High-resolution Analysis of the Ichnological Diversity, Depositional Dynamics, and Stratigraphic Architecture of the Middle Triassic Sunset Prairie Formation

by

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ABSTRACT

The Sunset Prairie Formation is a newly established lithostratigraphic formation within the Middle Triassic (Anisian) of western Canada. The interval had commonly been overlooked or placed within the underlying Montney Formation or overlying Doig Formation, or was considered to be partially within the two formations. However, the Sunset Prairie Formation is sedimentologically, ichnologically and palaeontologically distinct from the overlying and underlying formations. The Sunset Prairie Formation is an unconformity-bound unit, characterized by interbedded pervasively bioturbated and diminutively bioturbated siltstone, fine-grained sandstone, phosphatic sandstone with locally abundant bivalves, gastropods, lingulid brachiopods, spiriferid brachiopods, terebratulid brachiopods, echinoid skeletal elements, and crinoid ossicles. Trace fossils present within the interval, listed from most abundant to least abundant, include *Phycosiphon, Rosselia*, *Cylindrichnus*, *Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. Seven facies are identified in the formation and record deposition within the offshore, offshore transition and lower shoreface of a sheltered coastal setting. Facies stacking patterns exhibit up to three shoaling-upward parasequences. These parasequence exhibit a back-stepping or retrogradational stacking pattern, and are assigned to a transgressive systems tract. Structural features associated with the Western Canada Sedimentary Basin greatly influenced the deposition and preservation of the formation.

The Sunset Prairie Formation is the first stratigraphic occurrence of a pervasively bioturbated interval that is regionally extensive following the end-Permian mass extinction in Western Canada. The unit provides a unique dataset to investigate physico-chemical stresses influencing the distribution of trace fossils, and thereby infaunal biota, within a marine realm during post-extinction faunal recovery. Through the comparison of process ichnology data (bioturbation intensity, burrow diameter, ichnodiversity, and Size Diversity Index) and geochemical proxies for redox-sensitive elements (Mo, V, and V/Cr) collected at a high-resolution (10 cm intervals), vacillating redox conditions are interpreted to have occurred during the deposition of the Sunset Prairie Formation. The recognition and investigation of the Sunset Prairie Formation provides new sedimentological, ichnological, palaeontological and geochemical evidence to unravel the palaeoenvironmental and palaeoecological transition from the Lower Triassic to the Middle Triassic within Western Canada.

PREFACE

This thesis is original work by Carolyn Marie Furlong. The thesis contains material that has been submitted for publication and has involved collaboration with other researchers. The research project was designed by myself, with the assistances of my supervisors, J-P. Zonneveld, and supervisorial committee, M.K. Gingras and L.R. Leighton.

Chapters within this thesis have either been published within peer-reviewed journals or been submitted for publication, and include:

— Chapter 2 has been published as Furlong, C.M., Gingras, M.K., Moslow, T.F. and Zonneveld, J-P., "The Sunset Prairie Formation: Designation of a New Middle Triassic Formation between the Lower Triassic Montney Formation and Middle Triassic Doig Formation in the Western Canada Sedimentary Basin, Northeast British Columbia" in the Bulletin of Canadian Petroleum Geology (2018a, v.66, n. 1, p. 193-214). Data collection, analysis, and manuscript composition were the responsibility of myself. Co-authors provided discussion of research, editorial guidance and feedback.

— Chapter 3 has been published as Furlong, C.M., Gegolick, A., Gingras, M.K., González, P., Moslow, T.F., Prenoslo, D., Playter, T. and Zonneveld, J-P., "Sedimentology and Ichnology of the Middle Triassic (Anisian) Sunset Prairie Formation of the Western Canada Sedimentary Basin" in the Bulletin of Canadian Petroleum Geology (2018a, v.66, n. 1, p. 215-236ß). Core logging, facies analysis, well-log correlations, and manuscript composition were the responsibility of myself. Co-authors provided discussion of research, editorial guidance and feedback.

— Chapter 4 has been submitted for published as Furlong, C.M., Gingras, M.K. and Zonneveld, J-P., "High Resolution Sequence Stratigraphy of the Middle Triassic Sunset Prairie Formation, Western Canada Sedimentary Basin, Northeastern British Columbia" in an International Association of Sedimentologists special publication entitled, Petroleum Source Rocks: From Conventional Sources to Unconventional Targets. Background summary, core logging, sequence stratigraphic interpretations and manuscript composition were conducted by myself. Co-authors provided discussion of research, editorial guidance and feedback.

DEDICATION

This thesis is dedicated to my family: John, Mary Lou, and Jack Furlong.
Words cannot capture the love, support, and encouragement you have provided me throughout my life and through the journey I have taken to get where I am today. I am truly lucky.

ACKNOWLEDGMENTS

Seven years ago I joined the Ichnology Research Group (IRG) as a Master's student. From the moment I started doing fieldwork in Oregon and the Bay of Fundy with John-Paul Zonneveld and Murray Gingras, I was hooked on the Kool-Aid that is the IRG. Looking back, I have so many fond memories (and sometimes stressfully un-fond memories) of fieldwork, lab field trips, field schools, playing cribbage for hours, shenanigans on and off campus, Friday beers, road trips, conferences, short courses and consortium meetings. I have been blessed with the opportunities that I have been provided with during my time in the IRG lab. I am endlessly thankful for John-Paul Zonneveld and Murray Gingras believing in me, my work ethic, and my scientific potential, and providing me with the opportunity to further develop my geological knowledge by pursuing a PhD.

I would foremost like to thank my supervisor, John-Paul Zonneveld, and my supervisorial committee, Murray Gingras and Lindsey Leighton, for assisting in formulating my research project, providing me with guidance when I felt lost, and giving me feedback for my work. I am eternally grateful for the knowledge you have all passed onto me, and the support that has ben provided through the years. I would also like to thank George Pemberton, Dan Alessi and James MacEachern for sitting on my candidacy test committee and/or defense committee. I would also like to thank Tom Moslow for his input, feedback and discussions during the early stages of my research.

Thanks the members of the Montney Consortium: Aimée Gegolick, Patricia Gondaléz, Shelby Sanders, Donald Prenoslo and Tiffany Playter. From road tripping up to Fort St. John to log core, to scrambling to get things done for consortium meetings; we somehow pulled it off!

Thank you to my office mates through the years: Alina Schchepetkina, Olga Kovalchuk, Shimeng Zhang, Nabilah Adani, Brad Bobey, Reed Myers, Daniel Shaw, Shaliza Ali, Waqar Ahmad and Chundi Shan. I will forever treasure all the research brainstorming, life discussions, uplifting advice, and heart-to-hearts that occurred within those four walls.

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discussions on research, making figures and all things food related. Thanks to Tiffany Playter and Hilary Corlett for all the XRF help. Thanks to Reed Myers for all the research discussion and ditching our office to work in the lab. Thanks to Derek Hayes for making the lab an amusing place, and constantly telling me I should go to the bar instead of barre. Thanks to Brette Harris, Scott Melnyk, and Jared Kugler for making the Spring 2018 second year field school one of the best and most devious field schools to date. Thanks to David Herbers for being my rock through my PhD, providing endless help, support, and encouragement along the way.

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I would like to thank the Alberta Geological Survey for allowing me to use their XRF gun. Thanks to Gordie Jean and Rob Natyshen at the Alberta Geological Survey for letting me take over the Mineral Core Research Facility to store all my pallets of core. I would like to thank Ryan Olson, Sung-Eun Kim and John Ross from the British Columbia Oil and Gas Commission for always accommodating to my crazy core requests and always being incredibly kind in the process.

Finally, I would like to thank the funding companies of the Montney consortium: Birchcliff Energy Ltd, Canbriam Energy Inc, Progress Energy Canada Ltd., Sasol Canada, Shell Canada Ltd. and Taqa North Ltd. Without this funding, the project would not have been possible. Thanks to the Government of Alberta, University of Alberta and the Department of Earth and Atmospheric Sciences for supporting and funding this research.

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CHAPTER 1: INTRODUCTION

GENERAL OVERVIEW

The Western Canada Sedimentary Basin (Fig. 1.1) consists of a wedge of Phanerozoic strata above a Precambrian crystalline basement (Mossop and Shetsen, 1994). The basin tapers to a zero-edge towards the northeast along the Canadian Shield and strata is cannibalized within the Cordilleran deformation front to the west, which outcrops many subsurface equivalent intervals within the Canadian Rocky Mountains. During the Triassic, sediments were deposited within a large, central sub-basin, called the Peace River Embayment and consist of marginal-marine siliciclastic and carbonate rocks, with lesser amounts of evaporite intervals (Fig. 1.1; Douglas, 1970; O'Connell et al., 1990; Barclay et al., 1990; Edwards et al., 1994). Up to 1200 m of strata have been preserved in the west, and these thin eastwardly to an eroded zero edge (Edwards et al., 1994). The strata range in age from Early Triassic Griesbachian to Late Triassic Norian. Throughout Alberta and British Columbia, Triassic strata sit unconformably above Permian or Carboniferous strata and are unconformably overlain by Jurassic or Lower Cretaceous deposits (Fig. 1.2; Edwards et al., 1994).

Historically, Triassic subsurface strata within the basin have been composed of the lithostratigraphic intervals of the Montney, Doig, Halfway, Charlie Lake, Baldonnel and Pardonet Formations (Armitage, 1962; Gibson and Edwards, 1990; Davies et al., 1997a, 1997b). Recently, a new Middle Triassic formation, the Sunset Prairie Formation, was named to describe an interval of strata that sits stratigraphically between the Lower Triassic Montney Formation and the Middle Triassic Doig Formation (Fig. 1.2; Furlong et al., 2018a, 2018b). Work by Zonneveld and Moslow (2015), Zonneveld et al. (2015, 2016) and Furlong et al. (2016b, 2017a, 2017b) informally described the unit as the 'Anisian Wedge'.

The Sunset Prairie Formation consists of interbedded light gray, pervasively bioturbated sandstone and dark gray, diminutively bioturbated to non-bioturbated siltstone. Trace fossils within the unit include *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos*. *Glossifungites* Ichnofacies-demarcated discontinuity surface (firm-ground assemblage) are also common throughout the interval. Macrofossils include bivalves, gastropods, lingulid brachiopods, spiriferid brachiopods, terebratulid brachiopods, echinoid skeletal elements (particularly spines) and crinoid ossicles. Based on conodont biostratigraphy and the macrofossil assemblage, the unit is assigned a Middle Triassic (Anisian) age.

The formation previously has been overlooked and/or incorporated into underlying or overlying

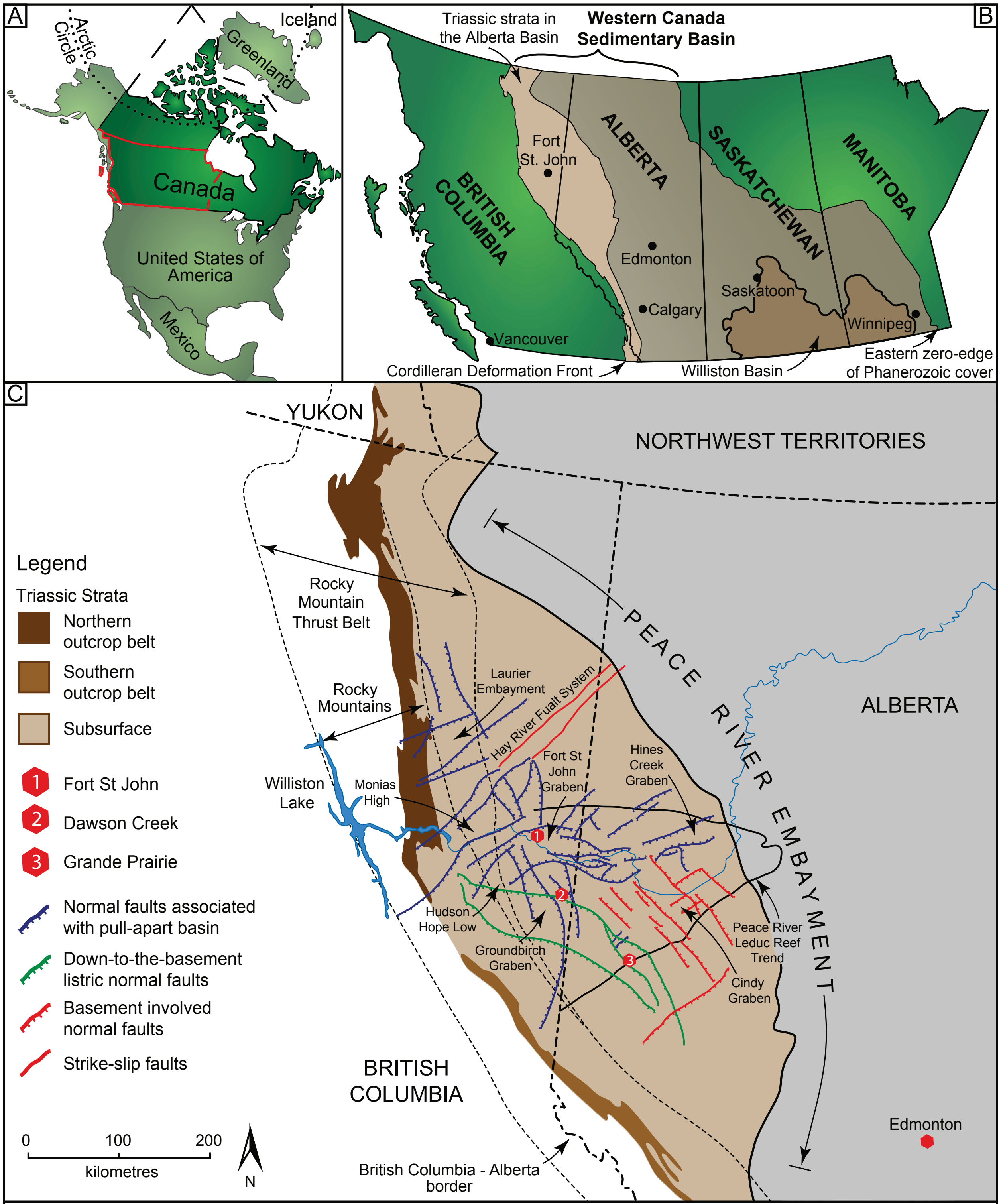


Figure 1.1–Location maps of the Western Canada Sedimentary Basin. A. Map of North America. Area enlarged in B is outlined in red. B. Map of Western Canada Sedimentary Basin (dark brown) and limits of Triassic strata (light brown) in British Columbia, Alberta, Saskatchewan and Manitoba. Modified Edwards et al. (1994). C. Regional map of British Columbia and Alberta showing the extent of Triassic strata in the Western Canada Sedimentary Basin (modified from Zonneveld et al., 2011). Major structural features that influence Lower and Middle Triassic strata are identified and were compiled from previously published studies and maps (Barclay et al., 1990; Davies, 1997a, 1997b; Davies et al., 1997; Berger, 2005; Berger et al., 2009).

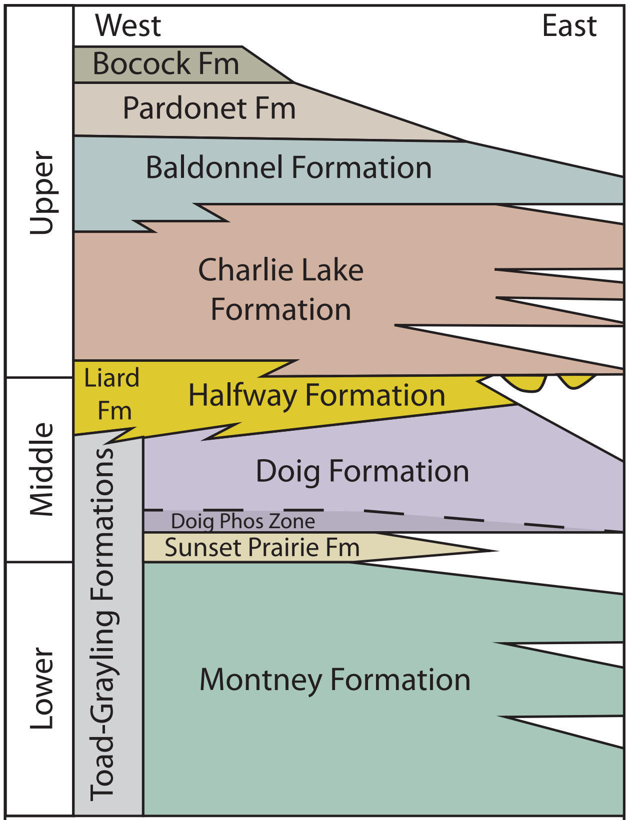


Figure 1.2–Lithostratigraphic nomenclature of the Triassic of the Western Canada Sedimentary Basin. Modified from Dixon (2011).

intervals. Therefore, the overall goal of this dissertation is to erect a sedimentologic, sequence stratigraphic and palaeoredox framework that explains the origin of the previously unrecognized stratigraphic unit in the Middle Triassic of the Western Canada Sedimentary Basin. This dissertation has five objectives: 1) introduce and describe the Sunset Prairie Formation as a new formation within the Middle Triassic of western Canada; 2) develop sedimentary facies models for the Sunset Prairie Formation in core, utilizing sedimentology, ichnology and palaeontology; 3) develop a detailed sequence stratigraphic model for the unit using a subsurface wireline well log and core dataset, which incorporates and relates the Sunset Prairie Formation to other formations within the Lower and Middle Triassic f western Canada; 4) investigate and interpret the physico-chemical stresses that influenced biotic/trace fossil distributions within the Sunset Prairie through the use of a process ichnology framework; and 5) integrate these ichnological data with high-resolution geochemical elemental data (X-ray fluorescence: XRF) to interpret palaeoredox conditions during the deposition of the Sunset Prairie Formation.

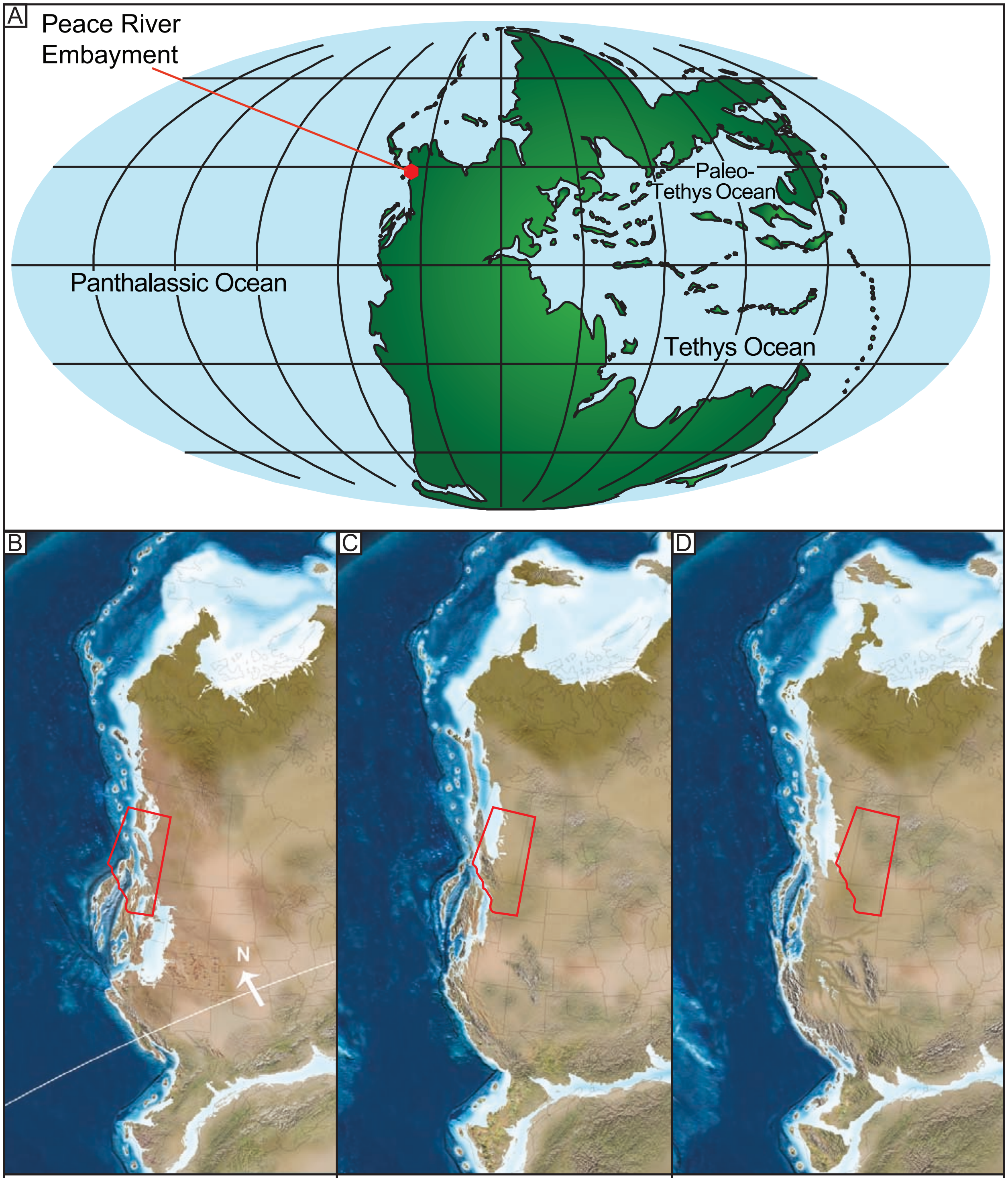
BIOSTRATIGRAPHIC FRAMEWORK

Numerous studies have been conducted on the biostratigraphy of microfossils to better constrain the age of Triassic intervals within the Western Canada Sedimentary Basin (e.g., Orchard and Tozer, 1997; Orchard and Zonneveld, 2009; Golding et al., 2014a; 2014b; 2015; Henderson and Schoepfer, 2017; Henderson et al., 2018). The Montney Formation and its outcrop equivalents, the Sulphur Mountain, Grayling and lower Toad Formations, have been dated to span the Induan and Olenekian (Gibson and Barclay, 1989; Davies et al., 1997; Orchard and Tozer, 1997; Paull et al., 1997; Utting et al., 2005; Orchard and Zonneveld, 2009; Wilson et al., 201; Golding et al., 2014a; 2014b; 2015). Prior to the identification of the Sunset Prairie Formation, the Montney-

Doig boundary had been suggested to be highly diachronous, with the boundary ranging from Spathian to Middle Anisian age (Wilson et al., 2014; Golding et al., 2015). Through the re-evaluation of published conodont biostratigraphic data, Furlong et al. (2018a) suggested that the newly described Sunset Prairie Formation was deposited during the Anisian, which reduced the magnitude of diachroneity associated with the Lower and Middle Triassic boundary. The Doig Formation has been dated to span the Anisian to Ladinian, with the Doig phosphate zone at the base of the formation, dated as Anisian (Gibson and Barclay, 1989; Davies et al., 1997; Orchard and Tozer, 1997; Paull et al., 1997; Utting et al., 2005; Orchard and Zonneveld, 2009; Wilson et al., 2014; Golding et al., 2014a; Henderson et al., 2018).

PALAEOGEOGRAPHIC SETTING

Deposition of the Lower and Middle Triassic strata of western Canada occurred on the western margin of Pangaea and the eastern margin of Panthalassa under arid, mid-latitudinal (~30^{O}N) conditions (Fig. 1.3; Wilson et al., 1991; Davies, 1997a; Davies et al., 1997; Dixon, 2000; Moslow, 2000; Zonneveld et al., 2010b). Historically, a passive margin basin has been associated with fostering the development of a marine ramp/shelf setting (Dickinson, 1977; Monger and Price, 1979; Coney et al., 1980; Gibson and Barclay, 1989; Edwards et al., 1994; Price 1994; Davies; 1997a; Dixon, 2009a; 2009b); however, recent work suggests that Triassic deposition occurred on an active margin, possibly associated with a back-arc-basin (Miall and Blakey, 2008; Zonneveld et al., 2010a; Schiarizza, 2013; Morris et al., 2014), fore-arc basin (Nelson et al., 2006; Colpron et al., 2007; Rohais et al., 2016) or early foreland basin (Ferri and Zonneveld, 2008; Golding et al., 2016). Provenance studies suggest that most Triassic sediment was derived from reworked Devonian rocks from the Laurentian continent to the east (Ross et al., 1997; Utting et al., 2005; Beranek et al., 2010; Morris et al., 2014), with small amounts potentially being sourced from western volcanic arcs settings (Morris et al., 2014; Golding et al., 2016). Regardless of sediment source, the main depocentre for Triassic sediment was the Peace River Embayment. This embayment formed as a result of the Peace River Arch, which was a topographic high during the Paleozoic, collapsing during the Carboniferous and ultimately forming the Dawson Creek Graben System (Douglas, 1970; Gibson and Edwards, 1990; O'Connell et al., 1990). The graben complex consists of three major elements, including the Fort St. John Graben, the Hudson Hope Low, and satellite grabens (Hines Creek, Whitelaw, and Cindy Grabens) (Barclay et al., 1990; O'Connell, 1994). Other structural features influencing Triassic deposition include: the Hay River Fault Zone, Laurier Embayment, Monias High, Beaton High, Grassy High, Sukunka Uplift, and faulting associated with Devonian reef trends (Leduc Reef and Swan Hills Reef) (Fig. 1.1; e.g.,



Early Triassic (245 Ma) | Middle Triassic (240 Ma) | Late Triassic (210 Ma)

Figure 1.3–Palaeogeography maps of the Triassic. A. Global schematic of the Triassic landmasses and oceans. B-D. Palaeogeographical reconstructed maps from the Early Triassic (B), Middle Triassic (C) and Late Triassic (D). Location of Alberta is outline in red. From Blakey (2006) mollwide plate tectonic maps.

Richards, 1989; Davies and Majid, 1993; Henderson et al., 1994; Davies, 1997a, 1997b). These structural features have been interpreted to be associated with shallow fault systems, deeper basement faults, and most importantly, graben faults (Evoy, 1997; Berger et al., 2009; Mei, 2009; Chalmers and Bustin, 2012). Structural features occur pre-depositionally, syn-depositionally, and post-depositionally with respect to Triassic strata. Additionally, the distribution of stratigraphic subdivisions (units, facies, parasequences, etc.) was commonly influenced by the accommodation space available during deposition and produced from differential compaction of pre-Triassic strata (Euzen et al., 2018; Rohais et al., 2018). The interplay between structural and sedimentological controls on accommodation space makes local and regional stratigraphic correlations complex.

PALAEOENVIRONMENTAL SETTING

The Lower and Middle Triassic record strata that were deposited within globally stressed conditions following the end-Permian mass extinction at ~250 Ma. Many have suggested that volcanism associated with the Siberian Traps was a likely catalyst for the end-Permian mass extinction (e.g., Benton and Twitchett, 2003; Payne and Clapham, 2012). The influx of atmospheric CO_2 and methane from the volcanic eruptions resulted in global warming, marine anoxia/dysoxia and ocean acidification (Erwin et al., 2002; Benton and Twitchett, 2003; Heydari and Hassanzadeh, 2003; Black et al., 2012; Hinojaosa et al., 2012; Payne and Clapham, 2012). The harsh oceanic conditions greatly influenced benthic assemblages and likely restricted them to narrow, shore-proximal habitable zones (Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011). These combined inputs caused the end-Permian mass extinction to be the most severe extinction the Earth has ever experienced, resulting in the disappearance of 90% to 95% of skeletonized marine species (Erwin, 1994; Benton and Twitchett, 2003; Algeo et al., 2011), and a conservative estimate of 79% of invertebrate genera (Payne and Clapham, 2012).

Within Western Canada, the Lower Triassic strata of the Montney Formation are generally devoid of diverse palaeontological and ichnological assemblages. Palaeontological assemblages commonly consist of bivalve and ammonoid impressions on bedding planes, with all original shell material being removed (Woods and Bottjer, 2000; Rampino and Caldeira, 2005; Zonneveld, 2011; Zonneveld and Moslow, 2018). Dissolution of shell material is a worldwide phenomenon and has been attributed to increased concentrations of CO_2 within the Early Triassic oceans (Woods and Bottjer, 2000; Zonneveld, 2011). Isolated intervals do have preserved shell material and are associated with the Coquina dolomite middle member in Alberta, as well as the *Claraia* Zone and the Altares Member in British Columbia (Mederos, 1995; Markhasin, 1997; Davies et al., 1997; Sanders et al., 2018, Zonneveld and Moslow, 2018). Trace fossils within the Lower Triassic are uncommon, but isolated areas with ichnological assemblages of high diversity have been found with the Pedigree-Ring-Kahntah area (Zonneveld et al., 2010a), La Biche River map area (Toad Formation) (MacNaughton and Zonneveld, 2010), Swan field (Zonneveld, personal observation), and Kawka and Karr fields (Davies et al., 2018). These areas have been interpreted to have been associated with environmental refugia, where oxygenated water was present within the shallow-marine realm and produced oases for infaunal organisms (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b; Zonneveld, 2010).

The Middle Triassic is marked by an initial shift to more hospitable oceanic conditions within the Sunset Prairie Formation, which led to preserved body fossil material and diverse trace fossil assemblages to be present (Furlong et al., 2018b). Fluctuating physico-chemical stresses were present, however, and influenced faunal distribution during Sunset Prairie Formation deposition, which persist into Doig Formation deposition (e.g., Proverbs and Bann, 2008). During the deposition of the upper Doig Formation and Halfway Formation, environmental conditions were once again suitable to support trace-making organisms and the preservation of body and trace fossils (Willis and Moslow, 1994; Zonneveld et al., 1997, 2001, 2002; Zonneveld, 2001). Although palaeontological and ichnological assemblages show signs of recovery during the Middle and Upper Triassic, pre-extinction diversity levels were likely not re-established until after the Triassic.

STUDY AREA AND DATASET

This thesis investigates the Sunset Prairie Formation at a regional scale within the Western Canada Sedimentary Basin. The study area is located in eastern British Columbia (Fig. 1.4). A total of 25 subsurface drill cores were investigated for a facies analysis (Table 1.1). Stratigraphic correlations between these drill cores were generated using petrophysical wireline data from GeoScout. Over 200 vertical wells with petrophysical well logs were used to determine stratigraphic architecture and distribution of the Sunset Prairie Formation.

A subset of the core was used to conduct a high-resolution process ichnology analysis and chemostratigraphy investigation (Fig. 1.4). Cores within the Fort St. John Graben system were investigated and selected as they exhibit the thickest preserved intervals of the Sunset Prairie Formation. Five cores were used to characterize process ichnological trends, and three cores were analyzed with a handheld X-ray fluorescence (XRF) device. Both ichnological data and geochemical data were collected every 10 centimetres along the core to generate a high-resolution dataset.

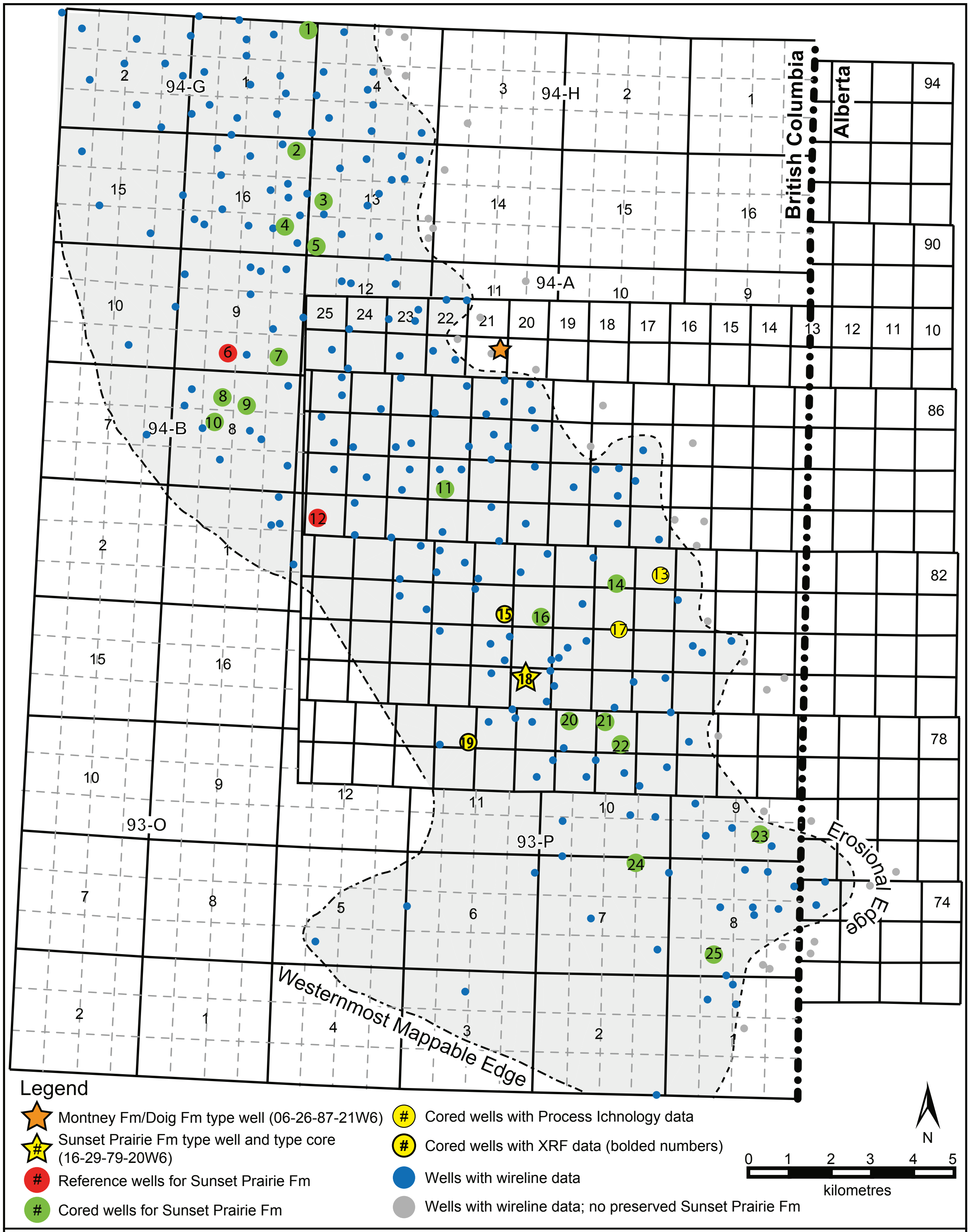


Figure 1.4–Study area map for this thesis. Area shaded grey indicates the spatial distribution of the Sunset Prairie Formation. The location of the Sunset Prairie Formation type core, reference core, other cored well that contain the Sunset Prairie Formation and wireline data used in this thesis are identified. The eastern limit of preserved Sunset Prairie Formation is labeled as an erosional edge, and the westward most mappable edge is identified.

	Location	Well Name	WA#
1	200/a-082-I/094-G-01/00	Progress Hz Laprise a-082-I/094-G-01	29565
2	200/d-066-I/094-B-16/00	Tourmaline Hz Beg d-66-I/094-B-16	28449
3	200/c-046-E/094-A-13/00	COP Hz Blueberry c-014-E/094-A-13	30406
4	200/b-078-A/094-B-16/00	Tourmaline Hz Gundy a-078-A/094-B-16	28770
5	200/a-018-D/094-A-13/00	Progress Hz Blueberry a-018-D/094-A-13	26894
6	200/c-033-C/094-B-09/00	CNRL Graham c-033-C/094-B-09	25738
7	200/d-048-A/004-B-09/00	Suncor Pc Hz Kobes d-048-A/004-B-09	22214
8	200/c-024-K/094-B-08/00	Progress Hz Graham c-024-K/094-B-08	27635
9	200/c-007-J/094-B-08/00	Progress Hz Altares c-007-J/094-B-08	27684
10	200/c-065-F/094-B-08/00	Progress et al Graham c-065-F/094-B-08	28756
11	100/04-09-084-22W6/00	ARCRES Attachie 04-09-084-22	26965
12	100/16-17-083-25W6/00	Progress et al Altares 16-17-083-25	25450
13	100/08-10-082-17W6/00	ARCRES Hz Tower 08-10-0ß82-17	27964
14	100/05-03-082-18W6/00	ARCRES Hz Septium 05-03-082-18	28046
15	100/04-11-081-21W6/00	Shell Monias 04-11-081-21	25261
16	100/13-11-081-20W6/00	ARCRES Groundbirch 13-11-081-20	24354
17	100/15-34-080-18W6/00	Shell Sunset 15-34-080-18	24410
18	100/16-29-079-20W6/00	Shell Groundbirch 16-29-079-20	25478
19	100/16-02-078-22W6/00	Shell Groundbirch 16-02-078-22	25398
20	100/ 11-28-078-19W6/00	Shell Hz Groundbirch 06-28-078-19	25466
21	100/12-29-078-18W6/00	ARCRES Groundbirch 12-29-078-18	24927
22	100/02-10-078-18W6/00	Murphy Heritage 02-10-078-18	24477
23	200/d-054-B/094-P-09/00	Murphy Swan d-054-B/094-P-09	22867
24	200/c-081-J/093-P-07/00	ECA et al Hz Sundown c-081-J/093-P-07	24253
25	200/d-056-C/093-P-08/00	CNRL Noel d-056-C/093-P-08	25669

Table 1.1–Summary of wells with Sunset Prairie Formation drill core, which were logged in this study. The number given to each well is the identification number for cored wells in Figure 1.4.

ORGANIZATION OF DISSERTATION

This dissertation centres on the Sunset Prairie Formation, a newly described lithostratigraphic unit within the Triassic strata (Anisian) of the Western Canada Sedimentary Basin (Furlong et al., 2018a, 2018b). This thesis is divided into 7 chapters (including the introduction and conclusion), which examine the sedimentology, ichnology, sequence stratigraphy and geochemistry of the Sunset Prairie Formation. A paper-based format was chosen to simplify the publication of each chapter within peer-reviewed journals, and therefore, some replication of data and figures inevitably occurs in order to provide the necessary context for each stand-alone chapter. The subject and content of each chapter is outlined below.

Chapter 2 introduces the reader to the Sunset Prairie Formation. Work by Zonneveld and Moslow (2015), Zonneveld et al. (2015; 2016), and Furlong et al. (2016b; 2017a; 2017b) informally described the unit as the 'Anisian Wedge'. This chapter demonstrates the need for a formal name for the interval and provides an overview of the characteristics that differentiate the Sunset Prairie

Formation from the underlying Montney Formation and overlying Doig phosphate zone, which thereby warrants a new lithostratigraphic name. The Sunset Prairie Formation is introduced to describe an unconformity-bound interval consisting of interbedded light gray, pervasively bioturbated sandstone and dark gray, diminutively bioturbated to non-bioturbated siltstone that stratigraphically occurs between the Montney and Doig Formations. The Sunset Prairie Formation is sedimentologically, ichnologically and palaeontologically discrete from the overlying and underlying formations, and is biostratigraphically dated to Middle Triassic (Anisian) age.

Chapter 3 describes the lithofacies of the Sunset Prairie Formation. Seven facies are identified, based on sedimentological, ichnological and palaeontological analyses of 25 cores that intersect the formation. Overall, these facies can be subdivided into three different groups: 1) diminutively bioturbated facies (Facies 1 and 2), where physical sedimentary structures are observable and trace fossils are rare and small in size; 2) pervasively bioturbated facies (Facies 3, 4), where burrowing organisms homogenized the sediment and destroyed most primary physical sedimentary structures; and 3) bathymetrically independent surfaces (Facies 6 = omission suites of the *Glossifungites* Ichnofacies; Facies 7 = lag deposit). These facies are interpreted to represent deposition in offshore, offshore transition and lower shoreface environments (*sensu* Reading and Collinson, 1996). Stratigraphic architectures of facies and facies associations, as well as formation distributions and their thickness are described. In addition, a discussion of biotic post-recovery trends following the end-Permian mass extinction within the Triassic of Western Canada provides insights into the environmental conditions influencing biotic distribution during the Middle Triassic. The Sunset Prairie Formation preserves the regionally extensive, moderately diverse assemblages of marine trace fossils in northwestern Pangea (western Canada) following the end-Permian mass extinction, which is not observed in the underlying Montney Formation.

Chapter 4 establishes a sequence stratigraphic framework for the Sunset Prairie Formation. Observations from core intervals and petrophysical well log data suggest that three coarsening-upward parasequences are identifiable in the formation. The base of the formation truncates the underlying Montney Formation and is marked by a transgressively modified sequence boundary (FS/SB). The lowermost parasequence set exhibits thick packages (< 7m thick) of pervasively bioturbated facies ascribed to the lower shoreface to proximal offshore transition. The upper two parasequence sets preserve thicker packages (< 12m) of diminutively bioturbated facies from offshore transition and offshore settings; proximal offshore transition and lower shoreface deposits occur as thinner beds (<2m thick). Collectively, facies associations and parasequences exhibit a retrogradational stacking patter, suggesting that the Sunset Prairie Formation was deposited as a transgressive systems tract. Overlying the Sunset Prairie Formation is the Doig phosphate zone, which is considered to be a condensed interval of transgressive deposits (Gibson and Barclay, 1989; Edwards et al., 1994; Evoy, 1997). The Doig phosphate zone truncates the Sunset Prairie and

Montney Formations, representing another transgressively modified sequence boundary (FS/SB) between the two formations. Understanding the sequence stratigraphic framework of the Sunset Prairie Formation can help to predict facies distribution and reservoir properties across the basin.

Chapter 5 investigates the Sunset Prairie Formation through a process ichnological analysis. Process ichnology utilizes trace fossils as biogenic sedimentary structures, in addition to their more classical usage as palaeontological features. The approach was introduced by Gingras et al. (2011) and integrates trace fossil characteristics and physical sedimentary features to interpret physico-chemical stresses acting on the environment during deposition. The framework builds off previous observations and studies within modern and ancient settings (e.g. Howard and Frey, 1973, 1975; Pemberton and Frey, 1984; Ekdale and Mason, 1988; Savarda and Bottjer, 1989, 1991; Gingras et al., 2000; Hubbard et al., 2004; Martin, 2004; MacEachern et al., 2005, 2007b). The process ichnology approach has primarily been used within marginal marine settings (Hauck et al., 2009; Botterill at al., 2015; Timmer et al., 2016a, 2016b) and this is the first attempt to formally apply the framework to a fully marine system. A process ichnological analysis was conducted on five wells within the Fort St. John Graben System, where the Sunset Prairie Formation is thickest. Ichnological data collected includes bioturbation intensity (BI) (*sensu* Reineck, 1963; 1967; Droser and Bottjer, 1986; Taylor and Goldring, 1993), change in bioturbation intensity (ΔBI), maximum burrow diameter (in mm), number of ichnogenera, Size Diversity Index (SDI) (*sensu* Hauck et al., 2009) and the percentage of different feeding strategies associated with the observed ichnogenera. Data were collected across 10 cm intervals of core, in order to provide a high-resolution analysis. Fluctuations in dissolved oxygen levels across the different depositional environments are interpreted to be the dominant stress that influenced influencing infaunal distributions. A secondary stress associated with elevated sedimentation/erosion was interpreted for several intervals. A summary on the background of process ichnology, and process ichnological trends, ethological trends, and interpreted environmental conditions/stressors for the Sunset Prairie Formation are addressed. The relationship of the ichnological trends observed in the Sunset Prairie Formation to the broader context of biotic recovery following the end-Permian mass extinction is also discussed.

Chapter 6 integrates ichnological and geochemical datasets to better interpret redox conditions during the deposition of the Sunset Prairie Formation. This study builds on the few studies that previously integrated ichnological and geochemical data (Werne et al., 2002; Algeo et al., 2004; Izumi et al., 2012; Kemp and Izumi, 2014; Dashtgard and MacEachern, 2016; Haddad et al., 2018). Process Ichnological data (BI, burrow diameter, observed ichnogenera, and SDI) from 3 cores were collected every 10 centimetres. Additionally, geochemical data were collected every 10 centimetres using a Thermo Scientific NITON XL3t 900 Analyzer hand-held X-ray fluorescence (XRF) devise to collect major and trace element abundance. Select samples (28 samples) from the core, representing the full range of facies, were analyzed using Thermo Scientific ICAP-Q quadrupole plasma mass spectrometry (ICP-MS), and were used to calibrate the XRF data. Facies, sub-formational units (parasequence), and overall stratigraphic trends between ichnological data and redox-sensitive elements (Mo, V, and V/Cr) are compared. Generally, redox-sensitive trace metals tend to be more soluble under oxidizing conditions and less soluble in reducing conditions, resulting in their enrichment in oxygen-depleted sedimentary deposits (Tribovillard et al., 2006; Little et al., 2015). Additionally, aerobic or well-oxygenated facies are recognizable by their pervasively bioturbated appearance and diverse trace fossil suites (Savrda and Bottjer, 1989), whereas dysoxic environments can exhibit a variable degree of bioturbation (Martin, 2004) and under anoxic or even dysoxic conditions, no bioturbation is present (Savrda and Bottjer, 1986, 1991; Savrda, 1992; Dashtgard and MacEachern, 2016). Observations from the Sunset Prairie Formation suggest that diminutively bioturbated and non-bioturbated facies as associated with a wide range of elemental values, reflecting deposition under oxic, dysoxic and anoxic conditions. By contrast, pervasively bioturbated facies exhibit narrow ranges and low concentrations of redox-sensitive elements, suggesting that deposition occurred under oxic to only slightly dysoxic conditions. This study demonstrates that the integration of ichnological characteristics and geochemical responses through a high-resolution dataset permits empirical interpretations of palaeoenvironmental conditions associated with strata deposited in a post-extinction setting.

CHAPTER 2: THE SUNSET PRAIRIE FORMATION: DESIGNATION OF A NEW MIDDLE TRIASSIC FORMATION BETWEEN THE LOWER TRIASSIC MONTNEY FORMATION AND MIDDLE TRIASSIC DOIG FORMATION IN THE WESTERN CANADA SEDIMENTARY BASIN, NORTHEAST BRITISH COLUMBIA

INTRODUCTION

The Lower Triassic Montney Formation in the subsurface of northeastern British Columbia and westernmost Alberta consists predominantly of siliciclastic, bioclastic, bituminous, and dolomitic siltstone. Traditionally, the Montney Formation has been described to be overlain by the Middle Triassic Doig Formation, with the Doig phosphate zone commonly preserved at the base of the formation. However, a new interval recently has been observed between the Montney and Doig Formations in western areas and is sedimentologically, ichnologically and palaeontologically distinct from the overlying and underlying formations and has been named the named the Sunset Prairie Formation (Furlong et al., 2018a, 2018b).

The Sunset Prairie Formation is composed of very fine-grained siltstone to fine-grained sandstone, with interbedded light grey, pervasively bioturbated and dark grey, minimally bioturbated strata. Planar-parallel-laminae are the most common sedimentary structure present within the non-bioturbated to minimally bioturbated siltstone beds. Erosional surfaces occur at the upper and basal contacts, which is consistent with being unconformity-bound. Trace fossils are of macro-scale, are visible within core, and occur in coarser gained (fine-grained sandstone) intervals. Trace fossils present include a dense fabric of *Phycosiphon* and robust *Rosselia*/*Cylindrichnus*, with subordinate *Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. *Glossifungites* Ichnofacies-demarcated discontinuity surfaces (burrowed firmgrounds) are also present throughout the interval. Macrofossils include bivalves, gastropods, lingulid brachiopods, spiriferid brachiopods, terebratulid brachiopods, echinoid skeletal elements (particularly spines), and crinoid ossicles. Based on conodont biostratigraphy and the macrofossil assemblage, the unit is assigned a Middle Triassic (Anisian) age. Overall, the unit is located in northeastern British Columbia and can reach 80 m in thickness.

This interval has been informally referred to as the 'Anisian Wedge' in previous publications, which consist primarily of conference abstracts (Zonneveld and Moslow, 2015; Zonneveld et al., 2015; 2016; Furlong et al., 2016b; 2017a; Davies et al., 2018). The unit has commonly been overlooked and placed within the Montney Formation or Doig Formation, or straddled both formations (e.g. Golding et al., 2014a, 2014b; Crombez et al., 2016). A new lithostratigraphic unit has been identified to describe the interbedded light grey, pervasively bioturbated, fine-grained sandstone and dark grey, minimally bioturbated siltstone that is lying between the Montney and Doig Formations (Furlong et al., 2018a). This interval is defined as the Sunset Prairie Formation.

HISTORICAL BACKGROUND

The Montney Formation and the Doig Formation were formally identified and described by Armitage in 1962 from the Texaco NFA Buick Creek 06-26-087-21W6 well, approximately 40 kilometres northwest of Fort St. John, British Columbia (Figs. 2.1 and 2.2). The type definition was based on well logs and cuttings, as the type well was not cored. In the type section, the Montney Formation rests unconformably on Permian strata of the Belloy Formation, and is abruptly overlain by the Middle Triassic Doig Formation (Armitage, 1962). Together, the Montney and Doig Formations make up the Daiber Group (Fig. 2.3; Armitage, 1962).

Stratigraphic nomenclatural discrepancies occur between Alberta and British Columbia for the Montney and Doig Formations (Playter et al., 2018; Zonneveld and Moslow, 2018). Herein, the authors refer to the Montney Formation from a British Columbia perspective. Therefore, the Montney Formation includes intervals referred to as both the Montney and Basal Doig Siltstone within the Alberta stratigraphic framework.

Montney Formation

Armitage (1962) described the Montney Formation as grading from dark grey shale upwards into dark grey, argillaceous siltstone and interbedded shale, with the formation being thickest in western wells (up to 350 m) and thinning to an eastern erosional edge. The name for the formation was derived from the village of Montney, 12 miles southeast of the Texaco NFA Buick Creek 06-26-087-21W6 type well (Armitage, 1962). The Montney Formation and its outcrop equivalents, the Sulphur Mountain Formation (Vega, Meosin Mountain, Mackenzie Dolomite Lentil and Phroso Members), Grayling Formation and lower Toad Formation, have been biostratigraphically dated to span the Induan and Olenekian (Fig. 2.3; Gibson and Barclay, 1989; Tozer, 1994; Davies et al., 1997; Paull et al., 1997; Utting et al., 2005; Orchard and Zonneveld, 2009; Wilson et al., 2014; Golding et al., 2014a).

Regionally, the westward thickening wedge of the Montney Formation consists of siltstone, sandstone and coquina (bioclastic packstone / grainstone) deposits. Depositional environments

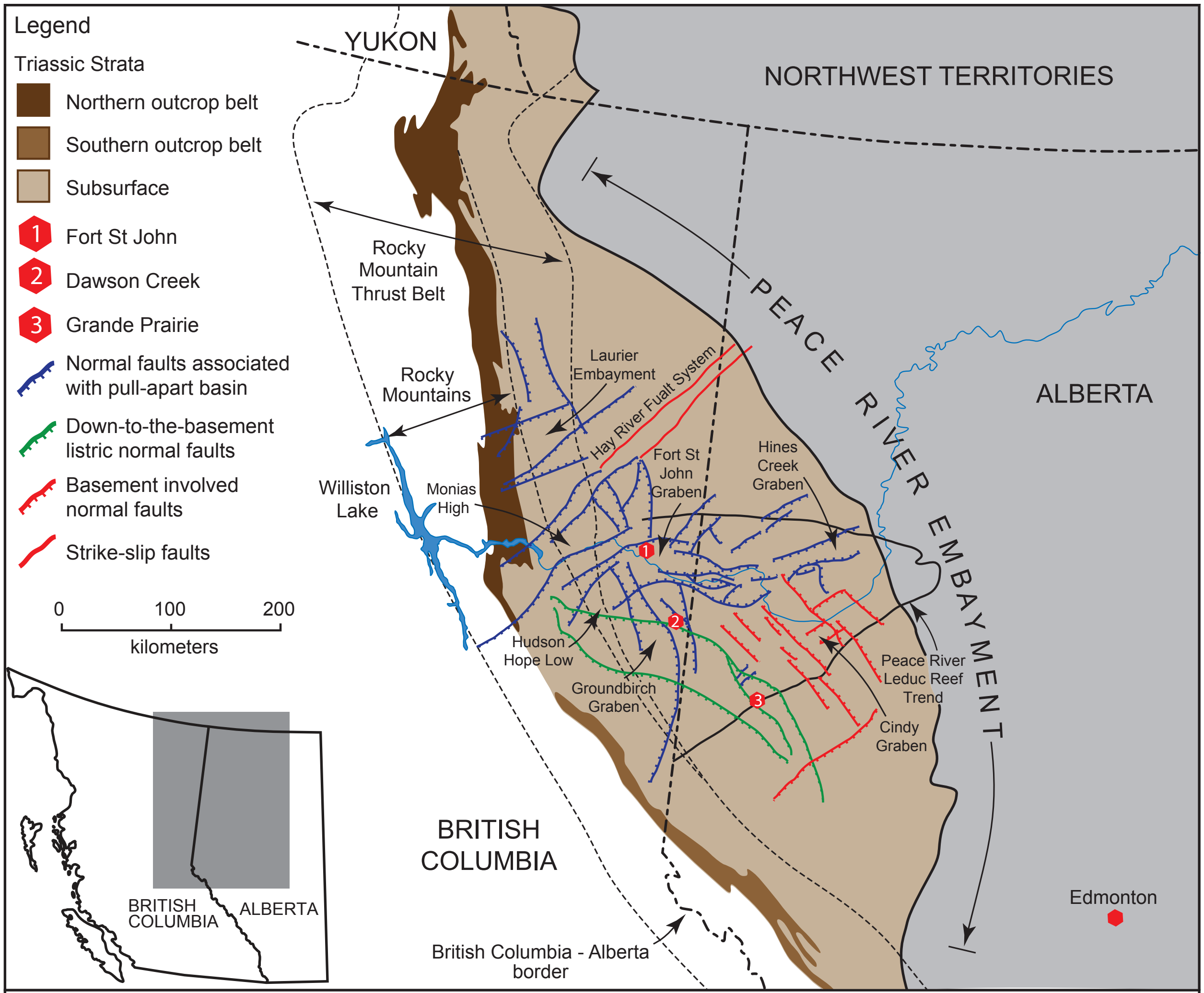


Figure 2.1–Regional map of British Columbia and Alberta showing the extent of Triassic strata in the Western Canada Sedimentary Basin (modified from Zonneveld et al., 2011). Major structural features that influence Lower and Middle Triassic strata are identified and were compiled from previously published maps (Barclay et al., 1990; Davies, 1997a, 199b; Davies et al., 1997; Berger, 2005; Berger et al., 2009).

associated with the formation vary and include distal offshore (turbidite channel and fan complexes) through upper shoreface settings, storm- and wave-dominated shorelines, deltaic (perennial and ephemeral deltas) and estuarine successions (Metherell, 1966; Miall, 1976; Davies et al., 1997; Moslow and Davies, 1997; Moslow, 2000; Zonneveld et al., 2010a, 2010b; Zonneveld and Moslow, 2014, 2015; Crombez et al., 2016; Davies et al., 2018). Locally, the top of the formation in northwestern Alberta is composed of very fine-grained to fine-grained sandstone (e.g., 'Gordondale' sandstone; Gibson and Edwards, 1990; Davies et al., 1997). The pervasively bioturbated 'Gordondale' sandstone, also referred to as the 'Moig' sandstone (LaMothe, 2008), is located within the Gordondale field and surrounding areas. This unconformity-bound shoreface sandstone unit sits stratigraphically below the Doig phosphate zone and is lithologically discrete from the underlying Montney Formation (also referred to as the 'Lower Doig Siltstone' within the

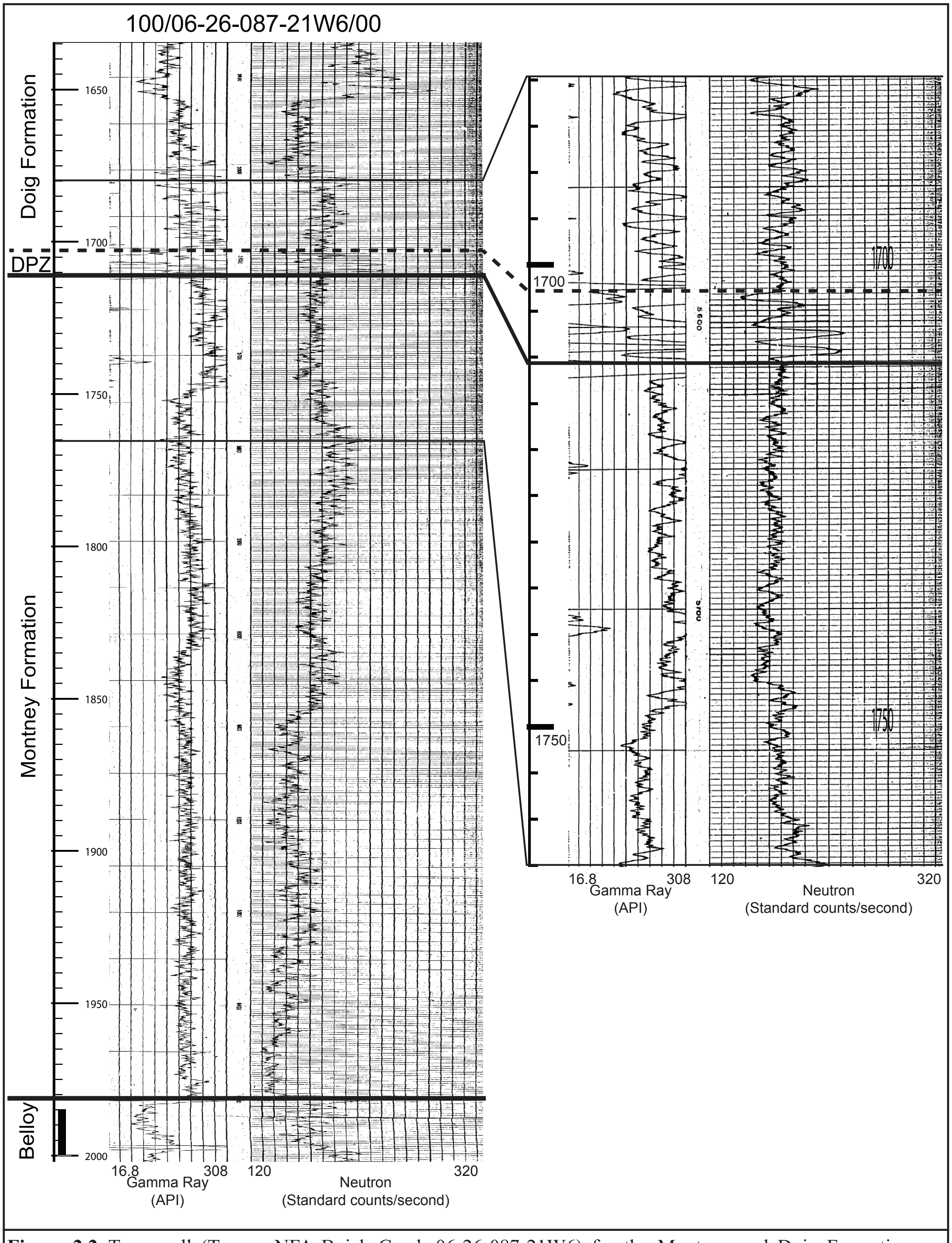


Figure 2.2–Type well (Texaco NFA Buick Creek 06-26-087-21W6) for the Montney and Doig Formations as identified by Armitage (1962). Doig phosphate zone (DPZ) also identified. Well depth in metres. It is important to note that the Sunset Prairie Formation is not present within the type well.

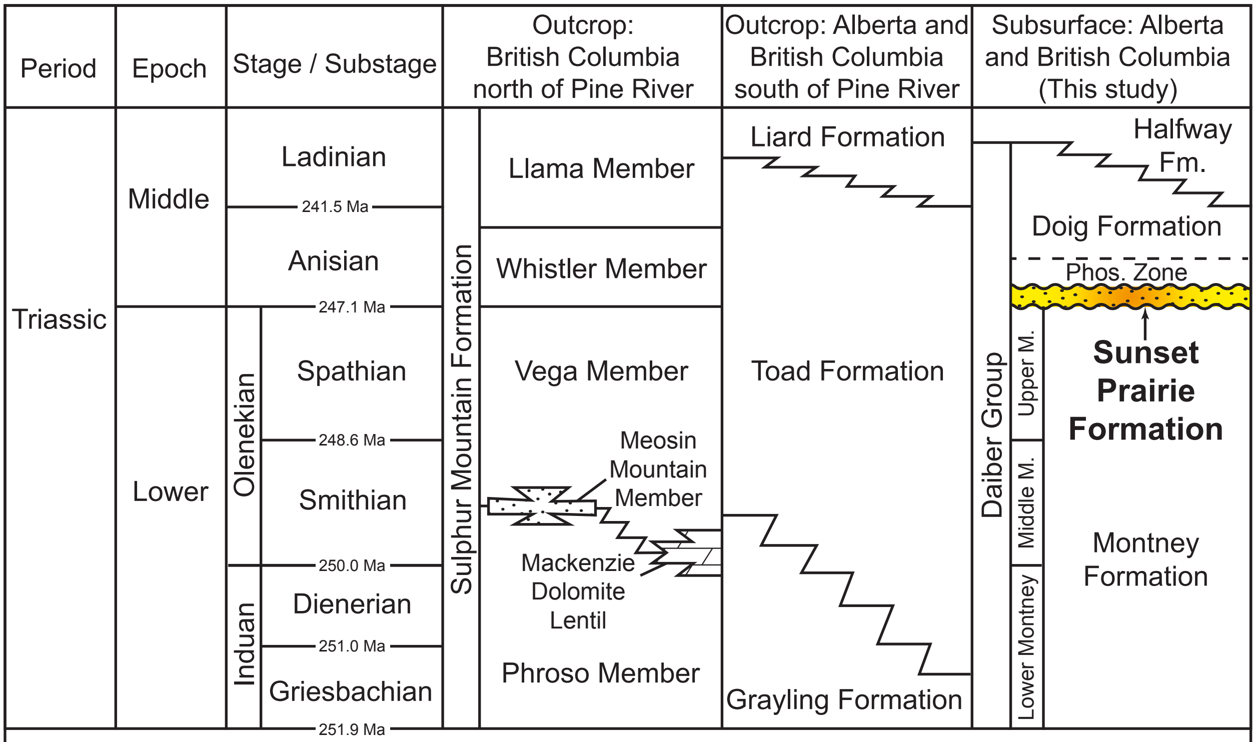


Figure 2.3–Lower and Middle Triassic lithostratigraphic nomenclature for outcrop and subsurface sections in Alberta and British Columbia. Ages of stages and substages identified by Henderson and Schoefer (2017), and Henderson et al. (2018). Modified from Zonneveld (2011) and Golding et al. (2015).

area) (Davies et al., 1997). Although the ‘Gordondale’ sandstone is geographically isolated from the Sunset Prairie Formation, the two intervals may be similar and/or equivalent, but correlations are not established or addressed within this paper.

Based only on west-central Alberta well data available within the mid 1990’s, the Montney Formation was subdivided into three informal members by Davies et al. (1997), which included the lower member, the coquinal dolomite middle member, and the upper member. Subsequently, Dixon (2000; 2009a) proposed a basin-wide scheme, which used the threefold subdivision suggested by Davies et al. (1997) within the eastern region, in addition to a twofold subdivision to the west. These original stratigraphic divisions, based on earlier phases of exploration and well control, now require revisions and upgrading to explain local and regional phenomena (Zonneveld et al., 2010b; Wilson et al., 2014). Most recently, Davies and Hume (2016) and Davies et al. (2018) proposed a basin-wide tripartite division with Griesbachian- and Dienerian-aged (Induan) strata belonging to the Lower Montney, mainly Smithian-aged (Olenekian) strata being associated with the Middle Montney, and Spathian-aged (Olenekian) strata being placed in the Upper Montney. Sequence stratigraphic frameworks proposed by Crombez et al. (2016, 2017) also suggest a similar three-part division of the Montney Formation, with three systems tracts being preserved.

Doig Formation

The Doig Formation was originally described as consisting of dark grey, argillaceous, bituminous siltstone, with the base of the formation being characterized by beds of nodular and granular phosphate (Armitage, 1962). The formation was named after the Doig River, located 28 miles east of the Texaco NFA Buick Creek 06-26-087-21W6 type well (Armitage, 1962). The Doig Formation, and its outcrop equivalents, the Sulphur Mountain Formation (Whistler Member), Toad Formation, and basal Liard Formation, has been dated to span the Anisian and Ladinian (Fig. 2.3; Gibson and Barclay, 1989; Gibson and Edwards, 1990; Golding et al., 2014a).

The base of the Doig Formation is placed at the base of an interval of very high gamma-ray response (Fig. 2.2; Armitage, 1962; Gibson and Edwards, 1990). The lowermost part of the Doig Formation is informally referred to as the Doig phosphate zone, formerly as the 'Black Shale Member' of the Doig Formation (Armitage, 1962). It consists of a highly radioactive, organic-rich, lithoclastic/bioclastic lag and heterolithic zone with abundant phosphatic sand, granule and shale (Creaney and Allan, 1990; Gibson and Edwards, 1990; Edwards et al., 1994; Evoy and Moslow, 1995; Golding et al., 2014b; 2015). In a stratigraphic sense, the phosphate zone can be considered as the distal and condensed equivalent of shelfal Doig siltstone, and further landward, Halfway Formation shoreface (J.E. Barclay, pers. comm., 2017). It should be noted that phosphate occurs at many horizons throughout the upper Montney and Doig Formations including an interval referred to as the 'upper Montney phosphate' (*sensu* Golding et al., 2015).

The Doig phosphate zone ranges between 10-80 m thick and has been interpreted to reflect both condensation and periodic deposition (Golding et al, 2015). The remainder of the Doig Formation is a medium to dark grey siltstone to very fine- to fine-grained sandstone and dolomitized coquina (Gibson and Edwards, 1990; Evoy, 1997; Evoy and Moslow, 1995, Dixon, 2011). Depositional environments are varied and include restricted/euxinic marine shelf, proximal shelf, lower shoreface, shallow-water tidal inlets and estuarine channels (Evoy and Moslow, 1995; Evoy, 1997; Rahman, 2005, Dixon, 2011).

The Montney-Doig Boundary

The base of the Doig Formation is marked by a concentration of high, commonly off-scale, gamma-ray log deflections, with each corresponding to a sharp-based phosphatic lag (Fig. 2.2; Armitage, 1962; Gibson and Edwards, 1990; Golding et al., 2015). Multiple phosphate lags can be observed within the base of the formation and consist of phosphatized clasts and phosphatic sand. In core, the Doig Formation commonly overlies a *Glossifungites* Ichnofacies-demarcated discontinuity developed on top of the Montney Formation (Zonneveld, 2010; Golding et al, 2014a, 2014b, 2015). The *Glossifungites* Ichnofacies is a trace fossil assemblage that is associated with firm substrates, and reflect pauses in sedimentation and/or periods of erosion, subsequently colonized by burrowing organisms (Seilacher, 1967; Frey and Pemberton, 1985; MacEachern et a., 1992). Trace fossils demarcating the firmground discontinuity include *Planolites*, *Rhizocorallium*, *Skolithos*, and *Thalassinoides*. The boundary between the Montney and Doig Formations has been interpreted to correspond to a major transgressive surface (Armitage, 1962; Gibson and Barclay, 1989; Gibson and Edwards, 1990), and/or a coplanar lowstand surface of erosion (regressive surface of marine erosion) and transgressive surface of erosion corresponding to a sequence boundary (Golding et al., 2014b). Most recently, this boundary has been suggested to be diachronous, with the boundary ranging from Spathian to Middle Anisian in age (Wilson et al., 2014; Golding et al., 2015).

Although historically, the base of the Doig Formation has been deemed to mark the top of the Montney Formation (Armitage, 1962; Gibson and Edwards, 1990; Golding et al., 2015), a new interval has been recently identified between the two formations within the subsurface of the northeastern part of British Columbia, Canada. There, an unconformity-bound interval consisting of interbedded light grey, pervasively bioturbated, fine-grained sandstone and dark grey, minimally bioturbated siltstone separates the Montney and Doig Formations. The interval is sedimentologically, ichnologically and palaeontologically discrete from the Montney and Doig Formations and warrants the establishment of a new lithostratigraphic unit of formation level (Furlong et al., 2018a).

INTRODUCTION OF A NEW FORMATION: SUNSET PRAIRIE FORMATION

The Sunset Prairie Formation is introduced to designate the interbedded light grey, pervasively bioturbated strata and dark grey, minimally bioturbated strata that sits stratigraphically between the Lower Triassic Montney Formation and Middle Triassic Doig Formation in northeastern British Columbia. The unit is lithologically, ichnologically and palaeontologically distinct from the Montney and Doig Formations. The Sunset Prairie Formation has been dated to be Middle Triassic (Anisian) in age based on the re-evaluation of conodont biostratigraphic data collected by Golding et al. (2015).

Justification For A New Formation

Geologists working in the westernmost subsurface Montney Formation have observed an unconformity-bound unit, characterized by interbedded pervasively bioturbated and sparsely bioturbated siltstone, fine-grained sandstone, phosphatic sand beds with locally abundant spiriferid brachiopods, terebratulid brachiopods, cidaroid echinoid skeletal elements and crinoid ossicles (Zonneveld and Moslow, 2015; Zonneveld et al., 2015; 2016; Furlong et al., 2016b; 2017a). Although this unit occurs below the base of the Doig phosphate zone (commonly considered to be the *de facto* Lower Triassic-Middle Triassic boundary), it contains macrofossils typically considered diagnostic of Middle Triassic deposition (Zonneveld et al., 2015, 2016). The Sunset Prairie Formation consists of a fine-grained siltstone to fine-grained sandstone, which is lithologically different than the underlying fine-grained siltstone of the upper Montney Formation and the overlying phosphate-rich beds of the lower Doig Formation. The trace fossil suites within the Sunset Prairie Formation have a high diversity (15 trace fossils observed) and a high abundance of ichnofossils (with many bioturbated intervals being biogenically homogenized), which is drastically different from the simple, low-diversity, and low-abundance ichnological assemblages that are generally observed within the Montney Formation. High diversity assemblages that are present within the Montney Formation are localized and have been interpreted to be associated with environmental refugia, where oxygenated water was present within the shallow-marine realm and locally produced an oases for infaunal organisms (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b). Bioturbation within the Doig Formation (and the outcrop equivalent Liard Formation) is common, but is sparse within the Doig phosphate zone (e.g., Zonneveld, 1999; Zonneveld et al., 2001, 2002). The Sunset Prairie Formation is mappable on a regional scale within the western-most part of the Western Canada Sedimentary Basin and the interval can reach thicknesses up to 80 m. All of these factors warrant its designation as a distinct lithostratigraphic formation.

SPECIFICATION OF STRATOTYPE, SELECTION AND DERIVATION OF NAME

The type section of the Sunset Prairie Formation is designated in the borehole of Shell Groundbirch 16-29-079-20W6 (WA# 25478) from core depths 2596.4 m to 2629.3 m (wireline total vertical depth 2598.8 m to 2632.1 m (TVD); wireline measured depth 2599.0 m to 2632.3 m (MD)) (Figs. 2.4 and 2.5), and totals 32.9 m in thickness. The well was drilled in 2009, with a total depth of 2849.7 m (TVD). Core was recovered at depths between 2595.0 m and 2795.0 m (TVD), and thus cored the entire Sunset Prairie Formation. The well lies equidistant between the Pine River and the hamlets of Sunset Prairie and Groundbirch. Although Groundbirch was our preferred name (after the field the core occurs within), the Groundbirch Member had already been designated for a dolostone interval in the Triassic Charlie Lake Formation (Glass, 1990). Similarly, the Pine River Formation was named for a Jurassic shale unit (Spieker, 1921) and thus, although now abandoned as a lithological name, should be avoided for naming new units in the area.

