

UNIVERSITY OF CALGARY

Sedimentology and Tectonic Controls on the Preservation of the Middle Triassic Halfway
Formation, Elmworth and Wapiti Fields, West-central Alberta

by

Mark A. Radomski

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Sedimentology and Tectonic Controls on the Preservation of the Middle Triassic Halfway Formation, Elmworth and Wapiti Fields, West-central Alberta" submitted by Mark A. Radomski in partial fulfilment of the requirements of the degree of Master of Science.

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Abstract

The Middle Triassic Halfway Formation in west-central Alberta is interpreted as a series of prograding shoreface facies associations in a ramp setting within a progradational series of parasequence sets. These parasequence sets have been reworked syn-depositionally by laterally discontinuous tidal inlet channels cutting perpendicular to the shoreline trend.

During the course of this study 131 core from the Middle Triassic Halfway Formation were analyzed which have led to the documentation of ten lithofacies from the Halfway Formation. Depositional environment interpretations range from offshore marine to arid continental. From these ten lithofacies, five genetically related facies associations have been created by grouping together commonly occurring lithofacies. These facies associations include: distal shoreface and proximal shoreface siliciclastics, tidal inlet/channel bioclastic fill, continental evaporates, and biostrome carbonates. Major hydrocarbon exploration targets from this region include tidal inlet/channel fill as well as proximal shoreface sandstone.

Evidence gathered in this study suggests a complex geological history to the region including multiple events of deposition, tectonism, and erosion prior to hydrocarbon emplacement. Extensive sedimentary structures indicative of seismic activity are observed in the study area suggesting that the Elmworth and Wapiti field areas were subjected to tectonic activity during or shortly after deposition of the Halfway Formation. This tectonic activity has complicated sequence stratigraphic correlations by creating over-thickened Halfway Formation sandstone intervals.

This study has also documented the first Middle Triassic biostrome discovered in the subsurface of the Western Canada Sedimentary Basin. This biostrome consists primarily of terebratulid brachiopods and sedimentological interpretations suggest it was formed within the lower shoreface. If discovered to have undergone the ideal paragenesis, biostrome deposits such as documented in this study could become highly significant hydrocarbon reservoirs within the Western Canada Sedimentary Basin.

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I would like to say a big thank you to both of my advisors; Dr. Charles H. Henderson and Dr. Thomas F. Moslow for their guidance, understanding, and patience throughout this study. Dr. Charles Henderson was required to put up with me on a day-to-day basis at the University of Calgary and Dr. Thomas Moslow provided me with employment as a sedimentologist at Midnight Oil Exploration during the summers. Tom granted me free reign to explore, meander, and build the various interpretations presented in this study but was always there to answer questions and talk about the core when needed.

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CHAPTER ONE: INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

The Halfway Formation consists of mixed siliciclastic-carbonate deposits of Middle Triassic age located within the Western Canada Sedimentary Basin in western Alberta and northeastern British Columbia. The Halfway Formation is so named because of the location of a well drilled by a now defunct company called Southern Production Canada Atlantic. This well, spud on November 11, 1954, was located near the junction of the Halfway River and the Peace River in Northeast British Columbia (Hunt and Ratcliffe, 1959). This specific Southern Production well (1-12-84-23W6) was one of the first wells with an “almost complete” core record through the subsequently named Halfway Formation, and at the time, was also considered the Halfway Formation type section (Hunt and Ratcliffe, 1959). This thesis presents the results of a geological investigation focused on the sedimentology, stratigraphy, and tectonics of the Halfway Formation in the Elmworth and Wapiti fields of west-central Alberta.

1.2 OBJECTIVES

This study focused on the uppermost Doig Formation, all of the Halfway Formation, and the lowermost portion of the Charlie Lake Formation in west-central Alberta Canada. The Halfway Formation contains abundant hydrocarbon reserves that in recent years have become an increasingly attractive primary exploration target within the Western Canada Sedimentary Basin.

Most production within this Middle Triassic interval is from a series of tidal inlet and shoreface facies which vary in thickness across the study area from three to fifteen metres. A greater understanding of the cause and origin of thickness variations of reservoir facies within the Halfway Formation is one of the goals of this study and should lead to more accurate hydrocarbon exploration models within the Halfway Formation. Variability in Middle Triassic sandstones elsewhere are interpreted to be the result of: a) tectonic activity and growth faulting (Wittenberg, 1992); b) mass wasting and slumping of slope sediments (Dixon 2002); and c) the result of river valley incision (Campbell and Horn, 1986; Campbell *et al.*, 1989).

The ultimate goal of this study is to determine the facies architecture, stratigraphic framework, and depositional environment of the Halfway Formation within the study area. This includes a determination of the origin and variability of facies associations within the Halfway Formation and find out what role, if any, is played by tectonism on sedimentation. Specific objectives of this thesis are:

(i) Conduct a detailed sedimentological study of the Halfway Formation within the pre-defined study area to determine the process sedimentologic interpretations of cored Doig, Halfway, and Charlie Lake Formation facies seen within core, and interpret depositional environments based on sedimentary characteristics and rock properties.

(ii) Create a conodont biostratigraphic framework for the Halfway Formation in order to discern gaps in the stratigraphic record caused by scouring or unconformities.

(iii) Provide a greater understanding of the interplay of tectonics and sedimentation during deposition of the Halfway Formation.

(iv) Construct a predictive stratigraphic framework of regional correlations within the Halfway-Doig interval;

(v) Construct an exploration model for hydrocarbon exploitation in the study area.

1.3 STUDY AREA

This study is confined to the subsurface of west-central Alberta and encompasses Townships 66-73, Ranges 7 to 12 west of the 6th meridian (Figure 1.01) which includes the Elmworth and Wapiti oil and gas fields southwest of Grand Prairie, Alberta, Canada.

Discovered in 1975 the Elmworth Field is one of the largest gas fields in the Western Canada Sedimentary Deep Basin, and has historically been a prolific Lower Cretaceous gas producer. Initial exploration and production with Elmworth centred on Cretaceous sandstone of the Falher Member of the Spirit River Formation, and the Paddy and Cadotte members of the Viking Formation (Cant, 1983). At this time, due to their depth, sour gas content, and lack of predictability the Middle Triassic Halfway and Doig formations were considered as a potential future exploration play. However, in recent years most of the true exploration within the field has been concentrated on the deeper Triassic strata of the Halfway and Doig formations.

It is estimated that the oil and gas in place within the Doig and Halfway formations within the Elmworth Field exceeds 164.3 BCF (AEUB, 2006), and that cumulative production from the Middle Triassic units is in excess of 72.9 BCF (AEUB, 2006). Fields neighbouring the study area include the large Wembley oil and gas field approximately thirty kilometres to the northeast, and the Sinclair gas field twenty-five kilometres to the northwest.

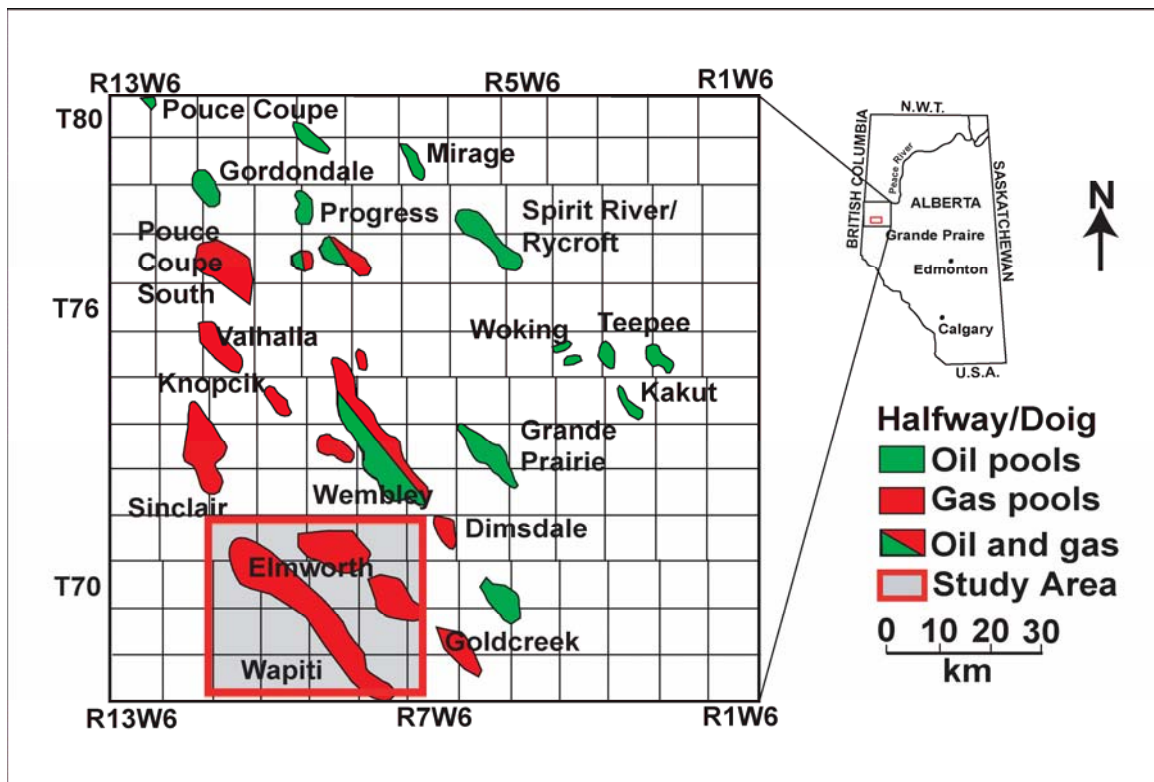


Figure 1.01 – Study area in west-central Alberta. Surrounding Halfway Formation oil and gas pools are highlighted (base map modified from Willis, 1992; oil and gas pools updated as of 2008).

1.4 STRATIGRAPHY

The Halfway Formation is confined to the subsurface of northwestern Alberta and northeastern British Columbia while its outcrop equivalent, the Liard Formation, recognized to be the distal western facies of the Halfway Formation, is found in the Main Ranges of northeastern British Columbia (Zonneveld, 1998). The Halfway Formation has been incorporated into the Schooler Creek Group, first defined by McLearn (1921), which spans the Late Ladinian, Carnian, and Norian stages (Armitage, 1962). The Schooler Creek Group consists of, in ascending order, the Halfway/Liard Formation, Charlie Lake/Ludington Formation, Baldonnel Formation, Pardonet Formation, and Bocoock Formation. In the subsurface the Schooler Creek Group has a maximum thickness of approximately 700 metres in central British Columbia south of Williston Lake, and like all of the Triassic deposits within the Western Canada Sedimentary Basin, thins to a zero point eastward under the central plains of Alberta (Figure 1.02).

Conformably and unconformably underlying the Schooler Creek Group is the Lower to Middle Triassic Diaber Group. This group consists of two formations, in ascending order, the Montney and Doig formations (Figure 1.03). The Doig Formation, located at the top of the Diaber Group immediately underlies the Halfway Formation, which is the lowermost formation in the Schooler Creek Group.

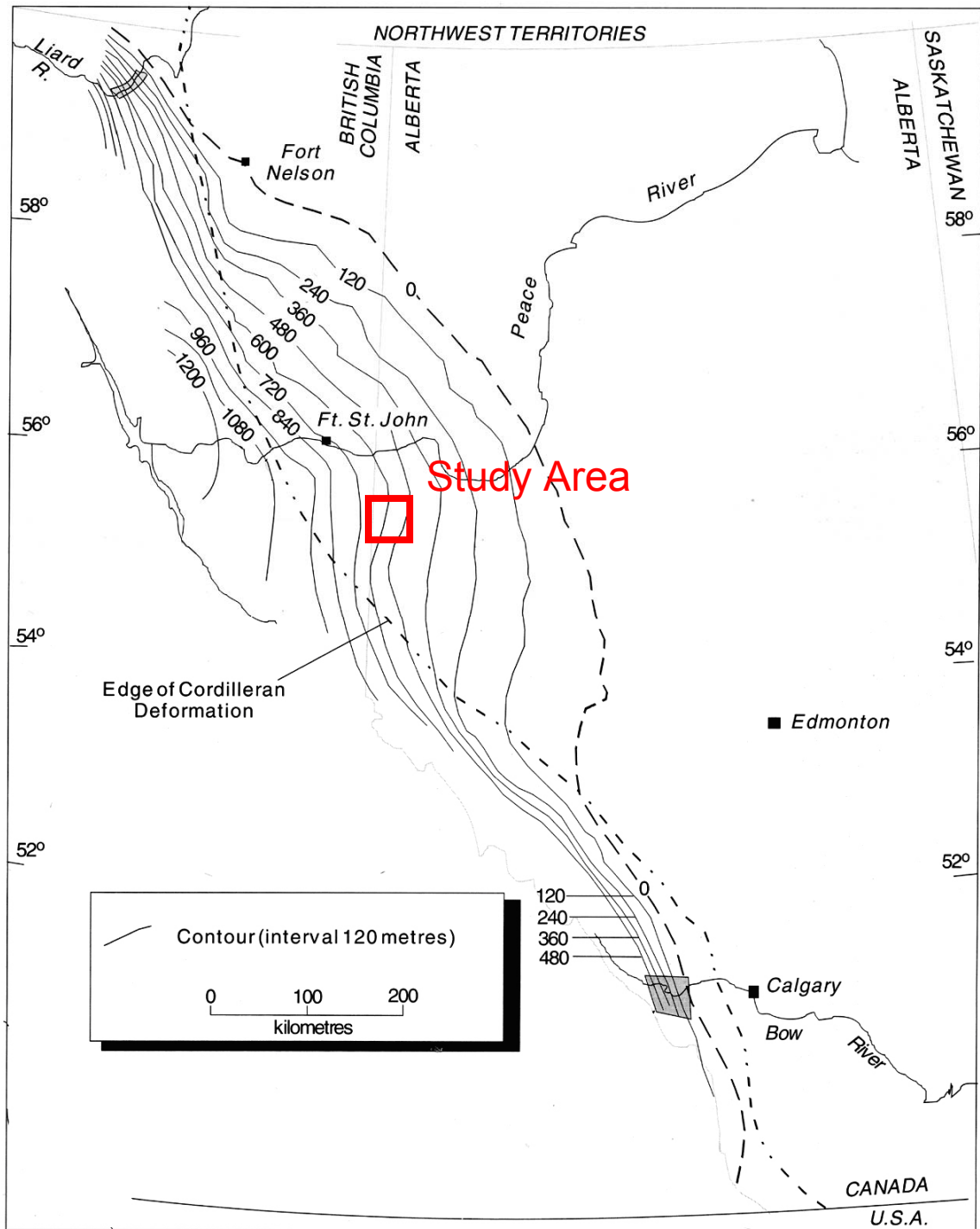


Figure 1.02 - Thickness of Triassic sediments in west-central Alberta and northeast British Columbia (Modified from Gibson and Barclay, 1989).

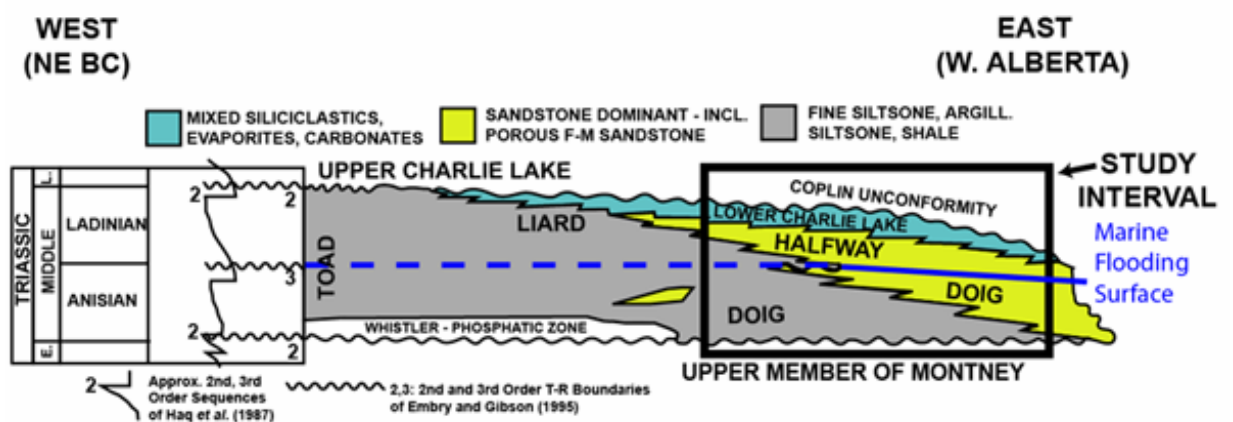


Figure 1.03 – Middle Triassic stratigraphy of west-central Alberta (Modified from Davies, 1997). Note marine flooding surface dividing the Doig and Halfway formation sandstone bodies. Approximate location of the study interval is highlighted with black rectangle.

1.5 MIDDLE TRIASSIC PALEOGEOGRAPHY AND DEPOSITIONAL ENVIRONMENT

During the Middle Triassic the Western Canada Sedimentary Basin was located along the northwestern margin of the Pangaea super-continent and was bounded to the west by the Panthalassa Ocean (proto-Pacific Ocean) (Figure 1.04) and to the east by the vast super-continent of Pangaea. The paleo-latitude of the Western Canada Sedimentary Basin is thought to have been approximately 30°N in latitude and rotated at an acute angle of approximately 30° clockwise relative to its modern-day position (Golonka *et al.*, 1994; Smith *et al.*, 1995). The continental shelf margin during the Middle Triassic lay a short distance west of the study area past the present-day border between Alberta and British Columbia (Davies *et al.*, 1997).

Global climatic conditions during the Middle Triassic have been interpreted as arid and relatively mild relative to present day conditions (Habicht, 1979; Mossop and Shetsen, 1994) and locally within the Western Canada Sedimentary Basin conditions were interpreted to be quite arid and hot with a desert-like environment existing eastward onshore of the basin (Davies *et al.*, 1997). Davies (1997) suggests that during the Middle Triassic seasonality had a strong effect on the Western Canada Sedimentary Basin region and that these seasons were greatly affected by oceanic currents and atmospheric winds. During the paleo-summer it is interpreted that dry onshore winds blew west across the Pangaeon-craton. These winds are thought to have pushed warm surface waters offshore, enhancing the up welling of cold anoxic waters off most of the western coast of Pangaea (Davies, 1997). Evidence of this oceanic upwelling includes the presence of the Doig Formation “Phosphate Zone” (Davies, 1997). Further evidence to support westward blowing winds during the Middle Triassic is documented by Arnold (1994) from paleo-current analysis of dune cross-bedding within the Artex Member of the Middle Triassic Charlie Lake Formation. These findings suggest that westward aeolian transport of sediment from cratonic Pangaea sources was likely a major contribution of sediment to the study area during the Middle Triassic. In addition, on a much larger scale, it

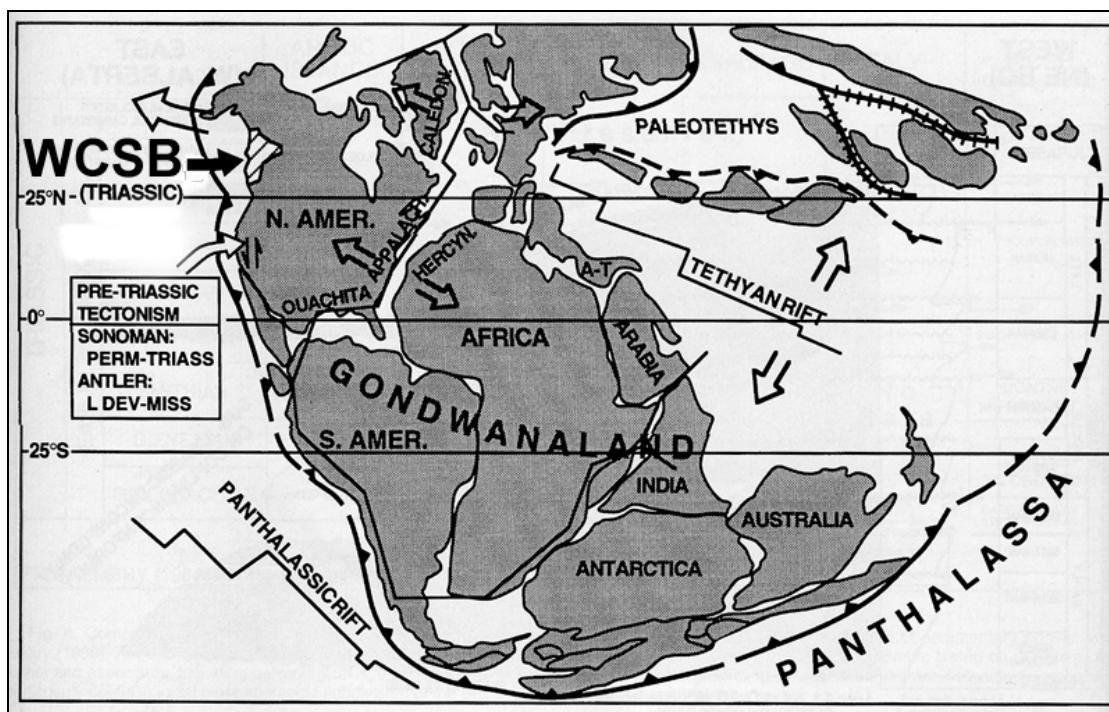


Figure 1.04 - Location of the Western Canada Sedimentary Basin during the Late Triassic (Modified from Dikek, 1994; in Davies, 1997).

is also thought that a westward high-altitude jet stream may have influenced climatic and sedimentological processes in the region during this time, carrying fine grained sediments far from the east across the continent (Davies, 1997), similar to the modern day jet stream transport of fine grain sediments to the Caribbean from Africa (Sarnthein and Diester-Haass, 1977).

Taking into account these climatic conditions, fluvial sedimentation in the Western Canada Sedimentary Basin during this time was probably minimal (Davies *et al.*, 1997), but may have occurred as a series of high discharge events during major storms, assuming modern day equivalent climates as an analog (Zonneveld, 1999).

1.6 TECTONIC SETTING

During the Middle Triassic the western margin of Pangaea may have been tectonically active, as offshore a series of subduction boundaries and volcanic island arcs are theorized to have existed (Moslow and Davies, 1992). These volcanic island arcs, or terrains, are thought to have later collided with the future North American craton in the Late Triassic and Early Jurassic during the initial stages of the Cordilleran Ominecan Orogeny. Based on a lack of evidence, previous Middle Triassic researchers have assumed that tectonic activity during the Middle Triassic was low and insignificant to deposition (Gibson and Barclay, 1989; Gibson and Edwards, 1990; Mossop and Shetsen, 1994). However, recent observations of slump deposits postulated to be the result of seismic activity in the Wembley Field (Wittenberg, 1992) and normal faulting within Triassic strata in the Pee Jay Field of northeast British Columbia (Caplan and Moslow, 1997) suggests that during the Middle Triassic tectonism may have been more significant than once thought.

Triassic sediments in Western Canada were derived from a low-relief, sediment-covered cratonic platform to the east and deposited in the Peace River Embayment (Mossop and Shetsen, 1994). The Peace River Basin, part of the Peace River Embayment, was the principal depocentre for Triassic sediments within the study area. This basin was approximately 900 km long and 350 km wide and was oriented in a NNW-SSE direction (Davies, 1997) along the margin of the North America craton

(Mossop and Shetsen, 1994). The Peace River Embayment formed due to a major tectonic down-warping of the crust which was initiated by the collapse of the Paleozoic Peace River Arch in the Early Carboniferous (Cant, 1988, O'Connell *et al.*, 1990). The Peace River Arch was a positive relief feature which existed throughout the Paleozoic and is thought to have formed due to basement uplift related to an oceanic fracture zone or a failed rifting event (O'Connell *et al.*, 1990).

The Peace River Embayment was centred on the Dawson Creek Graben Complex; an extensional structure formed from the collapse of the Peace River Arch dominated by northwest - southeast and northeast-southwest normal faults (Barclay *et al.*, 1990). O'Connell *et al.*, (1990) demonstrate that tectonic activity within the Dawson Creek Graben Complex was active from the Carboniferous to the Permian. However, evidence from Wittenberg (1992), Caplan and Moslow (1997), Davies (1997), and this study suggest that structural influence on sedimentation and deposition within the Peace River Embayment continued into at least the Middle Triassic.

1.7 METHODS

1.7.1 CORE ANALYSIS

Detailed logging and sedimentological descriptions were conducted for over 130 cored intervals from the Doig, Halfway, and Charlie Lake formations in the study area (Figure 1.05). All core used in this study are publicly available and are stored at the Alberta Energy and Utilities Board Core Laboratory Research Centre in Calgary, Alberta. All core selected for analysis were carefully measured and calibrated using characteristic lithological units to down-hole geophysical log responses in order to compensate for any depth errors made during drilling and boxing of cored intervals. Depths indicated on core logging figures are calibrated to geophysical log responses obtained from IHS AccuMap records.

