Petrography, Lithology, Stratigraphy, Bioturbation, and Trace Fossil-permeability Relationship of the Montney Formation of Lower Triassic, in Barrick Puskwa, Alberta, Western Canadian Sedimentary Basin

by

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ABSTRACT

In North Eastern British Columbia (NESB), the Montney Formation has been recognized as a world class tight gas reservoir. As previous work has shown, the Lower Triassic Montney Formation is a complicated succession of siltstone, sandstone, and bioclastic packstone/grainstone. The Montney Formation from three drill-cores have been examined and classified based on sedimentological and ichnological characteristics. By employing spot-minipermeametry methods, the influence of sedimentary fabric on reservoir properties is assessed. The sedimentary environments are interpreted as offshore to shoreface sedimentary conditions and perhaps rive influence shoreface environments. Results from core analysis and permeability and porosity testing demonstrate that grain size is the main impact factor and intergranular pore is the main type of pore for these facies; otherwise, the distribution of pore is disturbed by burrows.

PREFACE

This thesis is an original work by Shimeng Zhang. No part of this thesis has been previously published.

DEDICATION

This thesis is dedicated to my parents, Wei Zhang and Furong Chang. My studies would not have been finished without your endless love, support and encouragement. You are the most generous and kind people I know. Thank you for being there whenever I needed it. Thank you for teaching me respect, confidence, and proper etiquette. Thank you for letting me find my own way. You are my inspiration, and I love you forever.

Finally, this thesis is dedicated to all those who believe in the richness of learning.

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Besides my supervisor, I would like to thank the rest of my thesis committee, Dr. S. George Pemberton and Dr. John-Paul Zonneveld. The first geology class I ever took as a graduate was with George Pemberton. George, you are an absolute inspiration. You have taught me so much about earth science, geology, scientific method, and ichnology. To be honest, you are an amazing role model and I always look up to you. I would never forget the interesting stories that you shared with us during Ichnology course. Your passion of geology has inspired me and will stay with me forever. One day I hope to follow your footsteps that make contributions to studies of geology. Thank you to John-Paul Zonneveld for providing a helping hand when I needed. I am grateful for all of the support and help that you instilled in me. I hope that we can continue to have more geological talks.

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I am extremely lucky to have a great group of friends, who always keep me entertained with both geology and social related topics.

Last but not the least, I would like to thank my family, who have always support me, especially my parents: Wei Zhang and Furong Chang. You gave birth to me at the first place and support me spiritually throughout my life. You have always been my biggest fan. Your support, encouragement, quiet patience and love are always around me.

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LIST OF SYMBOLS AND ABBREVIATIONS

ICHNOFOSSILS

Ar	Arenicolites	Pa	Palaeophycus
As	Asterosoma	Ph	Phycosiphon
Cy	Cylindrichnus	Pl	Planolites
Di	Diplocraterion	Rh	Rhizocorallium
fu	Fugichnis	Sk	Skolithos
Hm	Helminthopsis	Te	Teichichnus

ICHNOFOSSISL OCCURRENCE

A	Abundant
C	Common
M	Moderate
R	Rare
VR	Very Rare

BIOTURBATION INDEX (BI)

Bioturbation index classification was proposed by Reineck (1963), and was modified by Droser & Bottjer (1986), and Taylor & Goldring (1993).

BI	Reworked	Classification
0	0%	no bioturbation recorded all original sedimentary structures preserved
1	1-10%	discrete, isolated trace fossils up to 10% of original bedding disturbed
2	10-40%	approximately 10-40% of original bedding disturbed burrows are generally isolated, but locally overlap
3	41-60%	last vestiges of bedding discernable burrows overlap and are not always well defined
4	61-90%	bedding is completely disturbed burrows are still discrete in places and fabric is not mixed
5	91-99%	bedding is nearly or totally homogenized burrows are recognizable and well defined
6	100%	original bedding is fully disturbed

CHAPTER II & III ABBREVIATIONS

F1	Facies 1
F2A	Facies 2A
F2B	Facies 2B
F3A	Facies 3A
F3B	Facies 3B
F3C	Facies 3C
F4A	Facies 4A
F4B	Facies 4B
F4C	Facies 4C
F5A	Facies 5A
F5B	Facies 5B

FA 1	Facies Association 1
FA 2	Facies Association 2
PC 1	Permeability Classification 1
PC2	Permeability Classification 2
PC3	Permeability Classification 3

This thesis follows a paper format. Several chapters are classified to state. Regarding to ease reading, a short summary of each chapter is present below.

CHAPTER I provides an introduction to the thesis research, including a general summary of fine-grained, low-permeability unconventional reservoir systems, the aim and objective of this thesis, and some previous work.

CHAPTER II presents a facies classification in the Montney Formation based upon physical sedimentary structures and ichnological characteristics.

CHAPTER III presents the result of permeability within each facies. Spot-minipermeametry is applied to evaluate the effect of permeability enhancement.

CHAPTER IV provides a detailed summary of Chapter II and Chapter III and give the conclusion of research findings.

CHAPTER I — INTRODUCTION

Background

Recently, the energy industry has experienced a major shift in exploration paradigms. Conventional reservoirs are considered to be those that can be developed at economic flow rates and will produce economic volumes of oil and gas without any special recovery process. Over the past 40 years, the volumes of oil resources classified as discoveries have exhibited a downward trend. Due to the declining production rates of conventional reservoirs, unconventional hydrocarbon reservoirs now produce significant volumes of oil and gas (Naik, 2003). Unconventional reservoirs occur in large volumes, although they are difficult to identify and develop either due to poor reservoir quality or unique gas storage and flow characteristics (Newsham & Rushing, 2001; Naik, 2003). In order to meet the increasing energy needs for the industrialized world, technical and engineering advances are now empowering companies to recover unconventional reservoirs economically. Although recent production rates of conventional reservoir gas will be sufficient for the next sixty years (Odedra et al., 2005), unconventional petroleum systems will make huge contributions in future.

The difference between conventional and unconventional resources is economic factors in North America during the 1970's. In the early 1970's, marginal energy resources, such as tight gas, coal bed methane, and shale gas, were regarded as unconventional resources with low economic potential were not considered as resources by most petroleum geologist. However, in the end of 1970's, with advances in industry and technology, these marginal resources were recognized to have economical potential and many petroleum companies now prefer to these unconventional resources due to their large potential reservoirs (Law and Curtis, 2002).

Unconventional reservoirs include tight gas, tight sand, coal bed methane, and shale gas. These resources provide potential for future growth and production (Newsham & Rushing, 2001; Naik, 2003). In the future, unconventional systems will be needed to supplement large volumes of oil and gas demand in industrialized markets. North America and Europe have already exploited more than 50% of their estimated conventional gas reserves (Odedra et al., 2005). In the United States, more than a quarter of the daily gas production is currently derived from unconventional gas reservoirs (Law and Curtis, 2002). Numerous unconventional gas reservoirs exist in fine-grained sandstone with low-permeability intervals. Analyses of tight reservoirs have led to an understanding of the pore-structure of some low permeability rocks, but it is difficult to generalize the pore-structure in tight unconventional reservoirs because varying degrees of diagenesis are recorded in those reservoirs (Chalmers et al., 2012). Hence an integration of different methods (e.g. core analysis, petrographic analysis, and spot-permeametry) for the characterization of these tight reservoirs provides insight into sedimentary rocks identified in this study and allows for the accurate characterization of the controls on reservoir quality. With the development of unconventional petroleum plays, geoscientists must continually review and modify their consideration and understanding of the low permeability of tight gas reservoirs. Correct identification of unconventional reservoir properties influences the use of appropriate assessment methodology and the derivation of reserve estimates.

There is significant potential for shale gas production in various regions of Canada, including traditional areas of conventional production like Alberta, British Columbia, and

Saskatchewan, and non-traditional areas like Quebec, Nova Scotia, and New Brunswick (Johnson et al., 2009). This study focuses on the Lower Triassic Montney Formation in Barrick Puskwa, Alberta, the Western Canadian Sedimentary Basin, as an unconventional reservoir for gas. Understanding oil and gas production from low permeability rocks requires assessing petrophysical and lithological facies association, porosities and permeability in reservoir conditions. The Montney Formation, a hybrid between a tight gas and shale gas, plays found in northeastern British Columbia and west-central Alberta, Canada. The very fine-grained sand of the Montney Formation has low to moderate permeability. Detailed analyses of physical and biogenic sedimentary structures have revealed that bioturbation plays an integral role for natural reservoir quality in the Montney Formation (Zonneveld and Gingras, 2012). The research indicated that Montney Formation primarily consists of siltstone and very fine-grained sandstone. Petrography result, associated with variable distribution of porosity and permeability showed that bioturbation played an integral role in reservoir qualities in the Montney Formation.

Generally, shallow, low permeability, tight gas-charged formations (e.g. the Montney Formation) comprised intervals of bioturbated rock fabrics (Dutton et al., 1993). Bioturbation has commonly been considered detrimental to the storativity and permeability of reservoirs. However, not all bioturbation is destructive and there are several examples where bioturbation-enhanced permeability has shown permeability enhancement as a resulted of biogenic processes (e.g., Dawson, 1978; Gunatilaka et al., 1987; Zenger, 1992; Gingras et al., 1999; 2004a, b; Mehrthens and Selleck, 2002; McKinley et al., 2004; Sutton et al., 2004; Pemberton and Gingras, 2005; Gingras et al., 2007; Cunningham et al., 2009). These studies show that bioturbation may contribute to the storativity and provide flow conduits for oil and gas. Although many examples have been suggested that permeability can be enhanced as a result of bioturbation, more research is needed to improve the understanding of the concept.

Objective

This thesis integrates sedimentology and ichnology to interpret the depositional environments of Montney Formation in Barrick Puskwa, Alberta, the Western Canadian Sedimentary Basin. Sedimentological and ichnological characteristics are used to classify the Montney Formation into five facies and two facies associations are defined. The facies association promotes understanding characteristics of the depositional settings, and also helps in the recognition of similar environments elsewhere. Additionally, permeability testing of each facies was conducted using spot-minipermeametry. The results of permeability data are integrated with the sedimentological and ichnological characteristics in order to assess the sedimentary fabric for unconventional reservoir properties.

The objective of this study is threefold: 1) to present a petrographic-lithologic facies for the Montney Formation; 2) to quantify the changes of permeability caused by sedimentary fabric within the various facies; 3) interpret the link among petrographic-lithologic facies, bioturbation, and reservoir properties.

CHAPTER II— SEDIMENTOLOGY AND ICHNOLOGY OF MONTNEY FORMATION OF LOWER TRIASSIC, IN BARRICK PUSKWA, ALBERTA

INTRODUCTION

The facies concept originally derived from analysis of the Jurassic of the Jura Mountains in Switzerland by Amanz Gressly (1838). The term facies is the sum of lithological and paleontological aspects of a stratigraphic unit with specific biogenic characteristics. Diverse definitions of facies can be used depending upon the scale of a study and research data. Lithofacies is identified based mostly on lithology and physical structures, whereas biofacies is distinguished by organic or paleotologic content. Generally, facies identification should be useful for paleo-environment interpretation and consistent with Walther's Law.

Facies identification integrates lithology, sedimentary structures, and ichnology. Sedimentary structures are generally considered as the most critical ways of interpreting sedimentary and post-depositional processes. Recognition and application of sedimentary structures are commonly considered as the key to defining depositional environments, geological history, and surface processes. Compared with importance of sedimentary structures, organisms and trace fossils are more sensitive to interpret the depositional environments (Pemberton et al., 1992a, 2001). Trace fossils play an important role in environment interpretation, the most important being: they can give specific information about the depositional rates and the presence of hiatuses in a sedimentary succession (Gruszczyński et al., 2008); they can provide information on re-inhabitation of a previous environment (Benner et al., 2009). Trace fossils often supply evidence of sedimentological conditions that is superior to information gained only by the study of physical structures. Organisms burrowing alter the characteristics of sedimentary structures, resulting in differential permeabilities and porosities between the burrow and surrounding matrix (Meadow and Tait, 1989; Lee and Foster, 1991; Pierret et al., 1999, 2002; Gingras et al., 2002a, b; Bastardie et al., 2003). Since trace fossils alter the characteristics of sedimentary structures for porous media, they may provide flow conduits for the migration and production of oil and gas (Gingras et al., 2004a; Pemberton and Gingras, 2005; Lemiski et al., 2011)

The Lower Triassic Montney Formation, a significant hydrocarbon unit in Western Canada, hosts numerous unconventional gas and oil reservoirs in Alberta and to a lesser extent in British Columbia (Zonneveld, et al., 2010). Since the 1950s the first Montney Formation has been a primary conventional reservoir. In west central Alberta and north-east British Columbia, the Montney Formation conventional production is provided from two distinguishable plays; firstly, production occurs in shallow water sandstone and bioclastic grainstone/packstone succession in the “Montney Subcrop South” play; secondly, production comes from deep water turbidite sandstone units in the “Montney Distal Shelf” play (Bird et al., 1994). At all events, siltstone rich successions of the Montney Formation in north-east British Columbia are regarded as high exploration potential reservoir (Bird et al., 1994; Young et al., 1995).

The purpose of this study is to present the sedimentological and ichnological characteristics and permeability measurements, in order to develop the environmental interpretation. The study is focused on the development of a petrographic framework for the Montney Formation in the regions of northwestern Alberta and northeastern British Columbia. Although abundant oil fields are developed in these regions, they still have huge potential for future exploration and exploitation (Bird et al., 1994). The detail of sedimentological and ichnological characteristics are collected from three wells, including Barrick Puskwa 14-33-73-26w5, 13-03-74-26w5, and 16-14-73-26w5.

GEOLOGIC DATASET

The Western Canadian Sedimentary Basin (WCSB) is a major area of deposition throughout the Phanerozoic. During Triassic, the WCSB faced the Panthalassa Ocean and was located on the northwestern margin of the Supercontinent Pangea (Davies, et al., 1997). Due to no major tectonic events during that time, the result was that deposits deformed of the accumulating sedimentary wedge in the adjacent continental-margin, extensional Triassic basin; and sedimentation was restricted in the WCSB to three tectonically controlled contiguous basins, namely the Peace River Basin, Continental Margin Basin, and the Liard Basin (Davies, et al., 1997).

The Montney Formation occurs in West Alberta and Northeastern British Columbia and is a significant hydrocarbon reservoir which is made up of mostly siliciclastic strata (Dixon, 2000; Zonneveld, et al., 2011). In North Eastern British Columbia (NEBC) the Triassic Montney Formation has been recognized as a world class shale gas reservoir, and provides a hydrocarbon source, reservoir and trap. Most of the early Triassic stratigraphic and paleontological studies undertaken in the Rocky Mountain Foothills of northeastern British Columbia were summarized by McLearn and Kindle (1950).