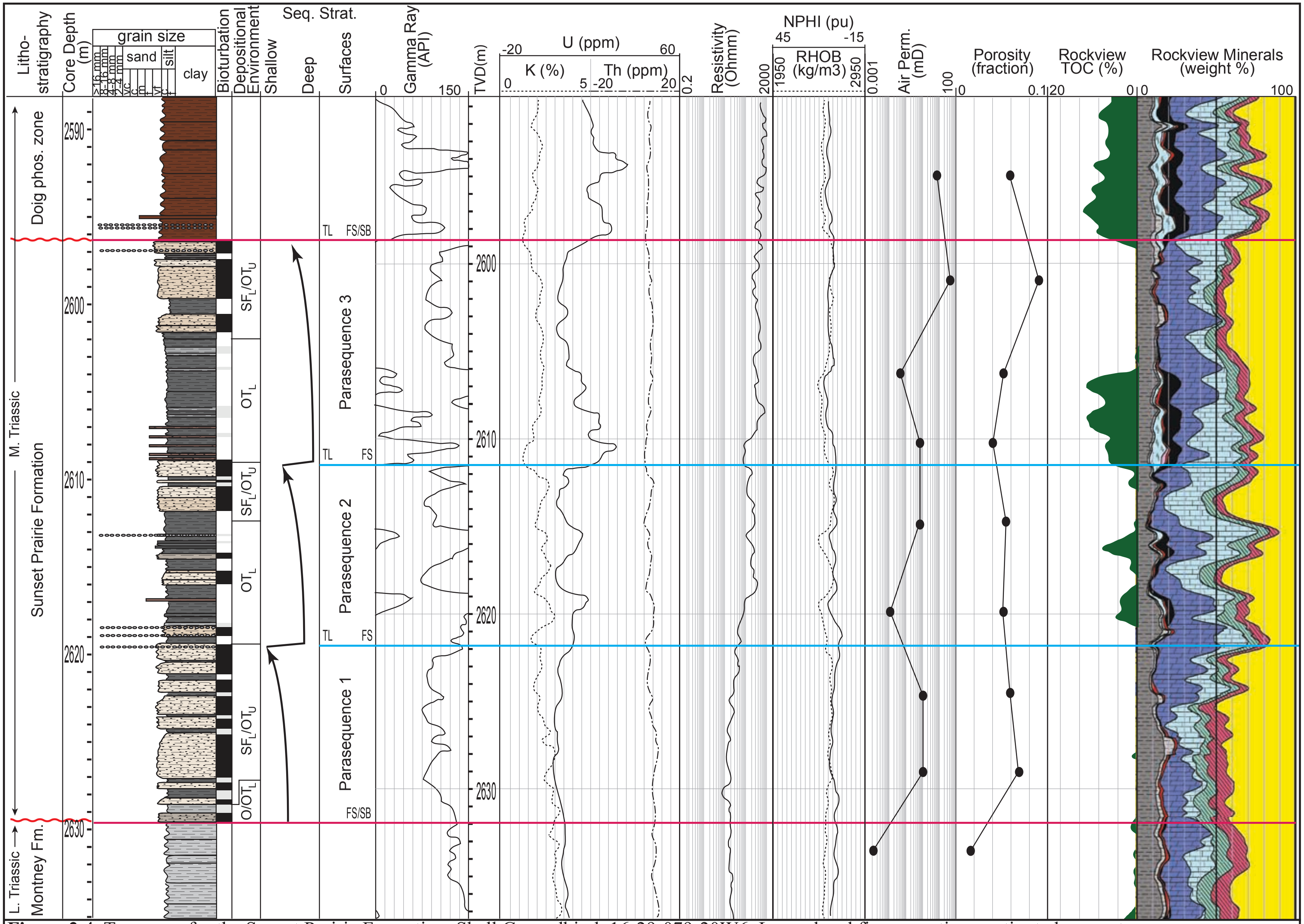


Figure 2.4–Type core for the Sunset Prairie Formation, Shell Groundbirch 16-29-079-20W6. Legend and figure caption continuted on next page.

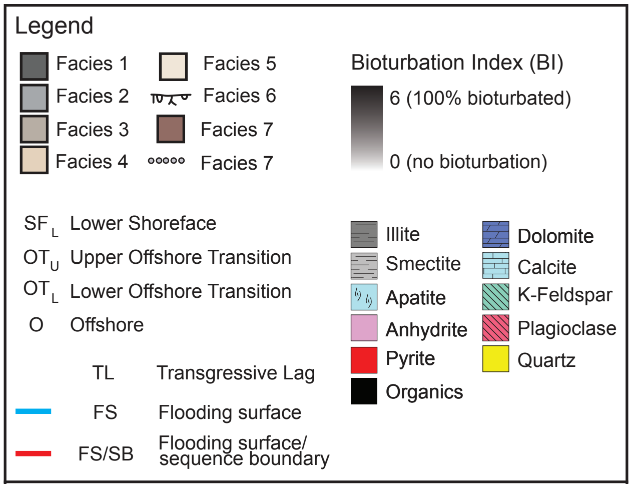


Figure 2.4 cont.–Lithostratigraphy, lithology, interpreted depositional environments and interpreted sequence stratigraphy are identified for the interval. Well logs include gamma ray, spectral gamma (U = Uranium; K = Potassium; Th = Thorium), resistivity, density porosity (RHOB) (limestone matrix) and neutron porosity (NPHI) (limestone matric). Air permeability data and porosity data are identified for the interval. Air permeability data and porosity data were collected by Core Laboratories from small-diameter core plugs. Total Organic Carbon (TOC) and Rockview Mineralogy data were collected and interpreted from a Flex logs by Backer Hughes.

The selection of this well as the stratotype is based on the presence of 32.9 m of Sunset Prairie Formation present within the 16-29-079-20W6 full diametre core. The cored interval includes the upper Montney Formation, the entirety of the Sunset Prairie Formation, and the lower portion of the Doig phosphate zone. Other core containing examples for reference sections of Sunset Prairie Formation include CNRL Graham c-33-C/94-B-9 (2186.6-2200.6 m core depth; 2187.0-2200.0 m TVD; Fig. 2.6) and Talisman Altares 16-17-083-25W6 (2245.4-2259.7 m core depth; 2245.1-2260.9 m TVD; Figs. 2.7). These, and other reference sections, are included within facies described by Furlong et al. (2018b). The Sunset Prairie Formation is not present within the Montney-Doig type well (06-26-087-21W6) defined by Armitage (1962), which is located landward/east of the erosional edge of the Sunset Prairie Formation (Fig. 2.8). This deems it necessary to distinguish a well with core possessing the Sunset Prairie Formation as the type well for the new formation.

Description of the Sunset Prairie Formation

The Sunset Prairie Formation is an organic-rich, fined-grained siltstone to fine-grained sandstone characterized by interbedded pervasively bioturbated and minimally bioturbated beds (Figs. 2.4, 2.5, 2.6, 2.7). In core, pervasively bioturbated beds are light grey to grey-blue in colour and minimally bioturbated beds are medium to dark grey in colour; this provides a diagnostic banded appearance (decimetre to metre scale interbeds) within the formation (Figs. 2.4, 2.5, 2.6, 2.7).

There are seven facies recognized in the Sunset Prairie Formation (Furlong et al., 2018b) and are described in Chapter 3. The facies are summarized in Table 2.1 and Figure 2.9. Facies are interpreted to represent deposition within offshore, offshore transition and lower shoreface settings (Facies 1-5), with two bathymetrically independent facies representing *Glossifungites* Ichnofacies-demarcated discontinuity surfaces (Facies 6) and lag deposits (Facies 7). Overall, lithologically, grain sizes vary from fine-grained silt to fine-grained sand. All grains are rounded to subangular.

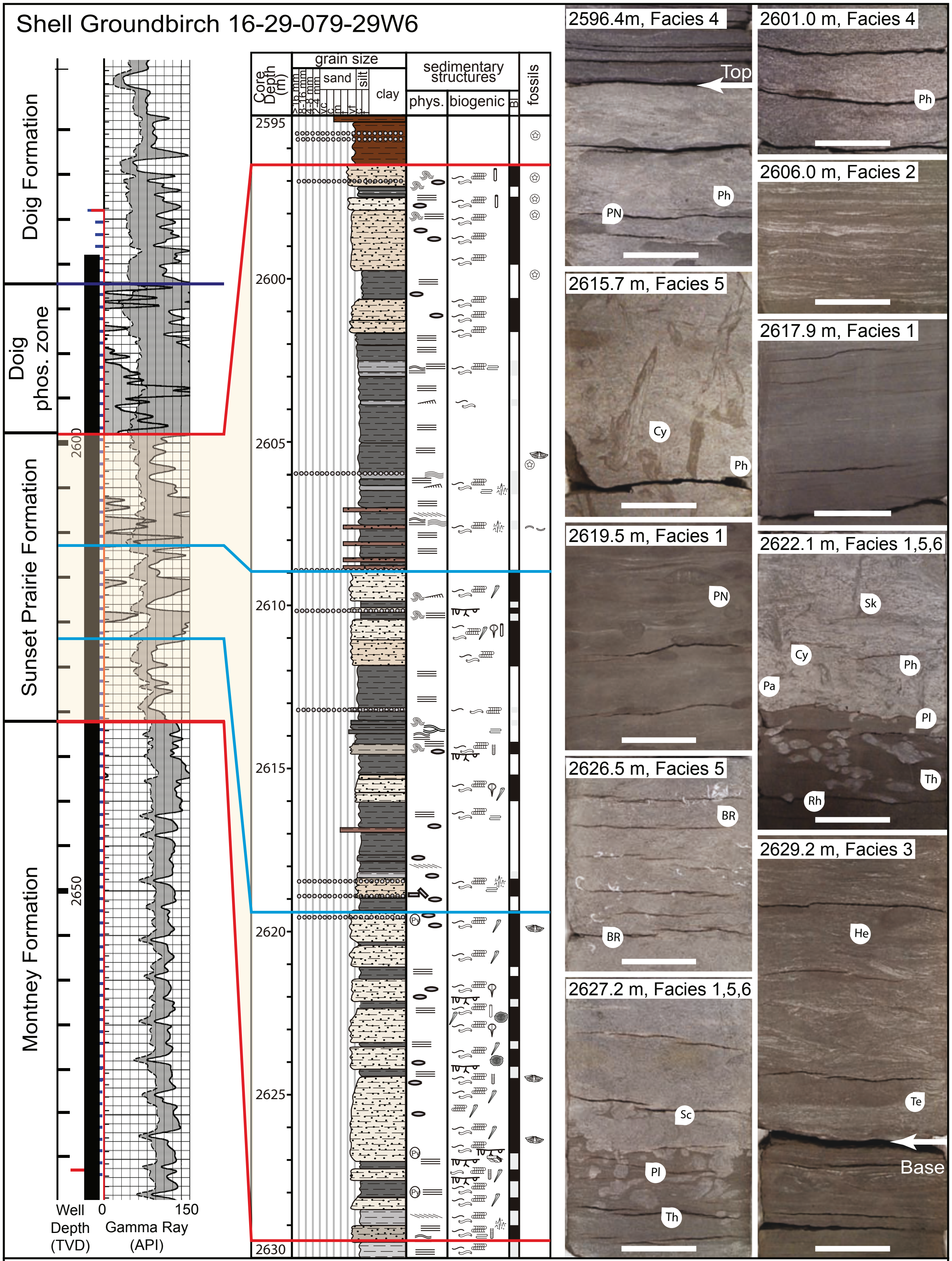


Figure 2.5–Montney, Sunset Prairie, and Doig Formations in Shell Groundbirch 16-29-079-20W6 core. Depths in litholog and photos correspond to core depths. All scale bars = 3 cm. See figure 2.6 for legend for symbols.

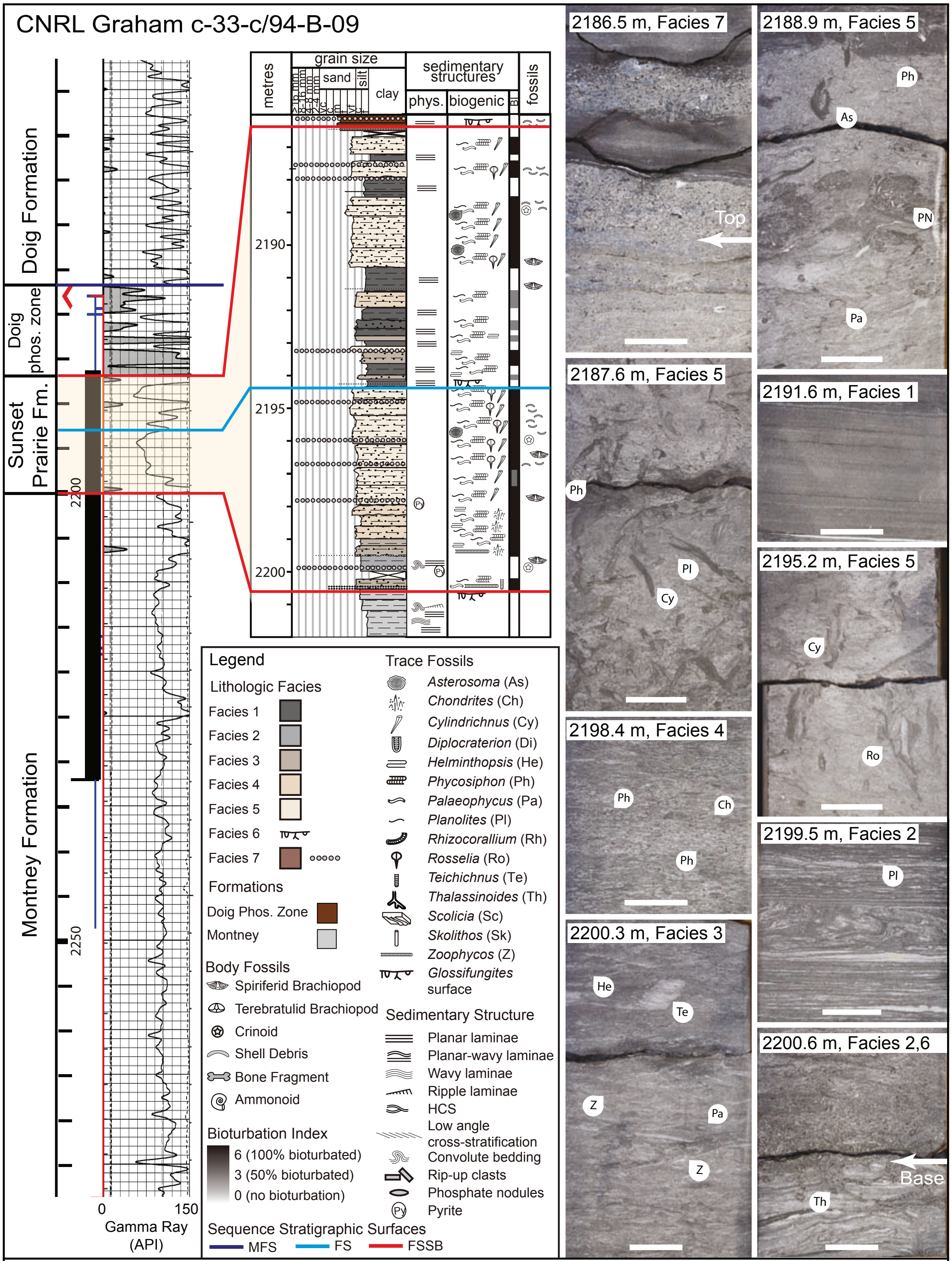


Figure 2.6–Montney, Sunset Prairie and Doig Formations in CNRL Graham c-33-C/94-B-09 core. Depths in litholog and photos correspond to core depths. All scale bars = 3 cm.

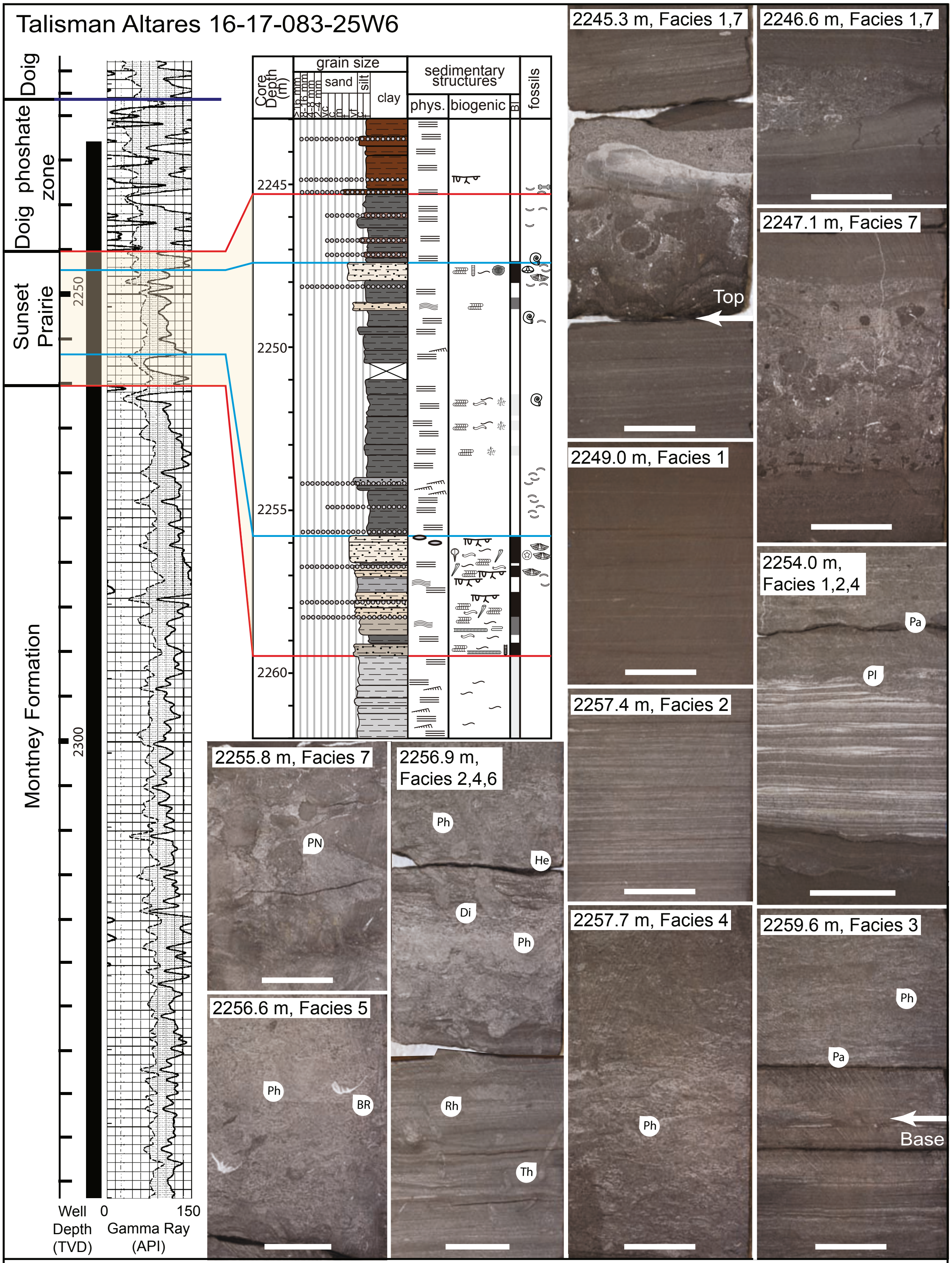


Figure 2.7–Montney, Sunset Prairie and Doig Formations in Talisman Altares 16-17-083-25W6 core. Depths in litholog and photos correspond to core depths. All scale bars = 3 cm. See figure 2.6 for legend for symbols.

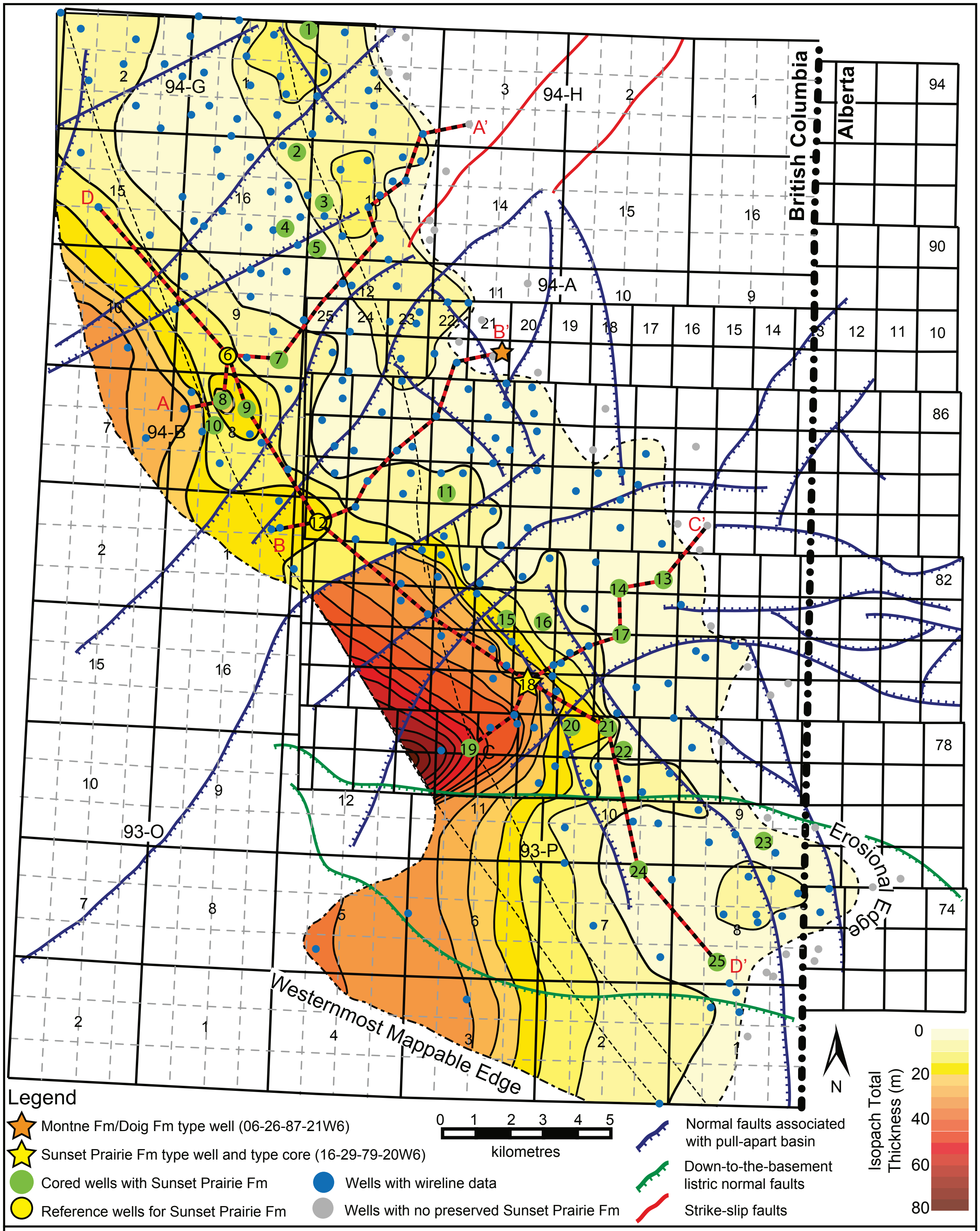


Figure 2.8–Location and thickness map of the Sunset Prairie Formation. Well control is shown through the location of wells in the dataset and includes wire line (n=248) and cored wells (n = 25). List of cored wells is identified in Table 1.1 Wells with wire line data that did not have preserved Sunset Prairie Formation (grey dots; n = 36) were used to determine erosional edge of the formation. Thickness ranges from 0-80 m, with the thickest accumulation coincident with the Hudson Hope Low (sensu Barclay et al., 1990). Contour interval = 5 m.

Description	Sedimentological Characteristics	Ichnological Characteristics	Palaeontological Characteristics	Interpretation
Facies 1 (F1) Dark to medium grey, laminated, bituminous siltstone with minimal bioturbation	○ Dark to medium grey, fine- to coarse-grained siltstone ○ Faint planar-parallel, wavy-parallel laminae, low- and high-angle planar cross-laminae, asymmetric ripples, and rare hummocky cross stratification and penecontemporaneous deformation structures ○ Isolated pyrite grains ○ Isolated beds rich with calcispheres ○ Phosphate silt, nodules, clasts, phosphate rich laminae and rare phosphatic ooids	○ Minimally bioturbated ○ *Ph, He, Pa, Pl, Ch* ○ BI = 0-2		○ Offshore to lower offshore transition ○ Distal *Cruziana* Ichnofacies
Facies 2 (F2) Diminutively bioturbated dark to light grey siltstone	○ Dark to medium grey, fine- to coarse-grained siltstone ○ Pinstripe-parallel, planar-parallel laminae, wavy-parallel laminae and asymmetric ripples ○ Rare penecontemporaneous deformation structures	○ Minimally bioturbated ○ *Ph, He, Pa, Pl, Ch* ○ BI = 0-2		○ Lower offshore transition ○ Low diversity *Cruziana* Ichnofacies
Facies 3 (F3) Dark to light grey bioturbated siltstone	○ Dark to light grey, fine-grained siltstone to very fine-grained sandstone ○ Phosphate nodules, silt and very fine sand sized phosphate grains are present in isolated beds	○ Pervasively bioturbated ○ *Ph, He, Te, Pa, Pl, Ch, Z* ○ BI = 5-6		○ Likely proximal expression of F5 ○ Lower to upper offshore transition ○ Distal *Cruziana* Ichnofacies
Facies 4 (F4) Pervasively bioturbated medium to light grey siltstone	○ Medium to light grey, fine-grained silt to very fine-grained sandstone ○ Faint planar-parallel laminae	○ Pervasively bioturbated ○ *Ph, He, Pa, Pl, Ch* ○ BI = 4-6	○ Bivalves, gastropods, brachiopods, echinoderm, crinoids	○ Likely proximal expression of F1/F2 ○ Lower to upper offshore transition ○ Low diversity *Cruziana* Ichnofacies
Facies 5 (F5) Pervasively bioturbated sandy siltstone	○ Medium to light grey, fine-grained siltstone to very fine-grained sandstone ○ Faint planar-parallel and wavy-parallel laminae, low- and high- angle planar cross laminae ○ Rare penecontemporaneous deformation structures, asymmetric ripples ○ Phosphate nodules, phosphate rich laminae, rip up clasts present within isolated beds ○ Sharp to gradual top and base contacts	○ Pervasively bioturbated ○ Large, robust traces ○ *Ph, Ro, Cy, As, Te, Pa, Pl, Sk, Sc, Rh, Di* ○ Bioturbation decreases upwards ○ BI = 4-6	○ Bivalves, gastropods, brachiopods, echinoderm, crinoids	○ Upper offshore transition to lower shoreface Archetypal *Cruziana* Ichnofacies
Facies 6 (F6) *Glossifungites* surfaces	○ Burrowed firmground; commonly at the base of bioturbated intervals Sometimes associated with lag deposit (F7)	○ Burrowed surface with *Pl, Sk, Th, Rh*		○ Firmground ○ Transgressive Surface of Erosion ○ *Glossifungites* Ichnofacies-demarcated discontinuity surface
Facies 7 (F7) Lag deposit	Sand to pebble sized clasts, phosphate nodules, phosphatic ooids, rip up clasts. Sometime associated with Facies 6		○ Shell fragments Bone fragments	○ Transgressive lag deposit /Transgressive Surface of Erosion

Table 2.1–Summary of sedimentologic, ichnologic and palaeontologic attributes of the Sunset Prairie Formation. Trace fossil abbreviations include: *As* = *Asterosoma*, *Ch* = *Chondrites*, *Cy* = *Cylindrichnus*, *Di* = *Diplocraterion*, *He* = *Helminthopsis*, *Pa* = *Palaeophycus*, *Ph* = *Phycosiphon*, *Pl* = *Planolites*, *Rh* = *Rhizocorallium*, *Ro* = *Rosselia*, *Sc* = *Scolicia*, *Sk* = *Skolithos*, *Te* = *Teichichnus*, *Th* = *Thalassinoides*, *Z* = *Zoophycos*. Body fossils include bivalve, gastropods, brachiopods (lingulid, spiriferid terebratulid), cidaroid echinoid skeletal fragments and isocrinid crinoid ossicles.

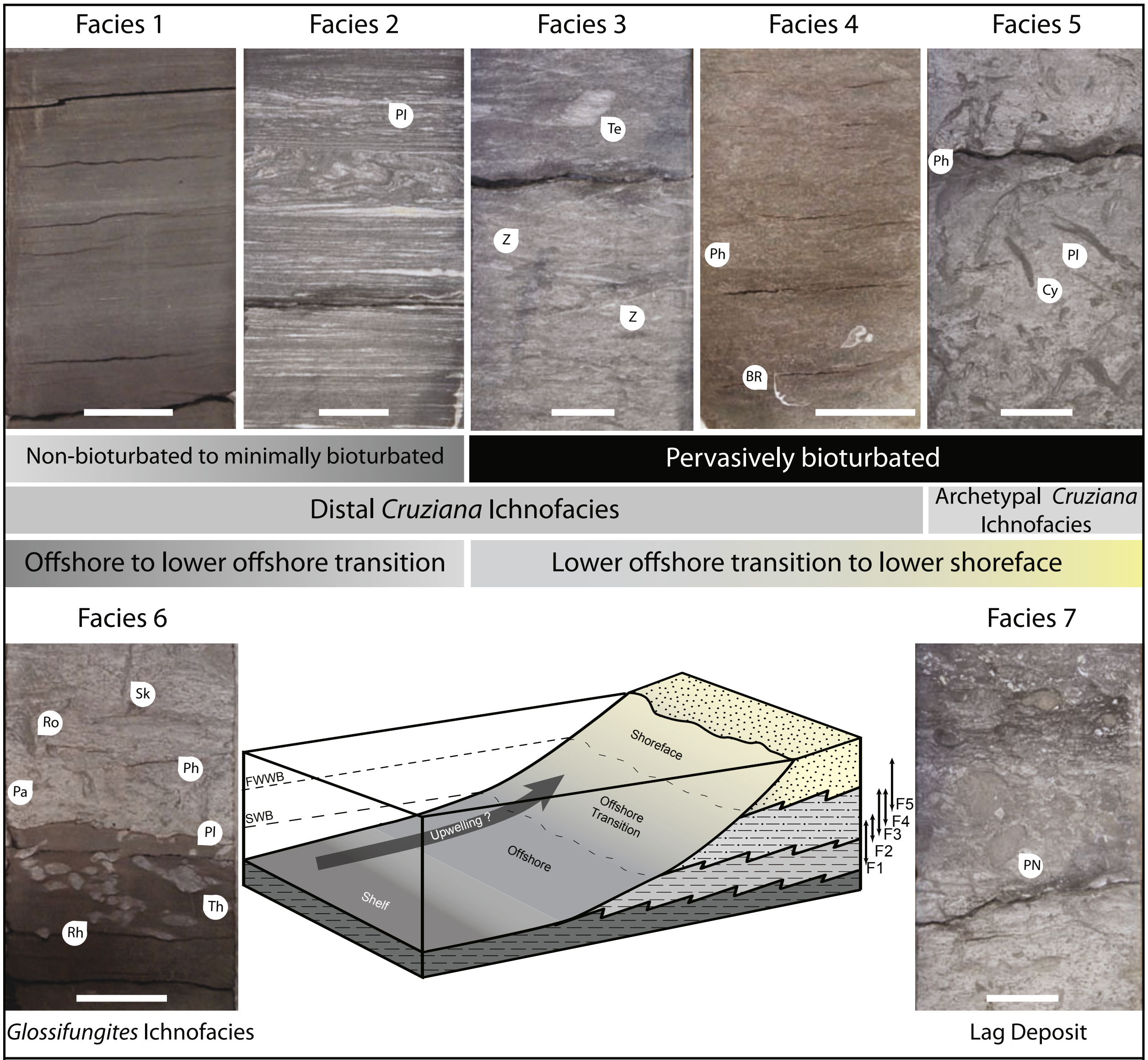


Figure 2.9–Summary of facies present within the Sunset Prairie Formation. Bioturbation intensity, ichnofacies and interpreted depositional environment are identified for each facies. Scale bars for core photos = 3 cm. Schematic at bottom shows distribution of facies and depositional environments within a siliciclastic ramp setting. Abbreviations include: Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Rh = *Rhizocorallium*, Ro = *Rosselia*, Sc = *Scolicia*, Sk = *Skolithos*, Te = *Teichichnus* and Th = *Thalassinoides*, Z = *Zoophycos*, BR = brachiopod shell and PN = phosphate nodule.

Grain minerology includes quartz, calcite, dolomite, plagioclase and K-feldspar (Fig. 2.4). Accessory minerals include pyrite, apatite/phosphate, anhydrite (likely due to brine water within the subsurface), smectite and illite/mica. Organics occur within concentrated zones throughout the interval and total organic content (TOC) is < 12% within the type well (Fig. 2.4). Limited preservation of physical sedimentary structures is due to the pervasively bioturbated rock fabric; where preserved, include planar-parallel-, pinstriped-parallel-, planar-wavy-parallel and wavy-parallel-laminae, low- and high- angle planar cross laminae, asymmetric ripples, hummocky cross-stratification and penecontemporaneous deformation structures. Phosphate-rich material is present as lithoclasts, rip-up clasts, nodules, pebbles, ooids, sand and silt, and are commonly limited to thin (<10 cm thick) beds, although phosphate-rich nodules can be present throughout the formation. Bounding surfaces at the basal and upper contacts of the formation are commonly associated with phosphate-rich material, rip-up clasts of Montney lithologies, pebbles and broken shell debris. These surfaces have been interpreted to represent erosional unconformities. Distal cores in westernmost British Columbia, especially within the Groundbirch area, may have gradational contacts at the top and base of the stratigraphic unit (e.g. Shell Groundbirch 16-02-078-22W6).

Interbedded pervasively bioturbated and minimally bioturbated strata are characteristic of the Sunset Prairie Formation. Bioturbation index (BI) (*sensu* Reineck, 1963, 1967; Taylor and Goldring, 1993) ranges from 0 (non-bioturbated) to 6 (pervasively bioturbated) within the interval. Ichnological assemblages of the Sunset Prairie Formation, listed by relative abundance, include *Phycosiphon*, *Rosselia, Cylindrichnus, Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos* (Fig. 2.9, Table 2.1). Minimally bioturbated facies (Facies 1 and Facies 2) contain include small (<1 mm in diameter) *Phycosiphon, Helminthopsis*, *Palaeophycus, Chondrites* and *Planolites* with variable, but low, bioturbation intensities (BI=0-2) (Furlong, et al., 2018b). Pervasively bioturbated facies have a homogenized rock fabric, owing to the high bioturbation intensity (BI=4-5). Each pervasively bioturbated facies possesses different ichnological assemblages (Fig. 2.9, Table 2.1), but overall, the ichnological assemblages represent distal to archetypal expressions of the *Cruziana* Ichnofacies. *Glossifungites* Ichnofacies-discontinuity surfaces (firm ground assemblage) with *Thalassinoides*, *Planolites*, *Diplocraterion* and *Rhizocorallium* are common throughout the unit. *Glossifungites* Ichnofacies-discontinuity surfaces can mark the top and base of the Sunset Prairie Formation and are interpreted to represent significant sequence stratigraphic surfaces; however, *Glossifungites* Ichnofacies-discontinuity surfaces locally are also intraformational and autogenic.

Macrofossil assemblages within the Sunset Prairie Formation include bivalves, gastropods, lingulid brachiopods (which also all occur within the Montney and Doig Formations), but also include spiriferid brachiopods, terebratulid brachiopods, echinoid skeletal elements (particularly spines) and crinoid ossicles (all of which are quintessential components of the Middle Triassic faunas in western Canada; cf. Zonneveld, 2001). Generally shell material within the Montney Formation is limited, but smooth-shelled terebratulid brachiopods locally occur in some horizons in the Upper Montney Formation (Davies and Sherwin, 1997; Sanders et al., 2018). Shell material of the Sunset Prairie Formation typically is concentrated in specific beds (commonly < 10 cm in thickness), but also may be dispersed throughout the interval. Bioclastic material is preserved as whole, articulated shells, as well as fragmented, abraded, and disarticulated shell debris.

Well logs provide characteristic features that allow the Sunset Prairie Formation to be readily identified in the subsurface (Figs. 2.4, 2.5, 2.6, 2.7). Gamma-ray logs show an upward decrease in API within each parasequence, represented by coarsening-upward successions. Regionally, gamma-ray values range from 60-2100 API. In spectral gamma-ray, the uranium component increases upwards (regionally ranging from 5-10 ppm), potassium decreases slightly upwards (regionally ranging from 1-3%), and the thorium component remains consistent across the Montney, Sunset Prairie and Doig Formations (around 2-10 ppm). Within a well, resistivity logs show a general increase upwards by one or two orders of magnitude from the base to the top of the Sunset Prairie Formation, with values ranging from 200-2000 ohms. Density log porosity values range from 2550-2750 kg/m^3, with higher values located within sandier facies. Porosity fraction from core ranges from 0.01-0.09 and permeability ranges (Kmax) 0.0001-1.0 mD, suggesting the potential for an economic reservoir. Local variability influences wireline log responses, but the general trends described in the type well are seen throughout the formation on a regional scale.

Up to three progradational parasequences can be identified within the Sunset Prairie Formation. This is best exemplified within the Fort St. John Graben system (Fig. 2.10). Flooding surfaces that separate the parasequences are associated with conglomerate lag deposits (F7), are commonly rich in phosphatic material, and may possess rip-up clasts. Parasequences coarsen upward in grain size from fine-grained silt to fine-grained sand and bioturbation increases upwards (Figs. 2.4, 2.5, 2.6, 2.7), though with interbedded pervasively bioturbated and minimally bioturbated facies present within the parasequences. Stacking pattern of the parasequences suggest relative sea level transgression, which resulted in the back-stepping of parasequences. Structural features of the Western Canada Sedimentary Basin greatly influenced the accommodation space available for the deposition and preservation of the Sunset Prairie Formation (Figs. 2.1, 2.5, 2.6, 2.7, 2.8, 2.10).

Definition of Boundaries

The Sunset Prairie Formation lies stratigraphically above the Montney Formation and below the Doig Formation. The base of the interval (top of the Montney Formation) is associated with substrate-controlled trace fossil assemblages (most commonly attributed to the *Glossifungites* Ichnofacies) and/or a phosphatic medium pebble-sized grain conglomerate lag at the contact, which has been interpreted to represent an erosional unconformity associated with a flooding surface/sequence boundary (Fig. 2.6; Furlong, et al., 2018b). The basal boundary is also locally a sharp contact between pervasively bioturbated and non-bioturbated facies, without an omission suite of the *Glossifungites* Ichnofacies present (Figs. 2.5 and 2.7). In well logs, the boundary is associated with a single, commonly off-scale, gamma-ray log deflection, which corresponds to the phosphatic lag/*Glossifungites* Ichnofacies-demarcated discontinuity surface encountered in core (Fig. 2.6). Within wells that do not possess a thick phosphatic lag or burrowed firmground,

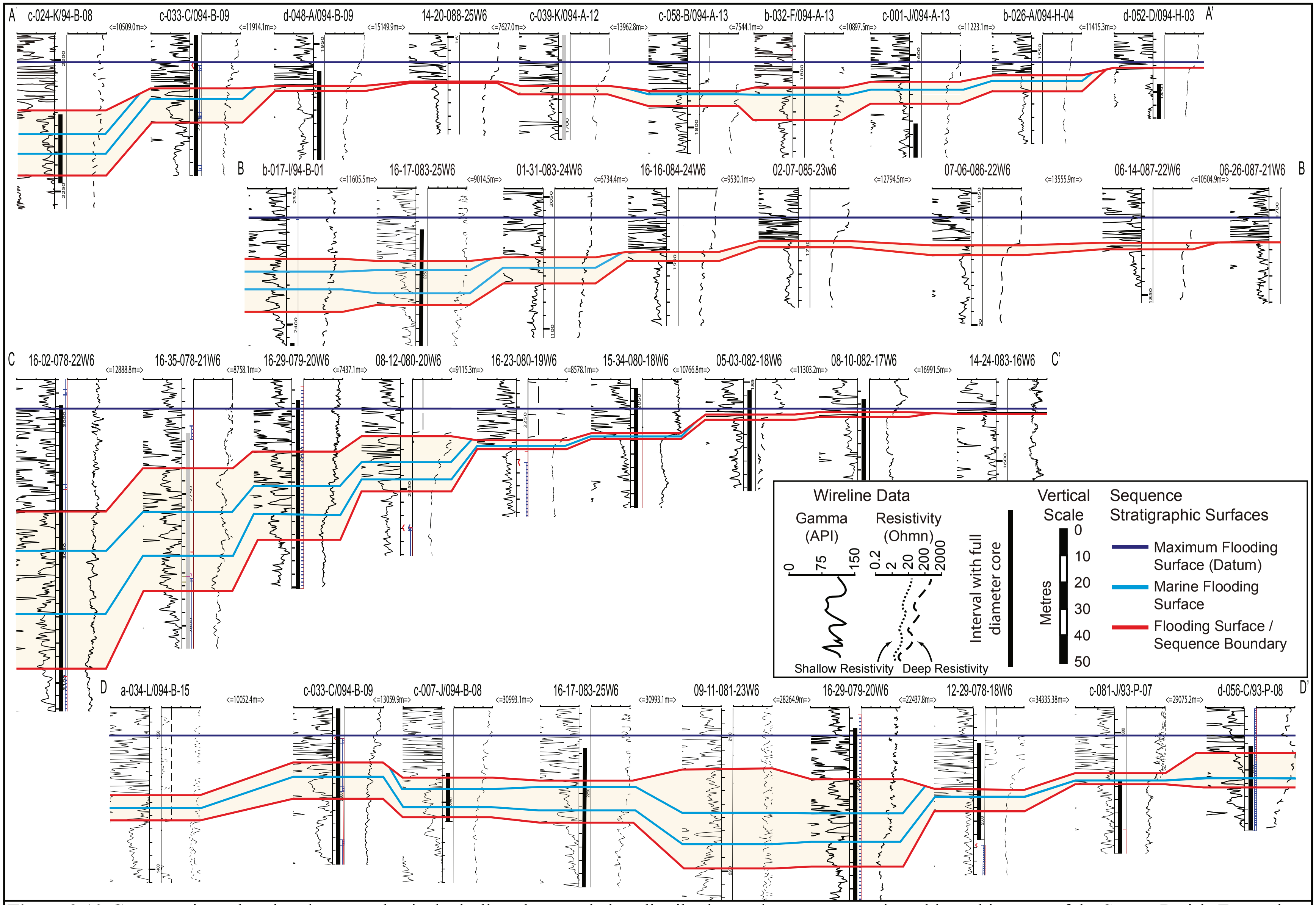


Figure 2.10-Cross sections showing the petrophysical wireline characteristics, distribution and sequence stratigraphic architecture of the Sunset Prairie Formation. Cross section locations identified in the total thickness isopach in Figure 2.8. Datum is the maximum flooding surface at the top of the Doig phosphate zone.

gamma-ray log signatures decreases sharply, which reflect the transition from the siltstone of the Montney Formation to the more sandy Sunset Prairie Formation (Figs. 2.5, 2.7). Within the spectral gamma-ray log, the uranium component increases upwards (from <15 ppm in the Montney Formation to 0-40 ppm in the Sunset Prairie Formation), potassium decreases slightly upwards (from 2-5% in the Montney Formation to 1-3% in the Sunset Prairie Formation), and the thorium component remains consistent between the Montney and Sunset Prairie Formations (around 2-10 ppm). Generally, resistivity of the Montney Formation within northwestern British Columbia is around 200 ohms. Within the Sunset Prairie resistivity ranges between 200-2000 ohms and gradually increases upward. No distinct change in the density log porosity occurs at the boundary, but intervals associated with sandstone facies (Facies 3, 4 and 5) commonly have increased porosity characteristics (Fig. 2.4).

The upper contact of the Sunset Prairie Formation with the overlying Doig phosphate zone is characterized by a conglomerate lag, rich in fine-grained sand- and medium pebble-sized phosphate material (Figs. 2.4, 2.5, 2.6, 2.7). Substrate-controlled trace fossil assemblages (most commonly *Glossifungites* Ichnofacies) may occur at the boundary between the two formations. Due to the high radioactive response of phosphate and other heavy minerals concentrated at the boundary, gamma-ray logs show a sharp increase, commonly leading to off-scale deflections (Figs. 2.4, 2.5, 2.6, 2.7). Within the spectral gamma-ray log, the uranium component slightly increases (from 0-40 ppm in the Sunset Prairie Formation to 15-50 ppm in the Doig phosphate zone), and the potassium and thorium component remains consistent between the two formations (around 1-3% and around 2-10 ppm respectively). Resistivity logs are generally high within the Doig phosphate zone, remaining around 200-2000 ohmns. No distinct change in the density porosity log occurs at the upper boundary. This contact is also interpreted as an erosional unconformity associated with a transgressively modified sequence boundary (Chapter 4).

Thickness and Areal Extent

The shaded region within Figure 2.8 indicates the distribution of the Sunset Prairie Formation. Overall, the Sunset Prairie Formation thins to the east and thickens distally to the west/southwest; however structural components greatly influence the distribution and total thickness of the interval (Figs. 2.1, 2.8, 2.10). The formation is thickest (66.5 m in the 03-06-078-22W6 well) in the western regions around the Groundbirch field, located within the Fort St. John Graben system and Hudson Hope Low. The northern limit of this thickening is associated with the Monias Fault, lying near the edge of the Hudson-Monias high (Figs. 2.1, 2.8). The southern limit of the thickening is influenced by faults associated with the Fort St. John Graben system. Thickening is broader than the Fort St. John Graben system, as described by Davies (1997a, 1997b) and Davies et al.

(1997), and the over-thickening is likely due to the graben being active during deposition of the Sunset Prairie Formation. To the north of this over-thickened region, the Sunset Prairie Formation thins and structures like the Monias High, Hay River Fault Zone, and Laurier Embayment locally influence distribution. Additionally, to the south of the Fort St. John Graben system, the Sunset Prairie Formation thins but there is no apparent correlation between its distribution and known structural trends, suggesting that structural features had a limited effect on deposition during this time. Further research is needed to understand the relationship between small-scale structural components and local distribution of the Sunset Prairie Formation. To date, the Sunset Prairie Formation has not been identified within outcrops of western British Columbia and has only been identified within the subsurface of British Columbia.

Age and Correlation

From the conodont biostratigraphic data published by Golding et al (2014a; 2014b; 2015), the Sunset Prairie Formation is lowest Anisian in age. No new biostratigraphy, conodont or otherwise, has been conducted on the Sunset Prairie Formation. However, wells with biostratigraphic data from Golding et al. (2014a; 2014b; 2015) have been re-evaluated for the presence of the Sunset Prairie Formation, as the authors did not recognize the Sunset Prairie Formation within their dataset. Therefore, ages have been reassigned to formations as needed. Wells included in evaluating the dating of the Sunset Prairie Formation are listed in Table 2.2.

Biostratigraphic studies of the Montney and Doig Formations have suggested that the boundary between the formations is highly diachronous, with latest Lower Triassic and earliest Middle Triassic occurring both above and below the boundary (Wilson et al., 2014; Golding et al., 2015). This however, may be an outcome of not recognizing the Sunset Prairie Formation previously, which has resulted in an over-exaggeration of the magnitude of diachroneity associated with the boundary. Samples that are assigned here to the Sunset Prairie Formation occur both above and below the Montney-Doig boundary as identified by Golding et al. (2015; Table 2.2). Additionally, many of the Montney Formation samples directly below the Montney-Sunset Prairie boundary are inconclusive due to the lack of diagnostic conodonts, making it difficult to define the age of this boundary. Biostratigraphic zonation can be problematic, especially within the Montney Formation, owing to many samples having inadequate conodont preservation and/or low abundance. However, it is most likely that the Upper Montney is Spathian (Lower Triassic) in age, the Sunset Prairie Formation is mainly Anisian (Middle Triassic) in age, and the Doig Formation is Anisian to Ladinian (Middle Triassic) in age.

The Sunset Prairie Formation is interpreted here to represent an unconformity-bound interval (Furlong et al., 2018b). Internal parasequence possess a back-stepping (deepening-upward) pattern

	Data from Golding et al. (2014b; 2015)					Formation assigned in this paper
Well	**GSC No.**	**Formation**	**Core Depth (m)**	**Conodonts Identified**	**Age**	
PCK d–048–A/094–B–09	V–002995	Doig	1965.00–1965.40	*Ng.* ex gr. *regalis α, Ng.* ex gr. *regalis δ*	L. to M. Anisian	Sunset Prairie & Doig
PCK d–048–A/094–B–09	V–002994	Doig	1964.80–1965.00	None		Sunset Prairie
PCK d–048–A/094–B–09	V–002993	Doig	1966.00–1967.00	None		Sunset Prairie
PCK d–048–A/094–B–09	V–002992	Doig	1967.30–1967.50	*Tr. homeri, Ng.* n.sp. I (*sensu* Golding, 2014a), *Ng.* ex gr. *regalis α, Ng. ex gr. regalis β*	U. Spathian to L. Anisian	Sunset Prairie
PCK d–048–A/094–B–09	V–002991	Montney	1967.85	*Ch. timorensis, Ns. triangularis*	U. Spathian to L. Anisian	Sunset Prairie
PCK d–048–A/094–B–09	V–002990	Montney	1968.25	None		Sunset Prairie
TA 16–17–083–25W6M	V–002977	Doig	2241.46–2242.35	*Ng.* sp.	U. Anisian to Ladinian	Doig
TA 16–17–083–25W6M	N/A	Doig	2243.00–2244.00	*Ng.* ex gr. *regalis*		Doig
TA 16–17–083–25W6M	N/A	Doig	2252.00–2253.00	*Ng.* ex gr. *regalis*	Anisian	Doig
TA 16–17–083–25W6M	V–002976	Doig	2254.44–2255.30	*Ng.* sp.		Sunset Prairie & Doig
TA 16–17–083–25W6M	N/A	Doig	2256.00–2257.00	None		Sunset Prairie
TA 16–17–083–25W6M	V–002975	Montney	2257.43–2258.30	*Ng.* cf. sp. A (*sensu* Orchard, 2008)	Spathian *	Sunset Prairie
TA 16–17–083–25W6M	N/A	Montney	2258.00–2259.00	*Ng.* sp.		Sunset Prairie
TA 16–17–083–25W6M	V–002974	Montney	2263.75–2264.70	None		Montney
TA 16–17–083–25W6M	V–002973	Montney	2276.50–2277.50	None		Montney
TA 16–17–083–25W6M	N/A	Montney	2281.25–2282.00	None		Montney
TA 16–17–083–25W6M	V–002972	Montney	2304.40–2305.30	None		Montney
TA 16–17–083–25W6M	N/A	Montney	2322.00–2323.00	None		Montney
TA 16–17–083–25W6M	V–002971	Montney	2330.80–2332.20	None		Montney
TA 16–17–083–25W6M	N/A	Montney	2356.00–2357.00	None		Montney
TA 16–17–083–25W6M	V–002970	Montney	2368.00–2369.00	None		Montney
TA 16–17–083–25W6M	N/A	Montney	2370.70–2371.50	*Ng.* sp., *Nv.* sp.		Montney
TA 16–17–083–25W6M	N/A	Montney	2380.10–2381.00	None		Montney
TA 16–17–083–25W6M	N/A	Montney	2384.00–2385.00	*Ng.* cf. sp. D (*sensu* Orchard, 2007)	Spathian	Montney

Table 2.2–Conodont samples from wells in northeastern British Columbia that were originally published by Golding et al. (2014b; 2015). Sample depths (core depths) are given in metres and the conodonts that were recovered within each sample are provided. Conclusive age dates for samples are given as assigned by Golding et al. (2015); samples with * have questionable age dates due to uncertainty in age range for conodont taxa present in the sample. Caption continued on next page…

	Data from Golding et al. (2014b; 2015)					Formation assigned in this paper
Well	GSC No.	Formation	Core Depth (m)	Conodonts Identified	Age	
SG 16–02–078–22W6M	V–002516	Doig	2999.20	*Ng.* ex gr. *constricta*, *Ng.* ex gr. *shoshonensis, Ng.* sp. "F"	Ladinian	Doig
SG 16–02–078–22W6M	V–002515	Doig	3020.30	*Ng.* sp. "A", *Ng.* sp. "O"		Doig
SG 16–02–078–22W6M	V–002514	Doig	3029.20	None		Doig
SG 16–02–078–22W6M	V–002512	Doig	3034.60	*Ng.* sp. "O"		Doig
SG 16–02–078–22W6M	V–002513	Doig	3034.80	*Ng. bifurcata, Ng.* n. sp. C (*sensu* Golding, 2014), *Ng.* n. sp. H (*sensu* Golding, 2014), *Ch.* sp.	l. to M. Anisiam	Doig
SG 16–02–078–22W6M	V–002511	Montney	3039.30	*Ng.* sp. "A", *Ng.* sp. "O"		Doig
SG 16–02–078–22W6M	V–002510	Montney	3045.50	*Ng.* sp. "A"		Doig
SG 16–02–078–22W6M	V–002509	Montney	3052.50	*Ng.* ex gr. *regalis, Ng.* sp. "A"		Doig
SG 16–02–078–22W6M	V–002508	Montney	3057.60	None		Sunset Prairie
SG 16–02–078–22W6M	V–002507	Montney	3067.60	*Ch.* sp., *Ng.* sp.		Sunset Prairie
SG 16–02–078–22W6M	V–002506	Montney	3073.00	*Ch. timorensis, Ng.* ex gr. *regalis*, *Ng.* ex gr. *regalis*	M. Anisian	Sunset Prairie
SG 16–02–078–22W6M	V–002505	Montney	3084.90	None		Sunset Prairie
SG 16–02–078–22W6M	V–002504	Montney	3089.00	None		Montney
SG 16–02–078–22W6M	V–002503	Montney	3094.40	None		Montney
SG 16–02–078–22W6M	V–002502	Montney	3094.80	None		Montney
SG 16–02–078–22W6M	V–002501	Montney	3113.00	None		Montney
SG 16–02–078–22W6M	V–002500	Montney	3127.54	None		Montney
SG 16–02–078–22W6M	V–002499	Montney	3150.40	None		Montney

Table 2.2 cont.–Formation names, originally assigned by Golding et al. (2014b; 2015) and re-interpreted formational divisions, with the addition of the Sunset Prairie Formation, are provided for each sample. Abbreviations include: PCK = Petro-Canada Kobes, TA = Talisman Altares, AD = Arc Dawson, MS = Murphy Swan, TG = Talisman Groundbirch, SG = Shell Groundbirch, *Bo.* = *Borinella*, *Ns.* = *Neospathodus*, *Nv.* = *Novispathodus*, *Ng.* = *Neogondolella*, *Ch.* = *Chiosella*, *Tr.* = *Triassospathodus*, *Cl.* = *Clarkina*, *G.* = *Guangxidella*, *P.* = *Paullella*, *Sc.* = *Scythogondolella*, *Co.* = *Conservatella*, *Pa.* = *Paragondolella.*

(Figs. 2.5, 2.10), suggesting a relative sea level transgression. The basal and upper contacts of the Sunset Prairie Formation are each interpreted to represent a transgressively modified sequence boundaries (Fig. 2.10; Furlong et al., 2018b). In many eastern parts of the basin, the Sunset Prairie Formation is absent (Fig. 2.8) and the basal and upper unconformities are amalgamated. This results in a marked temporal gap between Lower Triassic and Middle Triassic strata, which erroneously suggests a single unconformity of much longer duration than thought previously.

AMENDED DEFINITION OF THE MONTNEY FORMATION

With the introduction of the Sunset Prairie Formation, the definition of the Montney Formation needs to be amended to reflect nomenclatural and stratigraphic changes. The boundary between the Montney Formation and the overlying Sunset Prairie Formation is placed at an erosional contact/unconformity, locally demarcated by substrate-controlled trace fossil assemblages (most commonly firmground suites of the *Glossifungites* Ichnofacies) and/or a phosphatic conglomerate lag overlying the contact. The boundary may also be marked by a sharp change from non-bioturbated, fine-grained siltstone to pervasively bioturbated, fine-grained sandstone possessing a diverse assemblage of trace fossils. Ichnological assemblage of the Sunset Prairie Formation, listed by their relative abundance, include *Phycosiphon*, *Rosselia/Cylindrichnus Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. Such ichnodiversity is not observed at a basin-wide scale within the Montney Formation, and is only observed locally (e.g., Zonneveld et al., 2010a, 2010b; MacNaughton and Zonneveld, 2010; Davies et al., 2018). The Sunset Prairie Formation consists of interbedded fine-grained sandstone and fine-grained siltstone, which is lithologically discrete from the underlying, predominantly fine-grained siltstone beds of the Upper Montney Formation. This change in lithology is most noticeable on the gamma-ray logs, with gamma-ray API values decreasing in the sandier facies ascribed to the Sunset Prairie Formation. On the logs, the boundary between the Montney and Sunset Prairie Formations is associated with a single, commonly off-scale, gamma-ray deflection, which corresponds to the phosphatic lag/*Glossifungites* Ichnofacies-demarcated discontinuity surface (Fig. 2.6). Within wells that do not possess a thick phosphatic lag or burrowed firmground, gamma-ray log signatures decreases sharply, reflecting the transition from the siltstone of the Upper Montney Formation to the sandier Sunset Prairie Formation (Figs. 2.5, 2.7). Within the spectral gamma-ray log, the uranium component increases upwards (from < 15 ppm in the Montney Formation to 0-40 ppm in the Sunset Prairie Formation), potassium decreases slightly upwards (from 2-5% to 1-3%), and the thorium component remains consistent between the Montney and Sunset Prairie Formations (around 2-10 ppm). The Sunset Prairie Formation exhibits a progressive upward increase in resistivity in logs. Generally, resistivity in the Montney Formation of northwestern British Columbia is around 200 ohms, and this increases upwards in the Sunset Prairie, which fluctuates between 200-2000 ohms. In eastern regions, the Sunset Prairie Formation was either not been deposited or has been erosionally removed, and the original, classic definition of the boundary between the Montney Formation and Doig Formation (Armitage, 1962) is appropriate.

CONCLUSIONS

The Middle Triassic Sunset Prairie Formation is introduced herein to describe an interval of interbedded light grey, pervasively bioturbated sandstone and dark grey, minimally bioturbated siltstone that is stratigraphically located between the Lower Triassic Montney Formation and the Middle Triassic Doig Formation within the subsurface of northeastern British Columbia, Canada. The most common primary sedimentary structure is planar-parallel-laminae within the non-bioturbated to minimally bioturbated siltstone beds. Primary sedimentary structures are difficult to discern within the pervasively bioturbated beds, owing to the homogenization of the sediment by burrowing organisms. Trace fossils include a dense fabric of *Phycosiphon* and robust *Rosselia*/*Cylindrichnus*, with subordinate *Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. *Glossifungites* Ichnofacies-demarcated discontinuity surfaces (burrowed firmgrounds) are also present throughout the interval. Macrofossils include bivalves, gastropods, lingulid brachiopods, spiriferid brachiopods, terebratulid brachiopods, echinoid skeletal elements (particularly spines) and crinoid ossicles. Based on conodont biostratigraphy and the macrofossil assemblage, the unit is assigned a Middle Triassic (Anisian) age.

Seven facies are present within the formation and are interpreted to have been deposited within the offshore, offshore transition and lower shoreface environments (Furlong et al., 2018b). Facies stacking show up to three progradational parasequences (Furlong et al., 2018b). The interval is the thickest in the western part of the Western Canada Sedimentary Basin, and either has been erosionally removed or was never deposited towards the east. Structural features active during Triassic deposition greatly influenced the deposition and preservations of the Sunset Prairie Formation, with the thickest (80 m) interval being located within the Fort St. John Graben system and Hudson Hope Low. Erosional surfaces occur at the upper and basal contacts, which suggest the unit is unconformity-bound. These unconformities are interpreted to represent transgressively modified sequence boundaries.

Several authors previously have recognized the presence of the interval, and referred to it as the ‘Anisian Wedge’ (Zonneveld and Moslow, 2015; Zonneveld et al., 2015; 2016; Furlong et al., 2016b; 2017a, Davies et al., 2018). The introduction of the Sunset Prairie Formation eliminates this informal, ambiguous name, and provides a formal lithostratigraphic unit to clarify the regional stratigraphy.

CHAPTER 3: SEDIMENTOLOGY AND ICHNOLOGY OF THE MIDDLE TRIASSIC (ANISIAN) SUNSET PRAIRIE FORMATION OF THE WESTERN CANADA SEDIMENTARY BASIN

INTRODUCTION

Lower and Middle Triassic strata in the subsurface of the Western Canada Sedimentary Basin include the Montney, Doig and Halfway Formations (Fig. 3.1; Armitage, 1962; Gibson and Edwards, 1990; Davies et al., 1997). Recently, an unconformity-bound siliciclastic unit characterized by interbedded pervasively bioturbated sandstone and minimally bioturbated siltstone was identified between the top of the Montney Formation and the base of the Doig Formation. This interval has been introduced as the Sunset Prairie Formation, named after the hamlet of Sunset Prairie, near which the Shell Groundbirch 16-29-079-20W6 type well is located (Fig. 3.2; Furlong et al., 2018a). Previous authors have recognized the presence of this anomalous unit within northeastern British Columbia and have referred to it as the 'Anisian Wedge' (Zonneveld and Moslow, 2015; Zonneveld et al., 2015; 2016, Furlong et al., 2016b; 2017a, 2017b; Davies et al., 2018). This name is informally applied and problematic in its application (Furlong et al., 2018a). The Sunset Prairie Formation replaces this the informal name. The stratigraphic unit occurs regionally above the Montney Formation within the Western Canada Sedimentary Basin (Furlong et al., 2018a).

High bioturbation intensity, coupled with high diversity and robust character (large size) of trace fossils are characteristic of the Sunset Prairie Formation. This strongly contrasts with trace fossil assemblages observed throughout the underlying Montney Formation, which have been characterized as comprising of simple, low-abundance and low-diversity suites (Zonneveld, 2011). Several higher diversity assemblages have been identified and interpreted to be being associated with environmental refugia, or areas of oxygenated water within the shallow-marine realm (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b); however, these intervals are limited to localized areas. The Sunset Prairie Formation is the first regionally widespread interval that possesses robust and diverse trace fossil assemblages following the end-Permian mass extinction.

This study focuses on the sedimentology and ichnology of the Sunset Prairie Formation on a regional scale (Fig 3.3). Although local variability may be present within the formation, seven facies are identifiable through detailed analysis of 25 drill cores. Detailed investigation of the sedimentological, ichnological and palaeontological characteristics of the Sunset Prairie Formation provides insight into the processes of deposition, ecological conditions, and thereby the interpretation of depositional setting during the earliest Middle Triassic of western Canada.

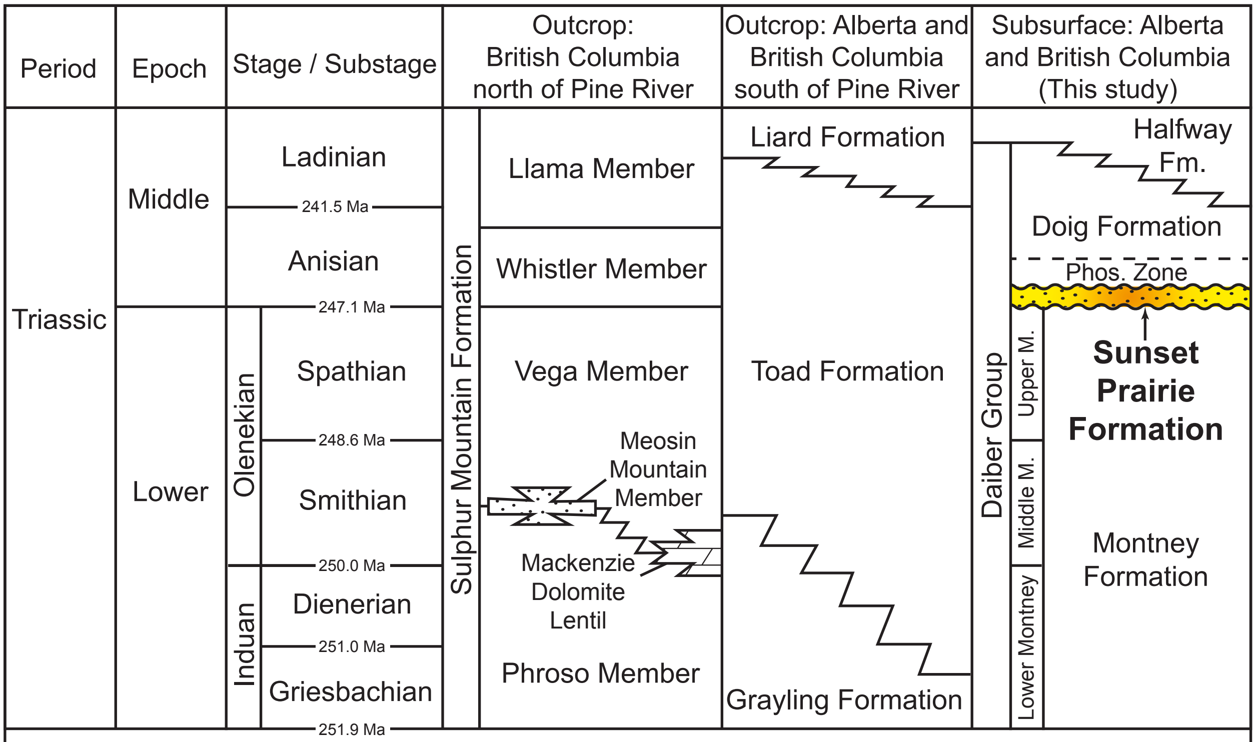


Figure 3.1–Lower and Middle Triassic lithostratigraphic nomenclature for outcrop and subsurface sections in Alberta and British Columbia. Ages of stages and substages identified by Henderson and Schoefer (2017), and Henderson et al. (2018). Modified from Zonneveld (2011) and Golding et al. (2015).

GEOLOGICAL FRAMEWORK

The Lower and Middle Triassic strata in the subsurface of the Western Canada Sedimentary Basin consist of four lithostratigraphic formations (Fig. 3.1). In ascending order, these westward-thickening formations include: marine siltstone, sandstone and bioclastic packstone / grainstone deposits of the Montney Formation (Armitage, 1962); marine siltstone and sandstone deposits of the Sunset Prairie Formation (Furlong et al., 2018a); marine shale, siltstone and minor sandstone deposits of the Doig Formation (Armitage, 1962; Evoy and Moslow, 1995; Evoy, 1997; Dixon, 2011); and shallow-marine shoreface and tidal-inlet sandstone deposits of the Halfway Formation (Hunt and Ratcliffe, 1959). The Montney Formation rests unconformably on Permian strata. The Sunset Prairie Formation is unconformity-bound and lies between the Montney and Doig Formations. The base of the Doig Formation is associated with a condensed section consisting of a highly radioactive, organic-rich, intraclastic lag and heterolithic zone with abundant phosphatic sand, granules and shale, and is informally referred to as the Doig phosphate zone (Armitage, 1962; Creaney and Allan, 1990; Gibson and Edwards, 1990; Edwards et al., 1994; Evoy and Moslow, 1995; Golding et al., 2015). Biostratigraphic dating shows the Montney Formation spans the Induan and Olenekian, whereas the Sunset Prairie Formation is Anisian in age and the Doig

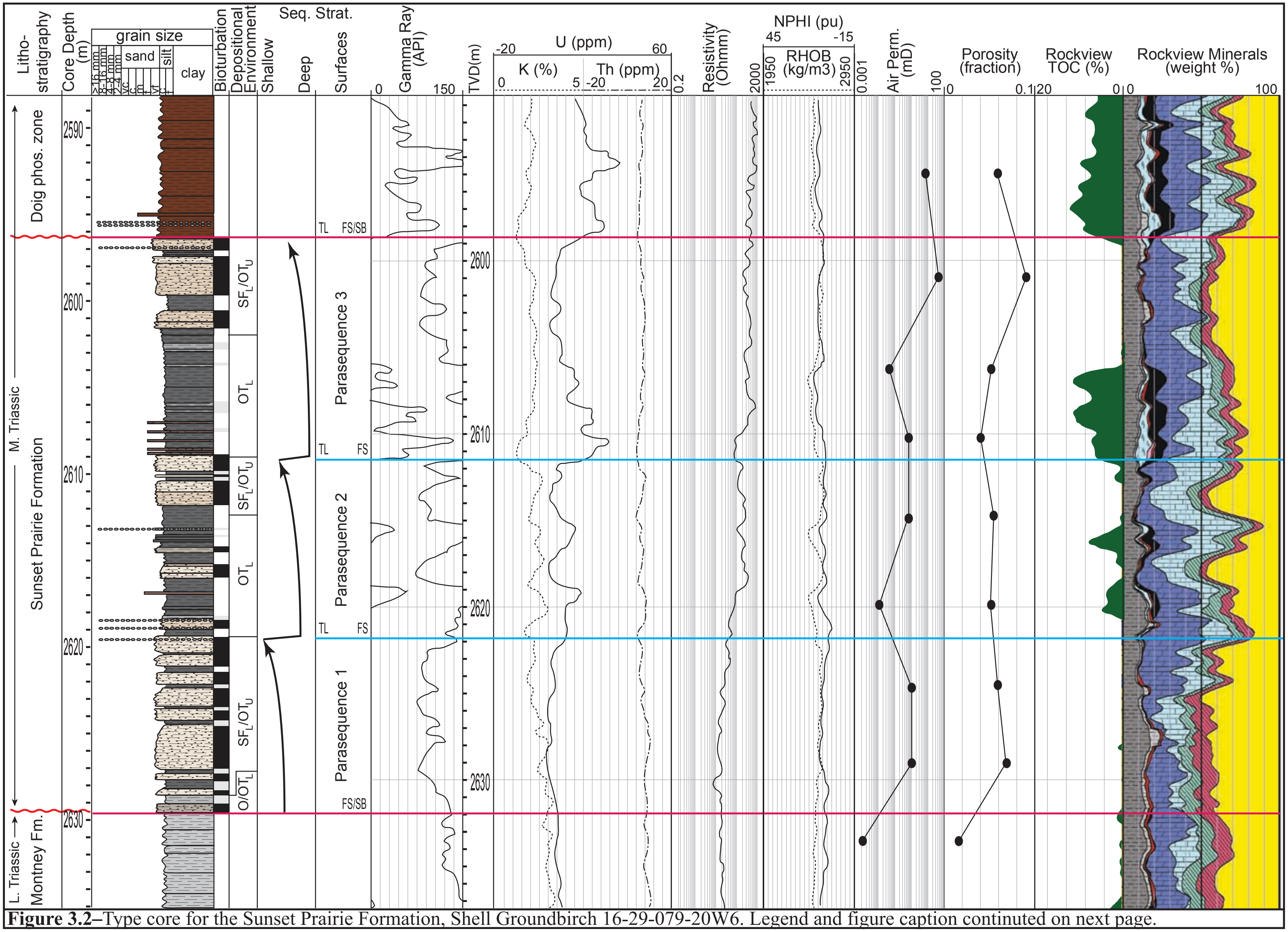


Figure 3.2–Type core for the Sunset Prairie Formation, Shell Groundbirch 16-29-079-20W6. Legend and figure caption continuted on next page.

