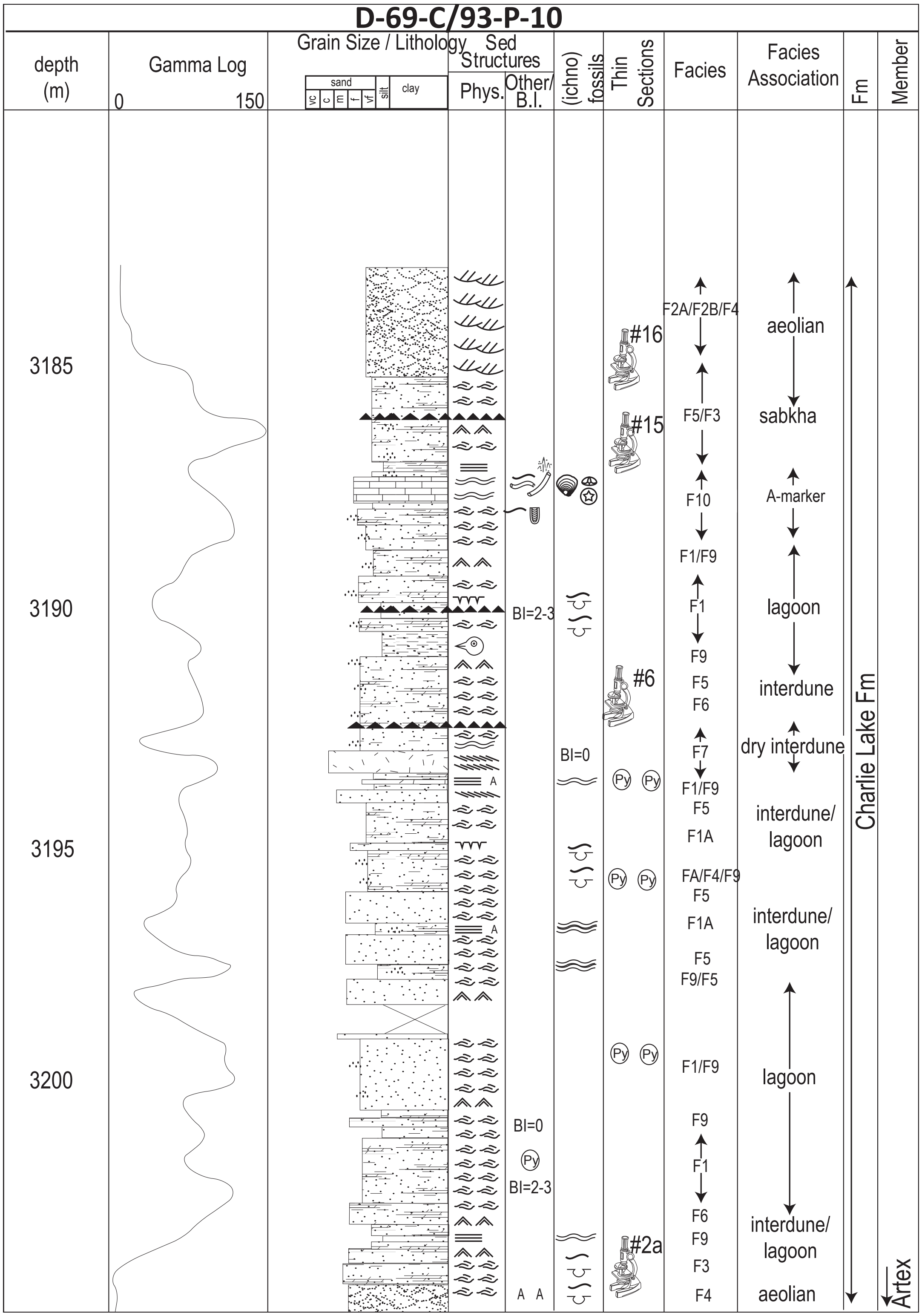
aeolian
sabhka
lagoon
dry interdune
interdune/ lagoon
Charlie Lake Fm
Artex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Other/ B.I.