Along the eastern subcrop edge, the Montney Formation comprises shallow-water marine interbedded sandstone and shale interpreted as being either deltaic origin by Miall (1975), or inner shelf origin (Gibson and Barclay, 1989). Davies et al. (1997) suggested that the Montney was deposited on the western margin of the North American Craton with the thickest accumulation occurring in the vicinity of the collapsed Peace River Arch. Montney shale gas potential is being realized in two other zones: 1) the Lower Montney, in sandy, silty shale of the offshore transition and offshore-marine parts of the basin; and 2) the Upper Montney, below the shoreface (e.g. Barss et al., 1964; Davies et al., 1997).

The Montney Formation is separated by unconformity from the underlying Permian Belloy Formation (Gibson and Barclay, 1989). The Montney Formation is conformably to unconformably overlain by laterally change from the Middle Triassic Doig Phosphate Formation in the west to the "black shale/siltstone" of the Nordegg Member (Jurassic Fernie Formation) (Gibson and Edwards, 1990a, b) (Figure 2-1). The Montney Formation has the highest thickness in the Peace River Embayment, but gradually thin eastwards (Davies et al., 1997; Gibson and Edwards, 1990a, b; Gibson and Barclay, 1989).

The Montney Formation is a complicated succession that is dominated by siltstone and sandstone with shale, and bioclastic that is deposited in a wide variety of depositional environments, including inner shelf and offshore succession (turbidite channels and fan complexes), to lower and upper shoreface deltaic intervals and estuarine successions (Miall, 1975; Gibson and Barclay, 1989; Zonneveld et al., 2011). The depositional environments of Montney Formation were recognized as a mid-latitudinal setting in an arid environment west of an extensive, low gradient contintental interior; and owing to the aridity of the region, fine-grained clastic sediment dominates within all the Montney facies because of long transport distances of grains from the source (Zonneveld et al., 2011).

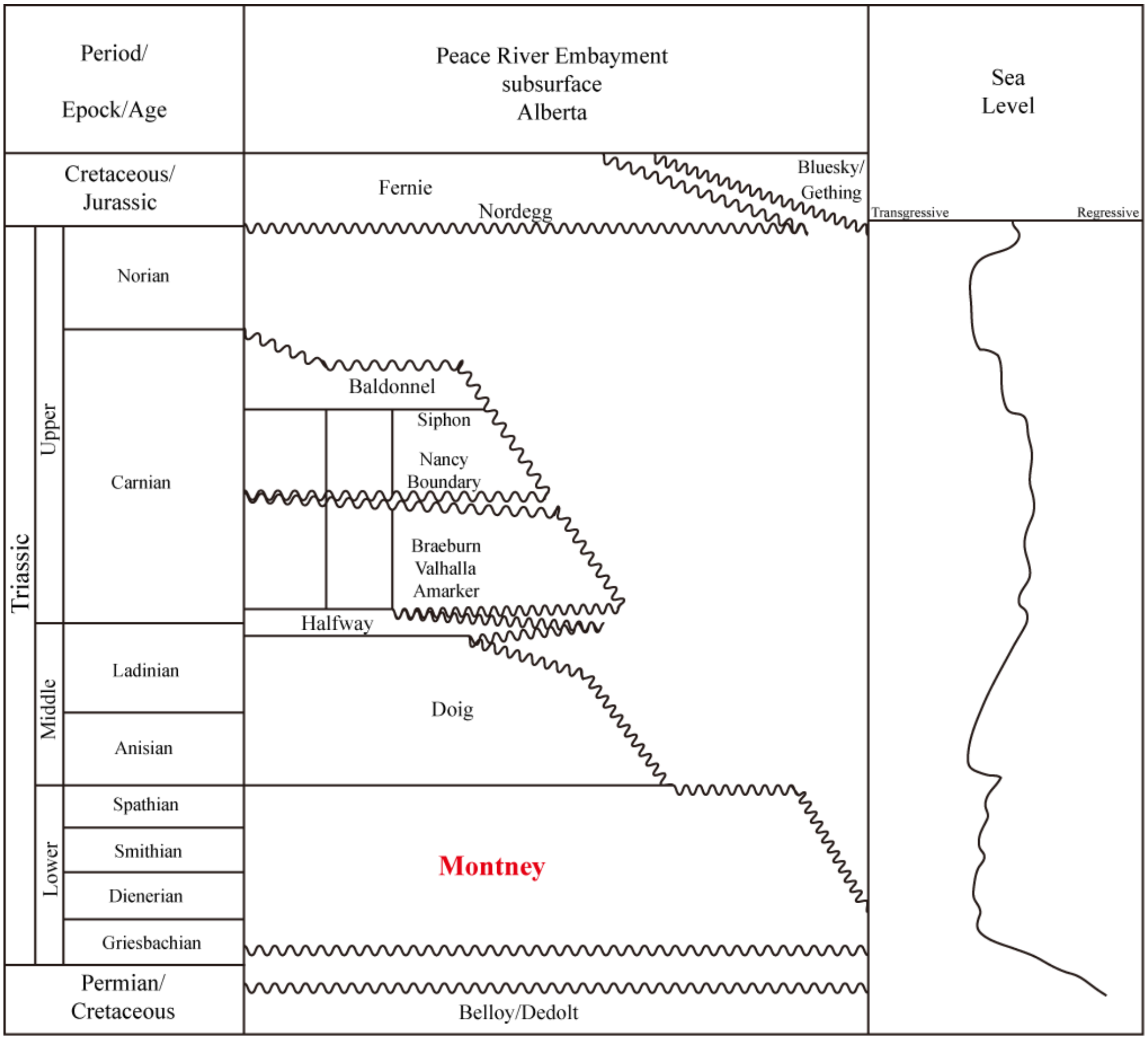


Figure 2-1: Stratigraphic chart showing Triassic and Cretaceous/Jurassic Formation in Peace River Embayment surface, Alberta., West Canada Sedimentary Basin.

Three cores (well 14-33-73-26w5, well 13-03-74-26w5, and well 16-14-73-26w5) were analyzed within this study and all are from the Puskwaskau Field, located near Grand Prairie (Fig.2-2). Detailed analyses were conducted on the cores to describe and interpret lithofacies and ichnofacies to better understand depositional environments.

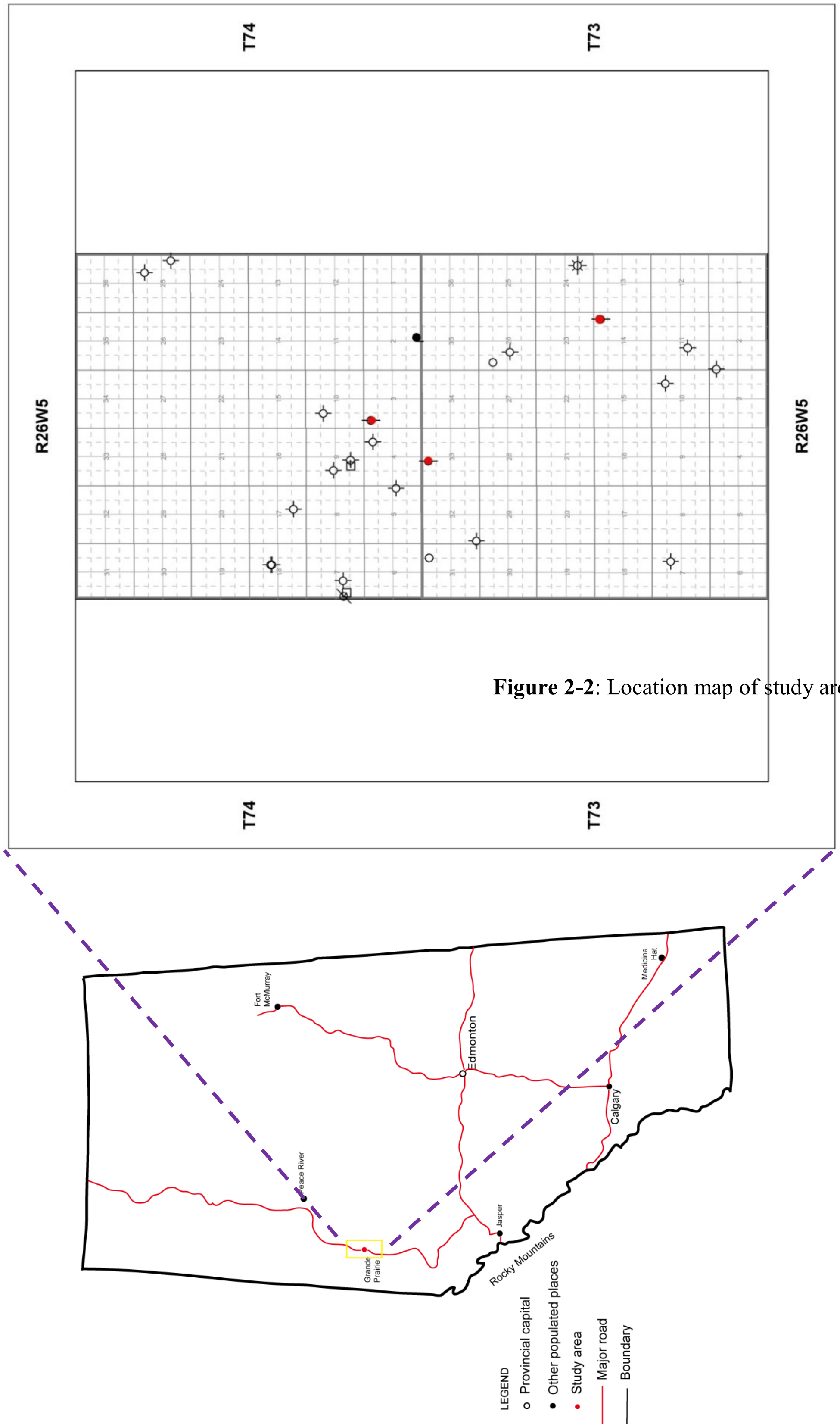


Figure 2-2: Location map of study area near Grand Prairie within three core

METHODS

All of the core logging data presented in this study were collected through the detailed sedimentological and ichnological characteristics of three cores from the entire Montney Formation, including well 14-33-73-26w5, well 13-03-74-26w5, and well 16-14-73-26w5 in the Puskwa Field which is located near Grand Prairie, Alberta. Core slabs were provided by Barrick Energy Inc. and were made available by AGAT laboratories. Cores provide assessment of the characteristics of the formation directly, and description and interpretation of lithofacies and ichnofacies.

Core analysis

Petrophysical logs along with conventional drilled core are used to collect the sedimentary, stratigraphic, and ichnological data from the Montney Formation. The details of facies analysis for Montney Formation depend on description of cores. Compared with conventional drill core which is used to interpret sedimentological, stratigraphic, and ichnological characteristics, petrophysical loggings can also establish facies correlation (Lemiski et al., 2011). Although lithofacies are similar in these three wells, the distribution of ichnofossils and the degree of bioturbation reveal a range of variety.

Core slabs were provided by Barrick Energy Inc. Cores provide assessment of the characteristics of the formation directly, and description and interpretation of lithofacies and ichnofacies. Analysis of cored intervals emphasized on description of color, grain-size, thickness, lithological characteristics, texture, depositional structures, stratification, lamination, characteristics of bedding, bedding contacts, soft sedimentary deformation structures, post-depositional features, and accessory minerals (e.g. pyrite). Except sedimentological features, ichnological data also make contributions to core analysis, including description of ichnotaxa, the size and distribution of ichnofossils, trace fossil assemblage, and the degree of bioturbation (bioturbation index). All bioturbation indices are used based on the classification documented by Droser and Bottjer (1986). Additionally, changes in grain-size are commonly subtle. A detailed summary of the facies classification scheme is revealed by a series of strip-logs in the Appendix, based upon sedimentological and ichnological observations.

Petrography

Eleven thin sections were prepared with thicknesses between 30-40μm which allows light to easily get transmitted through the slides, in order to microscopic analysis. Detailed thin-section analysis included the measurement of mean grain size, sorting, roundness, cementation, and point count determination of mineral abundances. The primary analysis of thin section is to determine the grain size of strata, characteristics reservoir properties (porosity), recognition of ichnofossils and cements, and observation of sedimentary structures at the micro-scale. Petrographic analysis was carried out using a Nikon Eclipse 50i POL Polarizing microscope at petrographic lab which is located in the Earth and Atmospheric Sciences building at University of Alberta. Plane-polarized and cross-polarized light were both used. These samples were studied mainly to investigate the rock texture and the petrophysical component. A summary of the thin sections observations is presented in Appendix.

Paleontological-Sedimentological Environment Setting

Based upon core logging analysis for the Lower Triassic Montney Formation, seven facies were identified. Facies were classified on the basis of lithology, physical sedimentary structures, bed contacts, and ichnologic characteristics. The designation of strata into lithofacies and the characterization of the stratigraphic intervals were used to interpret respective sedimentary environments. Sedimentological data include grain-size, lithology, thickness, color, sedimentary texture, depositional structures, stratification, lamination, characteristics of bedding, bedding contacts, soft sedimentary deformation structures, post-depositional features, and accessory minerals (e.g. pyrite). Ichnological data include bioturbation intensity, distribution, and identification of ichnospecies and ichnogenera. These sedimentological characteristics and their corresponding ichnological characteristics are summarized in Table 1. Physical sedimentary structures provide reliable information that can be related to sedimentary processes. The environmental factors (e.g., energy conditions, depositional rates, and oxygen content) have a strong influence on organism colonization and their behaviors (Ekdale et al., 1984; Pemberton et al., 1992a). The depositional environment is determined based on the lithology, bioturbation and the ichnofacies as well as sedimentary structures. All bioturbation indices are presented in Bioturbation Index Table.