Detailed sedimentological descriptions were constructed making note of physical and biogenic sedimentary structures, grain size, cementation, and contacts between various lithofacies. Information recorded on core descriptions sheets included: well location, date logged, reported core interval, corrected core interval, slabbled status, core diameter, interpreted depositional environment, nature of contacts, and lithology. Cored

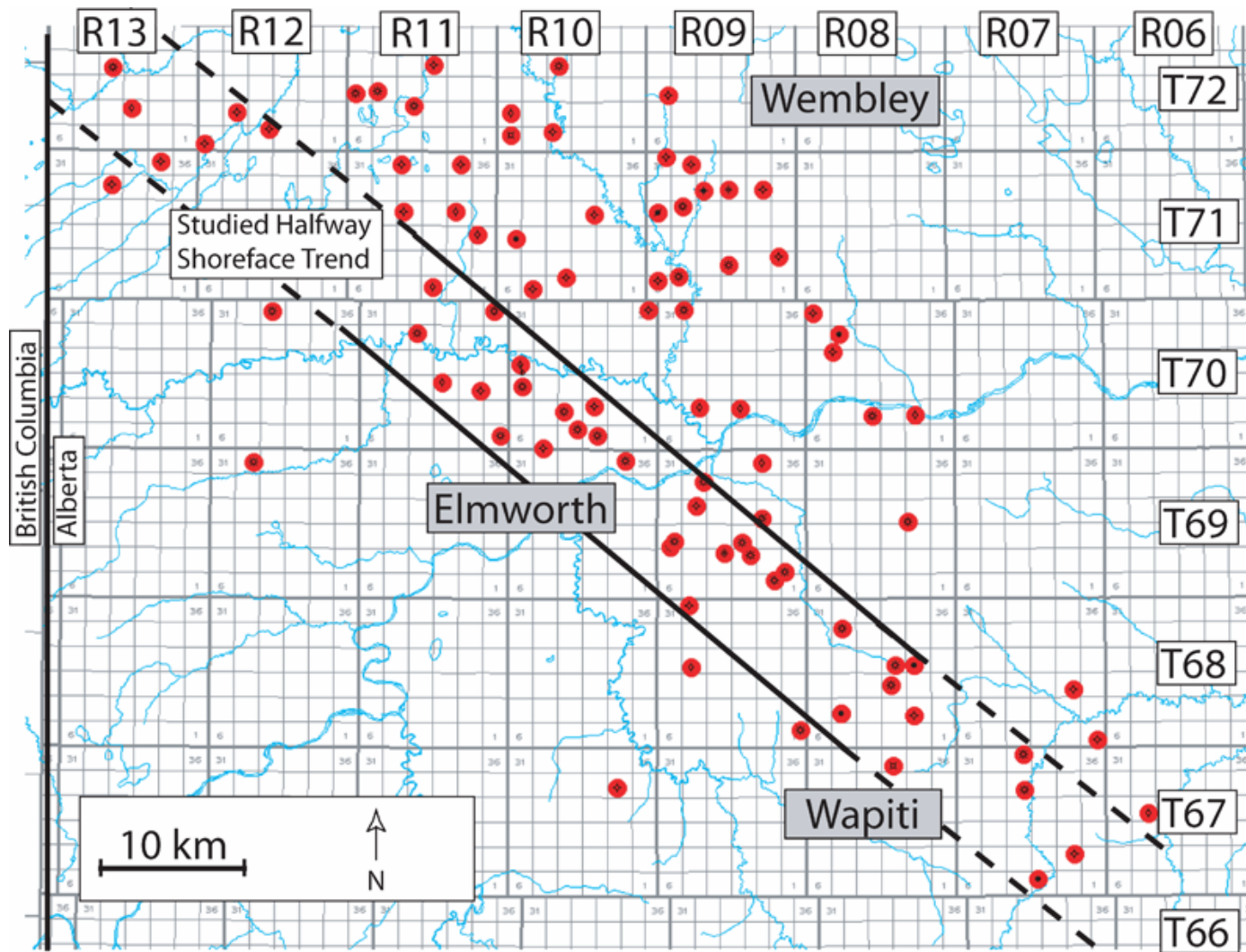


Figure 1.05 – Map of study area in west-central Alberta. During the course of this study 131 cored intervals of Halfway, Doig, and Charlie Lake formations were logged (highlighted with red circle).

successions containing the Halfway Formation were the main objective of this study but the bounding Doig and Charlie Lake formations were logged when available.

1.7.2 CONODONT SAMPLING

Core samples were collected in an attempt to obtain conodont biostratigraphic data. Samples were taken in potential conodont-bearing facies such as shale and bioclastic sandstone, as well as above and below key stratal surfaces such as erosional scours or flooding surfaces. Individual sample sizes ranged from 110 grams to 460 grams. Permission for each sample was obtained from the Alberta Energy and Utilities Board staff prior to removing any samples from the laboratory.

Sample preparation was conducted at the Applied Stratigraphy Research Group's Laboratory, University of Calgary. Samples with significant calcite cements were acidized in 10% acetic acid, while clay rich samples were boiled in diluted Quaternary-O detergent until defloculation of the clay occurred. This procedure was repeated until most of the sample disaggregated and could not be separated any further. Samples were then bleached and the heavy fraction was separated using tetrabromoethane. This heavy fraction was viewed under a microscope and carefully analyzed in an attempt to identify and document any and all conodont specimens found. In this study 43 samples were processed and conodont results from all were negative.

1.7.3 THIN SECTION PETROLOGY

Thin section samples were also obtained from core and were cut and analyzed at the University of Calgary. Sampling for thin sections was strategically performed to include significant stratigraphic successions seen within core. In regards to this study, thin sections were used in order to analyze and identify composition and morphology of the cements within each facies. Although detailed thin section petrology was not the goal of this study thin sections were used in documenting cements, framework grains, and composition of certain facies.

CHAPTER TWO: SEDIMENTOLOGY AND STRATIGRAPHY OF THE HALFWAY FORMATION, ELMWORTH FIELD

2.1 INTRODUCTION

Numerous sedimentological studies on the Halfway Formation, and bounding Middle Triassic strata, have been conducted throughout west-central Alberta and north-east British Columbia (e.g., Hunt and Ratcliffe, 1959; Aukes and Webb, 1986; Barclay and Leckie, 1986; Campbell and Horne 1986, Cant, 1986, Wittenberg, 1992, Wittenberg and Moslow, 1991; Willis and Moslow, 1994; Caplan and Moslow 1999). These studies are all older than ten years. Since their publication, exploration within the Halfway Formation has greatly increased. Exploration and economically viable production is now occurring from the Halfway Formation in regions that were once thought to be overly deep and water saturated. Many of the recently explored and producing Halfway Formation fields remain unstudied in the modern literature even though numerous new cored intervals of the Doig Formation, Halfway Formation, and Charlie Lake Formation now exist.

Data collected for this study from the Elmworth-Wapiti fields of west-central Alberta provided an opportunity to analyze core and wireline-logs from the Middle Triassic on a previously unstudied/unpublished locale within the Western Canada Sedimentary Basin. It is of note to mention that Willis (1992) conducted a study of the Wembley field approximately 15 kilometres northwest of the location of this study. Similar to Willis (1992), one of the objectives of this study was to document and characterize the facies associations of the Halfway Formation within the Elmworth and Wapiti fields in order to better understand the sedimentological characteristics and reservoir architecture of the deposits in this region.

2.2 STRATIGRAPHIC BACKGROUND

The Middle Triassic Halfway Formation was originally interpreted by Hunt and Ratcliffe (1959) as a mixed siliciclastic-carbonate marine transgressive sheet deposit. The Halfway Formation has since then been more recently reinterpreted as a series of prograding shoreface facies associations, within a progradational series of parasequence sets, which have been reworked by laterally discontinuous tidal inlet channels (Barclay and Leckie, 1986; Willis and Moslow, 1994; Caplan and Moslow, 1997).

In the study area the Halfway Formation is overlain by the supra-tidal, non-marine dolomitic mudstones, evaporates, and red beds of the Charlie Lake Formation (Arnold, 1994), and underlain by the offshore to lower shoreface fine sandstone, siltstone, and shale of the Doig Formation (Armitage, 1962). Within the study area these formations represent a relatively conformable shallowing-upward succession of clinoforming progradational parasequence sets deposited during a period of relative sea level regression. Also, within the study area the Middle Triassic consists of at minimum four parasequences with each parasequence displaying a coarsening-upward shoreface profile bounded by marine flooding surfaces.

2.3 SEDIMENTARY LITHOFACIES

Ten lithofacies (F1-F10) are identified in the study. Table 1 shows the detailed lithofacies description of the Middle Triassic (Doig Formation, Halfway Formation, and Charlie Lake Formation) deposits observed in the study interval. Recognition and classification of these lithofacies was determined from examination of over 125 cored Middle Triassic intervals throughout the course of this study. Grain size and rock type, physical and biogenic sedimentary structures, bed grading, basal contacts, and position in the vertical succession were used as the criterion and basis for the interpretation of depositional process and environment. Figure 2.01 displays the approximate location of deposition of each interpreted lithofacies on a typical clastic shoreline profile. In addition, these sedimentary lithofacies are the building blocks of the five facies associations created during this study. These facies associations, as well as their lithofacies are discussed in detail below in section 2.4.

Table 1 – Summary table of lithofacies and their sedimentary characteristics including interpretation of environment of deposition as observed and recognized in core from study area.

Litho-facies	Lithology	Basal bounding Surface	Lithologic accessories	Physical Sedimentary Structures	Bioturbation and trace fossils	Inferred Depositional Processes	Interpreted Environment of Deposition
F1	Laminated black shale	Variable (out of study interval)	Pyrite, Anhydrite nodules	Parallel lamination, massive bedding	Articulated Brachiopods, <i>Planolites</i> , <i>Chondrites</i>	Suspension sedimentation,	Offshore (deep water setting below storm wave base)
F2	Interbedded shale and siltstone	Gradational	None	Parallel lamination, ripples, HCS	<i>Planolites</i> , <i>Palaeophycus</i> , <i>Teichichnus</i>	Alternations of suspension and traction deposition due to storm induced geostrophic currents	Offshore Transition zone
F3	Interbedded shale and sandstone	Gradational to sharp	None	Parallel lamination, ripples, trough cross bedding.	<i>Planolites</i> , <i>Chondrites</i> , Brachiopods	Traction deposition from wave and current generated flows (within fair weather wave base)	Lower shoreface
F4	Fine grained sandstone	Gradational to sharp	None	Parallel lamination, ripple cross-lamination, low angle cross strat., cross trough bedding	<i>Skolithos</i>	Traction deposition from wave and current generated flows (within fair weather wave base)	Upper shoreface
F5	Medium grained sandstone	Gradational to Sharp	None	Parallel lamination, trough cross-bedding, massive appearing beds	<i>Skolithos</i> , <i>Macaronichnus</i>	Traction deposition from wave and current generated flows (within fair weather wave base)	Foreshore
F6	Bioclastic sandstone	Sharp (erosional)	Clasts of variable sizes and composition	Cross bedding, parallel lamination, massive	Composed of abraded shell material, no visible traces within	Episodic traction transport from high magnitude tidal or wave induced currents	Tidal Inlet Channel
F7	Grey-green shale and thinly bedded sandstone	Sharp based	None	Parallel lamination	<i>Chondrites</i>	Suspension settlement in back barrier lagoon. Sand beds deposited during wash-over events	Lagoonal (including washover deposits)

F8	Interlaminated dolomite and anhydrite	Sharp based	Some intra-formational clasts	Wavy contorted parallel lamination (chemoturbation?)	Crypt-algal laminae?	Suspension and Traction (playa lake)	Playa-Lake Margin (Caplan, 1992)
F9	Red dolomitic shale/siltstone	Sharp based	Abundance of anhydrite nodules	Crude parallel-lamination	None	Suspension and traction (mud flats?)	Playa-Lake (Caplan, 1992)
F10	Fine grained terebratulid brachiopod grainstone	Sharp based (lag of abraided shell material)	2-3 mm chert clasts present in lag	None visible	Abundance of terebratulid brachipods, crinoids, bivalves.	Traction deposition from wave and current generated flows (within fair weather wave base)	Shoreface biostrome (Zonneveld, 2001)

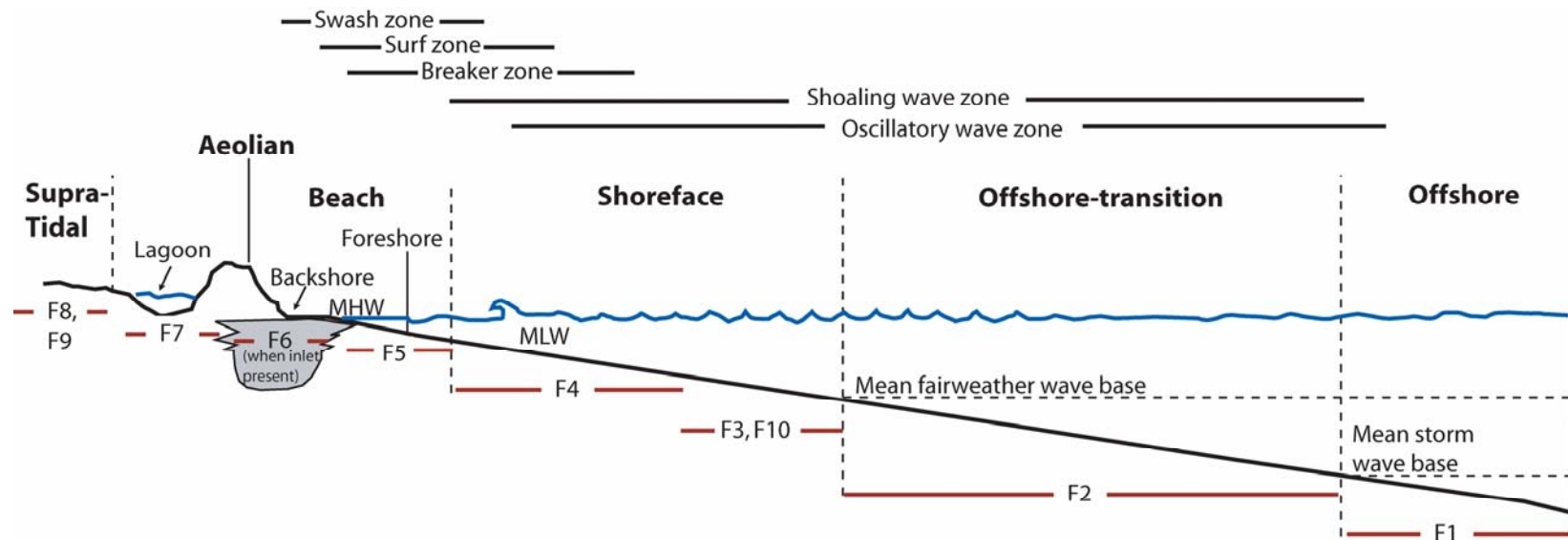


Figure 2.01 - Schematic diagram depicting lateral distribution of sub-environments on a siliciclastic shoreface. Note location of offshore-transition zone in between fairweather wave base and storm wave base. Approximate depositional location of facies F1 to F10 is indicated in red (Modified from Reading, 1976).

2.4 SEDIMENTARY FACIES ASSOCIATIONS

2.4.1 FACIES ASSOCIATION INTRODUCTION

All of the lithofacies described in Table 1 occur as regularly recurring components of genetically related facies associations. Within the study area, the following five commonly occurring vertical successions of sedimentary facies (facies associations) within the Doig, Halfway and Charlie Lake formations include:

- A. distal prograding shoreface;
- B. proximal prograding shoreface;
- C. tidal inlet channel;
- D. supra-tidal sabkha; and
- E. shoreface biostrome.

The sedimentary characteristics of these facies associations are summarized within this chapter in figures 2.03, 2.04, 2.06, 2.08, and 2.09; and are individually described in detail below.

2.4.2 FACIES ASSOCIATION A - DISTAL PROGRADING SHOREFACE

Facies association A, interpreted as the deposits of a distal prograding shoreface is composed of the individual lithofacies; F1 – laminated black shale, F2 – interbedded shale and siltstone, and F3 – interbedded shale and sandstone.

Lithofacies F1, a black shale, contains horizontal laminations as well as massive structureless intervals. A low percentage of articulated brachiopods are observed within this facies and rare trace fossils are also present including *Palaeophycus* and *Chondrites*, indicating that this unit was deposited in a marine environment. There is a notable lack of current generated sedimentary structures in this facies. These sedimentological observations infer that F1 is primarily the product of suspension deposition interpreted to be within an offshore environment (Reading, 1996). In the study area lithofacies F1 predominantly grades upward into F2, interbedded siltstone and shale.

Lithofacies F2, an interbedded shale and siltstone, contains a mixture of parallel lamination, hummocky cross stratification, and asymmetric ripple laminations inferring a mix of suspension and traction deposition (Reading, 1996). Thin siltstone interbeds in lithofacies F2 are normally graded and similar observations have been interpreted in other Halfway Formation studies as deposits generated by the storm ebb return flow from geostrophic currents (Caplan and Moslow, 1999). Hummocky cross stratification (HCS) in F2 is a sedimentary structure (Figure 2.02) that is the product of both deposition and erosion and found below fair weather wave base and above storm wave base on a typical clastic shoreface (Figure 2.01), which is the prime locality for the formation and preservation of HCS (Reading, 1996). HCS is produced by a combination of wave and current generated flows under storm conditions (Harms *et al.*, 1975; Walker and Plint, 1992). Trace fossils within lithofacies F2 include *Planolites*, *Palaeophycus*, and *Teichichnus*. Lithofacies F2 is interpreted as offshore transition environment deposits located between fair-weather wave base and storm wave base. In the study area lithofacies F2 grades upward into the deposits of lithofacies F3, interbedded shale and sandstone.

Lithofacies F3, an interbedded fine grained sandstone and shale, contains a mix of sedimentary structures including parallel lamination, asymmetric ripple laminations, trough cross bedding, and minor occurrences of HCS. The appearance of cross bedded sandstone and laminated shale interbeds in this lithofacies indicates periodic switches in energy from high to low. Trace fossils within lithofacies F3 include rare *Planolites*, *Palaeophycus*, and *Teichichnus*. Whole body fossils of articulated brachiopods are also present. Lithofacies F3 is interpreted as being a product of distal lower shoreface deposition.

Lithofacies F1, F2, and F3 all contain a low number of burrows (*Chondrites*, *Palaeophycus*, *Planolites*, and *Teichichnus* traces) consistent with a *Cruziana* ichnofacies assemblage (Pemberton and MacEachern, 1995) and are representative of a distal shoreface to offshore environment. Along with the low densities of preserved articulated brachiopod shells also observed are small quantities of phosphatic material, chert clasts, and anhydrite nodules within the offshore shale of lithofacies F1. These anhydrite nodules are approximately 0.5 – 4 cm in diameter and many appear to have pyritized rims

around them. These nodules appear to have originated along bedding planes and grown outward as the bedding surrounding them is distorted, indicating soft sediment at time of growth.

Lithofacies F1, F2, and F3 combine to form facies association A; interpreted as a product of deposition in a distal prograding shoreface (Figure 2.03). This facies association is quite common within the lower parasequences of the Doig-Halfway Formation interval. These parasequences are composed of coarsening upward cyclic repetitions of facies association A until the uppermost parasequences are bound above by a conformable succession of facies association B (proximal prograding shoreface) deposits, or disconformably by facies association C (tidal inlet channel) deposits.

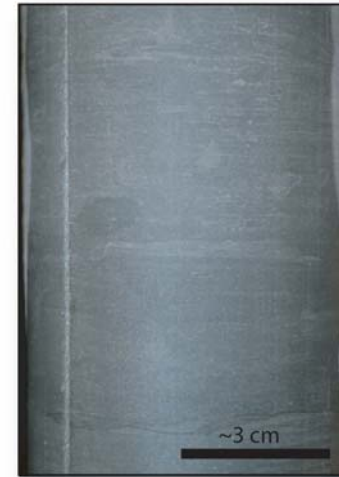
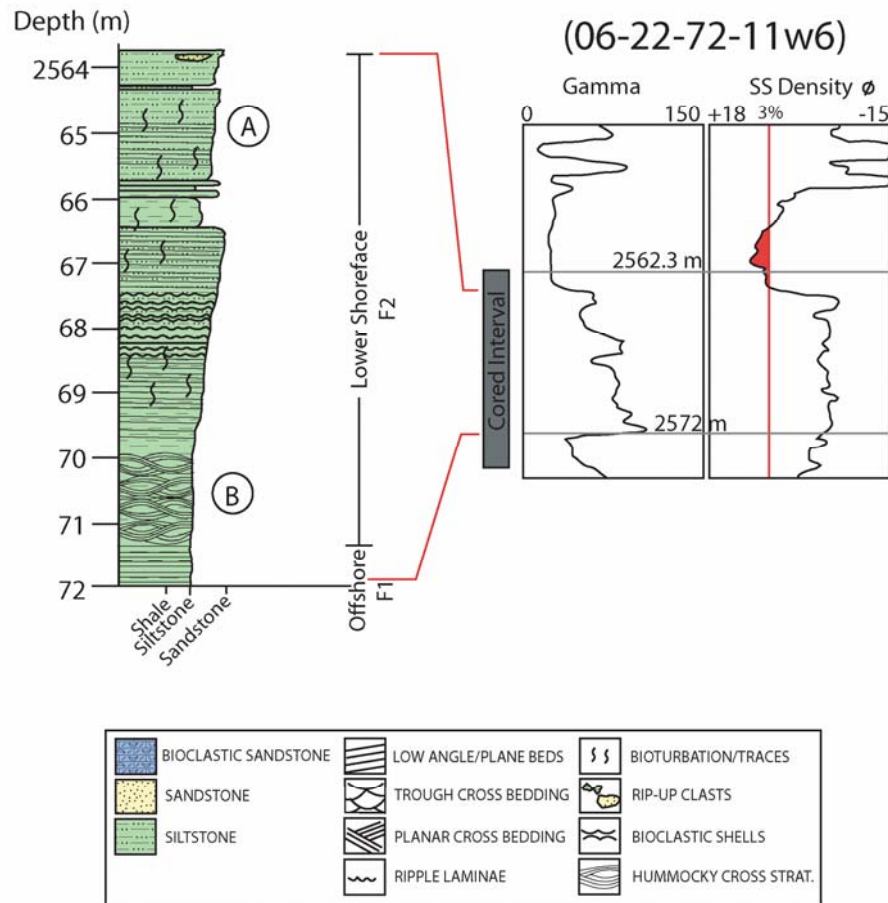
The most significant trend in bedding within facies association A is the coarsening upward profile from laminated shale at the base, to ripple laminated, hummocky cross stratified, and cross bedded siltstone and fine sandstone at the top. This coarsening upward trend is best observed in the 6-22-72-11W6 cored sedimentary profile (Figure 2.03). This profile is 9.5 metres thick; and is a graphic example of facies association A. Individual beds vary in grain size; however the overall sequence coarsens upward. The interbedded nature of this vertical succession is interpreted to be a product of differential sedimentation due to alternating periods of storm and fair weather depositional processes.

The major control on the thickness of facies association A within the study area appears to be erosion. When thinner intervals of facies association A are visible in core there exists sharp upper erosional contacts overlying the fine grained siltstone interval of facies association A. Where thicker intervals of facies association A are visible there is a noticeable lack of a sharp upper contact and a distinct coarsening upward profile is seen in grain size as facies association A grades into facies association B.

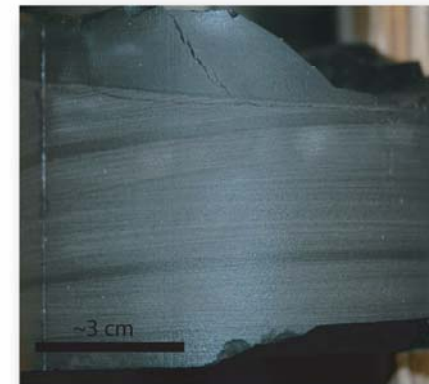


Figure 2.02 - Hummocky Cross Stratification within interbedded siltstone of facies association A. Core width is approximately 9 cm wide. (16-10-69-9W6 – 2649 m).

Facies Association A - Distal Prograding Shoreface



A. Horizontally laminated and partially bioturbated fine grained siltstones of the lower shoreface.



B. Low-angle hummocky cross-stratification displaying convex upward laminae within siltstone.

Figure 2.03 - Vertical sedimentary profile of Facies Association A and well log correlation of cored interval from the 6-22-72-11W6 well; includes core photographs displaying A) horizontally laminated fine grained siltstone, and B) Low-angle hummocky cross-stratification.

2.4.3 FACIES ASSOCIATION B - PROXIMAL PROGRADING SHOREFACE

Facies association B, interpreted as the deposits of a proximal prograding shoreface is composed of lithofacies F4 – fine grained sandstone and F5 – medium grained sandstone.

Lithofacies F4 is a fine grained sandstone unit containing a suite of structures including current ripple cross-lamination, trough cross-bedding, and low angle parallel lamination. A low number of *Skolithos* burrows are seen within this lithofacies as well as a low number of whole and fragmented articulated brachiopods. Sedimentary structures within this lithofacies are of much higher energy than those of lithofacies F1-F3. The presence of cross-bedding infers traction deposition from current generated currents (Reading, 1996) and these deposits are interpreted to be a part of a middle-upper shoreface environment. Within the study area lithofacies F4 grades upward into lithofacies F5 a medium grained sandstone.

Lithofacies F5, a medium grained sandstone, contains oscillation ripple cross-lamination, trough cross-bedding, parallel laminations, and intervals of massive bedding. Trace fossils within lithofacies F5 are limited to *Skolithos* and *Macaronichnus* burrows. *Macaronichnus* is characteristic of high energy/high oxygen shallow marine environments and typically occur in foreshore environments where sediments are subject to the breaking surf zone (Clifton and Thompson, 1978). Sedimentary structures seen within lithofacies F5 infer an upper flow regime with higher energy current generated flows than those seen in lithofacies F4. Lithofacies F5 is interpreted to be deposited within the upper shoreface to foreshore environment of a proximal prograding shoreface.

Lithofacies F4 and F5 combine to form facies association B, interpreted to be a product of deposition in a proximal prograding shoreface (Figure 2.04). This facies association varies in thickness across the study area from approximately 5 to 15 metres and is bound below by distal prograding shoreface deposits of facies association A. Facies association B is predominantly overlain in the study area by supra-tidal sabkha deposits of facies association D, but can also be sharply overlain by incisive tidal inlet channel deposits of facies association C.

Similar to facies association A, the most significant trend in bedding within facies association B is a predominantly coarsening upward profile from fine grained sandstone to medium grained sandstone. This coarsening upward trend is best observed in the 14-12-71-9W6 cored sedimentary profile (Figure 2.04). This profile is approximately 9 metres thick; and is a graphic example of facies association B. In this particular cored interval the deposits of facies association B are conformably underlain by distal prograding shoreface deposits of facies association A. Overlying the prograding shoreface deposits of facies association B in this succession are red shale and dolomitic of facies association D. Similar vertical successions of stacked facies associations as seen in Figure 2.04 are quite common throughout the Halfway Formation study area.

This proximal prograding shoreface facies association is an effective reservoir rock for natural gas within the study area. Most production within this facies association comes from the upper shoreface and foreshore sandstone. Average porosities from these intervals range from approximately 2 to 6 % on a sandstone density scale. This proximal prograding shoreface facies association is readily seen on wire line gamma logs as a distinct cleaning upward profile, sometimes with small radioactive kicks representative of thin shale rich intervals. These shale rich intervals have been interpreted to be the result of deposition during times of waning energy within the shoreface.

The major control on thickness of facies association B within the study area appears to be erosion and the effect of tectonics removing/creating accommodation space within the distal and proximal shoreface region. Where thinner intervals of facies association A occur sharp erosional surfaces are seen in core. When present these erosional surfaces appear to represent a minor localized disconformity as it appears that there is a lower shoreface to upper shoreface facies change across the boundary, and it is estimated that approximately 3-6 metres of sediment is missing within a typical shoreface succession. When such surfaces are present the facies association B deposits of the proximal prograding shoreface are much thinner (approx. 3-6 metres) than successions such as seen in 14-12-71-9W6 (Figure 2.04) where facies association B is 9 metres thick. These erosional surfaces are interpreted to be formed as the result of localized tectonic uplift and will be discussed in more detail in chapter 3.