(ichno) fossils
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Facies
Facies Association
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3195
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F5/F3
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F9
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sabkha
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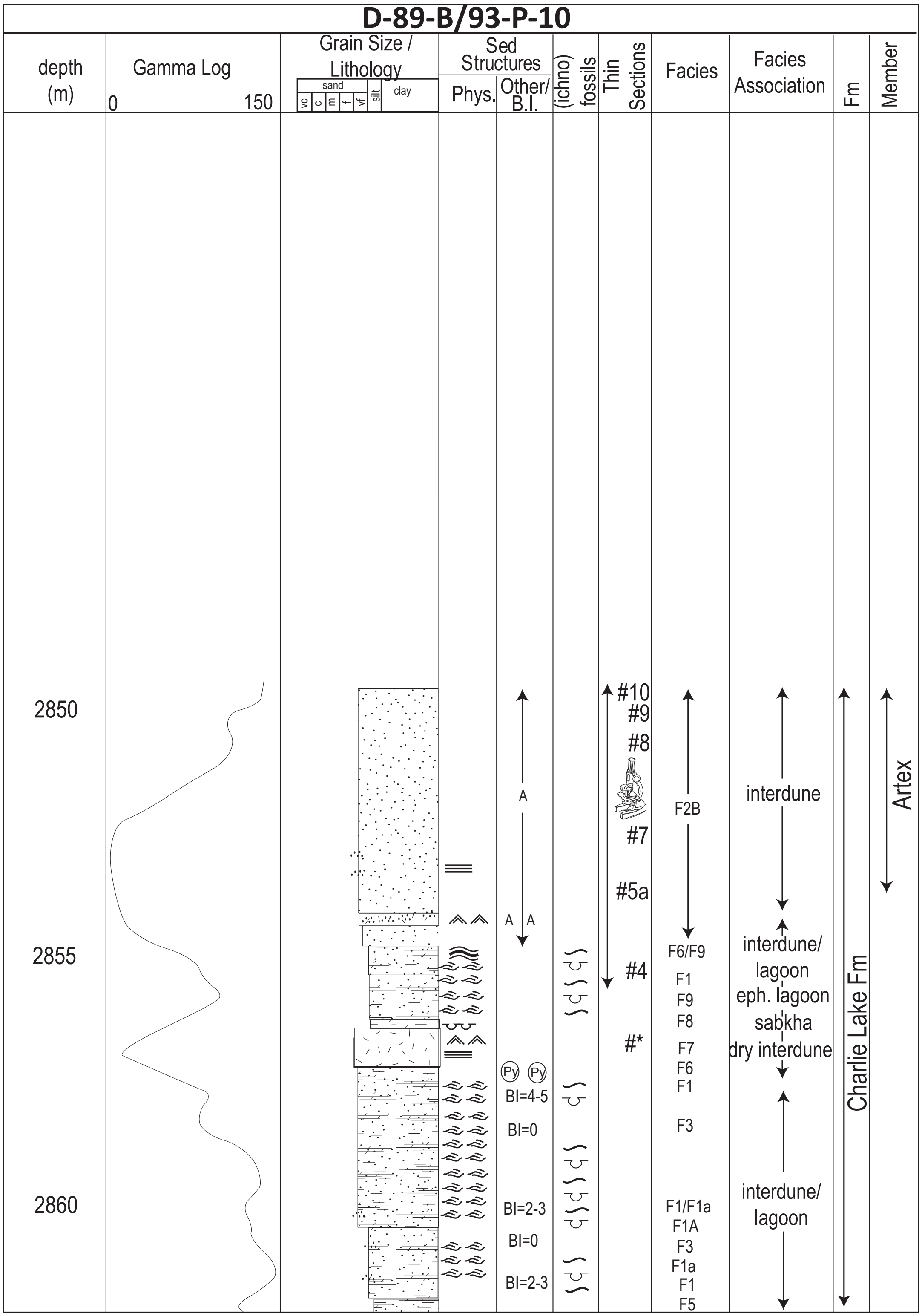
interdune/ lagoon
interdune/ lagoon
lagoon
interdune/ lagoon
aeolian
Charlie Lake Fm
Artex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c
m
f
vf
silt
clay
Sed Structures
Phys.
Other/ B.I.
(ichno) fossils
Thin Sections
Facies
Facies Association
Fm
Member
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2860
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A A
Py Py
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#*
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F1
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interdune
interdune/ lagoon
eph. lagoon
sabkha
dry interdune
interdune/ lagoon
Charlie Lake Fm
Artex