Description	Sedimentologic Characteristics	Ichnologic Characteristics	Interpretation
Facies 1 (F1) Structureless Mudstone	● mudstone layers ● structureless or mm- to cm-scale interlamination ● very rare horizontal lamination ● rare fissile laminae	No trace fossils	● deposit by suspension fall-out below storm wave base or sheltered from storm processes; ● absence of trace fossils may be ascribed to rapid sedimentation or lowered dissolved oxygen contents
Facies 2 (F2)			
F2A Weakly Burrowed Silt/sandstone Interbedded with Silty Mudstone	● rare organic content ● 1-2 cm thickness silty mudstone ● normally graded ● planar parallel and low-angle parallel laminated with HCS/SCS ● seldom oscillated ripples and current ripples ● rare lenticular bedding and fluid mud bed ● loading casts are rare to locally common ● macro-porosity rate to common ● rare pyrite	● rare, sporadically distributed and diminutive ● high diversity, including: Pl, r-m; Cy, r; Ph, r; Hm, r; Di, r; Sk, r; Te, r; As, r; Rh, vr ● escape structures ● small size ● Cruziana Ichnofacies ● BI (bioturbation index) =1-2	● Bedding and sedimentary structures reflect wave reworking; ● Soft-sediment deformation at bedding contacts indicate episodic sedimentation; ● The presence of the Cruziana Ichnofacies is consistent with lower shoreface to inner shelf environments; ● Diminution and low diversity of trace fossils suggest brackish water stress; ● Suspension feeding trace fossils are limited, suggesting turbidity in the water column
F2B Moderately Burrowed Silt/sandstone Interbedded with Silty Mudstone	● rare organic detritus ● 1-2 cm thickness silty mudstone ● primary physical sedimentary structures similar to those present in F2A, but double mud drapes are presented	● moderate distributed ● high diversity, including: Ph, m; Hm, m; Pl, m; Te, r-m; Sk, m; As, r-m; Cy, r; Di, r; ● small to moderate size ● Cruziana Ichnofacies ● BI = 2-4	● Bedding and sedimentary structures consistent with turbidity currents; ● High degrees and sporadically distributed of bioturbation reflect colonization during deposition; ● Proximal Cruziana Ichnofacies is consistent with lower shoreface to proximal offshore; ● The presence of suspension-feeding trace fossils indicate possibly lessened turbidity

Description	Sedimentologic Characteristics	Ichnologic Characteristics	Interpretation
Facies 3 (F3)			
F3A Planar Parallel Laminated Silty Sandstone	● planar to low-angle parallel lamination ● rare to moderate HCS/SCS ● rare lenticular bedding ● loading casts and micro-fault are locally rare to common ● locally capped by 2-5 cm of current ripple and oscillation ripple ● rare mud drapes ● macro-porosity is rarely presented ● pyrite are locally rare to common	● rare, sporadically distributed ● rare diversity, including: Pl, r; Cy, vr; As, vr; Sk, vr; Ph, r; Pa, r ● rare escape structures ● small size ● proximal Cruziana Ichnofacies ● BI = 0-1	● Bedding and sedimentary structures consistent with wave reworking under combined flow; ● Pyrite suggests anoxic conditions in the sediment; ● An impoverished trace fossil assemblage indicates variability in salinity or lowered dissolved oxygen content (or both)
F3B Loading Sedimentary Deformed Silty Sandstone	● loading casts and convolute bedding are locally common due to coarser sediment starvation ● flame structures ● rare lenticular bedding graded bedding and low-angle planar lamination ● micro-fault and mud drapes are locally common	● very rare, sporadically distributed ● very rare diversity, including: As, vr ● very small size ● BI = 0-1	● Sedimentary deformational structures reflect rapid sedimentation ● Convolute beds can be result from sediment loading, wave loading, storm shock, or slumping.
F3C Hummocky Cross-stratified (HCS/SCS)Silty Sandstone	● hummocky cross stratification (HCS) and swaley cross stratification (SCS) are locally common ● planar to low-angle parallel laminated ● low-angle with convex up and down laminations ● rare fluid mud and pyrite ● rare soft sedimentary deformation and mud drapes ● rare macro-porosity	● very rare, sporadically distributed ● very rare diversity, including: Pl, vr; Cy, vr; As, vr ● very small size ● BI = 0-1	● The heterolithic successions reflect fluctuating energy conditions; ● Hummocky cross stratification are formed under combined flow; ● Very rare colonization opportunities may support energy fluctuated and variability in salinity or dissolved oxygen content

Description	Sedimentologic Characteristics	Ichnologic Characteristics	Interpretation
Facies 4 (F4)			
F4A Sandstone with Muddy Silt Interlaminae	● planar to low-angle parallel lamination, HCS/SCS are presented in sandstone ● physical sedimentary structures are discernible in silt interval ● loading cast and mud drapes are presented on the contacts of sandstone and silt intervals ● rare micro-fault and current ripples	● very rare, sporadically distributed ● very rare diversity, including: Pl, vr; Te, vr; Di. vr ● very small size ● BI = 0-1	● The sharp-base and soft-sedimentary deformational structures may be linked to hyperpycnal and hypopycnal flows ● Bedding and sedimentary structure indicate wave reworking; ● The paucity of trace fossil indicates variability in salinity or dissolved oxygen content.
F4B Planar Parallel Laminated Sandstone	● pervasively planar to low-angle parallel lamination ● seldom HCS/SCS ● current ripple and oscillated ripple are locally rare		● The clean sandstone facies consistent with wave reworking; ● Bedding and sedimentary structures suggest combined flow and wave-reworking; ● The absence of trace fossils may be associated with high depositional energy
F4C Hummocky Cross-stratified (HCS/SCS) Sandstone	● hummocky cross stratification (HCS) and swaley cross stratification (SCS) are locally common ● forms a low angle with convex up and down laminations ● planar to low-angle parallel lamination		● The clean sandstone facies consistent with wave action in marine environment; ● Hummocky cross-stratification is generated under oscillatory-dominant combined flow; ● The absence of trace fossils may be associated with wave reworking

Table 1: Montney Formation facies description and interpretation

Description	Sedimentologic Characteristics	Ichnologic Characteristics	Interpretation
Facies 5 (F5)			
Facies 5A (F5A) Massive-Apparently Sandstone	● physical sedimentary structures are discernible ● bedding is unrecognizable ● mud drapes cap beds ● macro-pore are locally common ● several intervals with pervasive black mineral		● Massive sandstone may link to high sedimentation rates associated with limited range of sand grain sizes; ● The absence of trace fossil indicates may be associated with high sedimentation rates
Facies 5B (F5B) Cryptobioturbated Sandstone	● small in scale and exceedingly subtle ● fuzzy laminae ● physical sedimentary structures are discernible ● bedding is unrecognizable ● sedimentary structures are discontinuous and fuzzy in appearance	● cryptic bioturbation	● Cryptobioturbation is produced by marine fauna that disturb sedimentary structures; ● Cryptic bioturbation is generally formed in food/resource-rich environments; ● Cryptic bioturbation are most likely developed in marine environments

Montney Formation Facies Results

Five facies have been defined in the study area. The description and interpretation of each facies in Montney Formation is presented below.

Facies 1 (F1): structureless muddy siltstone

Description

Facies 1 consists of successions of dark grey siltstones. This facies is characteristically massive with some intervals of fissile siltstone (Fig. 2-3). Primary sedimentary structures are rarely observed. For the intervals of fissile siltstone, laminae are present as fissile sheets, breaking along parallel planes. Thicknesses of beds range between 1 cm to 6 cm. The lower contact of this facies is sharp. Trace fossils are not observed.

Interpretation

Facies 1 is interpreted to represent rapid deposition in a quiescent environment, which was deposited below the mean storm-wave base or was sheltered from storm processes. This interpretation is supported by the presence of siltstone-dominated lithofacies and the absence of wave-generated sedimentary structures. A difficulty with the siltstones is that they are very fine-grained and typically the primary sedimentary structures associated with these rocks are also small: also grain-size variability is so narrow, that sedimentary structures are indiscernible.

Generally, the siltstones may have been deposited from suspension, or during a sediment-gravity flow. Muddy siltstones that are structureless and massive may be deposited by sediment-gravity flows, including slumps and low-density turbidity currents

(Middleton and Hampton, 1976; Mulder and Alexander, 2001). However, without any observation of sediment deformational structures or graded bedding, it is unreasonable to suggest that these siltstones were deposited by sediment-gravity flows.

Based on the observation of the core, the presence of siltstone most likely results from episodic suspension fall-out, into low-energy settings. The dominance of horizontal (lower flow regime) lamination supports this interpretation.

The lack of trace fossils may be ascribed to rapid sedimentation or lowered dissolved oxygen contents. Notably, bioturbation is normally associated with facies adjacent to F1, and so the first interpretation, rapid sedimentation, is more likely, due to the direct correlation between increasing deposition rate and decreasing bioturbation intensity (Leithold 1994). However, recent work by Zonneveld et al. (2012) indicate that lowered O_2 levels were prevalent in the Montney shelf, and so oxygen stress cannot be entirely discounted.

In summary F1 present the following environmental characteristics:

1) Facies 1 can be interpreted to deposit by suspension fall-out below storm wave base or sheltered from storm processes;
2) The absence of trace fossils may be ascribed to rapid sedimentation or lowered dissolved oxygen contents

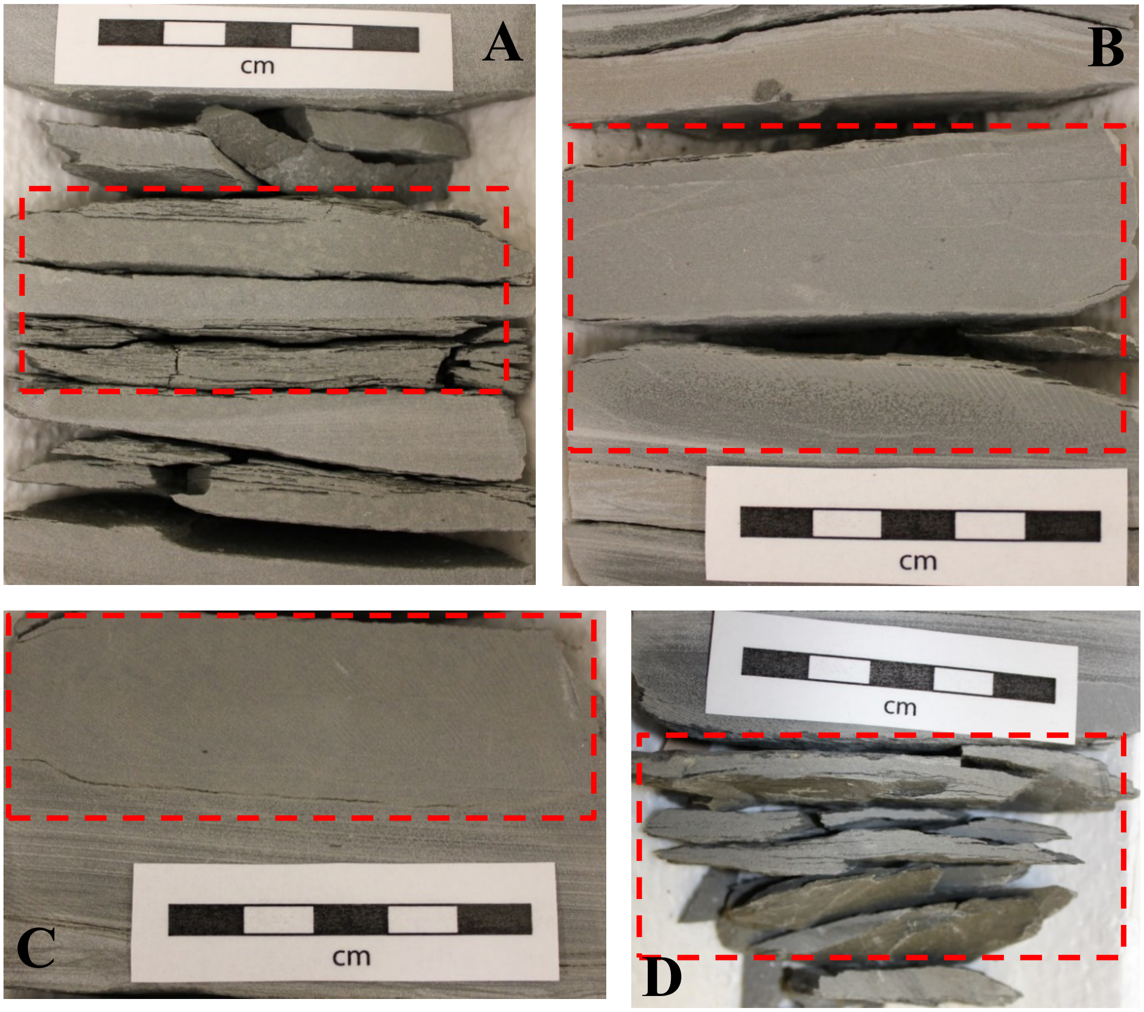


Figure 2-3: Facies1 (F1): Structureless mudstone. **A**. Fissile mudstone of F1 from core 14-33-73-26W5 (1480.76m). **B**. Massive mudstone of F1 from core 16-14-73-26W5 (1567.58m). **C**. Structureless mudstone of F1 from core 16-14-73-26W5 (1582.54-1582.51m). **D**. Fissile mudstone of F1 from core 16-14-73-26W5 (1584.43-1584.37m).

Facies 2A (F2A): weakly burrowed silty sandstone interbedded with siltstone

Description

Facies 2A is a heterolithic succession of regularly alternating (millimeter- to centimeter-thick) fine to very fine-grained siltstone and silty sandstone. This heterolithic facies is dominated by plane parallel lamination and low-angle lamination. Thicknesses of this facies are variable, ranging from 1 cm to 5 cm. Most occurrences of this facies coarsen upwards. The lower contact of this facies is gradational with F2B and F3A.

Sedimentological characteristics dominantly include plane parallel lamination and low-angle parallel lamination in silty sandstone beds (Fig. 2-4). In some intervals, there is development of hummocky cross-stratification and these are associated with combined flow ripple and oscillated ripple laminations (Fig. 2-4 A). Rare intervals of lenticular bedding are observed (Fig. 2-4). Soft sediment deformational structures are locally common.

This facies is weakly bioturbated in the silty sandstone with siltstone intervals. The distribution of trace fossils is sporadic. Trace fossils are small in size and the diversity of the assemblage is low. The ichnofauna comprises deposit-feeding structures and grazing structures, including *Planolites* (r-m), *Cylindrichnus* (r), *Phycosiphon* (m), *Helminthopsis* (m), *Diplocraterion* (vr), *Skolithos* (r), *Teichichnus* (r), *Asterosoma* (r), *Rhizocorallium* (vr). Escape structures (*fugichnia*) are rarely observed. Bioturbation intensities are low (1-2).