Facies Association B - Proximal Prograding Shoreface

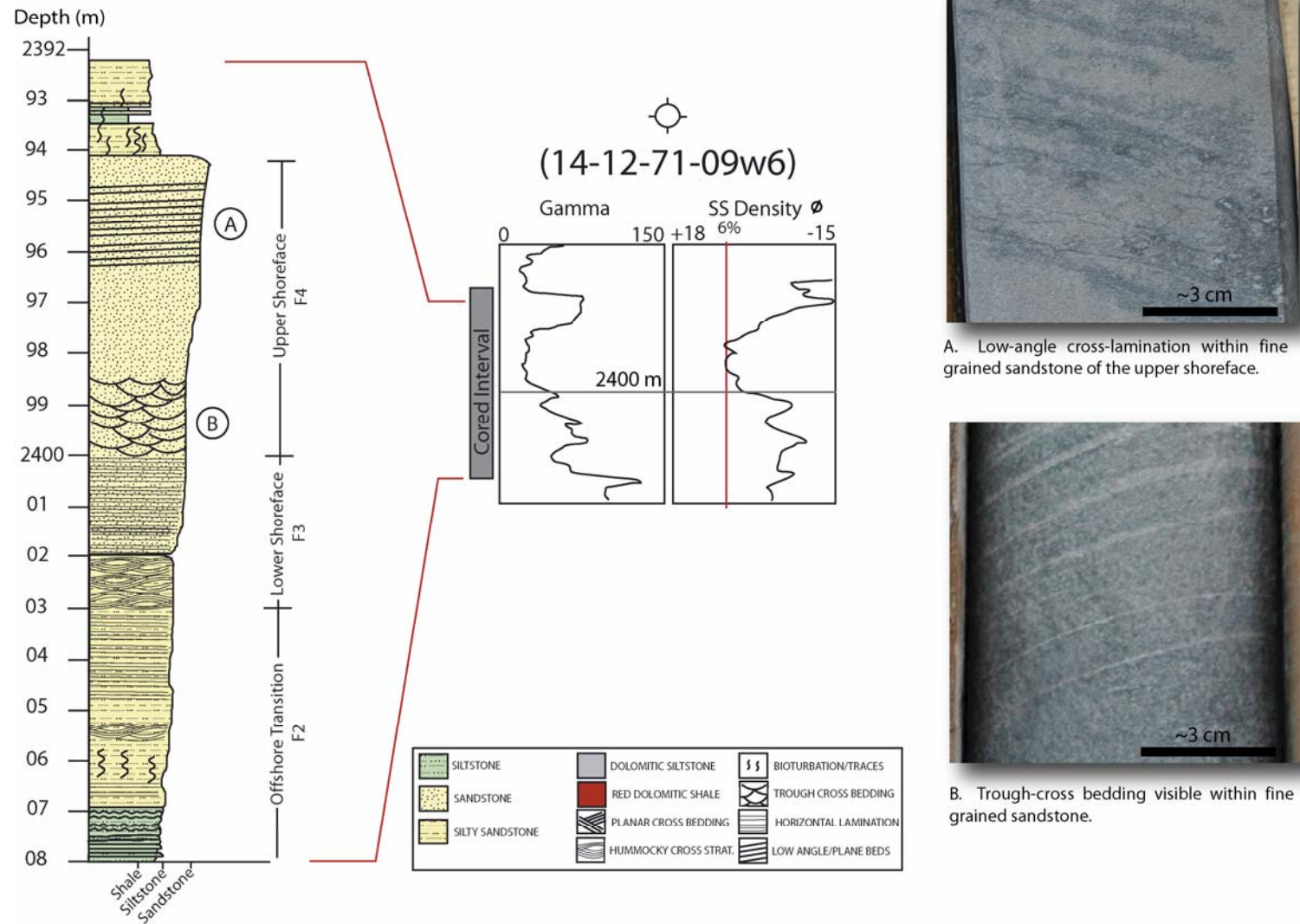


Figure 2.04 – Vertical sedimentary profile of Facies Association B and well log correlation of cored interval from the 14-12-71-9W6 well; includes core photographs displaying; A) Low-angle cross-lamination, and B) Trough cross-bedding.

2.4.4 FACIES ASSOCIATION C – TIDAL INLET CHANNEL

Facies association C, interpreted as the deposits of a tidal inlet channel is composed entirely of lithofacies F6 – bioclastic sandstone.

Lithofacies F6 is a medium to coarse grained bioclastic sandstone consisting of varying degrees of quartz sand and abraided shell material consisting of bivalves and brachiopods. Visible sedimentary structures in lithofacies F6 include cross-trough bedding, massive bedding, and parallel lamination, which are interpreted to be the product of tidal or wave induced currents (Willis, 1992). No trace fossils are present within lithofacies F6 most likely due to the coarse grain size of the deposit and the high energy of deposition. Lithofacies F6 always displays a sharp erosional base at its lowermost bounding interval - usually with an abundance of angular sandstone or shale clasts ranging from 3 mm's to 10 cm's in diameter above the scour (Figure 2.05). The angularity of these clasts suggest that the sediments were at least partially lithified or cohesive at time of transport and were not transported a great distance. These clasts are interpreted to be rip-up clasts along the base of a tidal inlet channel which has incised down into a previously deposited shoreface. Consequently as such, lithofacies F6 is interpreted to be the deposits of an incisive tidal inlet channel.

Within the study area facies association C is underlain by sediments of facies association B or facies association A depending on the degree of down-cutting and incision that the tidal inlet channel has inflicted on the shoreface. In either case, a sharp erosive contact always separates the tidal channel fill of facies association C from the underlying deposits. Overlying facies association C are the deposits of facies association D (supra-tidal). The upper bounding contact of facies association B is quite sharp as would be expected due to the erosional nature and exposure of supra-tidal deposits.

The deposits of facies association C are quite variable in thickness and can range from 1 metre to 12 metres across the study area. The thickness of this facies association



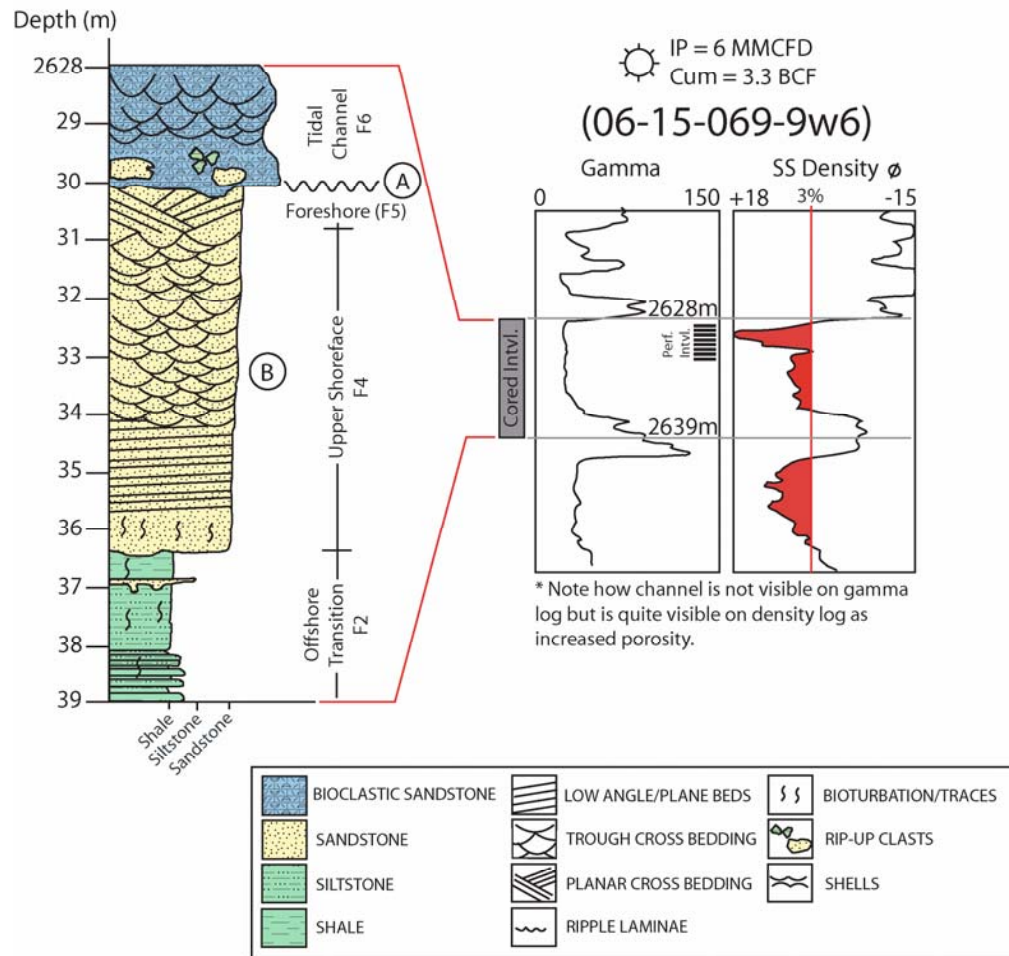
Figure 2.05 - Fractured lithified sandstone clast at the base of tidal channel. Note fractures within sandstone clast indicating semi-lithification at time of transport (lower-left) and shale rip-up clasts (middle-right). Core width is approximately 9 cm wide. (6-15-69-9W6, 2631m)

is dependent on paleo-hydrodynamic factors, such as current flow velocity and magnitude of the tidal regime, which in turn control the amount of erosion and incision of the specific channel by the rate and volume of flow (Reading 1996). To complicate matters many thicker sequences of facies association C represent a series of stacked channels deposits preserving multiple channel aggradation events that have incised and cannibalized each other over time. The overall trend in bedding within facies association C is a gradual fining upward profile. This fining upward trend is related to a waning channel flow velocity and the slow infilling of the tidal inlet channel and increased distance from the channel thalweg as the tidal channel migrates laterally across the shoreface.

A cored sedimentary profile of well 6-15-69-9W6 (Figure 2.06) displays some of the key sedimentary features of facies association C, including deposits of a bioclastic tidal inlet channel cutting into underlying shoreface sediments, a sharp basal scour, and a basal lag. The channel specific to well 6-15-69-9W6 is approximately two metres in vertical thickness and fines upward for a metre before being overlain by coarser grained bioclastic sandstone. This particular change in grain size has been interpreted to be the result of two channel events stacked on top of each other. Although not cored, the sediments above the tidal inlet channel within this well appear to be supra-tidal in nature which is inferred by the abundance of anhydrite visible in the wire-line well logs, as well correlations from neighbouring cored Halfway/Charlie Lake Formation intervals.

Tidal inlet channel deposits classified as facies association C have been a major exploration target within the Doig and Halfway formations. These deposits often contain both great primary and secondary porosity ranging from 6 to 25% on a sandstone porosity scale. As well, the fining upward profile of the channel and the overlying anhydrite rich supra-tidal deposits of facies association D act as a natural seal to the reservoir. Tidal inlet channel deposits in well 6-15-69-9W6 (Figure 2.06) have produced a cumulative 3.6 BCF since 2001 with an initial production of 6 MMCF a day. Facies association C is easily seen on a wire-line log as a fining upward gamma ray profile and a modest increase in porosity compared to the surrounding shoreface sands.

Facies Association C - Tidal Inlet Channel Cutting into Sharp Based Shoreface



A. Rip-up clasts (Shale and Sandstone) at the base of tidal inlet channel



B. Trough cross bedding visible in fine grained upper shoreface sandstone

Figure 2.06 - Vertical sedimentary profile of Facies Association C and well log correlation of cored interval from the 6-15-69-9W6 well; includes core photographs displaying; A) Channel scour and rip-up clasts, and B) Trough cross-bedding.

2.4.5 FACIES ASSOCIATION D – SUPRA-TIDAL SABKHA

Facies association D, interpreted to be the deposits of an arid supra-tidal sabkha environment is composed of lithofacies F8 – interbedded dolomitic siltstone and anhydrite, and F9 – red dolomitic shale.

Lithofacies F8, an interbedded dolomitic siltstone and anhydrite displays crude parallel lamination and wavy lamination (Figure 2.07). The contacts between these dolomitic siltstone and anhydrite interbeds in this lithofacies are very abrupt. Wavy lamination seen within this lithofacies appears to be soft sediment deformed, interpreted to be the result of chemoturbation and algal growth (Kendall, 1992; Arnold, 1994). No distinguishable trace fossils are present within this lithofacies indicating a harsh non-marine environment. Similar to other Halfway Formation studies this facies is interpreted to be arid deposits of a playa-lake/sabkha (Caplan, 1992; Arnold, 1994).

Lithofacies F9, normally graded dolomitic shale contains crude parallel lamination, soft sediment deformation, and is very red in colour. A high abundance of anhydrite is found within this lithofacies, usually lacking the interbedded quality seen within lithofacies F8, indicating a very arid evaporitic environment. Similar to lithofacies F8 no distinguishable trace fossils are present within lithofacies F9. This facies has been interpreted as the deposits of a playa-lake/sabkha (Caplan 1992, Arnold, 1994). Together these lithofacies are interpreted to be part of an evaporitic supra-tidal environment such as a playa-lake within an evaporitic sabkha.

Within the study area facies association D is bound beneath either by sediments of facies association B or facies association C. The upper boundary of facies association D was out of the limits of this study but it is assumed this facies encompasses the whole Charlie Lake Formation within the study interval. These deposits are the continental equivalent of the prograding marine Doig and Halfway Formation and within the immediate study area there is no apparent reservoir potential to the deposits of facies association D, possibly a reason as to why there is not a lot of core across this interval.

Within the study area the Charlie Lake Formation overlies the Halfway Formation and is separated by a sharp contact between upper shoreface sandstone and supra-tidal shale/dolomite siltstone. This sharp contact is interpreted to be the result of exposure to both aeolian non-marine processes and evaporite deposition on a tidal flat/sabkha

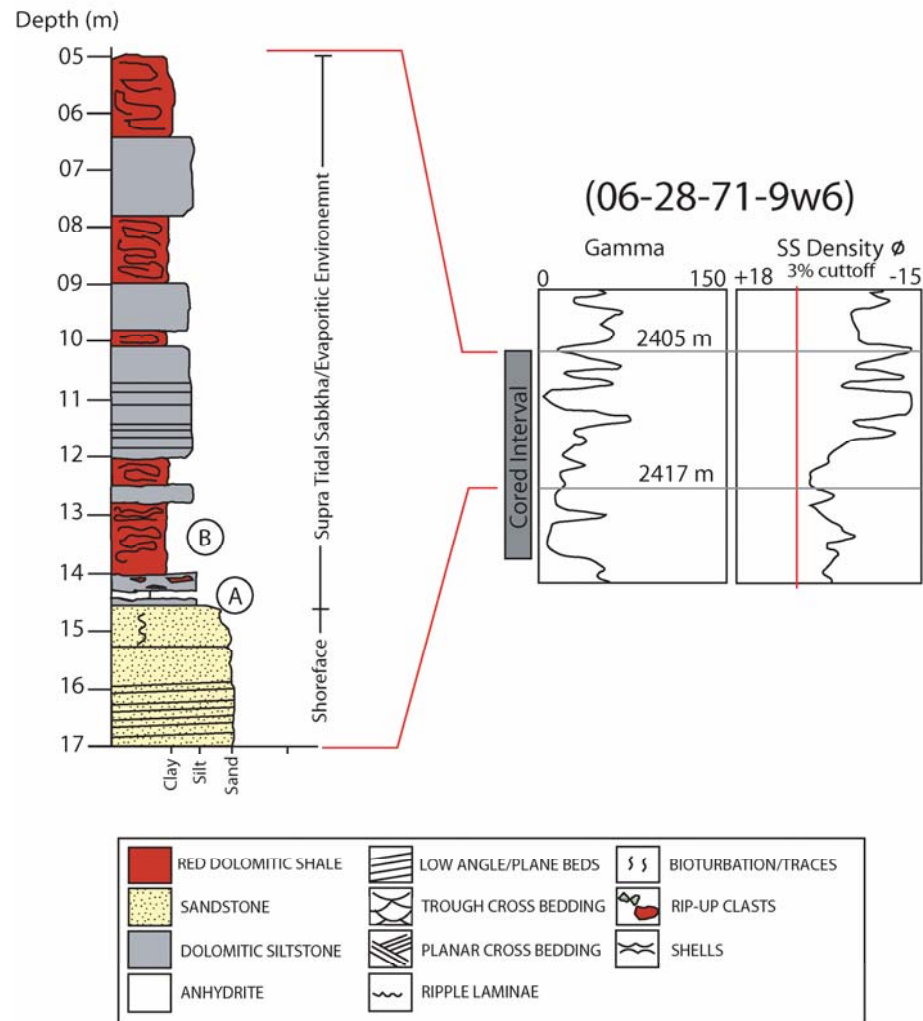
(Arnold, 1994) and does not represent a major unconformity above the Halfway Formation within the study area.

A cored succession of well 6-28-71-9W6 displays 10 metres of interbedded shale, dolomitic siltstone, and anhydrites sitting above proximal upper shoreface deposits of facies association B (Figure 2.08). Most beds appear to be slightly normally graded and many sharp contacts are visible between bedding. Although the reservoir potential of facies association D is lacking in this study area the deposits of facies association D are critical to the hydrocarbon potential of the Halfway Formation. The abundance of shale, siltstone, and anhydrite combine to form a good stratigraphic seal capping the porous deposits of the Doig and Halfway formations. Within wire-line logs, Facies Association D is discerned by sharp gamma log kicks and a sharp decrease in porosity.



Figure 2.07 - Wavy dolomitic siltstone and anhydrite of facies association D. Core width is approximately 9 cm wide.

Facies Association D - Supra-tidal Deposits



A. Sharp contact between red dolomitic shale and white anhydrite beds. Rip-up clasts present above anhydrite bed.



B. Bioturbated/brecciated red dolomitic shale of Charlie Lake Formation

Figure 2.08 - Vertical sedimentary profile of Facies Association D and well log correlation of cored interval from the 6-28-71-9W6 well; includes core photographs displaying; A) Contact between dolomitic shale and anhydrite beds, and B) Brecciated red dolomitic shale.

2.4.6 FACIES ASSOCIATION E – LOWER SHOREFACE BIOSTROME

This facies association is a hybrid facies association as it contains the previously discussed lithofacies of the distal prograding shoreface, F1 – laminated black shale, F2 – interbedded shale and siltstone, and F3 – interbedded shale and siltstone, but also contains lithofacies F9 - a terebratulid brachiopod floatstone within a fine grained siltstone matrix.

Biogenetic sedimentary structures within these lithofacies include those seen within the distal shoreface deposits of facies association A which include *Planolites*, *Palaeophycus*, and *Teichichnus*.

Terebratulid brachiopods present within lithofacies F9 are quite distinct from the abraided brachiopod fill within facies association F6 (tidal inlet channel) as approximately 85% of these brachiopods are complete un-abraided specimens and contain a geopetal fill within their shells. Geopetals are formed when a void or cavity has been filled with sediment, and are good “way up” indicators (Zonneveld, 2001). The presence of whole un-abraided shells, a geopetal fill, and fine grained siltstone matrix leads to the interpretation that these terebratulid brachiopods were not transported and grew and died within the lower shoreface within a biostrome.

The biostrome interval in well 14-5-71-9W6 is approximately 3 metres thick and appears to be truncated above by a marine flooding surface (Figure 2.09). Overlying this biostrome interval is a parasequence composed of facies association A (distal prograding shoreface) and above that deposits of facies association C (tidal inlet channel). Underlying this biostrome interval are distal shoreface deposits of facies association A.

There is no previously documented evidence of biostromes existing within the Middle Triassic subsurface although a study by Zonneveld (2001) documented similar aged Middle Triassic biostromes within the Liard Formation in north eastern British Columbia. These biostromes and their importance will be discussed in greater detail in Chapter 4.

Facies Association E - Lower Shoreface Biostrome

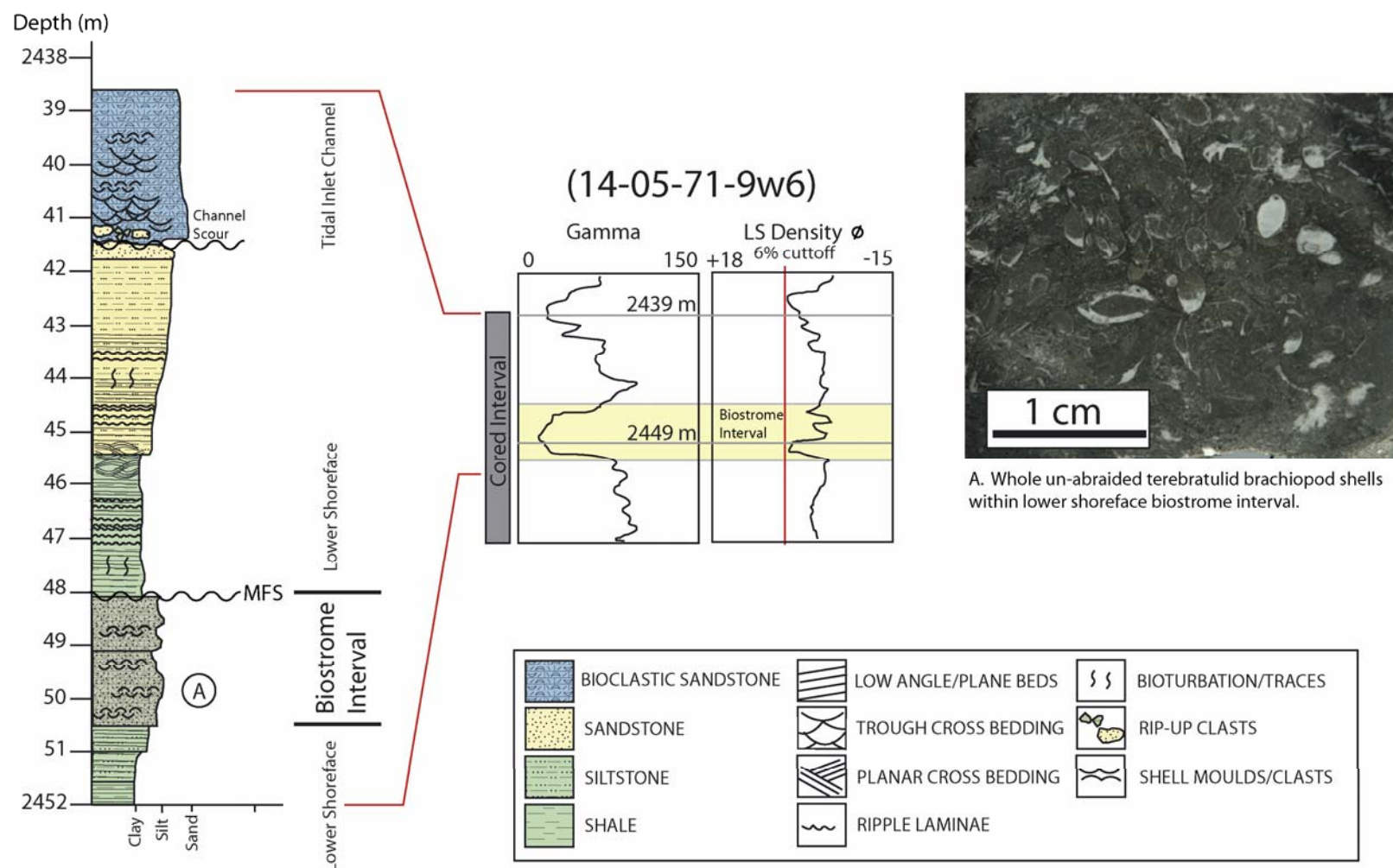


Figure 2.09 - Vertical sedimentary profile of Facies Association E and well log correlation of cored interval from the 14-05-71-9W6 well; includes core photograph displaying; A) Whole unabraded terebratulid brachiopod shells within a lower shoreface environment.

CHAPTER THREE: TECTONIC INFLUENCE ON HALFWAY FORMATION SHOREFACE DEPOSITION

3.1 INTRODUCTION

During the course of this study it was observed that the Halfway Formation displays anomalous variability in sediment isopach over short distances along strike of a mappable paleo-strandline trend. These variations in stratal thickness are not accounted for by lateral or vertical facies changes. This chapter's intent is to examine these thickness changes and attempt to provide a tectonic explanation as to their existence. This will be done by analyzing three sets of data; 1) sedimentological observations from cored wells displaying marine firmgrounds and seismites that are interpreted to be tectonically induced; 2) creation of an isopach map showing the lateral variability of

Halfway Formation thickness changes; and 3) creation of cross-sections analyzing correlations related to Halfway Formation thickness variations from wire-line log data.

3.2 STUDY AREA

During the course of this study a northwest-southeast orientated shoreface trend was observed running through the middle of townships 69-9W6 and 70-10W6 (Figure 3.01). This shoreface trend is easily correlated over distance using wire-line log data and appears to run linearly for approximately forty kilometres. The shoreface trend is characterized by highly variable thicknesses of the Halfway Formation - predominantly within shoreface sandstones. These sandstones are of significance as they are of reservoir quality and because of this, and the fact that there is a high degree of well and core control within this Halfway Formation shoreface trend, this portion of the study will concentrate on this shoreface trend to try to more accurately understand the controls of these thickness changes.

3.3 LOCAL STUDY AREA STRATIGRAPHY

In this region the Halfway Formation is overlain by the supra-tidal to non-marine dolomitic mudstone, evaporates, and red beds of the Charlie Lake Formation (Arnold, 1994), and underlain by the offshore to lower shoreface fine sandstone, siltstone, and shale of the Doig Formation (Armitage, 1962). At the very base of the Doig Formation in this region exists the Doig “Phosphate Zone.” The “Phosphate Zone” is a condensed series of stratigraphic horizons (Loutit *et al.*, 1988) and represents low rates of sedimentation and high phosphate input within an offshore environment (Caplan and Moslow, 1997). It is from this “Phosphate Zone” that most of the hydrocarbons in the Middle Triassic are sourced (Ejezie, 2006). At a more regional scale in this study area the Halfway and Doig formations represent a relatively conformable shallowing-upward succession of clinoforming progradational parasequence sets deposited during a period of relative sea level regression (Gibson and Barclay, 1989). Each parasequence contains a

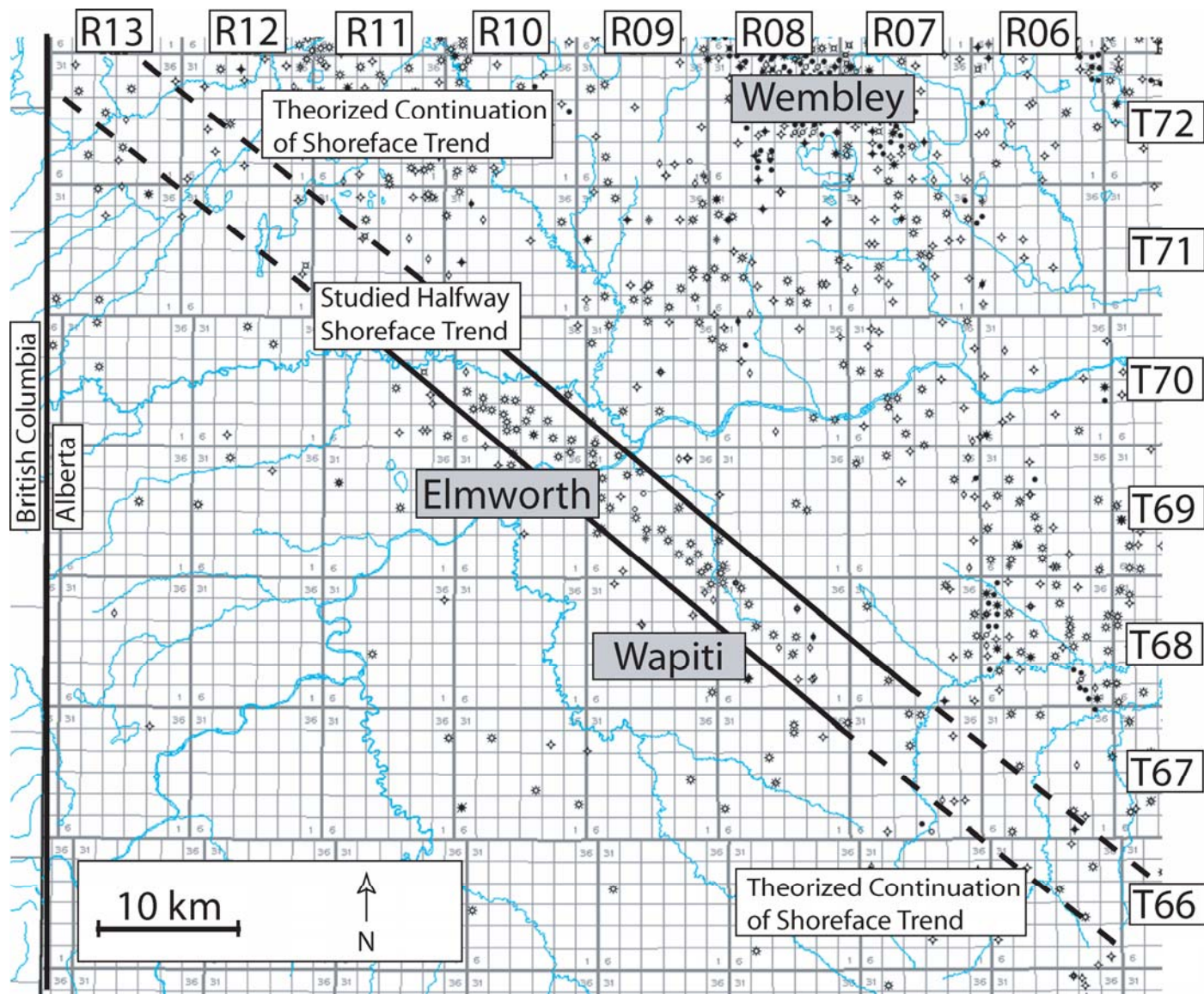


Figure 3.01 - Study area with correlatable shoreface trend in-between solid line and theorized continuation of same shoreface trend in-between dashed line to the northwest and southeast. Total distance of trend is approximately 78 km from end to end. Well penetrations through the Halfway Formation are displayed.

coarsening-upward shoreface profile bounded by marine flooding surfaces and off-laps to the west (Willis, 1992; Wittenberg, 1992; Willis and Moslow, 1994).