Formation is Anisian to Ladinian in age (Fig 3.1; Gibson and Barclay, 1989; Davies et al., 1997; Tozer, 1994; Paull et al., 1997; Utting et al., 2005; Orchard and Zonneveld, 2009; Wilson et al., 2014; Golding et al., 2014a, 2014b, 2015, Furlong et al., 2018a).

PALAEOGEOGRAPHY AND REGIONAL PALAEOENVIRONMENTAL SETTING

Deposition of Lower and Middle Triassic strata occurred on the western margin of Pangaea and the eastern margin of Panthalassa under arid, mid-latitudinal (~30^{O}N) conditions (Wilson et al., 1991; Davies, 1997a; Davies et al., 1997; Dixon, 2000; Moslow, 2000; Zonneveld et al., 2010b). Historically, this was believed to be a passive margin basin that fostered the development of a marine ramp/shelf setting (Edwards et al., 1994; Dixon, 2009a; 2009b). Recent work has suggested that during the Triassic, deposition occurred on an active margin, possibly a back-arc-basin (Ferri and Zonneveld, 2008; Schiarizza, 2013; Morris et al., 2014) or early foreland basin (Golding et al., 2016). Provenance studies suggest that most Triassic sediment was derived from reworked Devonian rocks of the Laurentian continent to the east (Ross et al., 1997; Utting et al., 2005; Beranek et al., 2010; Morris et al., 2014), with small portions potentially being sourced from western volcanic arc settings (Morris et al., 2014; Golding et al., 2016). The main depocentre for Triassic sediments was formed due to subsidence/collapse of the topographically high Peace River Arch during the Carboniferous, which formed the Peace River Embayment (Douglas, 1970; O'Connell et al., 1990). Structural features that influenced Early and Middle Triassic deposition include shallow fault systems, deeper basement faults, and most importantly, graben faults within the Peace River Embayment (Evoy, 1997; Berger et al., 2009; Mei, 2009; Chalmers and Bustin, 2012).

Deposits within the Montney Formation have been associated with a wide range of depositional environments including distal offshore settings, turbidite channel and fan complexes, storm- and wave-dominated shorelines, deltas (perennial and ephemeral deltas) and esturaties (Metherell,

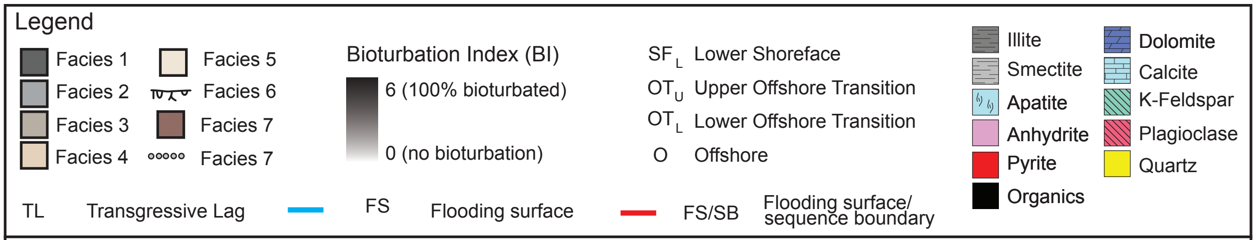


Figure 3.2 cont.–Lithostratigraphy, lithology, interpreted depositional environments and interpreted sequence stratigraphy are identified for the interval. Well logs include gamma ray, spectral gamma (U = Uranium; K = Potassium; Th = Thorium), resistivity, density porosity (RHOB) (limestone matrix) and neutron porosity (NPHI) (limestone matric). Air permeability data and porosity data are identified for the interval. Air permeability data and porosity data were collected by Core Laboratories from small-diameter core plugs. Total Organic Carbon (TOC) and Rockview Mineralogy data were collected and interpreted from a Flex logs by Backer Hughes.

1966; Miall, 1976; Davies et al., 1997; Moslow and Davies, 1997; Moslow, 2000; Zonneveld et al., 2010a, 2010b; Zonneveld and Moslow, 2014, 2015, 2018; Crombez et al., 2016; Davies et al., 2018). Overprinting many Early Triassic facies is evidence for anoxic or dysoxic water conditions (Wignall and Hallam, 1992; Wignall et al., 1998; Twitchett, 1999; Pruss et al., 2005; Hays et al., 2007). Worldwide anoxic water conditions, acidification of the water column and global warming are suggested to have been the result of volcanism associated with the Siberian Traps, which coincide with the end-Permian mass extinction at ~250 Ma (Benton and Twitchett, 2003; Black et al., 2012; Payne and Clapham, 2012). Ocean anoxia greatly influenced benthic assemblages and would have restricted them to narrow, shore-proximal habitable zones (Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011).

The Middle Triassic is marked by an initial shift to more hospitable oceanic conditions, as observed by the pervasively bioturbated strata containing a diverse assemblage of robust trace fossils within the Sunset Prairie Formation (Furlong et al., 2018a). However, the Doig Formation is generally characterized by low bioturbation intensities, low ichnodiversities and reduced sizes of trace fossils, suggesting persistent palaeoenvironmental stress (Proverbs and Bann, 2008). During the deposition of the upper Doig and Halfway Formations, environmental conditions once again became suitable to support trace-making organisms (Willis and Moslow, 1994; Zonneveld et al., 1997, 2001, 2002; Zonneveld, 2001).

FACIES DESCRIPTIONS AND INTERPRETATIONS

Seven lithofacies have been identified in the cores studied for the Sunset Prairie Formation (F1 through F7; Figs. 3.4, 3.5; Table 3.1). This dataset was derived from detailed sedimentological, ichnological and palaeontological analysis of 25 drill core from the Sunset Prairie Formation (Fig. 3.3). The Wentworth scale for siliciclastic sediments was used to define grain size. Bioturbation intensity was quantified using bioturbation index (BI), which ranges from non-bioturbated (BI = 0) to pervasively bioturbated (BI = 6) (*sensu* Reineck, 1963, 1967; Taylor and Goldring, 1993). Trace fossils are listed within each facies according to their relative abundance.

Facies within the Sunset Prairie Formation are described in the order of interpreted distal to proximal environments, with the exception of Facies 6 and 7. These facies are interpreted to represent *Glossifungites* Ichnofacies and lag deposits, respectively, and are not controlled by distal and proximal trends. Facies 1-5 are interpreted as offshore through lower shoreface deposits that were intermittently storm influenced (Fig. 3.4).

Within this paper, open-marine environmental subdivisions are based on Elliott (1986) and Reading and Collinson (1996), which place the offshore below the storm-wave base, the offshore

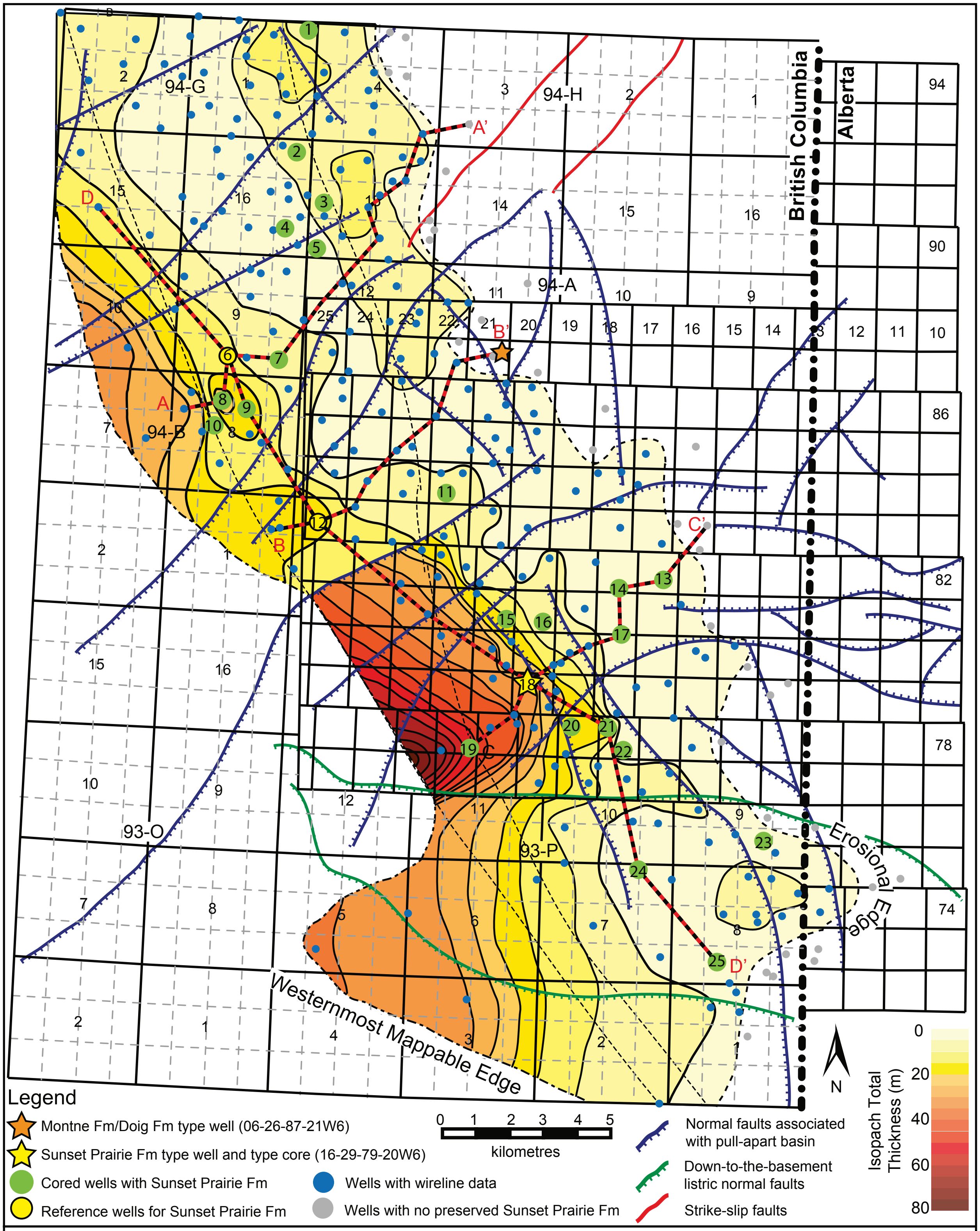


Figure 3.3–Location and thickness map of the Sunset Prairie Formation. Well control is shown through the location of wells in the dataset and includes wire line (n=248) and cored wells (n = 25). List of cored wells is identified in Table 1.1 Wells with wire line data that did not have preserved Sunset Prairie Formation (grey dots; n = 36) were used to determine erosional edge of the formation. Thickness ranges from 0-80 m, with the thickest accumulation coincident with the Hudson Hope Low (sensu Barclay et al., 1990). Contour interval = 5 m.

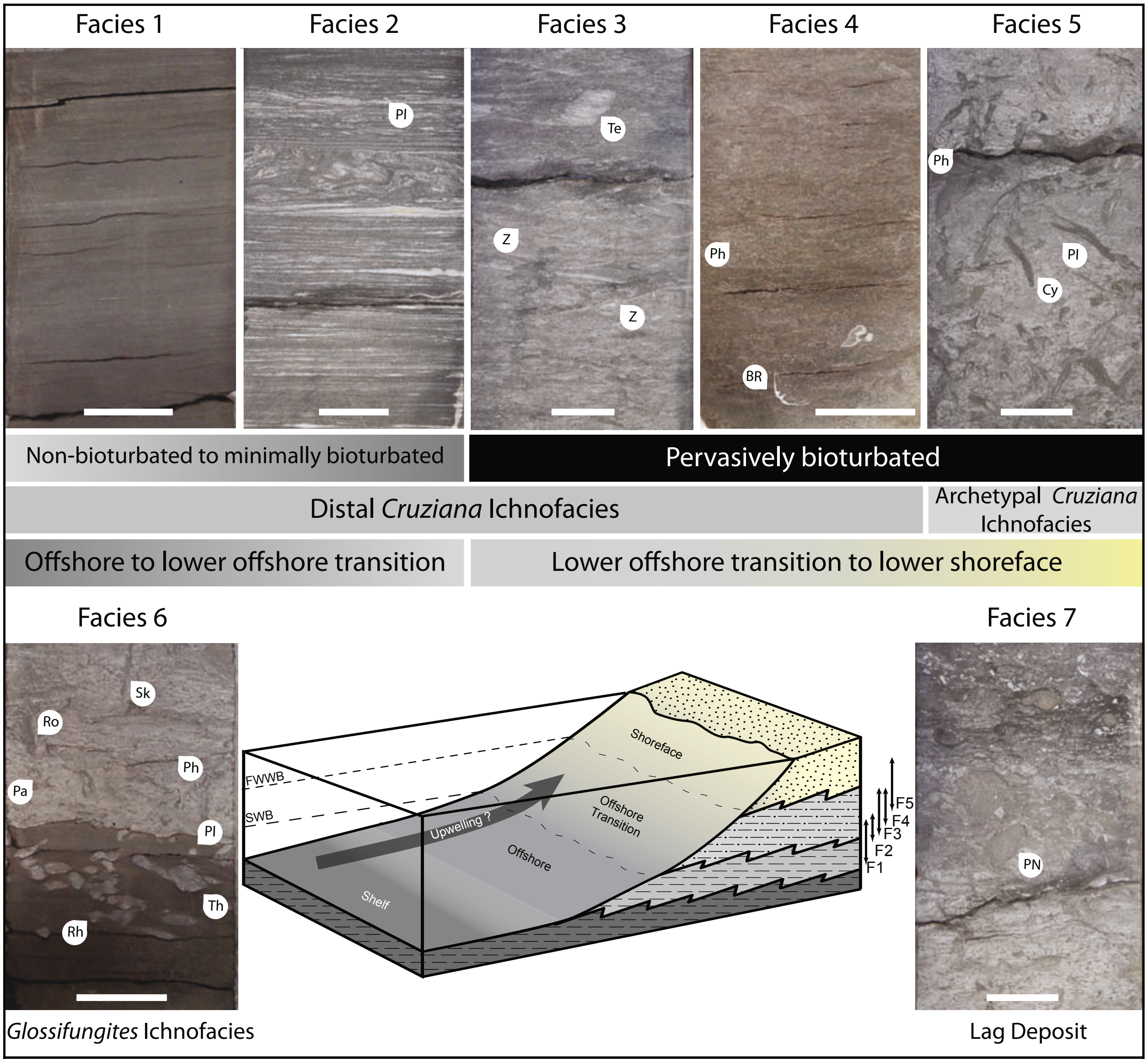
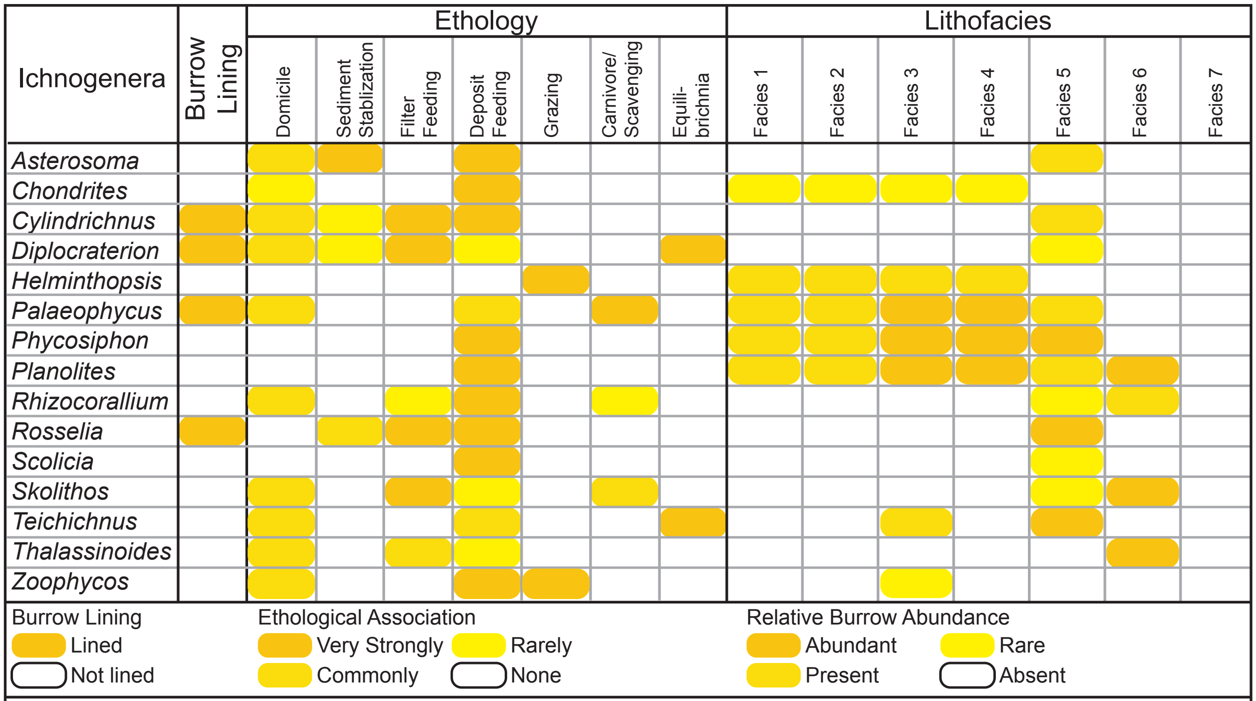


Figure 3.4–Summary of facies present within the Sunset Prairie Formation. Bioturbation intensity, ichnofacies and interpreted depositional environment are identified for each facies. Scale bars for core photos = 3 cm. Schematic at bottom shows distribution of facies and depositional environments within a siliciclastic ramp setting. Abbreviations include: Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Rh = *Rhizocorallium*, Ro = *Rosselia*, Sc = *Scolicia*, Sk = *Skolithos*, Te = *Teichichnus* and Th = *Thalassinoides*, Z = *Zoophycos*, BR = brachiopod shell and PN = phosphate nodule.

transition between the storm-wave base and the fair-weather wave base, and the shoreface between the fair-weather wave base and the low-tide line. Although a variety of different shoreface models have been suggested over the past few decades (e.g., Elliott, 1986; Reading and Collinson, 1996; MacEachern and Bann, 2008; Buatois and Mangano, 2011), the model used herein aligns with terminology used in many recent studies on Montney Formation stratigraphy (e.g., Crombez 2016, 2017; Euzen et al., 2018; Moslow et al., 2018; Prenoslo et al., 2018; Sanders et al., 2018; Zonneveld and Moslow, 2018)



Ichnogenera	Burrow Lining	Ethology: Domicile	Sediment Stablization	Filter Feeding	Deposit Feeding	Grazing	Carnivore/ Scavenging	Equili-brichnia	Lithofacies: Facies 1	Facies 2	Facies 3	Facies 4	Facies 5	Facies 6	Facies 7
Asterosoma		🟨	🟧		🟧								🟨		
Chondrites		🟡			🟧				🟡	🟡	🟡	🟡			
Cylindrichnus	🟧	🟨	🟡	🟧	🟧								🟨		
Diplocraterion	🟧	🟨	🟡	🟧	🟡			🟧					🟡		
Helminthopsis						🟧			🟨	🟨	🟨	🟨			
Palaeophycus	🟧	🟨			🟨		🟧		🟨	🟨	🟧	🟧	🟨		
Phycosiphon					🟧				🟨	🟨	🟧	🟧	🟧		
Planolites					🟧				🟨	🟨	🟧	🟧	🟨	🟧	
Rhizocorallium		🟨		🟡	🟧		🟡						🟡	🟨	
Rosselia	🟧		🟨	🟧	🟧								🟧		
Scolicia					🟧								🟡		
Skolithos		🟨		🟧	🟡		🟨						🟡	🟧	
Teichichnus		🟨			🟨			🟧			🟨		🟧		
Thalassinoides		🟨		🟨	🟡									🟧	
Zoophycos		🟨			🟧	🟧					🟡				

Burrow Lining
🟧 Lined
▭ Not lined

Ethological Association
🟧 Very Strongly
🟡 Rarely
🟨 Commonly
▭ None

Relative Burrow Abundance
🟧 Abundant
🟡 Rare
🟨 Present
▭ Absent

Figure 3.5–Distribution, facies abundance and range of ethologies of ichnogenera identified in core. Modified after Gingras et al. (2007) and MacEachern et al. (2007a; 2010).

Facies 1 Description

Facies 1 consists of dark to medium grey, bituminous siltstone (Fig. 3.6A-H, Table 3.1). Primary sedimentary structures include faint horizontal planar-parallel-laminae (Fig. 3.6A, 3.6B), horizontal planar-wavy laminae, horizontal wavy-parallel-laminae, low- and high-angle planar cross-laminae, asymmetric ripple laminae and rare hummocky cross stratification and penecontemporaneous deformation structures. Isolated pyrite grains are common and can be concentrated within thin beds (Fig. 3.6C). Calcispheres are also present and concentrated within thin beds that are light grey in colour (Fig. 3.6D). Phosphatic silt-sized grains, rare phosphate ooids, phosphate nodules, clasts and phosphate rich laminae occur within isolated beds (Fig. 3.6E-6H). Trace fossils are rare, but isolated beds (<5 cm in thickness) may be bioturbated with diminutive forms of *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites* (Figs. 3.5, 3.6E, 3.6H). Bioturbation intensity (BI) ranges from 0-2 at a bed scale. Facies 1 is the predominant non-bioturbated, or minimally bioturbated facies within the Sunset Prairie Formation.

Facies 1 is thickest and most prevalent within cores from the western portion of the study area. The facies can be up to 10 m thick, but can be as thin as 10 cm when interbedded with bioturbated facies (F3, F4, F5).

Description	Sedimentological Characteristics	Ichnological Characteristics	Palaeontological Characteristics	Interpretation
Facies 1 (F1) Dark to medium grey, laminated, bituminous siltstone with minimal bioturbation	○ Dark to medium grey, fine- to coarse-grained siltstone ○ Faint planar-parallel, wavy-parallel laminae, low- and high-angle planar cross-laminae, asymmetric ripples, and rare hummocky cross stratification and penecontemporaneous deformation structures ○ Isolated pyrite grains ○ Isolated beds rich with calcispheres ○ Phosphate silt, nodules, clasts, phosphate rich laminae and rare phosphatic ooids	○ Minimally bioturbated ○ *Ph, He, Pa, Pl, Ch* ○ BI = 0-2		○ Offshore to lower offshore transition ○ Distal *Cruziana* Ichnofacies
Facies 2 (F2) Diminutively bioturbated dark to light grey siltstone	○ Dark to medium grey, fine- to coarse-grained siltstone ○ Pinstripe-parallel, planar-parallel laminae, wavy-parallel laminae and asymmetric ripples ○ Rare penecontemporaneous deformation structures	○ Minimally bioturbated ○ *Ph, He, Pa, Pl, Ch* ○ BI = 0-2		○ Lower offshore transition ○ Low diversity *Cruziana* Ichnofacies
Facies 3 (F3) Dark to light grey bioturbated siltstone	○ Dark to light grey, fine-grained siltstone to very fine-grained sandstone ○ Phosphate nodules, silt and very fine sand sized phosphate grains are present in isolated beds	○ Pervasively bioturbated ○ *Ph, He, Te, Pa, Pl, Ch, Z* ○ BI = 5-6		○ Likely proximal expression of F5 ○ Lower to upper offshore transition ○ Distal *Cruziana* Ichnofacies
Facies 4 (F4) Pervasively bioturbated medium to light grey siltstone	○ Medium to light grey, fine-grained silt to very fine-grained sandstone ○ Faint planar-parallel laminae	○ Pervasively bioturbated ○ *Ph, He, Pa, Pl, Ch* ○ BI = 4-6	○ Bivalves, gastropods, brachiopods, echinoderm, crinoids	○ Likely proximal expression of F1/F2 ○ Lower to upper offshore transition ○ Low diversity *Cruziana* Ichnofacies
Facies 5 (F5) Pervasively bioturbated sandy siltstone	○ Medium to light grey, fine-grained siltstone to very fine-grained sandstone ○ Faint planar-parallel and wavy-parallel laminae, low- and high- angle planar cross laminae ○ Rare penecontemporaneous deformation structures, asymmetric ripples ○ Phosphate nodules, phosphate rich laminae, rip up clasts present within isolated beds ○ Sharp to gradual top and base contacts	○ Pervasively bioturbated ○ Large, robust traces ○ *Ph, Ro, Cy, As, Te, Pa, Pl, Sk, Sc, Rh, Di* ○ Bioturbation decreases upwards ○ BI = 4-6	○ Bivalves, gastropods, brachiopods, echinoderm, crinoids	○ Upper offshore transition to lower shoreface Archetypal *Cruziana* Ichnofacies
Facies 6 (F6) *Glossifungites* surfaces	○ Burrowed firmground; commonly at the base of bioturbated intervals Sometimes associated with lag deposit (F7)	○ Burrowed surface with *Pl, Sk, Th, Rh*		○ Firmground ○ Transgressive Surface of Erosion ○ *Glossifungites* Ichnofacies-demarcated discontinuity surface
Facies 7 (F7) Lag deposit	Sand to pebble sized clasts, phosphate nodules, phosphatic ooids, rip up clasts. Sometime associated with Facies 6		○ Shell fragments Bone fragments	○ Transgressive lag deposit /Transgressive Surface of Erosion

Table 3.1–Summary of sedimentologic, ichnologic and palaeontologic attributes of the Sunset Prairie Formation. Trace fossil abbreviations include: *As* = *Asterosoma*, *Ch* = *Chondrites*, *Cy* = *Cylindrichnus*, *Di* = *Diplocraterion*, *He* = *Helminthopsis*, *Pa* = *Palaeophycus*, *Ph* = *Phycosiphon*, *Pl* = *Planolites*, *Rh* = *Rhizocorallium*, *Ro* = *Rosselia*, *Sc* = *Scolicia*, *Sk* = *Skolithos*, *Te* = *Teichichnus*, *Th* = *Thalassinoides*, *Z* = *Zoophycos*. Body fossils include bivalve, gastropods, brachiopods (lingulid, spiriferid terebratulid), cidaroid echinoid skeletal fragments and isocrinid crinoid ossicles.

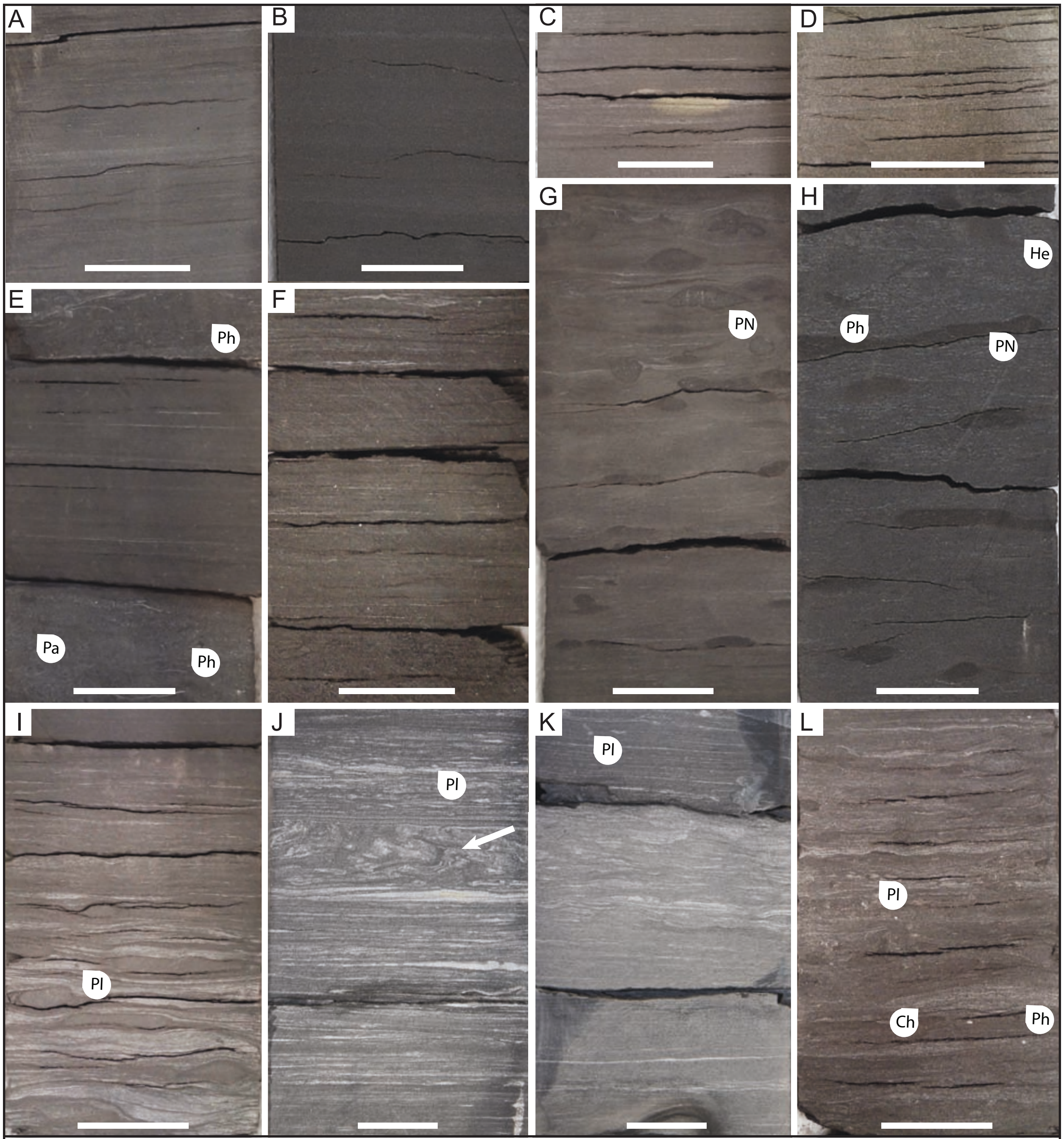


Figure 3.6–Core photographs of Facies 1 and Facies 2 from the Sunset Prairie Formation. All scale bars are 3cm in length. All depths represent core depths. A. Facies 1, medium grey fine-grained siltstone with fuzzy planar laminae due to bioturbation (well 16-29-079-20W6; 2617.9 m). B. Same as A (well c-65-F/94-B-08; 2082.7 m). C. Facies 1 with pyrite rich horizon (well 16-29-079-20W6; 2199.72 m). D. Facies 1, medium to light grey fine-grained siltstone with calcispheres (well 16-02-078-22W6; 3077.4 m). E-F. Facies 1, medium grey fine siltstone rich in phosphate (E. well 16-02-078-22W6; 2077.4 m; F. well 16-29-079-20W6; 2613.7 m). G. Facies 1, fine-grained siltstone with phosphate nodules (PN) (well 16-29-079-20W6; 2619.5 m). H. Facies 1, fine-grained phosphatically rich siltstone with phosphate nodules and phosphate rich laminae (well c-65F/94-B-08; 2298.8 m). I. Facies 2, fine- to coarse-grained siltstone with planar to wavy laminae (well 16-02-078-22W6; 3078.0 m). J. Facies 2 with pinstripe and penecontemporaneous deformation structures (arrow) (well c-33-C/94-B-09; 2199.5 m). K-L. Facies 2 with diminutive bioturbation (K. well c-33-C/94-B-09; 2193.5 m; L. well 16-02-078-22W6; 3065.0 m). Trace fossils include Ch = *Chondrites*, He = *Helminthopsis*, Pa = *Palaeophycus*, Ph = *Phycosiphon* and Pl = *Planolites*.

Facies 1 Interpretation

Facies 1 is interpreted to represent deposition within the offshore to lower offshore transition setting. The fine- to coarse-grained siltstone with horizontal planar-parallel-laminae as the dominant sedimentary structure was likely a product of suspension deposition. However, low- and high-angle planar cross laminae may be interpreted as hummocky cross stratification (HCS), and would have been produced by infrequent storm-wave generated currents, indicating that deposition occurred above mean storm wave base. Penecontemporaneous deformation structures are rare, and are likely seismites. Phosphate (Fig. 3.4E-H) occurs as coarse silt grains, rare phosphate ooids, nodules, clasts and phosphate-rich laminae. The high phosphate content is likely due to upwelling and/or transport of phosphate material from other regions (Butnett et al., 1982; Frohlich, 2004).

Calcispheres are present within isolated, thin beds (<10 cm in thick). They have been interpreted to represent spherical, calcareous bodies of algal origin and are associated with oxygenated, eutrophic and potentially anoxic water (Jarvis et al., 1988; Drzewiecki and Simo, 1997). Environmental settings favorable to calcispheres include shallow-water sheltered environments (e.g., reefs/lagoon), shelf, slope and basin settings (Marszalek, 1975; Hart, 1991; Drzewiecki and Simo, 1997). Calcispheres within the Sunset Prairie Formation are calcite cemented, making identification difficult to impossible.

Trace fossils within the facies are diminutive (<1 mm in diameter) and include forms associated with grazing/foraging (*Helminthopsis*), deposit feeding (*Chondrites*, *Phycosiphon* and *Planolites*) and passive carnivore (*Palaeophycus*) (Fig. 3.5). Trace fossils within F1 are known as 'facies-crossing' structures and occur in many different ichnofacies suites due to the ichnogenera commonly being associated with trophic generalist trace-makers (Gingras et al., 2007). However, the trace fossils present are interpreted to have been produced by grazing and deposit feeding organisms, which is characteristic of the *Cruziana* Ichnofacies (MacEachern and Bann, 2008). Trace fossils are diminutive and the suite shows low ichnodiversity with low bioturbation intensity (BI = 0-2), suggesting that environmental conditions were neither favorable to support prolonged periods of settlement, nor robust tracemaker.

Facies 2 Description

Facies 2 (Fig. 3.6I-L, Table 3.1) consists of dark bituminous to light grey, centimetre-scale, interbedded fine- to coarse-grained siltstone. Horizontal planar-parallel laminae, horizontal pinstripe-planar-laminae, wavy-parallel laminae, discontinuous planar-parallel laminae, with rare asymmetric ripples and penecontemporaneous deformation structures occur. Similar to F1, F2 occurs interbedded with pervasively bioturbated facies (F3, F4 and F5), with interbeds ranging from decimetre- to metre-scale. Contacts can be gradual or sharp. Trace fossils are diminutive (<1 mm in diameter) and bioturbation intensity is low (BI 0-2). Ichnogenera include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites* (Fig. 3.5).

Facies 2 Interpretation

Facies 2 is interpreted to indicate deposition within the lower offshore transition zone. Horizontal wavy-parallel-laminae, discontinuous-parallel-laminae and asymmetric ripple laminae indicate a process of current transport. However, Facies 2 does not possess obvious storm-generated sedimentary structures, such as tempestites or hummocky cross-stratification.

Similar to F1, the trace fossils present in F2 are 'facies-crossing' structures, which include the ichnogenera *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites*. The forms are interpreted to have been produced by grazers, deposit feeders and passive carnivores (Fig. 3.5), which indicate that the ichnological assemblage attributed to with *Cruziana* Ichnofacies (MacEachern and Bann, 2008). Trace fossils, however, are of diminutive size and form a low ichnodiversity suite in facies characterized by low bioturbation intensity (BI = 0-2).

Facies 3 Description

Facies 3 (Fig. 3.7A-E, Table 3.1) consists of dark to light grey, fine-grained siltstone to very fine-grained sandstone that is pervasively bioturbated. Silt to very fine-grained sand-sized phosphate grains and phosphate nodules are also present within the facies. No apparent or well-defined physical sedimentary structures are preserved, largely owing to the high bioturbation intensity (BI = 5-6). Trace fossils present include *Phycosiphon*, *Helminthopsis*, *Teichichnus*, *Palaeophycus*, *Planolites*, *Chondrites* and *Zoophycos* (Fig. 3.5). Facies 3 ranges in thickness from 10 cm to about 3 m.

Facies 3 Interpretation

Facies 3 is interpreted to represent deposition within the lower to upper offshore transition zone. The lack of physical sedimentary structures within F3 and other pervasively bioturbated facies (F4 and F5) poses problems for interpreting a depositional environment; however, grain size variations and trace fossil assemblages can provide some insight. Facies 3 contains fine-grained siltstone to very fine-grained sandstone, which is coarser than the texture of F1 and F2. This places F3 proximal to F1 and F2. Trace fossils are the only structures preserved within this facies, suggesting that the

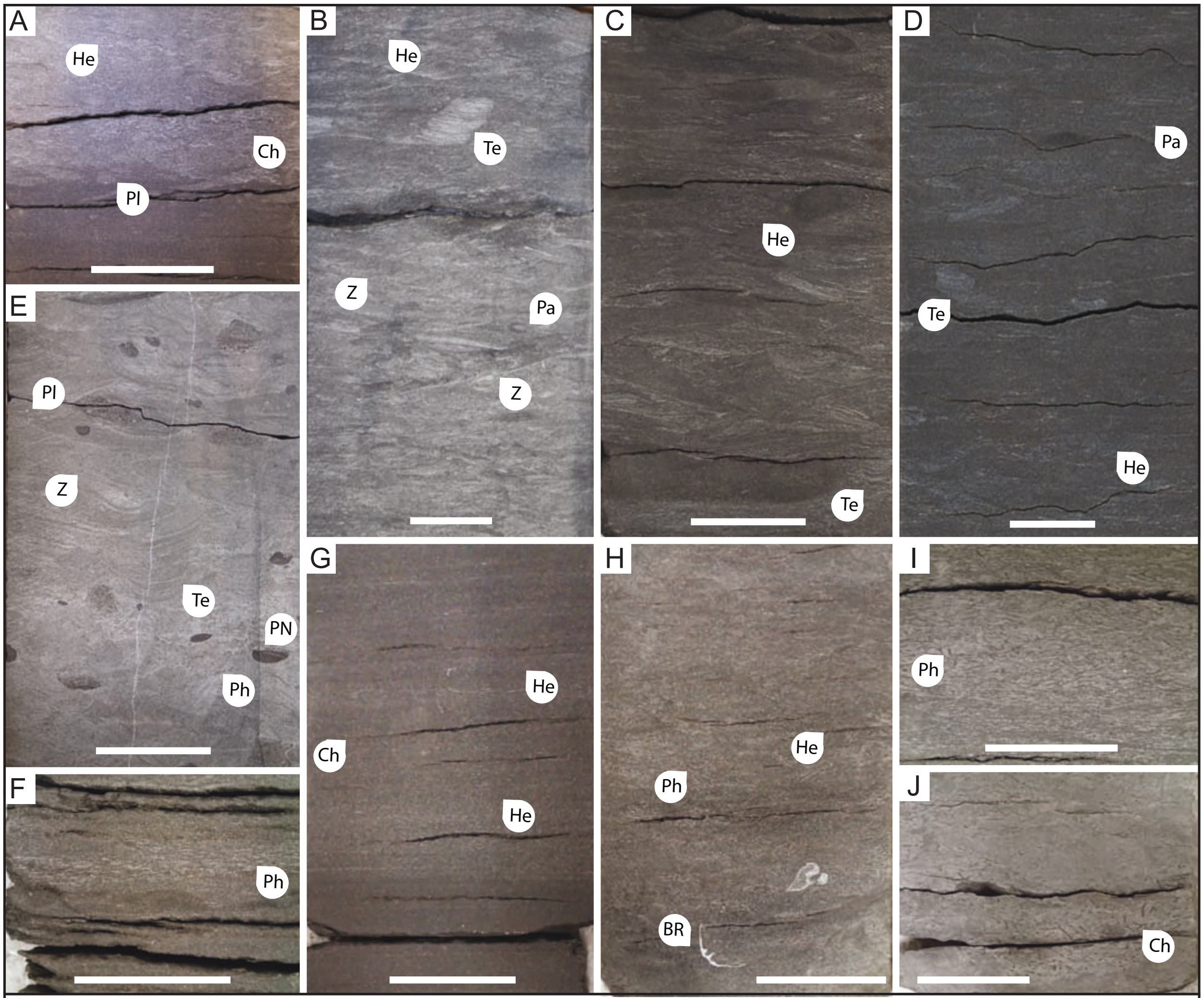


Figure 3.7–Core photographs of Facies 3 and Facies 4 from the Sunset Prairie Formation. All scale bars are 3cm in length unless otherwise denoted. All depths represent core depths. A. Facies 3, pervasively burrowed base separating Facies 3 from Facies 1 (well 16-02-078-22W6; 3096.4 m). B. Facies 3, pervasively bioturbated fine-grained siltstone (well c-33-C/94-B-09, 2200.3 m). C. Facies 3, dark grey, pervasively bioturbated fine-grained, phosphatic-rich siltstone (well 16-29-079-20W6; 2629.2 m). D. Same as C (well c-65-F/94-B-08; 2202.70 m). E. Facies 3 with phosphate nodules (PN) (well 2-10-078-18W6; 2554.7 m). F. Facies 4, thin bed of highly bioturbated siltstone, scale bar = 2 cm (well 16-02-078-22W6; 3067.4 m). G. Facies 4, pervasively bioturbated, medium grey siltstone with sharp contact between bioturbated and non-bioturbated zones (well 16-02-078-22W6; 3067.9 m). H. Facies 4, robust *Phycosiphon*, brachiopod shell (BR) present (well 16-02-078-22W6; 3094.0 m). I. Same as H, scale bar = 2cm (well 16-02-078-22W6; 3092.2 m). J. Same as H (well 16-02-078-22W6; 2086.5m). Trace fossils include Ch = *Chondrites*, He = *Helminthopsis*, Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Te = *Teichichnus*, and Z = *Zoophycos*.

depositional environment was well-oxygenated, had a high nutrient supply, a low sediment supply, and only infrequently influenced by storms. All of these environmental conditions foster complete biogenic homogenization of the sediment. Facies 3 possesses a “wispy” bioturbated texture (Fig 3.7C, 3.7E), which is likely due to the abundant biogenic activity that completely reworked the sediment (Raychaudhuri et al., 1992; Pemberton et al., 2008). The ichnofossil assemblage is diverse and abundant, and includes trace fossils associated with grazing/foraging (*Helminthopsis* and *Zoophycos*), deposit feeding (*Teichichnus*, *Chondrites*, *Phycosiphon* and *Planolites*) and passive carnivores (*Palaeophycus*) (Fig. 3.5). No vertical dwelling trace fossils or structures associated with filter-feeding organisms are present. The trace fossil assemblage represents the distal expression of the *Cruziana* Ichnofacies (MacEachern and Bann, 2008).

Facies 4 Description

Facies 4 (Fig. 3.7F-J, Table 3.1) consists of medium to light grey, fine-grained siltstone to very fine-grained sandstone. Faint horizontal planar-parallel-laminae are rare, due to pervasive bioturbation (BI = 5-6). Trace fossils include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites*. *Phycosiphon* is omnipresent and makes a dense, bioturbated fabric (Fig. 3.5). Scattered bivalves, gastropods, brachiopods (lingulid, spiriferid and terebratulid), cidaroid echinoid skeletal fragments, and isocrinid crinoid ossicles are present in this facies. The echinoderm material is invariably disarticulated but the bivalve and brachiopod shells occur as articulated, disarticulated and broken shell debris. Facies 4 is less than 2 m thick, and is commonly about 10 cm in thickness.

Facies 4 Interpretation

Facies 4 is interpreted to represent deposition within the lower to upper offshore transition zone. It is likely that F4 is a more proximal expression of F1 and F2 because grain size increases slightly; Facies 1 and 2 possess fine- and coarse-grained siltstone, whereas Facies 4 possesses fine siltstone to very fine-grained sandstone. Shell debris also indicates higher energy transport of allochthonous material. Trace fossil assemblages are the same as those in F1 and F2, which are characterized by *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites*; however, F4 is highly bioturbated (BI = 5-6 in F3; BI = 0-6 in F1 and F2). Trace fossils represent grazing/foraging, passive carnivore, and deposit-feeding strategies (Fig. 3.5). No vertical dwelling trace fossils are present. Facies 4 represents a low diversity expression of the *Cruziana* Ichnofacies (cf. MacEachern and Bann, 2008).

The bioclastic detritus within this facies has experienced some degree of post-depositional transport, due to the majority of shelly material being disarticulated, broken and abraded. The fossils preserved within F4 have been reported to originally inhabit a wide range of depositional environments. Triassic terebratulid brachiopods, cidaroid echinoids and isocrinid crinoids are typical of low-relief biostromes that occur in lower shoreface settings in the Middle Triassic Liard Formation (Zonneveld et al., 1997; Zonneveld, 2001). Spiriferid brachiopods are facies-crossing taxa, occurring in the proximal offshore, lower shoreface and upper shoreface in the Liard Formation (Zonneveld et al., 1997; Zonneveld, 2001). Lingulid brachiopods are common in a wide range of depositional settings from intertidal flats to the offshore (Zonneveld et al, 2007).

Facies 5 Description

Facies 5 (Fig. 3.8, Table 3.1) consists of a light grey, highly bioturbated fine-grained siltstone to very fine-grained sandstone. Physical sedimentary structures are faint and rare, but include horizontal planar-parallel-laminae and wavy-parallel-laminae, low- and high-angle planar cross laminae, penecontemporaneous deformation structures and asymmetric ripple laminae. Facies 5 is medium to light grey to blue grey in colour (Fig. 3.8A-D) or dark to medium grey (Fig. 3.8E-J), owing to the presence of phosphate material, including nodules, laminae and rip-up clasts. Contacts with overlying and underlying facies vary from gradational to sharp, and bioturbated beds can be decimetre- to metre-scale (Fig. 3.8I-J). Bioturbation intensity is high (BI = 4-6) and individual trace fossils are robust in size. The trace fossil assemblage is the most diverse of the succession and includes *Phycosiphon*, *Rosselia*, *Cylindrichnus, Asterosoma*, *Scolicia*, *Teichichnus*, *Palaeophycus*, *Planolites, Skolithos*, *Rhizocorallium* and *Diplocraterion* (Fig. 3.5). A dense ichnofabric of *Phycosiphon* is observed and lends to the salt-and-pepper appearance in the core (Fig. 3.8I). Bivalves, gastropods, brachiopods (lingulid, spiriferid and terebratulid), echinoderm and crinoids are present as articulated, disarticulated and broken shell debris. Generally, bioturbation and shell debris is most common at the base of the facies and decreases upward (Fig. 3.8I), however, bioturbation intensity can remain constant throughout the bed. Grain size can also decrease upward and F5 can gradually transition into the fine-grained siltstone characteristic of F1 and F2 (Fig. 3.5I). Transitions between facies may also be sharp (Fig. 3.5J). The base of F5 is most frequently observed as being sharp, and commonly exhibit *Glossifungites* Ichnofacies-demarcated discontinuity surfaces (Facies 6). Intervals of Facies 5 may reach 5 m thick, but can be as thin as 10 cm.

Facies 5 Interpretation

Facies 5 is interpreted to represent deposition within the upper offshore transition to lower shoreface. Low- and high-angle planar cross-laminae may be associated with low magnitude storm-wave processes, whereas parallel and wavy laminae are likely a product of current-generated processes under fair-weather conditions. Shell debris also infers sediment transport by higher velocity currents and transport of material at the sediment-water interface. Shell material is likely eroded from adjacent depositional environments.

Bioturbation includes a diverse suite of feeding strategies including deposit feeding (*Teichichnus, Asterosoma*, *Scolicia, Phycosiphon* and *Planolites*), detritus feeding (*Rosselia*), passive carnivory

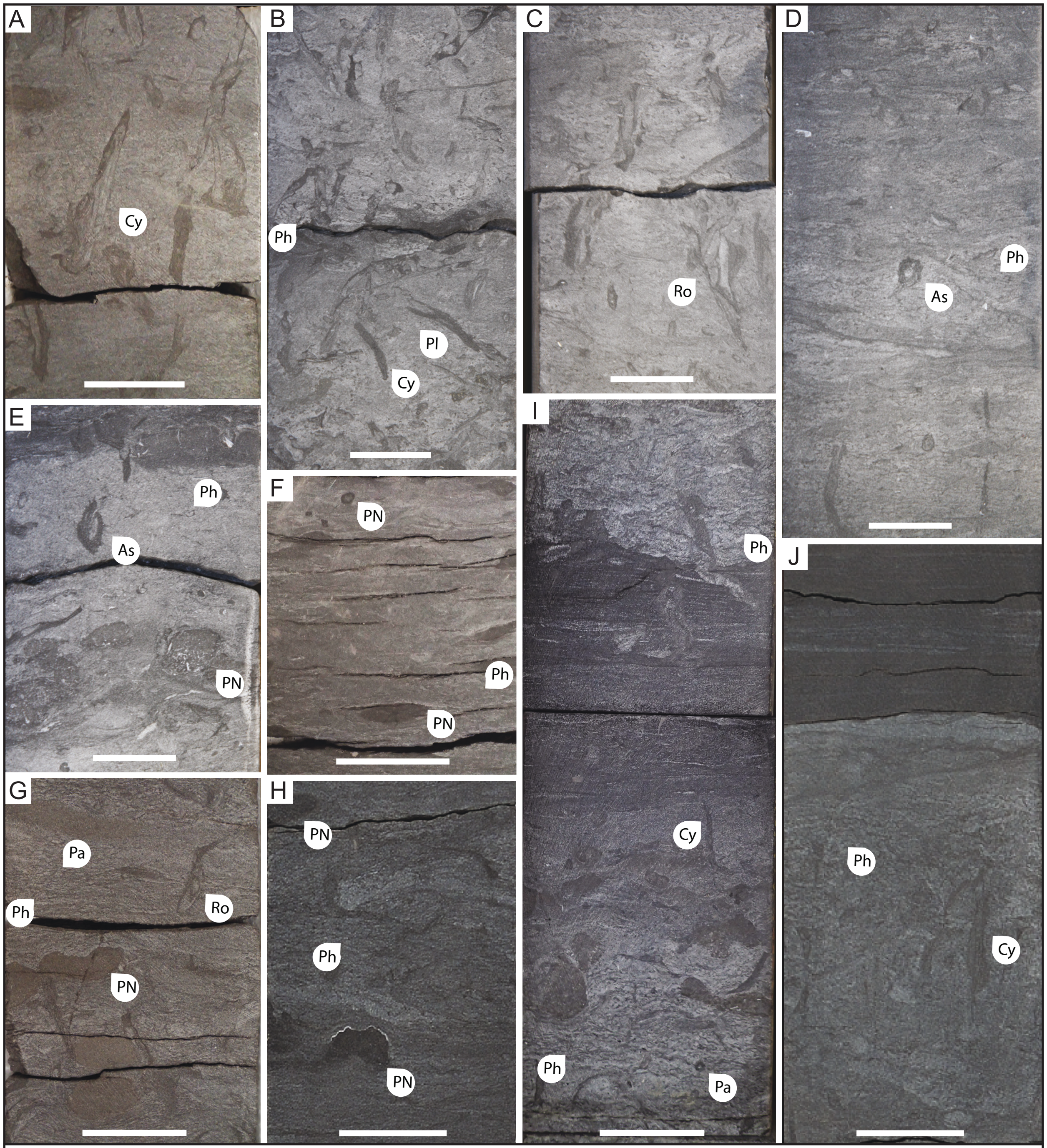


Figure 3.8–Core photographs of Facies 5 from the Sunset Prairie Formation. All scale bars are 3cm in length. All depths represent core depths. A-D. Pervasively bioturbated sandy siltstone with robust trace fossils (A. well 16-29-079-20W6; 2615.7 m; B. well c-33-C/94-B-09; 2187.6 m; C. well c-33-C/94-B-9; 2195.2 m; D. well c-33-C/94-B-09; 2195.9 m). E-G. Pervasively bioturbated sandy siltstone with robust trace fossils and phosphate nodules (PN). (E. well c-33-C/94-B-09; 2188.9 m; F. well 16-02-078-22W6; 3035.3 m; G. 16-29-079-20W6; 2621.9 m). H. Pervasively bioturbated, phosphatic-rich, sandy siltstone with robust trace fossils (well c-65-F/94-B-08; 2194.7 m). I. Facies 5 grading into Facies 1 overlain by a Glossifungites Ichnofacies (Facies 6) and Facies 5. Note the salt-and-pepper appearance of the dense *Phycosiphon* fabric at the base and top of the image (well 08-10-082-17W6; 1826.4 m). J. Facies 5 overlain by Facies 1, note the sharp contact between the two facies (well c-65-F/94-B-08; 2195.18 m). Trace fossils include As = *Asterosoma*, Cy = *Cylindrichnus*, Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites* and Ro = *Rosselia*.

(*Palaeophycus*), and suspension-feeding from vertical dwellings (*Cylindrichnus*, *Skolithos*, *Diplocraterion*) and deposit-feeding from dwellings (*Rhizocorallium*) (Fig. 3.5). Overall, F5 represents an expression of the archetypal *Cruziana* Ichnofacies, which is associated with fully marine, well-oxygenated settings characterized by lowered hydrodynamic energy and abundant marine food resources (Seilacher, 1967; MacEachern and Bann, 2008).

The diverse trace fossil assemblage and increased tiering (cross-crosscutting) of trace fossils suggest that the activities of organisms that inhabited the same ecospace, and were responding to different nutrients and food supplies within the environment, consistent with a relatively unstressed ecosystem (Bromley and Ekdale, 1986; Bromley 1990, 1996). *Asterosoma*, in particular, tend to be restricted to environments that are less prone to physico-chemical stresses (MacEachern et al., 2010), further supporting a relatively unstressed environment. However, phosphate grains, nodules and clasts present within parts of F5 suggest the presence of upwelling and/or of phosphatic-rich material being transported and deposited within the environment.

Similar to Facies 3 and 4, Facies 5 is pervasively bioturbated (BI = 5-6). The uniform distribution of ichnogenera and abundance of tiering/overprinting of softground trace fossils suggest that slow, continuous sedimentation occurred (Howard, 1975; Howard and Frey, 1984; MacEachern and Pemberton 1994). The trace fossil assemblage infers that a diverse array of feeding strategies were employed at the time of deposition and biogenic-modification of the substrate, consistent with multiple generations of organisms (e.g. juvenile vs. adult trace makers). This indicates that bioturbated intervals record ambient depositional conditions within the environment, and were not deposited as gravity-flows/tempestites that carried organisms into stressed environments (e.g., ‘doomed-pioneers’ of Föllmi and Grimm, 1990; Grimm and Föllmi, 1994).

Facies 6 Description

Facies 6 (Fig. 3.9A-E, Table 3.1) is a substrate controlled, burrowed firmground. Facies 6 commonly separates minimally bioturbated facies from overlying pervasively bioturbated facies. Trace fossils associated with F6 include firmground expressions of *Planolites*, *Skolithos*, *Thalassinoides* and *Rhizocorallium* (Fig. 3.5). Facies 6 is locally associated with F7 and commonly forms the base and/or top of the Sunset Prairie Formation (Figs. 3.9B). Burrowed surfaces also commonly occur internally within the Sunset Prairie Formation (Figs. 3.9A, 3.9C-E).

Facies 6 Interpretation

Facies 6 is interpreted to represent a trace fossils suite of the *Glossifungites* Ichnofacies, reflected by a burrowed firmground. Firmground assemblages are associated with depositional hiatuses

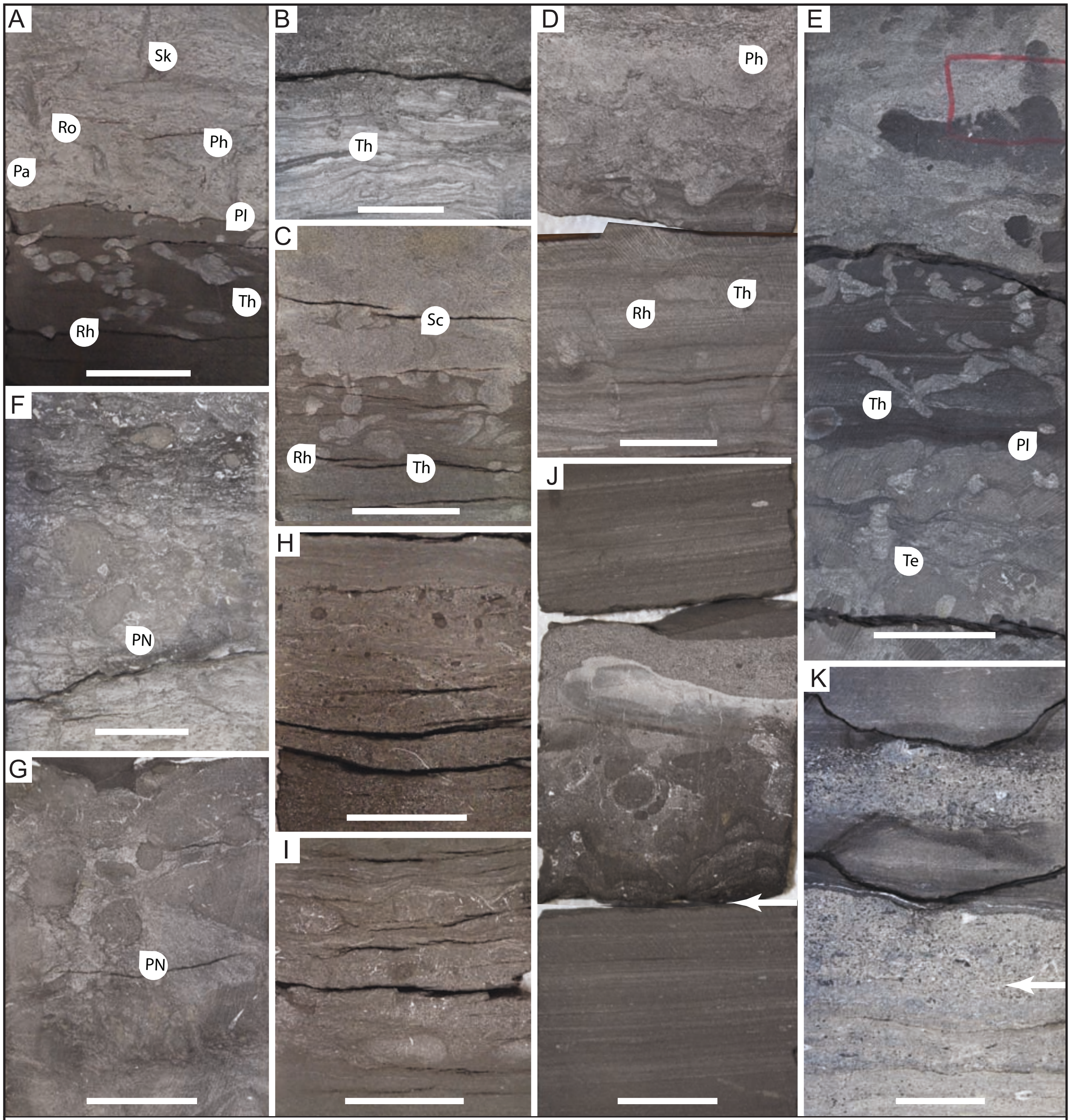


Figure 3.9–Core photographs of Facies 6 and 7 from the Sunset Prairie Formation. All scale bars are 3cm in length. All depths represent core depths. A. Facies 6, Glossifungites-demarcated discontinuity surface (well 16-29-079-20W6; 2622.1 m). B. Facies 6, Glossifungites-demarcated discontinuity surface located at the base of the Sunset Prairie Formation (well c-33-C/94-B-09; 2200.6 m). C-D. Facies 6, Glossifungites-demarcated discontinuity surface (C. well 16-29-079-20W6; 2627.1 m; D. well 16-17-083-25W6; 2256.9 m). E. Facies 5 grading into Facies 1 overlain by a Glossifungites Ichnofacies and Facies 5 (well 15-34-080-18W6; 2065.5 m). F. Facies 7, phosphate nodules (PN) and shell debris (well c-33-C/94-B-09; 2197.9 m). G. Facies 7, phosphate nodules (PN) (well 16-17-083-25W6; 2255.8 m). H. Facies 7, capping phosphatically rich sand and ooids (well 16-02-078-22W6; 3055.5 m). I. Facies 7, phosphate nodules within Facies 1 (well 16-02-078-22W6; 3055.9 m). J-K. Contact between the Sunset Prairie Formation and the overlying Doig phosphate zone; the contact is denoted with an arrow (J. well 16-17-083-25W6; 2245.3 m K. well c-33-C/94-B-09; 2186.5 m). Trace fossils include Cy = *Cylindrichnus*, Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Rh = *Rhizocorallium*, Sc = *Scolicia*, Sk = *Skolithos*, Te = *Teichichnus* and Th = *Thalassinoides*.

between the erosionally exhumed (dewatered and compacted) substrate and the sediment overlying the unit, and therefore correspond to erosional discontinuities (Bromley, 1975; Pemberton and Frey, 1985; MacEachern et al., 1992). Substrate-controlled suites of trace fossils are commonly associated with erosional features including phosphatic sand and granule lags (Zonneveld et al., 2012; Christ et al., 2012; Schwarz and Buatois, 2012; Schultz et al., 2016).

Omission suites of the *Glossifungites* Ichnofacies are frequently associated with marine flooding surfaces (parasequence boundaries) and transgressive erosional events (transgressive surfaces of erosion) (MacEachern et al., 1992; cf. MacEachern et al., 2012b for a summary). Although *Glossifungites* Ichnofacies-demarcated discontinuity surfaces can be present at the top and base of the Sunset Prairie Formation, burrowed firmgrounds can be localized. Many omission suites of the *Glossifungites* Ichnofacies occur intraformationally (Furlong, 2018a, fig. 5-7), suggesting that not all occurrences are associated with regionally significant sequence stratigraphic boundaries, but may, instead, be associated with fluxes in palaeoenvironmental conditions (e.g. sediment, nutrients, oxygen supply) or other allogenic processes.

Facies 7 Description

Facies 7 (Fig. 3.9F-K, Table 3.1) consists of a variety of poorly sorted, medium-grained pebble conglomerate that is concentrated in thin beds (<5 cm thick) directly overlying erosional surfaces. Sediment within F7 consists of moderately well-rounded sand to gravel, phosphate nodules, phosphate ooids and rip-up clasts. The conglomerate occurs as both matrix supported or clasts supported. Shell fragments and fossilized/mineralized bone fragments are also commonly present. Facies 7 is locally associated with F6. The base and top of the Sunset Prairie Formation is commonly marked by F6 and/or F7 (Fig. 3.9B, 3.9J, 3.9K).

Facies 7 Interpretation

Facies 7 is interpreted to represent lag deposits. Material is abraded, broken and well rounded, which suggests that material has been eroded and transported. Phosphate material within the lag deposits is similar to phosphate material within other phosphatically rich facies, and contains phosphatic silt, sand, and nodules. The conglomeratic lag deposit is concentrated at the bases of parasequences and represents erosion occurring during transgression.

DISCUSSION

Facies Model

The Sunset Prairie Formation is interpreted to represent deposition within an intermittently storm influenced siliciclastic ramp. Preserved facies reflect depositional environments associated with the offshore, offshore transition and lower shoreface, with offshore transition and lower shoreface deposits being most commonly observed (Fig. 3.2). Upper shoreface and more proximal depositional environments have been erosionally removed and are not observed in core. Storm-generated sedimentary structures, including hummocky cross stratification are not commonly observed within the Sunset Prairie Formation. The paucity of storm-generated deposits throughout the Sunset Prairie Formation suggests that storms were either uncommon during the deposition of the regionally expansive formation, which is deemed unlikely, or that that storm deposits were biogenically homogenized by burrowing organisms. Wave-dominated deposits, when protected from storm erosion, possess high trace fossil diversity, with uniform and elevated high bioturbation intensities (Howard and Reineck, 1981; MacEachern and Pemberton, 1992; Raychaudhuri et al., 1992; Gani et al., 2007). Additionally, the uniformity and abundance of softground trace fossils suggest that slow, continuous sedimentation rates occurred (Howard, 1975). The diverse benthic community supports the interpretation that the bioturbated zones occurred in fully marine, well-oxygenated environments, and had ample supply of nutrients. Fluctuations in environmental conditions, however, may have been responsible for the minimally burrowed intervals (Facies 1 and 2), making the setting unfavorable or uninhabitable for marine organisms.

Similar low storm-energy siliciclastic ramp settings have been described from the Viking Formation in Alberta (e.g., Raychaudhuri et al., 1992; MacEachern and Pemberton, 1992; MacEachern, 1994). Within the Giroux Lake succession of the Viking Formation, the diverse ichnogenera assemblage, intensely bioturbated fabric, and uniform distribution of trace fossils suggests a fully marine, unstressed environment with slow, generally continuous sedimentation rates. The general paucity of storm wave-generated sedimentary structures indicates that storms were uncommon and low intensity, allowing for infaunal organisms to biogenically homogenize the sediment.

Occurrence of Phosphate

Phosphate material occurs within offshore, offshore transition and lower shoreface deposits (F1, F3 and F5) and is commonly associated with *Glossifungites* Ichnofacies-demarcated surfaces (F6) and lag deposits (F7). Phosphate-rich material includes phosphatic silt, very fine-grained sand, ooids, nodules, rip-up clasts and phosphate-rich laminae/lenses (Table 3.1). Phosphate material generally increases in clast size moving more proximally from F1 through F3 and into F5, but phosphate nodules (< 2.5 cm in diameter) are present within all three facies.

Phosphatization is commonly associated with shallow-marine settings influenced by nutrient rich, upwelling water (e.g. Burnett, 1977; Burnett et al., 1982; Frohlich, 2004). Modern settings of phosphate formation include areas of intense coastal upwelling along the coasts of Mexico, Peru and Namibia (e.g. Manheim et al 1975; Burnett et al., 1982; Krom and Berner, 1981; Jahnke et al., 1983; Thomson et al., 1984; Baturin, 2000). In general, phosphate formation (phosphogenesis) likely involves the release of elemental phosphorous through the bacterial break-down of organic material and leads to the subsequent precipitation of apatite in anoxic pore waters (Veeh et al., 1973; Manheim et al 1975; Burnett, 1977; Jahnke et al., 1983; Thomson et al., 1984; Froelich et al., 1988; Baturin, 2000; Hiatt and Budd, 2001). This depositional interpretation is most plausible for the formation of F1 within the Sunset Prairie Formation; however, phosphate is also observed in zones that are intensely bioturbated (F3 and F5), insinuating that bottom water conditions were oxygenated, while pore waters were anoxic. Within F3 and F5, phosphate commonly occurs as rip-up clasts and were likely transported before being deposited. Some clasts are even bored (Fig. 3.9E), suggesting that the clasts were fully lithified, eroded, subsequently bored, transported and then deposited. Phosphate nodules are also found within bioturbated facies and suggest *in situ* phosphate production within a well-oxygenated depositional environment. Microbial mediated phosphate production can occur within oxic conditions and may be the catalyst for the phosphate nodules within these facies (e.g. Reimers et al., 1990; Kouchinsky et al., 1999; Schulz and Schulz, 2005; Bailey et al., 2007; Barale et al., 2013; Lepland et al., 2013).

Phosphate deposits can occur in non-upwelling environments associated with continental sourcing and weathering (Summerhayes et al., 1972; Southgate, 1986; Ruttenberg and Berner, 1993) and volcanic input (Sturesson et al., 2000). Such continental sources may have increased elemental phosphorous within the water column, producing algal blooms, a stratified water column and redox conditions suitable for the formation of phosphate.

Despite the specific mode of deposition of phosphate, strong bottom water currents are needed to mechanically remobilize and transport pre-existing phosphate particles, and “resting periods” are necessary to chemically concentrate and precipitate phosphate (e.g. Glen et al., 1994; Föllmi, 1996; Baturin, 1999; Dornbos et al., 2006; Föllmi et al., 2007; Dickinson and Wallace, 2009). More research is needed to fully understand the depositional implications of phosphate occurrence within the Sunset Prairie Formation.

The Sunset Prairie Formation thickens to the west and is present mainly in the subsurface of British Columbia (Figs. 3.3, 3.10). The thickest preserved interval occurs within the Hudson Hope Low (*sensu* Barclay et al., 1990). Around the Alberta-British Columbia border, the formation is absent, and was either not deposited or was subsequently eroded before the Doig Formation was transgressively deposited on top of the Sunset Prairie Formation.

The internal stratigraphic architecture of the Sunset Prairie Formation is depicted in Figure 3.10. One to three parasequences may be preserved within a given area (Figs. 3.2, 3.3, 3.10; Furlong, 2018a, fig. 5-7) due to structural influences on both sediment accumulation and preservation. Each parasequence represents a progradational package (shoaling-upward cycle), comprising of deposits associated with offshore, offshore transition and lower shoreface settings. Parasequences generally coarsen upward in grain size from fine-grained silt to fine-grained sand, and bioturbation increases upwards (Fig. 3.2). Locally, however, interbedding between pervasively bioturbated and minimally bioturbated facies do occur within the parasequences and some beds exhibit normal grading, which are observed when pervasively bioturbated facies gradually transition into minimally bioturbated facies (Fig 3.8I). Most flooding surfaces are marked by conglomerate lag deposits (F7), are commonly rich in phosphatic material, and may possess rip-up clasts. Overall, the parasequences exhibit a retrogradational stacking pattern (Fig. 3.2), suggesting transgression. The relative sea level rise was likely a result of accommodation space being produced by tectonism subsidence. This is best exemplified within the Fort St. John graben system (Fig. 3.10C).

The Sunset Prairie Formation is bound by unconformities at its top and base. The unconformities are marked by *Glossifungites* Ichnofacies-demarcated discontinuity surface (F6) and/or conglomerate lag deposits (F7). These surfaces are interpreted as flooding surface/sequence boundaries (FS/SB), and represent a coplanar sequence boundary and transgressive surface of erosion.