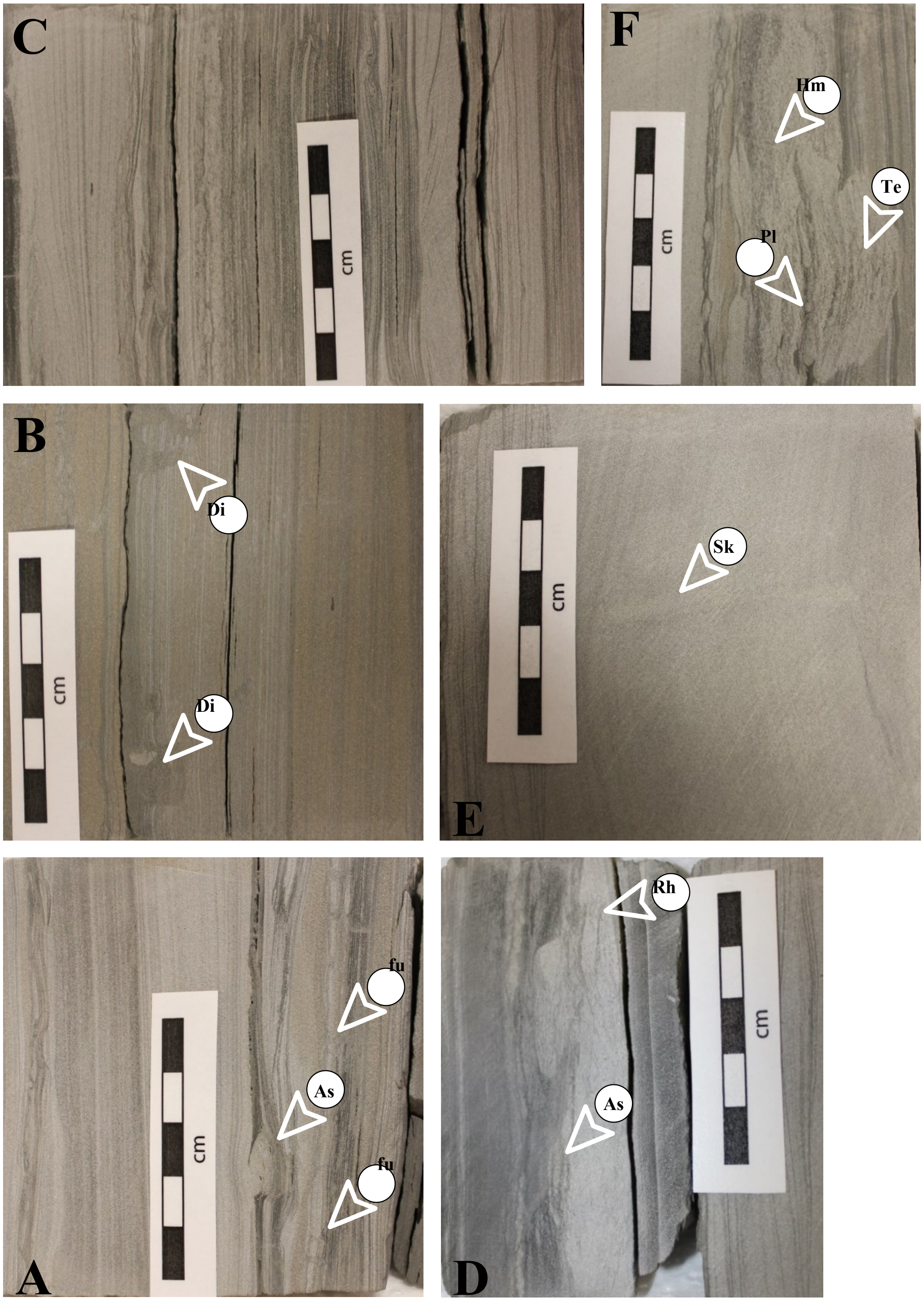


Figure 2-4: Facies2A (F2A): the description see next page.

Figure 2-4: Facies2A (F2A): Weakly burrowed silty sandstone interbedded with siltstone. **A**. *Fugichnia* (fu) and *Asterosoma* (As) in silty sandstone from core 14-33-73-26W5 (1463.37m) and (1463.36m) respectively. **B**. *Diplocraterion* (Di) in silty sandstone from core 14-33-73-26W5 (1452.10m). **C**. General characteristics of F2A, observation of planar parallel laminated, current ripple, hummocky cross-stratification and soft sedimentary deformation from core 14-33-73-26W5 (1487.75). **D**. *Asterosoma* (As) and *Rhizocorallium* (Rh) in siltstone from core 13-03-74-26W5 (1583.96m) and (1583.97m) respectively. **E**. 5cm long *Skolithos* (Sk) from core 16-14-73-26W5 (1584.07-1584.02m), which deform hummocky cross-stratified sandstone. **F**. Large size of *Teichichnus* (Te), *Planolites* (Pl), and *Helminthopsis* (Hm) from core 16-14-73-26W5 (1585.98m), (1585.97m), and (1585.96m) respectively.

Interpretation

The presence of plane parallel and low-angle parallel lamination, hummocky cross-stratification, and oscillation ripples all provide evidence of wave-reworking (Clifton and Dingler, 1984). The other sedimentary structures, such as small-scale deformational structures, suggest rapid deposition possibly during the storm events. Based on the sedimentary structures F2A, which is dominated by laminated siltstone and sandstone, records deposition above storm wave base and below fair-weather wave base.

The sporadic distribution and the low diversity of trace fossils are in part interpreted to result from persistent reworking of the sediment. Most of trace fossils occur within or at the bottom of the event beds. *Phycosiphon* and *Helminthopsis* are grazing traces. *Planolites* are deposit-feeding structures that reflect the activity of sediment-ingesting organisms. *Asterosoma* are deposit-feeding structures. *Teichichnus* are dwelling structures of inferred deposit-feeders. *Rhizocorallium* are the burrows of deposit feeders or the dwelling burrows of suspension feeders. *Skolithos* are dwelling structures of inferred suspension feeders.

Diplocraterion are U-shaped dwelling structures (Seilacher and Hemleben, 1966). All the trace fossils in this facies are dwelling, deposit-feeding or grazing structures. Although the diversity is low to moderate, the assemblage of trace fossils can be interpret as an example of the Cruziana Ichnofacies (Pemberton et al., 1992; Pemberton et al., 1992a; Pemberton et al., 1992b), suggesting marine lower shoreface to inner shelf bathymetry.

The trace fossils of F2A are dominantly diminutive and limited in diversity. Communities in brackish water present low diversity and small size of individuals due to the salinity variation (Dörjes and Howard, 1975; Pemberton and Wightman, 1987; 1992). However, the trace fossils such as *Asterosoma*, *Rhizocorallium*, and *Helminthopsis* are generally associated with marine salinities, thus the low dissolved oxygen contents may also be considered as a reason that influence the ichnofacies. The impoverishment of significant numbers of suspension-feeding ichnofossils indicate turbidity levels in the water column (Moslow and Pemberton, 1988; Gingras et al., 1998; Coates and MacEachern, 1999, 2000; Bann and Fielding, 2004; Hansen and MacEachern, 2007).

In summary F2A present the following environmental characteristics:

1) Bedding and sedimentary structures reflect wave reworking;
2) Soft-sediment deformation at bedding contacts indicate episodic sedimentation;
3) The presence of the Cruziana Ichnofacies is consistent with lower shoreface to inner shelf environments;
4) Diminution and low diversity of trace fossils suggest brackish water stress;
5) Suspension feeding trace fossils are limited, suggesting turbidity in the water column.

Facies 2B (F2B): moderately burrowed silty sandstone interbedded with siltstone

Description

Facies 2B comprises a heterolithic succession of regularly alternating (millimeter- to centimeter-thick) fine to very fine-grained siltstone and sandstone, similar to Facies 2A. This heterolithic facies contains both biogenic- and physical-sedimentary structures. Thicknesses of this facies range from 2 cm to 5 cm. The lower contact of this facies is gradational with F3A.

Sedimentological characteristics dominantly include plane parallel lamination, and low-angle parallel lamination in silty sandstone beds (Fig. 2-5). Unlike in F2A, in some intervals, the sediment structure is indiscernible due to high levels of bioturbation.

Trace fossils are sporadically distributed. Trace fossils are common and form an assemblage comprising *Phycosiphon* (m), *Helminthopsis* (m), *Planolites* (m), *Teichichnus* (r-m), *Skolithos* (m), *Asterosoma* (r-m), *Cylindrichnus* (r), and *Diplocraterion* (r). Most of the trace fossils are small in size, but trace fossils larger in size, such as *Teichichnus* (Fig. 2-7 D), are also observed (Fig. 2-7 D). Bioturbation intensity are higher than Facies 2A (BI = 0 - 5).

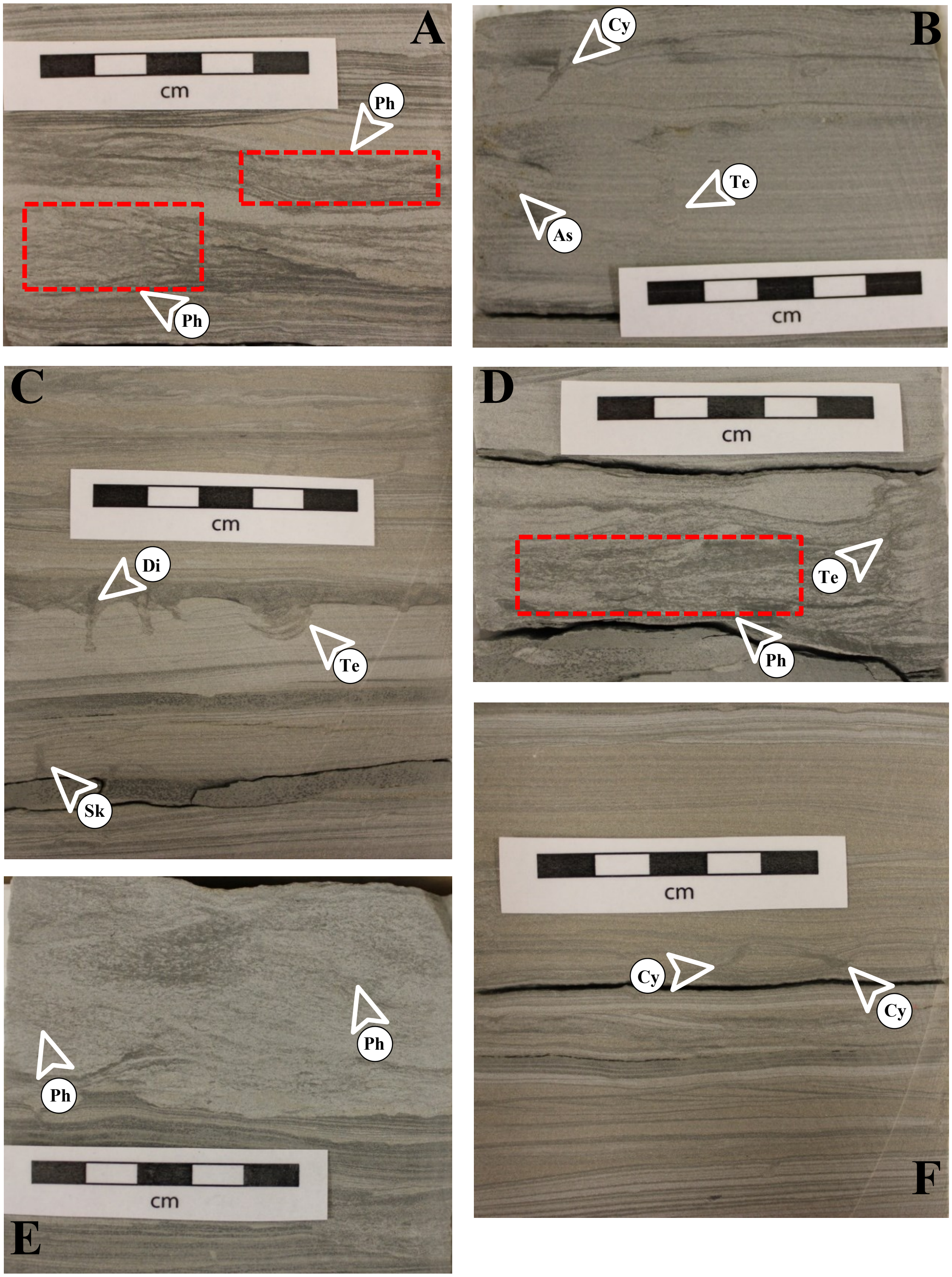


Figure 2-5: Facies2B (F2B): the description see next page.

Figure 2-5: Facies2B (F2B): Moderately burrowed silty sandstone interbedded with siltstone. **A**. Moderate occurrence of *Phycosiphon* (Ph)/*Helminthopsis* (Hm) in siltstone from core 14-33-73-26W5 (1484.71m). **B**. Rare *Cylindrichnus* (Cy), sparse *Asterosoma* (As), and small size of *Teichichnus* (Te) from core 14-33-73-26W5 (1472.85m), (1472.87m), and (1472.88m), respectively. **C**. *Diplocraterion* (Di) (1462.70m), *Teichichnus* (Te) (1462.70), and *Skolithos* (Sk) (1462.72m) from core 14-33-73-26W5. **D**. Large size of *Teichichnus* (Te) (3cm long) and moderate diversity of *Phycosiphon* (Ph) from core 14-33-73-26W5 (1484.45m). **E**. Moderate occurrence of *Phycosiphon* (Ph)/*Helminthopsis* (Hm) in siltstone from core 14-33-73-26W5 (1485.10m). **F**. Rare *Cylindrichnus* (Cy) from core 14-33-73-26W5 (1462.22m).

Interpretation

The presence of plane parallel and low-angle parallel laminae can be interpreted to result from wave reworking under the unidirectional flow (Arnott and Southard, 1990). Same style of planar laminae are observed in F3 and F4.

Trace fossils occur within the event beds and at event-bed tops. Traces on or subtending from event-bed tops provide evidence that organisms only able to exploit bed surfaces after a depositional event. *Phycosiphon* and *Helminthopsis* are grazing traces. *Planolites*, *Asterosoma*, and *Teichichnus* are deposit-feeding structures. *Skolithos* and *Cylindrichnus* are dwelling structures of inferred suspension or interface-deposit feeders. *Diplocraterion* are U-shaped dwelling structures (Seilacher and Hemleben, 1966). The trace fossils in this facies represent grazing, deposit-feeding, and suspension-feeding structures. The assemblage of trace fossils can be interpret as the proximal *Cruziana* Ichnofacies (MacEachern et al, 1992); i.e. containing some suspension-feeding trace fossils (Pemberton et al., 1992; Pemberton et al., 1992a; Pemberton et al., 1992b).

The variable distribution of trace fossils indicates colonization between sedimentation events, with some heavily bioturbated levels indicating longer-term colonization. Compared with Facies 2A, bioturbation in Facies 2B is locally higher in Bioturbation Intensity and diversity. The higher ichnodiversity and larger size of some burrows may be linked to less stressful environmental conditions than F2A; in other words, salinity and oxygenation may be comparably stable. The more abundant vertical burrows in F2B, which provide evidence of decreased turbidity (Hansen and MacEachern, 2007). The range of Bioturbation Intensities (0 to 5) evidence a broad range of environmental energy from quiescent to wave-reworked. The proximal *Cruziana* Ichnofacies is also consistent with sporadic wave influence (Pemberton, et al., 1992); *Skolithos* elements are present in the *Cruziana* Ichnofacies where storm conditions lift the sediment into suspension at times favoring suspension feeding organisms (Frey, et al., 1990)

In summary F2B presents the following environmental characteristics:

1) Bedding and sedimentary structures consistent with turbidity currents;
2) High degrees and sporadically distributed of bioturbation reflect colonization during deposition;
3) Proximal Cruziana Ichnofacies is consistent with lower shoreface to proximal offshore;
4) The presence of suspension-feeding trace fossils indicate possibly lessened turbidity.

Facies 3A (F3A): plane parallel laminated silty sandstone

Description

This facies is the thickest facies in the studied cores. Facies 3A comprises a heterolithic succession of regularly alternating (millimeter- to centimeter-thick) fine to very fine-grained sandstone and siltstone. Thicknesses of beds range from 2 cm to 20 cm. The lower contact is variable, ranging from sharp with F3B, F4A, F5, and F6 to gradational with F2B, F4B.