3.4 PARASEQUENCE STACKING

Wire-line (gamma-ray) log observations of the Doig-Halfway interval in this area display a series of high radioactive spikes within the vertical succession between the Lower Doig “Phosphate Zone” and the Halfway-Charlie Lake Formation contact. These radioactive spikes vertically bound less radioactive intervals between them and are easily correlated to abrupt shale intervals seen in core. These same radioactive shale beds can be correlated along strike of this shoreface trend across the study area, and have been interpreted as marine flooding surfaces bounding individual parasequences by this author and others including Willis (1992), Wittenberg (1992), and Willis and Moslow (1994).

A minimum of five marine flooding surfaces have been identified and correlated from wire-line and core data across the study area. These flooding surfaces bound four parasequences observed as coarsening upward facies associations (Figure 3.02). Previous studies by Wittenberg (1992), Caplan (1997), and Willis (1992) on the Doig and Halfway formations have revealed that the number of stacked parasequences within the Halfway and Doig formations varies from four to six depending on the specific location within the basin. Core based observations from this study note that the shale content of each parasequence increases to the southwest and eventually the parasequences taper and converge into the condensed horizon of the Doig Phosphate Zone.

Within the study area four distinct parasequences within Doig-Halfway Formation interval are identified above the Doig Phosphate Zone. (Figure 3.02). For the purpose of this study these parasequences have been numerically labelled in ascending order up the vertical succession and are simply classified as parasequence 1 through parasequence 4 (Figure 3.03).

Parasequence number one and two consist of laminated offshore sediments of lithofacies F1 (laminated black shale) and consist of facies association A (offshore) as discussed in Chapter 2. Parasequence three and four are

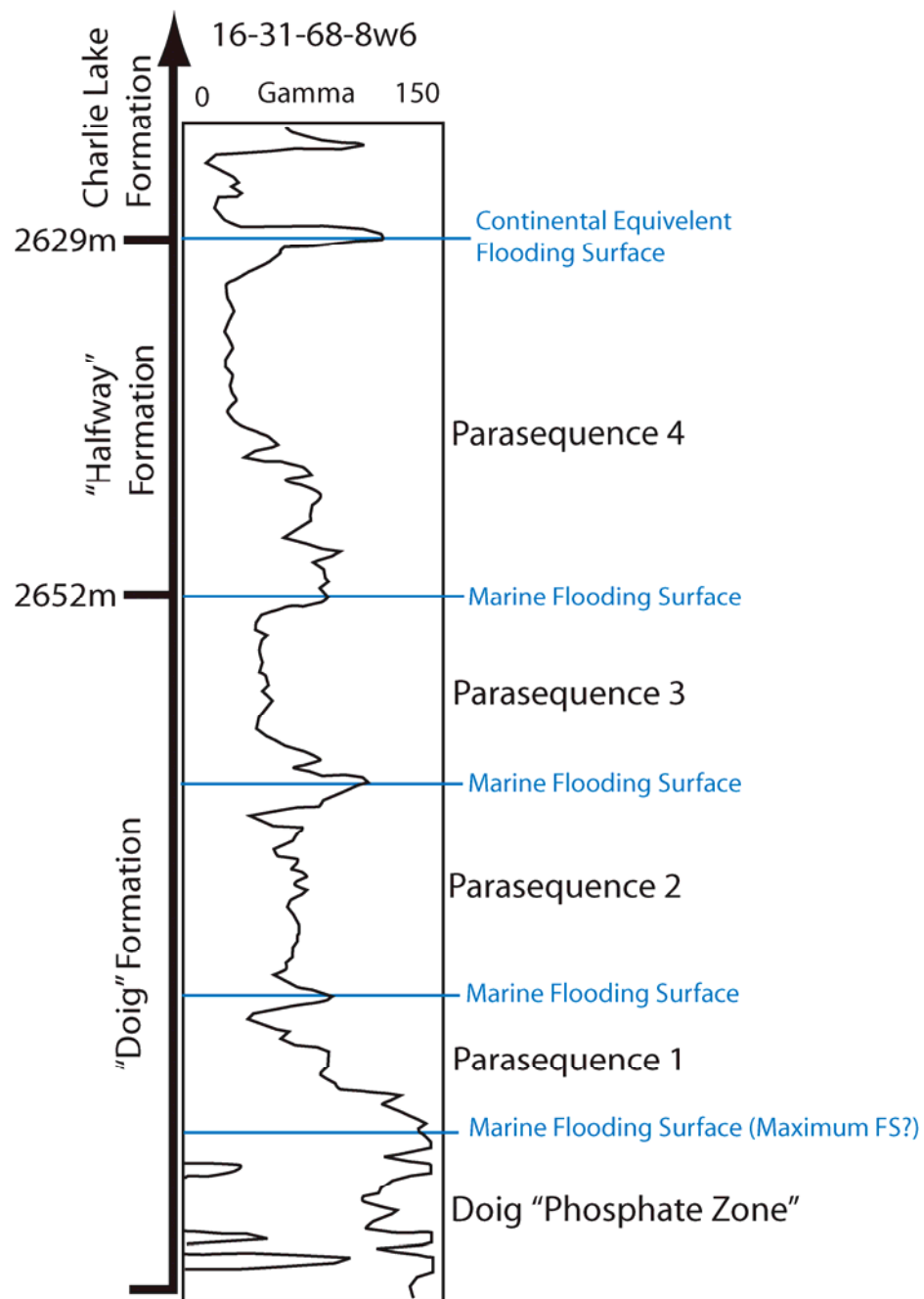


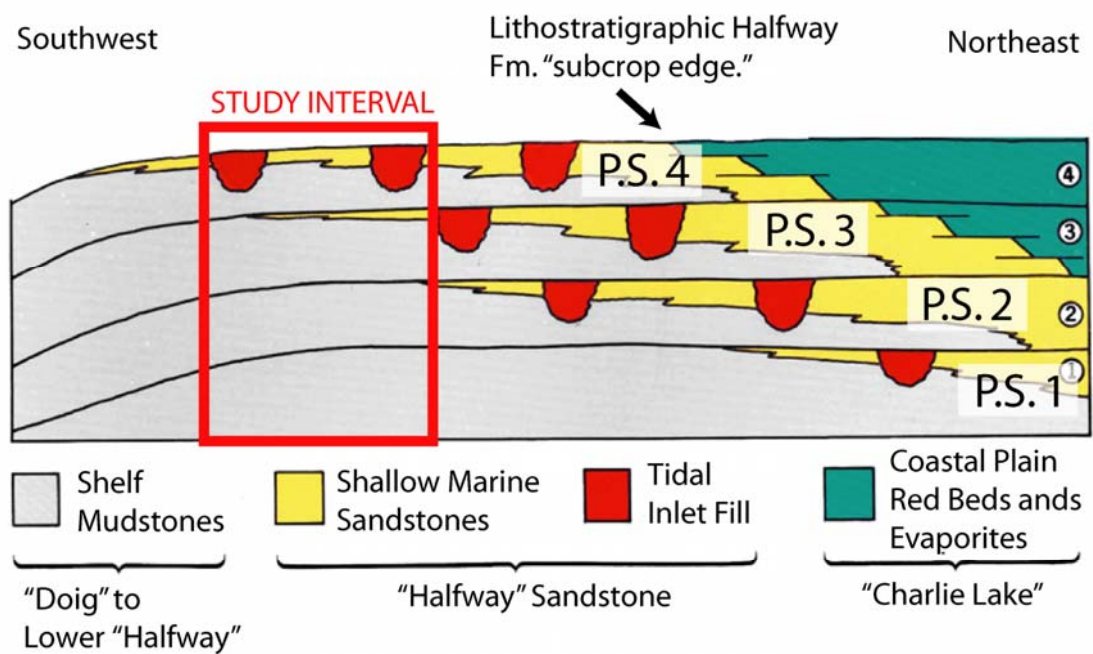
Figure 3.02 - Stacking of Parasequences one to four above the Doig "Phosphate Zone" in well 16-31-68-8W6.

composed of higher energy deposits, including lithofacies F3 to F5, and belong to facies association B (proximal shoreface) and C (tidal inlet channels) also discussed in Chapter 2. Each of these parasequences is slightly coarser than the underlying parasequence below. This overall shallowing upward succession of parasequences within this vertical succession indicates a prograding shoreface during the time of Doig-Halfway deposition. This means that at time of deposition of the fine grained offshore sediments in the lower parasequence one and two the paleo-shoreline would have been located further away to the east than during the deposition of parasequence three and four (Willis, 1992).

3.5 PARASEQUENCE NOMENCLATURE

It is important for the scope of this study to understand the petroleum industry nomenclature and terminology used to define the Halfway and Doig formations. The Halfway and Doig formations have historically been lithostratigraphically defined meaning any high energy near-shore deposits such as the shoreface sandstone and bioclastic tidal inlet channel fill (typically parasequence number three and four) are called the Halfway Formation, while the Doig Formation has been defined as the finer grained offshore siltstone and shale (typically parasequence one and two). It must be noted that both of these formations are of the same stacked clinoforming progradational parasequence set. For the clarity of this study the author will be describing the Doig-Halfway interval in terms of parasequence number. In the Elsworth Field, for the convenience of discussion parasequence four will be used interchangeably with the term “Halfway Formation” and parasequence three and lower will be considered the “Doig Formation.”

From core and wire-line well log observation it was discovered that the shoreface trend of parasequence number four dramatically varies in thickness across the study area. The precise details of this thickness variation will be discussed below. Parasequence number four is the uppermost parasequence in a parasequence set that runs northwest to southeast across the study area. In this shoreline trend parasequence four and the underlying parasequence three are reservoir targets and are composed of fine to medium-



West Alberta Middle - Upper Triassic Parasequence Stracking

Figure 3.03 - Parasequence stacking in the study area. This study interval is highlighted in the box. The Halfway, Doig, and lowermost Charlie Lake formations are placed into a sequence stratigraphic context as a progradational parasequence set (modified from Willis, 1992).

grained shoreface deposits of facies association B and bioclastic sandstone of facies association C. In order to more accurately understand the cause and intricacies of these thickness changes, as well as their effects, a detailed study on this parasequence was carried out.

3.6 SEDIMENTOLOGICAL EVIDENCE FOR TECTONISM IN THE HALFWAY FORMATION

3.6.1 MARINE FIRMGROUND

During the course of the study the presence of marine firmgrounds were interpreted from select Halfway Formation cores. These marine firmground surfaces are recognized by an irregular erosional scour with characteristic sedimentary or biogenic structures indicating a firm substrate underlying the erosional scour. One of the best indicators of a marine firmground, and the main indicator used in this study, is the presence of a *Glossifungites* ichnofacies assemblage (Seilacher, 1964) displaying evidence of burrowing.

Marine firmgrounds are formed predominantly by sediment compaction and subsequent exhumation allowing the compacted sediments to exist close to, or at, the sediment-water interface. When firmgrounds are influenced by organisms and burrowed they are classified as a *Glossifungites* ichnofacies assemblage. Burrows present in a *Glossifungites* ichnofacies assemblage usually have several distinct characteristics including 1) sharply-defined unlined walls; 2) scratch marks on burrows walls; 3) cross-cutting of trace fossils; and 4) burrow infills consisting of the above overlying sediment (Seilacher, 1964; Pemberton and Frey, 1985; Gingras *et al.*, 2001).

The presence of *Glossifungites* assemblages in the rock record are of significance as they imply that the sediments in question were either 1) sub-aerially exposed; or 2) were buried, compacted, and exhumed (Gingras *et al.*, 2001).

It is important to note that in the study area, marine firmgrounds are present within lower to middle shoreface sediments of parasequence number four and only appear in wells where parasequence number four is much thinner than the same parasequence in surrounding or neighbouring wells.

The presence of these surfaces within thin intervals of parasequence number four in this region *provides evidence that portions of the Halfway Formation underwent exhumation and/or erosion during or close after the deposition of the Doig-Halfway Formation parasequence number four.*

The localized nature and distribution of these *Glossifungites* ichnofacies assemblages/marine firmground surfaces present within thinner intervals of parasequence four, and absence in thicker intervals, suggests that the event, which created them, was not regional in scope.

It is important to note that although marine firmground surfaces can be formed by a eustatic sea level drop creating a lowering of the wave base and erosion into previously deposited sediments upon the shoreface. It is unlikely that a wide spread sea level drop resulted in the development of a marine firmground within parasequence four within the study area since the surface is not regional in extent. A more likely explanation is a localized relative sea level drop due to tectonic influences in the study area. Localized areas display a group of wells with thinner parasequence number four and cores displaying *Glossifungites* ichnofacies assemblages. These areas are juxtaposed by groupings of wells displaying thick Halfway Formation intervals and no *Glossifungites* ichnofacies assemblages.

3.6.2 FIRMGROUND SURFACES SEEN IN THE HALFWAY FORMATION.

Numerous marine firmground surfaces were seen throughout the study. Documented surfaces in core are listed in table 2 with their well identification and description. Figures of these surfaces are displayed in figures 3.04 to 3.09. Table 2 lists the well, depth, and description of each firmground observed in the study area.

Table 2 – Location, description, and interpretation of marine firmground surfaces seen in core.

Well I.D. & Depth	Description and Comments	Interpreted Significance	Figure #
16-10-69-9W6 2647.5 m	<i>Skolithos</i> burrows emanating down from sharp erosional scour. Burrows are unlined and filled with sediment piped down from overlying unit. Firmground suite cross-cuts lower shoreface sandstone with middle to upper shoreface sandstone.	Exhumation (uplift) exposed buried cohesive middle shoreface sediment to sediment water interface. Burrows in this sediment remained open and were filled by upper shoreface deposits.	Figure 3.04
15-2-69-9W6 2655.4 m	<i>Skolithos</i> burrows emanating down from sharp erosional scour. Burrows are unlined and filled with sediment piped down from overlying unit. Firmground cross-cuts massive middle shoreface sandstone. Burrows are greater than 10 cm in length and are filled with overlying sediments.		Figure 3.05
6-15-69-9W6 2637.5 m	Burrow within fine grained siltstone of lower shoreface origin. Unlined burrow has been filled with overlying fine grained mudstone.	Exhumation (uplift) exposed cohesive lower shoreface sediment which was burrowed and in filled by mudstone.	Figure 3.06
12-32-70-9W6 2479.0 m	Sharp erosional scour with coarse grained lag deposited above. Unlined burrows are filled with lag deposit. Firmground cross-cuts lower shoreface deposits with upper shoreface deposits. There is a facies change across the boundary.	Exhumation exposed cohesive middle shoreface sediment to sediment water interface. Burrows in this sediment remained open and were filled by lag deposit prior to deposition of upper shoreface deposits. Facies change across scour indicates sediments have been	Figure 3.07

		removed and are missing.	
11-17-66- 6W6 2783.0 m	Presence of a distinct erosional scour with separating fine grained horizontally laminated lower shoreface sandstone with cross bedded coarse grained upper shoreface sandstone. No burrows are visible in this core. Sharp facies change across boundary.	Exhumation exposed cohesive lower shoreface sediment to sediment water interface before re-deposition of upper shoreface deposits occurred. Estimated ~5 m of sediment is missing within facies change.	Figure 3.08
11-19-71- 8W6 2359.1 m	Sharp erosional scour, burrow tubes filled with sediments piped down from above. Deposits underlying scour are fine grained , deposits overlying appear to be upper shoreface in origin.	Exhumation exposed cohesive middle shoreface sediment to sediment water interface. Burrows in this sediment remained open and were filled by lag deposit prior to deposition of upper shoreface deposits. Facies change across scour indicates sediments have been removed and are missing.	Figure 3.09

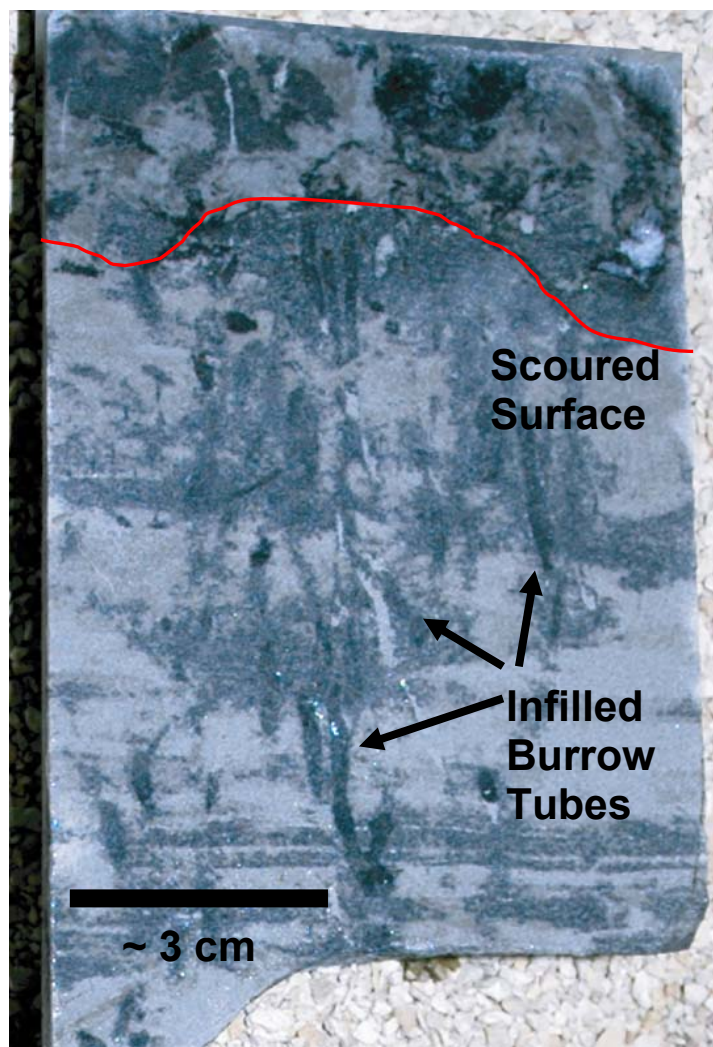


Figure 3.04 – Burrowed marine firmground (*Glossifungites* ichnofacies assemblage) surface in well 16-10-69-9W6 at 2647.5m depth. Note sharp erosional scour and abundance of vertical burrows in filled with overlying sediment.

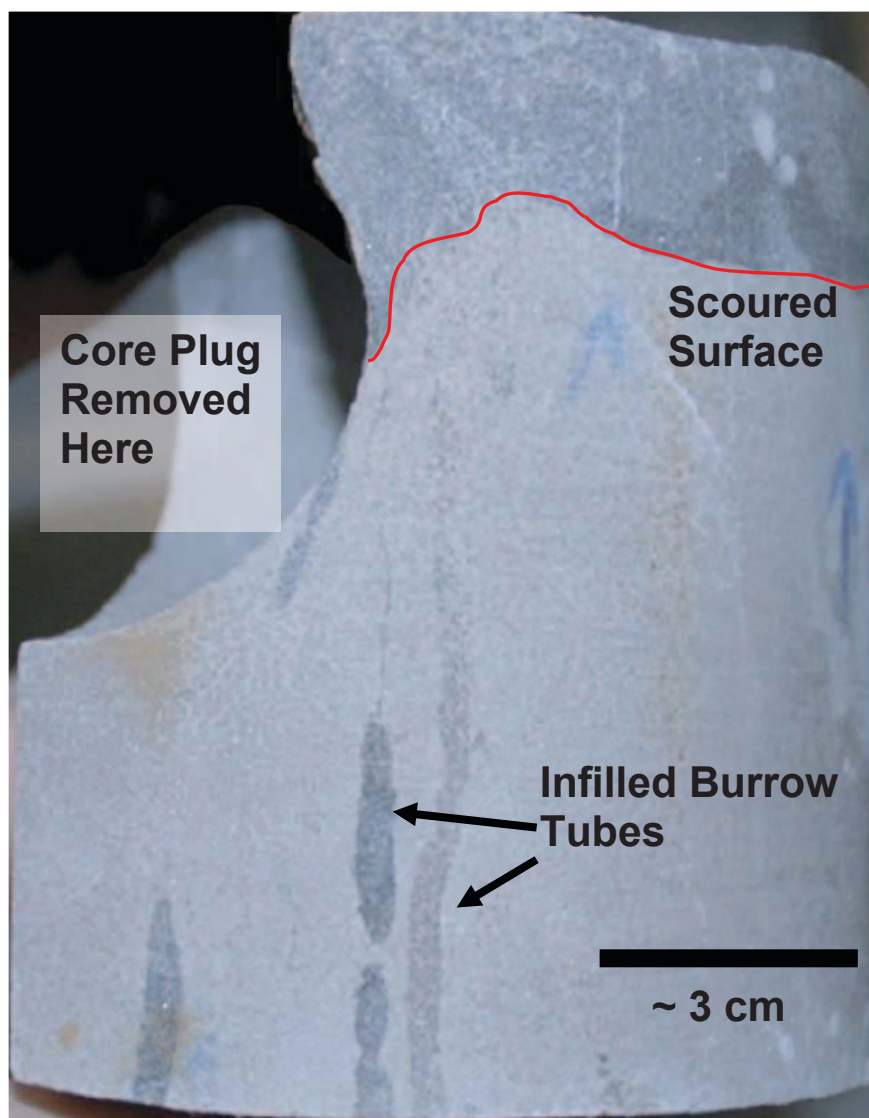


Figure 3.05 – Burrowed marine firmground (*Glossifungites* ichnofacies assemblage) surface in well 15-2-69-9W6 at 2655.4m depth. Burrows extend below surface for greater than ten centimetres and are filled with overlying sediment.

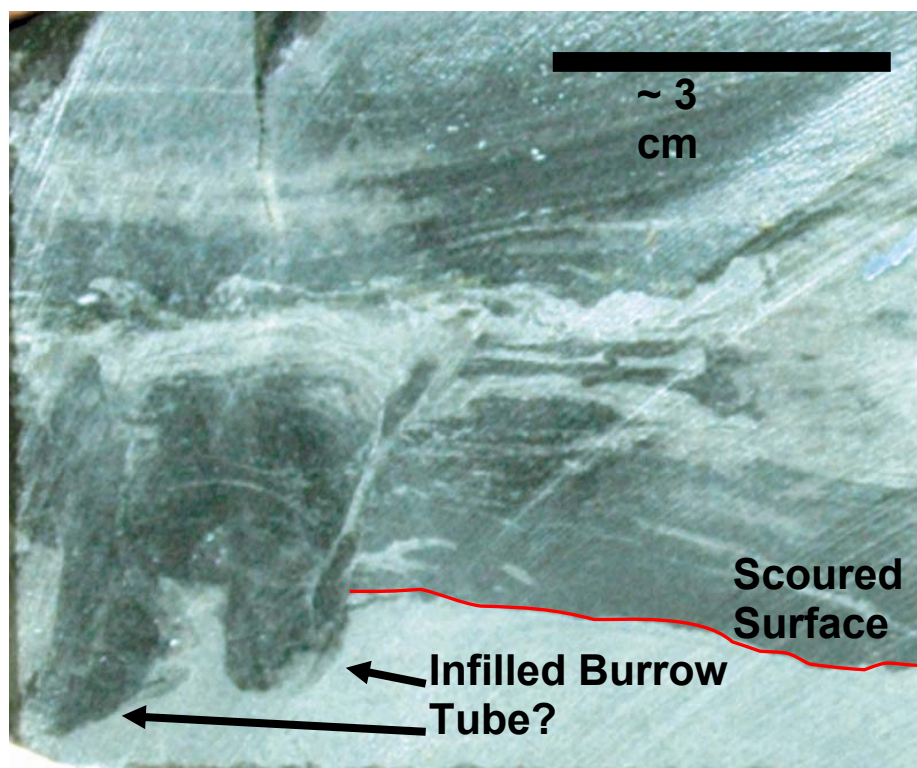


Figure 3.06 - Burrowed marine firmground (*Glossifungites* ichnofacies assemblage) surface in well 6-15-69-9W6 at 2637.5m depth. Burrows are sharp walled and extend down into siltstone.