ICHNOLOGICAL TRENDS IN THE LOWER AND MIDDLE TRIASSIC OF THE WESTERN CANADA SEDIMENTARY BASIN

Trace fossil suites within the Lower Triassic of the Western Canada Sedimentary Basin have been generally characterized as simple, low-diversity, and of low-abundance, which is followed by an increase in relative marine ichnofaunal diversity within the Middle Triassic (Zonneveld, 2011, fig. 1A). It has also been suggested that following the end-Permian mass extinction, infaunal recovery occurred more rapidly in high-palaeolatitude regions as compared to low-palaeolatitude

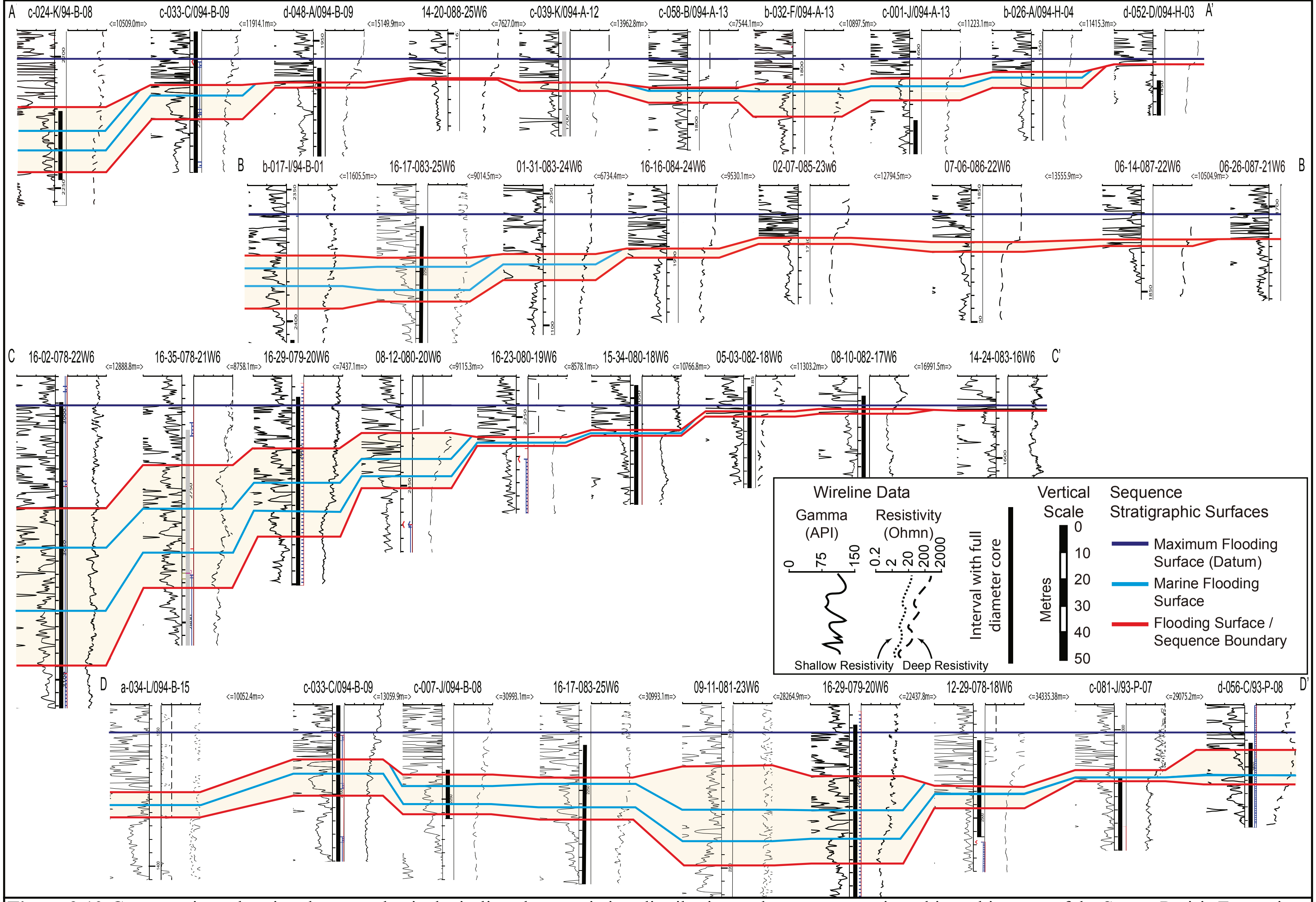


Figure 3.10-Cross sections showing the petrophysical wireline characteristics, distribution and sequence stratigraphic architecture of the Sunset Prairie Formation. Cross section locations identified in the total thickness isopach in Figure 3.3. Datum is the maximum flooding surface at the top of the Doig phosphate zone.

regions (MacNaughton and Zonneveld, 2010).

Trace fossil assemblages from the Lower Triassic Montney Formation and its outcrop equivalents (Toad, Sulphur Mountain and Grayling Formations) have been observed to possess low (0-2 taxa) to high (>10 taxa) diversity, but in general, bioturbation intensities are low (Beatty et al., 2008; MacNaughton and Zonneveld, 2010; Zonneveld et al., 2010a; Wood, 2012). High-diversity assemblages that have been identified are interpreted to be associated with environmental refugia, where oxygenated water was present within the shallow-marine realm and produce oases for infaunal organisms (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b). High diversity assemblages occur in the Pedigree-Ring-Kahntah area (Zonneveld et al., 2010a), La Biche River map area (Toad Formation) (MacNaughton and Zonneveld, 2010), Swan field (Zonneveld, personal observation), and Kakwa and Karr fields (Davies et al., 2018). Trace fossils are rare in offshore and proximal (upper shoreface and foreshore) settings, but are abundant within the offshore-transition and lower shoreface (Beatty et al., 2008; MacNaughton and Zonneveld, 2010; Zonneveld et al., 2010a). Highest diversities and bioturbation intensities within the lower shoreface suggests biotic distributions were limited by both wave-stressed proximal settings and oxygen-stressed distal settings, leading to a narrow habitable zone for biotic colonization (Beatty et al., 2008).

Similar to the Montney Formation, bioturbation in the Sunset Prairie Formation is rare within offshore deposits, whereas the offshore transition and lower shoreface exhibit diverse trace fossil assemblages. The intensely bioturbated intervals exhibit a high diversity of trace fossils, as well as large, robust trace fossils, which do not occur within the Lower Triassic of western Canada. The upper shoreface and foreshore are not preserved within the Sunset Prairie Formation, so that ichnological trend cannot be compared. Unlike the Montney Formation, the Sunset Prairie Formation contains intervals with highly bioturbated facies present across regionally expansive areas (Fig. 3.3). Diverse ichnological assemblages in the Montney Formation (Zonneveld et al., 2010a; MacNaughton and Zonneveld, 2010) are local expressions of diverse biological refugia, whereas during deposition of the Sunset Prairie Formation, environmental conditions that were favourable for widespread infaunal colonization, multi-generational settlement, and complex tiering of trace-making organisms employing diverse feeding strategies (Fig. 3.5).

Middle and Upper Triassic successions in the Western Canada Sedimentary Basin (Zonneveld et al., 1997, 2001, 2002, 2004; Zonneveld, 1999, 2001) show similar ichnological features and trace fossil distribution to most Cretaceous ramp to present-day ramp and shelf settings, with bioturbation being most intense and diverse within the offshore transition to distal lower shoreface (Howard and Reineck, 1972; Reineck and Singh, 1975; Howard and Frey, 1984; Moslow and Pemberton, 1988; Vossler and Pemberton, 1989; Pemberton et al., 2012). The Liard Formation (equivalent to the Doig and Halfway Formations) exhibits intervals with an array of trace fossil assemblages showing both low and high diversities across a wide range of depositional environments, including offshore through shoreface successions, bioclastic mounds, lagoons and intertidal settings (Zonneveld, 1999). Although ichnological diversity trends remain consistent across offshore to onshore settings throughout the Lower, Middle and Upper Triassic, the Sunset Prairie Formation is the stratigraphically oldest, pervasively bioturbated regionally expansive interval within the Triassic of the Western Canada Sedimentary Basin. This occurrence suggests that widespread ecosystem recovery after the end-Permian mass extinction started during the lowermost Middle Triassic and continued through the Middle and Upper Triassic.

CONCLUSIONS

The Middle Triassic Sunset Prairie Formation is a regionally extensive, unconformity-bound unit that erosively overlies the Lower Triassic Montney Formation and is erosively overlain by the Doig phosphate zone within northeastern British Columbia. Seven distinct facies are identified and described within the formation, and have been interpreted to represent depositional environments within the offshore, offshore transition and lower shoreface settings, with minimal preserved evidence of high-magnitude storm-wave processes. More proximal depositional environments, such as the upper shoreface and foreshore, have been erosionally removed and are not observed in core. The unconformity-bound unit exhibits transgressively modified sequence boundaries at its top and base, and internal geometries of the facies stacking suggest retrogradational parasequences.

The Sunset Prairie Formation is characterized by pervasively bioturbated strata interbedded with minimally bioturbated strata. Trace fossils present within the interval include abundant *Phycosiphon*, *Rosselia, Cylindrichnus*, *Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. Trace fossils are indicative of the *Cruziana* Ichnofacies. *Glossifungites* Ichnofacies-demarcated discontinuity surfaces are also present throughout the interval and are commonly associated with the top and base of the formation. Similar to other highly bioturbated intervals within Montney and Doig Formations, bioturbation is concentrated within the offshore transition to lower shoreface. The Sunset Prairie Formation is a regional, intensively bioturbated succession, which contrasts to the locally limited, diverse assemblages described from the Montney Formation (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b). The Sunset Prairie Formation has been overgeneralized and overlooked until recently, but it can provide important insights into the dynamic shallow-marine realm associated with the infaunal biotic recovery after the end-Permian extinction within the Western Canada Sedimentary Basin.

CHAPTER 4: HIGH-RESOLUTION SEQUENCE STRATIGRAPHY OF THE MIDDLE TRIASSIC SUNSET PRAIRIE FORMATION, WESTERN CANADA SEDIMENTARY BASIN, NORTHEASTERN BRITISH COLUMBIA

INTRODUCTION

The Middle Triassic Sunset Prairie Formation occurs in the subsurface of British Columbia within the Western Canada Sedimentary Basin. The Sunset Prairie Formation is a newly described stratal unit, which sits stratigraphically between the Lower Triassic Montney Formation and the Middle Triassic Doig Formation (Furlong et al., 2018a), and has previously been informally referred to as the 'Anisian Wedge' prior to its formal lithostratigraphic affiliation (Zonneveld and Moslow, 2015; Zonneveld et al., 2015, 2016; Furlong et al., 2016b; 2017; Davies et al., 2018). The interval consists of interbedded light gray, pervasively bioturbated sandstone and dark gray, diminutively bioturbated siltstone beds that are sedimentologically, ichnologically, and palaeontologically discrete than the underlying and overlying unit (Furlong et al., 2018a, 2018b).

A number of studies have investigated the sedimentology, stratigraphy and sequence stratigraphy of the Montney and Doig formations (e.g. Davies et al., 1997; Embry, 1997; Golding et al., 2014b; Crombez et al., 2016, 2017; Davies et al., 2018; Proverbs et al., 2018). The Sunset Prairie Formation, however, was not recognized by these studies, and the interval was either included in the Montney or Doig Formations (Doig phosphate zone), or straddled the two formations. More recent publications have acknowledged the presence of the Sunset Prairie Formation (e.g., Davies et al., 2018; Euzen et al., 2018; Moslow et al., 2018; Zonneveld and Moslow, 2018), but little work has been done to integrate the interval into the overall Triassic sequence stratigraphic framework. A revised stratigraphic framework is needed to better understand the transition between the Montney, Sunset Prairie and Doig Formations.

The objectives of this study include: 1) providing an overview of the lithofacies and facies associations present in the Sunset Prairie Formation; 2) describing facies distributions and lateral variability; 3) defining a sequence stratigraphic framework internal to the Sunset Prairie Formation; and 4) interpreting a sequence stratigraphic relationship between the Montney, Sunset Prairie and Doig Formations. Through this investigation, a better understanding can be made regarding the depositional models, stratigraphy, and basin evolution that occurred in Western Canada during the Lower to Middle Triassic.

GEOLOGICAL SETTING

Lithostratigraphic Framework

The Western Canada Sedimentary Basin consists of a westward-thickening wedge of Phanerozoic strata above the Precambrian crystalline basement (Mossop and Shetsen, 1994). Triassic subsurface strata of the Western Canada Sedimentary Basin consist of the Lower Triassic Montney Formation, the Middle Triassic Sunset Prairie, Doig and Halfway Formations, and the Upper Triassic Charlie Lake, Baldonnel, Pardonet and Bocock Formations (Fig. 4.1) (Clarke, 1957; Hunt and Ratcliffe, 1959; Armitage, 1962; Furlong et al., 2018a). Throughout Alberta and British Columbia, Triassic strata sit unconformably above Permian or Carboniferous strata and are unconformably overlain by Jurassic or Lower Cretaceous deposits (Edwards et al., 1994).

Stratigraphic nomenclatural discrepancies occur between Alberta and British Columbia for the Montney and Doig Formations (Playter et al., 2018; Zonneveld and Moslow, 2018). Herein, the authors refer to the Montney Formation from a British Columbian perspective. Therefore, the "Montney Formation" as used in this paper, includes intervals referred to as both the Montney Formation and Basal Doig Siltstone within the Albertan stratigraphic nomenclature.

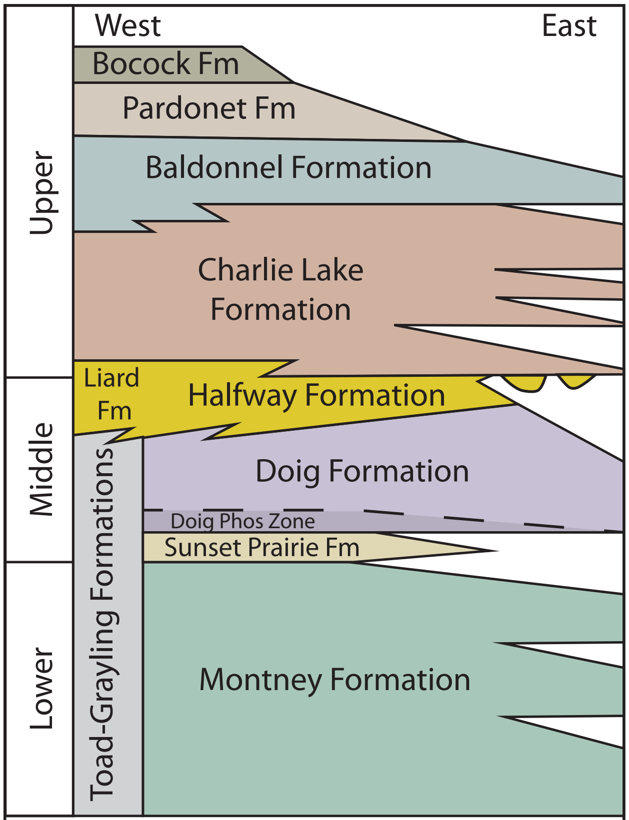


Figure 4.1–Lithostratigraphic nomenclature of the Triassic of the Western Canada Sedimentary Basin. Modified from Dixon (2011).

Palaeoenvironmental Setting

By the end of the Permian, the supercontinent of Pangea had formed from the amalgamation of the world's major landmasses (Ziegler, 1988; Lawyer et al., 2002, 2011). On the western margin of Pangea, Triassic sediments were deposited within a large, central sub-basin, called the Peace River Embayment, and consisted of marine and marginal-marine siliciclastic and carbonate sediment, and lesser volumes of evaporite deposits (Fig. 4.2) (Douglas, 1970; Barclay et al., 1990; O'Connell

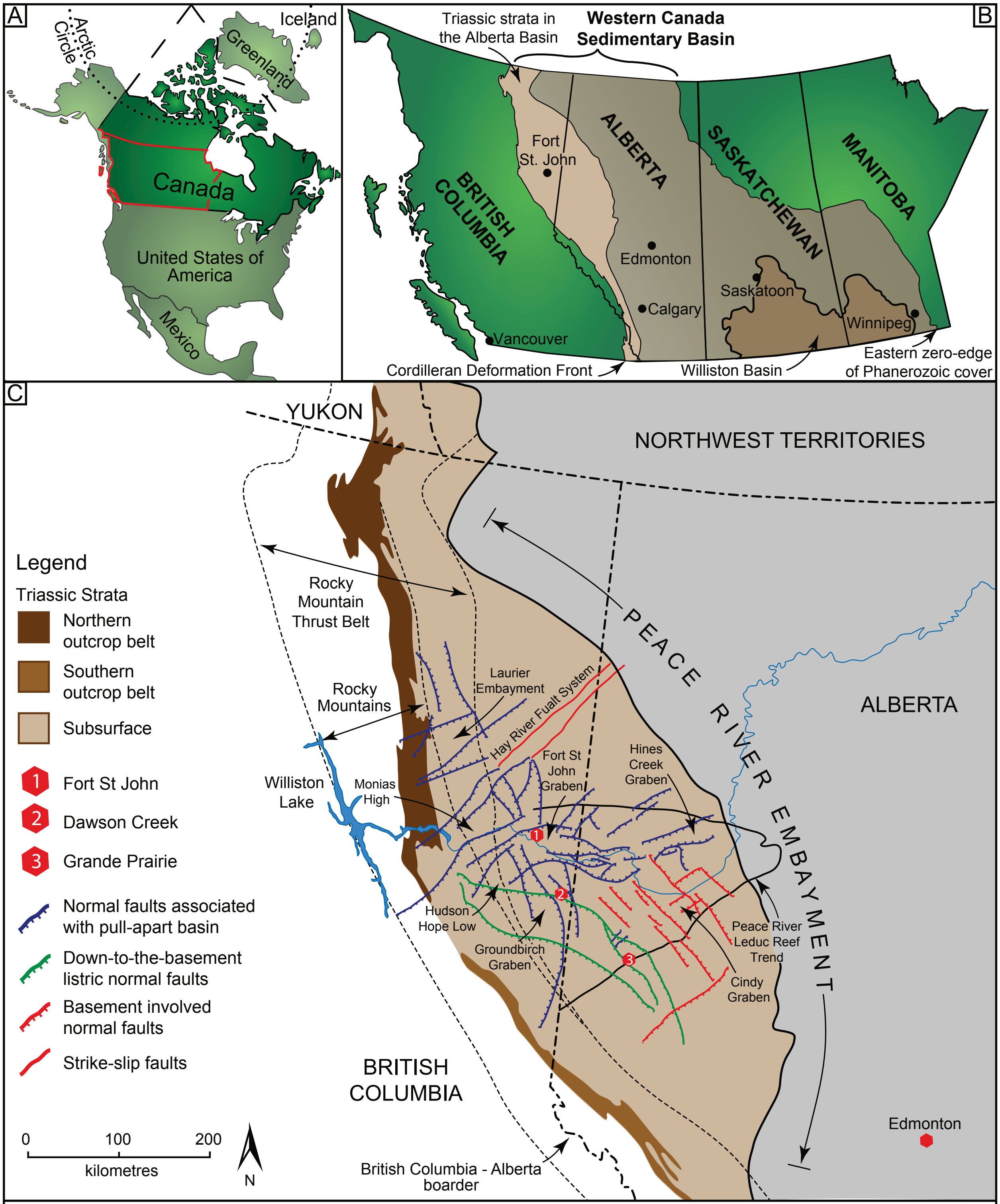


Figure 4.2–Location maps of the Western Canada Sedimentary Basin. A. Map of North America. Area enlarged in B is outlined in red. B. Map of Western Canada Sedimentary Basin (dark brown) and limits of Triassic strata (light brown) in British Columbia, Alberta, Saskatchewan and Manitoba. Modified Edwards et al. (1994). C. Regional map of British Columbia and Alberta showing the extent of Triassic strata in the Western Canada Sedimentary Basin (modified from Zonneveld et al., 2011). Major structural features that influence Lower and Middle Triassic strata are identified and were compiled from previously published studies and maps (Barclay et al., 1990; Davies, 1997a, 1997b; Davies et al., 1997; Berger, 2005; Berger et al., 2009).

et al., 1990; Edwards et al., 1994; Evoy and Moslow, 1995). These deposits accumulated under arid, mid-latitudinal (~32-34^{O}N) conditions (Wilson et al., 1991; Davies, 1997a; Davies et al., 1997; Dixon, 2000; Moslow, 2000; Golonka, 2007; Zonneveld and Moslow, 2018). During this time, Canada was rotated approximately 30^{O} clockwise from its current orientation and the regional shoreline approximately parallels the axis of the modern-day Rocky Mountains (Golonka et al., 1994; Davies, 1997a, 1997b; Golonka and Ford, 2000).

Many have suggested that the Triassic of Canada represents an arid coastline, mainly through evidence of aeolian dunes, regionally extensive anhydrite beds and solution-collapse breccia (resulting from evaporite dissolution) associated with latest Middle and early Upper Triassic marginal marine and non-marine strata (Gibson and Barclay, 1989; Zonneveld et al., 1997; Zonneveld, 2001). Although minimal direct evidence has been presented on the palaeoclimate of Lower to early Middle Triassic strata, palynology (e.g., taeniate bisaccate and polyplicate palynomorphs; Utting, 2001; Utting et al., 2005; Zonneveld et al., 2010b) and mineralogy (abundance of detrital dolomite, low clay proportions and reworked anhydrite nodules; Davies et al., 1997) are consistent with arid conditions. Palaeoshoreline reconstructions and coastal facies distributions are difficult to determine during the Lower and early Middle Triassic, owing to the presence of unconformities between many of the formations that cannibalized marginal marine and terrestrial deposits.

Tectonic Setting

Multiple structural features should be taken into consideration when trying to resolve depositional dynamics of Triassic strata in the Western Canada Sedimentary Basin. Prior to the Triassic, the Peace River Arch was a basement-uplifted topographic high, which persisted from the Precambrian to Devonian and greatly controlled deposition and its preservation (deMille, 1958; Cant, 1988; Stephenson et al., 1989; Barclay et al., 1990; O'Connell et al., 1990). During the Carboniferous, the Peace River Arch began to subside and collapse, which eventually formed the Dawson Creek Graben Complex (Barclay et al., 1990; Gibson and Edwards, 1990; O'Connell et al., 1990). The graben complex consists of three major elements, which comprise of the Fort St. John Graben, the Hudson Hope Low, and a number of smaller satellite grabens (Hines Creek, Whitelaw, and Cindy Grabens) (Barclay et al., 1990; O'Connell, 1994). These features formed a system of high-angle normal faults that subsided due to syndepositional and post-depositional growth-type block faulting (Barclay et al., 1990; Edwards et al., 1994). Subsidence associated with the Peace River Arch and Dawson Creek Graben Complex significantly influenced deposition of Carboniferous, Permian, and Triassic strata, and this region ultimately became the main sediment depocentre within the Peace River Embayment (Cant, 1988; Barclay et al., 1990; O'Connell, 1990; Wittenberg, 1992, 1993; Qi, 1995; Davies, 1997a). Other structural features influencing Triassic deposition include: the Hay River Fault Zone, Laurier Embayment, Monias High, Beaton High, Grassy High, Sukunka Uplift, and faulting associated with Devonian reef trends (Leduc Reef and Swan Hills Reef) (e.g. Richards, 1989; Davies and Majid, 1993; Henderson et al., 1994; Davies, 1997a, 1997b).

Traditionally, the northwestern margin of Pangea during the Cambrian to the Late Triassic has been considered to be a tectonically stable, passive margin with a single northeastern-derived sediment source (Dickinson, 1977; Monger and Price, 1979; Coney et al., 1980; Gibson and Barclay, 1989; Price 1994; Davies; 1997a). A passive margin would have fostered the development of a marine ramp/shelf setting (Edwards et al., 1994; Dixon, 2009a; 2009b, Onoue et al., 2016). Subduction and collision of island arcs have been suggested to have occurred in the Panthalassic Ocean, offshore of the margin of Pangea, with terrane accretion occurring only during the late Jurassic and early Cretaceous; thus, suggesting that the Triassic margin was passive (Gibson and Barclay, 1989; Davies, 1997a). Multidisciplinary evidence, including stratigraphic architecture, geochemical models, and zircon dating suggests, however, that basin evolution, margin development, and sediment provenance are more complex than previously interpreted (e.g. Ferri and Zonneveld, 2008; Berenak et al., 2010; Golding et al., 2016; Rohais et al., 2016; Morris et al., 2018). Terrane accretion likely occurred as early as the Early Triassic (Beranek and Mortensen, 2011; Golding et al., 2016; Zonneveld and Moslow, 2018; Rohais, et al., 2018). These terranes would have provided a minor, but significant, source of sediment to the Peace River Embayment, in addition to the primary sediment source from the Laurentian craton to the east (Ferri and Zonneveld, 2008; Berenak et al., 2010; Golding et al., 2016; Morris et al., 2018). Geodynamic settings and palaeogeographic reconstructions along an active margin have led to multiple hypothesized basin models for Triassic deposition, and include a back-arc-basin (Ferri and Zonneveld, 2008; Miall and Blakey, 2008; Zonneveld et al, 2010a; Schiarizza, 2013; Morris et al., 2014; 2018), fore-arc-basin (Nelson et al., 2006; Colpron et al., 2007; Rohais et al., 2016) and early foreland basin (Golding et al., 2016; Rohais et al., 2018; Zonneveld and Moslow, 2018). The evolution of Early Triassic basin architecture in Western Canada and its implications on depositional processes, palaeoenvironmental dynamics, and oceanic circulation remain in a state of debate.

SEQUENCE STRATIGRAPHY: GENERAL CONCEPTS

Sequence stratigraphy represents a markedly different approach than lithostratigraphy. Lithostratigraphic units are mappable intervals of rocks that share similar sedimentary characteristics, where facies are correlated and boundaries between units typically represent highly diachronous contacts (Hedberg, 1976). Sequence stratigraphy is the study of cyclic sedimentation patterns that have developed in response to variations in accommodation and sedimentation conditions (Catuneanu, 2019). A relative chronostratigraphic relationship can be interpreted from the relationship between coeval stratal units and bounding surfaces, in that strata lying above the discontinuity are younger than strata lying below it (Catuneanu, 2006). The Sunset Prairie Formation is an unconformity-bound lithostratigraphic formation; however, a sequence stratigraphic framework internal to the formation can be established.

This study predominantly utilizes the Exxon models of depositional cycles defined on the basis of bounding subaerial unconformities and their correlative conformities (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagner et al., 1988, 1990). Stratigraphic geometries and stratal pattern relationships within the Exxon model were based on the hypothesis of eustatic controls producing systems tracts (Posamentier et al., 1988; Posamentier and Vail, 1988). For the past few decades, however, it has been increasingly recognized that sequence stratigraphic architectures are a result of 'relative sea level,' which is a blend of eustasy, tectonism, and climate forcing functions that affect base level and therefore, accommodation space (Hunt and Tucker, 1992; Posamentier and James, 1993; Posamentier and Allen, 1999; Catuneanu, 2006; Cataneanu et al., 2009). Within the Peace River Basin, it has been suggested that there was a strong tectonic influence resulting in fault reactivation, which overprinted the higher-order eustatic signature (Embry, 1997; Kendall, 1999).

Due to the fact that sequence stratigraphic terminology is ever evolving, a brief summary of terms and concepts is outlined here. A 'sequence' is a package of genetically related strata that are bound by regionally extensive subaerial unconformities and their correlative conformities (Sloss, 1963; Mitchum, 1977). A sequence is the fundamental stratal unit of sequence stratigraphy and corresponds to depositional processes and products recording a full cycle of base-level change (Catuneanu, 2006; Cataneanu et al., 2009). Sequences are subdivided into systems tracts, which are defined by the types of bounding surfaces, origin of bounding surfaces, their position within a sequence, and the stacking pattern of parasequences and parasequence sets (e.g., Van Wagoner et al., 1988; Posamentier and Allen, 1999; Catuneanu, 2019). Parasequences are genetically related beds or bedsets recording progradational regression that have classically been described to be bound by marine flooding surfaces produced by an abrupt increase in water depth (Van Wagoner et al, 1988, 1990; Posamentier and Allen, 1999). The concept of a parasequence has been deemed obsolete by some (e.g., Catuneau, 2019) based on the inconsistency, ambiguity and confusion surrounding the identification and formation of flooding surfaces produced in different depositional settings. Transgression is required at the basal surface of a parasequence and it is likely that a thin transgressive package (likely <1 m thick) would be deposited at the base, which is then followed by regressive deposits, suggesting that parasequences consist of small-scale transgressive-regressive cycles with identifiable internal maximum flooding surface and maximum regressive surface. Such small-scale (metre-scale) features, however, are difficult to reliably map using petrophysical datasets. Therefore, the authors have decided to remain using the concept of parasequences within this study to represent packages of strata that overall record progradational deposition, but may also exhibit thin transgressive deposits at its base associated with an abrupt increase in relative sea level. Genetically related parasequences can be grouped into parasequence sets, which form distinctive stacking patterns, bound by major marine flooding surfaces (Van Wagoner et al., 1988; Posamentier and Allen, 1999). The distinct stacking patterns of parasequences and parasequence sets designate subdivisions within each sequence and are described as the lowstand-, transgressive-, highstand- and falling-stage systems tracts (Brown and Fisher, 1977; Van Wagoner et al., 1988; Catuneanu, 2006; Catuneanu et al., 2011). Three different sequence stratigraphic models have described the interplay between systems tracts and the timing of sequence boundaries (i.e. Depositional Sequence, Genetic Sequence and Transgressive-Regressive Sequence). A thorough description and discussion of the models are outlined by Catuneanu (2006, 2019) and Catuneanu et al. (2009, 2011).

STUDY AREA AND DATASET

This investigation of the Sunset Prairie Formation was undertaken on a regional scale within the Western Canada Sedimentary Basin. Stratigraphic correlations between drill cores were produced using geophysical well log data using GeoScout. A total of 248 wells were used to determine the stratigraphic architecture and distribution of the Sunset Prairie Formation. Geophysical data were supplemented with slabbed core from 25 wells. Core were logged and described for sedimentological, ichnological and palaeontological characteristics. Detailed observations of lithology, grain size, nature of contacts, physical sedimentary structures, biogenic sedimentary structures and body fossils were recorded for each core. Bioturbation intensity was quantified using bioturbation index (BI), which ranges from non-bioturbated (BI = 0) to pervasively bioturbated/completely biogenically homogenized (BI = 6) (Reineck, 1963, 1967; Taylor and Goldring, 1993). Trace fossils were identified down to the ichnogenus level and ichnofacies associations (*sensu* Seilacher, 1967; MacEachern et al., 2012a) were interpreted for the different bioturbated facies. Core characteristics were categorized into facies and combined into recurring facies associations to interpret their depositional settings. A thorough investigation of facies within the Sunset Prairie Formation and their interpreted depositional palaeoenvironments has been described by Furlong et al. (2018b).

Stratigraphic relationships within the Sunset Prairie Formation were established through the evaluation and interpretation of facies distribution and stacking patterns. Parasequences and sequence stratigraphic surfaces were interpreted in core and tied to geophysical well data. These surfaces were then correlated between cored wells. A grid of depositional dip- and strike-oriented, regional cross sections were constructed using gamma, resistivity and density porosity logs. Regional isopach maps were produced for each parasequence of the Sunset Prairie Formation to visualize the distribution and thickness of each package. All of the 248 vertical wells were included in the regional grid to ensure the integrity of the depositional sequence stratigraphic framework.

INTERNAL ARCHITECTURE OF THE SUNSET PRAIRIE FORMATION

Summary of Lithofacies

Seven lithofacies were identified in the Sunset Prairie Formation and have been described in detail by Furlong et al (2018b). Sedimentological, ichnological and palaeontological characteristics of each lithofacies are outlined in Figure 4.3. Overall, the facies can be subdivided into three categories: 1) diminutively bioturbated (Facies 1 and 2), where physical sedimentary structures are observable; 2) pervasively bioturbated (Facies 3, 4 and 5), where burrowing organisms have homogenized the sediment and destroyed most primary physical sedimentary structures; and 3) bathymetrically independent facies (Facies 6 = *Glossifungites* Ichnofacies; Facies 7 = conglomeratic lag deposit). Collectively, the facies are associated with deposition in the offshore, offshore transition and lower shoreface environments (Fig. 4.3; Furlong et al., 2018b).

Diminutively Bioturbated Facies.—Two diminutively bioturbated facies are present within the Sunset Prairie Formation. Facies 1 consists of a dark to medium grey, fine- to coarse-grained siltstone with faint horizontal planar-parallel-laminae and horizontal wavy-parallel-laminae. Low- and high-angle planar cross stratification, asymmetric ripples, pyrite grains, calcispheres and phosphate material are also occasionally present. Trace fossils are small (0-2 mm), bioturbation intensity is low (BI = 0-2), and observable ichnogenera, listed in order of relative abundance, include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. No body fossils are observed within this facies. Facies 1 is interpreted to have been deposited within the offshore to lower offshore transition.

Facies 2 consists of a dark to light grey, fine to coarse-grained siltstone with horizontal pinstripe-, planar- and wavy-parallel-laminae. Asymmetric ripples and penecontemporaneous deformation structures are rare. Trace fossils are small (0-3 mm), bioturbation intensity is low (BI = 0-2), and observable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and

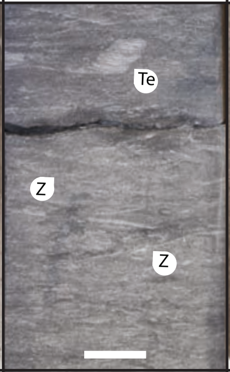
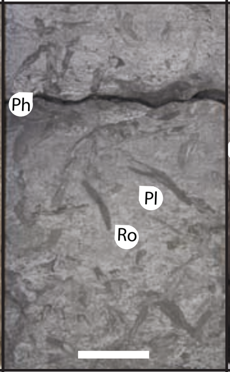
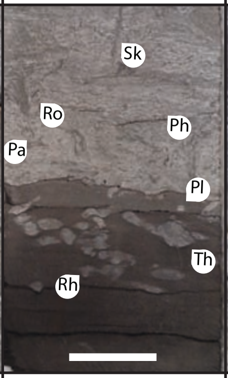
Facies	Diminutively Bioturbated		Pervasively Bioturbated			Bathymetrically Independent	
	F1	F2	F3	F4	F5	F6	F7
Core Expression							
Lithological Description	Dark to medium grey, laminated, bituminous siltstone with minimal bioturbation	Dark to light grey siltstone with minimal bioturbation	Dark to light grey bioturbated siltstone	Pervasively bioturbated medium to light grey siltstone	Pervasively bioturbated sandy siltstone	Burrowed firmground	Amalgamated sandstone and conglomerate bed
Primary Sedimentary Structures	PL, PWL, WL, LACL, HACL, AS, PG, Phos	PSL, PL, PWL, WL, AS, Phos	N/A	N/A	N/A	N/A	Phos
Secondary Sedimentary Structures	PDS, C, HCS	PDS	Phos	PL	PL, WL, LACL, HACL, PDS, AS, Phos	Phos	N/A
Body Fossils	N/A	N/A	N/A	BI, G, BR, E, CR	BI, G, BR, E, CR	N/A	Shell and Bone fragments
Grain Size	Fine to coarse silt	Fine to coarse silt	Fine silt to very fine sand	Fine silt to very fine sand	Fine silt to very fine sand	N/A	Sand to gravel
Ichnological Assemblage	*Ph, He, Pa, Pl, Ch*	*Ph, He, Pa, Pl, Ch*	*Ph, He, Te, Pa, Pl, Ch, Z*	*Ph, He, Pa, Pl, Ch*	*Ph, Ro, Cy, As, Te, Pa, Pl, Sk, Sc, Rh, Di*	*Pl, Sk, Th, Rh*	N/A
BI	0-2	0-2	5-6	4-6	5-6	N/A	N/A
Interpreted Depositional Environment	Offshore to Lower Offshore Transition	Lower Offshore Transition	Lower to Upper Offshore Transition	Lower to Upper Offshore Transition	Upper Offshore Transition to Lower Shoreface	*Glossifungites* surfaces	Lag deposit

Figure 4.3–Summary of lithological, sedimentological, ichnological and palaeontological characteristics of the lithofacies in the Sunset Prairie Formation. Sedimentary structure abbreviations include: AS = Asymmetrical ripples; C = Calcisphere; HACL = High Angle Cross Laminae; HCS = Hummocky Cross Stratification; LACL = Low Angle Cross Laminae; PDS = Penecontemporaneous Deformation Structures; PG = Pyrite Grains; Phos = Phosphate Material; PL = Planar Laminae; PSL = Pinstripe Laminae; PWL = Planar-wavy Laminae; Rup = Rip Up Clasts; WL = Wavy Laminae. Body fossil abbreviations include: G = Gastropod; BI = Bivalve; E = Echinoid; BR = Brachiopods; CR = Crinoid. Trace fossil abbreviations include: *As* = *Asterosoma*; *Ch* = *Chondrites*; *Cy* = *Cylindrichnus*; *Di* = *Diplocraterion*; *He* = *Helminthopsis*; *Pa* = *Palaeophycus*; *Ph* = *Phycosiphon*; *Pl* = *Planolites*; *Rh* = *Rhizocorallium*; *Ro* = *Rosselia*; *Sc* = *Scolicia*; *Sk* = *Skolithos*; *Te* = *Teichichnus*; *Th* = *Thalassinoides*; *Z* = *Zoophycos*.

Chondrites. No body fossils are observed within this facies. Facies 2 is interpreted to have been deposited in the lower offshore transition.

Pervasively Bioturbated Facies.—Three pervasively bioturbated facies are present within the Sunset Prairie Formation. Primary sedimentary structures are difficult to observe and identify because the intervals have been biogenically homogenized (BI 4-6). Ichnological assemblages and grain-sizes provide the main characteristics for determining the depositional environment associated these facies.

Facies 3 consists of dark to light grey, bioturbated fine-grained siltstone to very fine-grained sandstone. Phosphate material is observed within this facies. Trace fossils are variable in size (0.5-12 mm), bioturbation intensity is high (BI = 5-6), and observable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Teichichnus*, *Palaeophycus*, *Planolites*, *Chondrites*, and *Zoophycos*. No body fossils are observed within this facies. Facies 3 is interpreted to have been deposited in the lower to upper offshore transition.

Facies 4 consists of pervasively bioturbated medium to light grey fine-grained siltstone to very fine-grained sandstone with rare horizontal planar-parallel-laminae. Trace fossils are variable in size (0.5-6 mm), bioturbation intensity is high (BI = 4-6), and observable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. Body fossils observed in Facies 4 include bivalves, gastropods, brachiopods (lingulid, spiriferid terebratulid), cidaroid echinoid skeletal fragments, and isocrinid crinoid ossicles. This facies is interpreted to record deposition in the lower to upper offshore transition.

Facies 5 consists of medium to light grey, pervasively bioturbated fine-grained siltstone to very fine-grained sandstone. Rare horizontal planar-parallel-laminae, horizontal wavy-parallel-laminae, low- and high-angle planar cross laminae, penecontemporaneous deformation structures, asymmetric ripples and phosphate material is observed. Trace fossils are variable in size (1-15 mm), bioturbation intensity is high (BI = 5-6), and observable ichnogenera include *Phycosiphon*, *Rosselia*, *Cylindrichnus, Asterosoma, Teichichnus*, *Palaeophycus*, *Planolites*, *Skolithos, Rhizocorallium*, and *Diplocraterion.* The trace fossil assemblage associated with this grouping is the most diverse within the Sunset Prairie Formation. The same assemblage of body fossils is observed in Facies 4 and Facies 5. Facies 5 is interpreted to have been deposited in the upper offshore transition to lower shoreface.

Bathymetrically Independent Facies.—Two bathymetrically independent facies are identified in the Sunset Prairie Formation. Facies 6 a substrate-controlled, burrowed firmground characterized by *Planolites*, *Skolithos*, *Thalassinoides*, and *Rhizocorallium*. The interval is interpreted to represent a *Glossifungites* Ichnofacies-demarcated discontinuity surface. Firmground assemblages are associated with depositional hiatuses between the erosionally exhumed (dewatered and compacted) substrate and the sediment overlying the unit, and therefore correspond to erosional discontinuities (Bromley, 1975; MacEachern et al., 1992, 2012b).

Facies 7 consists of a variety of poorly sorted, coarse-grained conglomerate concentrated in thin beds (<5 cm thick) along discontinuity surfaces. Grains are moderately well-rounded and range from fine-grained sand to medium-grained pebble sized clasts. The conglomerate can occur as both matrix supported or clast supported. Phosphate nodules, phosphatic ooids, rip-up clasts, shell fragments and fossilized/mineralized bone fragments are locally present within the facies. Facies 7 is interpreted to represent transgressive lag deposits.

Facies Associations

Facies associations record the recurrence of lithofacies in a predictable vertical distribution. Collectively, the lithofacies of the Sunset Prairie Formation are interpreted to represent deposition along a wave-dominated, shallow-marine setting, within the offshore, offshore transitions and lower shoreface. The shallowing-upward pattern of lithofacies within the facies associations suggests a small-scale regression of relative sea level (Fig. 4.4).

A variety of different shoreface models have been suggested over the past few decades and use slightly variable terminology for environmental subdivision (e.g., Elliott, 1986; Reading and Collinson, 1996; MacEachern and Bann, 2008; Buatois and Mangano, 2011). Within this paper, the open-marine environmental subdivisions are based on Elliott (1986) and Reading and Collinson (1996), which place the offshore below the storm-wave base, the offshore transition between the storm-wave base and the fair-weather wave base, and the shoreface between the fair-weather wave base and the low-tide line. Ichnological characteristics observed within the Sunset Prairie Formation vary slightly from those that are classically associated with shoreface successions (e.g., Reading and Collinson, 1996; Buatois and Mangano, 2011), due to the stressed marine ecosystem attributed to the end-Permian mass extinction and the faunal recovery period that followed (Iszaki, 1994; Benton and Twitchett, 2003; Heydari and Hassanzadeh, 2003; Black et al., 2012; Hinojaosa et al., 2012; Payne and Clapham, 2012).

Offshore deposits (Facies 1) were characterized by a low trace fossil diversity (4 ichnogenera), low trace fossil abundance (BI = 0-2), and small trace fossil size (<1 mm in diameter). Lithologically, deposits consist of fine-grained to coarse-grained siltstone. Sedimentary structures include faint horizontal planar-parallel-laminae and horizontal wavy-parallel-laminae, which are indicative of deposition within a low-energy environment.

Offshore transition deposits are associated with a large range of sedimentological and ichnological characteristics. The offshore transition setting has been divided into a distal expression (lower

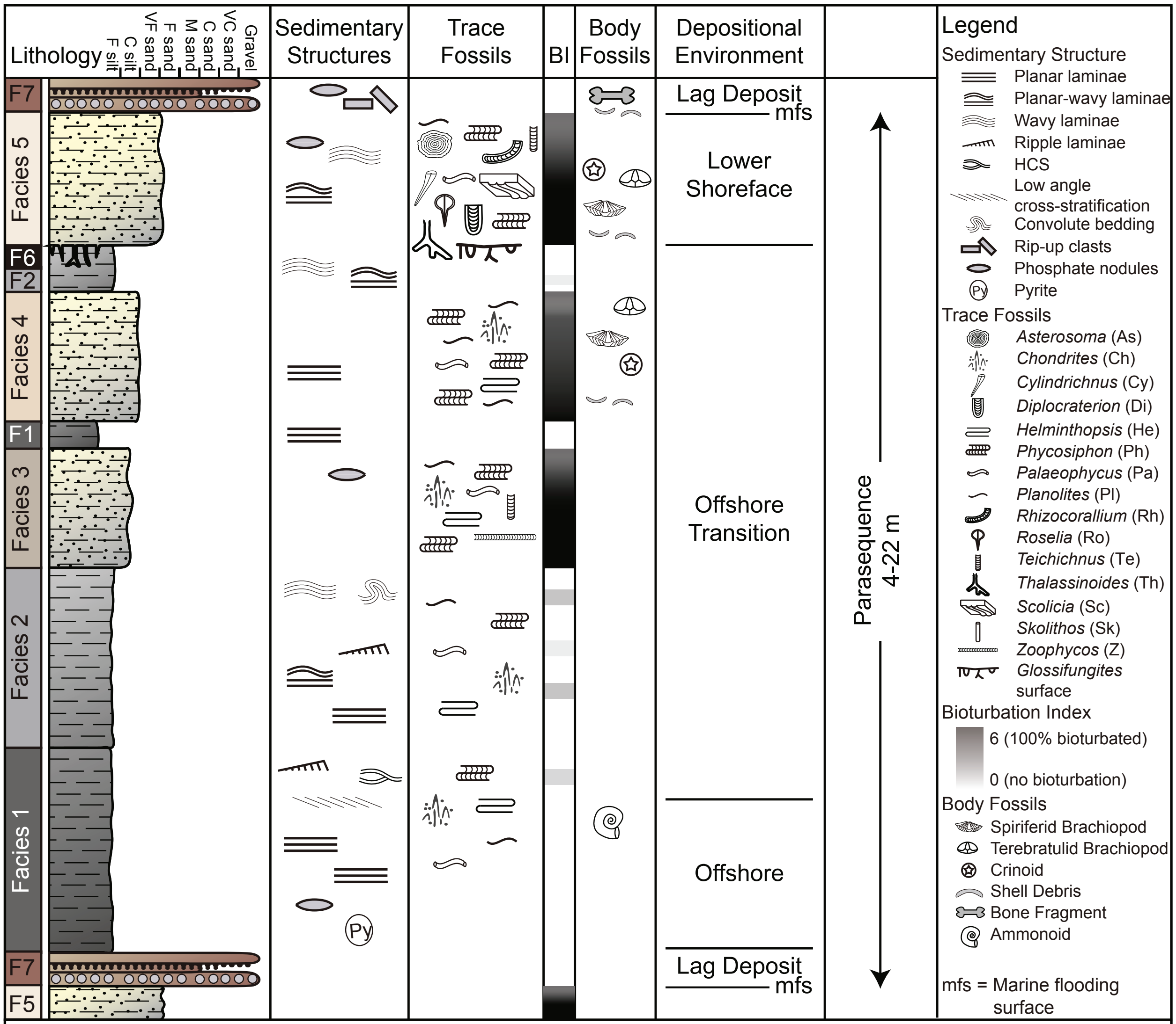


Figure 4.4–Schematic of a Sunset Prairie Formation parasequence. Generalized distribution of lithology, physical sedimentary structures, trace fossils, bioturbation intensity (BI), and body fossils are denoted. Associated depositional environments are interpreted.

offshore transition) and a proximal expression (upper offshore transition). The lower offshore transition is characterized by both diminutively bioturbated facies (Facies 1 and 2) and pervasively bioturbated facies (Facies 3 and 4). Lithologically, deposits consist of fine-grained to coarse-grained siltstone. Within bioturbated facies, trace fossil diversity is moderate (7 ichnogenera), trace fossil abundance is high (BI = 4-6), and trace fossil size is variable (0.5-12 mm in diameter). Fair-weather wave deposits are mainly associated with bioturbated intervals; however, non-bioturbated intervals exhibit horizontal planar-, wavy-, and -pinstripe-parallel-laminae, which can also be associated with fair-weather deposition when physico-chemical stresses reduce/hinder biotic colonization (Chapter 5 and 6). Rare low- and high-angle planar cross stratification, and asymmetric ripples are indicative of periodic increased energy, possibly associated with storm deposition. But the lack of strongly storm-influenced primary sedimentary structures and the presence of intensely bioturbated intervals within the offshore transition suggest that a sheltered coastal setting that was protected from storm erosion existed during deposition of the Sunset Prairie Formation. Deposition within the upper offshore transition (Facies 3, 4 and 5) is characterized by a moderately high trace fossil diversity (11 ichnogenera), large trace fossils (up to 15 mm in diameter) and intense bioturbation (BI = 4-6). Lithologically, deposits consist of fine-grained to coarse-grained siltstone. The lack of non-bioturbated facies suggests that bioturbation rates outpaced sedimentation rates, resulting in infaunal organisms completely homogenizing the sediment.

Lower shoreface deposits (Facies 5) are associated with a moderately high trace fossil diversity (10 ichnogenera), large trace fossils (up to 15 mm in diameter) and intense bioturbation (BI = 4-6). Lithologically, deposits consist of fine-grained siltstone to fine-grained sandstone. The coarse-gained sandstone material suggests that these intervals are more proximally located than the other facies of the Sunset Prairie Formation. Facies associated with more proximal settings, like the middle shoreface, upper shoreface and foreshore are not observed within the Sunset Prairie Formation and have been erosionally removed.

Ichnological Associations

Collectively, the ichnological assemblage of the Sunset Prairie Formation is characteristic of the *Cruziana* Ichnofacies (Seilacher, 1967). The assemblage is dominated by trace fossils associated with deposit-feeding strategies, with subordinate grazing and suspension-feeding affiliations (MacEachern et al., 2010). Lower offshore transition deposits are dominated by horizontal and inclined trace fossil orientations, whereas the introduction of more vertically-orientation trace fossils is observed in the lower shoreface, which reflects subtle changes in food supply.

Offshore to offshore transition trace fossil assemblages of the Sunset Prairie formation are characterized by the distal expressions of the *Cruziana* Ichnofacies (*sensu* MacEachern and Pemberton 1992; MacEachern and Bann, 2008). Ichnogenera observed include: *Chondrites*, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Teichichnus*, and *Zoophycos*. These trace fossils have been associated with grazing, deposit feeding and passive carnivore ethologies (e.g., MacEachern et al., 2007a, 2010). Trace fossils within Facies 1, 2 and 4 are typically small (< 1 mm in diameter) and exhibit lower diversities (5 ichnogenera), which represent an impoverished ichnological community, compared to Facies 3 that has a higher diversity (7 ichnogenera) and larger trace fossils (<12 mm in diameter).

An archetypal expression of the Cruziana Ichnofacies is characterized trace fossil assemblages of the lower shoreface. Ichnogenera include: *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *Palaeophycus*, *Phycosiphon Planolites*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, and *Thalassinoides*. These trace fossils have been associated with deposit feeders, passive carnivores, dwellings of filter-feeders, and dwellings of deposit-feeders (e.g., MacEachern et al., 2007a, 2010). Trace fossils are variable in size depending on the ichnotaxa, but the largest burrows can be up to 15 cm in diameter. Bioturbation is high (BI = 5-6), and both shallow- and deep-tiering trace fossils are present, suggesting that environmental conditions were suitable to sustain complex ichnological communities.

Distribution of Sedimentary Facies and Facies Associations

Vertical Distribution of Facies.—Upward-coarsening successions have a variety of origins within the rock record. Increased hydrodynamic energy resulting from relative sea level fall leading to depositional shallowing can generate upward-coarsening intervals (e.g., Van Wagoner et al., 1990; Catuneanu et al., 2009). However, when independent indicators of palaeoshoreline position or water depth are absent, coarsening-upward successions may reflect bedsets that form without relative changes in sea level (Hampson et al., 2008). Such conditions include: increase in sand influx due to river flow, or increase in storm waves and/or currents driven by variations in climate, ocean circulation or shoreline palaeogeography (e.g. Storms and Hampson, 2005; Somme et al., 2008; Mitchell et al., 2012). Although, the exact palaeoshoreline position during Sunset Prairie Formation deposition has not been preserved, it is most likely that the upward-coarsening successions are a result of changes in relative sea level due to: 1) the high bioturbation intensity suggesting prolonged periods of low intensity storms (e.g. Howard, 1975; Gani et al., 2007; Furlong et al., 2018b); 2) arid conditions during the Triassic would have fostered the development of ephemeral rivers (Zonneveld and Moslow, 2014), which would only increase sediment supply occasionally (seasonally or less frequently); and 3) spatial migration of the lower shoreface deposit capping the top of coarsening-upward packages (parasequences) through time can infer palaeoshoreline trajectory.

Facies stacking patterns within the Sunset Prairie Formation preserve regressively shoaling-upward successions, which are interpreted here as parasequences. The base of the parasequence is marked by a series of conglomerate lag deposits (Facies 7), which are interpreted to represent transgressive lags. The *Glossifungites* Ichnofacies (Facies 6) is also commonly associated with the boundaries of parasequence, but can also be interformational. Overlying the transgressive lag deposits is a shoaling upward succession, which records offshore deposits overlain by offshore transition deposits, which are then capped by lower shoreface deposits (Figs. 4.4, 4.5). Parasequences coarsen upward in grain size from fine-grained silt to very fine-grained sand and bioturbation increases upwards. Small-scale interbedding of diminutively bioturbated facies and pervasively bioturbated facies occur throughout the parasequence, but an overall shoaling

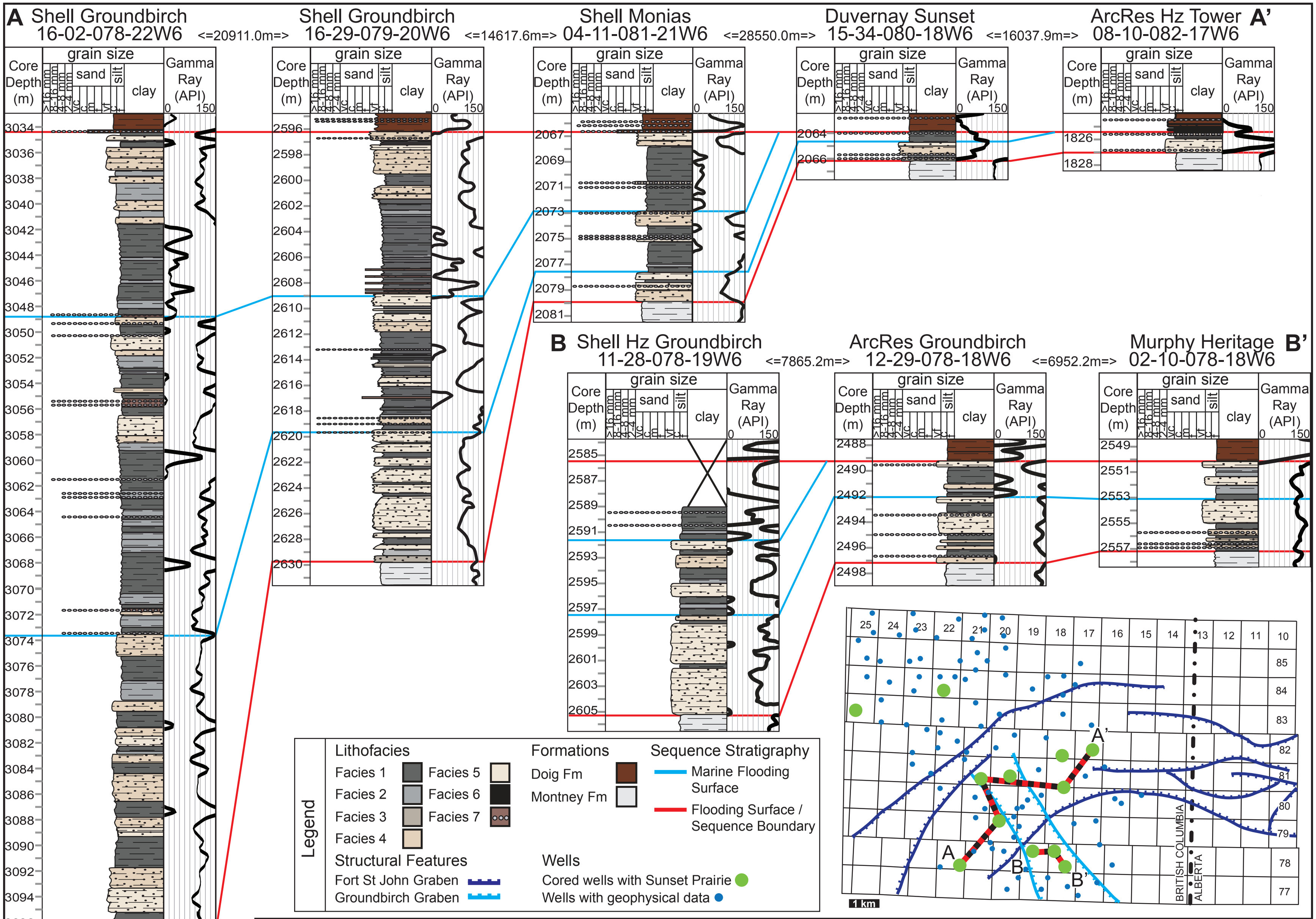


Figure 4.5–Facies distribution of the Sunset Prairie Formation in cored wells within the Fort St. John Graben system.

upward trend occurs. Up to three parasequences are observed within the Sunset Prairie Formation. Although each parasequence is capped by facies associated with the lower shoreface, the thickest packages of these proximal facies are preserved at the base of the Sunset Prairie Formation (in the first parasequence), and progressively thin in succeeding parasequences (Figs. 4.5, 4.6). Vertical distribution of parasequences suggests a retrogradational-stacking pattern, inferring that an increase in relative sea level occurred during the deposition of the Sunset Prairie Formation.

Lateral Distribution of Facies.— The Sunset Prairie Formation total thickness increases to the west and thins to an erosional edge to the east (Fig. 4.7). Wells located in western or distal locations within the basin preserve parasequences that exhibit offshore, offshore transition, and lower shoreface deposits, whereas eastern-located wells preserve parasequence that exhibit offshore transition and lower shoreface deposits (Fig. 4.5). Additionally, more proximally located wells contain thinner parasequences (Figs. 4.6, 4.7), which is likely a result of autogenic erosion associated with shallow-marine conditions redistributing sediment due to the lack of accommodation space.

Structural features also play a role in the distribution of the Sunset Prairie Formation. The formation is thickest (66.5 m in the 03-06-078-22W6 cored well), within the Fort St. John Graben system and the Hudson Hope Low, in the western region of the study area (Fig. 4.7). The interval thins across the Hudson-Monias High, where the formation is <25 m in total thickness (Fig. 4.7). In the Laurier Embayment, in the northern portion of the study area, the formation thickens to approximately 30 m. Localized, detailed studies would provide a better understanding of how facies, facies associations, and parasequence distributions change across these structural features.

Parasequence and Clinoform Geometry

Regional correlation suggests that three upward-coarsening parasequences are recognized within the Sunset Prairie Formation throughout the basin in core and geophysical wireline data (Figs. 4.6, 4.7, 4.8). Parasequences are interpreted here to represent clinoforms, which are seaward-dipping stratal surfaces that consist of a basin-dipping topset and bottomset, and an intervening, more steeply dipping foreset. Commonly, the base of the parasequence is identifiable by high, commonly off-scale, gamma ray log deflections, which are commonly associated with a lag deposit (Facies 7) and/or *Glossifungites* Ichnofacies-demarcated discontinuity surface (Facies 6) (Fig. 4.5; Furlong et al., 2018a, figs. 5-7). Where a lag deposit or *Glossifungites* Ichnofacies-demarcated discontinuity surface is not present, an abrupt change from proximal facies overlain by distal facies is observed in core; this corresponds to a shape decrease in gamma ray log signature, which may or may not be off-scale.

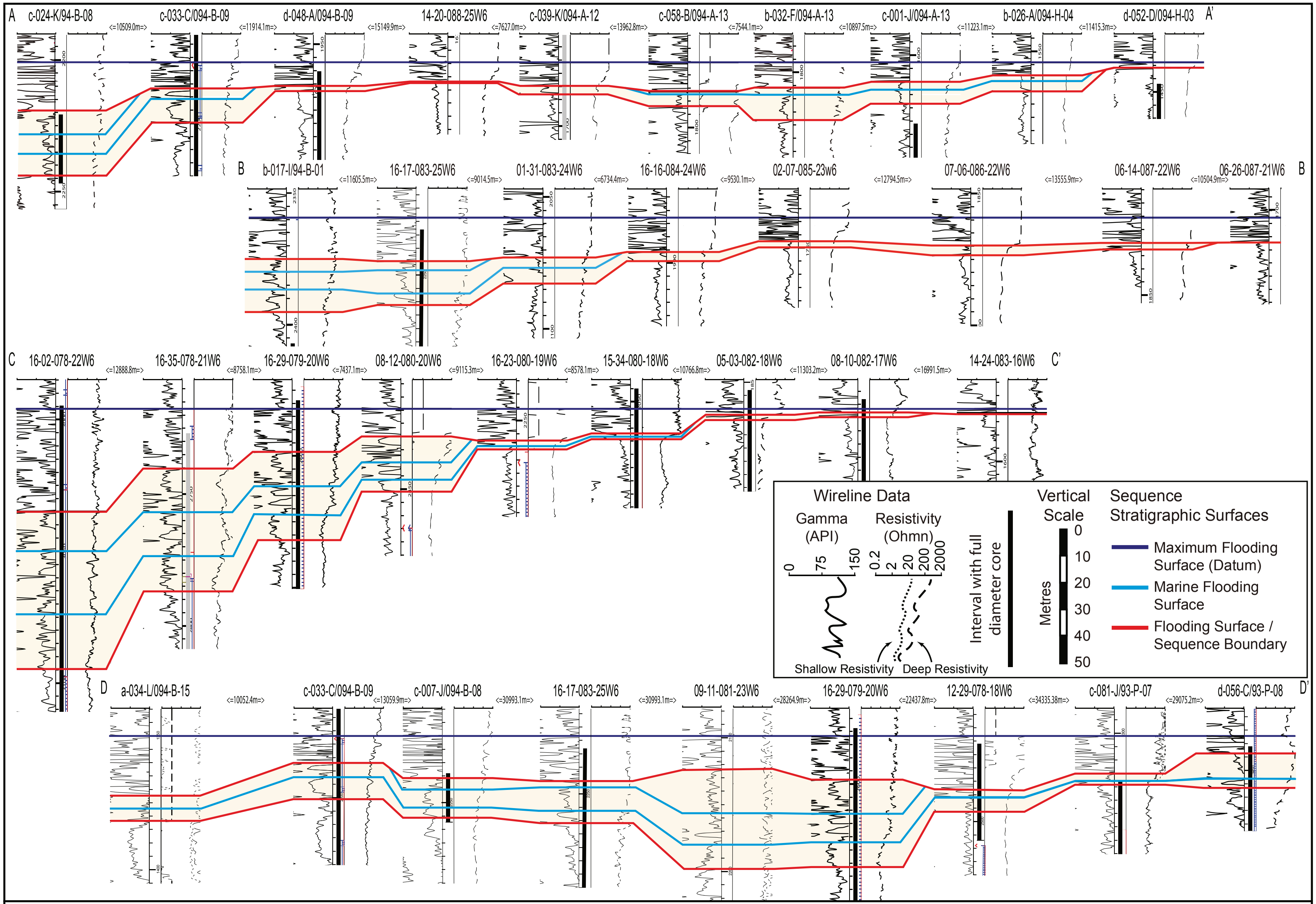
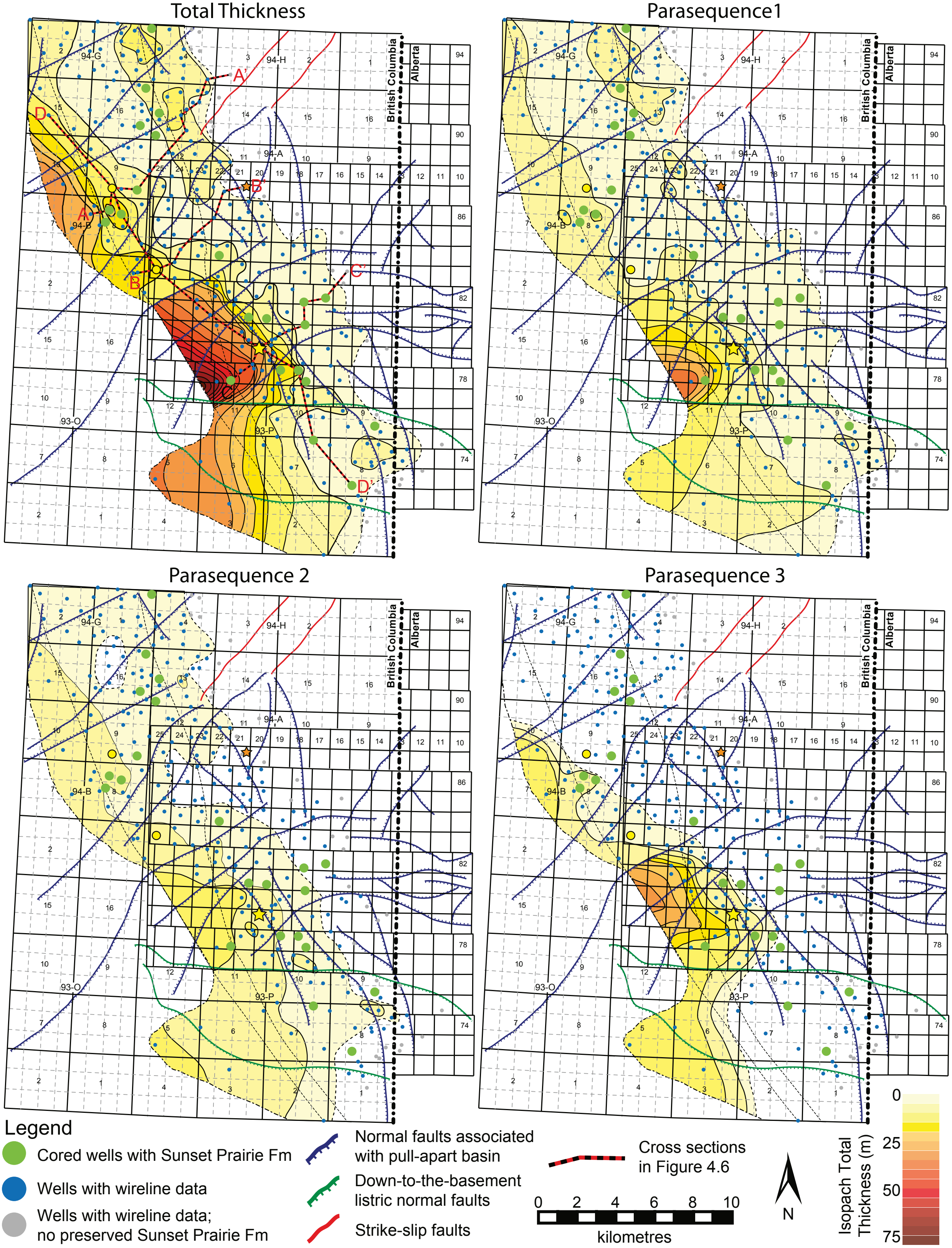


Figure 4.6-Cross sections showing the petrophysical wireline characteristics, distribution and sequence stratigraphic architecture of the Sunset Prairie Formation. Cross section locations identified in the total thickness isopach in Figure 4.7. Datum is the maximum flooding surface at the top of the Doig phosphate zone.



Total Thickness

Parasequence1

Parasequence 2

Parasequence 3

Figure 4.7–Location and thickness maps of the Sunset Prairie Formation. Isopachs depict total thickness of the formation and thickness of each parasequence present in the formation. Well control includes wells with wire line data (n=248) and cored wells (n = 25). Total thickness ranges from 0-80 m. Contour interval = 5 m.

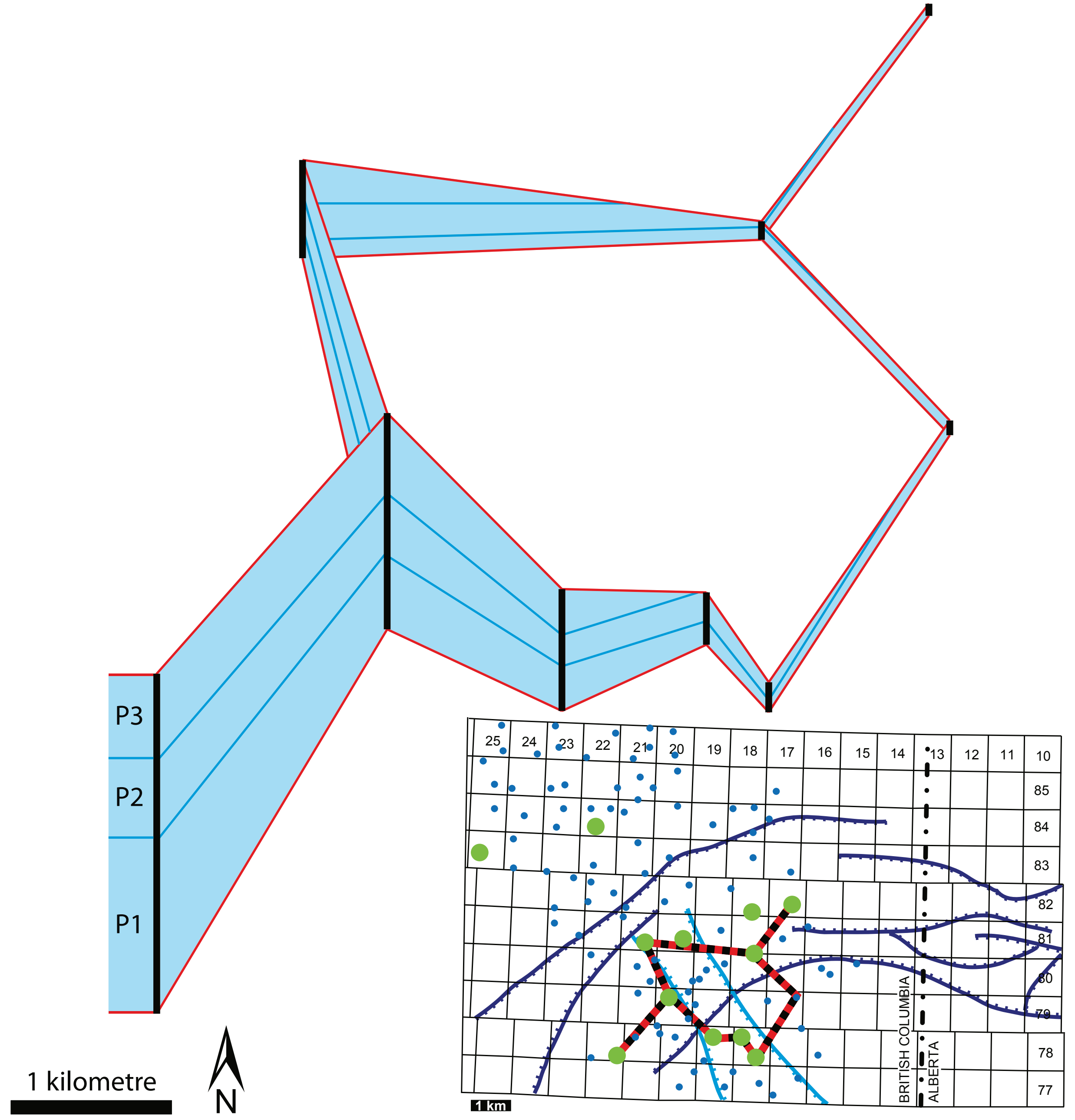


Figure 4.8–Fence diagram of the Sunset Prairie Formation within the Fort St. John Graben system. The distribution of parasequences is identified. P1 = parasequence 1; P2 = arasequence 2; P3 = parasequence 3.

Spatial distribution of the three parasequences is shown in the isopach of Figure 4.7. The first parasequence (P1) extends across the entire area where the formation is preserved. Parasequence 2 (P2) is preserved in a more distal/western location, as compared to P1. Parasequence 3 (P3) is preserved in the most western location as compared to the other two parasequences.

All parasequence are observed to thicken to the west and are erosionally removed to the east (Figs. 4.7, 4.8). Although there is a westward migration of the preserved parasequences, which would lead one to interpret progradation, facies associations within the parasequences exhibit a back-stepping stacking pattern and each subsequent parasequence preserves relatively less proximal associated facies (lower shoreface) at their tops. Significant erosion would have been needed to truncate the Sunset Prairie Formation and remove the eastern parts of the parasequences. The top of the Sunset Prairie is therefore interpreted to represent an unconformity associated with a transgressively modified sequence boundary (FS/SB).

Sequence Stratigraphic Models for the Sunset Prairie Formation

Transgressive Systems Tract.—Based on facies associations, parasequence stacking patterns sequence and stratal boundaries, the Sunset Prairie Formation is assigned to a transgressive systems tract. Each parasequence exhibits a back-stepping or retrogradational stacking pattern with respect to the underlying parasequence (Figs. 4.7, 4.9). The base and top of the Sunset Prairie Formation are unconformities that are interpreted as transgressively modified sequence boundary (FS/SB) due to the unconformity truncating the underlying formation. Little or no sedimentological evidence (e.g. root casts, palaeosols, karsting, etc.) has been observed at the boundary between the Montney Formation and the Sunset Prairie Formation to suggest prolonged subaerial exposure; however transgressive modification was capable of eliminating evidence of subareial exposure along the surface.