Sedimentary structures include thin (1-3mm) to very-thin (<1mm) plane parallel laminae, or low-angle laminae. Although hummocky cross-stratification is observed, it is rare. Load casts are rare. Other small scale features, including sedimentary micro-faults and soft-sedimentary deformational structures, are also rare. Mud drapes capped by 2-5cm of combined flow ripples are very rare. Macro-porosity is also observed. Pyrite, occurring as nodules, is locally common (Fig. 2-6).

Trace fossils are rare and sporadically distributed. The diversity of trace fossils is low, including *Planolites*, *Cylindrichnus*, *Asterosoma*, *Skolithos*, *Phycosiphon*, and *Palaeophycus*, as well as fugichnia. The trace fossils are small in size. Bioturbation intensity is very low in F3A (BI= 0-1).

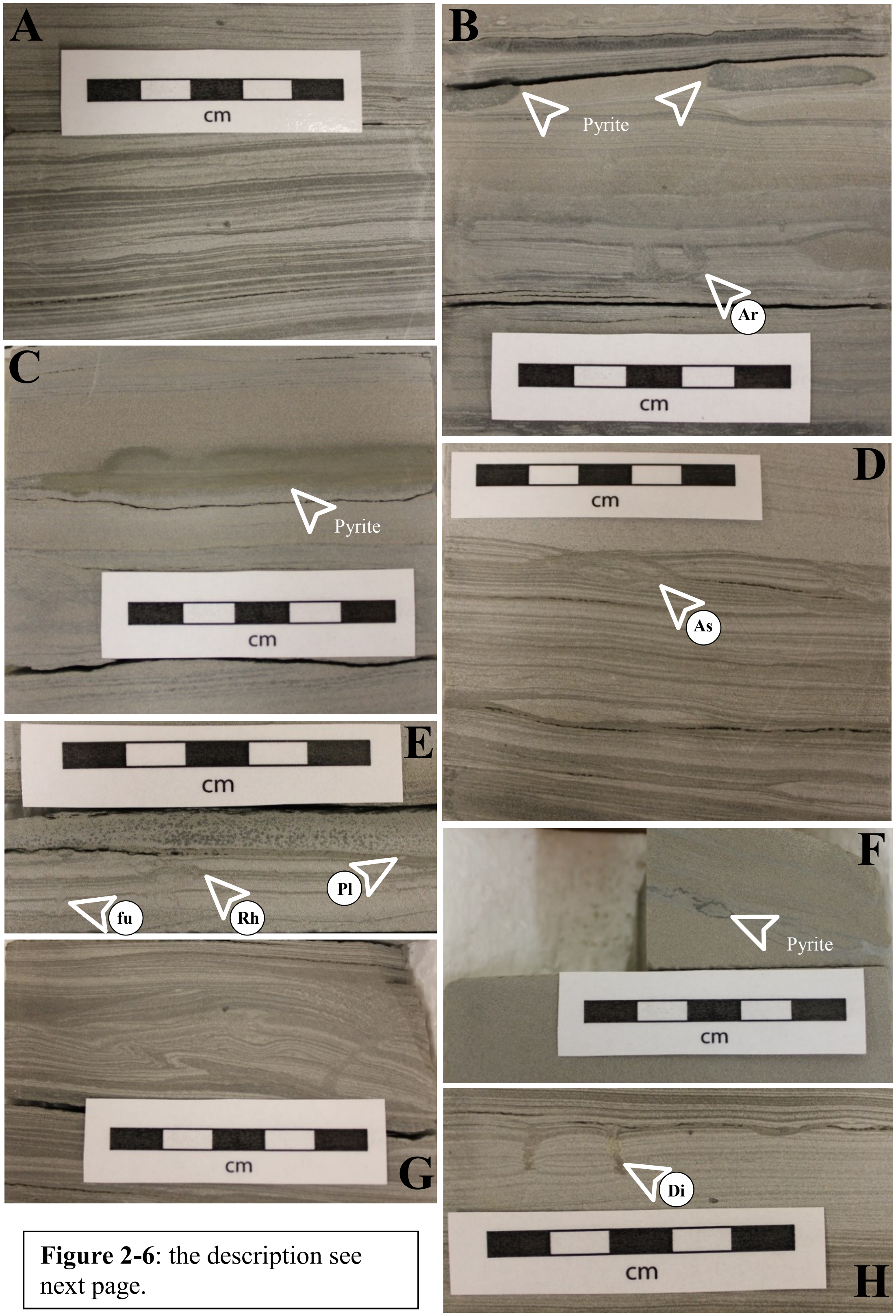


Figure 2-6: the description see next page.

Figure 2-6: Facies3A (F3A): Plane parallel laminated silty sandstone. **A**. Planar to low-angle parallel lamination in silty sandstone from core 16-14-73-26W5 (1585.46-1585.50m). **B**. Pyrite and *Arenicolites* (Ar) in silty sandstone from core 16-14-73-26W5 (1566.61m) and (1566.64m), respectively. **C**. Large pyrite in silty sandstone from core 16-14-73-26W5 (1559.72m). **D**. *Asterosoma* (As) from core 14-33-73-26W5 (1482.06m). **E**. *Planolites* (Pl), *Rhizocorallium* (Rh), and some *fugichnia* (fu) from core 14-33-73-26W5 (1464.99m). **F**. Pyrite in silty sandstone from core 16-14-73-26W5 (1557.17m). **G**. Soft sedimentary deformation from core 16-14-73-26W5 (1577.40m). **H**. *Diplocraterion* (Di) from core 14-33-73-26W5 (1471.26m).

Interpretation

Based on the observation that plane parallel lamination grade up into hummocky cross-stratification, the plane parallel to low-angle laminations and hummocky cross-stratification reflect wave reworking (Harms et al., 1982; Walker et al., 1983; Duke, 1985). Plane parallel lamination occur readily in very fine to fine sandstone under combined flow where the unidirectional component may represent a small percent of the oscillatory component (Arnott and Southard, 1990). Soft-sedimentary deformational structures represent a period of rapid sedimentation (Dzulynski and Kotlarcczyk, 1962). The presence of the combined flow ripple provides evidence that F3A was deposited under combined flow at relatively shallow depths.

Pyrite probably precipitated shortly after deposition (diagenetic) and indicates reducing (anoxic) conditions within the sediment (Bonnell and Anderson, 1985; Goldhaber et al., 1977; Zonneveld et al., 2010).

Based upon the ichnofauna noted above, the ichnological assemblage is dominated by deposit-feeding structures representative of a *Cruziana* Ichnofacies with reduced abundance and diversity of trace fossils, consistent with lower shoreface to inner shelf settings (MacEachern et al., 1999a, 2007a). The lower ichnodiversity and lower bioturbation intensities than F2 may be linked to stressful environmental conditions with comparably variable salinity. However, *Asterosoma*, *Rhizocorallium*, and *Diplocraterion* are normally associated with marine salinities, so low dissolved oxygen contents may also have influenced the ichnofacies (Zonneveld, et al., 2010).

In summary F3A presents the following environmental characteristics:

1) Bedding and sedimentary structures consistent with wave reworking under combined flow;
2) Pyrite suggests anoxic conditions in the sediment;
3) An impoverished trace fossil assemblage indicates variability in salinity or lowered dissolved oxygen content (or both). This may be due to seasonal variations within the sedimentary environment, but the dataset is too limited to make this determination.

Facies 3B (F3B): loading sedimentary deformed silty sandstone

Description

Facies 3B comprises a heterolithic succession of interbedded fine to very fine-grained sandstone and siltstone. This heterolithic facies is dominated by soft sediment deformation. Thicknesses of this facies range from 4 cm to 10 cm. The lower contact is sharp with F3A and F5.

Deformational structures such as flame structures, load casts, and micro-faults are abundance. Convolute bedding is locally common. Silty sandstone beds are typically sharp-based and characterized by load casts and/or flame structures. Small scale pillow structures are observed at the base of some beds. It is common to observe micro-scale structures, including micro-folds and micro-faults. Micro-faults consist of normal and reverse faults with normal faults being more common. Graded bedding, plane parallel to low-angle laminations are rarely observed. Mud drapes are locally common (Fig. 2-7). None trace fossils are observed.

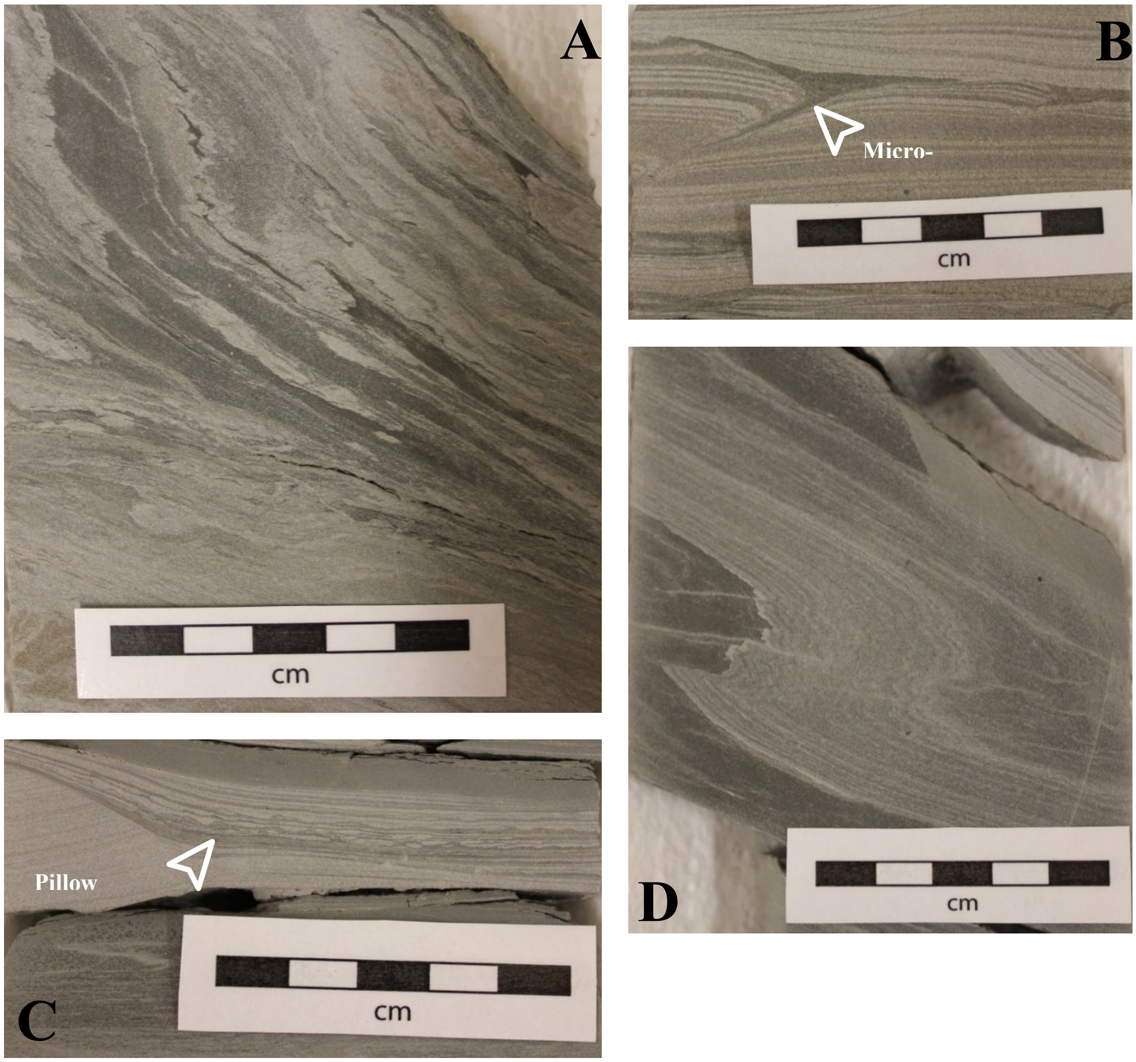


Figure 2-7: Facies3B (F3B): Loading sedimentary deformed silty sandstone. **A**. Soft sedimentary deformation in silty sandstone from core 14-33-73-26W5 (1454.06m). **B**. Micro-fault with drag structure in silty sandstone from core 13-03-74-26W5 (1451.15m). **C**. Pillow structures in silty sandstone from core 16-14-73-26W5 (1573.76m). **D**. Loading casts and convolute bedding from core 13-03-74-26W (1578.29m).

Interpretation

F3B is distorted by sediment loading or slumping. Soft sedimentary deformational layers form during or shortly after deposition and before consolidation (Reineck and Singh, 1973). The development abundant soft sediment (penecontemporaneous) deformation result from extremely rapid sedimentation generally results in (Dzulynski and Kotlarcczyk, 1962; MacEachern, et al. 2005). Deformational structures are generated due to mechanical forces resulting from gravity acting upon weak sediment prior to or soon after or at deposition along the sediment surface (Collinson, et al 2006). The processes of soft sediment deformational structures occur during deformational event at or near the contemporary surface of unconsolidated sediment either before, or soon after burial (Bhattacharya and Bandyopadhyay, 1998). Soft-sediment deformation can develop with appropriate forces that can trigger deformation mechanism, such as liquefaction, fluidization, slumps, slides, ad growth faults (Lowe, 1975; Allen, 1982; 1986).

Convolute beddings are formed by plastic deformation occurring shortly after deposition (Collinson, et al., 2006). Convolute bedding may result from sediment loading, storm shock, or wave loading due to storm deposit (Pemberton and MacEachern, 2001; Zonneveld et al., 2010; Zonneveld and Gingras, 2012). Slumps may also produce convolute bedding and micro-fault due to differential stress action (Frey et al., 2009). Small-scale convolute bedding may be produced from slumping on over-steepened slopes with fast sedimentation rates.

Facies associated with rapid sedimentation rates are generally characterized by reduction or non-bioturbation due to insufficient time for colonization (Howard 1975; MacEachern, et al., 2005).

In summary F3B presents the following environmental characteristics:

1) Sedimentary deformational structures reflect rapid sedimentation;
2) Convolute beds can be result from sediment loading, wave loading, storm shock, or slumping.

Facies 3C (F3C): hummocky cross-stratified (HCS) silty sandstone

Description

Facies 3C comprises regularly alternating fine- to very fine-grained sandstone, siltstone and silty sandstone. The thickness of silty sandstone is variable, ranging from 2 cm to 10 cm. The lower contact is gradational with F3A and F4B.

Hummocky cross-stratification (HCS) are the main physical sedimentary structures observed in this facies. Plane parallel to low-angle lamination is infrequently observed. Soft sediment deformation structures are rarely observed (Fig. 2-8).

The distribution of trace fossils is sporadic. The diversity of trace fossils is extremely low, and assemblages include only *Planolites*. The trace fossils are small in size. Bioturbation intensity is very low (BI =0-1).