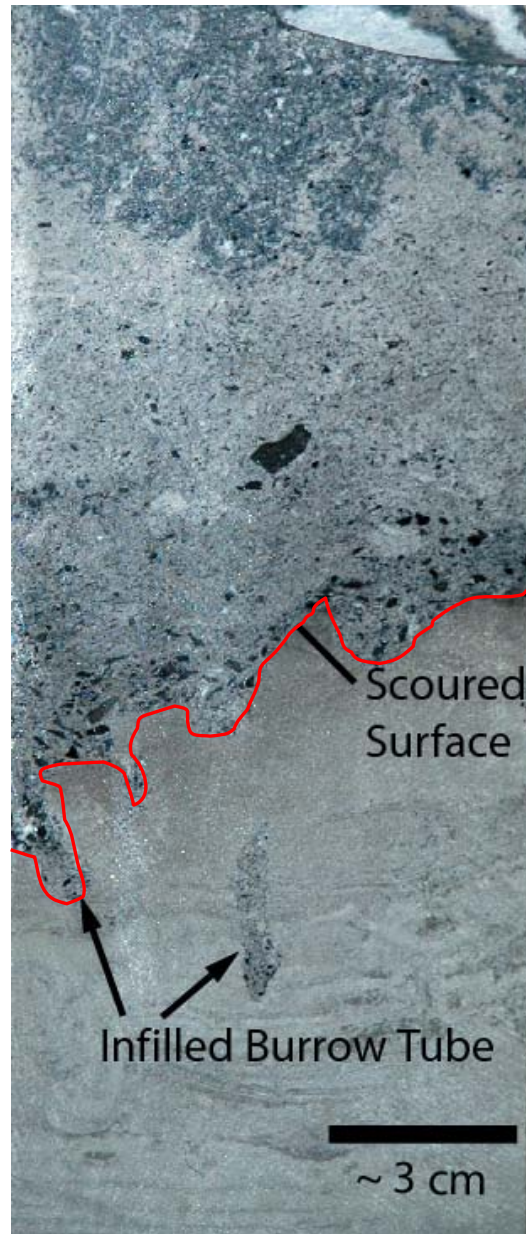


Figure 3.07 - Burrowed marine firmground (*Glossifungites* ichnofacies assemblage) surface in well 12-32-70-9W6 at 2479m depth. Burrows are sharp walled and have been filled with coarse grained lag material of overlying sediment.



Figure 3.08 - Marine firmground surface in well 11-17-66-6W6 at 2783.0m depth. Sharp erosional scour separates fine grained laminated lower shoreface sediments from overlying cross bedded upper shoreface sediments. Facies change across erosional scour suggests that approximately five metres of sediment has been removed if thickness comparisons of shoreface interval are made with adjunct wells.

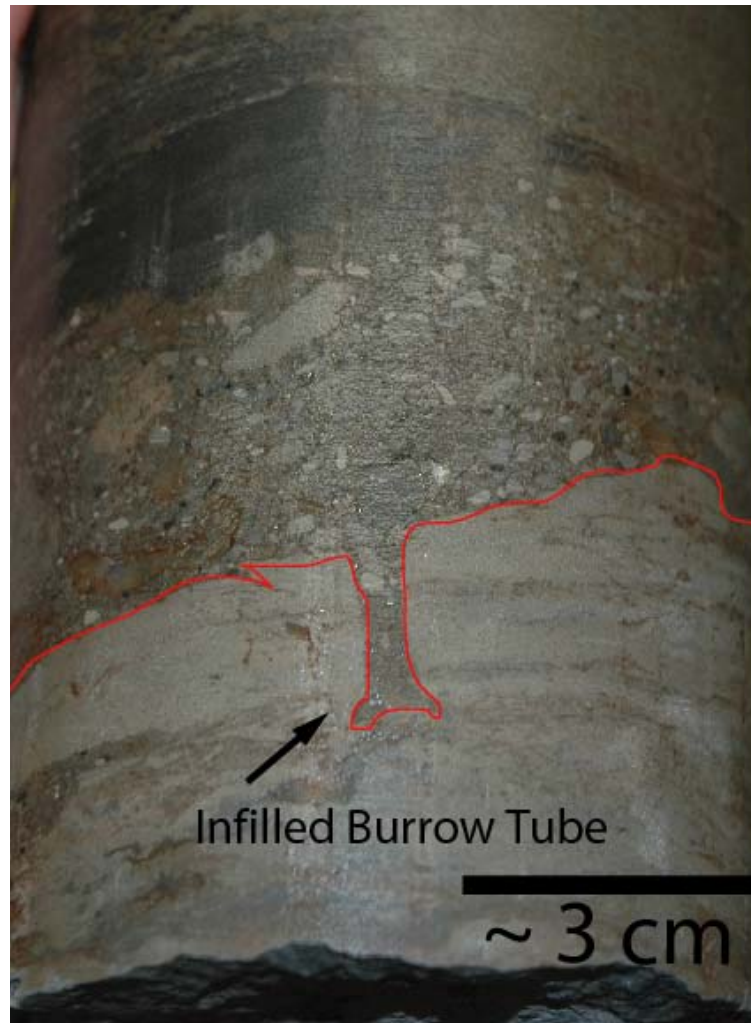


Figure 3.09 – Burrowed marine firmground (*Glossifungites* ichnofacies assemblage) surface in well 11-19-71-8W6 at 2359.1m depth. Burrows are sharp walled and have been filled with coarse grained lag material of overlying sediment.

3.6.3 SEISMITES SEEN WITHIN THE HALFWAY FORMATION

In addition to the presence of erosional marine firmgrounds, interpreted to be the product of tectonic uplift, seismite sedimentary structures seen in core also provide evidence for the occurrence of tectonism in the study area.

The term seismite was originally proposed by Seilacher (1969) and is defined as a bed that contains soft sediment deformation that is inferred to be earthquake generated (Greb and Dever, 2002). This term was later expanded by Cita and Lucchi (1984) to include all deformation and sedimentary structures induced by seismic events or tsunamis - which are themselves seismically generated (Greb and Dever, 2002).

Many authors have documented the occurrence of seismites within the Western Canada Sedimentary Basin (Haites, 1960; Hein, 1999; and Lemieux, 1999; Greggs, 2000; Greggs, 2006). Seismites seen within the study area include soft sediment deformation and sedimentary injection structures within the Halfway Formation and a large scale vertical fracture occurring within the upper Doig Formation. They will be discussed in more detail below.

Soft Sediment Deformation

Documented in core throughout the study area are instances of wavy deformed bedding within what was interpreted as facies association A (distal prograding shoreface). In all cases this deformed bedding appears to have been bent or folded while unlithified and is surrounded by a fine grained sandstone matrix. Bedding such as this has been interpreted to be soft sediment deformation created by tectonic movement or cyclic shock occurring within the study area after the time of deposition. An example of such bedding can be seen in the 14-28-71-8W6 cored interval (Figure 3.10). In this example we see deformed siltstone beds within a predominantly sandstone matrix. This deformed bedding is located near the upper interval of parasequence number four within what appears to be an overly thick interval of Doig Formation sands (greater than 22 metres). These overly thick sandstone units have been interpreted to be graben fill by other authors (Wittenberg, 1992) and the soft sediment deformation seen within has been



Figure 3.10 – Soft sediment deformation due to pore water evacuation of siltstone and sandstone interpreted to have been caused by cyclic shock (tectonic activity) within the study area. 14-28-71-8W6, 2199m.

interpreted to be the result of tectonic movement and slumping within the graben.

Sand Injection Structures

Also documented in core within the study area is the occurrence of a small sedimentary intrusion or sandstone dike. Such a feature can be found in well 14-28-71-8W6 within Halfway Formation upper shoreface sandstone (Figure 3.11). This sandstone dike appears to be a dewatering structure caused by loading and cyclic shock and displays typical characteristics of a seismically induced sediment intrusion, including an exotic sediment infill surrounded by the “enclosing strata” (Onasch and Kahle, 2002), and displays evidence of rapid, upward injection of material from a lower liquefied layer of sand (Stewart, *et al.*, 2002; Tuttle and Seeber, 1991). This specific feature is quite small in scale approximately one cm in width, and is a planar feature cutting diagonally through the core. This dike cuts through interpreted upper shoreface coarse sandstone deposits and is infilled by slightly finer grained sandstone interpreted to have originated from the underlying finer grained shoreface sandstone during a period of tectonic activity.

Fault/Fractures

A unique feature interpreted as an anhydrite filled fracture was also found in the study area that could represent the tapering out of a fault created by tectonic stress. This fracture is approximately 2 cm in width and runs sub-vertically through the upper Doig Formation of well 10-36-70-10W6 for 3 metres (Figure 3.12). The fracture is infilled by white anhydrite most likely derived from the evaporate-rich Charlie Lake Formation. Minor 1-2 cm offsets of horizontal laminae are visible on either side of the fracture. The fracture is very sharp walled and the surrounding laminae do not appear to show any bending or deformation leading to the interpretation that these sediments were lithified at the time of movement and anhydrite emplacement. The direct cause of this fracture is unknown but it is located directly to the north-east of the interpreted uplifted region of township 70-10W6.

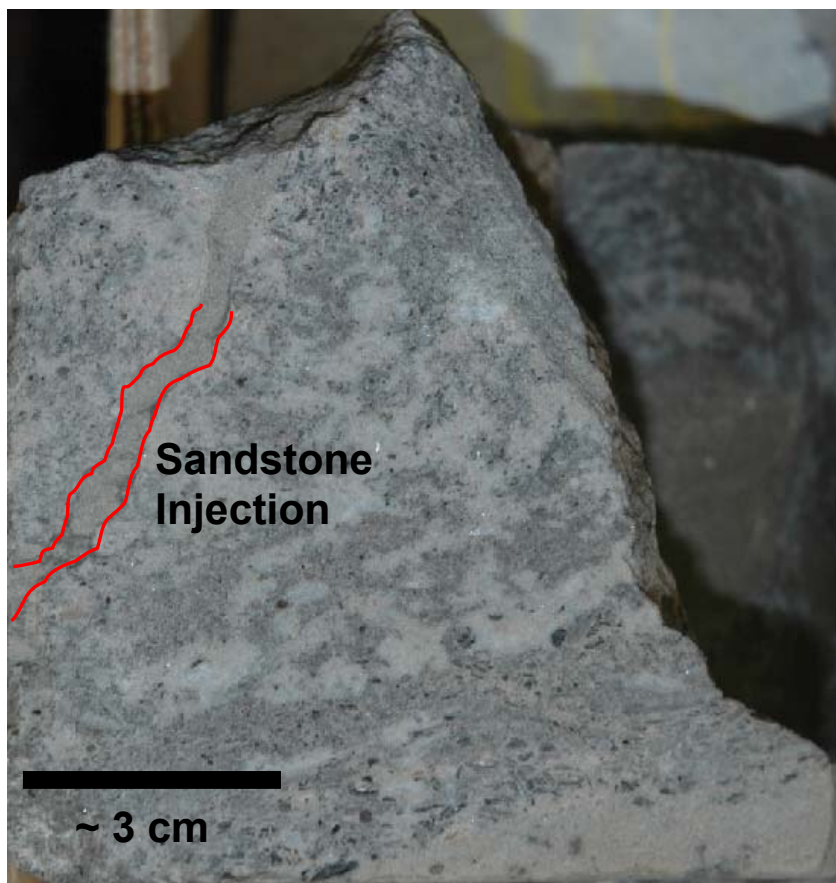


Figure 3.11 – Fine sandstone injection (highlighted in red) seen within medium grained shoreface sandstone of the Halfway Formation. The injection is a planar feature and is seen on both sides of core. 14-28-71-8W6, 2201m.



Figure 3.12 – Sharp walled fracture seen within black horizontally laminated shale of the Doig Formation. Fracture displays minor sub cm offsets (fault?) and is interpreted to have occurred after some lithification of surrounding shale. This feature is an indication of active tectonism (or fault reactivation) within the study area. Core is approximately 3 inches wide. 10-36-70-10W6, 2568m.

3.7 HALFWAY FORMATION THICKNESS VARIATION IN ISOPACH AND CROSS-SECTION

Thickness variations within the Halfway Formation are easily observed in strike and dip cross-sections, core, and wire-line logs. As previously mentioned, it was observed in core that where thinner intervals of Halfway Formation deposits are observed, a visible marine firmground (or *Glossifungites*) surface is present. These surfaces are recognized by an irregular erosional scour as well as a *Glossifungites* ichnofacies assemblage and only appear within core where parasequence 4 is much thinner than the same parasequence in neighbouring wells. Where the Halfway Formation is much thicker no firmground surfaces are observed. Two examples of these thickness variations are documented below.

Example 1 – 16-07-070-10W6 vs. 10-18-070-10W6/2

A dramatic example of such thickness variations can be seen when comparing the thickness of parasequence number four within wells 10-18-070-10W6 and 16-07-070-10W6 (Figure 3.13). These wells are approximately one kilometre apart along strike of the shoreface trend and are accurately correlated using a significant marine flooding surface which delimits the boundary between parasequence numbers three and four. Within well 16-07-070-10W6 the total thickness of parasequence four is approximately 16 metres with about 13 metres of shoreface sandstone (Figure 3.13). Less than one kilometre away, the same parasequence within well 10-18-070-10W6/2 displays a total thickness of 7 metres and about 3 metres of shoreface sandstone (Figure 3.13). From this example a dramatic difference in thickness is apparent between these two wells.

Although no core is available from these wells the cuttings show no evidence of bioclastic material or tidal channel influence in either core, indicating that these parasequences are of similar composition to each other. By correlation to nearby cored intervals it was determined that this parasequence corresponds to facies association B (proximal prograding shoreface) and displays a coarsening upward shoreface sequence of fine-medium grained sandstone.

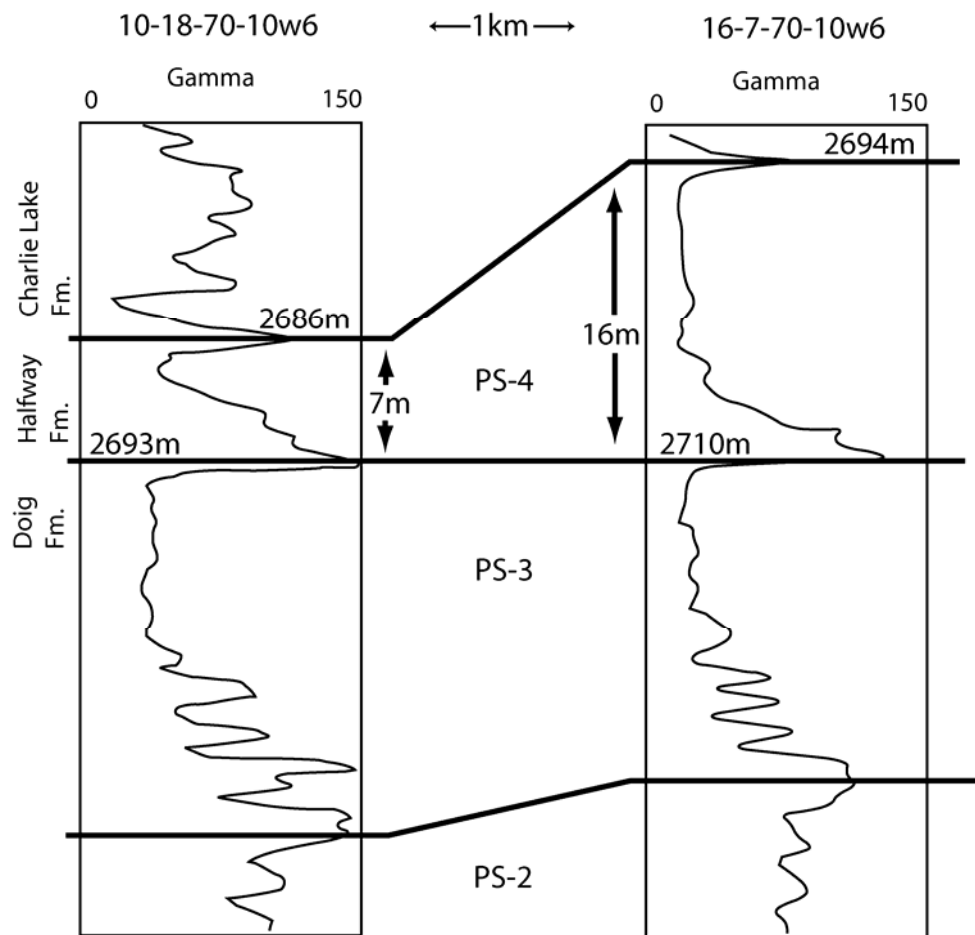


Figure 3.13 - Observed dramatic thickness variation of parasequence number four based on correlation of mappable surfaces in closed spaced wells (16-7-70-10W6 and 10-18-70-10W6). These wells are approximately 1 km apart along strike of the same shoreface trend.

Example 2 - 11-25-066-07W6 vs. 11-17-066-06W6

Another example of significant variation within parasequence thickness is observable in wells 11-25-066-07W6 and 11-17-066-06W6 (Figure 3.14). Both of these wells have a cored interval through parasequence number four and display a coarsening upward shoreface profile of facies association B, interpreted from the presence of cross-bedded and plane parallel laminated sands. A significant variation in the thickness of parasequence number four is seen in between these two wells. Within 11-25-066-07W6 parasequence four is 17 metres containing a net sand thickness of 12 metres, while within well 11-17-066-06W6 parasequence four is approximately 7 metres thick with a net sand thickness of 4 metres.

It is very interesting to note that within the cored interval of parasequence four of well 11-17-66-6W6 a marine firmground surface is present, displaying a sharp erosional surface and a abrupt facies break between lower shoreface and upper shoreface depositional environments within the thinner sandstone unit (Figure 3.08).

Similar thickness variations of parasequence number four are seen throughout the study area. Once again, wells displaying a *Glossifungites* ichnofacies/marine firmground surfaces within parasequence four are dramatically thinner than wells which have no visible *Glossifungites* ichnofacies assemblage. As the study progressed it became apparent that it was possible to predict the presence of a marine firmground appearance within parasequence four in core based on the thickness displayed from well-logs.

3.7.1 ISOPACH OF HALFWAY FORMATION SHOREFACE SANDSTONE

An isopach map of this Halfway Formation shoreface trend was created in order to more accurately map the thickness variations seen within the study area (Figure 3.15). The contour interval of this isopach map is five metres; with the addition a single contour at the 2 metre thickness mark to more accurately define the extent of deposits under five metres in thickness. Only wells with correlatable intervals of parasequence number four within the shoreface trend were included on this isopach map.

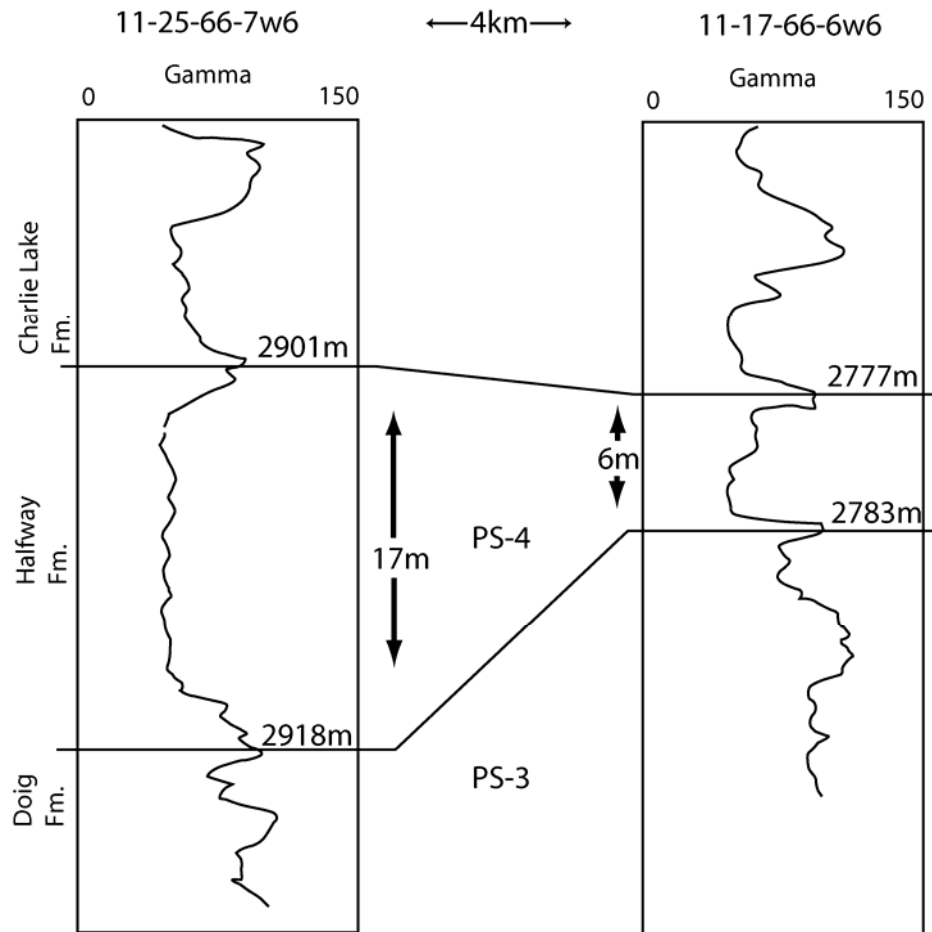


Figure 3.14 - Observed dramatic thickness variation of parasequence number four (Halfway Formation) between wells 11-25-66-7W6 and 11-17-66-6W6. These wells are approximately 4 km apart along depositional strike of the studied shoreface trend. Based on core observations, an interpreted erosional scour/marine firmground in PS-4 occurs in well 11-17-66-6W6.

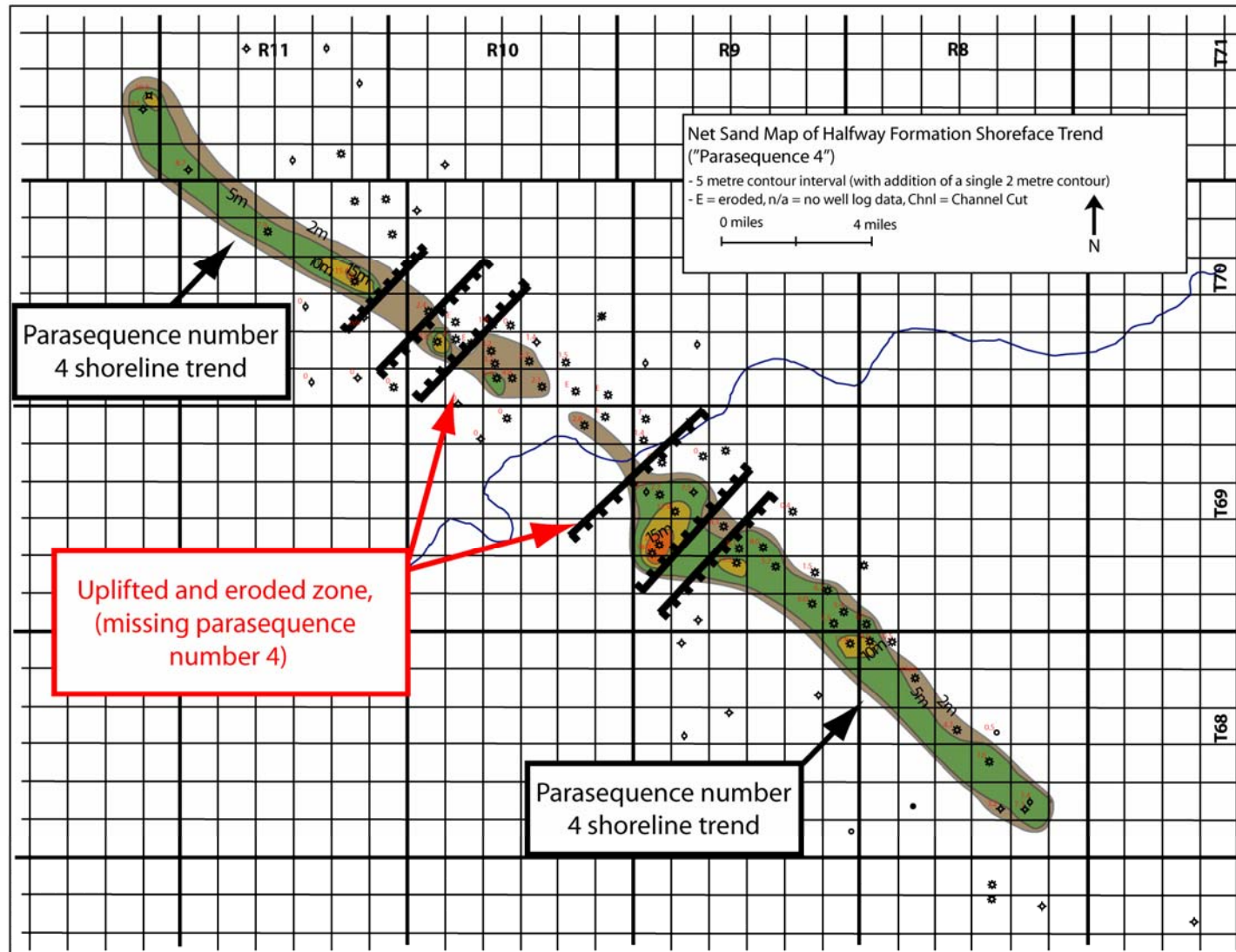


Figure 3.15 – Isopach map of parasequence 4 shoreface trend. Note discontinuous nature of shoreface trend and placement of hypothesized fault boundaries displaying grabens in the thicker portions of the shoreface and horsts in the thinner portions. Halfway well penetrations are shown.

Observed on the isopach map is the northwest to southeast trending shoreface sandstone. This sandstone averages a thickness of approximately eight metres along the shoreface trend and has been interpreted to belong to facies association B (proximal prograding shoreface).

It is apparent that there is an anomaly within the shoreface trend near the centre of the map within township 70-10W6. Within this township, parasequence number four, is very thin and is missing in areas, with the exception of six metre thick sandstone in section four and a 13.5 metre thick sandstone unit in section seven. These isolated pockets of thick sandstone within such a thin area are abnormal and are discussed in more detail in cross-section A-A'.

Northwest and southeast of the thin deposits in township 70-10W6 thick intervals of parasequence number four are observed. Looking closer at township 69-9W6 in figure 3.16 we can more accurately observe the relationship of variations in thickness and the presence of marine firmgrounds. Within section 18, well 7-18-69-9W6 displays thicknesses of greater than 18 metres within the Halfway Formation. This is contrasted with a well in section 9 (16-10-69-9W6) that displays a sandstone thickness of only 6 metres. Although these wells are greater than four kilometres apart along strike they are less than 1 kilometre apart along depositional dip, with the wells in section 18 being slightly more paleo-seaward than the well in section 9. *These wells both contain cored intervals of the Halfway Formation. In core a significant marine firmground surface is visible within the thinner lower shoreface of well 16-10-69-9W6. This marine firmground divides lower shoreface deposits from upper shoreface deposits and displays a distinctive Glossifungites ichnofacies assemblage. No firmground surface is present within the thicker shoreface deposits of well 7-18-69-9W6.*

It would appear that the Halfway Formation in well 16-10-69-9W6 had been subject to erosion before re-deposition of the higher energy shoreface occurred. If this erosional event was widespread in extent (such as a sea level drop or a forced regression) we would expect to see evidence of such an event in both cores. Hence, the erosion subjected to the deposits of well 16-10-69-9W6 must have been local in extent.