In this scenario, the lowstand systems tract would be predicted to be spatially detached and the boundary between the Montney Formation and Sunset Prairie Formation would represent a significant drop in relative sea level with subsequent base level rise. However, no observations have yet to suggest that detached lowstand deposits occur in the Rocky Mountain outcrop belt (see Orchard and Zonneveld, 2009 for descriptions of outcrop facies). The recognition of a lowstand systems tract between the Montney and Sunset Prairie Formations remains unresolved. The stratal relationship between the Sunset Prairie Formation and the Doig phosphate zone would also suggest that a lowstand systems tract and a highstand systems tract would be predicted in a basinward position. These deposits, too have yet to be recognized within the outcrop belt. Further investigating the Rocky Mountain outcrop belt can provide a better understanding of sea level fluctuations through the Triassic.

Alternative Interpretation: Lowstand Systems Tract and Transgressive Systems Tract.—Within the previous interpretation, the lowstand systems tract is not accounted for. This alternative sequence stratigraphic model interprets the Sunset Prairie Formation as a lowstand systems tract (preserved as parasequence 1) and a transgressive systems tract (preserved as parasequence 2 and 3) (Fig. 4.10). By definition, a lowstand system tract exhibits an internal normal regressive stacking

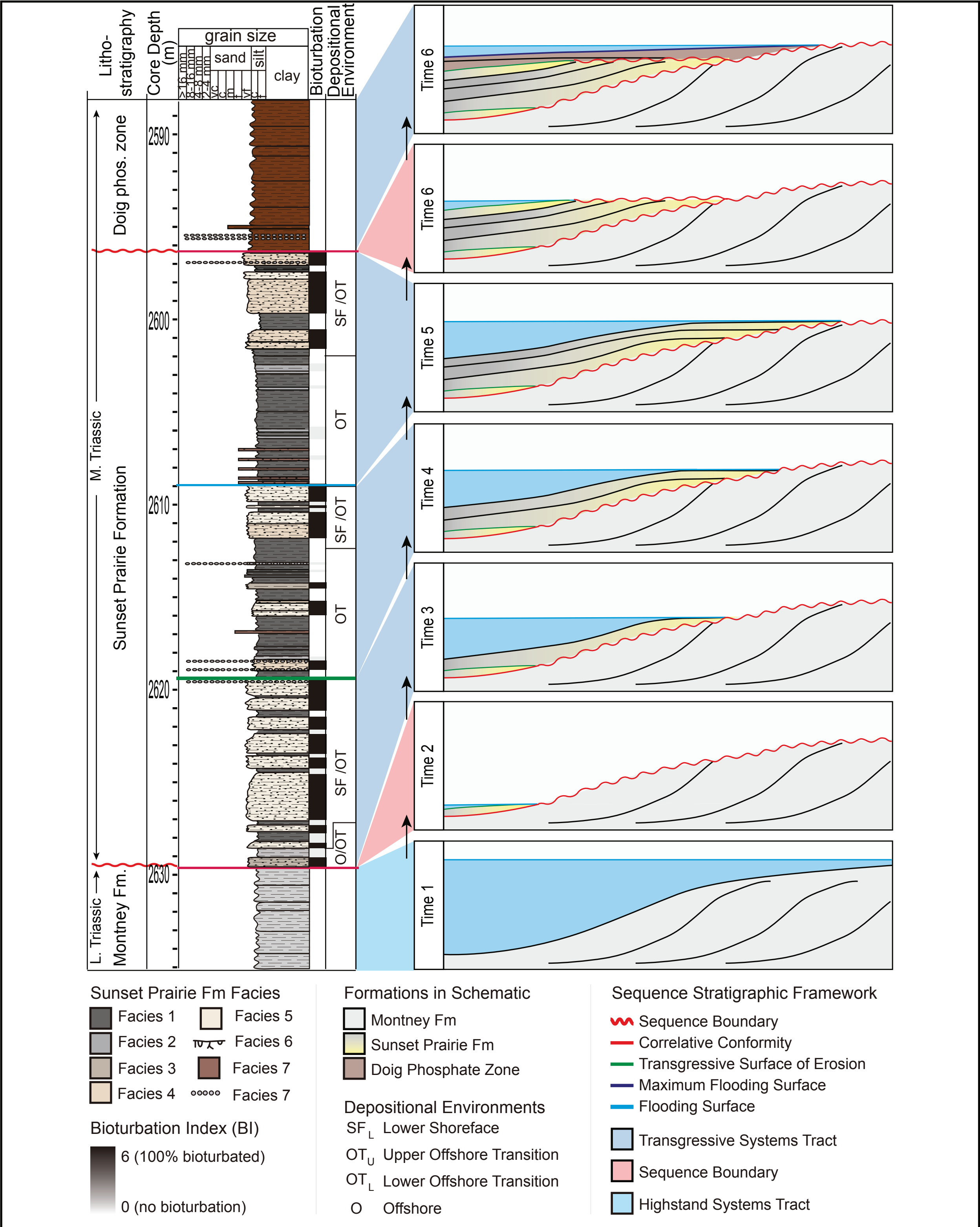


Figure 4.9–Sequence stratigraphic schematic of the Montney Formation, Sunset Prairie Formation and Doig phosphate zone. Litholog from the Shell Groundbirch 16-29-079-20W6 drill core showing the distribution of lithological characteristics and facies distribution of the Sunset Prairie Formation. Sequence stratigraphic schematic corresponding to the deposition of different parasequence sets and stratigraphic surfaces associated with the Upper Montney Formation, Sunset Prairie Formation and Doig phosphate zone.

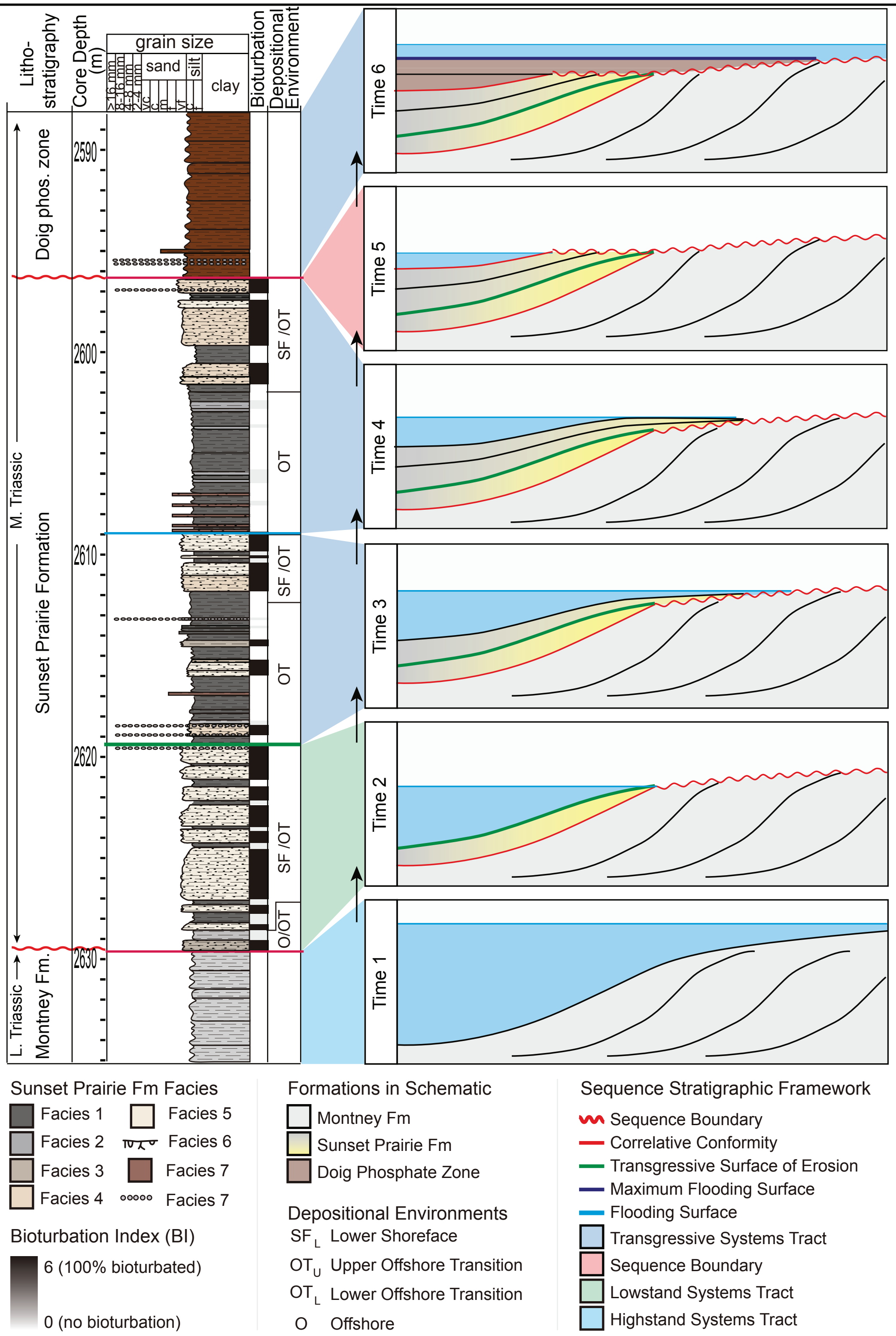


Figure 4.10–Alternative sequence stratigraphic framework schematic of the Montney Formation, Sunset Prairie Formation and Doig phosphate zone. Litholog from the Shell Groundbirch 16-29-079-20W6 drill core showing the distribution of lithological characteristics and facies distribution of the Sunset Prairie Formation. Sequence stratigraphic schematic corresponding to the deposition of different parasequence sets and stratigraphic surfaces associated with the Upper Montney Formation, Sunset Prairie Formation and Doig phosphate zone.

pattern, overlies a sequence boundary and/or correlative conformity and underlies a transgressive surface of erosion/regressive surface of marine erosion (Catuneanu, 2019). A regressive stacking pattern of parasequences cannot be determined due to the interpreted lowstand systems tract being composed of one parasequence; however, the basal parasequence of the Sunset Prairie Formation exhibits the much thickest accumulation of proximal (lower shoreface) facies (Fig. 4.5). These facies are more proximal and consist of coarser-grained material (up to very fine-grained sandstone) than the underlying Upper Montney Formation facies, which mainly consist of siltstone interpreted as offshore transition deposits (e.g., Zonneveld and Moslow, 2018). A decrease in relative sea level cut the unconformity and led to a slight basin shift in facies, supplying fine-grained sand to lower shoreface environments. The boundary between the Montney Formation and the Sunset Prairie Formation would be considered a correlative conformity. Capping the lowstand systems tract is a transgressive surface of erosion (or regressive surface of marine erosion), which records the most basinward migration of the lower shoreface and marks the onset of transgression. The transgressive systems tract consists of the upper two parasequences, each showing an increased abundance in distal facies (offshore transition) as compared to the first parasequence and an overall back-stepping of the palaeoshoreline. All three parasequences are truncated by an overlying coplanar sequence boundary and transgressive surface of erosion associated with the base of the Doig phosphate zone.

In this scenario, the lowstand systems tract would be attached (*sensu* Ainsworth and Pattison, 1994). An attached lowstand shoreface is differentiated from the highstand shoreface by the occurrence of a basin shift in facies at the base of the succession associated with a sharp base and lag deposit (Ainsworth and Pattison, 1994), which are features present within the base of the first parasequence of the Sunset Prairie Formation. An attached lowstand systems tract can possess subtle differences from the underlying highstand systems tract rendering it difficult to identify, but misidentifying an interval as the highstand instead of an attached lowstand may lead to the prediction of a nonexistent detached lowstand deposit in a down-dip, distal location (Ainsworth and Pattison, 1994). Although this alternative sequence stratigraphic interpretation is more speculative, the absence of the lowstand systems tract down-dip and the occurrence of coarse-grained (fine-grained sandstone) lower shoreface deposits located in a more distal locations, compered to underlying Montney Formation lithology, make this interpretation plausible.

DISCUSSION

Stratigraphic Architecture and Sequence Stratigraphy of the Lower and Middle Triassic of Western Canada

Many workers agree that the Montney Formation is composed of three unconformity-bound, third-order depositional sequences, corresponding to the Lower Montney (Griesbachian to Dienerian age), Middle Montney (Smithian-age) and Upper Montney (Spathian-age) (e.g. Embry and Gibson, 1995; Davies et al., 1997; Embry, 1997; Henderson and Schoepfer, 2017; Davies et al., 2018; Henderson et al., 2018). However, internal sequence stratigraphic frameworks vary greatly between workers (Fig. 4.11). The majority of studies have focused on the proximal parts of the formation (e.g. Davies et al., 1997; Moslow and Davies 1997; Moslow 2000; Markhasin, 1997; Kendall, 1999; Panek, 2000), isolated to localized spatial areas (e.g. Evoy and Moslow, 1995; Evoy, 1997; Harris, 2000; Dixon, 2002; 2007; 2010; 2011; Golding et al., 2014b; Proverbs et al., 2018; Moslow et al., 2018; Zonneveld and Moslow, 2018), or isolated stratigraphic intervals (Euzen et al., 2018; Prenoslo et al., 2018), with only a few studies looking at sequence stratigraphic correlations on a larger, basin-wide scale (e.g. Davies and Humes, 2016; Crombez et al., 2016; 2017; Davies et al., 2018). Although the scope of each publication differs, no unanimous sequence stratigraphic framework has emerged for the Lower and Middle Triassic, and the sequence stratigraphic surfaces identified are varied (Fig. 4.11).

To provide evidence for how the Sunset Prairie Formation ties into the sequence stratigraphic architecture of the Lower to Middle Triassic, stratigraphic surfaces were identified in the Upper Montney Formation, Sunset Prairie Formation and Doig phosphate zone in the Fort St. John Graben system. This area was chosen, based on it corresponding to the region where the Sunset Prairie Formation is most thickly preserved. Facies and stratigraphic surfaces were interpreted by the author in core and correlated across the area using petrophysical wireline data. Detailed description of facies, facies associations and basin-scale correlation of parasequences within the Upper Montney Formation and Doig phosphate zone were outside the scope of this paper.

Within the Fort St. John Graben system, the Upper Montney Formation consists of a lowstand systems tract at the base, with a thin (<5 m think) transgressive systems tract overlying it (Fig. 4.12). The highstand systems tract makes up the majority of the Upper Montney Formation. Three parasequences were identified in the lowstand systems tract, one parasequence in the transgressive systems tract, and up to eight parasequences are identified in the highstand systems tract. Thickness of parasequences in the topset and bottomset areas are typically 10 m or less, whereas foreset thicknesses can reach up to 55 m. Similar results were obtained by Euzen et al. (2018) when mapping the Upper Montney basin-wide. They, however, described the packages as parasequence

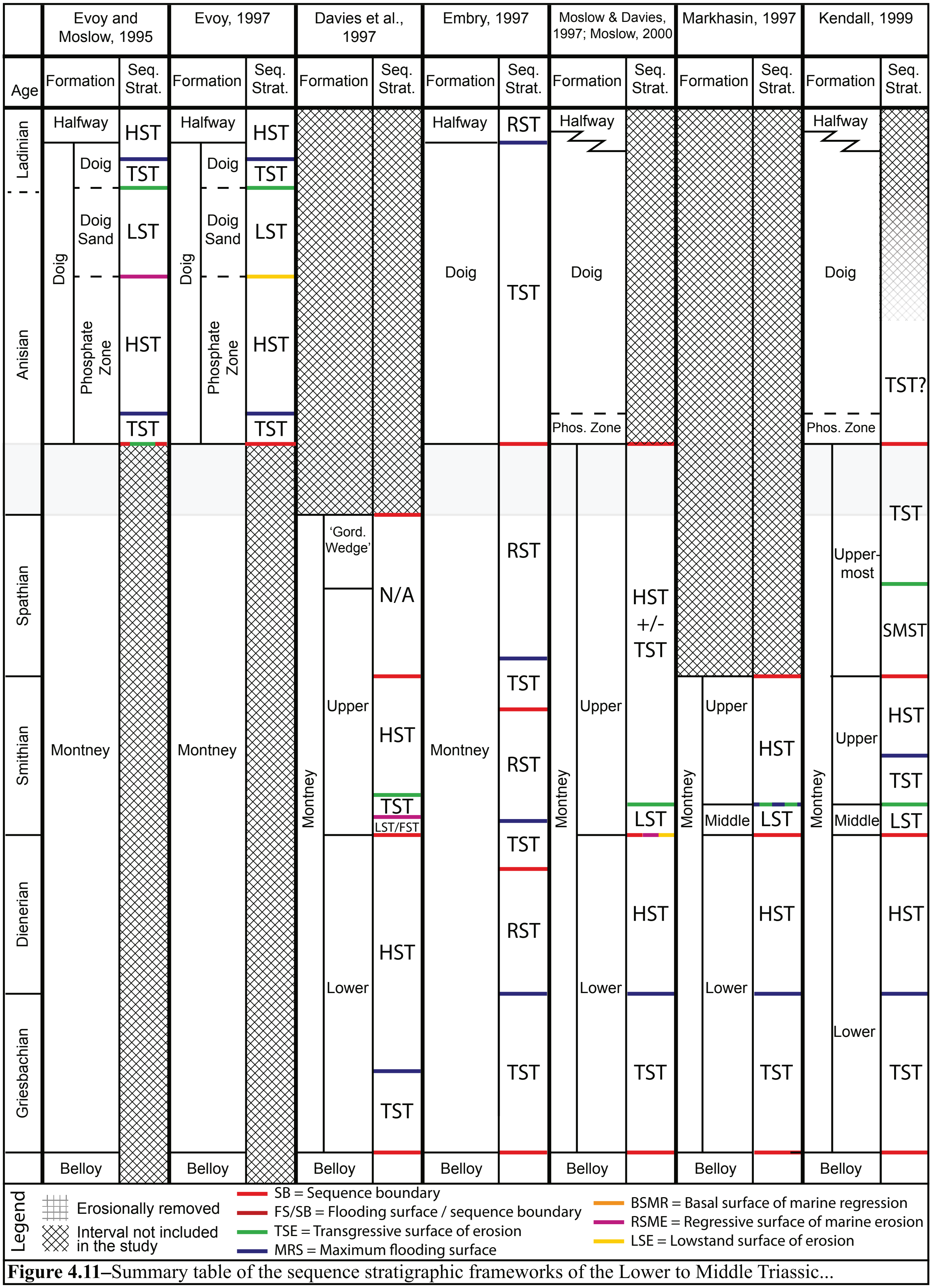


Figure 4.11–Summary table of the sequence stratigraphic frameworks of the Lower to Middle Triassic...

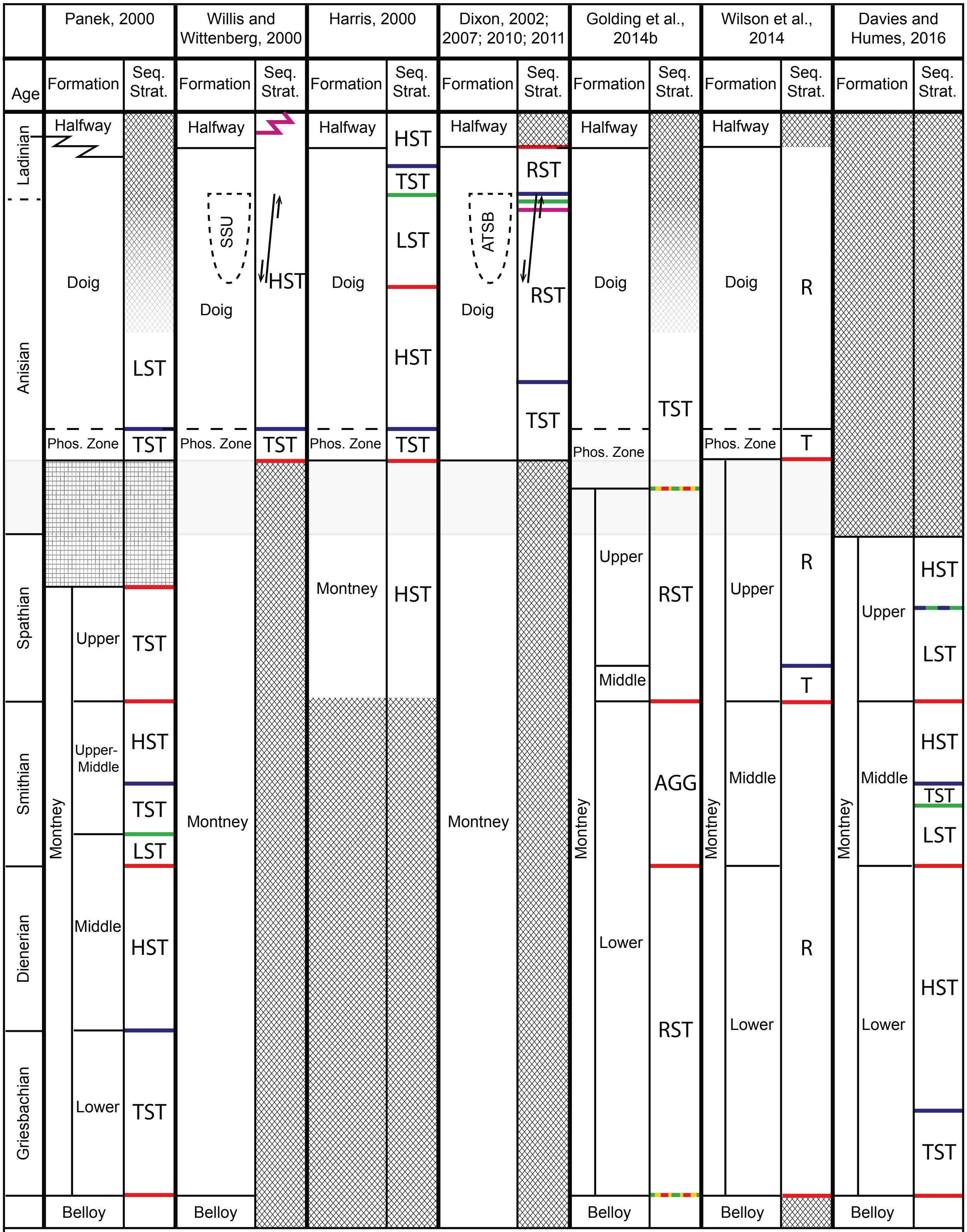


Figure 4.11 cont.–Summarized studies are limited to publications that provide detailed cross sections, reference well(s), or schematic drawings, which have sequence stratigraphic surfaces and/or systems tracts identified. Localized studies and high-resolution sequence stratigraphy frameworks for stratigraphically limited intervals were not considered in the table. Systems tracts and surfaces are labeled as they appear in their original publications...

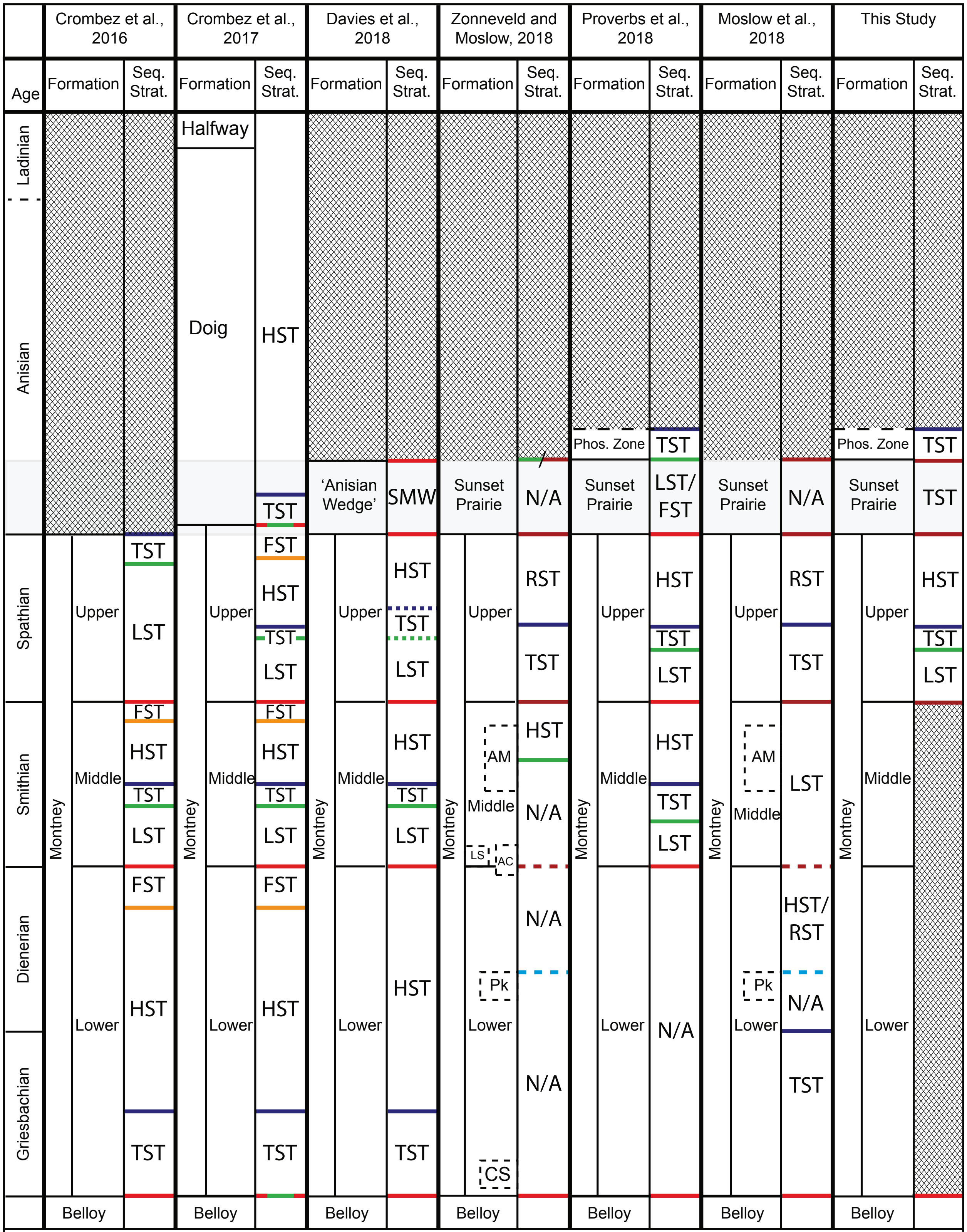


Figure 4.11 cont.–Abbreviations for systems tract include: AGG = aggredation (no systems tract specified); FST = falling stage systems tract; HST = highstand systems tract; LST = lowstand system tract; R = regressive; RST = regressive systems tract; SMST = shelf margin system tract; SWM = shelf-margin wedge; T = transgressive; TST = transgressive systems tract. Stratigraphic member abbreviations include: CS = Calais Sandstone Member; Pk = Pocketknife Member; LS = La Glace Sandstone Member; AC = Anten Coquina Member; AM = Altares Member.

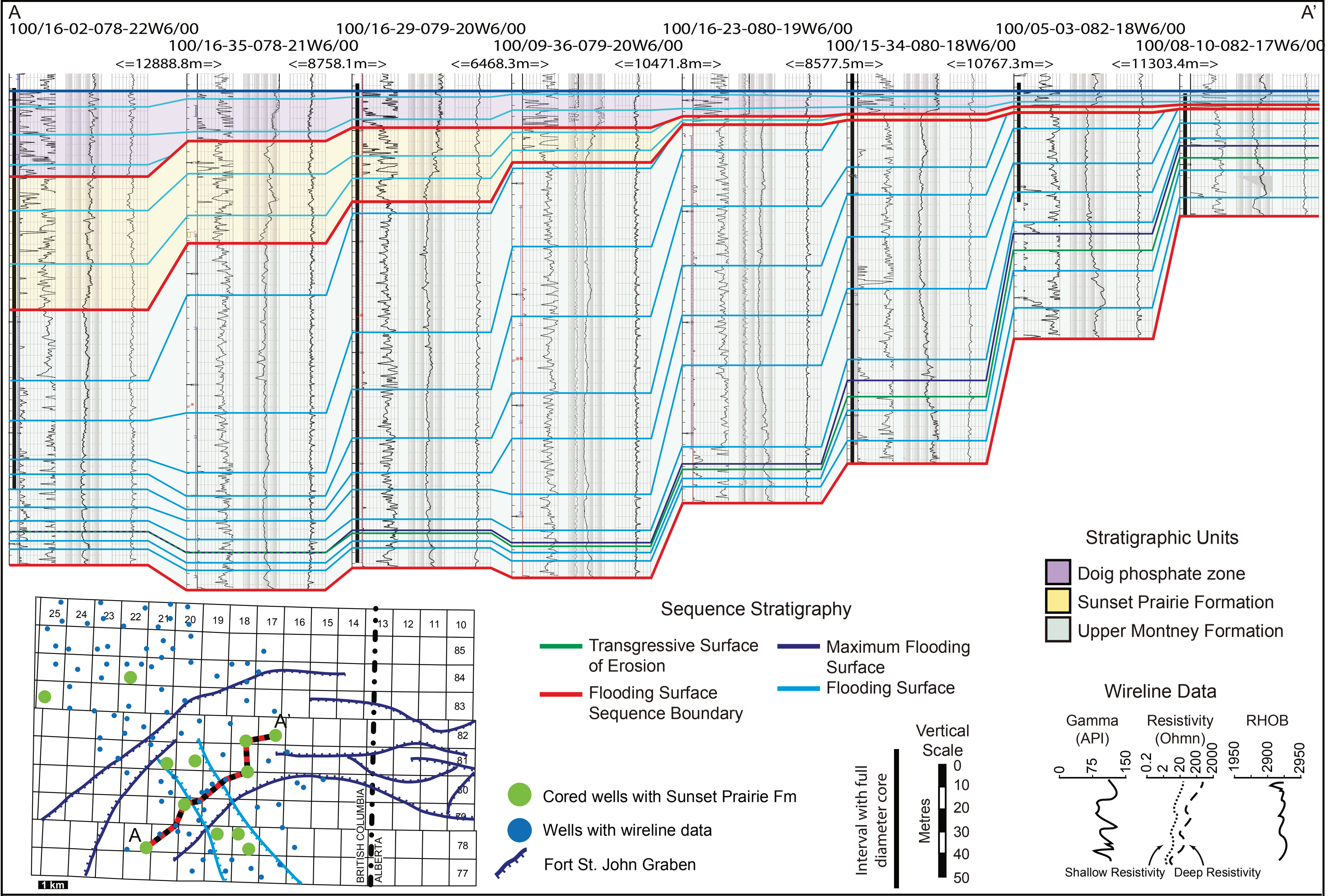


Figure 4.12–Dip-oriented cross section of the Upper Montney Formation, Sunset Prairie Formation and Doig phosphate zone located within the Fort St. John Graben system. Interpreted sequence stratigraphic surface are identified in core, tied to geophysical well logs and extrapolated between cored wells.

sets, instead of parasequences. They suggested that the parasequence sets were made up of multiple coarsening-upward parasequences, but lack any further description of facies distributions in the parasequences themselves, or the distribution of the parasequences within the parasequence sets. We suggest that the parasequence sets identified by Euzen et al. (2018) are more representative of parasequences and record a single, overall shallowing of relative sea level.

The top of the Montney Formation was truncated by the unconformity underlying the Sunset Prairie Formation. The Sunset Prairie Formation was deposited as a transgressive systems tract. The overlying Doig phosphate zone is classically considered a transgressive, condensed section (Gibson and Barclay, 1989). Within the Fort St. John Graben system, the Doig phosphate zone erosionally truncates and onlaps the top of the Sunset Prairie Formation, which suggests that the Sunset Prairie-Doig boundary is a coplanar sequence boundary and transgressive surface of erosion. Figure 4.9 provides a schematic depicting the interplay between relative sea level change and the deposition of the Upper Montney Formation, Sunset Prairie Formation and the Doig phosphate zone.

With the identification of the Sunset Prairie Formation in the Triassic strata of western Canada, the presence of another unconformity-bound sequence must be accommodated. The Montney Formation exhibits three third-order sequences (Douglas, 1970; Barclay et al., 1990; O'Connell et al., 1990; Edwards et al., 1994; Evoy and Moslow, 1995), and the Sunset Prairie Formation constitutes a portion of a fourth Triassic third-order sequence. The addition of another third-order sequence modifies the timing and processes associated with the evolution of the basin.

Structural Influences on Triassic Deposition

The Fort St. John Graben system and the Monias High are two regional structural features that have influenced deposition of both the Montney and Sunset Prairie Formations. Studies of the Montney Formation have suggested that differential subsidence across the basin due to tectonic movement and/or differential compaction of pre-Triassic sedimentary successions produced depositional palaeorelief, which influenced and switched the position of preserved thick intervals (Davies et al., 2018; Euzen et al., 2018; Rohais et al., 2018). The Hudson Hope Low experienced subsidence beginning in the Devonian and continued to be a palaeolow throughout the Triassic (Barclay et al., 1990). The Monias High was a palaeohigh, which can be seen in Belloy Formation structures map (Davies et al., 2018). Within the Montney, regions that exhibit thinned intervals generally correspond to zones where clinoforms change orientation as a result of being deflected around syndepositional highs (Euzen et al., 2018).

Evidence for syndepositional tectonism is present within the Sunset Prairie Formation. The strike-oriented cross section (Fig. 4.6) suggests that structural elements correlate to and likely influenced parasequence set thicknesses. Note that the cross section intersects the major palaeohighs and palaeolows, which impact parasequence distributions and stratigraphic architectures (Fig. 4.6). The Hudson Hope Low within the Fort St. John Graben system preserves the thickest interval of the Sunset Prairie Formation. Thickening that is wider than the area of the Fort St. John Graben system, as described by Davies (1997a, 1997b) and Davies et al. (1997), is likely due to the graben being active during deposition of the Sunset Prairie Formation. Thinning across the Monias High suggests that the structure remained a palaeohigh during the Middle Triassic; however, changes in clinoform orientation were not observed.

Other structural features have been identified and discussed within the Western Canada Sedimentary Basin to have influenced Triassic deposition (e.g. Barclay et al., 1990; Davies et al., 2018; Euzen et al., 2018; Rohais et al., 2018). Many of the small-scale features occur east of the erosional edge of the Sunset Prairie Formation, and are located outside of the study area and/or are of too small a scale to resolve at the scale of this study.

The active margin associated with the western margin of Pangea during Sunset Prairie Formation deposition likely controlled the reactivation and displacement of structural features. The fluctuations in relative sea level, which formed the parasequences, may have a strong correlation with the tectonic pulses associated with the movement of the island arcs along the coast. More research is needed to assess the structural controls on this and other Triassic strata.

Reservoir Distribution of the Sunset Prairie Formation

Understanding the sequence stratigraphic framework for the Sunset Prairie Formation and its stratigraphic relationship with underlying and overlying formations can lead to the better prediction of reservoir targets. Generally speaking, the pervasively bioturbated, very-fine grained sandstone facies have core permeability measurements that are an order of magnitude higher than the minimally bioturbated siltstone-rich facies (Furlong et al., 2016a, 2016b). This difference in permeability in facies is based on the complex interplay between grain size variability, diagenetic features (e.g., secondary porosity, cementation) and biogenic modification of grain distribution. This study does not elaborate on petrographic observations (e.g., grain size, diagenetic features) or specific reservoir properties (e.g., permeability, porosity, TOC distribution) due to the local variability of these characteristics; however, the discussion herein provides an overview of lithological distribution related to net-to-gross sand ratios to better predict where sand-rich reservoir intervals would be located.

Due to the retrogradational nature of the parasequences, the lowermost parasequence is where the thickest packages (up to 7 m) of pervasively bioturbated, very-fine grained sandstone intervals would be observed. Fine-grained sand content, thickness of coarse-grained beds and bioturbation intensity decrease with each following parasequence. The highest ratio of net-to-gross sand is observed at the base of the Sunset Prairie Formation and decrease stratigraphically up (Fig. 4.9; also see lithologs from Furlong et al., 2018a, figs. 4-7).

If the Sunset Prairie Formation were actually a continuation of the highstand systems trace associated with the uppermost part of the Upper Montney Formation, facies distribution and stratigraphic architecture would appear differently. Within the highstand systems tract, progradation of clinoforms produce coarsening-upward parasequence sets, with the most proximal, coarse-grained facies being observed stratigraphically at the top of the formation (Catuneanu, 2006, 2009). This is the opposite of what is observed in the Sunset Prairie Formation. Additionally, the Sunset Prairie Formation truncates the underlying Montney Formation (Figs. 4.9), which would further suggest against the Sunset Prairie Formation being deposited during highstand conditions associated with Montney Formation deposition.

This basin-wide study investigated here provides the overall facies distribution and sequence stratigraphic architecture of the Sunset Prairie Formation, and suggests that the highest net-to-gross sand ratios are observed at the base of the formation. These intervals have the potential to be favorable reservoir targets, when other reservoir characteristics are optimal. Localized studies and detailed hydrocarbon investigations will provide more insight into reservoir characterization of the Sunset Prairie Formation and its potential producibility.

CONCLUSIONS

This study contributes to the sequence stratigraphic framework of the Lower to Middle Triassic of Western Canada by characterizing the stratigraphic architecture of the Sunset Prairie Formation. Through the facies analysis and correlation of parasequences in 25 cored wells and petrophysical well logs of 248 wells, a basin-wide sequence stratigraphic model is proposed for the Sunset Prairie Formation.

Seven facies were identified in the Sunset Prairie Formation, consisting of two diminutively bioturbated facies (Facies 1 and 2), three pervasively bioturbated facies (Facies 3, 4, and 5), and two bathymetrically independent facies (Facies 6 and 7). These facies have been interpreted to represent deposition in the offshore, offshore transition and lower shoreface. Facies stacking patterns suggest that up to three upward-coarsening successions, or parasequences, can be observed in the formation. Each parasequence preserves lower shoreface deposits at their tops; however, the lowermost parasequence preserves the thickest interval of facies associated with proximal depositional settings (lower shoreface setting), whereas the two overlying parasequences preserve thinner beds of proximal facies and thicker intervals of distal facies (offshore transition to offshore deposits).

The stratigraphic architecture of the Sunset Prairie Formation consists of three parasequences constituting the transgressive systems tract. These parasequences are retrogradational, and suggest that the palaeoshoreline moved eastward during deposition of the formation. All three parasequences are truncated by the overlying Doig phosphate zone, indicating that the boundary represents a transgressively modified sequence boundary (FS/SB). The Sunset Prairie Formation directly overlies an unconformity that truncates the underlying Montney Formation, suggesting a transgressively modified sequence boundary (FS/SB) at the contact. Correspondingly, the Sunset Prairie Formation is an unconformity-bound sequence discrete from sequences of the underlying Montney Formation and those in the overlying Doig Formation. With the addition of the Sunset Prairie Formation into the Western Canada Sedimentary Basin, a revision of the sequence stratigraphic model associated with Triassic deposits is necessary.

CHAPTER 5: PROCESS ICHNOLOGY ANALYSIS OF A POST-PERMO-TRIASSIC EXTINCTION RECOVERY FAUNA: A CASE STUDY FROM THE MIDDLE TRIASSIC SUNSET PRAIRIE FORMATION, BRITISH COLUMBIA, CANADA

INTRODUCTION

Process ichnology is a framework outlined by Gingras et al. (2011) that uses biogenic sedimentary structures (trace fossils) to interpret the original physico-chemical parameters under which depositional successions accumulated. The framework builds on many previous trace fossil analyses, including ichnofabric studies (e.g., Taylor et al., 2003; McIlroy, 2008) and ichnofacies studies (e.g., MacEachern et al., 2007a, 2010), and integrates trace fossil characteristics with physical sedimentary structures to interpret depositional parameters acting on the palaeoenvironment. Process ichnology uses data and concepts from neoichnology (the study of modern trackways, burrows and trails), which provides actualistic data for associating biotic responses with physico-chemical stresses and provides a baseline to help interpret trace fossil distributions, diversities, and sizes observed in sedimentary strata.

Fundamental to ichnology is the association of burrow morphology with animal behavior (ethology), which is derived from the fact that organisms respond in predictable ways to variations in environmental conditions (Seilacher, 1964; Frey and Seilacher, 1980; MacEachern et al., 2007a, 2010; Dashtgard and Gingras, 2012; Buatois et a., 2017). Through neoichnological studies, organism responses and tracemaking behaviors can be observed and associated with varying environmental conditions (e.g., Gingras et al., 1999, 2001; 2008; Hauck et al., 2009; Dashtgard, 2011; Baucon and Felletti, 2013; Ayranci et al., 2014; Furlong et al., 2015; Hodgson et al., 2015; LaCroix et al., 2015). A wide range of stresses affect burrowing organisms including physical (grain size, substrate mobility/sedimentation rate [related to hydraulic energy], duration of subaerial exposure [in intertidal settings], substrate consistency and turbidity) and chemical (salinity, oxygen content in the water column, and oxygen content of pore water) (Pearson, 2001; Hubbard et al., 2004; MacEachern et al., 2007b; Dashtgard et al., 2008; Gray and Elliott, 2009; Buatois and Mángano, 2011, Gingras et al., 2011; Dashtgard and MacEachern, 2016; Furlong et al., 2016c). However, the impacts of physico-chemical stresses on burrowing behavior and the resulting ichnological characters are less understood (Dashtgard and Gingras, 2012). Generally, modern studies suggest that the abundance, diversity and size of organisms are the variables that are most directly affected by physico-chemical stresses (e.g. Gingras et al., 1999; MacEachern et al., 2005; Dashtgard and Gingras, 2005; Hauck et al., 2009; Dashtgard, 2011), which corresponds to the abundance, diversity and burrow sizes of element in the trace fossil assemblages preserved in the rock record. Additionally, facies-crossing trace fossils associated with opportunist or trophic generalist tracemakers are also abundant in stressed settings (Beynon et al., 1988; MacEachern et al., 2007b; MacEachern and Gingras, 2007). No single characteristic is diagnostic of a specific physico-chemical stress, but combined with sedimentological observations and when compared with archetypal ichnofacies (*sensu* Seilacher, 1967), physico-chemical stresses acting on a palaeoenvironment can be interpreted (e.g. Howard and Frey, 1973, 1975; Pemberton and Frey, 1984; Ekdale and Mason, 1988; Savarda and Bottjer, 1989, 1991; Gingras et al., 2000; Hubbard et al., 2004; Martin, 2004; MacEachern et al., 2005, 2007b; Hauck et al., 2009; Botterill at al., 2015; Hodgson et al., 2015; Furlong et al., 2015, 2016c; Timmer et al., 2016a, 2016b).

The following study investigates the Middle Triassic Sunset Prairie Formation in northeastern British Columbia, Canada using a process ichnology framework from a subsurface core dataset (Fig. 5.1). The Sunset Prairie Formation sits stratigraphically between the underlying siltstone-dominated units of the Lower Triassic Montney Formation and the overlying phosphatic-rich interval of the Middle Triassic Doig phosphate zone at the base of the Doig Formation (Fig. 5.2). The Sunset Prairie Formation preserves a regionally extensive diverse assemblage of marine trace fossils in northwestern Pangaea (western Canada), following the end-Permian mass extinction (Furlong et al., 2018b). Ichnological assemblages within the underlying Montney Formation generally exhibit low diversities and abundances of trace fossils (Beatty et al., 2008; MacNaughton and Zonneveld, 2010; Zonneveld et al., 2010a; Wood, 2012). However, high diversity assemblages are present within discrete, localized areas that have been interpreted as an environmental refugia, where oxygenated water was present within the shallow-marine realm and locally produced optimum environmental conditions for infaunal organisms (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b). The Sunset Prairie Formation, therefore, provides an excellent opportunity for interpreting depositional dynamics, physico-chemical factors, and biotic/trace fossil sizes and distributions during a biologically diverse time during the post-extinction recovery following the end-Permian mass extinction.

This paper aims to: 1) provide a background on process ichnology; 2) discuss process ichnological trends observed in the Sunset Prairie Formation; 3) interpret physico-chemical stresses influencing the palaeodepositional setting and infaunal organism/trace fossil distributions; 4) infer palaeoenvironmental conditions and trends during the deposition of the Sunset Prairie Formation; and 5) relate ichnological trends observed in the Sunset Prairie Formation to the broader context of biotic recovery following the end-Permian mass extinction.

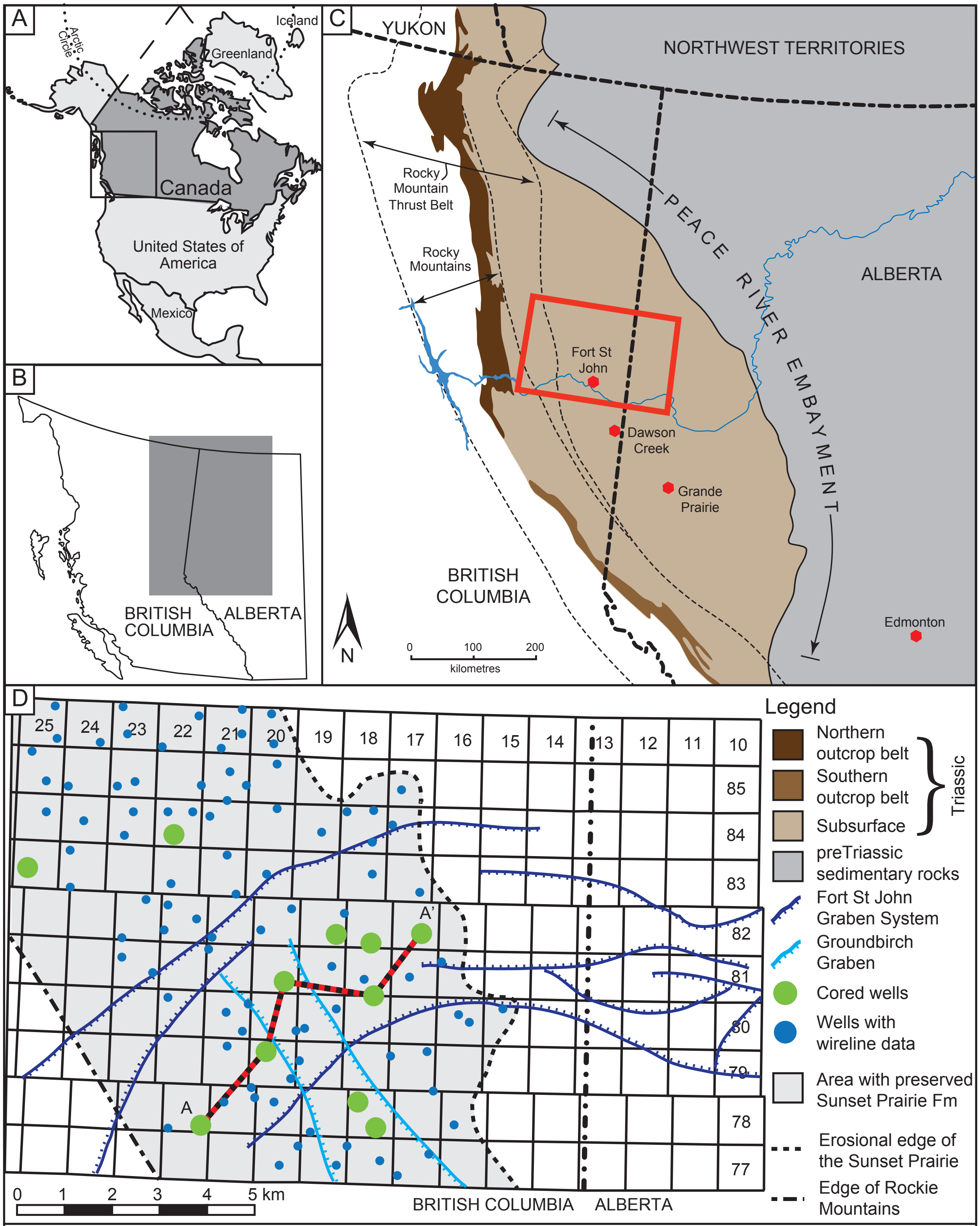


Figure 5.1–Study area map. A Map of North America. Box indicates area enlarged in B. B. Map of British Columbia and Alberta. Area enlarged in C is indicated by the box. C. Regional map of Triassic strata in the Western Canada (modified from Zonneveld et al., 2011). Study area is outlined in red. D. Study area.Structural features identified within the map were compiled from Barclay et al. (1990), Davies (1997a, 1997b), Davies et al. (1997), Berger (2005) and Berger et al. (2009). Erosional edge of the Sunset Prairie was defined by Furlong et al. (2018a, 2018b).

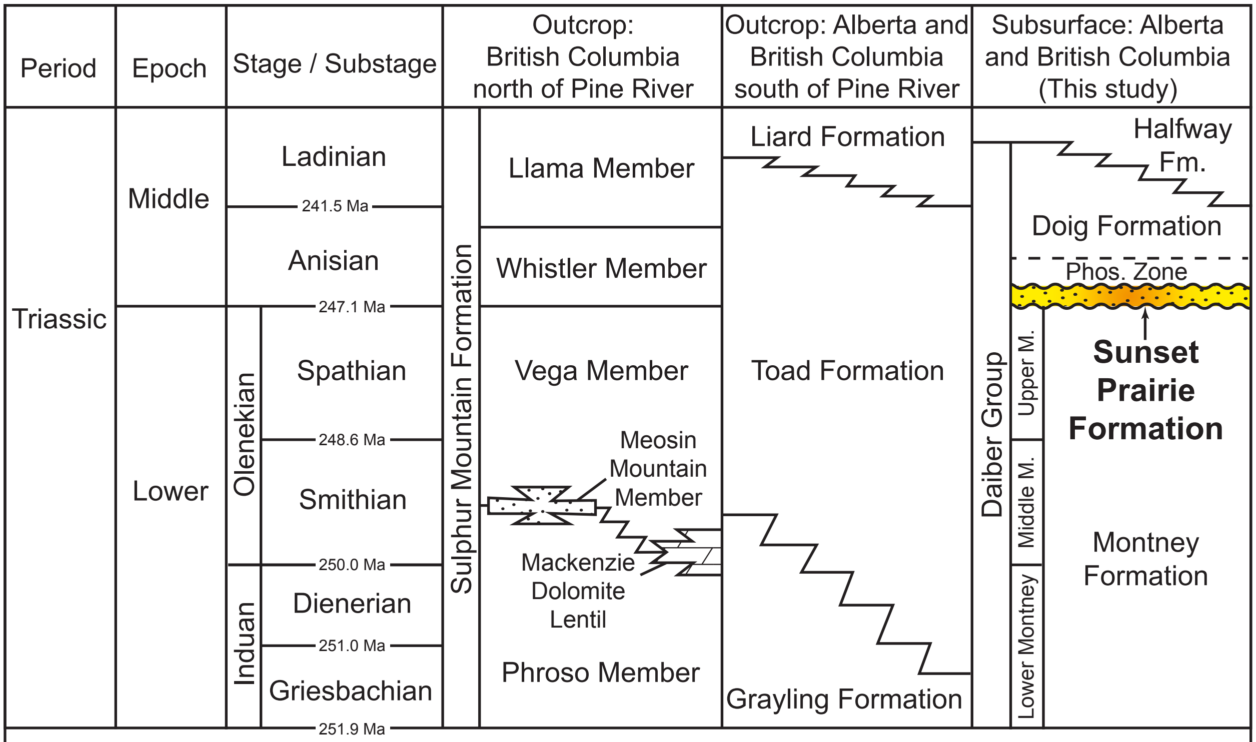


Figure 5.2–Lower and Middle Triassic lithostratigraphic nomenclature for outcrop and subsurface sections in Alberta and British Columbia. Ages of stages and substages identified by Henderson and Schoefer (2017), and Henderson et al. (2018). Modified from Zonneveld (2011) and Golding et al. (2015).

BACKGROUND INFORMATION

Process Ichnology Background

Process ichnology is a semi-quantitative approach to ichnological analysis, which utilizes trace fossils as biogenic sedimentary structures to estimate and infer the presence and magnitude of various physical and chemical stresses operating in the palaeoenvironment. Ichnological characteristics that are considered within the dataset include: 1) the spatial distribution of trace fossils; 2) the diversity and range of ethological characteristics as reflected by observed ichnogenera; 3) the presence or absence of burrow linings; 4) the presence or absence of specific ichnogenera; 5) the size of ichnofossils (burrow diameter); and 6) the degree of deformation of the trace fossils (Gingras et al., 2011). Additionally, bioturbation intensity (BI) (*sensu* Reineck, 1963; 1967; Droser and Bottjer, 1986; Taylor and Goldring, 1993) and Size Diversity Index (SDI) (*sensu* Hauck et al., 2009) can be used as semi-quantitative data to establish relationships between ichnological characteristics and depositional stresses further (e.g., Botterill et al., 2015; Timmer et al., 2016a, 2016b). Fundamentally, the distribution of trace fossils is linked to physical sedimentary processes, whereas the size and diversity of ichnofossils in burrowed substrates are most reflective of the chemical aspects of the depositional environment (Gingras et al., 2007).

Trace Fossil Distribution.—The distribution of trace fossils can be characterized through spatial variability in bioturbation intensity and vertical preservation of trace fossils. Bioturbation Index (BI) provides a semi-quantitative assessment of the percentage or degree of bioturbation within an interval using grades that range from BI 0 to 6 (*sensu* Reineck, 1963, 1967; Droser and Bottjer, 1986; Taylor and Goldring, 1993). The grades of BI include: BI 0 (no bioturbation); BI 1 (1-4%; 'sparse' bioturbation); BI 2 (5-30% 'low'); BI 3 (31-60%; 'moderate' bioturbation); BI 4 (61-90%; 'high' degree of bioturbation); BI 5 (91-99% 'high' degree of bioturbation); and BI 6 (100%, completely bioturbated) (Reineck, 1963, 1967). The intensity of bioturbation can provide information regarding sedimentation rates (although oversimplified); very low levels of BI may be associated with elevated rates of sedimentation, whereas high BI values commonly reflect sedimentation rates that are slow and less variable, and sporadically distributed changes in bioturbation intensities are characteristic of episodically energetic settings (see Ekdale and Bromley, 1991; Bromley, 1996; Taylor et al., 2003; Pemberton and MacEachern, 1997; MacEachern et al., 2005; Dafoe et al., 2008; Gingras et al., 2008). A departure from this trend is observed in high-energy foreshore sand deposits where animals are instratal and do not directly live on the seafloor, which commonly results in the sediment being completely bioturbated by *Macaronichnus* or cryptically bioturbated by meiofauna (Pemberton et al., 2008, 2012).

The vertical distribution of trace fossils reflects the degree of habitat stability and the temporal occurrence of physico-chemical stresses in an environment and can be described as: 1) homogeneous, 2) regularly heterogeneous, or 3) sporadically heterogeneous (Gingras et al., 2011). When nutrients and high dissolved oxygen concentrations are available, homogeneous distributions suggests low sedimentation rates, whereas regularly and sporadically heterogeneous distributions suggest variability and fluctuations in local conditions that may have either a physical or chemical control (i.e. physico-chemical parameters; see Gingras et al., 2011 for description and examples of each). Quantifying the change in bioturbation intensity (ΔBI) within a given bed or interval can describe the variation of infaunal inhabitance relating to fluctuations in sedimentation rates.

Diversity and Range of Ethological Characteristics.—The diversity and range of ethological (behavioural) characteristics are determined by using the number of ichnogenera observable in the facies and the ethology or ethologies commonly associated with the inferred tracemaker(s), respectively. Ethological affiliations are interpreted from neoichnological studies (see Gingras et al., 2007; MacEachern et al., 2007a, 2010). Low diversity assemblages are associated with physico-chemically stressed environments, whereas high diversity indicates optimum conditions (Bromley, 1990; Gingras et al., 2007, 2011; MacEachern and Bann, 2008; Dashtgard and Gingras, 2012). The number of ichnogenera present does reflect biodiversity to some degree; however, trace fossils are identified based on morphology, which reflect an organism's activity, and therefore cannot be ascribed to a single trace-making organism. A single trace-making organism or multiple trace-making organisms can form the same ichnogenera, and a single tracemaker can produce multiple morphologies of burrows associated with a variety of ichnogenera (Ekdale et al., 1984; Bromley, 1996). Ethology can help assess diversity and ichnodisparity by determining the different feeding strategies and favoured morphologies associated with the environment (Buatois et al., 2017). Assigning interpreted ethological affiliation of trace fossils relies heavily on modern setting analogues since body fossils of tracemakers in the rock record are commonly sparse, due to many infaunal organisms being soft-bodied (MacEachern et al., 2010; Dashtgard and Gingras, 2012). Although linking a trace fossil to a specific tracemaker is not necessarily critical, understanding the life strategies employed by infaunal organisms to survive helps establish relationship between ichnofossils, ichnological communities, sedimentary processes and physico-chemical stresses (Gingras et al., 2008).

Burrow Lining.—The presence or absence of burrow linings is commonly associated with the occurrence of shifting substrates in depositional environments (Gingras et al., 2011). Additionally, an increased occurrence of burrow linings is observed as grain size increases from sand to gravel (Dashtgard et al., 2008). Infaunal organisms line their burrows for a variety of reasons, including: burrow-margin lubrication, burrow-wall stability, maintenance of water-saturation levels, waste stowage, symbiotic association with bacteria, passive reaming or re-probing, and accumulation of a biogenic deposit (see Gingras et al., 2011 for further discussion on burrow lining rationales). Although caution needs to be taken when interpreting the reason(s) for an organism to lining its burrow, when combined with other ichnological characteristics and sedimentary features, a rationale can be inferred.

Ichnogeneric Occurrence.—The presence or absence of individual ichnotaxa is not necessarily diagnostic of specific depositional environments; rather, collectively the ichnological suite reflects the prevailing depositional parameters of the setting (Gingras et al., 2011). Classically, the ichnofacies paradigm is a framework derived from spatially and temporally recurring, strongly facies-controlled groupings of trace fossils that reflect specific ethologies (Seilacher, 1967; see MacEachern et al., 2012a for a review). These archetypal Seilacherian ichnofacies are effective in marine to marginal marine settings where animal-sediment responses reflect ambient or optimum environmental settings (MacEachern et al., 2012a). Departure from the archetypal ichnofacies has been associated with brackish-water environments, suboxic to anoxic settings and fluviodeltaic deposition (e.g., Beynon et al., 1988; Pemberton and Wightman, 1992; Martin, 2004; MacEachern et al., 2005; MacEachern and Gingras, 2007; Savrda, 2007; MacEachern and Bann, 2008; Boyer and Droser, 2011; Dashtgard and MacEachern, 2016). Generally, these stressed environments exhibit reduced diversities of trace fossils and are sometimes characterized by monogeneric ichnological assemblages. This makes the Seilacherian ichnofacies model difficult to use when describing such ichnological suites.

Trace Fossil Size.—Ichnofossil size / burrow diameter is directly related to the size of the organism. Any single ichnogenus can show a wide range of sizes within a facies, or from one facies to another. In unstressed settings, a range of burrow sizes can be observed for one ichnogenus due to trace makers performing the same behaviors and producing the same infaunal structures from juveniles to adulthood (MacEachern et al., 2010). By comparison, diminution commonly occurs in stressed settings as a morphologic adaption resulting from size selection and physiological stress (Gingras et al., 2011). Two main reasons for diminution include: 1) achieving a high body surface area to volume (facultative diminution); and 2) regulating physiological stress, which results in energy expenditure going towards regulatory processes and survival rather than towards growth (enforced diminutive) (e.g., Morre and Francis, 1985; Spaargaren, 1979; 1995; Peck, 2000). Both of these factors stem from the organisms dealing with the scaling problem; as the size of an organism increases, the volume increases faster than does the surface area. As organisms grow larger, more oxygen is needed to support the organism, but it becomes harder for the respiratory system of the organism to keep up with oxygen demands, unless the water is well oxygenated. Facultative diminution has been documented from brackish-water settings and warm, oxygen-poor settings (e.g., Gingras et al., 1999; Peck, 2002; MacEachern and Gingras, 2007), whereas enforced diminution has been observed in low- and fluctuating-salinity settings and along latitudinal gradients resulting from dissolved oxygen content and water temperature (e.g., Remane and Schlieper, 1971; Spaargaren, 1979; Roy and Martien, 2001; Peck 2002; Chapelle and Peck, 2004).

Burrow Deformation.—The style and extent of burrow deformation is influenced by the cohesiveness of the sediment, sedimentation rates, stability of the local sediment pile, local sediment-stabilizing influences (e.g., biolamination) and the horizontality of the depositional setting (i.e. higher slopes may occur in delta front, prodeltaic or tidal bar settings) (Gingras and Bann, 2006; Gingras et al., 2011). Post-burial compaction, however, can contribute to burrow deformation. Within soupgrounds, biogenic structures are easily compacted and deformed, whereas firmground substrata commonly preserve large-diameter, non-compacted burrows (Gingras et al., 2000, 2001, 2011). The preservation of unlined trace fossils, which have not been deformed, suggests that the sediment was compacted prior to biogenic modification, and was somewhat cohesive at the time of burrowing (Pemberton and Frey, 1985; Gingras et al., 2000).

Size Diversity Index (SDI).—Two recurring ichnological trends that are observed from studies in stressed settings (e.g., brackish-water settings, anoxic to dysaerobic settings and fluviodeltaic settings). These include: 1) reduction in trace fossil size due to animal-size reduction (diminution); and 2) the decrease in infaunal organism diversity, and therefore burrow morphology diversity (Savrda and Bottjer, 1989; Savrda, 1992, 1995; Gingras et al., 1999). To help quantify the relationship between burrow size and trace fossil diversity, a Size Diversity Index (SDI) was proposed to contribute to process ichnological observations (*sensu* Hauck et al., 2009). Size Diversity Index is calculated by multiplying ichnodiversity (number of ichnogenera observed) by the maximum burrow diameter (irrespective of ichnogenus) for a given bed/interval; SDI can be used as a "disturbance gradient proxy". The concept of SDI builds from size-diversity trends observed along salinity gradients observed within marginal marine settings (Howard and Frey, 1973, 1975; Dörjes and Howard, 1975; Frey and Howard, 1986; Frey et al., 1987; Gingras et al., 1999; Dastgard and Gingras, 2005; Virtasalo et al., 2006; Hauck et al., 2009). Commonly, stressed environments exhibit low diversity ichnological assemblages with small diameter traces, which equate to low SDI values. High ichnological diversity comprising some larger diameter traces (presence of fully developed adults) is associated with unstressed environments, and equate to a high SDI values (Hauck et al., 2009). The calculated SDI is typically an order of magnitude greater in unstressed environments compared to stressed environments. Only a few studies have attempted to calculate and tie SDI to physico-chemical stresses within modern (Hauck et al., 2009) and ancient settings (Botterill et al., 2015; Timmer et al., 2016a, 2016b) and have been interpreted to correspond to chemical stresses in those studies.

Each of these process ichnological characteristics can provide insight by which physico-chemical stresses on palaeoenvironmental settings can be interpreted. However, it is important to stress that no single parameter can be used independently to provide the full explanation of environmental stresses, because many characteristics can be observed in a variety of settings. The combination of process ichnological and sedimentological observations within modern and ancient settings can provide the tools necessary for understanding the relationships between physico-chemical stresses and biotic responses.

Process Ichnology Within Fully Marine Settings

Previous process ichnology studies have focused on shallow water, marginal marine settings (e.g. Hubbard et al., 2004; Hauck et al., 2009; Gingras et al., 2011; Botterill at al., 2015; Timmer et al., 2016a, 2016b). Within these settings, recruitment windows, salinity concentrations, and sedimentation rates act as major factors influencing trace fossil distribution, bioturbation intensity, ichnodiversity, and trace fossil size. Process ichnological analyses have not yet been formally applied to fully marine settings, although numerous investigations of physico-chemical stresses and ichnological responses have been conducted within these settings (Ekdale and Mason, 1988; Föllmi and Grimm, 1990; Savrda and Bottjer, 1986, 1987, 1989, 1991; Wignall, 1991; Savrda, 1995, 2007; Pemberton and MacEachern, 1997; Nilsson and Rosenberg, 2000; Martin, 2004; MacEachern et al., 2005; Dashtgard and MacEachern, 2016).

Both marginal marine and marine settings have advantages and disadvantages when conducting process ichnological studies. Marginal marine settings have a wide variety of physico-chemical stresses acting on the depositional environment, but these stresses have limited spatial and temporal ranges within a given location. This is a function of the ephemeral nature of marginal marine locales, residing between terrestrial and fully marine settings, and having a spatial extent that rarely exceeds a few tens of kilometers. For example, estuarine successions have many environmental components (tidal-fluvial channel, bayhead delta complex, estuary central basin, estuarine tidal flats, etc.) that have distinct facies associations and ichnological characteristics (Ranger and Pemberton, 1991; MacEachern and Pemberton, 1994; Gingras et al., 1999, 2012; Hubbard et al., 2004; Bann et al., 2004; Boyd, 2010). Although assessing the range of physico-chemical stresses in marginal marine settings is complex, attempts have been made to measure and interpret relationships between infaunal assemblages and environmental stresses (e.g., Gingras et al., 2000; Hauck et al., 2009; Botterill et al., 2015; LaCroix et al., 2015; Timmer et al., 2016a).

Fully marine settings, on the other hand, exhibit facies that extend over broader distances and show temporal changes at much slower rates (Plint, 2010; Pemberton et al., 2012). Shoreline successions can persist laterally for tens to hundreds of kilometres along a coastline and can extend tens of kilometres into the ocean resulting in similar facies associations, physico-chemical stresses and ichnological assemblages over vast distances (Plint, 2010; Pemberton et al., 2012). A variety of physico-chemical factors influence fully marine environments, including current and wave energies, grain size, river-sediment influx, distribution and availability of nutrients, mode of food supply, water temperature, ocean chemistry, ocean circulation, and climate. However, many of these environmental parameters are difficult to measure or discern within the rock record. It is also important to note that infaunal organism distributions and abundances constitute multi-variable responses, and are not typically influenced by a single, isolated factor (Newell, 1979). Due to these prolonged, stable environments, multiple generations of infaunal organisms can bioturbate the sediment producing tiering or the ecological stratification of burrows (Seilacher, 1978; Bromley and Ekdale, 1986). For example, large trace fossils like *Zoophycos* have been reported to extend into over one metre into the substrate, with the area of the whorls expanding up to one square metrr (Ekdale and Lewis, 1991; Bromley and Haken, 2003). Three-dimensional complexity of infaunal ecosystems in marine deposits produce challenges for process ichnological data collection that need to be considered. The Sunset Prairie Formation records deposition within a fully marine setting and provides an avenue to formally assess the process ichnological approach within a fully marine dataset.

Sunset Prairie Formation Geological Background

The Sunset Prairie Formation consists of lithofacies deposited in offshore, offshore transition and lower shoreface environments (Furlong et al., 2018b). The deposits accumulated in western Canada during the earliest Middle Triassic (Furlong et al., 2018a, 2018b). Deposition of Lower and Middle Triassic sediment in western Canada occurred on the western margin of Pangea under arid, mid-latitudinal (~30^{O}N) conditions (Wilson et al., 1991; Davies, 1997a; Davies et al., 1997; Dixon, 2000; Moslow, 2000; Zonneveld at al., 2010b). Historically, this was believed to be a passive margin basin, which fostered the development of a marine ramp/shelf setting (Edwards et al., 1994; Dixon, 2009a; 2009b). However, recent work has suggested that Triassic deposition occurred on an active margin, possibly a back-arc-basin (Ferri and Zonneveld, 2008; Miall and Blakey, 2008; Zonneveld et al, 2010a; Schiarizza, 2013; Morris et al., 2014; 2018), a fore-arc basin (Nelson et al., 2006; Colpron et al., 2007; Rohais et al., 2016), or an early foreland basin (Golding et al., 2016; Rohais et al., 2018; Zonneveld and Moslow, 2018).

The Sunset Prairie Formation sits stratigraphically between the underlying Montney Formation and the overlying Doig Formation (Fig. 5.2). The interval is bound by erosional unconformities at its upper and lower contacts (Furlong et al., 2018 a, 2018b). The formation is geographically limited to northeastern British Columbia, with the eastern erosional limit occurring near the British Columbia-Alberta border (Fig. 5.1). Deposition of the Sunset Prairie Formation was basin-wide, but distribution and preservation are greatly influenced by structural components (Furlong et al., 2018b). The interval is thickest within the Fort St. John Graben system around the Hudson Hope Low, thins to the east, and thickens distally to the west/southwest (Furlong et al., 2018b; *in press*).

Palaeoecologically, the Sunset Prairie Formation was deposited during a time of biotic recovery that occurred well after the end-Permian mass extinction. Worldwide anoxic water conditions, acidification of the water column and global warming associated with volcanism from the Siberian Traps coincide with the end-Permian mass extinction at ~250 Ma (Benton and Twitchett, 2003; Black et al., 2012; Payne and Clapham, 2012). Anoxic or dysoxic ocean water conditions greatly influenced benthic assemblages and would have restricted them to narrow, shore-proximal habitable zones (Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011). Ecosystem recovery started during the lowermost Middle Triassic and ichnological communities did not attain pre-extinction levels of diversity and trophic complexity until much later (Twitchett, 1999; Chen and Benton, 2012; Hofmann et al., 2015).

The Sunset Prairie Formation provides a dataset to conduct a process ichnological analysis on interbedded bioturbated and non-bioturbated facies. The interbedded appearance is characteristic of the formation and does not occur in the underlying Montney Formation, suggesting that physico-chemical conditions were different during the deposition of the two formations. Through a process ichnology analysis, a better understanding of the relationship between environment stresses and organism distributions can be deduced for a post-extinction recovery period following the end-Permian mass extinction.

STUDY AREA AND DATASET

The study area is located in the Fort St. John Graben system within the Western Canada Sedimentary Basin (Fig. 5.1). This area was chosen due to the relatively thick preservation of the Sunset Prairie Formation (Furlong et al., 2018b) and the availability of cored wells, which provide stratigraphic control. Five cored wells (16-02-078-22W6, 16-29-079-20W6, 04-11-081-21W6, 15-34-080-18W6 and 08-10-082-17W6) were selected for this detailed process ichnological study. Each selected well had the entirety of the Sunset Prairie Formation present within the drill core, as well as the contacts between the underlying Montney Formation and overlying Doig Formation.

Facies analyses were conducted and described grain size, lithology, physical sedimentary structures, biogenic sedimentary structures (trace fossils), and body fossils. Ichnological data was collected every 10 cm along the core. The 10 cm vertical section of core was used for the data collection bin size due to the high variability in facies thicknesses. Each facies can be less than 4 cm or greater than 3 m in thickness. Other published papers that have analyzed process ichnology data have gathered data every 75 cm (in the Bluesky Formation: Botterill et al., 2015; in the McMurray Formation: Timmer et al., 2016a) and on a bed scale (in the McMurray Formation; Timmer et al., 2016b). However, neither scale was reasonable for the Sunset Prairie Formation dataset as a bin size of 75 cm is too large to capture fine-scale facies changes. Conversely, a bed-scale analysis would be almost impossible owing to the thinly bedded (laminated) character of the interval.