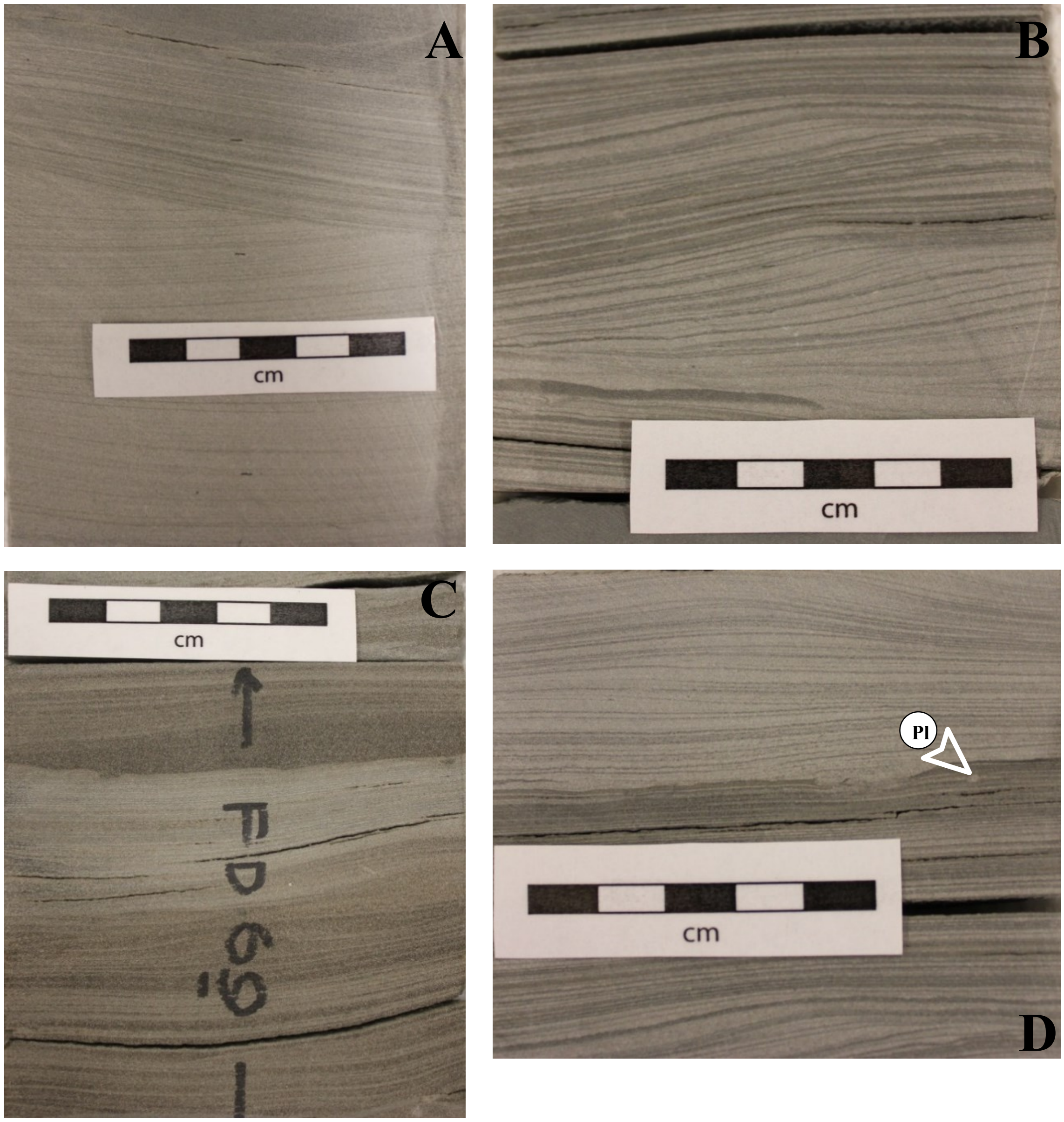


Figure 2-8: Facies3C (F3C): Hummocky cross-stratified (HCS) silty sandstone. **A**. HCS in silty sandstone from core 14-33-73-26W5 (1476.42m). **B**. HCS in silty sandstone from core 16-14-73-26W5 (1581.29-1581.33m). **C**. HCS with rare dolomite from core 13-03-74-26W5 (1441.77m). **D**. *Planolites* (Pl) in silty sandstone from core 16-14-73-26W5 (1581.26m).

Interpretation

The heterolithic successions of siltstone and sandstone indicate fluctuating energy conditions. Hummocky cross stratification is most likely generated above storm wave base under combined flow where the oscillatory component is strong but with a weak unidirectional component (Arnott and Southard, 1990; Dumas and Arnott, 2006). According to different researches, hummocky cross stratification can be interpreted to represent from middle shoreface to lower shoreface, even offshore transition (Harms et al., 1982; Walker et al., 1983; Duke, 1985; Dumas and Arnott, 2006).

It is likely that the depositional energy fluctuated, as evidenced by the heterolithic nature of the facies and the very rare colonization opportunities manifested by the trace fossils. The paucity of trace fossil assemblage indicates variability in salinity or dissolved oxygen content. This may be due to seasonal variations within the sedimentary environment; however, due to the limited dataset, it is difficult to make this determination.

In summary F3C presents the following environmental characteristics:

1) The heterolithic successions reflect fluctuating energy conditions;
2) Hummocky cross stratification are formed under combined flow;
3) Very rare colonization opportunities may support energy fluctuated and variability in salinity or dissolved oxygen content.

Facies 4A (F4A): sandstone with silt interlaminae

Description

Facies 4A consists of regularly alternating (millimeter- to centimeter-thick) very fine to fine-grained sandstone and siltstone. Thicknesses of siltstone intervals range from 0.5 cm to 3 cm. Thicknesses of sandstone range between 4 cm and 10 cm. The lower contact is sharp with F3A and F3C. The siltstone is observed by a sharp-based with sandstone.

Sedimentary structures observed within the sandstone include planar to low-angle lamination, and HCS. Load casts and mud drapes are observed on the contacts between the sandstone and siltstone. Soft-sediment deformation and micro-faults are locally observed. Current ripples are rarely observed. Some laminae have broken along parallel planes (Fig. 2-9).

The distribution of trace fossils is sporadic. The ichnodiversity is very low and only *Planolites*, *Asterosoma*, *Teichichnus* and *Diplocraterion* are observed in this facies, including. All trace fossils are small in size. Bioturbation intensity is extremely low (BI= 0-1).

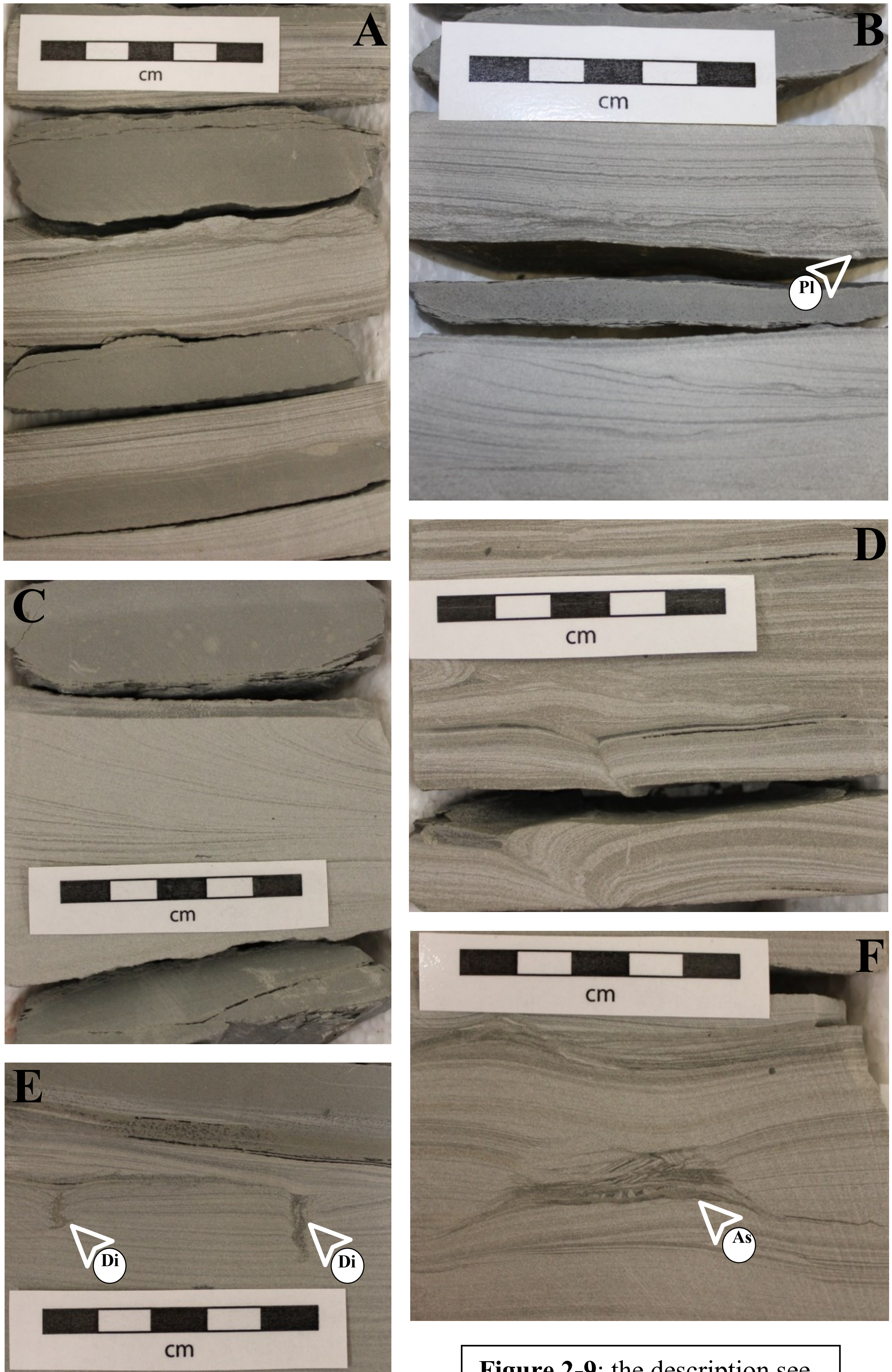


Figure 2-9: the description see next page.

Figure 2-9: Facies4A (F4A): Sandstone with silt interlaminae. **A**. Plane to low-angle parallel laminated sandstone with silt intervals from core 16-14-73-26W5 (1576.11-1576.22m). **B**. Current ripple and plane parallel lamination sandstone with muddy silt interval from core 16-14-73-26W5 (1586.97-1587.07m). **C**. Sandstone with deformational structures from core 14-33-73-26W5 (1484.74m). **D**. Micro-fault in sandstone from core 13-03-74-26W5 (1454.23m). **E**. *Diplocraterion* (Di) in sandstone from core 14-33-73-26W5 (1460.16m). **F**. *Asterosoma* (As) in sandstone from core 14-33-73-26W5 (1466.31m).

Interpretation

The presence of sharp-base between siltstone and sandstone reflect an erosion after sandstone deposition. This erosion surface may be linked to hyperpycnal flows when river discharge enters the ocean with suspended concentrations. There are several observation for recognizing hyperpycnal flow deposits: 1) grain size variation within beds; 2) limited trace fossils; 3) associated cross bedding. Mulder et al. (2003) summarized that hyperpycnal flow can be produced from a flood-associated plume. This is also supported by earlier work of Reineck and Singh (1973), who reported that laminated sharp-based sand and mud beds are associated with flooding-events.

The dominance of planar and rarer hummocky cross-bedded sandstone indicates the sedimentary environment was influenced by high-energy wave reworking (Hams et al., 1982; Walker et al., 1983; Duke, 1985; Arnott and Southard, 1990; Dumas and Arnott, 2006). Plane parallel lamination and hummocky cross-stratification are developed under the combined flow (Arnott and Southard, 1990; Dumas and Arnott, 2006). The observations of soft-sedimentary deformational structures within the sandstone result from rapid sedimentation.

The extremely low ichnodiversity bioturbation intensities may be linked to stressful environmental conditions with comparably variable salinity. However, *Asterosoma* and *Diplocraterion* are normally associated with marine salinities, so low dissolved oxygen contents may also have influenced the ichnofacies. Therefore, the paucity of trace fossil indicates variability in salinity or dissolved oxygen content or both (Zonneveld et al., 2010).

In summary F4A presents the following environmental characteristics:

1) The sharp-base and soft-sedimentary deformational structures may be linked to hyperpycnal and hypopycnal flows;
2) Bedding and sedimentary structure indicate wave reworking;
3) The paucity of trace fossil indicates variability in salinity or dissolved oxygen content. This may be due to seasonal variations within the sedimentary environment, but it is difficult to make this determination due to the limited dataset.

Facies 4B (F4B): plane parallel laminated sandstone

Description

This facies consists of well sorted, fine to very fine-grained sandstones. Thicknesses of this facies range from 2 cm to 10 cm. F4B is generally overlain by F4C with gradational lower contact.

Plane parallel lamination and low-angle lamination is the dominant primary physical sedimentary structure. Lamination in the planar bedded sandstone ranges from 1 mm to 3 mm thick. Hummocky cross-stratification is locally common. Combined flow ripples and oscillation ripples are rare observed (Fig. 2-10).

No trace fossils are observed.

Interpretation

The characteristics of F4B are very fine-grained to fine-grained clean sandstone that permit recognition of wave reworked, high energy depositional setting. The absence of distinct silt interbeds also suggests deposition above fair-weather wave base.

Plane parallel lamination are commonly formed in very fine to fine sandstone under combined flow (Arnott and Southard, 1990). The formation of plane parallel lamination is always a heated discussion. Based upon experiments of Leclair and Arnott (2005), plane parallel lamination may be formed by turbidity currents associated within deeper water. However, overall consideration of sedimentary structures, it is unreasonable to interpret F4C (sandstone facies) represent deeper water. On the basis of core observations and laboratory experiments, some studies had interpreted that plane parallel lamination were produced by flat symmetrical to strongly asymmetrical sand waves (Jopling, 1964, 1967;

Smith, 1971; McDonald and Vincent, 1972; Allen, 1982). Therefore, the planar laminations are expected to be more common with combined flows at relatively shallow depths where both the oscillatory and the unidirectional flow should be strongest (Arnott and Southard, 1990).

The absence of trace fossils may linked to high energy within marine deposition conditions.

In summary F4B presents the following environmental characteristics:

1) The clean sandstone facies consistent with wave reworking;
2) Bedding and sedimentary structures suggest combined flow and wave-reworking;
3) The absence of trace fossils may be associated with high depositional energy.

Facies 4C (F4C): hummocky cross-stratified (HCS) sandstone

Description

This facies consists of well sorted, fine to very fine-grained sandstones. Thicknesses range from 3 cm to 10 cm. The laminae range from 1 mm to 3 mm. F4B is generally overlain by F4C with gradational lower contact.