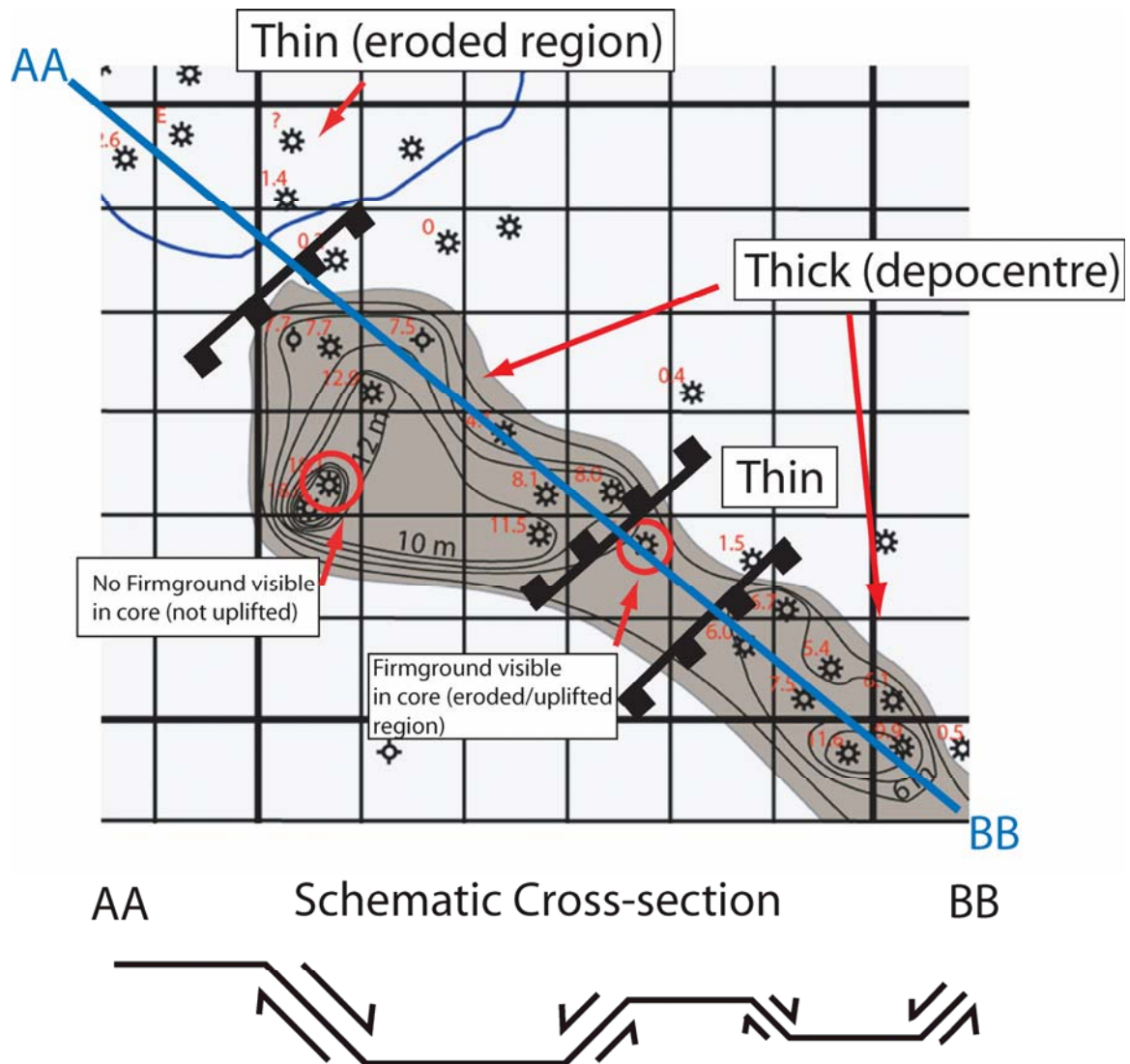


Figure 3.16 - Isopach map of parasequence number four highlighting township 69-9W6. Wells of interest are circled. Hypothesized fault trends are drawn on map. Schematic cross-section AA-BB displays theorized horst/graben architecture across the township.

With the understanding that similar erosional surfaces are only found in the thinner Halfway Formation wells, and these erosional surfaces are not widespread across the region, these thickness changes are interpreted to be the result of tectonic uplift induced by extensional normal faulting in the sub-10 metre scale. These faults are thought to be orientated perpendicular to the shoreface trend in a northeast-southwest direction similar to faults seen around the Dawson Creek graben zone (O'Connell, *et al.*, 1990). It appears from this isopach map that most of township 70-10W6 was eroded as the result of this tectonic uplift which created small depocentres in grabens on either side of this township creating extra accommodation space and causing thicker intervals of the Halfway Formation.

3.7.2 CROSS-SECTIONS AND STRUCTURAL CONTROL ON PARASEQUENCE CORRELATIONS

In order to better represent and understand the impact of tectonics on the deposition of this particular Halfway Formation shoreface trend, three cross-sections were created across the study area (Figure 3.17).

- Cross-section A-A' is a stratigraphic cross-section consisting of twelve wells running along strike (parallel) to paleo-shoreline, and orientated in a northwest to southeast direction (Figure 3.18).
- Cross-section B-B' is a structural cross section using the same wells as in A-A' but hung on a structural datum within the Charlie Lake Formation to see if any modern day structural variations exist (Figure 3.19).
- Cross-section C-C' is a stratigraphic dip-section cutting across paleo-shoreline in a southwest to northeast direction (Figure 3.20).

Each cross-section will be described in detail below. It is recommended that the reader follow along by viewing the specified cross-section as they continue below.

Cross-section A-A' (Figure 3.18)

This cross-section is a stratigraphic section hung on a correlatable anhydrite bed within the lower intervals of the Charlie Lake Formation. The section runs in a northwest to southeast direction and encompasses the uppermost Doig Formation, the entire Halfway Formation, and the lowermost Charlie Lake Formation; each formation is labelled along the left side of the figure.

Shoreface sandstone of the Halfway Formation (parasequence number four), which are potential reservoir intervals are coloured yellow across the cross-section. Shoreface sandstone of the Doig Formation (defined as the parasequences below parasequence number four) are coloured green.

The Halfway Formation is bound above by the continental equivalent flooding surface of the first supra-tidal anhydrite beds (green line), and bound below by a marine flooding surface of marine origin (blue line). Other flooding surfaces between individual parasequences are labelled and correlated across the cross-section.

Most noticeable on this cross-section are 1) dramatic thickness changes of parasequence number four across township 70-10W6; and 2) the complete removal of the marine flooding surface dividing parasequence number three and four in certain wells creating “over-thickened” intervals of sandstone (green and yellow intervals together) and the complete removal of the marine flooding surface bounding parasequence number three and four effectively merging the Halfway and Doig formations together. A schematic version of this strike cross-section is included as figure 3.21

1. When moving from northwest to southeast (left to right) on the cross-section variations in the thickness of parasequence number four are easily apparent. In well 7-23-70-11W6 the Halfway Formation is of average thickness for this particular shoreface trend. Moving one well to the southeast in well 10-18-70-10W6 a dramatic thinning of parasequence number four to down to a thickness of 7 metres is observed, and moving on a thicker 16 metres in well 16-7-70-10W6 is observed. Moving further to the south-east

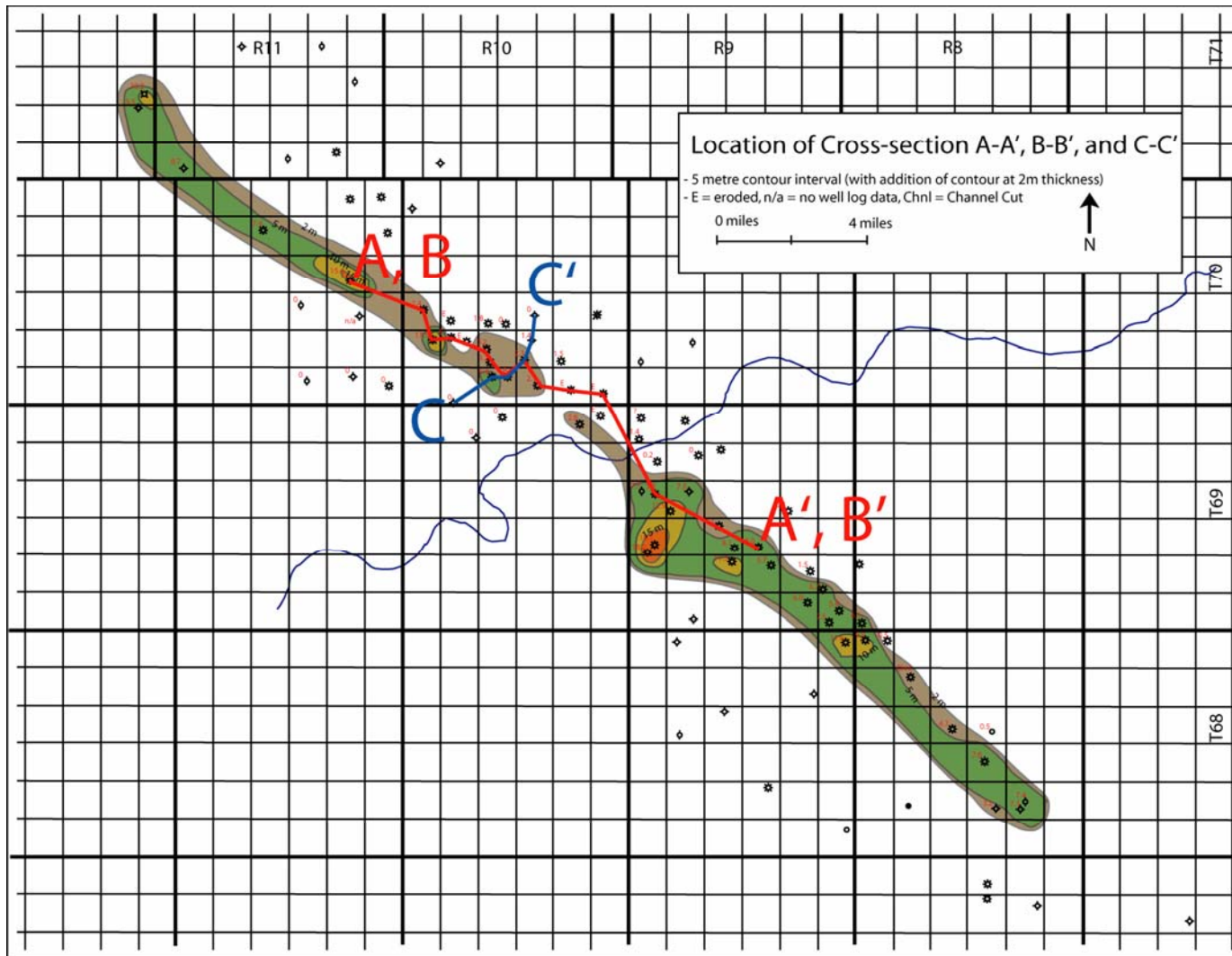


Figure 3.17 – Location of cross-sections A-A' (stratigraphic section), B-B' (structural section), and C-C' (stratigraphic) across the study area, within the studied Halfway Formation (parasequence number four) shoreface trend.

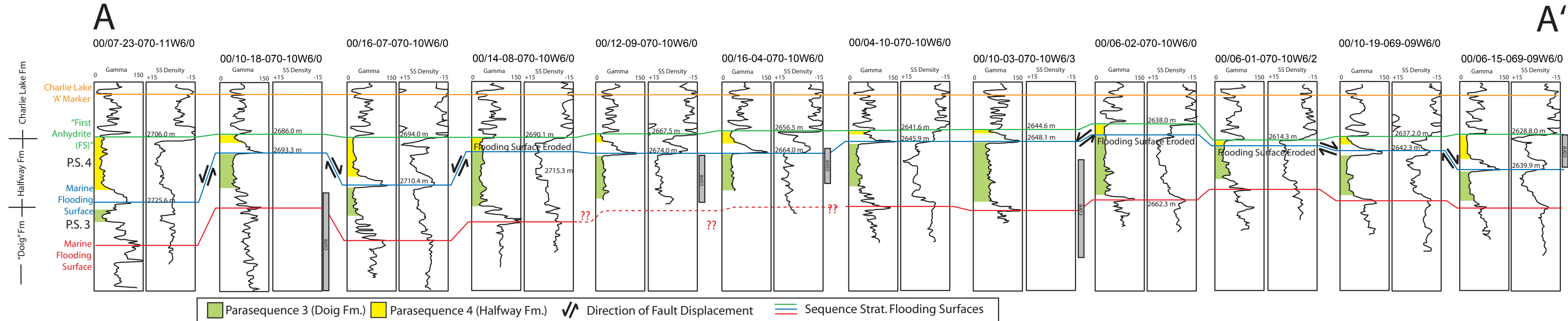


Figure 3.18 - Stratigraphic strike cross-section along shoreface trend displaying thickness variations in the Halfway Formation (yellow) and Doig Formation (green). Interpreted fault movements are displayed. Datum is the Charlie Lake 'A' marker. See Figure 3.17 for location map.

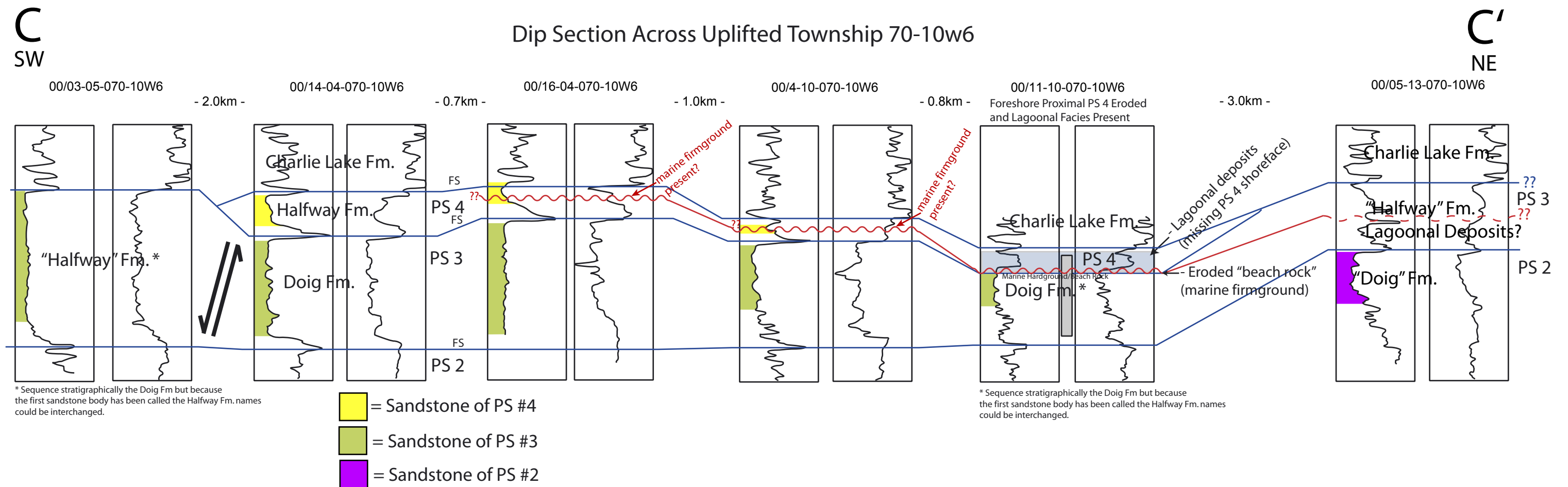


Figure 3.20 - Stratigraphic dip cross-section perpendicular to shoreface trend across uplifted township 70-10w6 displaying thickness variations in the Halfway Formation (yellow) and Doig Formation (green). Relationship of shore distal to proximal can be observed moving from C - C'. Note thinning of Halfway Formation sandstone (yellow) as section moves shore proximal. Distinct erosional surface is observed in core in well 11-10-70-10w underlying interpreted lagoonal deposits and displaying complete removal of Halfway Formation parasequence number 4. See Figure 3.17 for location map.

Strike Cross-section Schematic of Fault Movement and Position of Marine Firmground Surfaces

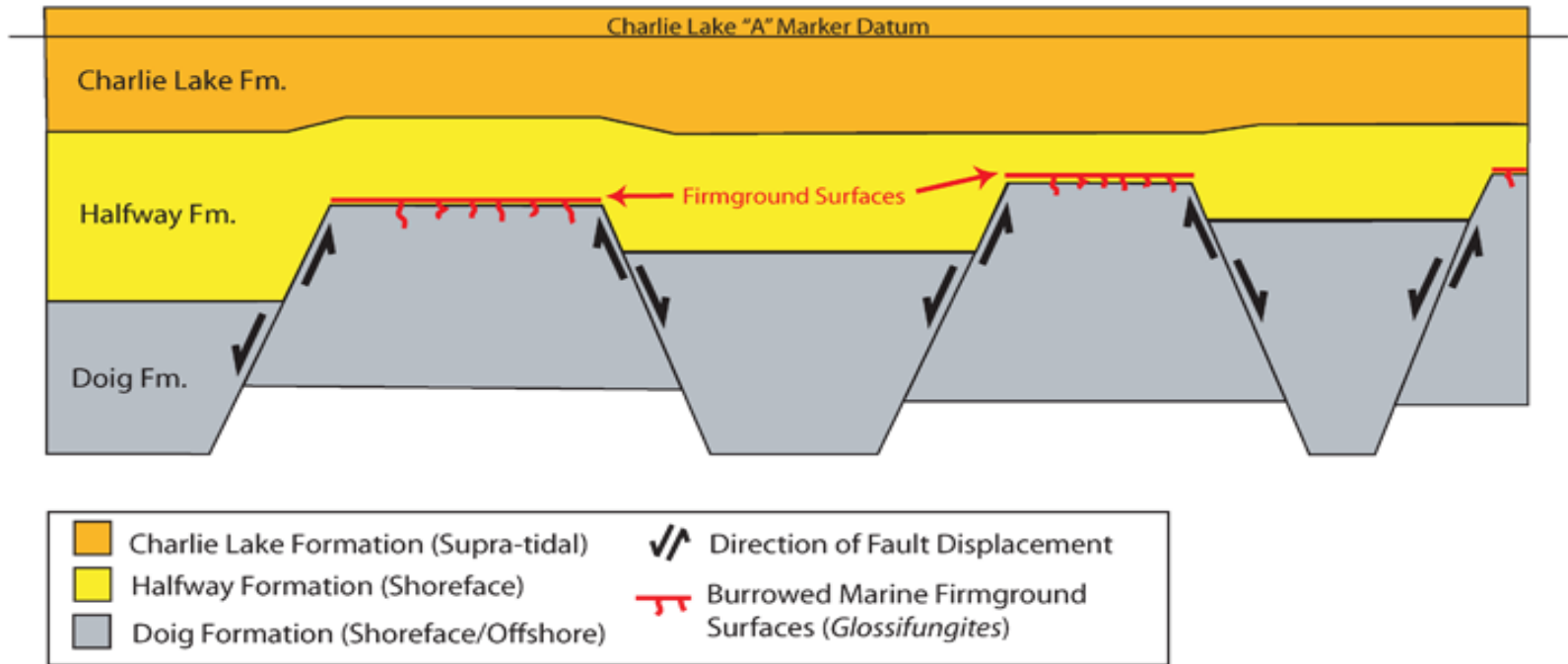


Figure 3.21 – Schematic cross-section along strike of shoreface trend displaying relationships between interpreted fault movement and position of marine firmground surfaces. Datum is the Charlie Lake “A” Marker. See section 3.8 and figure 3.22 for a more detailed dip-section schematic model.

a dramatic thinning pattern over the south-eastern portion of township 70-10W6 occurs indicating a large region of erosional uplift. Southeast of well 10-19-69-9W6 parasequence number four thickens and returns to an average shoreface thickness of approximately 12 metres within 6-15-69-9W6.

2. Three wells in this cross-section (14-8-70-10W6, 6-2-70-10W6, and 6-1-70-10W6) all display a lack of a marine flooding surface (blue line) separating parasequence number three from parasequence number four. This lack of a marine flooding surface becomes apparent after correlating the lower (red line) and upper (blue line) bounding marine flooding surfaces of parasequence number three (Doig Fm.) across the region. The lower marine flooding surface (red line) is picked on the highest radioactive interval before the cleaning upward profile of parasequence number three begins. The upper bounding marine flooding surface (blue line) is correlated across the region as a very distinct and characteristic shale bed.

When comparing the correlations of wells 14-8-70-10W6, 6-2-70-10W6, or 6-1-70-10W6 with their neighbours, the precision of the lower marine flooding surface (red line) correlations along the shoreface trend can be easily observed, as well as the precision of the upper flooding surface (green line) of parasequence four (supra-tidal anhydrite bed). These surfaces are consistent and easily correlatable across the region. What is different about these wells is what is in-between these two flooding surfaces, there is lack of the marine flooding surface separating parasequence number three from four, and the presence of an interval of sandstone that is greater than 20 metre in thickness.

This “over-thickened” sandstone body can be explained if it is understood that these wells have been subjected to greater amounts of uplift and erosion than their neighbours. This erosion occurring at time of deposition of the Halfway Formation has removed any evidence of the highly distinctive shale bed and marine flooding surface that was once deposited across this shoreface trend. This erosion has effectively joined the sandstone of parasequence three and four into one “over-thickened” interval. *Without detailed correlation work such as seen in this cross-section one would assume that this*

thick sandstone body was deposited by an increase in accommodation space, however, this thick sandstone body is interpreted to have been created due to a decrease in accommodation space brought on by tectonic uplift in the localized area.

Cross-section B-B' (Figure 3.19)

This cross-section displays all of the same wells, correlations, and stratigraphic intervals seen within cross-section A-A', but is hung on a structural datum of mean sea level. The purpose of this cross-section B-B' (Figure 3.19) is to illustrate that the structural interpretations made on the stratigraphic cross-section A-A' do coincide with actual present day sub-surface structure.

It is well known that Triassic strata within the Western Canada Sedimentary Basin dip toward the west (Barclay and Leckie, 1986). This westward dipping is evident in cross-section B-B', as the flooding surface bounding parasequence three and four (blue line) in well 7-23-70-11W6 is approximately 93 metres lower than the same flooding surface in 6-15-69-9W6.

Ignoring this overall westward dipping structure of the Western Canada Sedimentary Basin overprinted within the structural cross-section we can see that there are anomalies present suggesting that structural movement has occurred along this trend since the deposition of the Doig-Halfway interval. This is especially evident when comparing wells 7-23-70-11W6, 10-18-70-10W6, and 16-7-70-10W6 on the far left (southwest) of the cross-section. Of these three wells, the middle well (10-18-70-10W6) has a thinner eroded interval of parasequence four than compared to its neighbours. Present day structure does show that the flooding surfaces bounding parasequence three and four in 10-18-79-10W6 are higher in elevation than both its neighbours providing evidence that tectonic activity may have occurred within the study area.

Structural control can also be seen when comparing well 6-1-70-10W6/2 to its neighbour 6-2-70-10W6. These two wells are approximately one kilometre apart and yet the supra-tidal flooding surface of 6-1-70-10W6/2 is approximately 25 metres higher in elevation than its nearby neighbour 6-2-70-10W6. The small horizontal distance and relatively great vertical change structurally between these two wells, provides evidence of

structural influence in this region. Both of these wells are missing the flooding surface dividing parasequence number three and four (blue line) so strong stratigraphic evidence for the occurrence of tectonism exists.

These findings suggest that wells with thinner intervals of Halfway Formation have been influenced by structural controls and are uplifted in relation to their neighbours. It is the interpretation of the author that these thinner well are located on the uplifted horst block, relative to their neighbours. A schematic horst and graben model has been drawn under the structural cross-section of B-B' (Figure 3.19) displaying the authors interpreted structural movement within the study area.

Cross-section C-C' (Figure 3.20)

This cross-section is a dip section orientated in a southwest to northeast direction perpendicular to the studied Halfway Formation shoreface trend, as well as the previous discussed cross-sections A-A' and B-B'. Cross-section C-C' is a stratigraphic cross-section using the lower bounding marine flooding surface of the Doig parasequence number 3 as a datum. Displayed on this cross-section is the upper intervals of the Doig Formation (parasequence number three), the complete Halfway Formation (parasequence number four), and the lower interval of the Charlie Lake Formation. This whole cross-section is located within the highly eroded uplifted township 70-10W6 displayed in figure 3.15 and in cross-section A-A' (Figure 3.18). In most of this township the Halfway Formation is quite thin as it has been partially eroded and/or removed.

Cross-section C-C' is of interest as it displays the distal to proximal relationship of the studied Halfway Formation parasequence number four shoreline trend. Moving from southwest to northeast (left to right) on the cross-section the Halfway Formation (parasequence number four) is first visible in well 14-4-70-10W6, existing as a 8 metre thick interval of sandstone. Although no core is available for these wells, parasequence number four appears to be overly thin compared to average thicknesses seen along this shoreface trend. It is the author's interpretation that a marine firmground or erosional scour would be visible within 14-4-70-10W6 if a cored interval was present.

Moving shore proximal toward the northeast a thinning of the Halfway Formation is observed which is to be expected as we are moving into shallower more erosive waters closer to the paleo-shoreline. The typical coarsening upward shoreface profile of parasequence number four disappears and is no longer visible in well 11-10-70-10W6.

Well 11-10-70-10W6 is of interest as it has a core through the Halfway Formation. Visible in this core is a sharp erosional scour with sandstone clasts immediately overlying the scoured surface. These sandstone clasts are quite angular indicating that they were lithified prior to being transported. Above this sharp erosional scour is a shale bed that has been interpreted to be lagoonal in origin. The sharp erosional scour and the lagoonal deposits seen within the 11-10-70-10W6 cored interval have led to the interpretation that these sediments were deposited very close to paleo-shoreline during the deposition of parasequence number four. Having lagoonal deposits directly overlying lower shoreface deposits provide evidence that shoreface sediments were uplifted into shallower water and eroded causing lagoonal sediments to be deposited unconformably on top of lower shoreface sediments. The presence of this sharp erosional scour within this cored interval of parasequence number four in this well adds evidence to the hypothesis that the thin more distal sandstone seen to the southwest were eroded as well. Moving further landward to the northeast the disappearance of parasequence number four is observed and a facies change into the continental deposits of the Charlie Lake Formation is visible within well 5-13-70-10W6.

It is also of note in cross-section C-C' that well 3-5-70-10W6 down-dip to the southwest displays an "over-thickened" approximately 30 metre thick interval of clean sandstone. Based on previous work completed by Wittenberg (1992) this thick sandstone body has been interpreted as a half-graben fill. Unfortunately, no nearby wells are available to more precisely interpret this feature.

3.8 TECTONIC HISTORY OF THE HALFWAY FORMATION

Observations and data collected during the course of this study suggest that the reservoir history and evolution of this Middle Triassic Halfway Formation in the Elmworth field is quite complex and includes multiple events of deposition, tectonism,

and erosion. An attempt at summarizing the geological history of the Halfway Formation within this shoreface trend is illustrated in figure 3.22 and explained below.