Bioturbation intensity was quantified every 10 cm using bioturbation index (BI), which ranges from non-bioturbated (BI = 0) to pervasively bioturbated/completely biogenically homogenized (BI = 6) (Reineck, 1963, 1967; Droser and Bottjer, 1986; Taylor and Goldring, 1993). The change in bioturbation intensity (ΔBI) is calculated based on the difference between the highest BI and lowest BI observed within the 10 cm interval. The maximum burrow diameter was recorded and was measured using a digital caliper. The diversity (richness) of trace fossils was determined, based on the number of ichnogenera present within the 10 cm vertical section of core. Evaluating diversity by ichnospecies was not employed because of the general inability to classify traces down to an ichnospecies level in the core dataset. Size Diversity Index (SDI) (*sensu* Hauck et al., 2009) was calculated as the product of the ichnodiversity multiplied by the maximum burrow diameter within each 10 cm interval. Additionally, the percentage of different ethologies ascribed to the ichnogenera was calculated. Ethologies associated with burrowing organisms, and thereby their traces, were interpreted based on extensive published data collected from modern analogues (e.g., Gingras et al., 2007). Ethological classification summarized by Rindsberg (2012) was used to interpret feeding strategies associated with trace fossils.

An example of how the process ichnological data would be collected is outlined here: A 10 cm bed possesses *Cylindrichnus* (12 mm in diameter), *Phycosiphon* (0.75 mm in diameter), *Teichichnus* (10 mm in diameter) and *Skolithos* (3 mm in diameter), with bioturbation intensity ranging from moderate (BI = 4) to intense (BI = 6). The change in bioturbation (ΔBI) is 2, maximum burrow diameter is 12 mm, the ichnodiversity is 4 and SDI is 48. Ethologies interpreted to be strongly associated with the preserved burrows include 50% filter-feeding (*Cylindrichnus* and *Skolithos*) and 50% deposit-feeding (*Phycosiphon* and *Teichichnus*) strategies. From the data, process ichnology logs can be produced for each well to visualize changes in ichnological characteristics and interpreted physico-chemical stresses over time.

RESULTS

Lithofacies of the Sunset Prairie Formation

Seven facies were identified within the Sunset Prairie Formation (Figs. 5.3, 5.4). Overall, the facies can be broken into three different groups: 1) Diminutively bioturbated facies (Facies 1 and 2; Fig. 5.5), where physical sedimentary structures are observable and trace fossils are rare and small in size; 2) Pervasively bioturbated facies (Facies 3, 4 and 5; Fig. 5.6), where burrowing organisms homogenized the sediment and destroyed most primary physical sedimentary structures; and 3) Bathymetrically independent surfaces (Facies 6 = *Glossifungites* Ichnofacies; Facies 7 = lag deposit; Fig. 5.7). The seven facies are interpreted to have been deposited within the offshore, offshore transition and lower shoreface environments within a sheltered coastal setting (Furlong et al. 2018b). A thorough description of each lithofacies and rational of depositional environment interpretations are described by Furlong et al. (2018b) and are provided in Chapter 3 of this thesis.

Facies stacking patterns show coarsening-upward packages with distal facies attributed to the offshore and lower offshore transition (Facies 1 and 2), overlain by facies dominantly attributed to the lower to upper offshore transition (Facies 3 and 4), and transition into facies attributed primarily to the lower shoreface (Facies 5) (Figs. 5.5, 5.6). The progradational packages (parasequences) are separated by marine flooding surfaces, which show an abrupt change in facies and interpreted

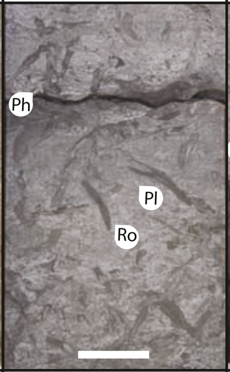
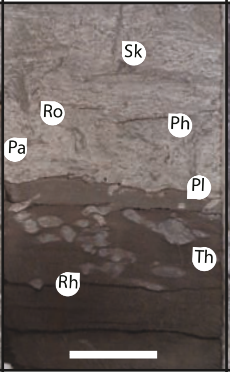
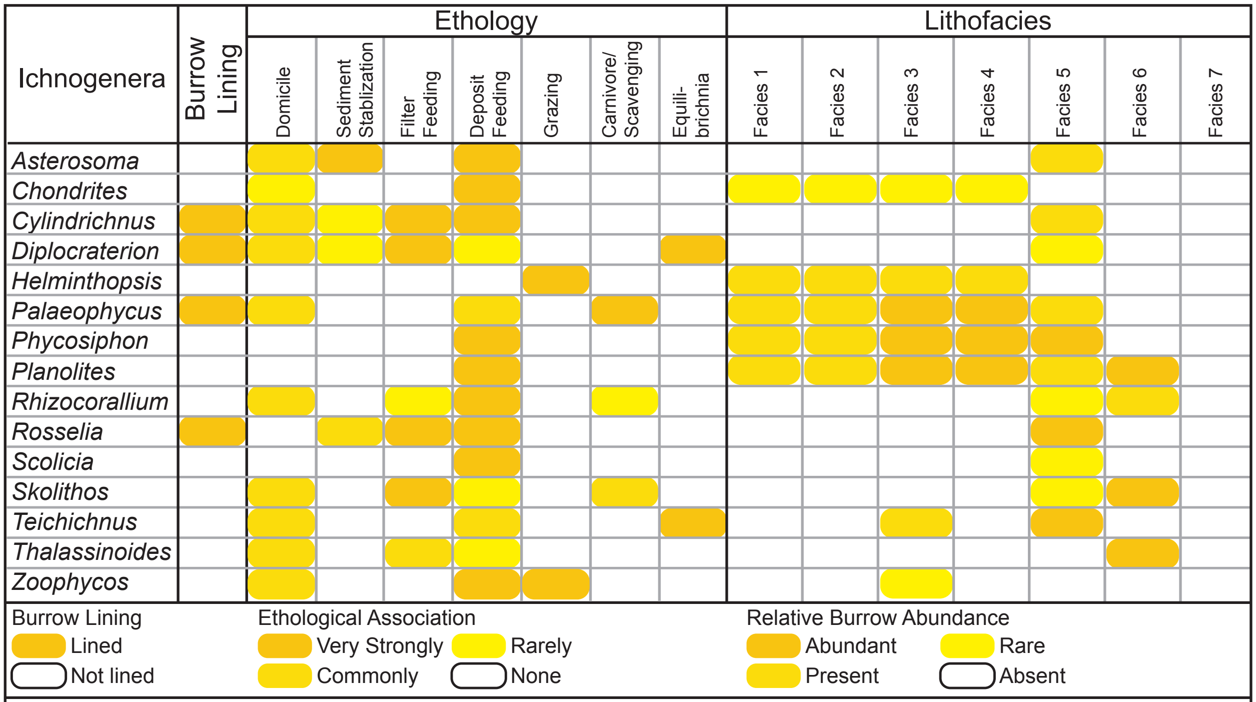
Facies	Diminutively Bioturbated		Pervasively Bioturbated			Bathymetrically Independent	
	F1	F2	F3	F4	F5	F6	F7
Core Expression							
Lithological Description	Dark to medium grey, laminated, bituminous siltstone with minimal bioturbation	Dark to light grey siltstone with minimal bioturbation	Dark to light grey bioturbated siltstone	Pervasively bioturbated medium to light grey siltstone	Pervasively bioturbated sandy siltstone	Burrowed firmground	Amalgamated sandstone and conglomerate bed
Primary Sedimentary Structures	PL, PWL, WL, LACL, HACL, AS, PG, Phos	PSL, PL, PWL, WL, AS, Phos	N/A	N/A	N/A	N/A	Phos
Secondary Sedimentary Structures	PDS, C, HCS	PDS	Phos	PL	PL, WL, LACL, HACL, PDS, AS, Phos	Phos	N/A
Body Fossils	N/A	N/A	N/A	BI, G, BR, E, CR	BI, G, BR, E, CR	N/A	Shell and Bone fragments
Grain Size	Fine to coarse silt	Fine to coarse silt	Fine silt to very fine sand	Fine silt to very fine sand	Fine silt to very fine sand	N/A	Sand to gravel
Ichnological Assemblage	*Ph, He, Pa, Pl, Ch*	*Ph, He, Pa, Pl, Ch*	*Ph, He, Te, Pa, Pl, Ch, Z*	*Ph, He, Pa, Pl, Ch*	*Ph, Ro, Cy, As, Te, Pa, Pl, Sk, Sc, Rh, Di*	*Pl, Sk, Th, Rh*	N/A
BI	0-2	0-2	5-6	4-6	5-6	N/A	N/A
Interpreted Depositional Environment	Offshore to Lower Offshore Transition	Lower Offshore Transition	Lower to Upper Offshore Transition	Lower to Upper Offshore Transition	Upper Offshore Transition to Lower Shoreface	*Glossifungites* surfaces	Lag deposit

Figure 5.3–Summary of lithological, sedimentological, ichnological and palaeontological characteristics of the lithofacies in the Sunset Prairie Formation. Sedimentary structure abbreviations include: AS = Asymmetrical ripples; C = Calcisphere; HACL = High Angle Cross Laminae; HCS = Hummocky Cross Stratification; LACL = Low Angle Cross Laminae; PDS = Penecontemporaneous Deformation Structures; PG = Pyrite Grains; Phos = Phosphate Material; PL = Horizontal Planar-parallel-laminae; PSL = Horizontal-pinstripe Laminae; PWL = Horizontal Planar-parallel-wavy Laminae; Rup = Rip Up Clasts; WL = Wavy Laminae. Body fossil abbreviations include: G = Gastropod; BI = Bivalve; E = Echinoid; BR = Brachiopod; CR = Crinoid. Trace fossil abbreviations include: *As = Asterosoma*; *Ch = Chondrites*; *Cy = Cylindrichnus*; *Di = Diplocraterion*; *He = Helminthopsis*; *Pa = Palaeophycus*; *Ph = Phycosiphon*; *Pl = Planolites*; *Rh = Rhizocorallium*; *Ro = Rosselia*; *Sc = Scolicia*; *Sk = Skolithos*; *Te = Teichichnus*; *Th = Thalassinoides*; *Z = Zoophycos*.



Ichnogenera	Burrow Lining	Ethology							Lithofacies						
		Domicile	Sediment Stablization	Filter Feeding	Deposit Feeding	Grazing	Carnivore/ Scavenging	Equili-brichnia	Facies 1	Facies 2	Facies 3	Facies 4	Facies 5	Facies 6	Facies 7
Asterosoma		🟨	🟧		🟧								🟨		
Chondrites		🟡			🟧				🟡	🟡	🟡	🟡			
Cylindrichnus	🟧	🟨	🟡	🟧	🟧								🟨		
Diplocraterion	🟧	🟨	🟡	🟧	🟡			🟧					🟡		
Helminthopsis						🟧			🟨	🟨	🟨	🟨			
Palaeophycus	🟧	🟨			🟨		🟧		🟨	🟨	🟧	🟧	🟨		
Phycosiphon					🟧				🟨	🟨	🟧	🟧	🟧		
Planolites					🟧				🟨	🟨	🟧	🟧	🟨	🟧	
Rhizocorallium		🟨		🟡	🟧		🟡						🟡	🟨	
Rosselia	🟧		🟨	🟧	🟧								🟧		
Scolicia					🟧								🟡		
Skolithos		🟨		🟧	🟡		🟨						🟡	🟧	
Teichichnus		🟨			🟨			🟧			🟨		🟧		
Thalassinoides		🟨		🟨	🟡									🟧	
Zoophycos		🟨			🟧	🟧					🟡				

Burrow Lining
🟧 Lined
⬭ Not lined

Ethological Association
🟧 Very Strongly
🟨 Commonly
🟡 Rarely
⬭ None

Relative Burrow Abundance
🟧 Abundant
🟨 Present
🟡 Rare
⬭ Absent

Figure 5.4–Distribution, facies abundance and range of ethologies of ichnogenera identified in core. Modified after Gingras et al. (2007) and MacEachern et al. (2007a; 2010).

depositional environment and are associated with an increase in relative base level (Chapter 4; Furlong et al., 2018b, *in review*). Up to three parasequences are present within the Fort St. John Graben system, which exhibit an overall retrogradational stacking pattern (Fig. 5.8) representing the transgressive systems tracts (Chapter 4; Furlong, *in review*).

Process Ichnological Characteristics of the Sunset Prairie Formation

Process ichnology logs were produced for the five wells with drill core (Figs. 5.9, 5.10, 5.11). The logs illustrate facies distribution, the change in bioturbation intensity (ΔBI), maximum burrow size (mm), number of ichnogenera, Size Diversity Index (SDI) and feeding strategies (that are most commonly associated with the trace fossils observed) present within each of the 10 cm intervals. Process ichnological data are summarized in Table 5.1.

Facies 1 and 2 are characterized by low bioturbation intensities (BI = 0-2; ΔBI = 2), and contain a low diversity of trace fossils (0-5 ichnogenera) that are diminutive in size (F1 range = 0-3 mm, F1 mean = 0.09 mm; F2 range = 0.3 mm, F2 mean = 0.23 mm). The calculated SDI values therefore low, ranging from 0-6. Trace fossils include *Chondrites*, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, and *Planolites*. Trace fossils structures are horizontal burrows, with the exception of *Chondrites*, which is exhibit downward radiating probes (Buatois, et al., 2017). Trace fossils associated with deposit-feeding ethologies are most common, however, some grazing forms are

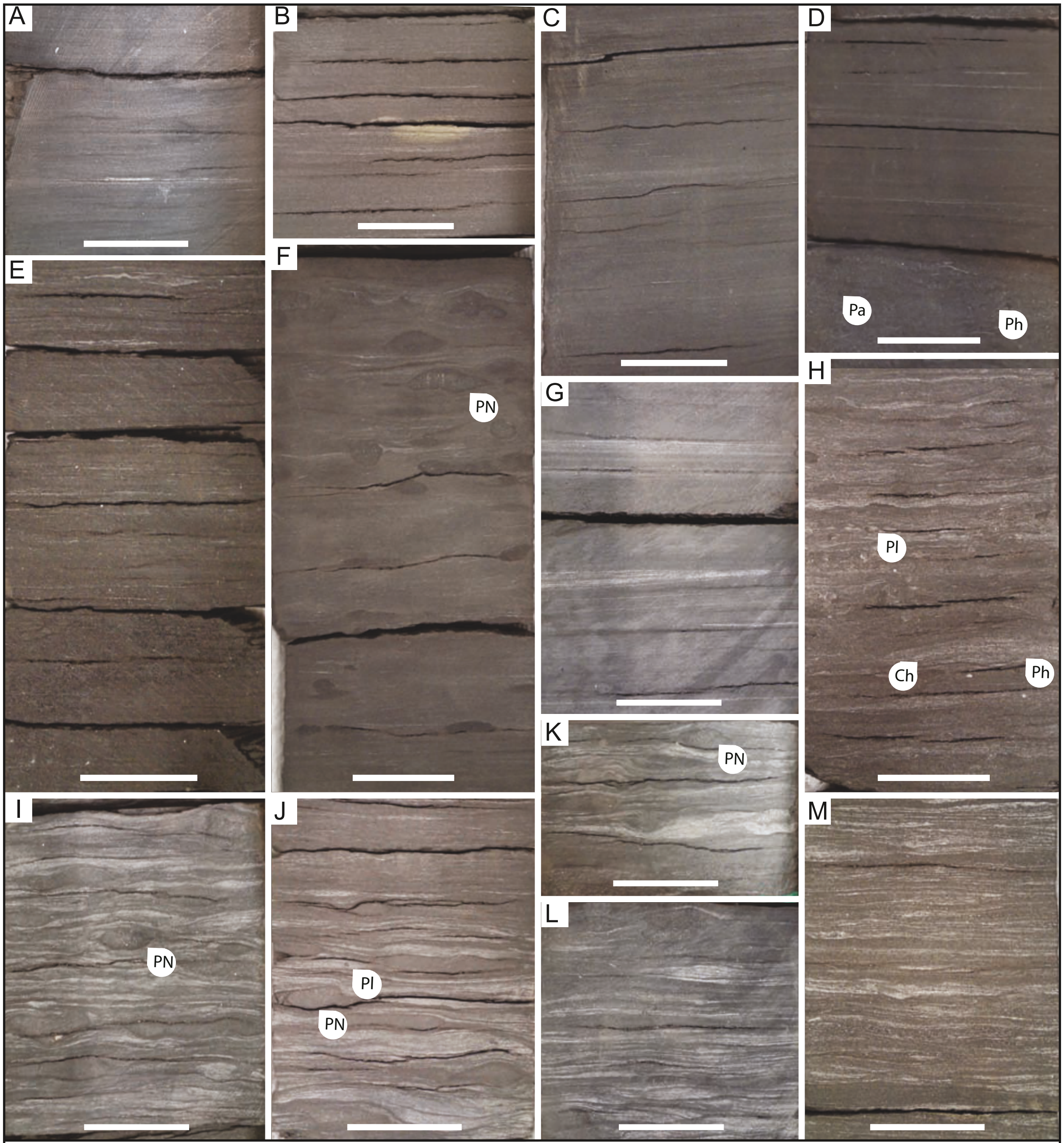


Figure 5.5–Core photographs of Facies 1 and Facies 2 from the Sunset Prairie Formation. All scale bars are 3cm in length. All depths represent core depths. A. Facies 1, medium gray fine-grained siltstone with faint planar laminae (well 04-11-081-21W6, 2077.85 m). B. Facies 1 with pyrite rich horizon (well 16-29-079-20W6; 2199.72 m). C. Facies 1 with fuzzy planar laminae due to cryptobioturbation (well 16-29-079-20W6; 2617.9 m). D-E. Facies 1, medium grey fine siltstone rich in phosphate (D. well 16-02-078-22W6; 2077.4 m; E. well 16-29-079-20W6; 2613.7 m). F. Facies 1, fine-grained siltstone with phosphate nodules (PN) (well 16-29-079-20W6; 2619.5 m). G. Facies 2, fine-grained siltstone with hummocky cross stratification (well 16-02-078-22W6; 3087.0 m). H. Facies 2 with diminutive bioturbation (H. well 16-02-078-22W6; 3065.0 m). I-K. Facies 2, fine- to coarse-grained siltstone with planar to wavy laminae and phosphate nodules (I. well 16-02-078-22W6; 3079.0 m; J. well 16-02-078-22W6; 3078.0 m; K. well 16-02-078-22W6; 3071.1 m). L-M. Facies 2, fine- to coarse-grained siltstone with planar to wavy laminae and unidirectional ripples (L. well 16-02-078-22W6; 3078.5 m; M. well 16-29-079-20W6; 2606.1 m). Trace fossils include Ch = *Chondrites*, Pa = *Palaeophycus*, Ph = *Phycosiphon*, and Pl = *Planolites*.

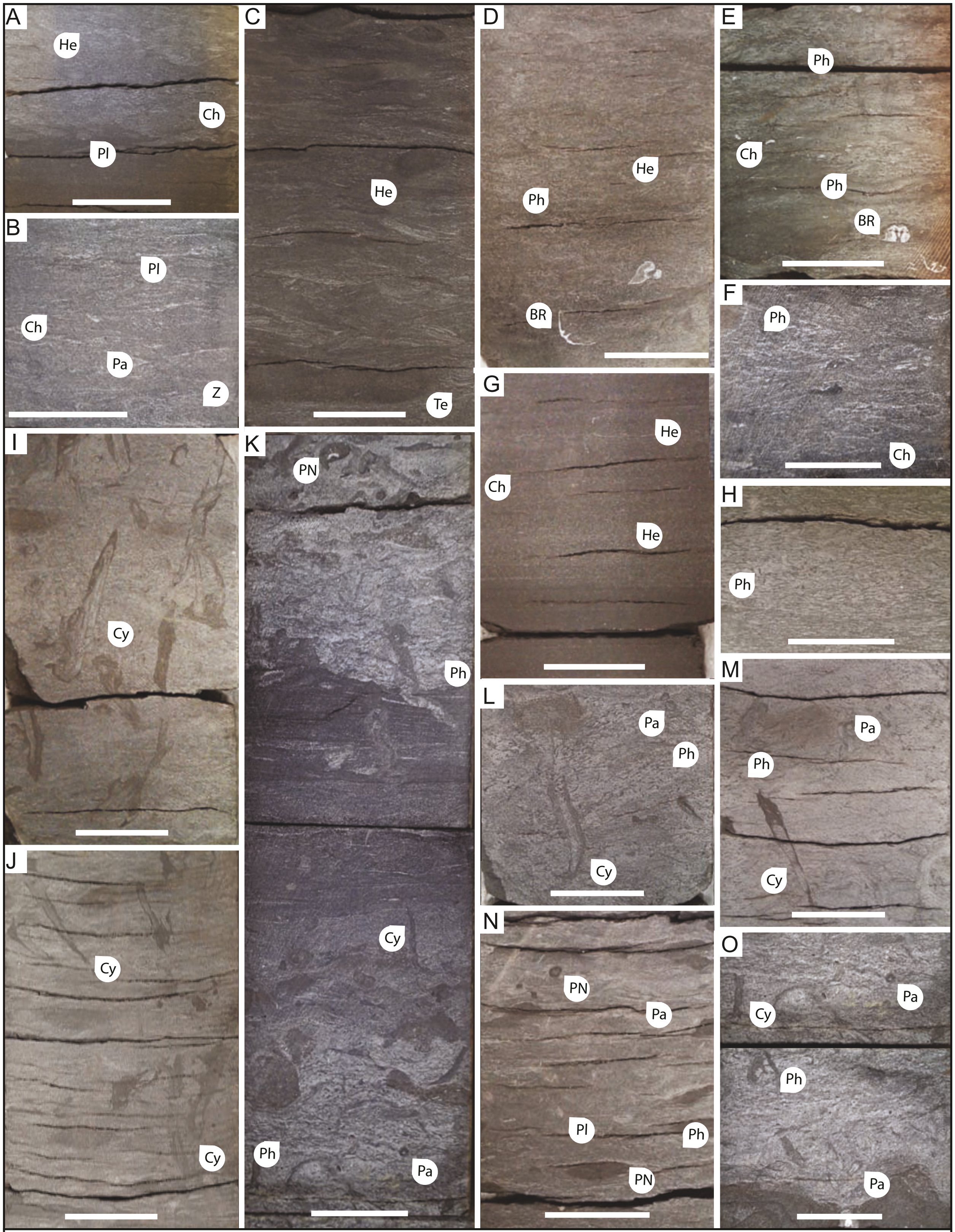


Figure 5.6–Core photographs of Facies 3, Facies 4 and Facies 5 from the Sunset Prairie Formation. All scale bars are 3cm in length unless otherwise denoted. All depths represent core depths. A. Facies 1 overlain by highly bioturbated Facies 3 (well 16-02-078-22W6; 3096.4 m). Figure caption continued on next page ...

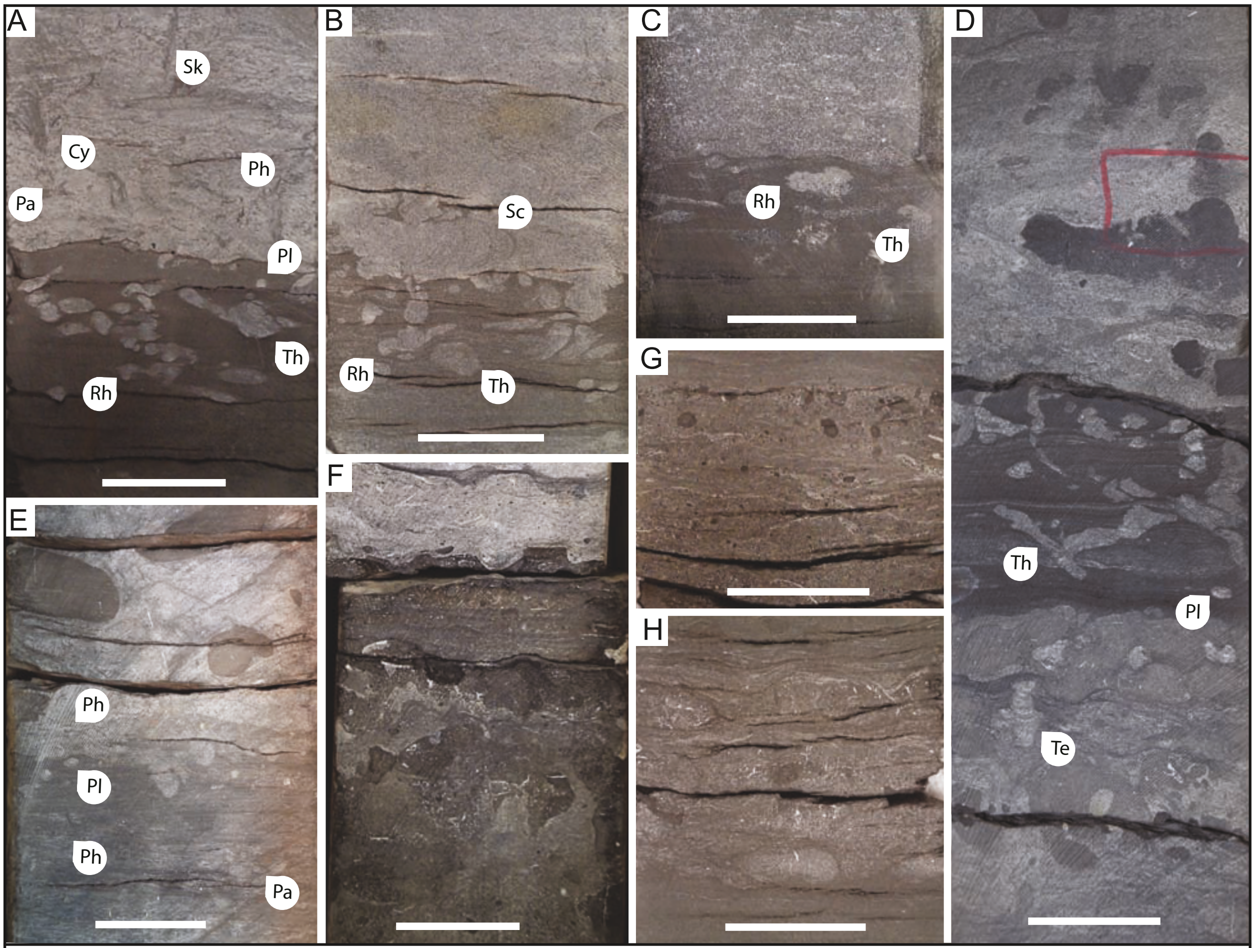


Figure 5.7–Core photographs of Facies 6 and 7 from the Sunset Prairie Formation. All scale bars are 3cm in length. All depths represent core depths. A. Facies 6, *Glossifungites*-demarcated discontinuity surface (well 16-29-079-20W6; 2622.1 m). B-C. Facies 6, *Glossifungites*-demarcated discontinuity surface (B. well 16-29-079-20W6; 2627.1 m; C. well 08-10-082-17W6; 1825.0 m). D. Facies 5 grading into Facies 1 overlain by a *Glossifungites* Ichnofacies and Facies 5 (well 15-34-080-18W6; 2065.5 m). E. Facies 4 capped by a *Glossifungites*-demarcated discontinuity surface, with Facies 5 overlying. Large lithoclasts occur within Facies 5 (well 04-11-081-21W6; 2078.9 m). F. Facies 7 overlain by Facies 6 at the boundary between the Sunset Prairie and the Doig phosphate zone (well 08-10-082-17W6; 1824.5 m). G. Facies 7, capping phosphatically rich sand and ooids (well 16-02-078-22W6; 3055.5 m). H. Facies 7, phosphate nodules within Facies 1 (well 16-02-078-22W6; 3055.9 m). Trace fossils include Cy = *Cylindrichnus*, Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Rh = *Rhizocorallium*, Sc = *Scolicia*, Sk = *Skolithos*, Te = *Teichichnus* and Th = *Thalassinoides*.

Figure 5.6 cont–B. Facies 3, pervasively bioturbated fine-grained siltstone (well 08-10-082-17W6; 1825.4 m). C. Facies 3, dark grey, pervasively bioturbated fine-grained, phosphate-rich siltstone (well 16-29-079-20W6; 2629.2 m). D-F. Facies 4 with robust *Phycosiphon* and isolated brachiopod shells (BR) (D. well 16-02-078-22W6; 3094.0 m; E. well 04-11-081-21W6; 2079.5 m; F. well 15-34-080-18W6; 2065.4 m). G. Facies 4, pervasively bioturbated, medium grey siltstone with sharp contact between bioturbated and non-bioturbated zones (well 16-02-078-22W6; 3067.9 m). H. Facies 4, scale bar = 2cm (well 16-02-078-22W6; 3092.2 m). I-J. Facies 5 consisting of pervasively bioturbated sandy siltstone with robust trace fossils (I. well 16-29-079-20W6; 2615.7 m; J. 16-02-078-22W6; 3058.0 m). K. Facies 5 grading into Facies 1 overlain by a Glossifungites Ichnofacies (Facies 6) and Facies 5 (well 08-10-082-17W6; 1826.4 m). L-M. Facies 5 (L. well 16-02-078-22W6; 2621.8; m. 16-02-078-22W6; 2623.8 m). N. Facies 5 with phosphate nodules (PN) (well 16-02-078-22W6; 3035.3 m). O. Facies 5 with a dense fabric of *Phycosiphon* producing a salt-and-pepper appearance, which is characteristic of the facies (well 08-10-082-17W6; 1826.5 m). Trace fossils include Ch = *Chondrites*, Cy = *Cylindrichnus*, He = *Helminthopsis*, Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Te = *Teichichnus*, and Z = *Zoophycos*.

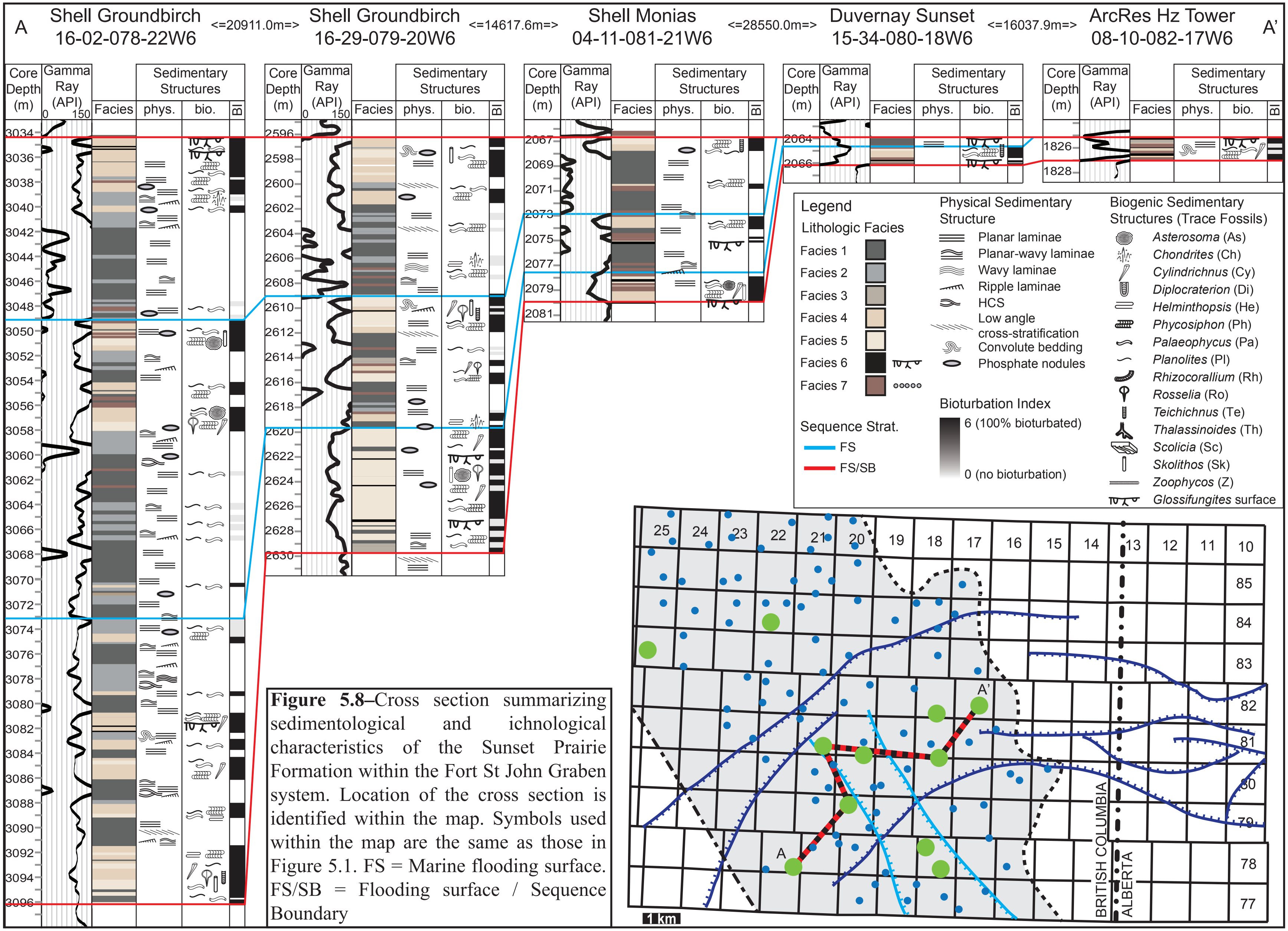


Figure 5.8–Cross section summarizing sedimentological and ichnological characteristics of the Sunset Prairie Formation within the Fort St John Graben system. Location of the cross section is identified within the map. Symbols used within the map are the same as those in Figure 5.1. FS = Marine flooding surface. FS/SB = Flooding surface / Sequence Boundary

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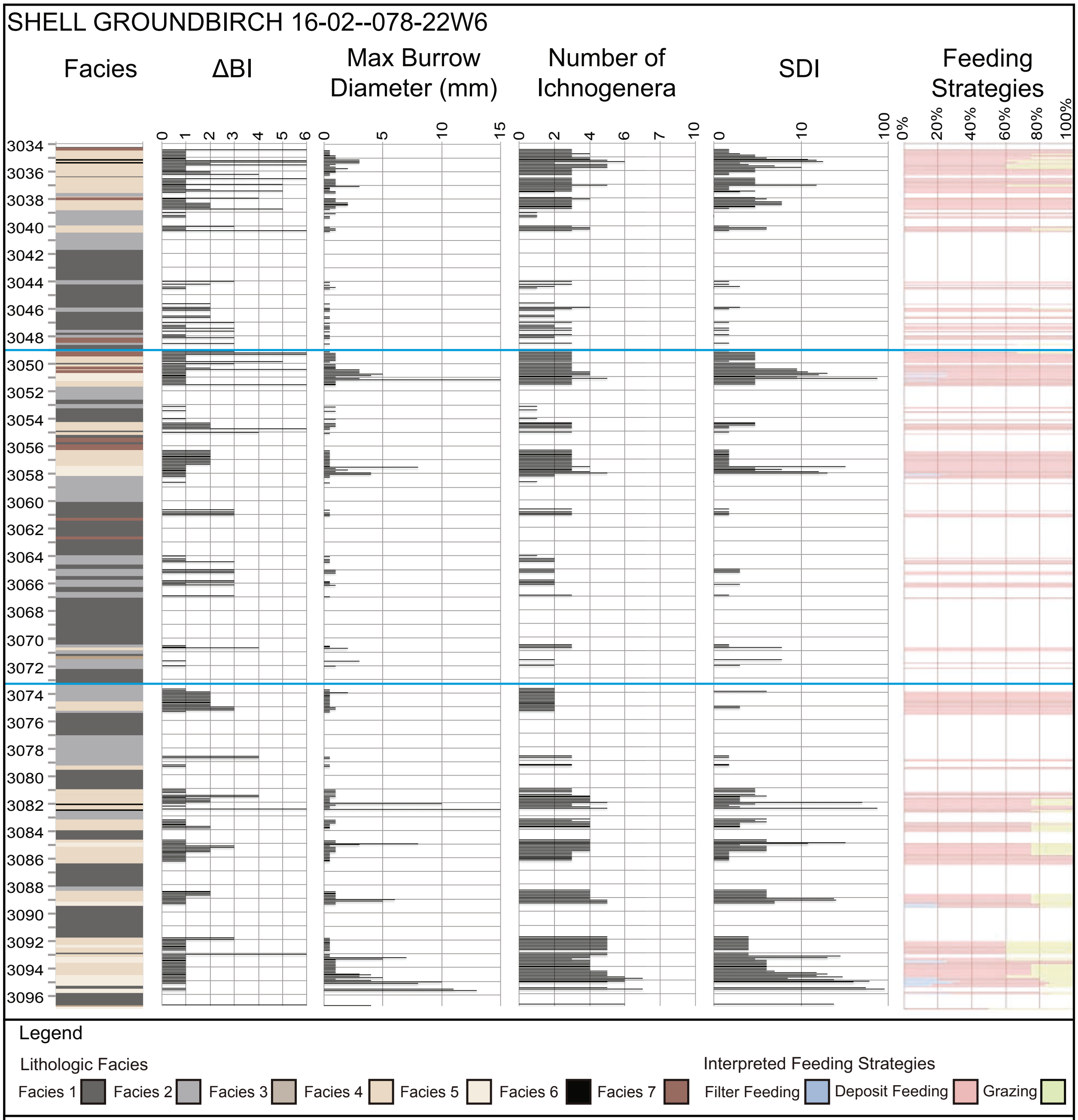


Figure 5.9–Process ichnology log of the core Shell Groundbirch 16-02-078-22W6. Data described includes facies distribution, change in bioturbation intensity (ΔBI), maximum burrow diameter (mm), number of ichnogenera, Size Diversity Index (SDI) and inferred feeding strategies associated with the ichnological assemblage. Data were collected within a 10 cm interval of core. Blue lines represent flooding surfaces.

present (Fig. 5.4).

Pervasively bioturbated facies (Facies 3, 4 and 5) possess high bioturbation intensity (BI = 5-6), minimal change in bioturbation intensity (ΔBI = 0-1) and contain a moderately diverse assemblage of trace fossils (up to 11 ichnogenera). The diameters of trace fossils observed within these facies range from 0.5-15 mm in diameter. Size Diversity Index is variable between different pervasively

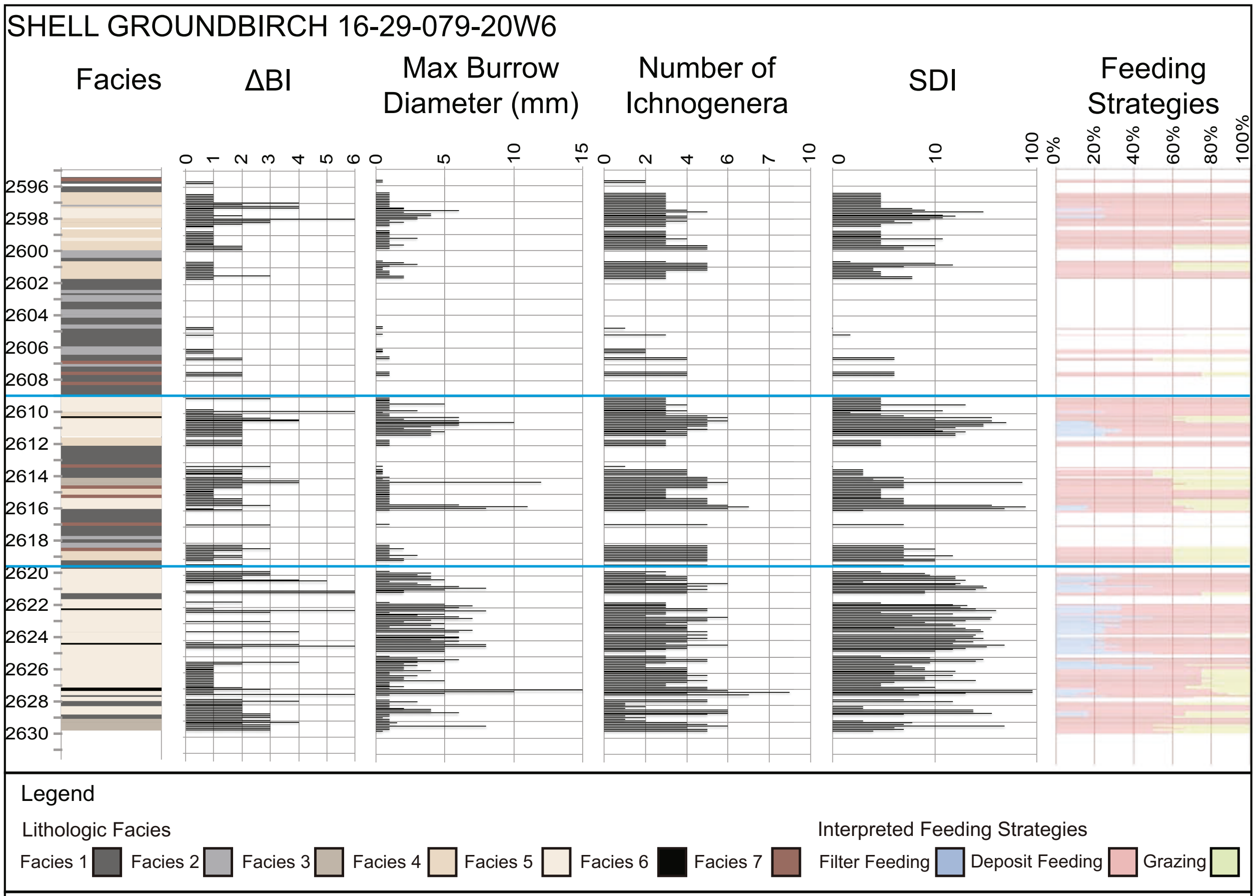


Figure 5.10– Process ichnology log of the core Shell Groundbirch 16-29-079-20W6. Data described includes facies distribution, change in bioturbation intensity (ΔBI), maximum burrow diameter (mm), number of ichnogenera, Size Diversity Index (SDI) and inferred feeding strategies associated with the ichnological assemblage. Data were collected within a 10 cm interval of core. Blue lines represent flooding surfaces.

bioturbated facies and ranges from 4-60 in Facies 3, 2-20 in Facies 4, and 3-90 in Facies 5 (Table 5.1). Trace fossils present in Facies 3 include *Chondrites*, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Teichichnus,* and *Zoophycos*. Facies 4 exhibits a trace fossil assemblage consisting of *Chondrites*, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, and *Planolites*. Trace fossils present in Facies 5 include *Asterosoma*, *Cylindrichnus*, *Diplocraterion*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Rosselia*, *Scolicia*, *Skolithos*, and *Teichichnus*. Trace fossil morphologies include a variety of horizontally- and vertically-oriented, actively- and passively-filled burrows (see Buatois, et al., 2017 for morphologic descriptions and affiliations of each trace fossil). Collectively, trace fossils are associated with deposit-feeding strategies constitutes the main ethology, but grazing forms can be found within Facies 3 and dwellings of inferred suspension-feeding forms are present within Facies 5 (Fig. 5.4).

Glossifungites Ichnofacies (Facies 6) exhibit a low number of ichnogenera (4 ichnogenera) at the surface itself, but up to 9 different ichnogenera are observed within the 10 cm interval where process ichnological data were collected around the discontinuity surface. Trace fossil

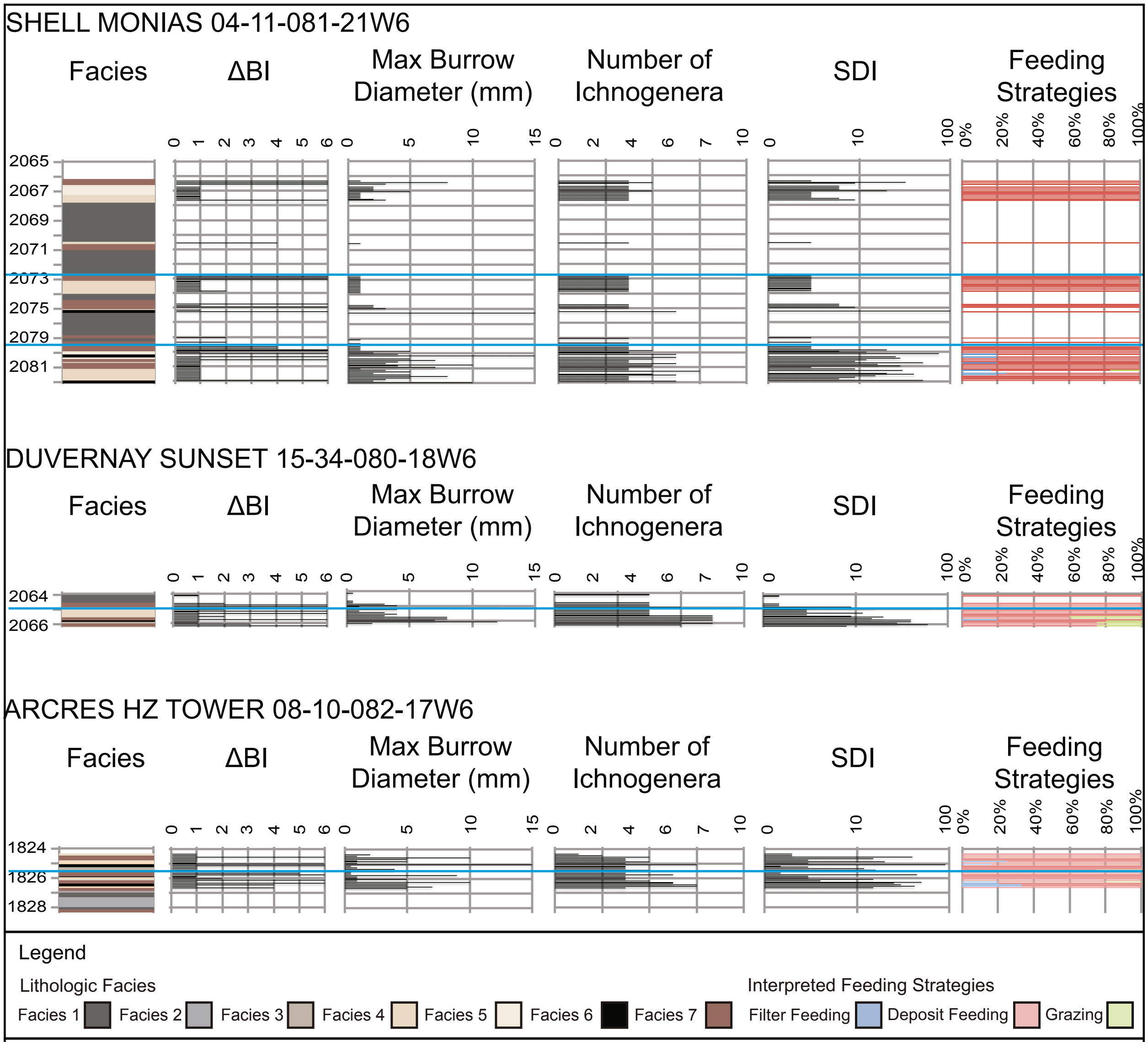


Figure 5.11–Process ichnology logs of the cores Shell Monias 04-11-081-21W6, Duvernay Sunset 15-34-080-18W6 and ARCRES Hz Tower 08-10-082-17W6. Data described includes facies distribution, change in bioturbation intensity (ΔBI), maximum burrow diameter (mm), number of ichnogenera, Size Diversity Index (SDI) and inferred feeding strategies associated with the ichnological assemblage. Data were collected within a 10 cm interval of core. Blue lines represent flooding surfaces.

diameters are large and range from 3-20 mm. Consequently, the calculated SDI is large (12-100). Ichnogenera diversity and SDI are likely overestimated due to those values representing observed trends within a 10 cm interval and not specifically along the *Glossifungites* Ichnofacies-demarcated discontinuity surface itself. Due to the nature of the *Glossifungites* Ichnofacies, different facies are going to lie above and below the borrowed firmground surface. Process ichnological data for this facies, therefore, represents at least three different facies instead of being related to a single facies.

There is a distinct difference between the pervasively bioturbated and minimally bioturbated facies in regards to their process ichnological data. The mean value for the number of ichnogenera,

Facies	**Number of intervals**	**Number of Ichnogenera**				**Burrow Diameter (mm)**				**Size Diversity Index**			
		Range	**Mean**	**Mode**	**SD**	**Range**	**Mean**	**Mode**	**SD**	**Range**	**Mean**	**Mode**	**SD**
1	518	0-5	0.32	0	0.98	0-2	0.09	0	0.28	0-6	0.23	0	0.79
2	159	0-5	0.70	0	1.11	0-3	0.23	0	0.42	0-2	0.50	0	1.02
3	15	3-5	4.63	5	0.96	0.5-12	4.25	1	4.02	4-60	21.31	5	33.63
4	185	2-5	3.60	3	0.80	0.5-6	1.21	1	0.96	2-20	4.46	3	4.10
5	132	3-7	4.10	4	1.11	1-15	4.16	1	2.80	3-90	18.49	3	16.55
6	15*	2-9	5.375	5	1.15	3-20	9.75	10	4.65	12-100	52.75	40	26.07

Table 5.1–Statistical analysis of process ichnological data. Range, mean mode and standard deviation (SD) is provided for the number of ichnogenera (ichnological diversity), burrow diameter (mm) and Size Diversity Index foe each facies. Facies 7 (conglomeratic lag deposit) was not included because it did not possess any traces fossils. The number of 10 cm intervals used to collect process ichnological data is identified for each facies (total of 1024 intervals between the five core). Intervals that exhibited multiple facies were not included in the dataset (totaling 140 data points), with the exception of Facies 6.

burrow diameter, and SDI are all a magnitude lower within the minimally bioturbated facies (Facies 1 and 2) as compared to the pervasively bioturbated facies (Facies 3, 4 and 5) (Table 5.1). Additionally, Facies 4 has a lower mean value for ichnogenera, burrow diameter, and SDI compared to the other pervasively bioturbated facies, suggesting that physico-chemical stresses were different from those associated with the depositional settings of Facies 3 and Facies 5.

Bioturbation index and SDI values generally increase upward stratigraphically within each parasequence (Figs. 5.9, 5.10. 5.11). Facies 1 is most commonly at the base of each parasequence and represents deposition within the most distal setting. Here, bioturbation intensity and SDI are low. Facies 5 caps each parasequence and has the highest bioturbation index and SDI values. Overall, the more distal wells (16-02-078-22W6 and 16-29-079-20W6) possess the thickest and most well-defined expression of the three parasequences, whereas more proximal wells (15-34-080-18W6 and 08-10-082-17W6) possess thin packages that are eroded, amalgamated, and condensed. Different characteristics of the process ichnology logs are further discussed below.

DISCUSSION

Process Ichnology Characteristics and Interpreted Physico-Chemical Stresses

An array of ichnological characteristics can assist in the interpretation of physico-chemical stresses within a depositional setting. Such ichnological characteristics include: 1) characteristic ichnogenera; 2) trace fossil distribution and bioturbation intensities; 3) trace fossil diameter, diversity, and Size Diversity Index (SDI); 4) trace fossil deformation; and 5) trace fossil lining.

Characteristic Ichnogenera.—Generally, individual ichnogenera are not diagnostic of a specific depositional environment; however, trace fossil suites do reflect depositional parameters within the ecosystem. Within this study, ichnogenera present within pervasively bioturbated and minimally bioturbated facies of the Sunset Prairie Formation include *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides*, and *Zoophycos* (Figs. 5.3, 5.4). Collectively, the trace fossils are indicative of marine environments and are characteristic of the *Cruziana* Ichnofacies (Seilacher, 1967; MacEachern et al., 2010, 2012a; Gingras et al., 2011). The *Cruziana* Ichnofacies generally occurs within depositional settings characterized by cohesive soft substrates, low deposition rates, abundant food resources supplied by variable modes, and high levels of dissolved oxygen (MacEachern et al., 2007a, 2010, 2012a; Gingras et al., 2011). These conditions result in a diverse assemblage of trace fossils, a wide range of ethologies, high intensities of bioturbation, and well-developed tiering of trace fossils (Seilacher, 1967, 1978; Ekdale and Bromley, 1983, 1991; Bromley, 1990, 1996; Goldring, 1993; MacEachern et al., 2007a; McIlroy, 2008; Gingras et al., 2011; Buatois and Mángano, 2011).

Trace fossils observed in Facies 6 (*Glossifungites* Ichnofacies-demarcated discontinuity surface; Figs. 5.4, 5.7) include: firmground *Planolites*, *Rhizocorallium*, *Skolithos* and *Thalassinoides*. Substrates associated with the *Glossifungites* Ichnofacies consist of dewatered, cohesive mud/silt, which formed due to either subaerial exposure, or burial and subsequent exhumation (Frey and Seilacher, 1980; Pemberton and Frey, 1985; MacEachern et al., 1992). The substrate is dominated by sharp-walled, vertical to sub-vertical dwelling structures of suspension- and deposit-feeding organisms (Bromley, 1975; Frey and Seilacher, 1980; Pemberton and Frey, 1985; MacEachern et al., 1992; 2010). Trace fossils are typically robust, commonly penetrating 20-100 cm below the bed, and burrow shafts are normally 0.5-1.0 cm in diameter (e.g., MacEachern et al., 2012a). Although the burrow diameter of trace fossils in the *Glossifungites* Ichnofacies within the Sunset Prairie Formation are comparable to published examples, the depths at which burrows penetrate the underlying substrate are much less (<10 cm in depth). From a process ichnology viewpoint, *Glossifungites* Ichnofacies-demarcated discontinuity surfaces can specifically provide several key interpretations about sedimentation rates, duration of colonization, etc. (Pemberton and Frey, 1985; Gingras et al., 2000; 2001), which are addressed later in the discussion of this paper.

Trace Fossil Distribution and Bioturbation Intensity.—Facies present within the Sunset Prairie Formation consist of both minimally (Facies 1 and 2; BI = 0-2) and pervasively (Facies 3, 4 and 5; BI = 4-6) bioturbated facies. In pervasively bioturbated intervals (Facies 3, 4 and 5), physical sedimentary structures are completely disrupted, but individual trace fossils can be observed and identified (Fig. 5.6). Trace fossils within pervasively bioturbated intervals can be described as being homogeneously distributed. In this distribution pattern, trace fossils are evenly distributed both vertically and horizontally in core (Gingras et al., 2011). In order for high degrees of bioturbation to be present, biogenic reworking must exceed physical reworking (Wheatcroft, 1990, Gingras et al., 2007), which suggests that within the extensively bioturbated facies, bioturbation rates surpassed sedimentation rates. According to Gingras et al. (2008), this characteristic is easier to accomplish when ethologies are deposit-feeding and grazing. Additionally, in order to support a diverse association of trace-making organisms, abundant food supply, and ample dissolved oxygen would have been needed. Interpretation of sedimentation rates for minimally bioturbated facies (Facies 1 and 2) are more difficult to render, due to low bioturbation intensities (BI = 0-2) and planar-parallel-laminae being the dominant primary sedimentary structure. However, it is hypothesized that sedimentation rates generally would have been low in the interpreted depositional setting (offshore / offshore transition) (e.g., Reading and Collinson, 1996). The absence of trace fossils observed in minimally bioturbated facies was likely due to physico-chemical stresses other than sedimentation rate.

Changes in bioturbation intensity within individual beds and bedsets are is generally low within the Sunset Prairie Formation. The majority of the intervals have a ΔBI under 2; however, minimally bioturbated facies display low bioturbation intensities (Facies 1 and 2; BI = 0-2), whereas pervasively bioturbated facies exhibit high, though variable, bioturbation intensities (Facies 3, 4 and 5; BI = 4-6). Areas where the change in bioturbation is low generally mean that more consistent conditions were present (Gingras et al., 2011). These conditions can either be optimal for occupation (habitable settings with high bioturbation intensity; BI = 5-6) or inimical to life (uninhabitable settings with low or non-existent bioturbation intensity; BI = 0-1). In both cases, the change in bioturbation intensity is 1, but the percentage of the substrate that has been bioturbated is drastically different. This indicates that the minimally bioturbated facies and pervasively bioturbated facies exhibit different physico-chemical stresses acting on their respective environments, to have made some settings favourable for trace-making organisms (Facies 3, 4 and 5), whereas the others were unfavorable (Facies 1 and 2). The change in bioturbation intensity, coupled with SDI can help illuminate whether a low ΔBI is related to favorable and unfavorable conditions.

Large changes in bioturbation intensity (up to 6) can be observed sporadically throughout the cored dataset (Figs 5.9, 5.10, 5.11). These areas are strongly associated with abrupt changes in facies, thinly bedded fluctuations in facies and with the occurrence of *Glossifungites* Ichnofacies-demarcated discontinuity surface (Facies 6). Because process ichnological data for this study were collected within a consistent 10 cm interval along the drill core, multiple facies could potentially be present within the data collection interval. Understanding the facies distribution of the formation is critical for distilling the rationale for interpreting interpretation of high and low changes in bioturbation intensity.

The occurrence of interbedded pervasively bioturbated and minimally bioturbated facies is largely diagnostic of the Sunset Prairie Formation. Throughout the three observable parasequences in the formation, the distribution of the interbedding of facies changes vertically. The lowermost parasequence has thicker packages (10 cm to 4 m thick) of homogeneously bioturbated sandstone facies with thin intervals (5 cm to 2 m thick) of minimally bioturbated facies (Fig. 5.8). The upper two parasequences have increased thicknesses of minimally bioturbated facies (up to 12 m) and thinner packages of pervasively bioturbated facies (up to 2 m) (Fig. 5.8). The Shell Groundbirch 16-29-079-20W6 cored well best depicts these trends (Fig. 5.8). The changes in internal facies distribution within each parasequence suggest that the lowermost parasequence exhibited prolong depositional periods where fluctuations in physico-chemical stresses were minimal and environmental conditions were generally favourable for trace-making organisms, allowing them to bioturbated thick packages of sediment. However, fluctuations in physico-chemical stresses can be inferred where facies shift to intervals having minimal bioturbation. The upper two parasequences have thicker packages of minimally bioturbated facies suggesting that there were prolonged periods during which the depositional environment was not favorable for supporting infaunal life.

Trace Fossil Diameter, Diversity and Size Diversity Index (SDI).— Tables 5.1 and 5.2 summarized the process ichnological features associated with each facies of the Sunset Prairie Formation. Overall, Facies 1 and 2 have the smallest diameters of trace fossils (F1 = 0-2 mm, F2 = 0-3 mm), lowest diversity (5 ichnogenera) and the lowest SDI (< 6). Facies 3 has larger trace fossil diameters (0.5-12 mm), moderate diversity (7 ichnogenera), and high SDI (4-60). Facies 4 has small diameter trace fossils (0.5-6 mm), low diversity (5 ichnogenera), and moderate SDI (2-20). Facies 5 has large diameter trace fossils (1-15 mm), the highest diversity (11 ichnogenera), and the highest SDI (3-90). Facies 6, which is a *Glossifungites* Ichnofacies-demarcated discontinuity surface, possesses large trace fossils (3-20 mm), low diversity (4 ichnogenera), and moderate to high SDI (12-100). Overall, maximum trace diameter, ichnological diversity and SDI increase stratigraphically upwards within each parasequence, but decrease upwards over the entirety of the formation (Figs. 5.9, 5.10, 5.11).

Process ichnological variables suggest that the mechanisms supporting infaunal settlement and recruitment are limited during the deposition of Facies 1 and 2, were not as restricted during the deposition of Facies 4, and were optimal during the deposition of Facies 3 and 5. This indicates that Facies 1 and 2 were deposited under stressed conditions, Facies 4 was deposited under moderately stressed conditions and Facies 3 and 5 were deposited in more normal marine conditions. Additionally, the *Glossifungites* Ichnofacies (Facies 6) have the largest burrows, moderate to high diversity and SDI, inferring that physico-chemical conditions were optimal to support large-sized organisms.

Trace Fossil Deformation.—Within the dataset, little or no deformation of trace fossils are observed. Many of the trace fossils within the assemblages are very small (<1 mm in diameter), rendering it difficult to assess deformation visually. However, large diameter trace fossils, such as *Rosselia* and *Cylindrichnus*, within Facies 5 are also non-deformed (Fig. 5.6). It is likely that trace fossils are not deformed as a result of the fine-grained nature of the substrate. In previously published examples, burrow deformation generally decreased as grain size decreases from sand to silt, especially when there is no evidence of sediment remobilization (soft-sediment deformation structures and convolute laminae) (Botterill et al., 2015). The lack of soft sediment deformation features suggests a steady, slow supply of sediment, which was mixed by infauna over time (Gingras and Bann, 2006; MacEachern and Bann, 2008). The presence of non-deformed biogenic structures suggests that the substrate consistency was not soupy, and potentially stiff (cf. Gingras et al., 2000 for a discussion of substrate firmness in modern settings).

Trace Fossil Lining.—The most common lined burrow in the Sunset Prairie Formation is *Palaeophycus*, which is observed in all facies. Other lined trace fossils occur within Facies 5, and include *Cylindrichnus*, *Diplocraterion* and *Rosselia*. Lined burrows are commonly associated with shifting substrates (grain entrainment, agitation, and mobilization) (e.g. Gingras et al., 2011); however, sedimentological evidence (limited physical sedimentary structures and no occurrence of biogenic re-equilibration structures) and high bioturbation intensities suggest that low sedimentation rates occurred during the deposition of Facies 5 (Furlong et al., 2018b).

The occurrence of *Teichichnus*, *Rosselia* and *Diplocraterion* have also been used to infer pronounced water turbidity, as the trace-making organisms appear to rely on the collection of fine-grained material (fine-grained silt and mud) from the water column or at the sediment-water interface to use in the burrow lining and biogenic deposit (Gingras et al., 2011; Botterill et al., 2015). However, Facies 5 also contains traces fossils, like *Cylindrichnus*, *Diplocraterion*, *Rosselia* and *Skolithos*, which can be ascribed to suspension-feeding organisms. Such structures are normally associated with generally reduced turbidity (Coates and MacEachern, 1999; Gingras et al., 2007; Bann et al., 2008; MacEachern and Bann, 2008), suggesting that turbidity fluctuations did not play a critical role in infaunal distribution.

Ethological Trends

Ethological (behavioural) activity associated with tracemakers allows feeding strategies, and therefore mechanics of food supply, to be interpreted. A variety of ethological groups have been ascribed to trace fossils and include resting, locomotion, dwelling, feeding, grazing, farming, escape, predation, re-equilibrium and sediment-swimming (Seilacher, 1967; Ekdale et al., 1984;

Gingras et al., 2007; Rindsberg, 2012). Persistent conditions within stable environments favour uniform sedimentary parameters, which allow for ecological optimization, specialization of traces and an overall increase in diversity (cf. MacEachern et al., 2010). High-diversity assemblages, with ichnogenera attributed to a variety of ethologies, reflect depositional settings with reduced physico-chemical stresses or disturbances. As physico-chemical stresses or disturbances are imposed on a depositional setting, organism diversities decline and the specialized structures decrease on favour traces reflecting generalized and opportunistic behaviors (see MacEachern et al, 2007b for a review).

Within the Sunset Prairie Formation, feeding strategies are diverse (Figs. 5.4, 5.9, 5.10, 5.11) and include grazing traces (*Helminthopsis* and *Zoophycos*), deposit-feeding traces (*Asterosoma*, *Chondrites*, *Phycosiphon*, *Planolites*, *Rosselia, Teichichnus, Scolicia*, *Zoophycos*), passive carnivores (*Palaeophycus*), dwellings of filter-feeders (*Cylindrichnus*, *Diplocraterion, Skolithos* and) and dwellings of deposit-feeders (*Rhizocorallium* and *Thalassinoides*). Overall, Facies 1, 2, 3 and 4 possess assemblages of ichnogenera associated with grazing and deposit-feeding organisms, which are mainly characterized by horizontally oriented structures. Facies 5 possesses ichnogenera associated with deposit feeding- and suspension-feeding organisms, which include both horizontally and vertically oriented trace fossils. Although a range of ethologies can be associated with the same trace fossil, the dominant ethology expressed in a trace fossil suite is closely linked to the availability and delivery of food (i.e. the food-resource paradigm; Frey, 1975; Ekdale et al., 1984; Bromley, 1990, 1996; MacEachern et al., 2007b; 2007c; 2012a). When food is suspended within the water column, suspension-feeding strategies are present, but when food is supplied through suspension settling, surface- and subsurface-deposit-feeding behaviors are predominant (Buatois and Mángano, 2011). Although deposit-feeding organisms overwhelmingly dominate the overall ichnological assemblage of the Sunset Prairie Formation, grazing strategies do occur in distal facies (Facies 1, 2 and 3), associated with the offshore and offshore transition. Trace fossils ascribed to suspension-feeding strategies are mainly observed in lower shoreface settings that lie above fair-weather wave base (Facies 5).

Many of the ichnofossils observed are associated with facies-crossing, trophic generalist tracemakers and can be interpreted to represent more than a single ethology. Various trace fossils observed in the Sunset Prairie Formation are associated with infaunal, opportunistic tracemakers suggesting that such flexible behaviours are useful in various ecological niches (Gingras et al., 2007; MacEachern et al., 2010). These trace fossils include Planolites, Teichichnus, Cylindrichnus, Palaeophycus, Skolithos, Rosselia and Thalassinoides. Process ichnology logs (Figs. 5.9, 5.10, 5.11) produced within the study employ the ethological association that is most strongly attributed to each trace fossil present (Fig. 5.4). If other ethological associations are considered when interpreting ethological trends, all trace fossils present can be associated with deposit-feeding strategies, with the exception of Helminthopsis, which is associated only with grazing strategies. This alternate interpretation would suggest that there was no change in food supply, or its availability and delivery between the various facies. On the other hand, some trace fossils can alternatively be associated with suspension-feeding tracemakers. Some trace fossils have very strongly associations with suspension-feeding ethologies (e.g., Cylindrichnus, Diplocraterion and Skolithos), whereas others are commonly or rarely associated suspension-feeding ethologies (e.g., Rhizocorallium) (Fig. 5.4). This slightly shifts the ethological demographic to support palaeoenvironmental conditions favorable for increased suspension-feeding strategies. Unfortunately, there is no way to discern which interpreted ethology best represents a specific trace fossil within the rock record; therefore, using the range of feeding strategies associated with present-day tracemaking organisms is the most effective way to interpret the rock record.

Palaeoenvironmental Implications

Several physico-chemical factors can influence infaunal colonization and distribution, including: sedimentation stresses (heightened depositional rates, episodic deposition, and variability in current energy and direction), salinity stresses, oxygen stresses, variability in food delivery/supply (previously discussed), and substrate consistency (Hubbard et al., 2004; MacEachern et al., 2007b; Buatois and Mángano, 2011). Additionally, larval recruitment is influenced by chemical signals produced by incumbents (individuals already inhabiting the substrate) and predation of larva through micro-grazing (e.g. Maldonado and Young, 2009); however many of these factors are difficult to render within the rock record. Elevated environmental stresses cause ichnological assemblages to depart from archetypal ichnofacies (cf. MacEachern et al., 2007b, 2010). By using different sedimentological and process ichnological characteristics as proxies for physico-chemical stresses, a better understanding of environmental conditions can be deduced.

Sedimentation Stress.—Primary sedimentary structures provide detailed evidence of sedimentation mechanisms, current movement and fluid dynamics within a palaeoenvironment. Sedimentary structures within Facies 1 and 2 indicate that both facies were associated with low- and moderate-energy environments respectively. Facies 1 is a fine-grained siltstone with planar-parallel-laminae. Facies 2 is a fine- to coarse-grained siltstone that exhibits a range of sedimentary structures, including asymmetric ripples, wavy-parallel laminae, pinstripe-parallel laminae and rare penecontemporaneous deformation structures, which suggest increased sedimentation rates associated with depositional currents or oscillatory conditions. Pervasively bioturbated facies (Facies 3, 4 and 5) do not have many observable primary sedimentary structures, owing to infaunal organisms redistributing and disrupting the sediment. This suggests that the rate of bioturbation outpaced the rate of sedimentation. Omission suites of the *Glossifungites* Ichnofacies (Facies 6) are interpreted to be associated with erosion, since the substrate had to be compacted, eroded and exposed for colonization (Gingras et al., 2007). Additionally, Facies 7 (lag deposit) is composed of a variety of grain sizes (sand to gravel), and is interpreted to be associated with transgressive lags (Furlong et al., 2018b). In order for such coarse-grained material to be transported and deposited, hydraulic energies (current, wave or combined flow) needed to be substantial.

The rate of sediment shifting is proportional to grain size and hydraulic energies. Flow from hydraulic energy also influences infaunal settlement and distribution and the degree to which infaunal organisms can interact with sediment (Buatois and Mángano, 2011). Generally, low-energy, marine environments have high bioturbation intensities, whereas increasingly higher-energy marine environments have low bioturbation intensities (Howard and Reineck, 1981; Pemberton and Frey, 1984; MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1997; Gani et al., 2007; Gingras et al., 2007; 2011; MacEachern et al., 2010; Buatois and Mángano, 2011). The change in bioturbation intensity (ΔBI) within high-energy environments is great due to unstable, dynamic conditions; pulses of sedimentation hinder the settlement, growth, and survival of organisms, which may be followed by periods of more ambient conditions, where organisms can partially to fully bioturbate the sediment. One example of such sedimentation and bioturbation trends is observed in storm deposits, where the sediment is laminated to burrowed (lam-scram; Pemberton and Frey, 1984). Conversely, sheltered open coastal environments, when protected from storm erosion, possess high trace fossil diversities, with uniform and high bioturbation intensities (Howard and Reineck, 1981; MacEachern and Pemberton, 1992; Raychaudhuri et al., 1992; Gani et al., 2007).

Rapid/episodic deposition and turbidity can also be associated with influencing the distribution of infaunal activity. Rapid deposition rates are reflected by an overall decrease in bioturbation intensity, a decrease in specialized-feeding strategies for more mobile or temporary (sessile) depositing-feeding strategies (MacEachern et al., 2007b) and an increase in escape traces / equilibrichnia. Dwellings that are indicative of readjustment or re-equilibration, such as *Rosselia* and *Teichichnus*, are common structures associated with rapid, episodic deposition (Nara, 1997; Gingras et al., 2007, 2011; Campbell et al., 2016). *Rosselia* and *Teichichnus* are present within specific facies (F5) of the Sunset Prairie Formation (Furlong et al., 2018b), but no large-scale re-equilibration structures (e.g., stacked *Rosselia*; MacEachern et al., 2005; Buatois et al., 2016; Campbell et al., 2016) are observed in core, suggesting that pulses of rapid sedimentation or storm scouring did not occur.

Settings with increased water turbidity (decrease in relative clarity of the water column) are characterized by ichnological assemblages that exhibit reduced bioturbation intensity and decreased ichnological diversity, and possess trace fossils associated with locomotion, resting, deposit-feeding, and grazing behavior (MacEachern et al., 2005, 2007b). Suspension-feeding organisms are not present due to turbid water reducing primary productivity and clogging feeding apparatuses of filter-feeding organisms (Moslow and Pemberton, 1988; Gingras et al., 1998, 1999; MacEachern et al., 2005, 2007b). Additionally, trace fossils, like *Teichichnus*, *Rosselia*, and *Diplocraterion*, have been used to infer pronounced water turbidity; organisms making these traces likely collect fine-grained material (fine-grained silt and mud) from the water column or at the sediment-water interface to use in the burrow lining and biogenic deposit (Gingras et al., 2011; Botterill et al., 2015). Such traces are present within Facies 5 of the Sunset Prairie Formation, but this facies also contains trace fossils ascribed to suspension-feeding organisms. Therefore, it is unlikely that water turbidity played a significant role inhibiting infaunal colonization by suspension-feeding organisms.