Sedimentary structures include HCS, and plane tabular cross stratification. HCS is the main physical sedimentary structures observed in this facies. The sedimentary structures form low angle, convex up and down laminations. The tops of hummocky bed sets commonly have wave ripples or combined flow ripples. Other physical sedimentary structures, such as plane parallel lamination and low-angle lamination, are limited to observe. No evidence of bioturbation is observed (Fig. 2-10).

Interpretation

As to F4B, the lack of silt and mud in a sandstone provides evidence of wave reworking deposition such as wave action on a shoreface.

The hummocky cross-stratification beds are deposited between fair weather and storm wave base. Hummocky cross-stratification is generally formed in the water where is shallow enough for wave orbitals to become large and fast and deep enough for unidirectional currents (Dumas and Arnott, 2006). Therefore, hummocky cross-stratification is considered to develop under oscillatory-dominant combined flow (Arnott and Southard, 1990; Dumas and Arnott, 2006).

As to F4B, the absence of trace fossils may also linked to wave reworking within marine deposition conditions.

In summary F4C presents the following environmental characteristics:

1) The clean sandstone facies consistent with wave action in marine environment;
2) Hummocky cross-stratification is generated under oscillatory-dominant combined flow;
3) The absence of trace fossils may be associated with wave reworking.

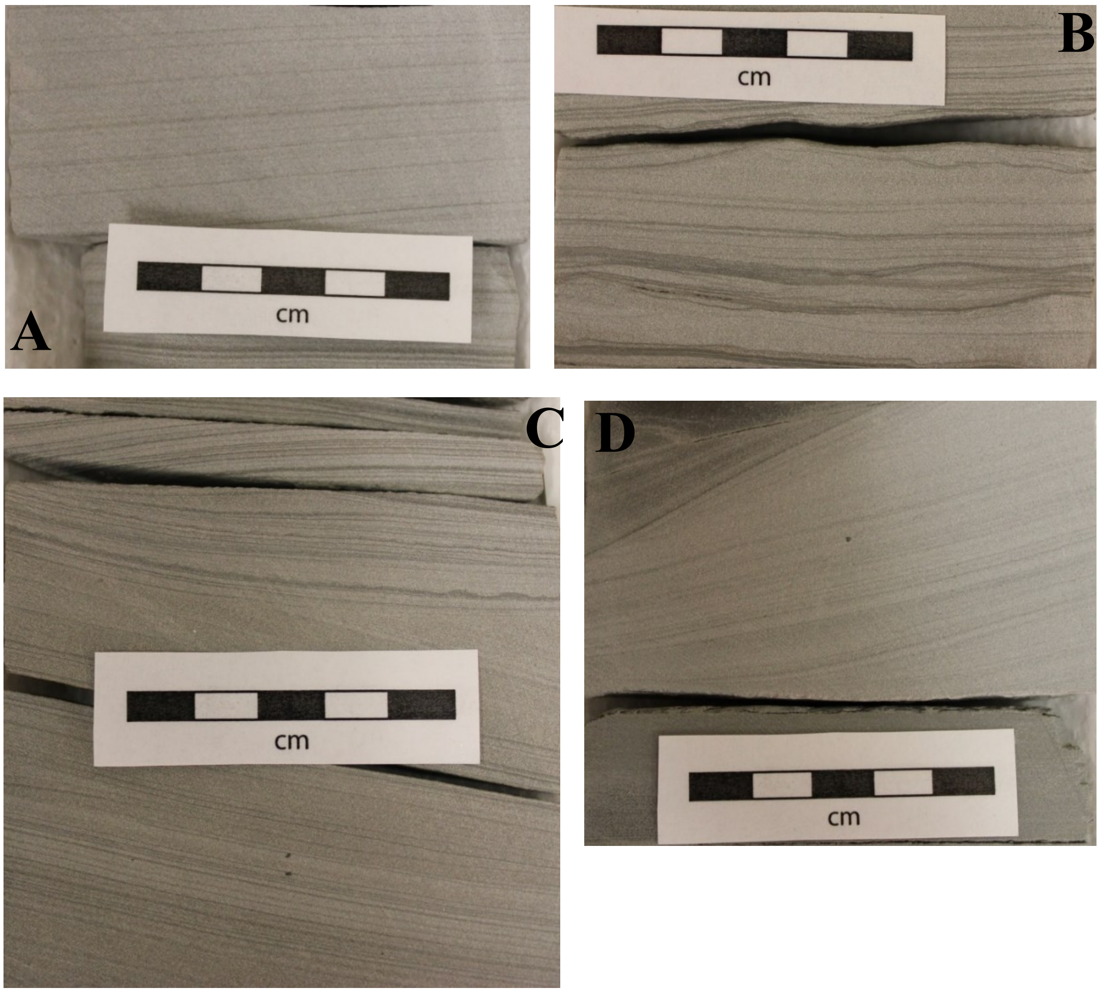


Figure 2-10: Facies4B (F4B): Plane parallel laminated sandstone. **A**. Plane to low-angle parallel laminated sandstone from core 14-33-73-26W5 (1448.60m). **B**. Rare oscillated ripples in sandstone from core 14-33-73-26W5 (1448.95m).
Facies4C (F4C): Hummocky cross-stratified (HCS) sandstone. **C**. **D**. Hummocky-cross stratified sandstone from core 14-33-73-26W5 (1477.35m) and (1477.45m), respectively.

Facies 5A (F5A): massive-appearing sandstone

Description

Facies 5A consists of fine-grained sandstone. Massive-appearing sandstone beds range from 0.2 to 10 cm and are generally overlain by parallel-bedded sandstone or silty sandstone (F3A and F4B). The lower contact can be sharp to gradational and well defined.

Physical sedimentary structures are not discernible and bedding is unrecognizable. The sandstone appears structureless, but in some intervals there are small-scale cracks and macro-pores on the surface along with discontinuous planar laminations in the core. The surface of this core seems completely structureless, but vague stratification or lamination is rarely observed. In some intervals details of individual layers are observed by a series of grains of dark material (kerogen?). These massive sandstones show no evidence of bioturbation (Fig. 2-11).

Interpretation

The origin of structureless sandstone may have several explanations. Based on the experiment on massive sandstone using x-ray radiography from Hamblin (1962), 97% of massive bedding actually contains bedding that is otherwise difficult to see megascopically.

Massive-appearing sedimentary characteristics can be developed by the following processes: 1) difficult to distinguish sedimentary lamination due to invariable grain-size; 2) high sedimentation rates associated with abrupt downward jumps in sediment transport capacity (Boggs, 2001; Simpson et al., 2002; Baas, 2004); 3) sediment-gravity flows; 4) high degrees of biogenic chaos (Gingras et al. 2007).

In this facies, the massive bedding is interpreted to result from high sedimentation rates, but is probably exacerbated by the limited range of sand grain sizes observed in the core. It is unreasonable to interpret these massive sandstone link with sediment-gravity flows due to the absence of soft-sedimentary deformational structures. Discontinuous observation of planar laminations without characteristics of bioturbation indicated that these massive sandstone may not be produced by the processes of biogenic chaos.

The absence of trace fossils reflects an inhospitable depositional environment that may be associated with high sedimentation rates.

In summary F5A presents the following environmental characteristics:

1) Massive sandstone may link to high sedimentation rates associated with limited range of sand grain sizes;
2) The absence of trace fossil indicates may be associated with high sedimentation rates.

Facies 5B (F5B): cryptobioturbated sandstone

Description

Facies 5B consists of very fine to fine-grained sandstone. Thicknesses of this facies range from 6 cm to 17 cm. The lower contact is sharp with F3A and F4B.

This facies is challenging to differentiate from Facies 5A because they look very similar; however, in Facies 5B the sedimentary structures tend to be discontinuous and fuzzy in appearance. Some samples appear to be unbioturbated, but with close inspection, the lamination appear fuzzy and contain weakly defined burrows. On even closer inspection, the samples are commonly 100% bioturbated (Fig. 2-11).

Interpretation

The unit is characterized by cryptobioturbation. Howard and Frey (1975) were first researchers to recognize cryptic bioturbation. This kind of bioturbation is subtle and easily over looked. Recent studies further suggest that cryptobioturbation is an important ichnological process (Rouble and Walker, 1997; Pemberton et al., 2001; Pemberton and Gingras, 2005). Cryptobioturbation occurs at a limited grain size, ranging from upper very fine to upper fine sand (Blanpied and Bellaiche, 1981; Dashtgard et al., 2008). The massive appearance is due to abundant marine plankton that disrupt the original lamination and stratification (Gingras et al. 2007). Based on the fuzzy sedimentary structure of F5B, cryptobioturbation can result in a thoroughly bioturbated deposition where the sedimentary structures are still visible (Pemberton et al., 2008). The process of cryptobioturbation is modified by the activities of the meiofaunal organisms living within sediment, so cryptobioturbation is generally formed in the environment where food resources are rich enough (Dörjes and Howard, 1975). Therefore, cryptic bioturbation commonly occur in shallow- to marginal-marine depositional environments where it considerable volumes of sediment may be influenced (Pemberton et al., 2008; Gingras et al. 2008)

In summary F5B presents the following environmental characteristics:

1) Cryptobioturbation is produced by marine fauna that disturb sedimentary structures;
2) Cryptic bioturbation is generally formed in food/resource-rich environments;
3) Cryptic bioturbation are most likely developed in marine environments.

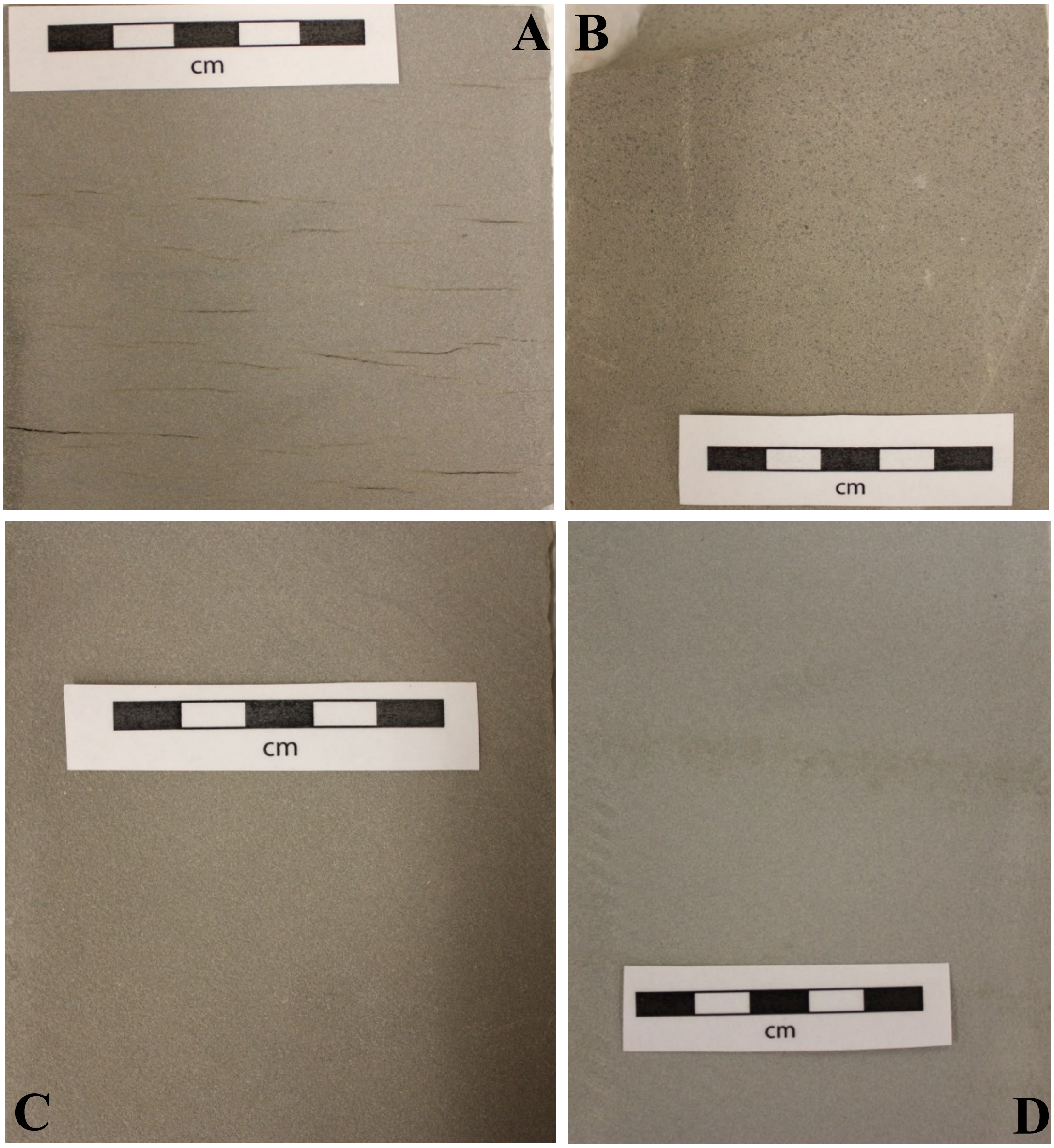


Figure 2-11: Facies5A (F5A): Massive-apparently sandstone. **A**. Massive-apparently sandstone with macro-porosity from core 14-33-73-26W5 (1444.37m). **B**. Structureless sandstone with pervasive kerogen from core 16-14-73-26W5 (1561.32m). Facies5B (F5B): Cryptobioturbated sandstone. C. Fuzzy laminae from core 14-33-73-26W5 (1453.77m). **D.** Cryptobioturbated sandstone from core 14-33-73-26W5 (1474.74m)

FACIES ASSOCIATIONS

Facies associations are vertical successions of commonly related facies and are essential to understanding the regional distribution and geometry of reservoirs. Due to the non-unique interpretation arrived at using physical and biogenic sedimentary processes, individual facies have inexact interpretations. Interpreting facies in relation to neighbouring facies (both laterally and vertically), allows for a more meaningful interpretation of depositional environments. Thus, by grouping facies into genetically related successions, Walther's Law can be applied more dependably. These facies associations are essential for developing palaeo-environmental interpretations (Anderton, 1985; Reading, 1986, 2003).

The classification of facies associations depends on specific physical and biological criteria that represent the environment during sedimentation. From the limited dataset within this study only one facies association is defined. These characteristic sedimentary successions are grouped into the facies associations described below.

Facies Association 1 - shoreface

This Facies Association has an upward-coarsening profile and is interpreted to represent a shoreface environment. A typical shoreface succession comprises F2B (silty sandstone with moderate bioturbation), F4 (plane parallel laminated sandstone) and F4C (hummocky cross-stratified sandstone). (Fig. 2-12)

Description

FA1 is dominated by sandstone. Physical sedimentary structures within the sandstones, including plane parallel lamination, hummocky cross-stratification, current ripples and oscillation/wavy ripples (F4B and F4C). These sedimentary structures follow a vertical order of succession: plane to low-angle parallel lamination grading to hummocky cross-stratified, capped by combined-flow ripples grading into siltstones. The recurring order records fair-weather suspension settling of silty sediments to relative high energy conditions transitioning and back to fair-weather suspension settling of very-fine sediments with decreasing flow conditions. Similar features have been suggested by Reading (1996) to indicate that storm generated waves were responsible for reworking the sediment.