- 1) Formation of a south-westward progradational parasequence set consisting of at least four shallowing upward parasequences. Uppermost parasequences consist of shoreface sediments and tidal inlet channels.
- 2) Reactivation of northeast to southwest trending upper Paleozoic normal faults during deposition of parasequence number four due to structural relaxation of the Fort St. John Graben (Caplan and Moslow, 1997) or reactivation of deep seated basement faults (Evoy, 1997). These reactivated faults formed a series of horst and graben structures. Uplift of shoreface strata occurred on horst structures causing sediments to be eroded as they are uplifted into wave base.
- 3) Continued uplift of horst blocks in study area caused sediments which were compacted and buried to be exhumed. These sediments were subsequently burrowed and inhabited by marine organisms forming marine firmground *Glossifungites* assemblages seen in core.
- 4) Deposition along shoreface is resumed as fault movement is stopped and environments equilibrate. Because erosional marine firmground surfaces are near wave base, higher energy sediments are deposited above exhumed/erosion surface. This deposition fills in open burrow tubes preserving their record. In regions more shore proximal and undergoing more erosion the marine flooding surface dividing parasequence number three from four was removed. This removal of the marine flooding surface and subsequent deposition makes the Halfway Formation appear overly thick similar to well 14-8-70-10W6.

In summary the thickness of potential Halfway Formation reservoir intervals in the Elmworth field is dependant on the amount of tectonic influence and uplift they have undergone. Overly thick reservoirs appear to have been created by the adjoining of

parasequence three and four sandstones occurring after an erosional event removed the marine flooding surface separating them. This cutting down and eroding into parasequence number three greatly complicates sequence stratigraphic correlations across the study area. Thin intervals of the Halfway Formation sandstone have also undergone uplift and erosion (indicated by marine firmground surfaces), although this uplift was not great enough to erode down to the marine flooding surface bounding parasequence three and four.

3.9 TECTONIC UPLIFT ANALOGS

Seafloor uplift such as proposed in this study is not uncommon and a literature search has turned up studies documenting similar interpretations.

A recent historical example of shoreface uplift proposed in this study occurred during the Alaskan Good Friday earthquake of 1964 on the eastern and southern shore of Montague Island, located off the western shore of Alaska. The shoreline surrounding this island was raised approximately eleven metres (Figure 3.23) over a period of minutes during the earthquake (Ward *et al.*, 1987). An example of such exposure is seen on the southern shore of Montague Island when the Hanning Bay fault was reactivated, popping up marine sediments on one side of the fault scarp by three metres (Figure 3.24). A series of bathymetric surveys were run southwest of Montague Island in 1927 and again after the earthquake in 1964. The survey documented seafloor uplift in the region ranging from five to sixteen metres in elevation (Malloy, 1964).

A study by Chaabani and Razgallah (2006) on Lower Cretaceous shallow marine siliciclastics in Central Tunisia has interpreted a series of thickness changes in the proximal shoreface to be the result of extensional tectonics and variations in siliciclastic sediment supply. Thickness changes within Chaabani and Razgallah (2006)'s study are controlled by northwest trending faults. These faults initiated differential subsidence and localized uplift during a period of high sea level.

Another study performed by Oujidi, *et al.*, (2006) on the Triassic of the Oujda Mountains in Morocco documented thickness variations of up to thirteen metres and the

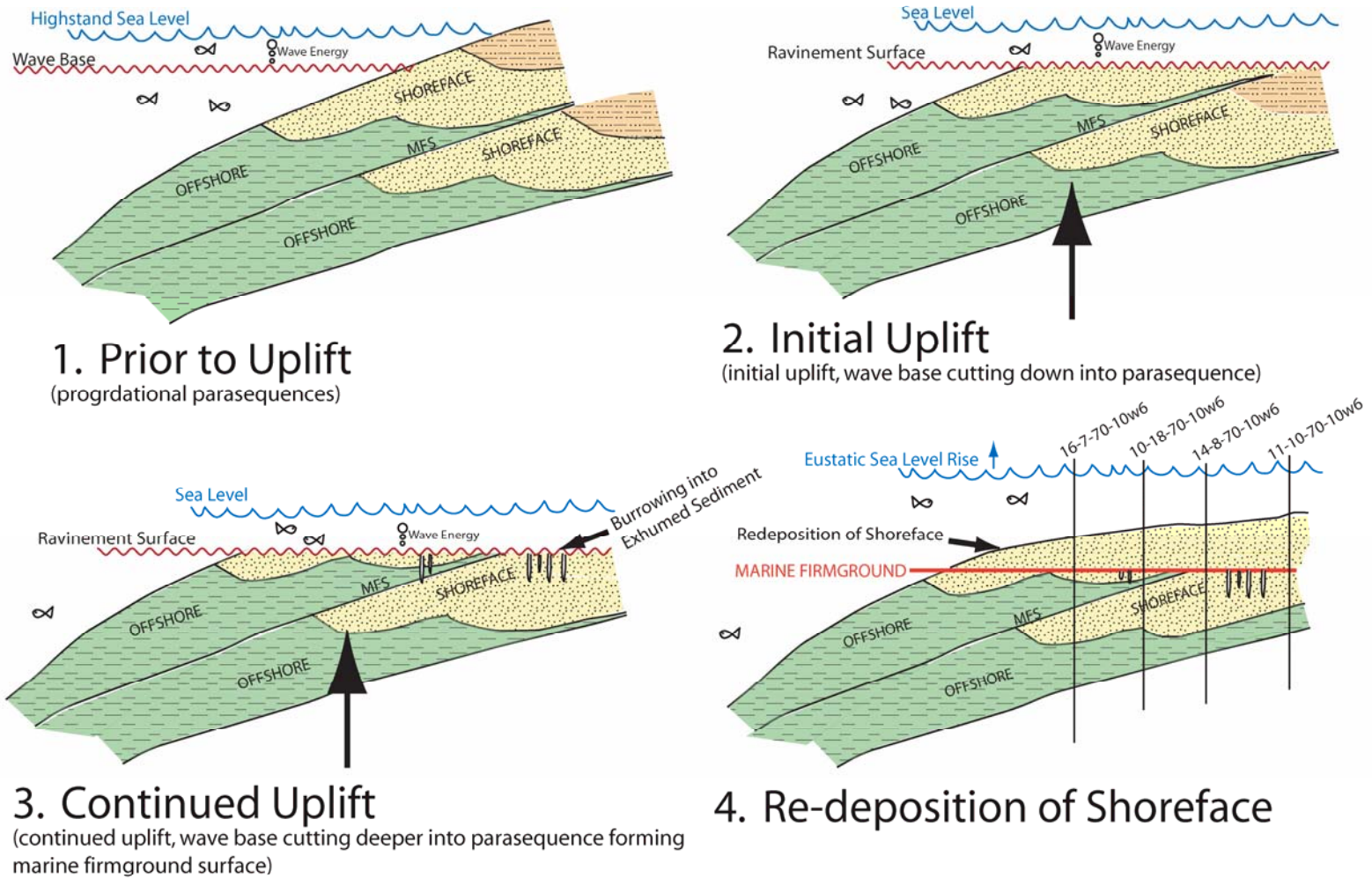


Figure 3.22 – Schematic diagram summarizing the interpreted depositional history of the Halfway Formation (parasequence number 4) and the Doig Formation along the studied shoreface trend. Theorized well placements from study are placed on the fourth panel showing variations in sandstone thickness as the result of tectonic uplift.

presence of many syn-sedimentary deformation features such as 1) slump structures in the vicinity of normal faults; 2) breccias and soft sediment deformation; 3) as well as syn-sedimentary normal faults. These syn-sedimentary faults are recorded to display abrupt thickness changes across their fault plane.

3.10 EXPLORATION AND PETROLEUM IMPLICATIONS

An understanding of the tectonic intricacies of the Halfway and Doig formations described in this study will lead to a more precise exploration model in the Elmworth and Wapiti fields and region. Middle Triassic exploration within these two fields is relatively recent, with in place gas reserves exceeding 164 BCF (AEUB, 2006), and many more similar pools likely exist along this studied shoreface trend.

The implications of the tectonic uplift and faulting described in this study can have a profound effect upon reservoir continuity and size and should be carefully considered during both exploration and development phases within these fields. Within the studied shoreface trend, pressure and sulphur content of hydrocarbons appears different from well to well.

In addition, an understanding of the origin and formation of marine firmgrounds and *Glossifungites* ichnofacies surfaces seen in core within thin Halfway Formation upon uplifted horsts can lead to the discovery of thicker Halfway Formation deposits within graben features immediately adjacent.

Although the offsets on fault movement depicted within the Halfway Formation in this study are of sub-geophysical resolution, such offsets may be recognizable using geostatistical analysis of the type discussed by Mei (in press); he suggests that metre-scale offsets can be mapped. Such a process, combined with a detailed sedimentologic study observing erosional marine firmgrounds or *Glossifungites* ichnofacies surfaces in core may lead to the discovery of other similar fields/pools within the region.

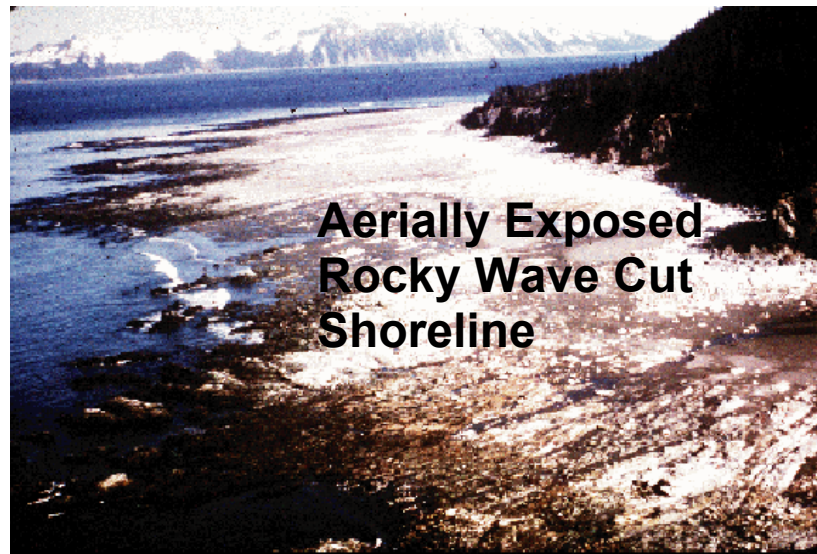


Figure 3.23 – Uplifted rocky shoreface on Montague Island, Alaska. White colouring represents a rocky wave cut shoreline that was below sea level before the earthquake (modified from McGregor and Abston, 1995)



Figure 3.24 – View of the Hanning Bay fault scarp on the southwest side of Montague Island. The Hanning Bay fault trends obliquely across the photo. The fault plane dips steeply and the scarp displays approximately 3 metres of uplift. White colour on right is result of desiccation of calcareous marine organisms (modified from McGregor and Abston, 1995)

CHAPTER FOUR: BIOSTROMES WITHIN THE MIDDLE TRIASSIC SUBSURFACE

4.1 INTRODUCTION

Bioclastic deposits within the Triassic of the Western Canada Sedimentary Basin are not uncommon and have a high degree of economic significance due to their effectiveness as hydrocarbon reservoirs. Often referred to as a “coquinas,” bioclastic accumulations occur within the Lower Triassic Montney Formation and are interpreted as parallel upper shoreface beach ridges. It is within these deposits that some of the largest gas pools in the Western Canada Sedimentary Basin are found namely the prolific Kaybob, Fir, and Sturgeon Lake pools.

Within the Middle Triassic Halfway and Doig formations, an abundance of bioclastic material is found within tidal inlet channel deposits such as those documented

in Chapter 2 of this study in Facies Association C. These deposits cut syn-depositionally through the shoreface perpendicular to the shoreline orientation and are composed of a high degree of abraded shell material. Tidal inlet channel fill creates effective reservoirs due to their ability to contain significant primary porosity and bio-moldic secondary porosity. They also have a natural tendency to be overlain by fine grained deposits forming effective stratigraphic seals throughout the Triassic of the Western Canada Sedimentary Basin (Caplan and Moslow, 1997). Major fields producing from tidal channel deposits within the Halfway and Doig formations include Wembley and Peejay fields.

In addition to the bioclastic material found within these beach ridges and tidal channel inlet fill, a third, lesser known and understood bioclastic accumulation called a biostrome has been discovered in the Lower-Middle Triassic subsurface within the Doig Formation. Prior to this discovery, Lower-Middle Triassic biostromes were previously only documented in outcrop by Zonneveld (2001), and an extensive literature search subsequently has not uncovered any documented Triassic examples of biostromes within the subsurface of the Western Canada Sedimentary Basin. This chapter's intent is to document and record the existence of a biostrome trend within the Lower-Middle Triassic Doig Formation and draw some comparisons to biostromes documented by Zonneveld (2001).

4.2 TRIASSIC BIOSTROMES IN N.E. BRITISH COLUMBIA OUTCROP

Middle Triassic biostromes documented by Zonneveld (2001) in north-eastern British Columbia were discovered within the upper Liard Formation along the shore of Williston Lake. The Liard Formation at this site is composed of a “series of coarsening-upwards, mixed siliciclastic-carbonate-evaporite, shoreface to marine parasequences” and is considered to be the depositional equivalent to the Doig and Halfway formations found within the subsurface of the Western Canada Sedimentary Basin (Figure 4.01) (Zonneveld, 1999; Zonneveld, 2001). Biostromes discovered in outcrop at Williston Lake are composed

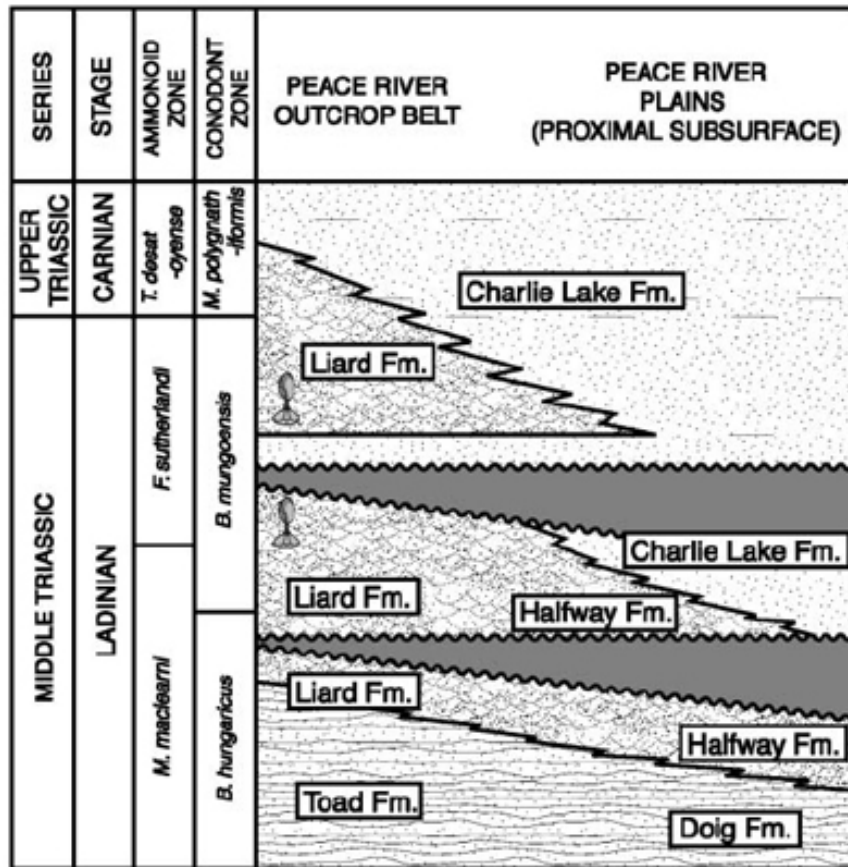


Figure 4.01 - Middle Triassic outcrop to subsurface correlation, nomenclature, and biostratigraphic zonation within the Middle Triassic. The Liard Formation is the outcrop equivalent to the Halfway Formation in subsurface. (From Orchard and Tozer, 1997 in Zonneveld, 2001).

primarily of whole and abraded terebratulid brachiopods, articulate crinoids, cidaroid echinoids, bivalve pelecypods, and spiriferid brachiopods. These deposits sit within and adjacent to fine grained hummocky cross-stratified, ripple cross-laminated sediments interpreted to be deposited in a lower shoreface environment above storm wave base.

4.3 TRIASSIC BIOSTROMES IN THE SUBSURFACE

Middle Triassic biostromes discovered during this study occur within the subsurface of west-central Alberta approximately 30 kilometres west of the town of Grand Prairie. These biostromes were discovered within the lower shoreface deposits of a southeast-northwest oriented shoreline trend similar to the one documented in chapter three of this study. This shoreface trend is mappable for approximately thirty kilometres and is centered across township 71-10W6 and 72-11W6. Biostromes were discovered within this trend at an average depth of 2445 metres at the up-dip portion of this trend and at 2550 metres at the down-dip portion.

4.4 GEOLOGICAL SETTING OF BIOSTROME STUDY AREA

Triassic strata in the Western Canada Sedimentary Basin consist of a westward thickening wedge of both marine and continental sediments that were deposited along the western margin of Pangea (Gibson and Barclay, 1989). The Halfway and Doig formations in the study area are composed of a series of stacked coarsening upward parasequences consisting of relatively conformable shoreface deposits deposited in environments ranging from offshore, through shoreface, to continental. Within this interval the Doig Formation is typically defined as the lower three parasequences of the Doig/Halfway Formation interval and consists of offshore to lower-shoreface deposits. The Halfway Formation is typically defined as the upper most parasequence in this interval and consisting of the coarser grained sandstone and coquinas representing the lower shoreface to upper shoreface/foreshore deposits.

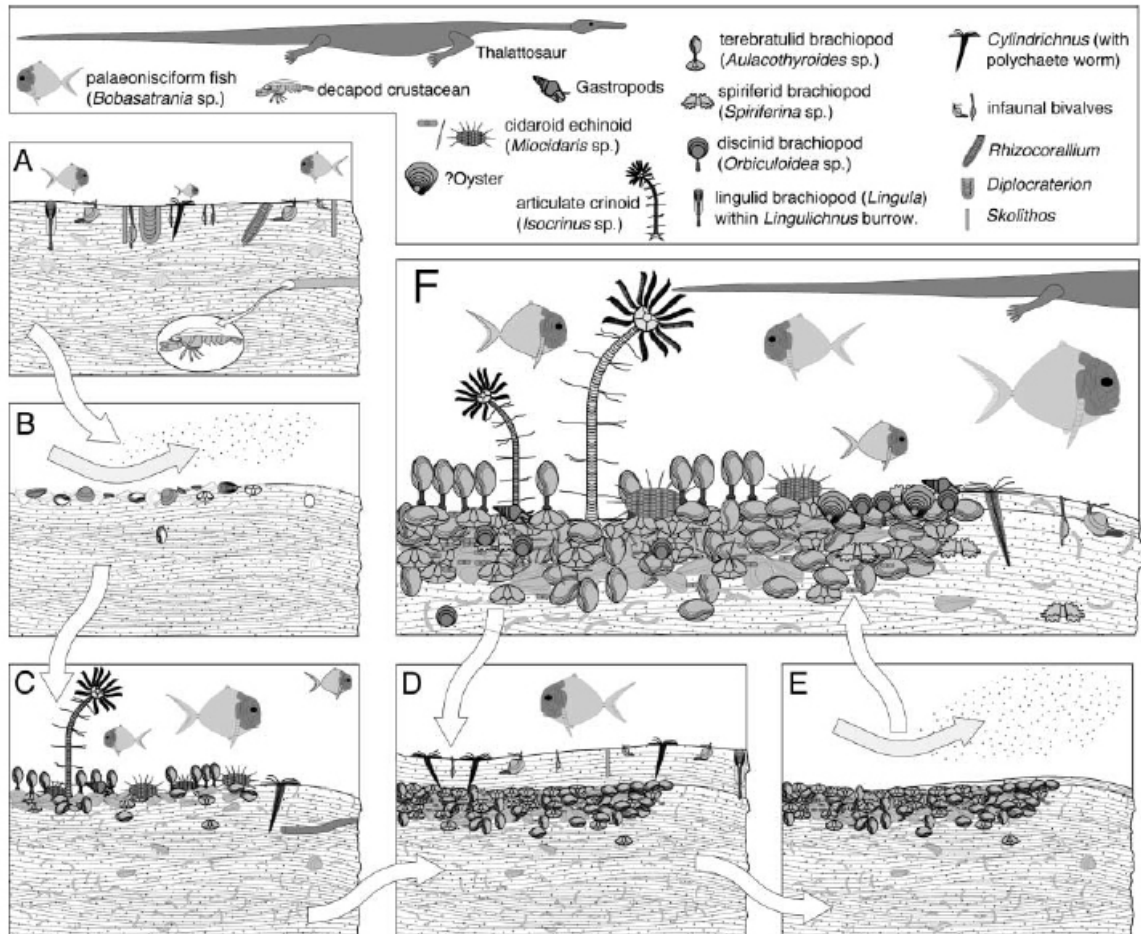
4.5 BIOSTROME FORMATION

In general, biostromes need a hard substrate to anchor onto and as such are known to form on substrates such as rocky shorefaces and marine hardgrounds. In the absence of these environments, shell detritus near or at the sediment water interface can provide a stable enough substrate for colonization (Driscoll and Brandon 1973; Kidwell and Jablonski, 1983). Zonneveld (2001) in his study of Liard Formation biostromes theorized that biostromes within the Middle Triassic were formed by epizoan larvae attaching to and colonizing semi-stable storm-generated bioclastic lags.

The Middle Triassic of the Western Canada Sedimentary Basin has long been known to contain bioclastic lag deposits (Willis, 1992; Caplan and Moslow, 1997; Zonneveld, 1999). These lags are caused by storm generated currents which carry coarser grained sediment and bioclastic debris out into deeper portions of the shoreface and deposit them as the storm passes. Biostromes documented in this study appear to have colonized off of such a lag deposit as directly above is the first appearance of terebratulid brachiopods. These terebratulids become more abundant upwards and appear to colonize on top of each other, and thrive with time. This pattern seems to repeat itself multiple times over the course of the interval. The development and growth of a biostrome is summarized in figure 4.02 and well documented in Zonneveld (2001).

4.6 PALEONTOLOGY OF DOIG FORMATION BIOSTROMES

Unlike the great diversity seen in biostromes from Middle Triassic outcrop by Zonneveld (2001), biostromes from the Doig Formation appear to be composed predominantly of articulate and inarticulate brachiopods, of which the most highly identified fossil (in percentages greater than 80%) are terebratulid brachiopods. Other



fossils are present within this interval but are too abraded for identification. In addition, the current available dataset of known biostrome core may be too narrow to have accurately displayed all possible species.

4.7 TEREBRATULID BRACHIOPODS

Terebratulid brachiopods are the most abundant fossil found within the biostromes of the upper Doig Formation. These brachiopods were initially classified as ‘Terebratula’ Liardensis in outcrop by Whiteaves (1898), and are referred to by Sandy (1996) as *Aulacothyroides liardensis*. Specimens seen in the Liard Formation outcrop are classified by Zonneveld (2001) as *Aulacothyroides liardensis* (*A. liardensis*). Terebratulid brachiopods found within the Doig Formation subsurface appear to also be classified as such by visual comparison.

Within the discovered biostrome interval, *A. liardensis* appear to range in size from 1-2 cm in length and form an elongate oval when cut in a cross-section. Terebratulids brachiopods found in the Halfway Formation subsurface are slightly smaller than Middle Triassic terebratulids brachiopods found in the Liard outcrop, where Zonneveld (2001) has documented them to range approximately 1.5 cm to 3 cm in length. It was hypothesized by Zonneveld (2001) that size variations within terebratulids brachiopods are the result of local environmental stresses and are not taxonomically significant. Many terebratulids found within the Biostrome interval contain a preserved geopetal structure (Figure 4.03) which displays that they are in growth position and indicates a lack of major transportation activity.

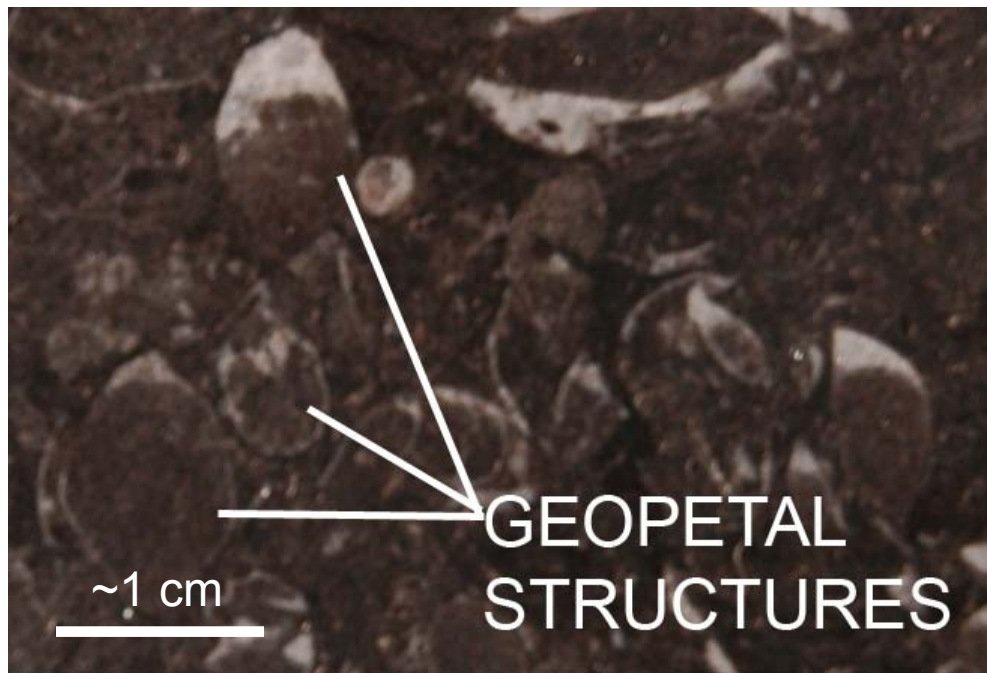


Figure 4.03 – Geopetal structures seen infilling Terebratulid brachiopod's located within biostrome deposit. Well 14-5-71-9W6, 2447.6 m.

4.8 BIOSTROME LITHOFACIES

The Middle Triassic biostrome discovered during this study occurs in the upper Doig Formation (parasequence three) directly below a marine flooding surface that defines the boundary between the Doig Formation and the Halfway Formation. This Doig Formation parasequence number three consists of laminated shale, fine grained siltstone, and fine grained laminated sandstone and has been classified as deposits of facies association A (distal prograding shoreface) as covered in chapter 2 of this study. Biostrome deposits described in this study were grouped into three major lithofacies and assigned a depositional environment based on their comparison to facies seen in the outcrop study by Zonneveld (2001). These lithofacies are simply classified as BF1 (biostrome flank), BF2 (biostrome core), and BF 3 (bioclastic lag) and described in detail in table 3.

Table 3 – Lithofacies descriptions and interpretations of three biostrome facies seen in this study.