Salinity Stress.—Generally, brackish-water settings exhibit decreased diversity of traces, great abundance of simple, opportunistic structures produced by trophic generalists; locally high bioturbation intensities; and a variation in substrate consistency and depositional rates (e.g. Pemberton et al., 1982; Beynon et al., 1988; Pemberton and Wightman, 1992; Bann and Fielding, 2004; Bann et al., 2004; Buatois et al., 2005; MacEachern and Gingras, 2007; MacEachern et al., 2007b). Due to the low ichnological diversities and diminutive size of trace fossils, SDI values are small in brackish-water settings. Importantly, no ichnogenera are indicative of brackish-water conditions solely based on their presence or absence within the suite (Gingras et al., 2011). However, minute *Gyrolithes, Arenicolites, Skolithos, Cylindrichnus, Planolites, Palaeophycus, Teichichnus, Ophiomorpha* and *Thalassinoides* are commonly observed in brackish-water settings (e.g. Beynon et al., 1988; Gingras et al., 1999, 2007; MacEachern and Gingras, 2007).

The Sunset Prairie Formation does exhibit some of the trace fossils that are commonly associated with brackish-water settings (*Skolithos, Cylindrichnus, Planolites, Palaeophycus, Teichichnus* and *Thalassinoides*), however, the ichnogenera are associated with facies-crossing elements and can be components of fully marine settings (Seilacher, 1964, 1967, 1978). Additionally, facies distribution, palaeogeographic position and basin evolution of the Western Canada Sedimentary Basin suggest that the Sunset Prairie Formation was deposited within a fully marine setting. During the Triassic, the Western Canada Sedimentary Basin was located on the eastern edge of the fully marine, Panthalassic Ocean (Davies, 1997a). Although there has been some discussion of deltaic (perennial and ephemeral deltas) and estuarine environments within the underlying Montney Formation (Miall, 1976; Gibson, 1974; Panek, 2000; Zonneveld and Moslow, 2014; Crombez et al., 2016), little is known about the Early and Middle Triassic shoreline, due to the sub-Jurassic unconformity truncating Triassic strata in an eastward (landward) direction.

Oxygen Stress.—The relationships between ichnological assemblages and reduced oxygen have been summarized by Martin (2004), MacEachern et al., (2007b, 2010), Buatois and Mángano (2011) and Gingras et al (2011). Generally, low dissolved oxygen conditions possess trace fossil suites that reduced in diversity and abundance, have decreased depth/tiering of trace fossils, and have reduced burrow diameters (e.g., Rhoads and Morse, 1971; Bromley and Ekdale, 1984; Savrda and Bottjer, 1987, 1989, 1991, 1994; Diaz and Rosenberg, 1995). That said, other workers suggest that reduced oxygenation does not always exhibit these characteristics (Hudson and Martill, 1991; Wignall, 1991; Wignall and Pickering, 1993). However, the sensitivity of infaunal populations to bottom-water oxygen conditions render ichnological assemblages an excellent proxy for palaeo-oxygenation conditions, where sedimentation and salinity stresses have been deemed unimportant factors in the colonization of the substrate. Aerobic or well-oxygenated facies are recognizable by their intensely bioturbated appearance, diverse trace fossil suite (e.g. Savrda and Bottjer, 1986, 1989; Wignall, 1994; Martin, 2004), whereas dysoxic environments can manifest variable degrees of bioturbation (Martin, 2004). Under anoxia, no bioturbation is present (Savrda and Bottjer, 1986, 1991; Föllmi and Grimm, 1990; Grimm and Föllmi, 1994; Savrda, 1992, 1995; Buatois and Mángano, 2011). However, non-bioturbated substrates do not necessarily indicate anoxic conditions, but can be associated with only slightly lowered dissolved oxygen saturations (Dashtgard and MacEachern, 2016).

Within the Sunset Prairie Formation, minimally bioturbated facies (Facies 1 and 2) have a reduction in burrow size (< 3 mm), ichnological diversity (up to 5 ichnogenera) and SDI (<6) (Table 5.1), which are interpreted to have been a product of reduced oxygen conditions. Due to the presence of isolated burrows throughout these facies, the interval was influenced by episodic dysoxic water conditions at the sediment-water interface and/or within the sediment pore waters. The presence of low-oxygen conditions (dissolved oxygen between 2 and 5 mg/L) suggest that oxygenation was sufficient to support benthic life but insufficient to sustain a diverse assemblage of burrowing organisms (Dashtgard and MacEachern, 2016).

In pervasively bioturbated intervals within the Sunset Prairie Formation (Facies 3, 4 and 5), physico-chemical constraints such as reduced salinity, anoxia and increased sedimentation were not in play. Facies 4 exhibits smaller sized trace fossils (<3 mm in diameter), lower ichnodiversity (2-5 ichnogenera), and lower SDI (2-20) compared to Facies 3 (0.5-12 mm in diameter, 3-5 ichnogenera, SDI = 4-60) and Facies 5 (1-15 mm in diameter, 3-7 ichnogenera, SDI = 3-90). Ichnotaxa in Facies 4 are associated with opportunistic tracemakers. Facies 4 represents environments that were more strongly stressed than the other pervasively bioturbated intervals of Facies 3 and 5, but significantly less stressed than those of the minimally bioturbated facies. These likely represent a shift from suboxic/dysoxic settings (Facies 1 and 2) to more oxygenated settings (Facies 3-5). All five of these facies are interpreted to overlap in an offshore transition setting (Furlong et al., 2018b), and reflect a shift in the oxic-dysoxic boundary within the water column. Facies 1 and 2 are more likely observed when the depositional environment was suboxic/dysoxic, Facies 4 is observed when conditions are slightly more oxygenated, and Facies 3 and 5 are observed when oxic conditions are present.

Substrate Consistency.—Substrate consistency is related to a variety of factors (e.g. grain size, sorting, water content, organics content, mucus binding) and defines the mechanical properties of the sediment (Bromley, 1990, 1996). The consistency of the substrate can be described as soupgrounds, softgrounds, woodgrounds, stiffgrounds, firmgrounds, and hardgrounds (Ekdale 1985; Bromley et al., 1984; Buatois and Mángano, 2011; Gingras et al., 2000, 2001, 2011). Process ichnological data, like trace fossil deformation and the presence/absence of burrow linings, can help interpret substrate consistency types within the rock record (e.g., Pemberton and Frey, 1985).

The Seilacherian ichnofacies framework is divided into five softground marine types (*Psilonichnus, Skolithos, Cruziana, Zoophycos* and *Nereites*), three substrate-controlled types (*Trypanites, Glossifungites* and *Teredolites*), and six softground continental types (*Scoyenia, Mermia*, *Coprinisphaera*, *Termitichnus*, *Celliforma* and *Octopodichnus-Entradichnus*) (Seilacher, 1964, 1967; Frey and Seilacher, 1980; Bromley et al., 1984; Ekdale 1985; Frey and Pemberton, 1987; Buatois and Mángano, 1995; Genise et al., 2000; Buatois and Mángano, 2011). Although it is acknowledged that other, additional, ichnofacies have been proposed (e.g., *Chelichnus*, *Batrachichnus*, and *Brontopodus* Ichnofacies [Hunt and Lucas, 2007]; *Grallator* Ichnofacies [Lockley et al., 1994]; *Entobia* and *Gnathichnus* Ichnofacies [Bromley and Asgaard, 1993; De Gibert et al., 2007]) these are not as yet well established and have not been demonstrated to exhibit the same temporally and regionally extensive consistency as established Seilacherian ichnofacies.

Softground environments are diverse (e.g., marine, marginal marine, terrestrial), and are generally associated with persistent sediment aggradation over time. Substrate-controlled ichnofacies possess trace fossils made by organisms that are capable of penetrating into hardgrounds (*Trypanites* Ichnofacies), firmgrounds (*Glossifungites* Ichnofacies) or woodgounds (*Teredolites* Ichnofacies). Each ichnofacies reflects different substrate consistencies at the time of colonization, and represent palimpsest ichnological suites that cross-cut original trace fossil assemblages. In many instances, substrate-controlled ichnofacies are associated with very slow sediment accumulation and are typically erosionally exhumed discontinuity surfaces (MacEachern et al., 1992; Pemberton and MacEachern, 1995; Gingras et al., 2001; MacEachern et al, 2007, 2012a; Furlong et al., 2015, 2016; Schultz et al., 2016).

In the Sunset Prairie Formation, Facies 1-5 are considered to have been softgrounds (not soupgrounds), during the time of deposition and colonization by infaunal organisms. A variety of trace fossils exhibit burrow linings (Fig. 5.4), there are variable degrees of cross-cutting relationships between trace fossils, and limited deformation of trace fossils is observed within these facies. Softgrounds, generally, have diverse assemblages of burrowing organisms, and high preservation potentials for trace fossils (Buatois and Mángano, 2011).

Facies 6 is associated with a firmground substrate attributed to the *Glossifungites* Ichnofacies. Establishing a firm substrate either implies subaerial exposure and desiccation, or burial, compaction, and exhumation (Frey and Seilacher, 1980; Pemberton and Frey, 1985; MacEachern et al., 1992). Occupants of *Glossifungites*-demarcated discontinuity surfaces are physiologically constructing domiciles in a firm substrate. In high-energy settings, vertical domiciles made by suspension-feeding organisms are commonly observed, whereas horizontal domiciles of deposit-feeding organisms are predominant in low-energy environments (Frey and Seilacher, 1980; MacEachern and Burton, 2000; MacEachern et al., 2007c). Variation in the distribution of firmground burrowing organisms has been related to bathymetry, wave-energy, sediment texture, thickness of overlying sediment veneers, small-scale topographic features, and rheology of the firmground in studies of modern settings (e.g. Pemberton and Frey, 1985; Gingras et al., 2000). Stresses related to bathymetry and tidal zonation (fluctuations in salinity, temperature, desiccation and oxygen saturation) normally occur along shore-parallel trends, whereas lateral variations reflect heterogeneities in sediment texture, sediment veneer and firmness of the substrate (Gingras and Pemberton, 2000; Gingras et al., 2001). Substrate morphology related to small-scale topographic variations influences water current energies, which can expose or cover the firmground with fine- and coarse-grained sediment veneers (e.g. Gingras et al., 2001; Furlong et al., 2015). *Glossifungites* Ichnofacies-demarcated discontinuity surfaces represent a break between erosion and deposition, and is commonly, but not always, related to stratigraphic importance (e.g. MacEachern et al., 1992; Pemberton and MacEachern, 1995; Schultz et al., 2016; see MacEachern et al, 2012 for a review).

Interpreted Palaeoenvironmental Conditions During Deposition

In the Sunset Prairie Formation, oxygen levels appear to have been the dominant physico-chemical stress influencing the biological community. Facies 1 and 2 are minimally bioturbated (BI = 0-2) with diminutive trace fossils (<3 mm in diameter) and represent the most oxygen-deprived settings. Portions of these facies that lack ichnofossils may have experienced reduced dissolved oxygen conditions during deposition. Where trace fossils do occur, elevated oxygen conditions likely prevailed, allowing for a limited infaunal population. Secondary to oxygen stress, increased sedimentation/current energy may have hindered biotic colonization and settlement within Facies 2, where asymmetric ripples, wavy laminae and rare penecontemporaneous deformation structures are observed.

Facies 3 and 5 were deposited within a fully oxygenated environment. A diverse community of infaunal organisms inhabited the sediment and completely bioturbated the substrate (BI = 5-6). Large diameter trace fossils (F3 = 0.5-12 mm; F5 = 1-15 mm) and diverse assemblages (F3 = 7 ichnogenera; F5 = 11 ichnogenera) occur. Deposit-feeding and grazing strategies appear in Facies 3 as a result of food being supplied through suspension settling, whereas suspension-feeding strategies become present in Facies 5, as food suspended in the water column was introduced into the sedimentary environment. Changes in productivity and food supply associated with offshore transition (Facies 3) versus lower shoreface (Facies 5) depositional settings drove the variation in the mode of food exploitation and infaunal recruitment.

Facies 4 was deposited in a somewhat more stressed environment than Facies 3 and 5. The smaller sizes of traces (< 3 mm in diameter), lower ichnodiversity (5 ichnogenera), and greater abundance of ichnotaxa that are associated with opportunistic organisms may reflect a relative decrease in oxygen. The high bioturbation intensity (BI = 4-6) suggests that the environment was not anoxic, nor was the interstitial water as dysoxic as it was during the deposition of Facies 1 and 2. However, large-sized trace fossils, similar to those in Facies 3 and 5, are absent, suggesting that the biological community suffered some stress, possibility due to intermittently reduced oxygen conditions.

Substrate consistency is the main factor influencing infaunal characteristics for Facies 6. Fundamentally, organisms that produced structures attributed to the *Glossifungites* Ichnofacies had to be physiologically capable of penetrating into firm substrates. In the Sunset Prairie Formation, suites of the *Glossifungites* Ichnofacies are associated with erosional events, and therefore increased hydraulic conditions were in operation to erode and remove portions of the substrate. Additionally, a break in sedimentation was necessary to allow organisms to colonize the substrate and produce large burrows (up to 20 mm in diameter). Where Facies 7 directly overlies Facies 6, conglomeratic intervals were deposited, which made the setting inhospitable for burrowing organisms to colonize. Facies 7 is interpreted to be associated with transgressive lag deposits. Increased current and/or wave energies were required to transport the large gravel-sized clasts, silt- to medium sand-sized matrix grains, and abraded shell debris in this facies. All other facies of the Sunset Prairie Formation consist of grains that are fine-grained sand sized or finer, which is significantly finer than grains within Facies 7, and suggests that current and wave energies were much higher during the deposition of Facies 7. Other physico-chemical stresses acting on the infaunal community cannot be assessed due to the lack of preserved trace fossils.

Palaeoenvironmental Trends

In the five facies associated with softgrounds (Facies 1-5), facies stacking patterns exhibit shoaling upward and coarsening upward trends within each parasequence and represents progradational deposition from the offshore though the offshore transition, to the lower shoreface (Fig. 5.12). Parasequences typically have the fine-grained siltstone of Facies 1 and 2 at the base, Facies 3 and 4 interbedded with Facies 1 and 2 within the middle of the parasequence, and the fine-grained sandstone of Facies 5 at the top. At the base of each parasequence is a series of decimetre-scale beds of the conglomerate lag deposit (Facies 7). Facies 6 (*Glossifungites* Ichnofacies) can occur coplanar with Facies 7, but can also separate minimally bioturbated facies from overlying pervasively bioturbated facies. Bioturbation trends with shallowing-upward deposition, in that both trace fossil abundance and diversity increase upward. Although deposit-feeding strategies constitute the purpose of dominant structures throughout the formation, trace fossils associated with grazing are seen in distal facies (offshore transition; Facies 3) and suspension-feeding forms are observed in more proximal facies (lower shoreface; Facies 5). A complete progression of marine ichnofacies (from distal *Nereites* Ichnofacies and *Zoophycos* Ichnofacies, to intermediate *Cruziana* Ichnofacies and finally to shallow-water *Skolithos* Ichnofacies) was not observed within the Sunset Prairie Formation.

Broadly speaking, ichnological data (e.g. SDI) show a trend wherein the depositional basin had oxygen-reduced conditions in the offshore to offshore transition and oxygen-rich conditions in the offshore transition and lower shoreface (Fig. 5.12). Many have suggested that a relationship exists between dissolved oxygen at the sediment water interface/pore water and size of organisms, and therefore their resulting traces (e.g. Savrda and Bottjer, 1986, 1987; Martin 2004). Maximum burrow diameter and ichnodiversity generally increase upward within each parasequence and suggest an increase in dissolved oxygen concentrations in an upward stratigraphic direction within each parasequence. The occurrence of both oxygen-reduced and oxygen-rich environments within the offshore transitions suggests that the bottom water within this setting was variable during the time of deposition.

Although the cores are confined to a relatively small study area within the Fort St. John Graben system, the recurrence of minimally bioturbated intervals interbedded with pervasively bioturbated intervals is observed basin-wide (Furlong et al., 2018b). Thus, general trends in ichnological assemblages, interpreted depositional environments and interpreted physico-chemical stresses as assessed herein can be extended regionally.

Implications for Biotic Recovery Following the End-Permian Mass Extinction

The end-Permian mass extinction was the largest mass extinction of the Phanerozoic. Anoxic and euxinic ocean water have been ascribed as the primary kill mechanism contributing to the rapid decline in biotic diversity (Bottjer et al., 2008). Delayed faunal recovery has also been linked to prolonged global conditions of reduced-oxygen concentrations within marine settings (Hallam,

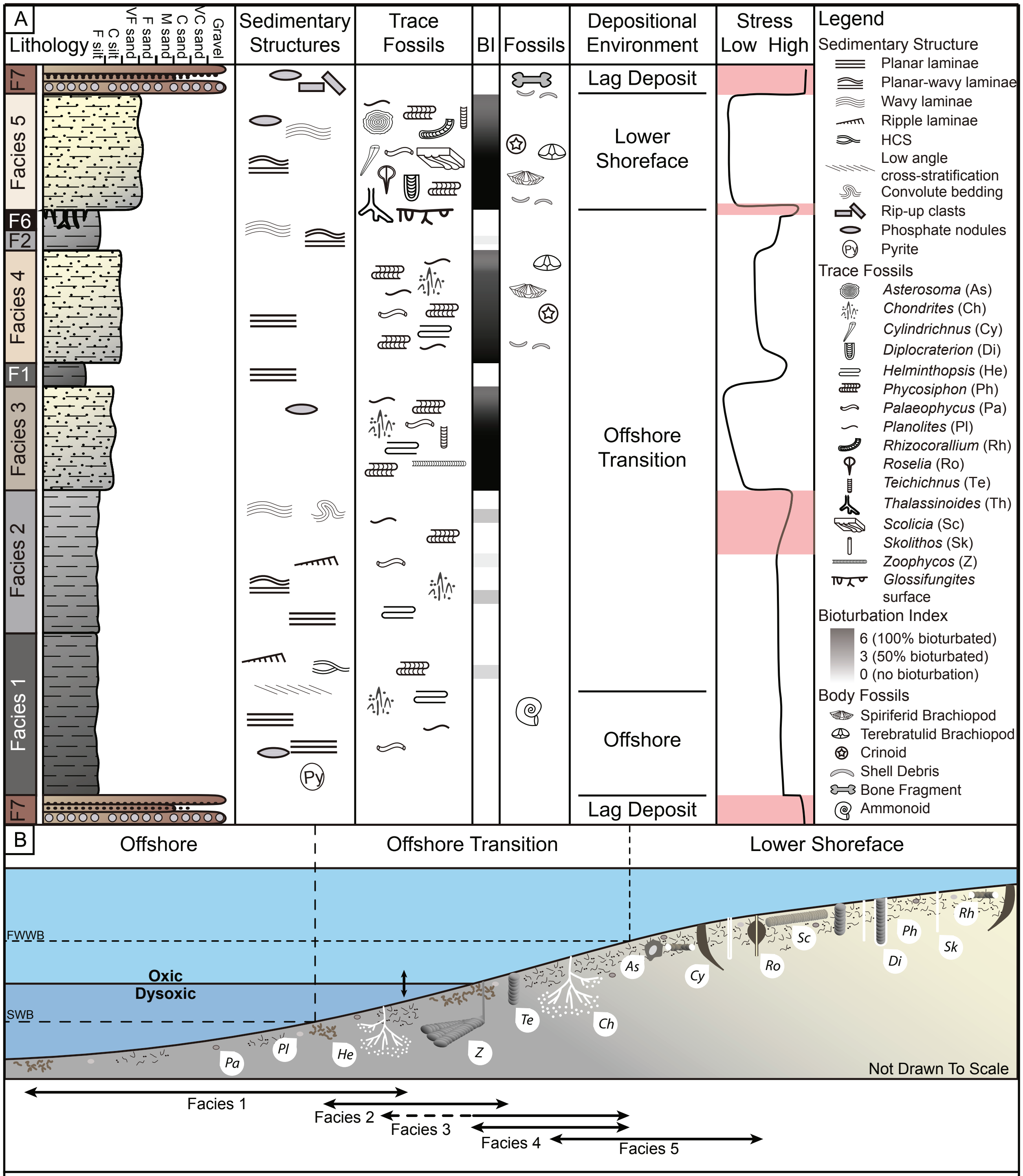


Figure 5.12– Schematic of facies distribution within a parasequence of the Sunset Prairie and interpreted depositional setting. A. Sedimentologic, ichnologic, palaeontologic characteristics of the seven facies associated with the Sunset Prairie. A generalized Bioturbation Index (BI) is provided. Interpreted depositional environments are identified. A physico-chemical stress curve in interpreted to represent fluctuations dissolved oxygen and sedimentation input. Zones with low stress have normal marine conditions with high oxygen levels, whereas high stressed regions have lowered oxygen levels and increased sedimentation rates when supported by observed primary sedimentary structures (e.g., convolute bedding). Areas highlighted in red are facies that are associated with increased sedimentation and/or erosion. B. Generalized shoreface model with trace fossil and facies distribution for the Sunset Prairie Formation. The oxic-dysoxic boundary fluctuates in water depth within the offshore transition.

1991; Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011). Diversity and ecological structure remained diminished through the Early Triassic and observed trace fossils were produced by tracemakers favouring opportunistic behaviours (Harries et al., 1996; Looy et al., 2001; Fraiser and Bottjer, 2004, 2007, 2009; Pruss et al., 2005). Both body fossils and trace fossils have been reported to be considerably smaller relative to those in pre-extinction strata, suggesting that the end-Permian mass extinction is an example of the Lilliput effect (*sensu* Urbanek, 1993; Twitchet, 2007; Schaal et al., 2016). Although ecosystem recovery began during the lowermost Middle Triassic, the tempo and timing of diversity and trophic complexity to pre-extinction levels still remains under debate.

A step-wise recovery of trace-making organisms has been suggested by the documentation of gradual increases in ichnodiversity, burrow size, tiering level and appearance of key ichnotaxa from the Griesbachian to Spathian (e.g., Twitchett and Barras, 2004; Twitchett, 2006); however, other ichnological assemblages favoured a "refuge zone mode," where narrow mid-water regions within shallow-marine settings were locally devoid of anoxic water conditions (Beatty et al., 2005; Beatty et al., 2008; Zonneveld et al., 2010a; Song et al., 2014). Trace fossil distribution for the Sunset Prairie Formation is concentrated within the offshore transition zone and lower shoreface. Distal settings associated with lower offshore transition and offshore environments are typically devoid of all trace fossils; however, when burrows are observed, ichnological assemblages lack the diversity associated with the *Zoophycos* or *Nereites* Ichnofacies. Unlike the Lower Triassic examples (Beatty et al., 2005; Beatty et al., 2008; Zonneveld et al., 2010a;), which record geographically limited occurrences of diverse trace fossil assemblages, the Sunset Prairie Formation represents a regionally expansive habitable zone recoded by bioturbated strata being preserved on a basin-wide scale. However, the interbedded nature of the pervasively bioturbated, diminutively bioturbated and non-bioturbated facies that is characteristic of the formation suggests that bottom water conditions were still periodically reduced (suboxic and potentially dysoxic/ anoxic).

Many studies have begun to investigate recovery of individual ichnogenera, as well as ichnological communities after the end-Permian mass extinction (e.g. Twitchett and Wignall, 1996; Pruss et al., 2005; Twitchett and Barras, 2004; Twitchett et al., 2004; Fraiser and Bottjer, 2009; Chen et al., 2011, 2012; Shi et al., 2015; Zhou et al., 2015; Feng et al., 2017a, 2017b; Luo et al., 2019). Ichnodiversity, burrow size and tiering depth are generally low in early Lower Triassic (Griesbachian to Dienerian) examples, and gradually increase in the late Lower Triassic (Smithian to Spathian) to Middle Triassic (Beatty et al., 2005; Beatty et al., 2008; Fraiser and Bottjer, 2009; Zonneveld et al., 2001, 2010a; Chen et al., 2011, 2012; Shi et al., 2015; Zhou et al., 2015; Feng et al., 2017a, 2017b; Luo et al., 2016, 2019). A few studies show exceptions to this trend, where high diversity assemblages are observed in the Lower Triassic (e.g. Beatty et al., 2005; Beatty et al., 2008; Zonneveld et al., 2010a; Hofmann et al., 2011; Shi et al., 2015; Zhou et al., 2015).

The occurrence of specific ichnotaxa has been associated with different stages of post-extinction recovery (Twitchett and Barras, 2004), with trends in *Planolites*, *Thalassinoides*, *Rhizocorallium* and *Zoophycos* commonly being studied (e.g. Twitchett, 1999; Pruss and Bottjer, 2004; Chen et al., 2011; Feng et al., 2017b; Luo et al., 2019). Temporal and spatial trends in ichnodiversity, burrow size, and tiering depth associated with these ichnogenera have been compiled and summarized by Fraiser and Bottjer (2009), Feng et al. (2017b) and Luo et al. (2019). Notably, the absence of *Zoophycos* has commonly been noted within the Lower and Middle Triassic strata and the form does not appear until the upper Middle Triassic (Knaust, 2004). This observation has been thought to represent a large gap across the Permian-Triassic transition where *Zoophycos*-tracemaking organisms did not exist or that the deep-tier burrowing strategy was not necessary or exploited for survival. However, the Sunset Prairie Formation and Anisian-aged strata (JMC section) in South China (Feng et al., 2017b; Luo et al., 2019) record the first occurrences of *Zoophycos* during the Triassic biotic recovery. Both examples suggest that the tracemaker lineage survived the end-Permian mass extinction, became re-established in nearshore settings, and progressively colonized deeper marine settings throughout the Mesozoic (Knaust, 2004).

Anisian-aged ichnological assemblages are limited worldwide and have been reported from South China (Luo et al., 2016, 2019), Poland (Jaglarz and Uchman, 2010; Kowal-Linka and Bodzioch, 2011; Chrzastek, 2013), Svalbard (Mørk and Bromley, 2008), Israel (Korngreen and Bialik, 2015) and Germany (Knust, 1998, 2007, 2013). Examples of Anisian-aged ichnotaxa were not identified and described in Western Canada, until the recent recognition of the Sunset Prairie Formation (Furlong et al., 2018a). Through this study of the Sunset Prairie Formation, the relationship between ichnological diversity, burrow size and physico-chemical stresses have started to be described, evaluated and interpreted. However, more research is needed to understand ichnological recovery within Western Canada and how it relates to worldwide observations and trends.

CONCLUSIONS

The Sunset Prairie Formation records the deposition of Middle Triassic strata in an embayment on the western margin of Pangea. The formation consists of seven facies, which have been interpreted to represent deposition along the offshore, offshore transition and lower shoreface settings. Overall, facies can be broken into three categories: 1) Diminutively bioturbated (Facies 1 and 2), where physical sedimentary structures are observable; 2) Pervasively bioturbated (Facies 3, 4 and 5), where burrowing organisms have homogenized the sediment and destroyed most primary physical sedimentary structures; and, 3) Bathymetrically independent surfaces (Facies 6 = *Glossifungites* Ichnofacies; Facies 7 = lag deposit).

Oxygen level fluctuations across the different depositional environments are interpreted to be the dominant stress influencing infaunal distribution. Minimally bioturbated siltstone facies (Facies 1 and 2) represent deposition in suboxic (to potentially dysoxic/anoxic) settings of the offshore and offshore transition, pervasively bioturbated siltstone to sandstone intervals (Facies 3 and 5) are interpreted to be deposited within the offshore transition and lower shoreface where the sediment-water interface exhibited oxic conditions. The pervasively bioturbated Facies 4 is interpreted to represent deposition in the offshore transition when dissolved oxygen levels were higher than those in minimally bioturbated facies, but were not fully oxygenated. Trace fossils associated with trophic generalists are observed in Facies 4, consistent with an oxygen-decreased setting. Subtle morphological and ethological changes in the ichnological assemblage are observed in pervasively bioturbated facies, suggesting changes in productivity and food supply. Although all three facies are dominated by horizontally oriented structures associated with deposit-feeding tracemakers, grazing forms are observed in Facies 3, whereas vertically-oriented, suspension-feeding forms are observed in Facies 5. Secondary to oxygenation variability across the shoreline succession, sedimentation/erosion is interpreted to influence Facies 2 (where asymmetrical ripples, wavy laminae or convolute beds are present), Facies 6 (*Glossifungites* Ichnofacies–demarcated discontinuity surfaces) and Facies 7 (conglomeratic lag deposits).

Through the framework of process ichnology, physico-chemical stresses acting on the palaeodepositional environment can be interpreted. Collectively, this is the first study to formally use the process ichnological model to assess physico-chemical stresses influencing a fully marine setting. This investigation provides the validation that the framework can be expanded beyond marginal marine settings and adapted to explore the relationship(s) between physico-chemical stresses and ichnological responses within marine environments. Findings from ichnological trends within the Middle Triassic Sunset Prairie Formation can be used to better understand the biotic recovery trends within western Canada and worldwide following the end-Permian mass extinction.

CHAPTER 6: INTEGRATION OF ICHNOLOGY AND GEOCHEMISTRY: EVIDENCE FOR OXYGEN FLUCTUATION DURING THE DEPOSITION OF THE MIDDLE TRIASSIC SUNSET PRAIRIE FORMATION, BRITISH COLUMBIA, CANADA

INTRODUCTION

Fluctuations in dissolved oxygen have been inferred through ichnological analysis throughout the past few decades and stem from a few foundational oxygen-related models (Rhoads and Morse, 1971; Savrda and Bottjer, 1986, 1987, 1989; Ekdale and Mason, 1988; Wignall and Myers, 1988). Aerobic or well-oxygenated facies are recognizable by their heavily bioturbated appearance and diverse trace fossil suites, whereas dysoxic environments can exhibit a variable degree of bioturbation (Savrda and Bottjer, 1986, 1989; Wignall, 1994; Martin, 2004). Generally, successions deposited under low dissolved oxygen conditions possess trace fossil suites that are reduced in diversity and abundance, have decreased depth/tiering of trace fossils, and decreased burrow diameters (e.g., Rhoads and Morse, 1971; Bromley and Ekdale, 1984; Savrda and Bottjer, 1987, 1989, 1991, 1994; Diaz and Rosenberg, 1995), although others have suggested that reduced oxygenation does not always exhibit these characteristics (Hudson and Martill, 1991; Wignall, 1991; Wignall and Pickering, 1993). Under anoxic conditions, no bioturbation is present (Savrda and Bottjer, 1986, 1991; Föllmi and Grimm, 1990; Grimm and Föllmi, 1994; Savrda, 1992, 1995; Buatois and Mángano, 2011).

Geochemistry has played an even larger role in interpreting palaeoredox conditions, in addition to many other palaeoenvironmental proxies (e.g. Calvert and Pedersen, 1993; Tribovillard et al., 2006; Little et al., 2015). However, the integration of ichnological and geochemical data has only been conducted by a handful of authors (Wignall and Myers, 1988; Werne et al., 2002; Algeo et al., 2004; Martin, 2004; Izumi et al., 2012; Kemp and Izumi, 2014; Dashtgard and MacEachern, 2016; Haddad et al., 2018). In many of these studies, geochemical marine redox proxies and ichnofabric index were plotted according to outcrop height. The ichnofabric index used in those studies is analogous to the bioturbation index (BI), or the degree in which sediment has been disrupted and reworked by burrowing organisms (Reineck, 1963, 1967; Droser and Bottjer, 1986; Taylor and Goldring, 1993). Trends between bioturbation intensity and redox-sensitive elements were discussed, but datasets were not empirically compared.

The purpose of this study is to present empirical data demonstrating the relationship between ichnological characteristics and geochemical responses to redox conditions during deposition of the Middle Triassic Sunset Prairie Formation in the Western Canada Sedimentary Basin. The formation provides a unique dataset in which pervasively bioturbated facies are interbedded with diminutively bioturbated and non-bioturbated facies. Through the high-resolution sedimentological, ichnological and geochemical analysis of three drill cores, palaeoredox conditions are interpreted for the facies associated with the formation. Additionally, vertical and lateral trends are discussed. Understanding the palaeoredox conditions associated with the Sunset Prairie Formation can provide insight into the dynamic palaeoenvironmental conditions associated with the lowermost Middle Triassic of Western Canada.

GEOLOGIC SETTING

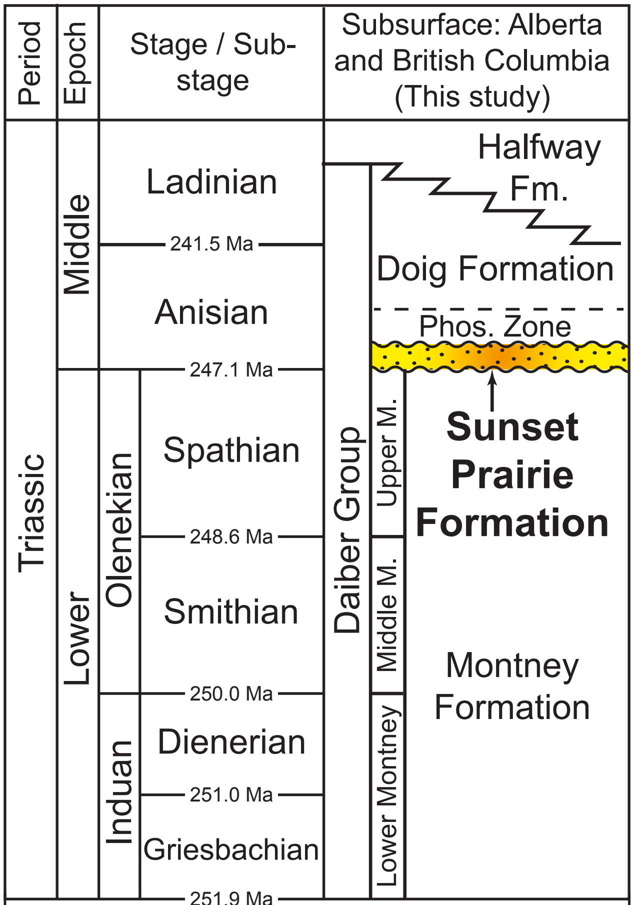


Figure 6.1–Lower and Middle Triassic lithostratigraphic nomenclature for outcrop and subsurface sections in Alberta and British Columbia. Ages of stages and substages identified by Henderson and Schoefer (2017), and Henderson et al. (2018). Modified from Zonneveld (2011) and Golding et al. (2015).

Deposition of Lower and Middle Triassic sediment occurred on the western margin of Pangaea under arid, mid-latitudinal (~30$^{\mathrm{O}}$N) conditions (Wilson et al., 1991; Davies, 1997a; Davies et al., 1997; Dixon, 2000; Moslow, 2000; Zonneveld at al., 2010b). Historically, a passive margin was associated with the basin fostering the development of a marine ramp/shelf setting (Edwards et al., 1994; Dixon, 2009a; 2009b). However, recent work suggests that Triassic deposition occurred on an active margin, possibly a back-arc-basin (Ferri and Zonneveld, 2008; Miall and Blakey, 2008; Zonneveld et al, 2010a; Schiarizza, 2013; Morris et al., 2014; 2018), fore-arc basin (Nelson et al., 2006; Colpron et al., 2007; Rohais et al., 2016) or early foreland basin (Golding et al., 2016; Rohais et al., 2018; Zonneveld and Moslow, 2018).

The Middle Triassic Sunset Prairie Formation sits stratigraphically between the underlying Montney Formation and the overlying Doig Formation (Fig. 6.1). The interval is bound by erosional unconformities at the upper and lower contacts (Furlong et al., 2018a, 2018b). The formation is geographically limited to northeastern British Columbia, with the eastern erosional limit located close to the British Columbia-Alberta border (Furlong et al., 2018a, 2018b).

The Sunset Prairie Formation is the oldest stratigraphic occurrence of a pervasively bioturbated interval that is spatially widespread following the end-Permian mass extinction in Western Canada. Worldwide anoxic water conditions, acidification of the water column and global warming associated with volcanism from the Siberian Traps coincide with the end-Permian mass extinction at ~250 Ma (Benton and Twitchett, 2003; Black et al., 2012; Payne and Clapham, 2012). Anoxic or dysoxic ocean water conditions greatly influenced benthic assemblages during this time and habitable zones were restricted to narrow, shore-proximal settings (Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011). The Lower Triassic Montney Formation predominantly exhibits ichnological assemblages with low diversity and abundance of trace fossils (Beatty et al., 2008; MacNaughton and Zonneveld, 2010; Zonneveld et al., 2010a; Wood, 2012). However, high diversity assemblages were present within localized areas that have been interpreted to be associated with environmental refugia, where oxygenated water was present within the shallow-marine realm (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b). In contrast, the Middle Triassic Sunset Prairie Formation consists of interbedded pervasively bioturbated, diminutively bioturbated and non-bioturbated intervals that occur on a basin-wide scale (Furlong et al., 2018b). Although ecosystem recovery likely started during the lowermost Middle Triassic, ichnological communities did not exhibit pre-extinction levels of diversity and trophic complexity until the upper Middle Triassic or later (Twitchett, 1999; Hofmann et al., 2015).

MATERIALS AND METHODS

Core Sites

Ichnological and geochemical analyses were taken from three continuous drill cores located in the Fort St. John Graben system in northeastern British Columbia (Fig. 6.2). Cores were selected based on their continuous coverage of the Sunset Prairie Formation and its contacts with the underlying and overlying formations. Additionally, the core locations establish a northeast-to-southwest oriented cross section, which runs perpendicular to the inferred palaeoshoreline. From distal to proximal, the cores investigated include: 16-02-078-22W6, 16-29-079-20W6, and 04-11-081-21W6. The thickness of the Sunset Prairie Formation within the core dataset ranges from 14 m to 62 m. Facies characteristics, facies associations and interpreted depositional environments for the Sunset Prairie Formation were described in detail by Furlong et al. (2018b) and are summarized here in the results.

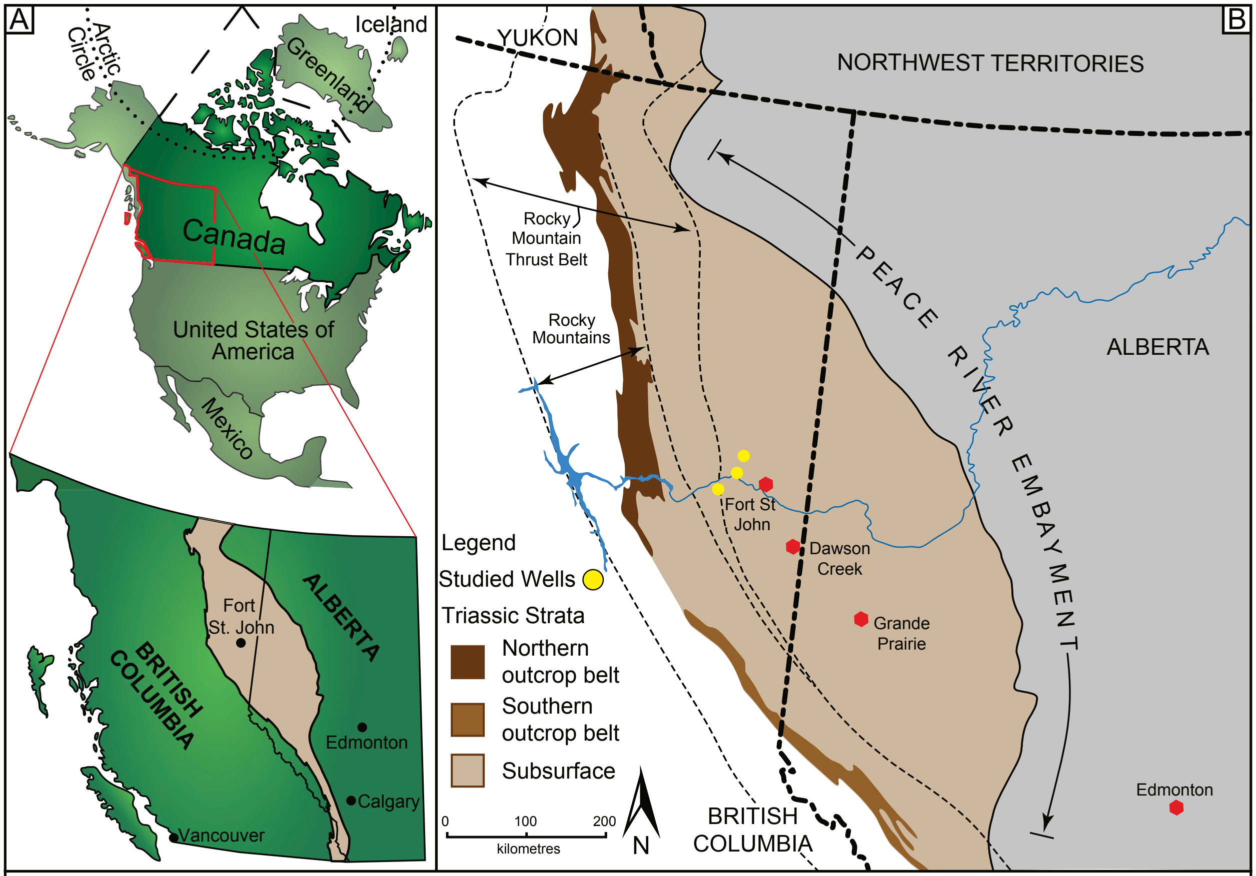


Figure 6.2–Location map of the study. A. Map of North America with the location of Alberta and British Columbia identified. B. Regional map of British Columbia and Alberta showing the extent of Triassic strata in the Western Canada Sedimentary Basin (modified from Zonneveld et al., 2011). Locations of the wells used within this study are identified.

Ichnology

Ichnological data was collected along the core from a process ichnology scope. Process ichnology is a framework introduced by Gingras et al. (2011), which utilizes traces fossils as biogenic sedimentary structures to interpret the original physico-chemical parameters under which depositional successions accumulated. Ichnological characteristics were recorded from each 10 cm interval along the core and data was continuously collected unless intervals had been removed, destroyed or preserved in plastic/wax for routine core analyses. Ichnological characteristics considered within the dataset of this study include: 1) bioturbation intensity; 2) diversity of ichnogenera; 3) diameter of burrows; and 4) Size Diversity Index. Bioturbation Index (BI) describes the degree of bioturbation within an interval using BI values that range from 0 to 6 (*sensu* Reineck, 1963, 1967; Droser and Bottjer, 1986; Taylor and Goldring, 1993). The grades of BI include: BI 0 (no bioturbation); BI 1 (1-4% 'sparse' bioturbation); BI 2 (5-30% 'low' bioturbation); BI 3 (31-60% ‘moderate’ bioturbation); BI 4 (61-90% ‘high’ bioturbation); BI 5 (91-99% ‘high’ bioturbation); and BI 6 (100%) (Reineck, 1963, 1967). Trace fossil diversity was identified by tallying the number of ichnogenera observed within each 10 cm interval. Ichnogenera are listed based on their relative abundance, from most to least abundant. Neither ichnospecies, nor trace fossil abundance was identified. The maximum burrow diameter was recorded every 10 cm and was measured using a digital caliper. Size Diversity Index (SDI) (*sensu* Hauck et al., 2009) was calculated by multiplying ichnodiversity (number of ichnogenera observed) by the maximum burrow diameter (irrespective of ichnogenus) within each 10 cm interval. Fluctuations in SDI have been associated with changes in physico-chemical stresses acting on a depositional environment (Hauck et al., 2009; Gingras et al., 2011; Botterill et al., 2015; Timmer et al., 2016a, 2016b) and are inferred to represent a disturbance gradient proxy for palaeoenvironmental settings. When physico-chemical stresses are present, SDI is at least an order of magnitude below its stable, unstressed, fully marine counterpart.

X-ray Fluorescence (XRF)

Redox-sensitive elements behave differently under oxic and anoxic conditions due to changes in solubility of their oxyanions (Morford et al., 2005). A variety of elements (V, Mo, U, Zn, Ni, Pb, Cu, Co and Cr) have been reported to be useful marine redox proxies and are commonly used to infer bottom water oxygen conditions and variations in water column sulfide (e.g., Jones and Manning, 1994; Tribovillard et al., 2006; Algeo and Tribovillard, 2009). Classification of bottom water oxygen concentrations for present-day ocean conditions follow a redox gradation, which include oxic (8.0-2.0 ml/l O_2), suboxic/dysoxic (2.0-0 ml/l), anoxic (O_2 < 0ml/l; no free H_2S in water), euxinic ($O_2 = 0$; free H_2S in water) conditions (Tyson and Pearson, 1991). Redox-sensitive trace metals tend to be more soluble under oxidizing conditions and less soluble in reducing conditions, resulting in the enrichment of these elements in oxygen-depleted sedimentary deposits (Tribovillard et al., 2006; Little et al., 2015). Each redox-sensitive element has particular trends and thresholds associated with the redox gradient, which can be used to interpret palaeo-oxygen conditions within sedimentary rock datasets. Within this study, Mo, V, and V/Cr were used as redox proxies due to their reliable detectability in the Sunset Prairie Formation and common use within other palaeo-redox proxy datasets (e.g., Algeo and Tribovillard, 2009; Dahl et al., 2013; Costa et al., 2018).

A total of 1093 samples from the Sunset Prairie Formation were analyzed for major and trace element geochemistry using a Thermo Scientific NITON XL3t 900 Analyzer hand-held X-ray fluorescence (XRF) gun. Analysis was conducted every 10 cm along the slabbed surface of the drill core. Ichnological data was gathered across the 10 cm interval below the point where the XRF data was taken. The XRF scanned for 180 seconds using the Mining Cu-Zr Mode and recorded forty elements. Select samples (28 samples) from the cores, representing the range of facies, were analyzed using a Thermo Scientific ICAP-Q quadrupole plasma mass spectrometry (ICP-MS). Samples were digested in acid for ICP-MS preparation. Empirical calibrations of the XRF data were generated by a linear regression between the XRF data and ICP-MS for each element. Similar calibration techniques have been used for XRF studies (e.g. Rowe et al., 2012; Dahl et al., 2013; Costa et al., 2018). The same calibration factor for a given element was used for data collected from the three cores studied (Table 6.1). Accuracy and precision errors were element-dependent and were determined by using a USGS certified reference standard (Green River Shale: 0151Shale SGR-1; Govindaraju, 1994). Table 6.1 provides a summary of errors associated with ICP-MS,

Green River Shale Standard (SGR-1b)		Mo	V	Cr	P
USGS Standard	Concentration (ppm)	35	130	30	1432
	Standard Deviation (ppm)	0.9	6	3	288
	2 Standard Deviation (ppm)	1.8	12	6	576
ICPMS 4 sample runs	Range of Concentrations (ppm)	31.1-37.2	110-133	23.6-28.2	1059-1278
	Average Concentration (ppm)	34	120	26	1157
	Standard Deviation (ppm)	5.9	10	2.2	92.3
	Standard Error (ppm)	1.5	5.0	1.1	46.1
	2 Standard Deviation (ppm)	5.9	20	4.4	185.5
	95% Confidence Interval	2.9	9.8	2.13	90.4
	Precision (% RSD)	8.68	8.32	8.44	7.98
	Accuracy (% Error)	2.2	7.4	13.9	19.2
Non-calibrated XRF 90 sample runs	Range of Concentrations (ppm)	19.82-22.48	182.4-260	70-140	19.82-22.48
	Average Concentration (ppm)	20.0	221	102	20
	Mode (ppm)	20.0	230	100	20
	Standard Deviation (ppm)	0.6	17.1	14.7	0.6
	Standard Error (ppm)	0.06	1.8	1.5	0.06
	2 Standard Deviation (ppm)	1.2	34.3	14.7	1.2
	95% Confidence Interval (ppm)	0.13	3.5	3.0	0.13
	Precision (% RSD)	3.04	7.75	14.4	3.04
	Accuracy (% Error)	42.1	70.2	239.8	98.6
Calibrated XRF 90 sample runs	Range of Concentrations (ppm)	37.6-38.5	131.7-202.1	59.6-88.7	980.2-982.8
	Average Concentration (ppm)	38	167	72.88	820.5
	Mode (ppm)	37.6	174.9	72.1	980.2
	Standard Deviation (ppm)	0.2	15.5	6.1	0.6
	Standard Error (ppm)	0.02	1.6	0.6	0.07
	2 Standard Deviation (ppm)	0.4	31.1	12.2	1.3
	95% Confidence Interval (ppm)	0.04	3.2	1.3	0.13
	Precision (% RSD)	0.56	9.31	8.38	0.06
	Accuracy (% Error)	7.8	28.4	142.9	31.5
Calibration	Slope	0.3428	0.9709	0.4258	1.02461
	y-intercept	30.784	-33.763	-30.483	-959.738
	r^2 value	0.05	0.89	0.16	0.7627
	p value	0.57	<0.0001	0.06	<0.0001
Detection Limit	ICPMS (ppm)	0.02	0.05	0.05	5
	XRF (ppm)	3	12	25	600

Table 6.1—Errors associated with the Green River Shale standard for elements used in this study.

non-calibrated XRF and calibrated XRF data. Calibration factors, r^2 and p-values are also provided for each element used in this study. The table includes redox-sensitive elements (Mo, V, Cr) and phosphate (P). Phosphate has been reported to exhibit a strong influence on the distribution of a variety of elements (Ag, Br, Cd, Cu, Cr, I, Mo, Pb, Se, U, V, Y and Zn), which results in these elements being included in the phosphate structure (e.g., Prévôt and Lucas, 1980; Breit and Wanty 1991; Tribovillard et al., 2006; Khan et al., 2012; Turner et al., 2015). Nickel was not detected by ICMSP or XRF within the Green River Shale standard sample and therefore could not be calibrated. Detection limits for each element are variable for ICPMS (Mo = 0.02 ppm; V = 0.05 ppm; Cr = 0.05 ppm; P = 5 ppm) and XRF (Mo = 3 ppm; V = 12 ppm; Cr = 25 ppm; P = 600 ppm).

The normalization of data was not conducted for this study. Many studies (e.g., Morford and Emerson, 1999; Morford et al., 2005; Kemp and Izumi, 2014; Gambacorta et al., 2016) have normalized elemental data to Al to remove byproducts of mineral phases, often biogenic in origin, that dilute trace element abundance (Calvert and Pederson, 1993). Additionally, enrichment factors ($EF_{\text{element X}} = (X/Al_{\text{samlple}})/(X/Al_{\text{reference material}})$) of elements are commonly calculated to help further normalize data (e.g., Tribovillard et al., 2006). Reference material used in calculating enrichment factors includes the average upper crust (McLennan, 2001), Post-Archean average Australian shale (Taylor and McLennan, 1985), average shale (Wedepohl, 1971, 1991) and average black shale (Vine and Tourtelot, 1970). However, Al normalization and calculating enrichment factors each have pitfalls (see Van der Weijden, 2002 and Tribovillard et al., 2006 for discussion). It is suggested to focus on stratigraphic variations and trends in enrichment factors or Al-normalized elemental concentrations rather than absolute values due to uncertainty in digenesis and provenance associated with the average shale, which still remains poorly understood (Tribovillard et al., 2006). Additionally, the ambiguous meaning and usage of the word “enrichment” has muddled geochemical studies. Elements are said to become enriched under reducing conditions, but specific redox conditions associated with the depositional setting of the average shale, or other reference material, are unknown, and does not necessarily represent a threshold between oxic and anoxic settings. Therefore, a suite of elements could potentially be enriched as compared to the average shale and still be deposited within an oxic or dysoxic setting (see Haddad et al., 2018, figs 3-6).

Although it has been suggested to look at the overall trends of XRF data instead of the absolute value, a couple elemental ratios have reported threshold values for different redox states (e.g., Mo and V/Cr). These elemental concentrations and ratios should be taken with caution, and supported by other geochemical evidence and/or by the integration of additional geological datasets to better render a fuller interpretation. A variety of elemental ratios and their specific thresholds are evaluated within this study in conjunction with ichnological data to help interpret the redox conditions during deposition of the Sunset Prairie Formation, but absolute values of ratios should not be considered absolute truth.

RESULTS

Lithologic Characteristics

Lithofacies.—Overall, the Sunset Prairie Formation consists of interbedded light gray, pervasively bioturbated, very fine-grained sandstone and dark gray, diminutively bioturbated to non-bioturbated, fine- to coarse-grained siltstone (Furlong et al., 2018a, 2018b). Seven lithofacies were identified within the Sunset Prairie Formation (Fig. 6.3). The facies can be broken into three general groups: 1) diminutively bioturbated facies (Facies 1 and 2); 2) pervasively bioturbated facies (Facies 3, 4 and 5); and 3) bathymetrically independent surfaces (Facies 6 = *Glossifungites* Ichnofacies; Facies 7 = lag deposit). A thorough description of each lithofacies and rationale of depositional environment interpretations are described by Furlong et al. (2018b) and are provided in Chapter 2 of this thesis.

Diminutively bioturbated intervals consist of two facies (Facies 1 and 2) that exhibit observable physical sedimentary structures and rare, small-diameter trace fossils. Facies 1 is characterized as a dark to medium grey, fine- to coarse-grained siltstone with faint horizontal planar-parallel-laminae and horizontal wavy-parallel-laminae. Low-angle planar cross stratification, high-angle planar cross stratification, asymmetric ripples, pyrite grains, calcispheres and phosphate material are also occasionally present. Trace fossils are small in size (0-2 mm; mean = 0.09 mm), bioturbation intensity is low (BI = 0-2), and observable ichnogenera, listed by relative abundance, include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. No body fossils are observed within this facies. Facies 1 is interpreted to have been deposited within the offshore to lower offshore transition. Facies 2 is characterized as a dark to light grey, fine to coarse-grained siltstone with horizontal pinstripe-, planar- and wavy-parallel-laminae. Asymmetric ripples and penecontemporaneous deformation structures are rare. Trace fossils are small in size (0-3 mm; mean = 0.23 mm), bioturbation intensity is low (BI = 0-2), and observable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. No body fossils are observed within this facies. Facies 2 is interpreted to have been deposited in the lower offshore transition.

Pervasively bioturbated intervals consist of three facies (Facies 3, 4 and 5), where burrowing organisms have homogenized the sediment and destroyed most primary physical sedimentary structures. Facies 3 consists of dark to light grey, bioturbated fine-grained siltstone to very fine-grained sandstone. Phosphate material is observed within this facies. Trace fossils are variable in size (0.5-12 mm; mean = 4.36 mm), bioturbation intensity is high (BI = 5-6), and observable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Teichichnus*, *Palaeophycus*, *Planolites*, *Chondrites*, and *Zoophycos*. No body fossils are observed within this facies. Facies 3 is interpreted to have been

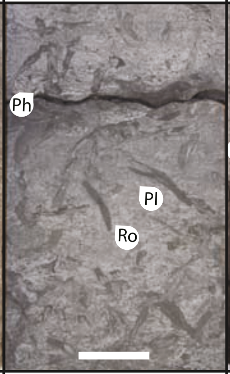
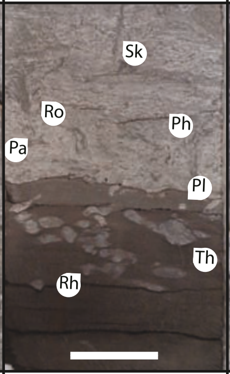
Facies	Diminutively Bioturbated		Pervasively Bioturbated			Bathymetrically Independent	
	F1	F2	F3	F4	F5	F6	F7
Core Expression							
Lithological Description	Dark to medium grey, laminated, bituminous siltstone with minimal bioturbation	Dark to light grey siltstone with minimal bioturbation	Dark to light grey bioturbated siltstone	Pervasively bioturbated medium to light grey siltstone	Pervasively bioturbated sandy siltstone	Burrowed firmground	Amalgamated sandstone and conglomerate bed
Primary Sedimentary Structures	PL, PWL, WL, LACL, HACL, AS, PG, Phos	PSL, PL, PWL, WL, AS, Phos	N/A	N/A	N/A	N/A	Phos
Secondary Sedimentary Structures	PDS, C, HCS	PDS	Phos	PL	PL, WL, LACL, HACL, PDS, AS, Phos	Phos	N/A
Body Fossils	N/A	N/A	N/A	BI, G, BR, E, CR	BI, G, BR, E, CR	N/A	Shell and Bone fragments
Grain Size	Fine to coarse silt	Fine to coarse silt	Fine silt to very fine sand	Fine silt to very fine sand	Fine silt to very fine sand	N/A	Sand to gravel
Ichnological Assemblage	*Ph, He, Pa, Pl, Ch*	*Ph, He, Pa, Pl, Ch*	*Ph, He, Te, Pa, Pl, Ch, Z*	*Ph, He, Pa, Pl, Ch*	*Ph, Ro, Cy, As, Te, Pa, Pl, Sk, Sc, Rh, Di*	*Pl, Sk, Th, Rh*	N/A
BI	0-2	0-2	5-6	4-6	5-6	N/A	N/A
Interpreted Depositional Environment	Offshore to Lower Offshore Transition	Lower Offshore Transition	Lower to Upper Offshore Transition	Lower to Upper Offshore Transition	Upper Offshore Transition to Lower Shoreface	*Glossifungites* surfaces	Lag deposit

Figure 6.3–Summary of lithological, sedimentological, ichnological and palaeontological characteristics of the lithofacies in the Sunset Prairie Formation. Sedimentary structure abbreviations include: AS = Asymmetrical ripples; C = Calcisphere; HACL = High Angle Cross Laminae; HCS = Hummocky Cross Stratification; LACL = Low Angle Cross Laminae; PDS = Penecontemporaneous Deformation Structures; PG = Pyrite Grains; Phos = Phosphate Material; PL = Horizontal Planar-parallel-laminae; PSL = Horizontal-pinstripe Laminae; PWL = Horizontal Planar-parallel-wavy Laminae; Rup = Rip Up Clasts; WL = Wavy Laminae. Body fossil abbreviations include: G = Gastropod; BI = Bivalve; E = Echinoid; BR = Brachiopod; CR = Crinoid. Trace fossil abbreviations include: *As = Asterosoma*; *Ch = Chondrites*; *Cy = Cylindrichnus*; *Di = Diplocraterion*; *He = Helminthopsis*; *Pa = Palaeophycus*; *Ph = Phycosiphon*; *Pl = Planolites*; *Rh = Rhizocorallium*; *Ro = Rosselia*; *Sc = Scolicia*; *Sk = Skolithos*; *Te = Teichichnus*; *Th = Thalassinoides*; *Z = Zoophycos*.

deposited in the lower to upper offshore transition. Facies 4 consists of pervasively bioturbated medium to light grey fine-grained siltstone to very fine-grained sandstone with rare horizontal planar-parallel-laminae. Trace fossils are variable in size (0.5-6 mm; mean = 1.21 mm), bioturbation intensity is high (BI = 4-6), and observable ichnogenera include *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. Body fossils observed in Facies 4 include bivalves, gastropods, brachiopods (lingulid, spiriferid terebratulid), cidaroid echinoid skeletal fragments, and isocrinid crinoid ossicles. This facies is interpreted to record deposition in the lower to upper offshore transition. Facies 5 consists of medium to light grey, pervasively bioturbated fine-grained siltstone to very fine-grained sandstone. Rare horizontal planar-parallel-laminae, horizontal wavy-parallel-laminae, low- and high-angle planar cross laminae, penecontemporaneous deformation structures, asymmetric ripples and phosphate material is observed. Trace fossils are variable in size (1-15 mm; mean = 4.16 mm), bioturbation intensity is high (BI = 5-6) and observable ichnogenera include *Phycosiphon*, *Rosselia*, *Cylindrichnus, Asterosoma, Teichichnus*, *Palaeophycus*, *Planolites*, *Skolithos, Rhizocorallium*, and *Diplocraterion.* The same assemblage of body fossils is observed in Facies 4 and Facies 5. Facies 5 is interpreted to have been deposited in the upper offshore transition to lower shoreface.

Bathymetrically independent surfaces (Facies 6 and 7) represent facies that are not associated with specific water depth along the shoreline. Facies 6 is a burrowed firmground or *Glossifungites* Ichnofacies-demarcated discontinuity surface. Trace fossil size is relatively large (3-20 mm, mean = 9.75 mm) and ichnogenera present include *Planolites*, *Skolithos, Thalassinoides*, and *Rhizocorallium*. Such burrowed firmgrounds consist of dewatered, cohesive mud/silt, which formed due to either subaerial exposure, or burial and subsequent exhumation (Frey and Seilacher, 1980; MacEachern et al., 1992). No evidence of subaerial exposure (e.g., absence of desiccation cracks and salt casts) is present within the Sunset Prairie Formation, suggesting that the *Glossifungites* Ichnofacies-demarcated discontinuity surfaces are associated with erosion (Gingras et al., 2007). Facies 7 consists of an amalgamated sandstone and conglomerate. Grains and clasts are fine-grained sand to medium-grained gravel size and occur in beds that are <10 cm in total thickness. Phosphate material, shell and bone fragments are observed within the interval. Facies 7 is interpreted to have been deposited as a transgressive lag deposit. Both Facies 6 and 7 can be observed as coplanar or as isolated facies.

Lithofacies Distribution.—Facies within the Sunset Prairie Formation are associated with a shallow-marine shoreface succession. The facies associations correspond to shoaling-upward packages (parasequence), which have been identified based on vertical facies distribution (Furlong et al., *in review*). The base of the parasequence exhibits facies attributed to the offshore and lower offshore transition (Facies 1 and 2) overlain by facies dominantly attributed to the lower to upper offshore transition (Facies 3 and 4), which gradually shift to facies attributed primarily to the lower shoreface (Facies 5) (Fig 6.4). Commonly, Facies 6 and/or 7 occur at the very base of each parasequence and represent a flooding surface that separate the sub-formational units. Three parasequences or sub-formational units are observed within the Sunset Prairie Formation. Interbedding of facies is common, however the three sub-units have distinct lithological and petrophysical characteristics that make them mappable across the basin (Furlong et al., *in review*).

The lowermost sub-formational unit exhibits thick packages (up to 7 metres) of pervasively bioturbated, sandy siltstone intervals, with thin intervals (<2 m in thickness) of diminutively bioturbated siltstone facies. The upper two sub-units exhibit increased bed thickness of diminutively bioturbated facies (<10 m thick) and a decrease in bed thickness of pervasively bioturbated facies (<2 m). Fine-grained sand content, thickness of coarse-grained beds and bioturbation intensity decrease with each following parasequence set.

Biological Signals of Episodic Bottom Water Oxygenation

Many have suggested that the amount of biotic disruption compared to the original sedimentary fabric can be related to relative oxygen levels in the environment (e.g., Savrda and Bottjer, 1986, 1989; Savarda, 1992). Bioturbation intensity, burrow diameter and ichnological diversity can provide an independent palaeoecological perspective, which can complement geochemical redox proxy datasets to better understand palaeoenvironments.

Facies 1 and 2 are characterized by low bioturbation intensity (BI = 0-2), and exhibit low diversity trace fossil assemblages (0-5 ichnogenera) that are diminutive in size (Facies 1 range = 0-3 mm, F1 mean = 0.09 mm; Facies 2 range = 0-3 mm, F2 mean = 0.24 mm) (Table 6.2). The calculated SDI is therefore low and ranges from 0-10. Minimal to no bioturbation within an interval can result from many physico-chemical factors, including increased sediment supply, decreased salinity and decreased dissolved oxygen (e.g., Martin, 2004; Gingras et al., 2011; MacEachern et al., 2007b, 2010; Buatois and Mángano, 2011). Salinity fluctuation was not applicable during the depositions of the Sunset Prairie Formation due to its fully marine palaeogeographic location. Additionally, increased sediment supply and hydraulic energy could be inferred for only select intervals of Facies 2, where asymmetric ripples, horizontal wavy-parallel-laminae, horizontal pinstripe-parallel-laminae and penecontemporaneous deformation structure are observed. These sedimentary features are rare and are isolated to beds <5 cm in thickness. Horizontal planar-parallel-laminae are the predominant sedimentary structure observed in both Facies 1 and 2, which suggests low energy, pelagic sedimentation occurred. Based on the occurrence of isolated trace fossils throughout the interval, dissolved oxygen levels were likely reduced. Total anoxic conditions would classically be interpreted for non-bioturbated intervals (e.g. Savrda and Bottjer,

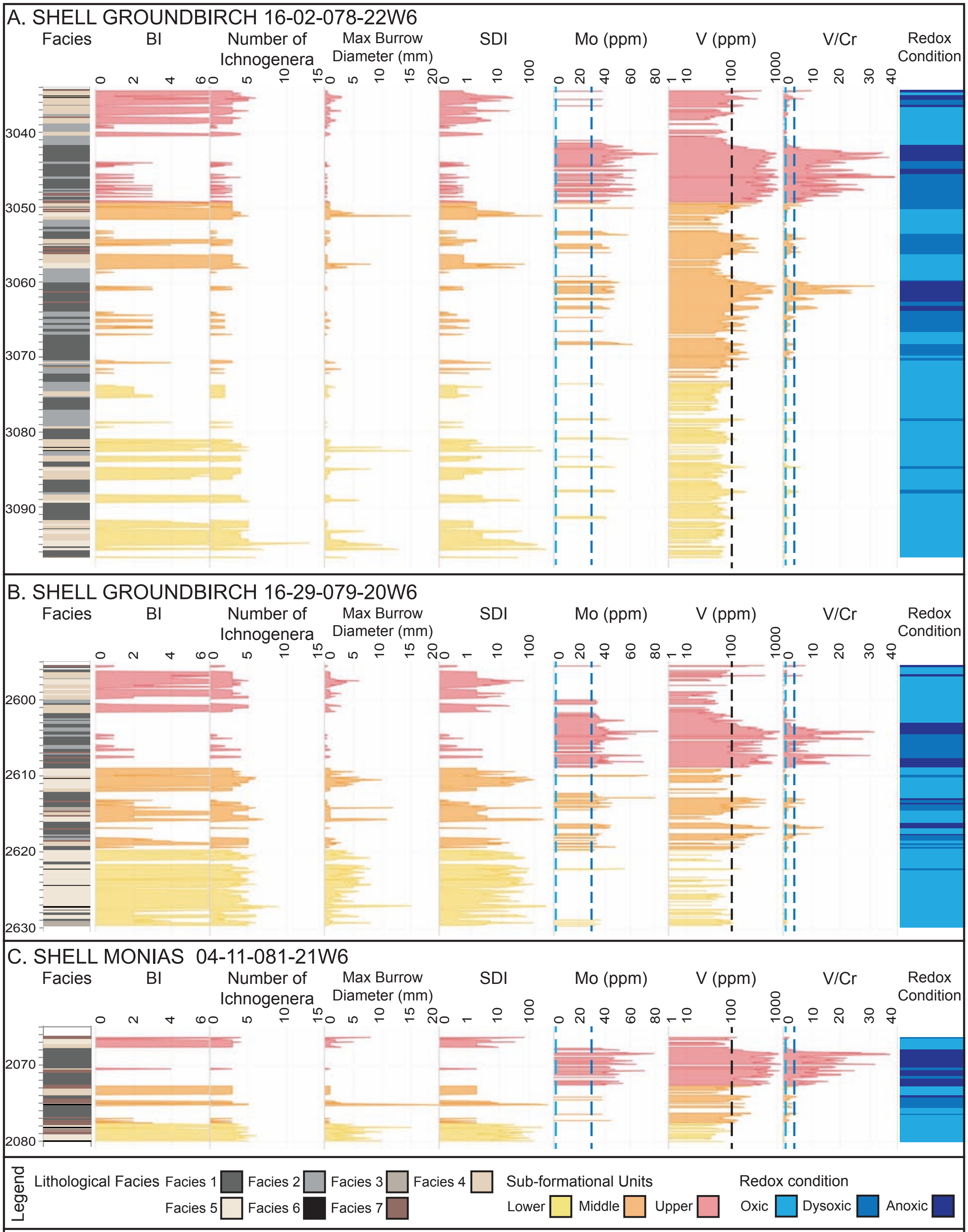


Figure 6.4–Composite lithological, ichnological and geochemical records. Dashed lines represent redox thresholds. Molybdenum cutoffs include: <2 ppm = oxic, ~2-30 ppm = dysoxic, >30 ppm = anoxic (Scott and Lyons, 2012). Vanadium enrichment, as compared to the average shale, occurs above concentrations of 130 ppm (Turekian and Wedopohl, 1961). V/Cr cutoffs include: <2 = oxic, 2-4.45 = dysoxic, >4.25 = suboxic to anoxic (Rimmer, 2004).

Variable	Facies	Minimum	Maximum	Average	Standard Deviation
Maximum Bioturbation Intensity	Facies 1	0	3	0.23	0.69
	Facies 2	0	3	0.62	0.99
	Facies 3	4	6	5.25	1.04
	Facies 4	3	6	5.81	0.55
	Facies 5	4	6	5.97	2.57
Maximum Burrow Diameter (mm)	Facies 1	0	2	0.09	0.25
	Facies 2	0	3	0.24	0.42
	Facies 3	0.5	12	3.69	4.28
	Facies 4	0.5	6	1.15	0.86
	Facies 5	1	15	4.10	2.67
Number of Ichnogenera	Facies 1	0	5	0.32	0.98
	Facies 2	0	5	0.73	1.12
	Facies 3	4	6	5.25	0.71
	Facies 4	3	5	3.61	0.79
	Facies 5	2	7	4.11	1.11
Size Diversity Index	Facies 1	0	10	0.26	0.91
	Facies 2	0	6	0.52	1.03
	Facies 3	2.5	72	21.4	26.21
	Facies 4	1.5	25	4.23	3.71
	Facies 5	3	91	18.15	15.56
Mo (ppm)	Facies 1	31.80	82.20	44.22	10.39
	Facies 2	31.94	61.63	38.89	7.21
	Facies 3	31.94	32.53	33.34	2.03
	Facies 4	32.21	62.35	42.90	16.87
	Facies 5	31.96	32.48	32.22	0.37
V (ppm)	Facies 1	8.13	5113.02	654.26	926.96
	Facies 2	14.78	4442.10	175.71	541.23
	Facies 3	4.09	34.20	15.60	9.51
	Facies 4	4.09	519.65	59.12	60.02
	Facies 5	11.08	131.29	38.51	26.54
V/Cr	Facies 1	0.18	39.83	6.07	7.86
	Facies 2	0.25	39.90	1.95	4.49
	Facies 3	0.18	0.90	0.37	0.27
	Facies 4	0.16	6.46	0.99	0.79
	Facies 5	0.25	1.93	0.69	0.41

Table 6.2—Ichnological and geochemical characteristic by facies. Minimum, maximum, average and standard deviation provided for each variable.

1986, 1991; Föllmi and Grimm, 1990; Grimm and Föllmi, 1994; Savrda, 1992, 1995; Buatois and Mángano, 2011); however, the absence of trace fossils does not always correspond to anoxic conditions (Dashtgard and MacEachern, 2016).

Pervasively bioturbated facies (Facies 3, 4 and 5) exhibit high bioturbation intensity (BI = 4-6), and contain a moderately diverse assemblage of trace fossils (up to 11 ichnogenera). The diameter of trace fossils observed within these facies range from 0.5-15 mm in diameter (Table 6.2). Size Diversity Index is variable between the different pervasively bioturbated facies and ranges from 2.5-75 in Facies 3, 1.5-25 in Facies 4 and 3-91 in Facies 5 (Fig 6.5A; Table 6.2). A

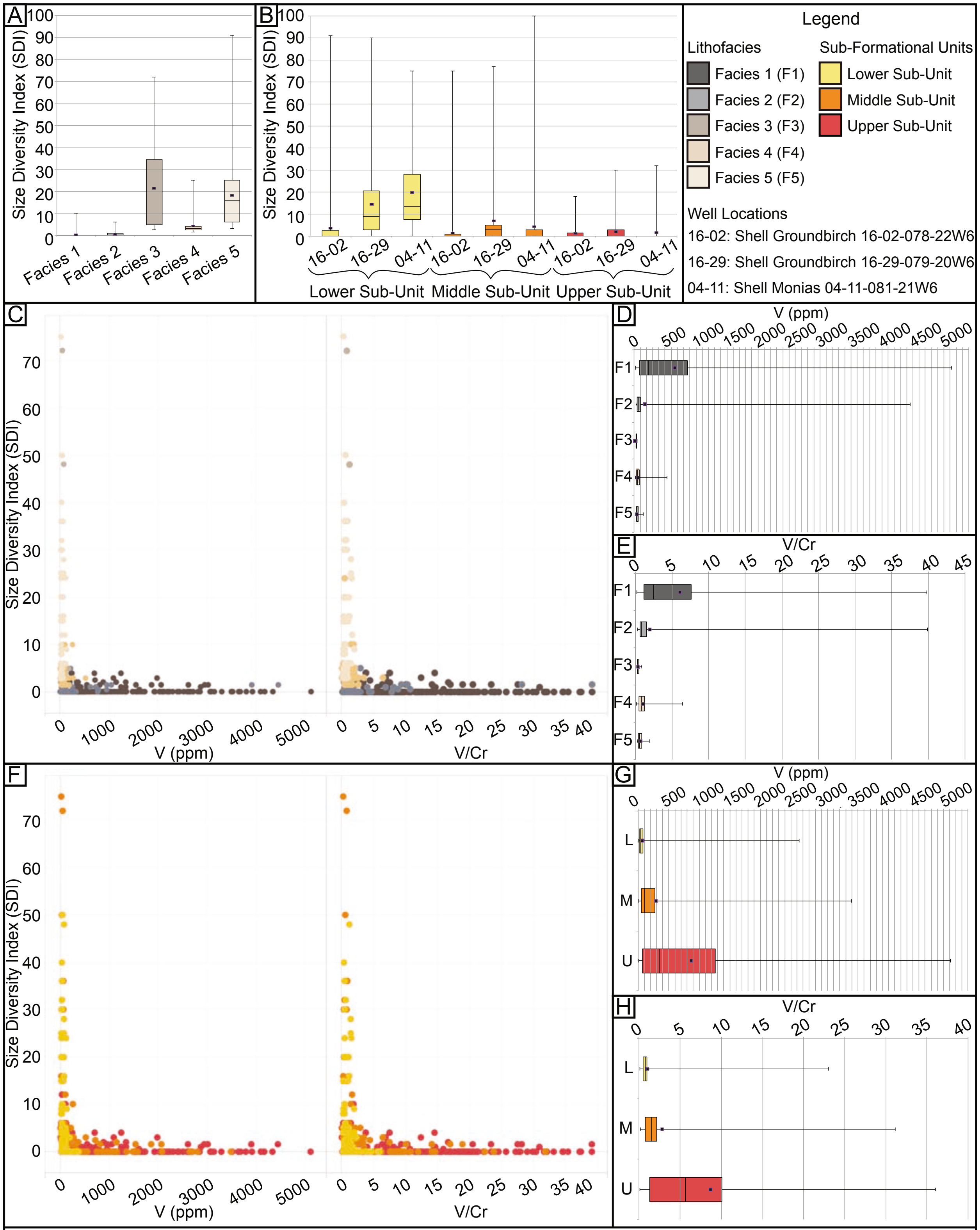


Figure 6.5–Comparison of Size Diversity Index (SDI), redox-sensitive elements, facies and sub-formational units. A. Distribution of SDI by facies. B. Distribution of SDI of each sub-formational unit per well. C. Cross plots of SDI vs. V and SDI vs. V/Cr. Points coloured by facies. D. Distribution of V by facies. E. Distribution of V/Cr by facies. F. Cross plots of SDI vs. V and SDI vs. V/Cr. Points coloured by sub-formational units. G. Distribution of V by sub-formational units. H. Distribution of V/Cr by sub-formational units.

fully oxygenated environment would be needed to support this diverse and robust assemblage of burrowing organisms. Additionally, physical sedimentary structures are not commonly observed within the pervasively bioturbated facies due to burrowing organisms completely churning and redistributing sediment. Therefore, bioturbation rates had to have outpaced sedimentation rates.

Glossifungites Ichnofacies (Facies 6) exhibit a low number of ichnogenera (4 ichnogenera) at the surface itself, but up to 9 different ichnogenera are observed within the 10 cm interval where ichnological data were collected around the discontinuity surface. Trace fossil diameters are large, ranging from 3-20 mm, and burrows can penetrate up to 10 cm below the preserved discontinuity surface. Due to this, the calculated SDI is large (12-100). Ichnogenera diversity, bioturbation intensity, and SDI are likely overestimated as a result of the variables being recorded across a 10 cm interval of core and are not specifically associated with the *Glossifungites* Ichnofacies-demarcated discontinuity surface itself. Due to the nature of the *Glossifungites* Ichnofacies, different facies are observed above and below the burrowed firmground surface. Ichnological data, therefore, represents at least three different facies, instead of a single facies. This characteristic renders itself as the highest peaks in SDI observed in the Sunset Prairie Formation. *Glossifungites* Ichnofacies-demarcated discontinuity surfaces have many environmental and stratigraphic implications, which have been discussed by Pemberton and Frey (1985), MacEachern et al. (1992) and Gingras et al. (2000, 2001).

Ichnological diversity, bioturbation intensity, burrow size, and SDI increase stratigraphically up within each sub-formational unit and overall decrease from the lower sub-formational unit to the upper sub-formational unit (Figs. 6.4, 6.5B, Table 6.3). Pervasively bioturbated facies make up the majority of strata in the lowermost sub-formational unit, which is where the highest and most consistent ichnological presence is observed. The upper two sub-formational units have decreased abundance of pervasively bioturbated facies, which influences ichnological trends respectively. Distal wells generally have lower SDI as compared to their proximal counterpart for each sub-formational unit (Fig. 6.5B)

Trace Metal Signals of Episodic Bottom Water Oxygenation

A variety of trace metals can be used to interpret palaeoredox conditions. Within the dataset, Mo, V, and V/Cr are the most useful elements collected to provide insight into palaeoredox conditions during the deposition of the Sunset Prairie Formation. Each is outlined below:

Molybdenum.—Molybdenum concentrations in the Sunset Prairie Formation range form 31.8 ppm to 82.2 ppm (Table 6.2). Non-bioturbated to diminutively bioturbated facies have a large range of Mo concentrations (Facies 1: range = 31.80-82.20 ppm, mean = 44.22 ppm; Facies 2:

Variable	Sub-formational Unit	Minimum	Maximum	Average	Standard Deviation
Maximum Bioturbation Intensity	Upper	0	6	1.77	2.52
	Middle	0	6	1.87	2.57
	Lower	0	6	3.20	2.82
Maximum Burrow Diameter (mm)	Upper	0	8	0.50	0.93
	Middle	0	20	0.78	1.97
	Lower	0.5	15	1.75	2.71
Number of Ichnogenera	Upper	0	6	1.25	1.66
	Middle	0	7	1.38	1.84
	Lower	0	9	2.35	2.14
Size Diversity Index	Upper	0	32	1.73	3.75
	Middle	0	100	3.31	10.29
	Lower	0	91	7.75	14.31
Mo (ppm)	Upper	31.94	82.20	44.39	10.96
	Middle	31.80	79.81	41.25	8.76
	Lower	31.93	31.93	43.10	11.65
V (ppm)	Upper	4.09	5113.02	871.39	1080.35
	Middle	8.42	3490.61	262.45	446.68
	Lower	5.07	2636.22	68.16	173.11
V/Cr	Upper	0.09	39.08	8.74	9.34
	Middle	016	31.88	2.79	4.06
	Lower	0.11	23.20	1.07	1.72

Table 6.3—Ichnological and geochemical characteristic by sub-formational unit. Minimum, maximum, average and standard deviation provided for each variable.

range =31.94-61.63 ppm, mean = 38.89 ppm). Pervasively bioturbated facies have a narrower range of Mo concentrations (Facies 3: range = 31.94-32.53 ppm, mean = 33.35 ppm; Facies 4: range = 32.21-62.35 ppm, mean = 42.90 ppm; Facies 5: range = 31.96-32.48 ppm, mean = 32.22 ppm).

Concentrations of sedimentary Mo below ~2 ppm has been related to oxic conditions, Mo content between ~2 ppm and 30 ppm are recognized in dysoxic bottom water, Mo values above 30 ppm are interpreted to represent intermittent/seasonal euxinia and permanent euxinic conditions correspond to enriched Mo values exceeding 100 ppm (Morford and Emerson, 1999; Werne et al., 2002; Sageman et al., 2003; McManus et al., 2006; Scott et al., 2008; Gordon et al., 2009; Scott and Lyons, 2012). Although these threshold values are associated with specific redox conditions, the boundary values do overlap (e.g. Scott and Lyons, 2012, fig. 1) and caution should be taken when using the absolute values when interpreting datasets. Plots herein use these Mo thresholds to help interpret palaeoredox conditions during the deposition of the Sunset Prairie Formation (Fig. 6.4), but some variability in the specific value associated with each redox boundary should be considered.

Molybdenum concentrations within the Sunset Prairie Formation are greater than 30 ppm suggesting that these samples correspond to anoxic conditions. Molybdenum does not exceed 100 ppm in any sample, suggesting that euxinic conditions did not occur. However, Mo is rarely detected in samples in pervasively bioturbated intervals; only 9 samples out of a total of 309 pervasively bioturbated samples had Mo concentrations above the XRF detection limit (3 ppm). Due to this, other elements may be more useful in determining palaeoredox conditions. However, it is hypothesized that samples with Mo concentrations under the detection level are associated with oxic conditions.

Stratigraphically, Mo enrichment occurs as isolated peaks in the lowermost sub-formational unit of the Sunset Prairie Formation (Fig. 6.4; Table 6.3). The second sub-formational unit exhibits two notable occurrences of increased Mo, which have concentrations reaching 80 ppm. The third sub-formational unit has increased Mo concentration at the base (up to 82 ppm), and no Mo was detected at the top. These peaks correspond to increased concentrations of other redox-sensitive elements.

Vanadium.—Overall, V concentrations within the Sunset Prairie Formation span from 4.09 ppm to 5113.02 ppm. Each facies has a distinct range of V content; diminutively bioturbated facies (Facies 1 and 2) have V concentrations that span four orders of magnitude, whereas pervasively bioturbated facies (Facies 3, 4 and 5) have V concentrations under 34.20 ppm, 519.65 ppm and 131.29 ppm respectively (Figs. 6.5C, 6.5D, Table 6.2). All facies exhibit concentrations that span below and above the average shale value (130 ppm); however, pervasively bioturbated facies have concentrations that are generally below the enrichment level. Facies 4 is the exception and exhibits V concentrations that extend up to 519.65 ppm. Vanadium concentrations are generally low (range = 5.07-2636.22 ppm; mean V = 68.16 ppm) in the lower sub-formational unit, the middle sub-formational unit has two high spikes of V (range = 8.43-3490.62 ppm; mean V = 262.47 ppm) and the upper sub-formational unit has increased V at the base (range = 4.09-5112.02 ppm; mean V = 871.40 ppm) (Figs. 6.4, 6.5E, 6.5F, Table 6.3). Concentrations of V and Mo have a positive trend (Fig. 6.6) and exhibit similar stratigraphic fluctuations (Fig. 6.4).

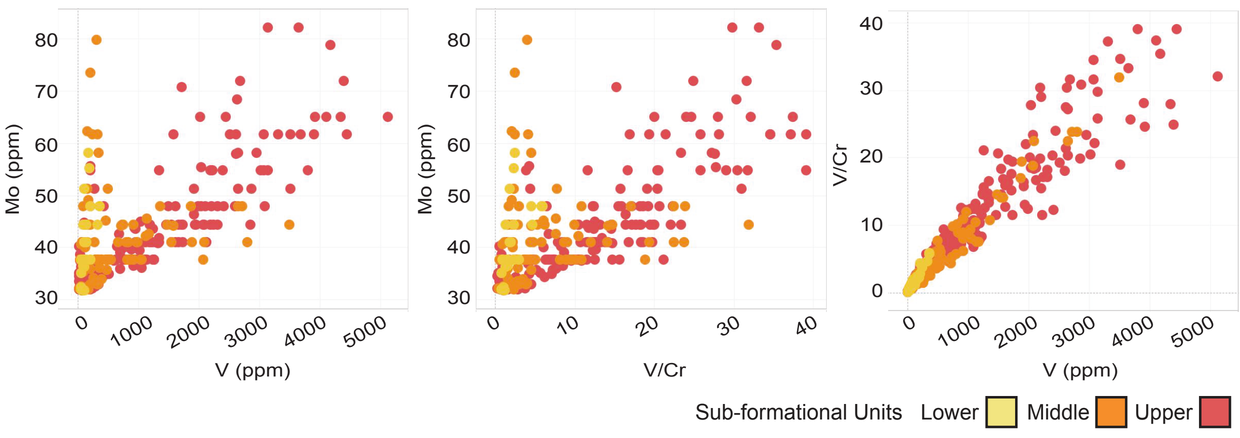


Figure 6.6–Cross plots of redox-sensitive elements. Points coloured by sub-formational units.

Specific thresholds of V associated with different redox conditions have not been reported. Commonly, V enrichment is associated with concentrations higher than the baseline content of the average shale (V = 130 ppm) or average continental value (107 ppm) (Turekian and Wedopohl, 1961; Goldberg and Humayan, 2016). However, there is a lack of evidence suggesting that V concentrations above that of the average shale or average continental values are actually reflective of deposition under anoxic conditions. The average shale might not accurately represent the sediment being studied (see Van der Weijden, 2002 for discussion) and V concentrations in shale can span a wide range of values globally and locally (Xu et al., 2013; Haung et al., 2015). However, out of all the redox-sensitive elements, V was the most continuously detected element recorded from the drill cores studied and frequently had concentrations above the detection limit of the XRF gun (12 ppm). The overall fluctuating trend of V concentrations stratigraphically through the Sunset Prairie Formation suggests that dissolved oxygen conditions vacillated during the deposition of the formation. Although specific cutoffs cannot be determined, it can be interpreted that when V is relatively low, dissolved oxygen levels would have been high, whereas elevated V concentrations would be associated with reduced-oxygen conditions.

Trace Metal Ratio: V/Cr.—Expanding on the usage of V, the elemental ratio V/Cr and has been used to better understand different redox conditions. Here, V is associated with redox conditions and is compared to an element that is more strongly associated with detrital fractions (Jones and Manning, 1994; Tribovillard et al., 2006). The ratio of V/Cr below 2 is associated with oxic conditions, 2-4.25 with dysoxic conditions, and > 4.25 with suboxic to anoxic conditions (Jones and Manning, 1994; Rimmer, 2004).

Within the Sunset Prairie Formation V/Cr varies per facies (Figs. 6.5C, 6.5E; Table 6.2). Diminutively bioturbated facies have a large range in V/Cr ratios (Facies 1: 0.18-39.84; Facies 2: 0.25-39.88) and is interpreted to represent deposition associated with oxic, dysoxic and anoxic conditions. Pervasively bioturbated facies have a smaller range in V/Cr ratios, ranging from 0.18-0.90 in Facies 3, 0.16-6.46 in Facies 4 and 0.25-1.93 in Facies 5. The pervasively bioturbated intervals of Facies 3 and Facies 5 are at or slightly above the reported threshold of 2, which separates oxic and dysoxic conditions (Rimmer, 2004). Both facies are interpreted to correspond to oxic conditions during deposition. Facies 4 exhibits a larger range of V/Cr values and suggests that bottom water conditions may have been oxic to dysoxic; however, the high degree of bioturbation intensity (BI = 4-6) would suggest that prolonged periods of dysoxic to anoxic conditions did not occur.

Stratigraphically, V/Cr ratio indicates that bottom water conditions fluctuated between oxic to anoxic conditions during the deposition of the Sunset Prairie Formation (Figs. 6.4, 6.5F, 6.5H; Table 6.3). The lower sub-formational unit mainly remains under a value of 2, (mean = 0.85), which suggests that the water conditions at the sediment-water interface were oxic for prolonged periods. A few peaks in V/Cr are observed in the lower sub-formational unit in the most distal well (16-02-078-22W6) at 3087.9 m, 3084.6 m and 3078.3 m, which represent relatively short-lived episodes of dysoxic to suboxic conditions during deposition. The upper two sub-formational units fluctuate between low V/Cr ratios in the middle sub-formational unit (mean = 2.79) and higher values in the upper sub-unit (mean = 8.72), suggesting that water conditions vacillated between oxic and dysoxic conditions. However, two noticeable peaks in V/Cr occur within the Sunset Prairie Formation that are associated with high V/Cr ratios (over 10), and are interpreted to represent prolonged anoxic conditions. The first interval is located in the middle of the second sub-formational unit and the second interval is located at the base of the uppermost sub-formational unit. The two peaks in V/Cr are apparent in the two distal wells, but the most proximal well studied (04-11-081-21W6) does not exhibit a prominent peak in V/Cr within the middle sub-formational unit (Fig. 6.4), suggesting that during this time, distal water conditions were under anoxic conditions whereas proximal locations experienced oxic conditions.

DISCUSSION

Relationships between Ichnological Characteristics and Trace Metal Abundance

Comparing ichnological characteristics to redox-sensitive trace metals suggests that diminutively bioturbated facies and pervasively bioturbated were deposited under different redox conditions. Although this idea is not revolutionary and many researchers have suggested such relationships between the presence/absence of trace fossils and redox conditions, this dataset provides empirical data within an interval containing pervasively bioturbated, diminutively bioturbated and non-bioturbated facies that can be linked to geochemical signatures using an XRF dataset.

Facies 1 and Facies 2 consist of fine-grained siltstone to coarse-grained siltstone, respectively, with little to no bioturbation. All elements and ratios evaluated within this study exhibit a large range of values (Figs. 6.4, 6.5D, 6.5E). When trace fossils are present, the diversity and size of the burrows are limited (Fig. 6.3). The calculated SDI values within these facies are low (Facies 1 = 0-10; Facies 2 = 0-6). When bioturbation is present, redox-sensitive elements are not elevated; however, a couple intervals within the Sunset Prairie Formation are enriched in redox-sensitive trace metal concentrations when bioturbation is present. Most notably is the occurrence of trace fossils within the lower part of the upper sub-formational unit (Fig. 6.4). Within all three cored wells, this interval has observable bioturbation (BI = 3) and high Mo, V, and V/Cr concentrations/ratios. This contradicting data may be a result of phosphate content (discussed later) or from fluctuations in redox conditions overprinting original conditions associated with deposition. Additionally, the minimally bioturbated zones within Facies 1 and 2 are commonly limited to beds that are only a few centimetres in thickness. The XRF data was not collected at such high-resolution, and the small-scale changes in palaeoenvironmental conditions were not recorded.

Pervasively bioturbated facies are interpreted to record deposition in oxic to dysoxic environments. Facies 3 and 5 have high bioturbation intensities (BI = 5-6), large diameter traces (up to 23 mm), moderately diverse assemblages and large SDI values (Fig. 6.3). Redox-sensitive elements have low concentrations, which generally fall within the oxic threshold for that specific element (Figs. 6.4, 6.5C, 6.5D, 6.5E). Both Facies 3 and Facies 5 are interpreted to have been deposited within well-oxygenated conditions. Facies 4 is also pervasively bioturbated (BI = 4-6), but lacks the large burrow diameter and trace fossil diversity that is observed in Facies 3 and Facies 5. This suggests that the facies was deposited in a more stressed environment, which could not support the same diverse assemblage of trace-making organisms as observed in the other pervasively bioturbated facies. Additionally, Facies 4 has a larger range of concentrations for redox-sensitive elements, which extend into concentrations that are associated with dysoxic conditions (Figs. 6.5C, 6.5D, 6.5E).

Commonly, the presence of bioturbation is associated with oxic conditions and the lack of bioturbation is associated with anoxic settings (Savrda and Bottjer, 1986, 1991; Föllmi and Grimm, 1990; Grimm and Föllmi, 1994). However, the absence of trace fossils does not necessarily mean that the setting was influenced by anoxic water conditions. Dashtgard and MacEachern (2016) demonstrated that unburrowed mudstone can have similar geochemical signatures to bioturbated facies and both reflect deposition under oxic conditions. Results from the Sunset Prairie Formation suggest that a wide range of concentrations for redox-sensitive elements are recorded within non-bioturbated intervals and reflect deposition under aerobic, dysoxic and anoxic conditions (Fig. 6.4, 6.5C).

Implications for Oxygenation Fluctuations within the Sunset Prairie Formation

Generally, ichnological and geochemical data have an inverse relationship; well-oxygenated conditions are interpreted when redox-sensitive element concentrations are low and bioturbation intensity is high, whereas dysoxic to anoxic conditions are interpreted when concentrations of redox-sensitive elements are high and bioturbation intensity is low or nonexistent. This overall trend is observed within the Sunset Prairie Formation when comparing V to SDI (Table 6.2). Diminutively to non-bioturbated facies exhibit low SDI values (0-10), but are associated with a large range of V concentrations (8.13-5113.02 ppm) (Figs. 6.5C). This suggests that these intervals were deposited under a wide range of dissolved oxygen concentrations (oxic to anoxic), rather than just reduced-oxygen conditions. Conversely, pervasively bioturbated facies (Facies 3, 4 and 5) exhibit lower V concentrations (Facies 3: 4.09-34.20 ppm; Facies 4: 4.09-519.65 ppm; Facies 5: 11.08-131.29 ppm) and higher SDI values (Facies 3: 2.5-72; Facies 4: 1.5-25; Facies 5: 3-91) (Fig. 6.5C; Table 6.2). Both Facies 3 and 5 have V concentrations below the V enrichment of the average shale (130 ppm), suggesting that relatively aerobic conditions existed. Facies 4 records V concentrations that extend higher than enrichment levels, but due to the presence of high bioturbation intensity of the facies, the interval is interpreted to be associated with oxic to slightly reduced oxygen levels.

Ichnological characteristic for each sub-formational unit in summarized in Table 6.3. Overall, the lower sub-formational unit exhibits higher values in average bioturbation intensity, burrow diameter, number of ichnogenera and SDI, as compared to the two overlying sub-formational units. This trend reflects the change in facies distribution between the three sub-formational units. The lower sub-formational unit predominantly exhibits thick beds of pervasively bioturbated facies (up to 7 m in total thickness), with thin intervals (<2 m in thickness) of diminutively bioturbated facies, whereas the upper two sub-formational units exhibit increased bed thickness of diminutively bioturbated facies (<10 m thick) and a decrease in bed thickness of pervasively bioturbated facies (<2 m) (Fig. 6.4)

Geochemically, Mo, V, and V/Cr concentrations/ratios are low or not detected within the lower sub-unit, with the few exceptions of a of couple peaks that have increased concentrations of redox-sensitive elements and ratios (Figs. 6.4, 6.5G, 6.5H; Table 6.3). In the middle sub-formational unit, Mo, V, and V/Cr concentrations/ratios are more variable, but there are two general peaks associated with increased concentrations/ratios. The upper sub-formational unit has the largest range of concentrations for each of the respective element and ratios. Overall, each redox-sensitive element increases in average concentration moving stratigraphically up (Table 6.3) and is reflective of the decrease in average dissolved oxygen level within each sub-formational unit.

The lower sub-formational unit is interpreted to have been deposited in oxic conditions with a couple short-lived periods of dysoxia. The depositional setting fostered prolonged periods of habitable conditions, which allowed organisms to colonize and thoroughly bioturbate the sediment. The middle sub-formational unit exhibits more fluctuations in dissolved oxygen, which is interpreted by the vacillating SDI values and elemental concentrations (Fig. 6.4). The upper sub-formational unit is interpreted to have been deposited in dysoxic to anoxic conditions at the base and more oxic conditions at the top, which is then capped by a thin interval of dysoxic to anoxic conditions (Fig. 6.4). A high concentration of Ni is observed at the base, suggesting anoxic conditions. However, when isolated bioturbation is present, the interval cannot be permanently anoxic but is instead associated with dysoxic bottom water conditions. When bioturbation is not observed and redox-sensitive element concentrations are high, anoxic to euxinic conditions likely occurred. A sharp shift in the middle of the upper sub-formational unit is observed where all redox-sensitive concentrations drop drastically and ichnological assemblages reappear.

Phosphate Influences on Trace Metal Signatures

Throughout the Sunset Prairie Formation, phosphate material is present as phosphate grains, ooids, and nodules, which have been associated with coastal upwelling (Furlong et al., 2018b). Facies 1, 3, 5 and 7 have been identified in core to exhibit visible phosphate material (Furlong et al., 2018b). Classically, in upwelling settings, phosphorites are typically associated with chert and black shale deposits (Riggs, 1979; Sandstrom, 1990; Glenn et al., 1994). The presence of phosphate material within the organic-rich siltstone intervals provides evidence that the Sunset Prairie Formation supports that phosphate concentrations were influenced by upwelling. Shale and chert are not observed within the formation; however little clay material is observed within the Sunset Prairie Formation and underlying Montney Formation, hindering the formation and preservation of shale deposits.

Geochemically, phosphorite can have a strong influence on the distribution of a variety of elements (Ag, Br, Cd, Cu, Cr, I, Mo, Pb, Se, U, V, Y, and Zn), as a result of these elements being included into the phosphate structure (e.g., Prévôt and Lucas, 1980; Breit and Wanty 1991; Tribovillard et al., 2006; Khan et al., 2012; Turner et al., 2015). Redox-sensitive elements used in this study that have the potential to be influenced by phosphate content include V, Mo, and Cr. When P content recorded by the XRF was plotted against the different redox-sensitive elements/ratios, no correlations are observed (Fig. 6.7). Some of the very high concentrations of V do correspond to the facies that exhibit observable phosphate material in core, but there are no clear correlations. Additionally, Ni is not as easily influenced by phosphate concentrations and

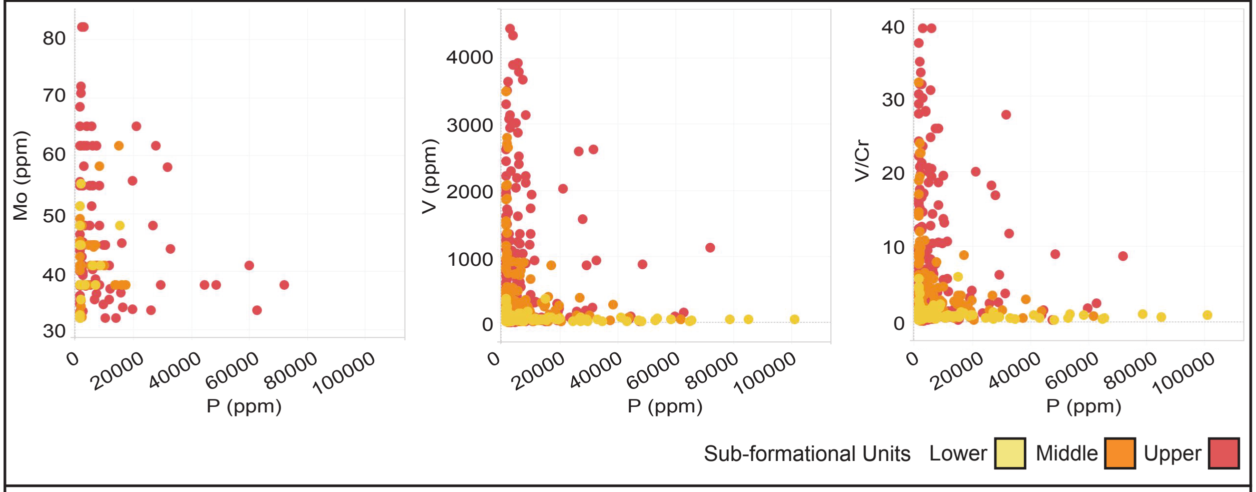


Figure 6.7–Cross plots of redox-sensitive elements vs. phosphate content. Points coloured by sub-formational units.

occurs in low concentrations in phosphorites (<50 ppm), but behaves similarly to V under redox conditions (Prévôt and Lucas, 1980). Trends observed in Ni can be better used to interpret redox when phosphate material is abundant within the rock record. Although phosphate might alter the absolute concentrations of different redox-sensitive elements and ratios, the overall trends between the different redox-sensitive elements and ratios used in this study suggest that similar palaeoredox trends and support fluctuations in palaeoredox conditions throughout the deposition of the Sunset Prairie Formation.

COMPARISON OF ICHNOLOGICAL MODELS FOR REDUCED OXYGEN CONDITIONS

Fundamental models describing ichnological characteristics in reduced oxygen conditions have been proposed by Rhoads and Morse (1971), Savrda and Bottjer (1986, 1987, 1989), Ekdale and Mason (1988) and Wignall and Myers (1988). Major oxygen-related ichnological models are briefly summarized below. Comparison of ichnological trends observed within the Sunset Prairie Formation through the lens of the different models demonstrates the validation and limitation of each model.

Rhoads and Morse Model: Oxygen-related Biofacies

Rhoads and Morse (1971) synthesized published data from modern oxygen-deficient basins (Black Sea, Gulf of Mexico and continental borderland basins in southern California) to describe observed relationships between species diversity and dissolved oxygen levels. Three major benthic biofacies were described and attributed to dysaerobic basins: 1. A diverse assemblage of infaunal and epifaunal organisms consisting of numerous species that secrete calcareous body parts, which was associated with aerobic conditions; 2. An assemblage chiefly composed of small soft-bodied infaunal species that was associated with dysaerobic conditions; and 3. A region essentially devoid of benthic metazoans and was dominated by sediment with laminae was attributed to anaerobic conditions (Rhoads and Morse, 1971, fig. 5). The two end-member biofacies were well defined and all intermediate strata were lumped together in dysaerobic conditions.

Only some aspects of the Rhoads and Morse model are observed in the Sunset Prairie Formation. Based on geochemical redox-proxies, facies associated with oxic conditions exhibit diverse assemblages of traces fossils (Facies 3, 4 and 5); however, some intervals of non-bioturbated and diminutively bioturbated facies (Facies 1 and 2) also record low Mo, V, and V/Cr concentrations/ratios, suggesting aerobic conditions (Fig. 6.4). Facies 3 and 5 have the largest observed trace fossils size (Facies 3 mean diameter = 5.25 mm; Facies 5 mean diameter = 4.10) and Facies 4 exhibits smaller burrow diameters (mean diameter = 1.15 mm), but Facies 4 and 5 are intervals that calcareous body fossil material is preserved. The occurrence of small trace fossils co-occurring with calcareous shell material in the same facies is contradictive of the Rhoads and Morse model.

Savrda and Bottjer Model: Oxygen-related Ichnocoenoses

The recognition and application of oxygen-related ichnocoenoses (ORI) was established by a series of papers (Savrda and Bottjer, 1986; 1987; 1989, 1991, 1994) to describe the relative degree of palaeo-oxygenation within the broad dysaerobic realm. This model is based on burrow diversity, size/diameter and penetration depth. The occurrence/absence of trace fossils, particularly *Thalassinoides*, *Zoophycos* and *Chondrites* (Savrda and Bottjer, 1989), and the cross-cutting relationships associated with trace fossil tiering (Bromley and Ekdale, 1984, 1986) are important factors of the model. Generally aerobic conditions exhibit all three ichnogenera, with deep trace fossil tiering, whereas decreasing oxygen levels result in the disappearance of *Thalassinoides*, then *Zoophycos*, and leaving shallowly tiering *Chondrites* preserved in dysoxic to anoxic conditions. Specific details of the model have evolved over time, with early publications identifying five different ORI trends (Savrda and Bottjer, 1986, fig. 1) and four levels or tiers of bioturbation (Savrda and Bottjer, 1989, fig. 1), to more recent publications describing complex burrow stratigraphy that form from the relationships between the mixed layer and transition layer within the preserved substrate (Savrda, 2007, fig. 9.1). A variety of limitations have been attributed to this model (outlined in Savrda and Bottjer, 1989; Savrda, 2007), due to studies mainly focusing on ichnofabric characteristics in pelagic and hemipelagic muds. Time averaging, differential compaction, visibility of trace fossils, other physico-chemical stresses influencing organism distribution, and variability in organism response to dissolved oxygen changes are amongst the notable limitations described (Savrda and Bottjer, 1989; Savrda, 2007).

Several observations from the Savrda and Bottjer model are exhibited within the Sunset Prairie Formation. In particular, a decrease in burrow diameter and ichnological diversity (number of ichnogenera) is observed as interpreted dissolved oxygen concentrations decrease. Distinct tiering of trace fossils was difficult to assess due to sediment being completely reworked in pervasively bioturbated facies, making distinct bed contacts difficult to observe. Tiering depths of trace fossils in diminutively bioturbated facies (Facies 1 and 2) were impossible to determine within the core dataset due to vertical expressions of traces not being observed; only the horizontally oriented portions of the burrows were observed. The *Glossifungites* Ichnofacies associated with Facies 6 provides the best indication of penetration depth. Here burrows can extend up to 10 cm below the borrowed surface. However, other attributed physico-chemical factors (substrate consistency, erosion rate, exposure duration, temperature and salinity fluctuations, etc.) suggest that the burrowed discontinuity surfaces are more complex than just reduced-oxygen conditions influencing trace fossil distribution (Gingras et al., 2000, 2001).

The most discordant aspect of the Sunset Prairie Formation ichnological assemblage, as compared to the Savrda and Bottjer model, is the relationship between *Thalassinoides*, *Zoophycos* and *Chondrites*. The distinct transition between the three ichnogenera with decreasing dissolved oxygen is not observed within the Sunset Prairie Formation. The occurrence of *Thalassinoides* is limited to the burrowed firmground surface of Facies 6. *Zoophycos* is only observed in Facies 3, which has been associated with offshore transition settings. The range of redox-sensitive element concentrations associated with Facies 3 remains within oxic thresholds (Figs. 6.5D, 6.5E; Table 6.2) and is not indicative of reduced oxygen conditions. Additionally, *Chondrites* is not limited to facies associated with the most depleted dissolved oxygen but is instead observed in almost all facies (Facies 1, 2, 3 and 4); *Chondrites*, therefore, can be associated with both oxic and reduced-oxygen conditions within the Sunset Prairie Formation dataset.

Ekdale and Mason Model: Low-oxygen Trace Fossil Morphology

Observations from late Palaeozoic and modern deep-water trace fossil assemblages suggest that certain morphological characteristics (and therefore behavioural characteristics) are typical in low-oxygen environments (Ekdale and Mason, 1988). As dissolved oxygen concentration of the interstitial water increases, the substrate transitions from non-burrowed sediment to possessing trace fossil assemblages dominated by inferred deposit-feeding structures, and then to exhibiting trace fossil assemblages dominated by dwelling traces and structures associated with suspension feeding strategies (Ekdale and Mason, 1988). Lowered oxygen conditions correlate to shallower penetration depths of trace fossils, similar to the Savrda and Bottjer model. Particular ichnogenera are also interpreted to be associated with different redox conditions; endostratal pascichnia (*Scalarituba*, *Spirophyton*, *Phycosiphon*, etc.) are structures of deposit feeding organisms that do not maintain connection with the sediment-water interface, which suggests that at least some remaining oxygen is present in the porewater; whereas fodinichnia-dominated ethologies (grazing and deposit feeding strategies) that maintain connection with the sediment-water interface (e.g., *Chondrites*, *Zoophycos*), were interpreted to reflect anoxic porewater and dysoxic water above the sediment-water interface (Ekdale and Mason, 1988; MacEachern et al., 2007b). This model parallels trends described in the Seilacherian model of Ichnofacies (Seilacher, 1964, 1967), but provides an alternative mechanism of oxygen conditions, as opposed to water depth, for trace fossil morphology distribution. Some have contributed the *Zoophycos* Ichnofacies itself to reduced oxygen conditions due to its characteristically low diversity trace fossil assemblage of horizontal to slightly inclined burrows consisting of *Zoophyco*s, *Chondrites*, *Planolites*, *Phycosiphon*, *Spirophyton*, *Helminthopsis* and diminutive *Thalassinoides* (e.g., Frey and Seilacher, 1980; Pemberton et al., 1992). The Ichnofacies model, however, has evolved from its origins to consider many factors, including energy conditions, depositional rates, food resource types, substrate consistency, water salinity, oxygenation, temperature, substrate exposure, among others (e.g., MacEachern et al., 2007a). Others have identified a *Chondrites-Zoophycos* ichnoguild (groups of ichnospecies that express a similar trophic group and occupy a similar location/tier within the substrate) to correspond to deep-tier deposit-feeding structures (e.g. *Zoophyco*s, *Chondrites*, *Teichichnus* and *Trichichnus*) associated with oxygen-restricted environments (Bromley, 1990; 1996; Savrda, 1992). However, care needs to be taken when evaluating if deep-tier colonization occurred during periods of dysoxia or due to exploitation of buried anoxic beds from overlying oxygenated positions higher in the substrate (e.g. Vossler and Pemberton, 1989). Although the occurrence of specific ichnotaxa have been attributed to reduced-oxygen conditions, many of the ichnogenera listed above can be found in a wide range of settings under varying redox conditions (e.g. Ekdale and Bromley, 1983; Frey et al., 1990; Bromley and Asgaard, 1991; Wignall, 1991; McEachern et al., 2010).

Changes in trace fossil morphology are relatively limited within the Sunset Prairie Formation. The majority of burrows observed are horizontally oriented and have been associated with deposit feeding tracemakers (Furlong et al., 2018b, fig. 5). Facies 5 and 6 are the only intervals to exhibit vertically oriented burrows associated with domiciles of inferred suspension-feeders (Furlong et al., 2018b, fig. 5). All pervasively bioturbated facies exhibit a dense background fabric dominated by *Phycosiphon, Palaeophycos* and *Planolites*. Opportunistic trace-making organisms are associated with these trace fossils, which can survive in both oxic and reduced-oxygen conditions (Fraiser and Bottjer, 2009; MacEachern et al., 2010). In particular, the ichnological assemblage of Facies 4 is solely made up of small sized trace fossils of inferred deposit feeding and opportunistic tracemakers, which supports the interpretation of the facies being deposited under reduced oxygen conditions.

Similar to the discordance with other models, geochemical evidence from the Sunset Prairie Formation suggests that the pervasively bioturbated facies were associated with oxic to slightly reduced-oxygen conditions and non-bioturbated to diminutively bioturbated facies record deposition in a variety of redox conditions. Trace fossil morphology and occurrence of specific ichnogenera (e.g., *Chondrites* and *Zoophycos*) is not necessarily dependent on redox conditions. However, trace fossils that occur only in Facies 3 or Facies 5 (*Asterosoma, Cylindrichnus, Diplocraterion, Rhizocorallium*, *Rosselia*, *Skolithos*, *Teichichnus*, and *Zoophycos*) may be more strongly tied to aerobic conditions and their tracemakers cannot survive under reduced-oxygen conditions.

Wignall and Myers Model: Palaeoecology and Geochemistry Approach

The first study to integrate geochemical signatures with ichnological trends was Wignall and Myers (1988). The investigation of the Jurassic Kimmeridge Clay from England compared spectral gamma ray (U, Th, K), semi-quantitative geochemical data from optical emission spectrography (Mo and organic matter data form Dunn, 1974), degree of fragmentation of body fossils, species richness, and Shannon-Weaver dominance-diversity index. Fundamental to previous models was that the depositional environment under investigation was a deep-water setting where pelagic to hemipelagic processes dominated; however, the Kimmeridge Clay records shallower-water, organic- and carbonate-rich shale deposits interbedded with storm-influenced, organic-poor mudstone, which record brief oxygenation events (Wignall and Myers, 1988). Organic matter, U, and Mo were used as proxies for redox conditions and showed an overall decrease in concentrations as species richness and dominance-diversity increased, and fragmentation of body fossils decreased (Wignall and Myers, 1988). Building from this original work by Wingall and Myers (1988), many other studies have integrated geochemical techniques (spectral gamma, XRF, isotope, iron speciation, total organic carbon, etc) with palaeontological data (ichnology, macro- and micro-fossils, biomarkers) to produce more robust datasets for interpreting palaeoredox conditions (e.g. Joachimski et al., 2001; Algeo and Maynard, 2004; Martin, 2004; van Bentum et al., 2009; Gordon et al., 2009; Algeo and Rowe, 2012; Izumi et al., 2012; Sperling et al., 2013; Kemp and Izumi, 2014; Large et al., 2014; Haddad et al., 2018; Han et al., 2018; Planavsky et al. 2018).

The Sunset Prairie Formation exhibits similar trends between elemental redox proxies and ichnological data. The Wignall and Myers (1988) study documented an inverse trend between Mo concentrations and dominance-diversity index. In the Sunset Prairie Formation, as Mo and V concentrations increase, burrow diameter, number of ichnogenera, and SDI decrease (Figs 6.4, 6.5; Table 6.2). Other ecological and geochemical data used by Wignall and Myers (1988) were not obtained or assessed within the Sunset Prairie Formation dataset. Spectral gamma for the drill core was not measured and synthetic gamma ray logs from XRF data could not be produced due to poor detection of U and Th by the XRF machine. Additionally, Shannon-Weaver dominance-diversity index was not calculated due to the relative abundance of each ichnogenera not being recorded in the Sunset Prairie Formation dataset. Relative abundance of ichnotaxa may be difficult to determine and may provide skewed results, since a single trace-making organism or multiple trace-making organisms can form the same ichnogenera, and a single tracemaker can produce multiple morphologies of burrows associated with a variety of ichnogenera (Ekdale et al., 1984; Bromley, 1996). Further integrating geochemical, palaeoecological and palaeontological methods into future investigations of the Sunset Prairie Formation and other intervals can assist in producing a more robust framework to better assess palaeoredox conditions.

METHODOLOGICAL SUGGESTIONS FOR FUTURE STUDIES

The current study documents the first attempt at integrating geochemical and ichnological datasets at a high-resolution (10 cm intervals) to better understand and interpret the biological and geochemical characteristics associated with different palaeoredox conditions. Although a few studies have previously integrated geochemical and ichnological datasets (e.g. Dashtgards and MacEachern, 2016, Haddad et al., 2018), many studies use geochemical approaches independently of palaeontological and ichnological characteristics.

A variety of methods have been used to interpret palaeoredox conditions. Many studies have used and compared different elements and ratios to interpret bottom water conditions, which include elements like U, Zn, Pb, Cd, Cu, Co, U/Th, Ni/Co, Ni/V, and (Cu+Mo)/Zn (e.g., Dypvik, 1984; Jones and Manning, 1994; Rimmer, 2004; Tribovillard et al., 2006; Algeo and Tribovillard, 2009; Zarasvandi et al., 2019). Many of these elements, however, were under detection limits of the XRF machine and were not recorded in many cored intervals within this study. Therefore, other elements were used to interpret palaeoredox conditions. Some of the listed elements were better detected through the use of an ICP-MS machine, due to the machine having lower detection limits. However, the current study only examined 28 samples using ICP-MS to help calibrate XRF data. A high-resolution analysis (samples collected and analyzed very 10 cm or 50 cm along a core or outcrop) of elemental concentrations conducted using ICP-MS analysis would provide information and trends on trace elements that have low concentrations.

Interdisciplinary approaches to interpreting redox conditions use datasets that include elemental isotope, elemental concentrations from XRF and ICP-MS, total organic carbon, iron speciation and biomarkers (e.g. Hatch and Leverthal, 1992; Joachimski et al., 2001; Algeo and Maynard, 2004; Martin, 2004; Piper and Perkins, 2004; van Bentum et al., 2009; Gordon et al., 2009; Algeo and Rowe, 2012; Izumi et al., 2012; Sperling et al., 2013; Kemp and Izumi, 2014; Large et al., 2014; Haddad et al., 2018; Han et al., 2018; Planavsky et al. 2018). Elemental isotopic data commonly used for interpreting redox conditions has included $\delta^{13}C$, $\delta^{34}S$, and $\delta^{97/95}Mo$ (e.g., Schouten et al., 2000; Arnold et al., 2004; Owens et al., 2013). These complementary datasets were outside the scope of this project, but could be useful in future studies to further integrate and validate geochemical redox proxies for the Sunset Prairie Formation.

CONCLUSIONS

The relationship between ichnological characteristics and geochemical signatures was evaluated within the Middle Triassic Sunset Prairie Formation to better interpret palaeoredox conditions during deposition. The integration of ichnological and geochemical datasets has been conducted by a few authors (Wignall and Myers, 1988; Werne et al., 2002; Algeo et al., 2004; Martin, 2004; Izumi et al., 2012; Kemo and Izumi, 2014; Dashtgard and MacEachern, 2016; Haddad et al., 2018), but none have conducted a high-resolution analysis to empirically relate the two datasets together. This study incorporates sedimentological, ichnological and geochemical (XRF) comparisons on a facies scale, as well as on a formational scale, to understand vertical and lateral variability of redox conditions during the deposition of the Sunset Prairie Formation.

Two of the pervasively bioturbated facies (Facies 3 and 5) of the Sunset Prairie Formation have high bioturbation intensities (BI = 5-6), large burrow diameters (up to 15 mm), and moderately diverse trace fossil assemblages (up to 7 ichnogenera). The calculated Size Diversity Index (SDI) ranges from 2.5-75 in Facies 3 and 3-91 in Facies 5, and is indicative of prolonged, stable conditions. These facies correspond to relatively low concentrations of geochemical signatures of redox-sensitive elements and ratios (Mo: 31.94-32.53 ppm; V: 4.09-131.29 ppm; V/Cr: 0.18-1.93) and are interpreted to be deposited under aerobic or well-oxygenated conditions. The two facies differ in their ichnological assemblages and interpreted depositional environment along coastline. Facies 3 described siltstone deposits with a trace fossil assemblage consisting of *Phycosiphon*, *Helminthopsis*, *Teichichnus*, *Palaeophycus*, *Planolites*, *Chondrites*, and *Zoophycos*, which was deposited in the lower to upper offshore transition. Facies 5 records sandy-siltstone deposits with a trace fossil assemblage consisting of *Phycosiphon*, *Rosselia*, *Cylindrichnus, Asterosoma, Teichichnus*, *Palaeophycus*, *Planolites*, *Skolithos, Rhizocorallium*, and *Diplocraterion*, which was deposited within the upper offshore transition to lower shoreface.

An additional pervasively bioturbated siltstone facies (Facies 4) is observed within the Sunset Prairie Formation; however, this facies has slightly lower bioturbation intensity (BI = 4-6), smaller burrow diameter (up to 6 mm), and a lower ichnological diversity (up to 5 ichnogenera), as compared to the other bioturbated facies. The calculated SDI is low (1.5-25) and is indicative of a more stressed depositional setting. A larger range of redox-sensitive elements and ratios is observed (Mo: 21.94-62.35 ppm; V:4.09-519.65 ppm; V/Cr: 0.18-0.90), suggesting that deposition occurred under oxic to dysoxic conditions. The ichnological assemblage consists of *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. Opportunistic trace-making organisms are commonly associated with *Phycosiphon*, *Palaeophycus*, and *Planolites*, which can survive within reduced oxygen settings (MacEachern et al., 2010). Facies 4 is interpreted to record deposition in the lower to upper offshore transition.

Diminutively bioturbated to non-bioturbated facies (Facies 1 and 2) are interpreted to record deposition in offshore to lower offshore transition settings. Bioturbation intensity is low (BI = 0-2), small burrow diameters are observed (up to 3 mm), and a low ichnological diversity is present (up to 5 ichnogenera). The calculated SDI is low (Facies 1: 0-10; Facies 2: 0-6) and is indicative of a more stressed depositional setting. However, geochemical palaeoredox proxies show that all redox-sensitive elements and ratios span previously documented threshold values between oxic, dysoxic, anoxic and euxinic conditions. Redox-sensitive element concentrations and ratios for diminutively bioturbated facies include: Mo: 31.80-82.20 ppm; V: 8.13-5113.02 ppm; and V/Cr: 0.18-39.90. The presence of bioturbation is indicative of oxic to dysoxic conditions during deposition; however, non-bioturbated facies were deposited in variable oxygen conditions. This makes rending redox conditions solely based on physical and biogenic sedimentary structures problematic.

Overall, the Sunset Prairie Formation can be subdivided into three different sub-formational units that represent coarsening-upwards/shoaling-upwards parasequences. The lower sub-formational unit is characterized by the occurrence of thick (<7 m) pervasively bioturbated facies and thinner diminutively bioturbated facies (<2 m). The upper two sub-formational units exhibit increased bed thickness of diminutively bioturbated facies (<10 m thick) and a decrease in bed thickness of pervasively bioturbated facies (<2 m). Fine-grained sand content, thickness of coarse-grained beds, and bioturbation intensity decrease with each following sub-formational unit. Average concentrations of redox-sensitive elements and ratios increase with each overlying sub-formational unit. An overall decrease in dissolved oxygen is interpreted for the Sunset Prairie Formation, however small-scale fluctuations are observed.

The Sunset Prairie Formation provides a unique case study to evaluate the integration of high-resolution ichnological and geochemical (XRF) datasets to understand palaeoredox conditions. The formation consists of interbedded pervasively bioturbated, diminutively bioturbated and non-bioturbated intervals, which exhibit geochemical signatures that are associated with a variety of redox conditions. Investigating inferred palaeoredox conditions during the deposition of the Middle Triassic Sunset Prairie Formation can help to understand the depositional dynamic of Triassic deposits of Western Canada.

CHAPTER 7: SUMMARY AND CONCLUSIONS

SUMMARY OF THESIS

The studies in this dissertation introduce and describe the Sunset Prairie Formation as a new lithostratigraphic formation and provide new sedimentological, ichnological and geochemical information on the previously overlooked interval. The purpose of this thesis is five-fold: 1) formally name the Sunset Prairie Formation as a lithostratigraphic formation; 2) describe the sedimentological, ichnological and palaeontological characteristics of the formation through a facies analysis and interpret palaeodepositional environments associated with the interval; 3) discuss a sequence stratigraphic framework based on facies stacking patterns and petrophysical well log signatures; 4) interpret physico-chemical stresses acting on the palaeoenvironment through a process ichnological scope and discuss paleoecological trends of a post-Permo-Triassic extinction recovery fauna; and 5) integrate ichnological characteristics and geochemical signatures to infer palaeoenvironmental redox conditions influencing infaunal distribution.

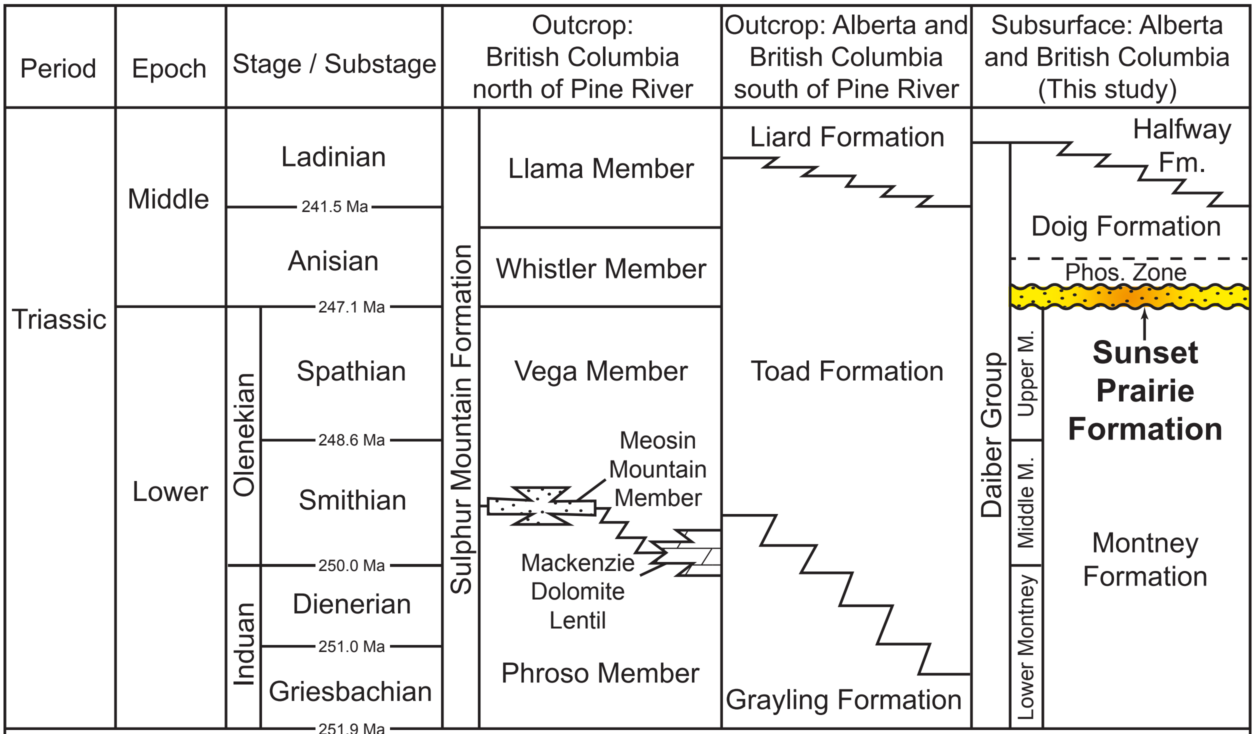


Figure 7.1–Lower and Middle Triassic lithostratigraphic nomenclature for outcrop and subsurface sections in Alberta and British Columbia. Ages of stages and substages identified by Henderson and Schoefer (2017), and Henderson et al. (2018). Modified from Zonneveld (2011) and Golding et al. (2015).

Lithostratigraphy Contributions

The Sunset Prairie Formation is a newly identified lithostratigraphic formation within the Middle Triassic of the Western Canada Sedimentary Basin (Fig. 7.1; Furlong et al., 2018b). The unit sits stratigraphically between the Lower Triassic Montney Formation and the Middle Triassic Doig Formation. Work by Zonneveld and Moslow (2015) Zonneveld et al. (2015; 2016), Furlong et al. (2016; 2017a; 2017b) and Davies et al. (2018) informally described the unit as the 'Anisian Wedge'. Previous studies have overlooked the interval and included it as a part of the Montney Formation or Doig Formation (Doig phosphate zone), or straddling the two formations (e.g. Golding et al., 2014a, 2014b; Crombez et al., 2016). The interval is unconformity-bound and is sedimentologically, ichnologically and palaeontologically different than the underlying and overlying units. These features warrant a new lithostratigraphic name designation. The Sunset Prairie Formation characteristically consists of interbedded light gray, pervasively bioturbated sandstone and dark gray, diminutively bioturbated to non-bioturbated siltstone beds. Within pervasively bioturbated intervals, shell debris and body fossils of bivalves, gastropods, brachiopods (lingulid, spiriferid and terebratulid), echinoderm, and crinoids are preserved. Conodont biostratigraphic dates the Sunset Prairie Formation as Middle Triassic (Anisian) age.

Sedimentological, Ichnological and Palaeontological Characteristics

Seven lithofacies were identified in the Sunset Prairie Formation from the 25 drill cores that were investigated across the basin. Facies were subdivided into three general groups: 1) diminutively bioturbated facies (Facies 1 and 2), where physical sedimentary structures are observable and trace fossils are rare and small in size; 2) pervasively bioturbated facies (Facies 3, 4 and 5), where burrowing organisms have homogenized the sediment and destroyed most primary physical sedimentary structures; and 3) bathymetrically independent surfaces (Facies 6 = *Glossifungites* Ichnofacies-demarcated discontinuity surface; Facies 7 = lag deposit), which are not associated with specific water depth. Trace fossils present within the interval, listed in order of their relative abundance, include *Phycosiphon, Rosselia*, *Cylindrichnus*, *Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. Body fossil assemblages are limited to Facies 4 and 5 and include bivalves, gastropods, brachiopods (lingulid, spiriferid, and terebratulid), cidaroid echinoid skeletal fragments, and isocrinid crinoid ossicles. Lithofacies are associated with deposition within the offshore, offshore transition and lower shoreface along a sheltered marine coastline (Fig. 7.2). Facies associated with more proximal settings are not preserved.

The Sunset Prairie Formation provides the oldest, regionally expansive, intensively bioturbated

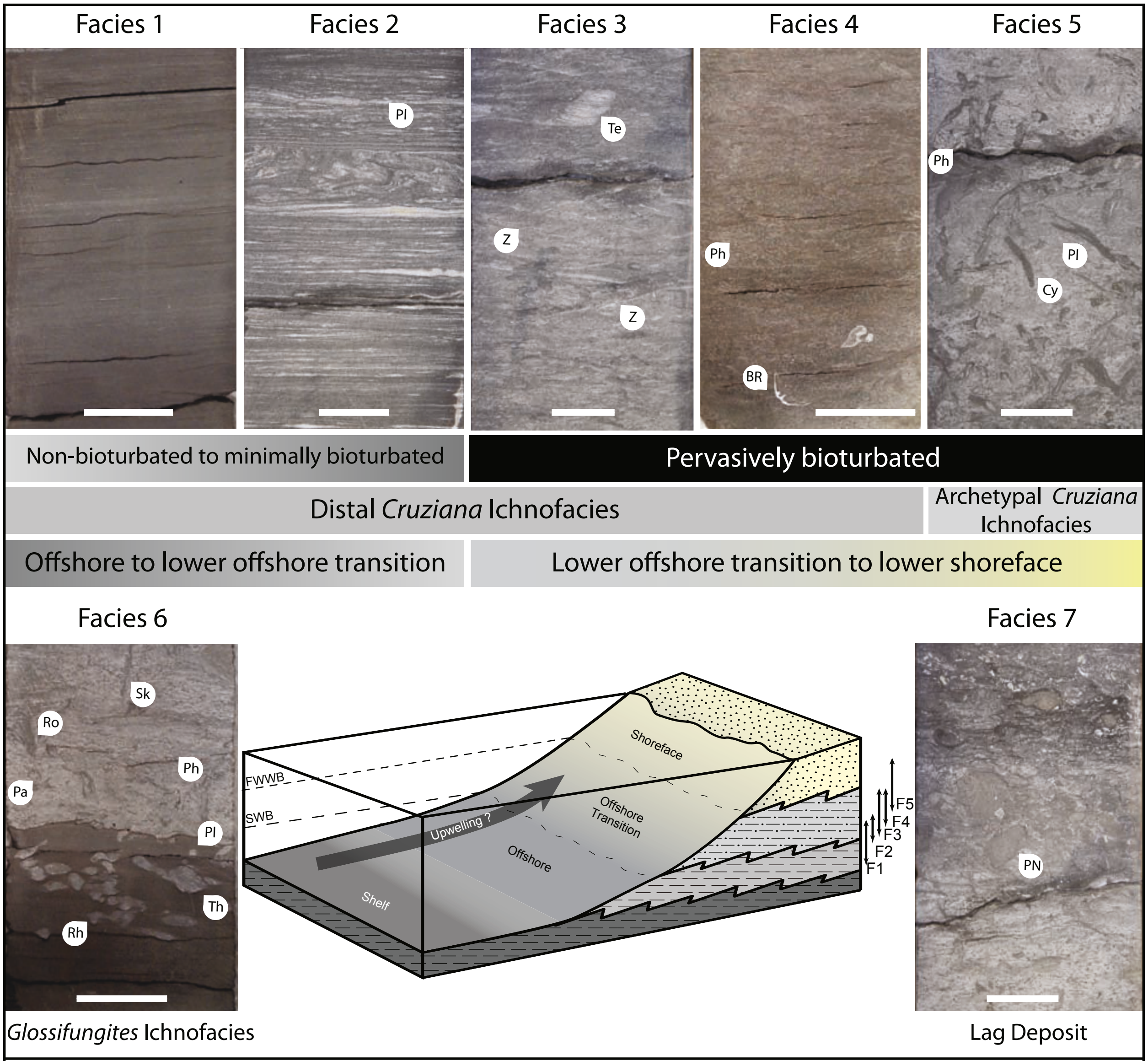


Figure 7.2–Summary of facies present within the Sunset Prairie Formation. Bioturbation intensity, ichnofacies and interpreted depositional environment are identified for each facies. Scale bars for core photos = 3 cm. Schematic at bottom shows distribution of facies and depositional environments within a siliciclastic ramp setting. Abbreviations include: Pa = *Palaeophycus*, Ph = *Phycosiphon*, Pl = *Planolites*, Rh = *Rhizocorallium*, Ro = *Rosselia*, Sc = *Scolicia*, Sk = *Skolithos*, Te = *Teichichnus* and Th = *Thalassinoides*, Z = *Zoophycos*, BR = brachiopod shell and PN = phosphate nodule.

interval with a diverse assemblage of trace fossils within the Middle Triassic strata of the Western Canada Sedimentary Basin. Bioturbation is limited to the lower offshore transition to lower shoreface settings, which is similar to the few examples of diverse ichnological assemblages within the Montney Formation. However, those earlier published examples are associated with refugia environments (areas where oxygenated waters were present in isolated zones across shallow-marine settings) and are not laterally extensive (Beatty et al., 2008; Zonneveld et al., 2007, 2010a, 2010b). The lateral distribution of the Sunset Prairie Formation suggests that favourable environmental conditions were widespread during the earliest Middle Triassic (Anisian) and could play a key role in understanding the biotic recovery following the end-Permian mass extinction.

Sequence Stratigraphy Framework

Due to its new recognition, the Sunset Prairie Formation has not been incorporated into sequence stratigraphic frameworks of the Triassic. Through the investigation of 25 cored wells, facies characteristics, vertical facies stacking and lateral facies distribution were identified and described. The Sunset Prairie Formation is geographically located with northeastern British Columbia, with its erosional eastern limit roughly following the Alberta-British Columbia border. The formation can reach up to 80 m in total thickness, and the distribution of the interval is greatly influenced by structural features.

Sequence stratigraphic surfaces were interpreted in the core dataset and extrapolated between 248 wells within the basin, which possessed petrophysical wireline data. Through this analysis, the Sunset Prairie Formation can be divided into three, upward-coarsening parasequences (sub-formational units). The lowermost parasequence preserves thick proximal facies (lower shoreface), whereas the two overlaying parasequences exhibit abundant distal facies (offshore transition to offshore). Fine-grained sand content, thickness of coarse-grained beds and bioturbation intensity decrease with each following parasequence. Collective, the parasequences represent a back-stepping or retrogradational stacking pattern and are interpreted to record deposition within the transgressive systems tract. All parasequences of the Sunset Prairie Formation are truncated at the top by the Doig phosphate zone and the Sunset Prairie Formation truncates the underlying Montney Formation, suggesting that the Sunset Prairie Formation is unconformity-bound with transgressively modified sequence boundaries (FS/SB). The addition of the Sunset Prairie Formation reveals that a separate sequence containing transgressive deposits has been previously unaccounted for within the Triassic sequence stratigraphy framework and basin evolution.

Process Ichnology Interpretation

A subset of five cored wells within the Fort St. John Graben system were chosen to test the application of the process ichnology framework within a fully marine setting. The process ichnology framework was introduced by Gingras et al. (2011) and utilizes biogenic sedimentary structures (trace fossils) to identify spatial and temporal relationship between physico-chemical stresses and ichnological responses. The framework builds off neoichnological studies (the study of modern track-ways, burrows and trails), which provides actualistic data that can then be extrapolated to the rock record.

The high-resolution analysis describes sedimentological and process ichnological characteristics of the Sunset Prairie Formation (facies, sedimentary structures, number of ichnogenera, diameter of trace fossils, bioturbation identity and Size Diversity Index) across every 10 cm intervals of the cores. Diminutively bioturbated to non-bioturbated facies (Facies 1 and 2) exhibit low bioturbation intensities (BI = 0-3), small burrow diameters (up to 3 mm), a moderate ichnological diversity (up to 5 ichnogenera), and SDI is low (0-6). Pervasively bioturbated facies (Facies 3, 4 and 5) of the Sunset Prairie Formation have high bioturbation intensities (BI = 4-6), large burrow diameters (up to 15 mm), and diverse trace fossil assemblages (up to 7 ichnogenera). The calculated SDI ranges from 4-60 in Facies 3, 2-20 in Facies 4, and 3-100 in Facies 5. Ichnological and sedimentological characteristics led to the identification of several inferred physico-chemical stresses, showing an overall evolution from dysoxic/suboxic conditions within the offshore, fluctuating dysoxic/suboxic to oxic conditions within the offshore transition and fully oxygenated conditions within the lower shoreface. A secondary stress of elevated sedimentation/erosion was interpreted for several intervals, which exhibited current generated sedimentary structures (e.g., asymmetric ripples and penecontemporaneous deformation structures). Although the majority of studies have used the process ichnological approach within marginal marine settings, this is the first attempt to formally apply the framework to a fully marine system and validates that the analysis can be extended to other depositional environments.

Additionally, this study provides insights onto the environmental conditions influencing biotic distribution during the recovery period following the end-Permian mass extinction. Worldwide anoxic water conditions have been strongly associated with Permo-Triassic oceans and restricted biota to narrow, shore-proximal habitable zones (Hallam, 1991; Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011). Reported localized, highly bioturbated intervals have been described from the Lower Triassic Montney Formation (Beatty et al., 2008; Zonneveld, 2011; Davies et al., 2018), however, the Middle Triassic Sunset Prairie Formation exhibits pervasively bioturbated facies that are regionally extensive. The interbedded appearance of pervasively bioturbated, diminutively bioturbated and non-bioturbated facies suggest that dissolved oxygen conditions fluctuated during the deposition of the Sunset Prairie Formation, and normal marine dissolved oxygen conditions had not been completely re-established. Through this study of the Sunset Prairie Formation, the relationship between ichnological diversity, burrow size and physico-chemical stresses have been described, evaluated and interpreted. These datasets can be incorporated into understanding biotic recovery signatures within Western Canada and how it relates to worldwide observations and trends.

Integration of Ichnology and Geochemistry

The connections between ichnological characteristics and elemental geochemistry with palaeoredox conditions have commonly been conducted independently. A few studies have begun the integration of ichnological and geochemical data (Wignall and Myers, 1988; Werne et al., 2002; Algeo et al., 2004; Martin, 2004; Izumi et al., 2012; Kemo and Izumi, 2014; Dashtgard and MacEachern, 2016; Haddad et al., 2018), but more work is needed to empirically compare the datasets. The interbedded pervasively bioturbated, diminutively bioturbated and non-bioturbated intervals of the Sunset Prairie Formation provide a unique dataset to interpret palaeoredox conditions from the comparison of ichnological characteristic and geochemical data. A subset of 3 drill cores, which penetrated the thickest region of the Sunset Prairie Formation, were analyzed every 10 cm for ichnological and geochemical data. Ichnological characteristic recorded included bioturbation intensity, maximum burrow diameter, ichnogenera present and calculated Size Diversity Index (SDI). Elemental geochemistry was rendered through the use of a Thermo Scientific NITON XL3t 900 Analyzer hand-held X-ray fluorescence (XRF) device. Redox-sensitive elements and ratios evaluated include Mo, V, and V/Cr, all of which have different enrichment factors and/or thresholds associated with variable redox conditions (e.g., Morford and Emerson, 1999; Turekian and Wedopohl, 1961; Jones and Manning, 1994; Rimmer, 2004; Scott et al., 2008).

Two of the pervasively bioturbated facies (Facies 3 and 5) of the Sunset Prairie Formation have high bioturbation intensities (BI = 5-6), large burrow diameters (up to 15 mm) and diverse trace fossil assemblages (up to 7 ichnogenera). The calculated Size Diversity Index (SDI) ranges from 3 to 100 and is indicative of prolonged, stable conditions. These facies correspond to relatively low concentrations of redox-sensitive elements and ratios, and are interpreted to represent deposition in aerobic or well-oxygenated conditions. The pervasively bioturbated siltstone assigned to Facies 4 has slightly lower bioturbation intensities (BI = 4-6), small burrow diameters (up to 6 mm), and moderate ichnological diversities (up to 5 ichnogenera), as compared to the other bioturbated facies. The calculated SDI values are low (2-20) and are indicative of a more stressed depositional setting. A larger range of redox-sensitive elements and ratios are observed, and suggests that deposition occurred under oxic to dysoxic conditions. Diminutively bioturbated to non-bioturbated facies (Facies 1 and 2) exhibit low bioturbation intensities (BI = 0-3), small burrow diameters (up to 2 mm), moderate ichnological diversities (up to 5 ichnogenera), and low SDI values (0-6), which all are indicative of more stressed depositional settings. However, geochemical palaeoredox proxies show that all redox-sensitive elements and ratios span threshold values associated with oxic, dysoxic, anoxic and euxinic conditions, suggesting that not all non-bioturbated intervals represent anoxic conditions.

Stratigraphically, the base of the Sunset Prairie Formation is characterized by the occurrence of thick (<7 m) pervasively bioturbated facies and thinner diminutively bioturbated facies (< 2m). All redox-sensitive elements remain within their respective oxic thresholds values for the majority of the sub-formational unit. The upper two sub-formational units have increased lithologic heterogeneities and record fluctuating values for redox-sensitive elements. Notably, the middle sub-formational unit has two spikes of increased concentrations of redox-sensitive elements, and the upper sub-formational unit has greatly increased concentrations of redox-sensitive elements at its base. Overall, geochemical trends suggest that dissolved oxygen concentration at the sediment-water interface decrease vertically through the formation.

CONCLUSIONS

Collectively, the five studies presented within this dissertation lay down the geological foundation for the Sunset Prairie Formation. The interval is sedimentologically, ichnologically and palaeontologically different than the underlying Lower Triassic Montney Formation and overlying Middle Triassic Doig Formation. Characteristic of the formation is the interbedded occurrence of pervasively bioturbated, diminutively bioturbated and non-bioturbated intervals, which record deposition within the offshore, offshore transition and lower shoreface along a sheltered marine coastline. Trace fossils present within the formation include *Phycosiphon, Rosselia*, *Cylindrichnus*, *Teichichnus*, *Asterosoma*, *Scolicia*, *Helminthopsis*, *Palaeophycus*, *Chondrites*, *Planolites*, *Diplocraterion*, *Rhizocorallium*, *Thalassinoides*, *Skolithos* and *Zoophycos*. Body fossils occur in select facies and include bivalve, gastropods, brachiopods (lingulid, spiriferid, and terebratulid), cidaroid echinoid skeletal fragments and isocrinid crinoid ossicles. Relative sea level fluctuations associated with a transgressive systems tract deposited three shoaling-upward parasequences. However, fluctuations in palaeoredox conditions, interpreted from XRF elemental data, influenced habitable locations along the shoreface profile and affected biotic distribution.

This dissertation investigated the Sunset Prairie Formation through a sedimentologic, ichnologic, palaeontologic, stratigraphic and geochemical scope. Future studies should focus on aspects including, but not limited to, petrography (e.g., mineralogy, diagenesis), reservoir characterization (e.g., permeability, porosity, hydrocarbon distribution, geomechanics) and biotic evolutionary trends through the Triassic. Although the Sunset Prairie Formation is relatively thin (<80 m), the interval holds a piece of the puzzle in unraveling the palaeoenvironmental and palaeoecological transition between the Lower Triassic and Middle Triassic within Western Canada.

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