Litho-facies #	Description	Bioclastic Component	Depositional Environment
BF 1	Fine grained sandstone, well sorted, no visible structures (bioturbated?), moderate abundance of bioclasts, fine grained sandstone matrix in biostrome (Figure 4.04)	20-30 % bioclastic component, whole unabridged terebratulid brachiopods, some fragmented bioclastic debris	Biostrome flank within lower shoreface environment (mix of insitu growth and transported clasts) (Zonneveld, 2001)
BF 2	Fine grained sandstone, poorly sorted, Terebratulid brachiopod grainstone present, no visible structures, geopetal structures visible in shell material (Figure 4.05)	40-80% bioclastic component, predominantly terebratulid brachiopods. Visible geopetals. No obvious abraided shell material	Closer to biostrome centre, bioclastic material formed in situ, clastic sediment brought in during storms (Zonneveld, 2001)
BF 3	Fine grained siltstone mixed with a medium grained bioclastic sandstone, moderate sorting, graded bedding?, thin interbeds of vf sandstone. Small rounded clasts of chert (Figure 4.06)	30% bioclastic component, high abundance of abraided shell material less than 2mm in diameter. Very few, if any, whole unabridged shells.	Tempestite storm bed. Biostrome lag. Storm bring in abraided shell material and clastic sediment from higher up in the shoreface, biostrome colonizes upon lag deposit.

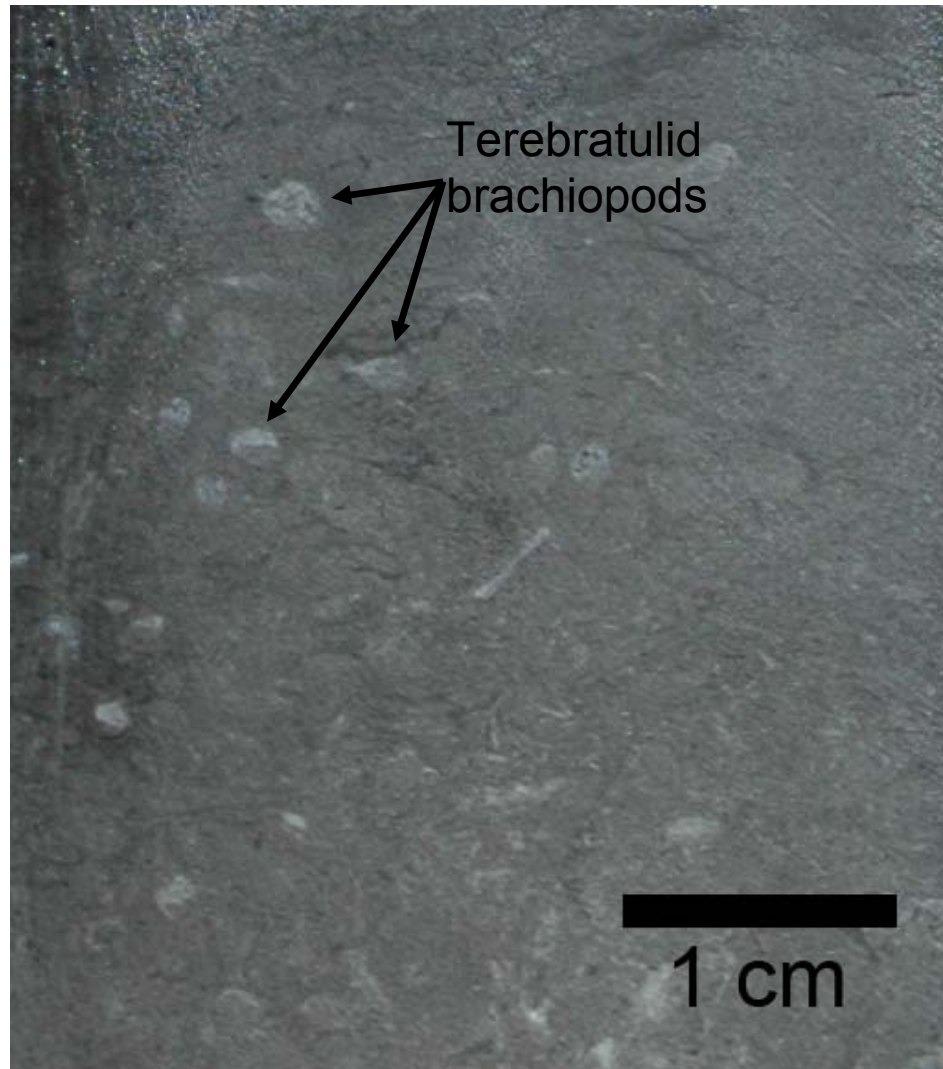


Figure 4.04 – BF1 - Lesser amounts of Terebratulid brachiopods (compared to figure 4.04) situated within fine grained sandstone, this deposit is interpreted to be on flank of a biostrome. Well 14-5-71-9W6. Depth 2447 m.

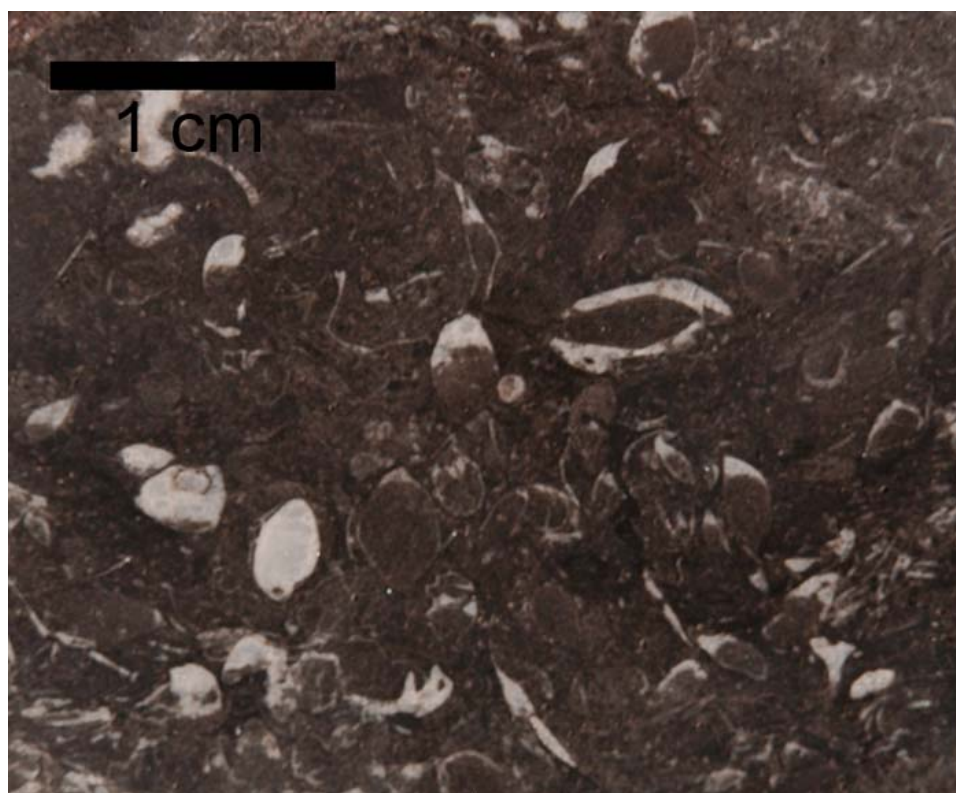


Figure 4.05 – BF2 - Abundance of Terebratulid brachiopods situated within interpreted biostromes centre. No evidence of abraded shell material. Well 14-5-71-9W6. Depth 2447.6 m.

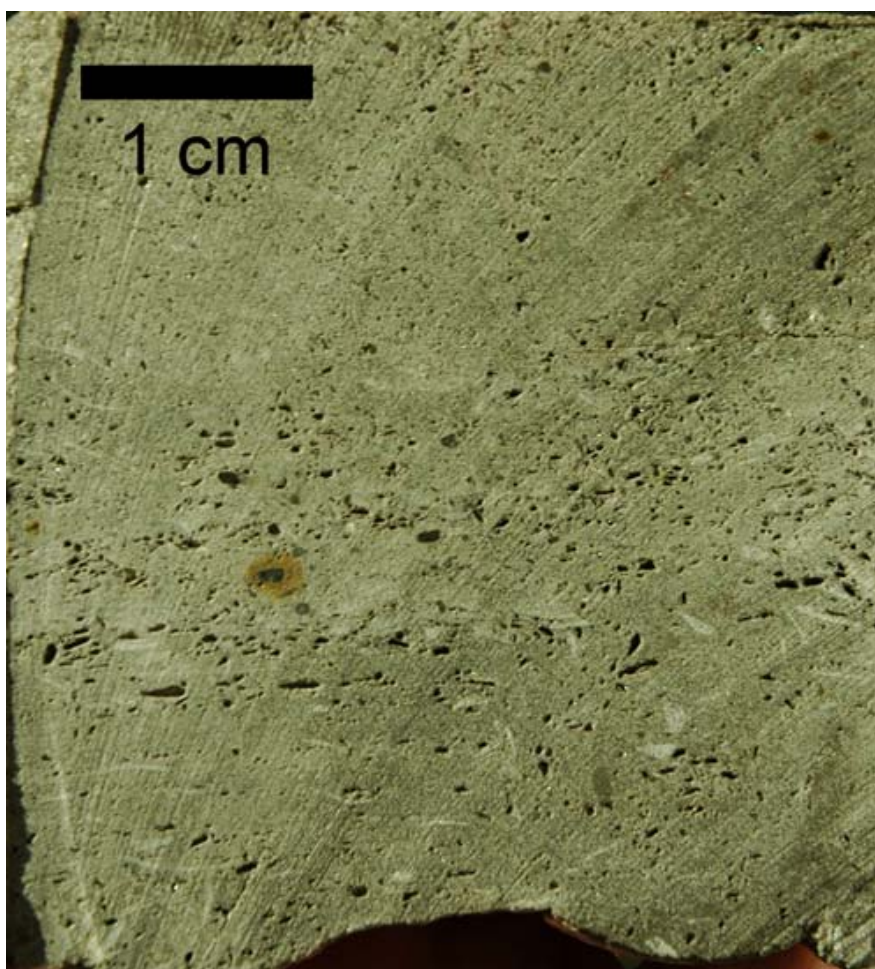


Figure 4.06 – BF3 - Lag deposit consisting of abraded shell debris and lithics including rounded chert clasts situated at base of a biostromes bed. Well 14-5-71-9W6. Depth 2447.4 m.

4.9 BIOSTROME WELL LOCATIONS

During the course of this study three wells were discovered that contained interpreted Doig Formation lower shoreface biostrome deposits. These wells include 6-22-72-11W6, 7-29-71-10W6, and 14-5-71-9W6 and are displayed in a cross-section oriented along strike of paleo-shoreline in figure 4.07. This cross-section uses the first anhydrite appearance of the Halfway-Charlie Lake Formation contact as a stratigraphic datum. The biostrome interval is highlighted in grey and is correlated across all three wells. Noticeable at the top of the biostrome interval, is a sharp increase in radioactivity of the gamma log representing a rapid change from fine grained sandstone into black laminated shale. This contact is a marine flooding surface and is also the bounding flooding surface between parasequence three, the Doig Formation, and parasequence four, the Halfway Formation. The individual wells and their biostrome interval are each discussed below.

14-5-71-9W6

Being the well furthest southeast on the cross-section 14-5-71-9W6 is the highest up-dip. The biostrome discovered in this well is located between the depths of 2447-2451 metres (Figure 4.08). The cored Doig Formation interval of this well runs through the upper shoreface of the Halfway Formation and down into the lower shoreface and offshore deposits of the Doig Formation. Of the three wells discovered, 14-5-71-9W6 contains the largest accumulation of shell material with bioclastic percentages in excess of 70%. The biostrome within this well contains all three interpreted biostrome facies and contains the most complete biostrome interval of the three wells discovered.

7-29-71-10W6

The biostrome discovered in 7-29-71-10W6 is located between the depths of 2556-2559 metres. The cored Doig interval within this well penetrates just the uppermost 30 centimetres of the biostrome, and as such, only a small portion of the biostrome interval is visible. The biostrome in this well contains an abundance of non-abraded

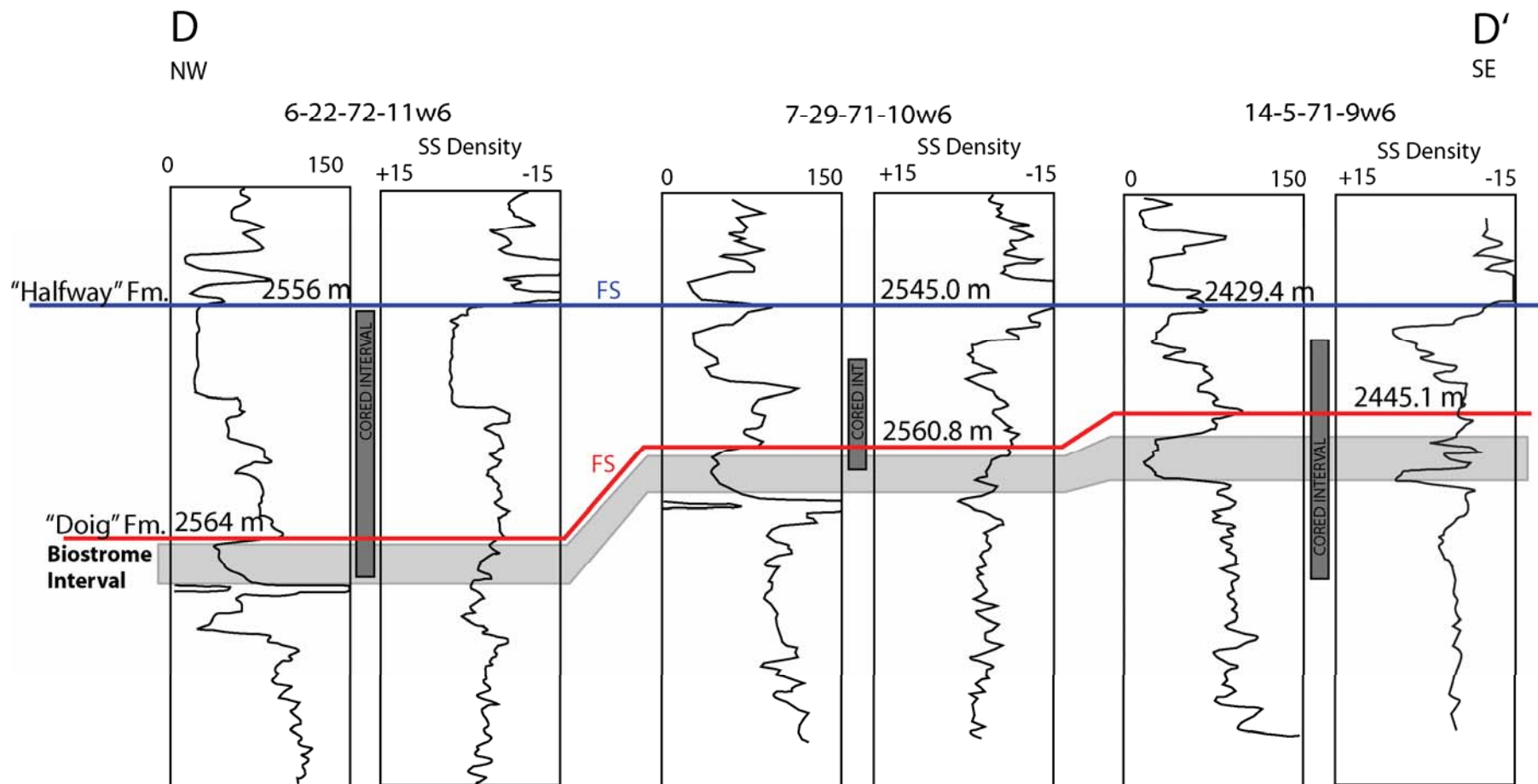


Figure 4.07 – Stratigraphic cross-section D-D' displaying cored wells displaying the discovered Doig Formation Biostrome interval (grey shading). Datum is the first anhydrite bed (continental equivalent of flooding surface) of the Charlie Lake Formation.

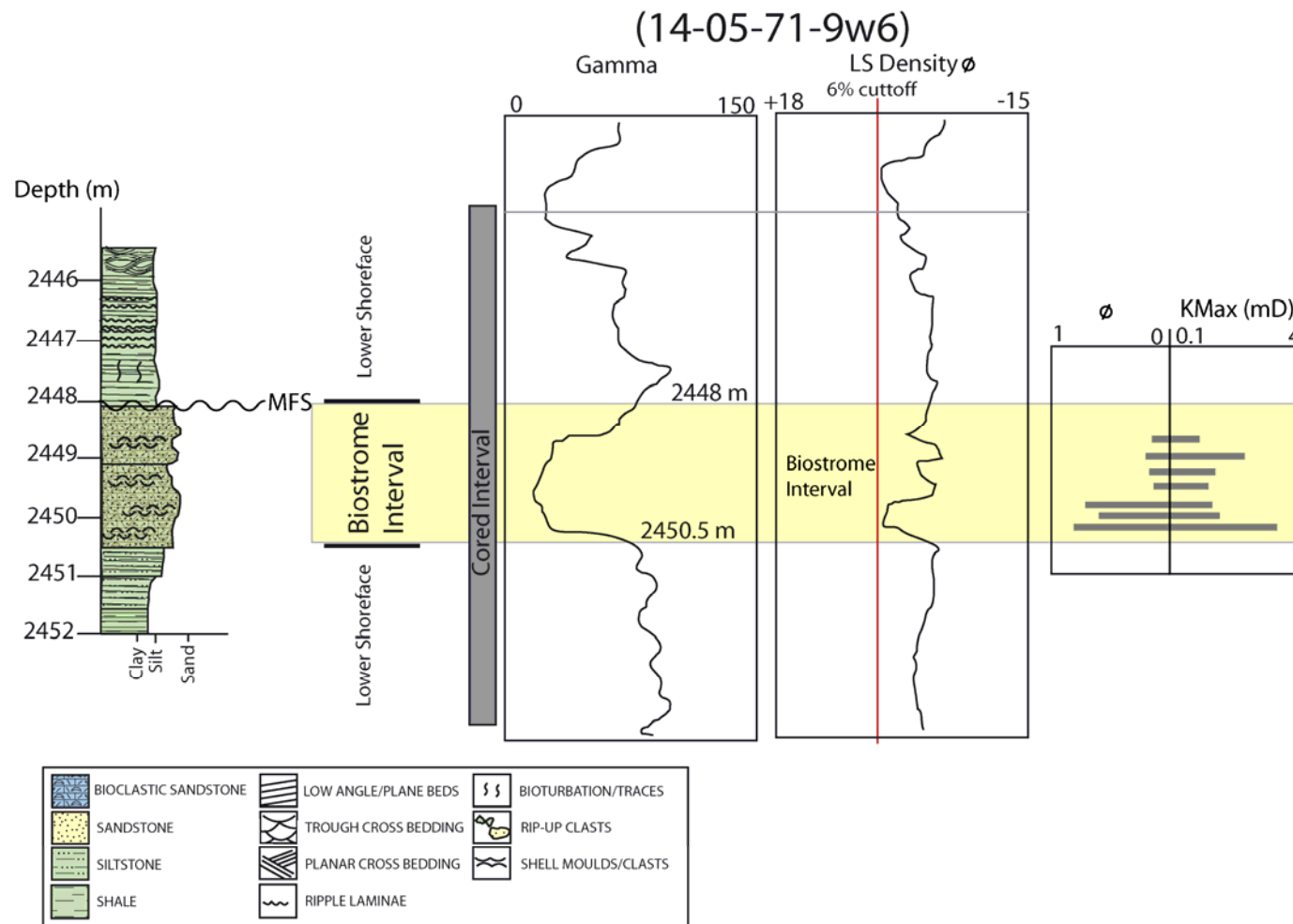


Figure 4.08 – Vertical sedimentary profile of well 14-05-71-9W6 displaying properties of the discovered biostrome interval (highlighted in yellow). Included are a gamma log profile, limestone density profile, and the results of core analysis performed over the biostrome interval.

terebratulids as well as larger articulated brachiopods within fine grained sandstone (Figure 4.09).

6-22-72-11W6

6-22-72-11W6 is the furthest northwest well on the cross-section and is the lowest well down-dip. The biostrome interval in this well is located between the depths of 2576-2579 metres. The cored interval of this well runs through interpreted upper shoreface deposits of the Halfway Formation down into the hummocky cross-stratified lower shoreface deposits of the Doig Formation. The biostrome interval consists of fine grained sandstone and contains visible terebratulid brachiopod shells. Shell material seen in this interval appears to exist in linear horizontal beds interbedded between fine grained sandy-siltstone beds. This interbedded nature has lead to the interpretation that periodically colonization by organisms was “drowned” by the deposition of sediment, effectively halting biostrome growth. A decrease in the overall abundance of shell material is observed, in comparison to well 14-5-71-9W6, with an estimated maximum bioclastic percentage of less than 50%. The interbedded nature of these terebratulid beds also leads to the conclusion that this well was possibly located near the flank of a biostrome deposit and shells in this core were only living during high periods of biostrome colonization.



Figure 4.09 – Bedding plane view of small Terebratulid brachiopods and larger brachiopods within interpreted lower shoreface sandstone. Well 7-29-71-10W6. Depth 2561 m.

4.10 FUTURE BIOSTROME EXPLORATION AND PRODUCTION

The fine grained nature of biostrome deposits seen within the Doig Formation at first appear to be lacking in reservoir potential, but, if the ideal diagenetic conditions dissolve the abundant shell material these biostromes have the potential to make very effective reservoirs. The high percentage of aragonite from shell material within these deposits is enough that significant biomoldic porosity can be created - although no significant biomoldic biostrome porosity is visible within cored study area intervals.

It is important to note that a well does exist along this shoreface trend which appears to be producing from this biostrome interval. Well 3-5-72-9W6 is an active gas producer drilled in 2002 and has produced over 2.2 Bfc of gas as of September 2008. Unfortunately the interpreted biostrome interval located at a depth of 2417 metres within this well is not cored, but an analysis of the drill cuttings displays fine grained sandstone and bioclastic deposit, which lead to the belief that this interval could very well be a biostrome.

Further work analyzing and mapping the distribution of biostrome deposits within the Doig and Halfway formations needs to be performed in order to more accurately interpret the reservoir potential of these biostromes. Previous interpretations of shell rich deposits within the Doig and Halfway formations as tidal inlet channel fill may in fact be incorrect. Upon discovering a shell rich deposit in the Middle Triassic care careful attention should be considered as to the bounding facies of the interval. If the bounding deposits are interpreted as shoreface in origin, and whole unabraded shells are present, the deposits may very well be a biostrome.

CHAPTER FIVE: STUDY CONCLUSIONS

5.1 CONCLUSIONS

- 1) Four distinct coarsening upward parasequences have been identified within the Elmworth and Wapiti fields. These four parasequences have been designated parasequence 1 to 4 upwards in the vertical succession and are bounded by five marine flooding surfaces. Within the study area these parasequences represent a relatively conformable shallowing-upward succession of westward clinoforming progradational parasequence sets deposited during a period of relative sea level regression.

- 2) It has been shown that these four parasequences within the Elmworth-Wapiti fields are genetically related in terms of depositional environment. Lithographic correlations of formations should be disregarded as similar lithologies occur throughout the study in different parasequences. Instead a sequence stratigraphic framework should be applied to accurately map depositional facies relationships within the Middle Triassic strata of the Western Canada Sedimentary Basin. The “Halfway” Formation within this study has been assigned to belong to the uppermost parasequence of marine sandstone

origin, with underlying parasequences belonging to the “Doig” Formation, regardless of lithology.

3) Paleo-shoreline during the deposition of the Halfway Formation within the Elmworth and Wapiti fields trended in a north-west to south-east direction. During the study this became apparent as individual parasequences of the Doig and Halfway Formation were mapped and correlated.

4) Ten lithofacies were identified as part of this study. These lithofacies range in depositional environment from offshore marine all the way to arid continental with a wide range of deposits in between, including shoreface and tidal inlet channel fill. These lithofacies were then grouped together based on regularly recurring genetic components into facies associations. These facies associations consist of the deposits of; A) distal prograding shoreface, B) proximal prograding shoreface, C) tidal inlet channel, D) supratidal sabkha, and E) shoreface biostrome.

5) The most significant contribution of this study is the documentation of evidence supporting tectonic controls on the deposition and preservation of the Halfway Formation. Sequence stratigraphic correlations of the Doig and Halfway formations within the Elmworth and Wapiti field are greatly hindered by anomalous thickness variations with the uppermost Middle Triassic parasequences and the absence of significant marine flooding surfaces in select wells. This study has proposed a tectonic component of localized shoreface uplift to explain these anomalies and has disregarded a widespread eustatic sea level drop or forced regression as the answer due to the non-regional extent of the anomalies. Wells that display thin intervals of Halfway Formation contain an erosional marine firmground surface and are interpreted to have undergone a certain amount of uplift (uplift amount = “x”) forcing deposited sediments into the erosional wave base thereby removing them and re-depositing them elsewhere. Wells that contain an “over-thickened” interval of the Halfway Formation are interpreted to have undergone a greater amount of uplift (uplift amount > “x”) eroding through the marine flooding surface dividing the shoreface sandstone of parasequence number 3 and

merging them with the consequently re-deposited shoreface sandstone of parasequence number 4. During this process the marine flooding surface dividing the Doig Formation from the Halfway Formation was completely eroded away merging sandstones of parasequence 3 and 4 together into what appears to be one overly thick interval of parasequence 3 sandstone. The implications of the tectonic uplift and faulting described in this study can have a profound effect upon reservoir continuity and size and should be carefully considered during both exploration and development phases within these fields.

6) Significant amounts of seismite sedimentary structures were observed within the study area that suggests the Elsworth and Wapiti fields were the subject of tectonic activity during or shortly after deposition of the “Halfway” Formation (parasequence number 4). These structures include soft sediment deformation, sediment injectites, vertical fractures several metres in extent within lithified sediments, and an abundance of erosional and marine firmground surfaces presenting *Glossifungites* ichnofacies assemblages. Marine firmground surfaces are observed within the Halfway Formation, but only within wells that contain a thinner the normal interval of Halfway Formation shoreface sandstone.

7) The presence of previously undocumented shoreface biostromes were discovered to exist with the Elsworth field. Middle Triassic shoreface biostromes were, prior to this study, only documented in outcrop near Williston Lake, British Columbia, but are now seen to exist within the economically significant subsurface of the Western Canada Sedimentary Basin. These biostromes consist primarily of Terebratulid brachiopods and contain evidence of in-situ growth such as a lack of abrasion and consistent geopetal fill. Under the correct diagenetic conditions these biostromes would make effective hydrocarbon reservoirs. Although no core is available to confirm well 3-5-72-9W6 appears to be producing out of a biostromes horizon. Biostromes in this study appear to be less diverse than those seen in the Liard Formation documented by Zonneveld (2001) although that could be a product of the limited dataset available to this study. Both biostromes are dominated by terebratulid brachiopods which make up more than an estimated 70% of the bioclastic component of each.

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