This Facies Association shows a moderate bioturbation with sporadic distribution. The ichnofossils of FA1 are dominantly diminutive but large trace fossils exist. Most of trace fossils occur within or at the bottom of the event beds. The ichnofauna primarily comprises deposit-feeding structures and grazing structures, as well as suspension-feeding structures. Bioturbation intensities are relatively high (BI=0-5).

Interpretation

1) Vertical order of this facies association (F2A to F4C) represent an upward-coarsening profile within increase energy influence;
2) Sedimentary structures and beddings suggest combined flow and wave reworking;
3) The assemblage of trace fossils in FA1 can be interpret as an example of the Proximal Cruziana Ichnofacies that is consistent with lower shoreface to proximal offshore;
4) Sporadically distribution but high degree of bioturbation reflect colonization during deposition. The variable distribution of trace fossils indicates colonization between sedimentation events, with some heavily bioturbated levels indicating longer-term colonization;
5) The presence of suspension-feeding trace fossils indicate possibly lessened turbidity;
6) The range of Bioturbation Intensities (0 to 5) evidence a broad range of environmental energy from quiescent to wave-reworked;
7) The higher ichnodiversity and larger size of some burrows may be linked to less stressful environmental conditions.

Facies Association 2 – river influence shoreface

The Facies Association 2 has an upward-coarsening profile and is interpreted to represent a river influence shoreface environment. The succession consists of F1 (siltstone), F2A (weakly bioturbated silty sandstone), F3A (plane parallel laminated silty sandstone), F4A (sandstone with silt interlaminae), F3B (loading sedimentary deformed silty sandstone), F3C (hummocky cross-stratified silty sandstone), and F5A (massive-apparently sandstone), and F5B (cryptobioturbated sandstone) (Fig. 2-12).

Description

This Facies Association is dominated by silty sandstone. Physical sedimentary structures within the silty sandstones, including plane parallel lamination, hummocky cross-stratified, current ripples and oscillation/wavy ripples (F3A and F3C). Soft sedimentary deformational structures can be observed. Pyrite, occurring as nodules, is locally common. The vertical succession records coarsening upwards.

This Facies Association shows a weakly bioturbation with sporadic distribution. The ichnofossils of FA1 are dominantly diminutive and limited in diversity. Most of trace fossils occur within or at the bottom of the event beds. The ichnofauna primarily comprises deposit-feeding structures and grazing structures. Suspension feeding trace fossils are absence. Bioturbation intensities are low (BI=1-2). Although the diversity is low to moderate, the assemblage of trace fossils can be interpret as an example of the Cruziana Ichnofacies.

Compared with FA1, bioturbation in FA2 is locally lower in Bioturbation Intensity and diversity. Due to the salinity variation communities reveal low diversity and small size of individuals in brackish water (Dörjes and Howard, 1975; Pemberton and Wightman, 1987; 1992).

Interpretation

1) Lithological characteristics of FA2 contain more silty component that may indicate river influence mixed with wave reworking;
2) Sedimentary structures and beddings suggest wave reworking;
3) Sedimentary deformational structures reflect rapid sedimentation, and Convolute beds can be result from sediment loading, wave loading, storm shock, or slumping;
4) The assemblage of trace fossils in FA2 can be interpret as an example of the Cruziana Ichnofacies (Pemberton et al., 1992; Pemberton et al., 1992a; Pemberton et al., 1992b), suggesting marine lower shoreface to inner shelf bathymetry;
5) The sporadic distribution and the low diversity of trace fossils are in part interpreted to result from persistent reworking of the sediment;
6) Cryptic bioturbation is generally formed in food/resource-rich marine environments;
7) The fluvial invasion can impact the preserve of trace fossils, as a result of low bioturbation intensities (BI=1-2).

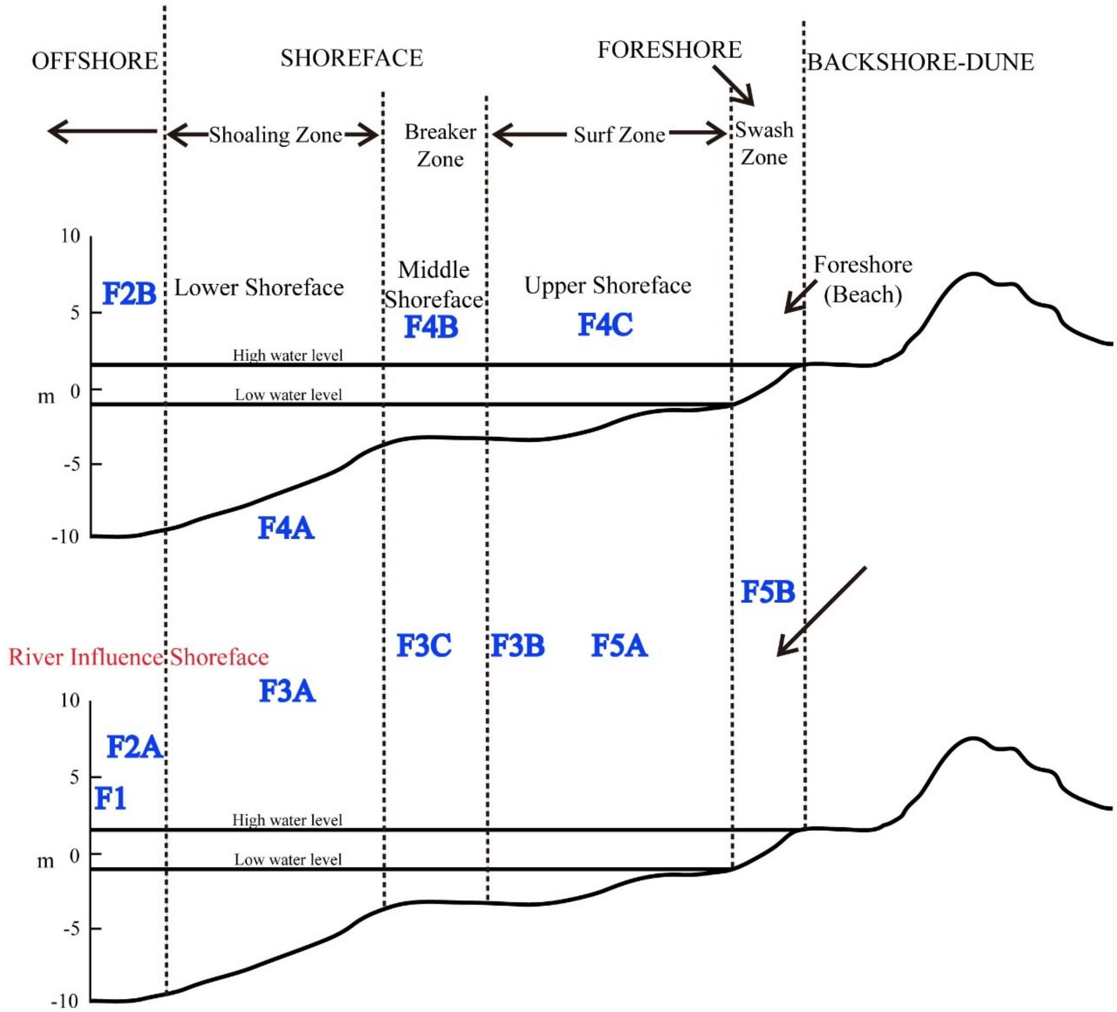


Figure 2-12: Facies association is interpreted to represent shoreface and wave-dominated delta environments (modifies from *Reinson, 1984*).

PETROGRAPHY

Petrographic analysis is very important because it is a method that defines the reservoirs on a smaller scale, e.g. the pore scale. Analysis on a smaller scale allows for the identification of controls on the reservoir properties (Newsham and Rushing, 2001).

Petrographic analysis includes identifying the mineralogy, texture and composition of the rocks because of their effect on porosity and permeability of the reservoirs, as well as the diagenesis (Newsham and Rushing, 2001). Diagenesis is also a significant feature to identify on the thin section scale because it is a process by which the original properties of the rocks are altered due to post-depositional processes (Pettijohn et al., 1987).

For studies of sandstone composition, texture, diagenesis and porosity, thin sections are routinely used. Eighteen samples are presented to illustrate the understanding the mineralogy and composition. Mineralogically, the Montney Formation is dominated by quartz. Although the percent of minerals vary, the percentage of quartz is 60% or less. To this end, a detailed description of nine thin sections from F4A, F4B, F4C, F5A, and F5B is presented below.

Table 2: Petrographic data for each facies

Facies	Grain size (mm)		Sorting	Roundness	Grain Fabric	Cement Type	Grain Contacts
F1	0.0106	Very fine silt			matrix supported		no contacts
F2A	0.0253	coarse silt	moderately	angular	grain supported	carbonate	point contacts
F2B	0.0441	coarse silt	moderately	angular	grain supported	carbonate	line contacts
F3A	0.0317	coarse silt	moderately	angular	grain supported	carbonate	point-line contacts
F3B	0.0498	coarse silt	moderately	angular	grain supported	carbonate	line contacts
F3C	0.0582	coarse silt	moderately	angular	grain supported	carbonate	concavo convex
F4A	0.0492	coarse silt	moderately	angular	grain supported	carbonate	point-line contacts
F4B	0.0605	very fine sand	moderately	angular	grain supported	carbonate	point contacts
F4C	0.0634	very fine sand	moderately	angular	grain supported	carbonate	point contacts
F5A	0.0712	very fine sand	well	sub-angular	grain supported	carbonate	concavo convex
F5B	0.0687	very fine sand	moderately	angular	grain supported	carbonate	line contacts

Table 3: mineral composition of each sandy facies

	Components						
	Quartz	Feldspar	Mica	Kerogen	Pores	Cement	Matrix
F4A	50%	0%	9%	8%	3%	19%	11%
F4B	51%	0%	9%	7%	6%	20%	7%
F4C	52%	0%	9%	7%	4%	19%	9%
F5A	53%	0%	7%	10%	9%	19%	2%
F5B	52%	0%	8%	7%	6%	21%	6%

Facies 4A (F4A): sandstone with muddy silt interlaminae

The F4A thin section sample shows that the mineralogy consists of quartz (50%) and mica (9%). Quartz grains range in size from medium silt to very fine sand. They are moderately sorted with and angular roundness, and subhedral in shape. Cementation accounts for 19% around the quartz, which is considered as carbonate. Kerogen (8%) is isolated. Porosity (3%) is observed by blue dye epoxy, and the rest is matrix. Very fine sand laminae are dominated by calcite and quartz. The contacts between grains range from point to line contacts. Features visible in thin section include planer to low angle lamination (Fig. 2-13).

Facies 4B (F4B): plane parallel laminated sandstone

The F4B thin section sample shows that the mineralogy consists of quartz (51%) and mica (9%). Quartz grains range in size from medium silt to very fine sand. They are moderately sorted with angular roundness, and subhedral in shape. Cementation accounts for 20% around the quartz, which is considered as carbonate. Kerogen (7%) is isolated. Porosity (6%) is observed by blue dye epoxy, and the rest is matrix. The contacts between grains are point contacts. Features visible in thin section include planer to low angle lamination (Fig. 2-14).

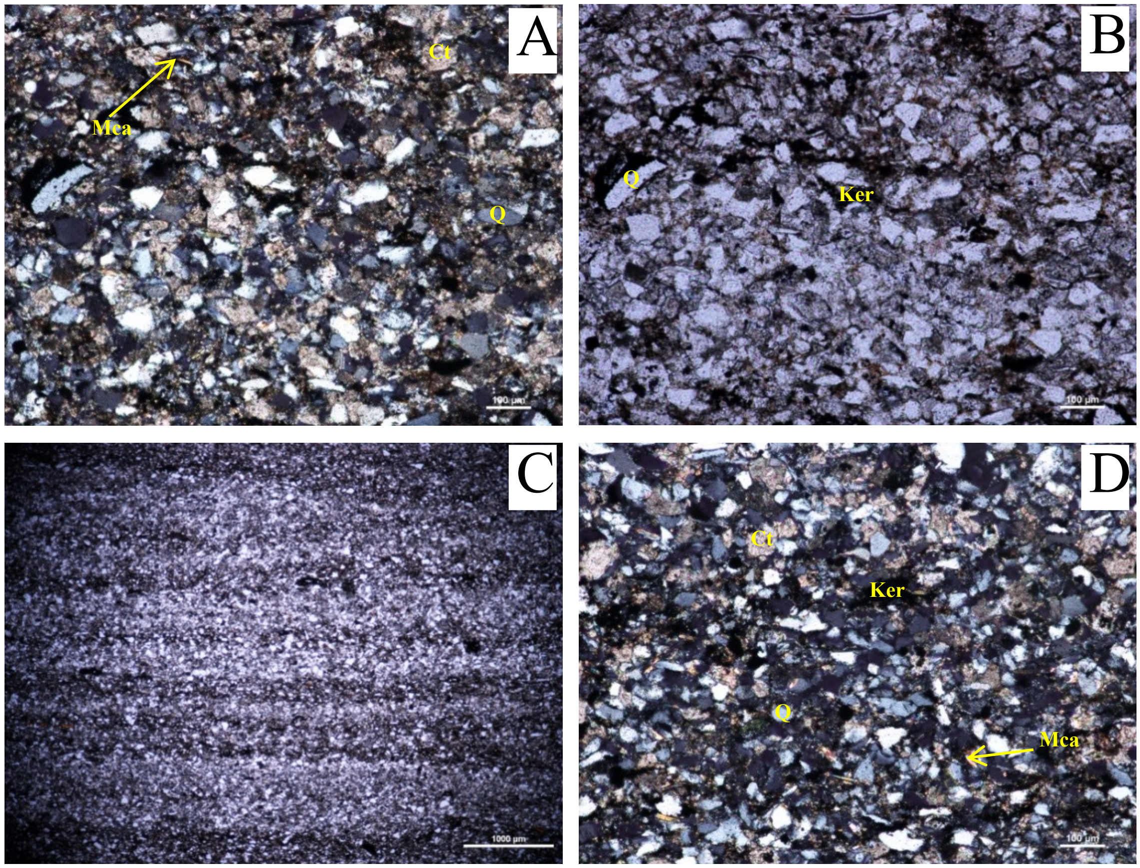


Figure 2-13: Facies4A (F4A): Sandstone with muddy silt interlaminae. **A**. Quartz, mica, kerogen, pores, and cement in fine-grained sands under crossed polars. **B**. Under plane-polarized light. **C**. Plane parallel lamination under plane-polarized light. **D**. Quartz, mica, kerogen, pores, and cement in fine-grained sands under crossed polars.

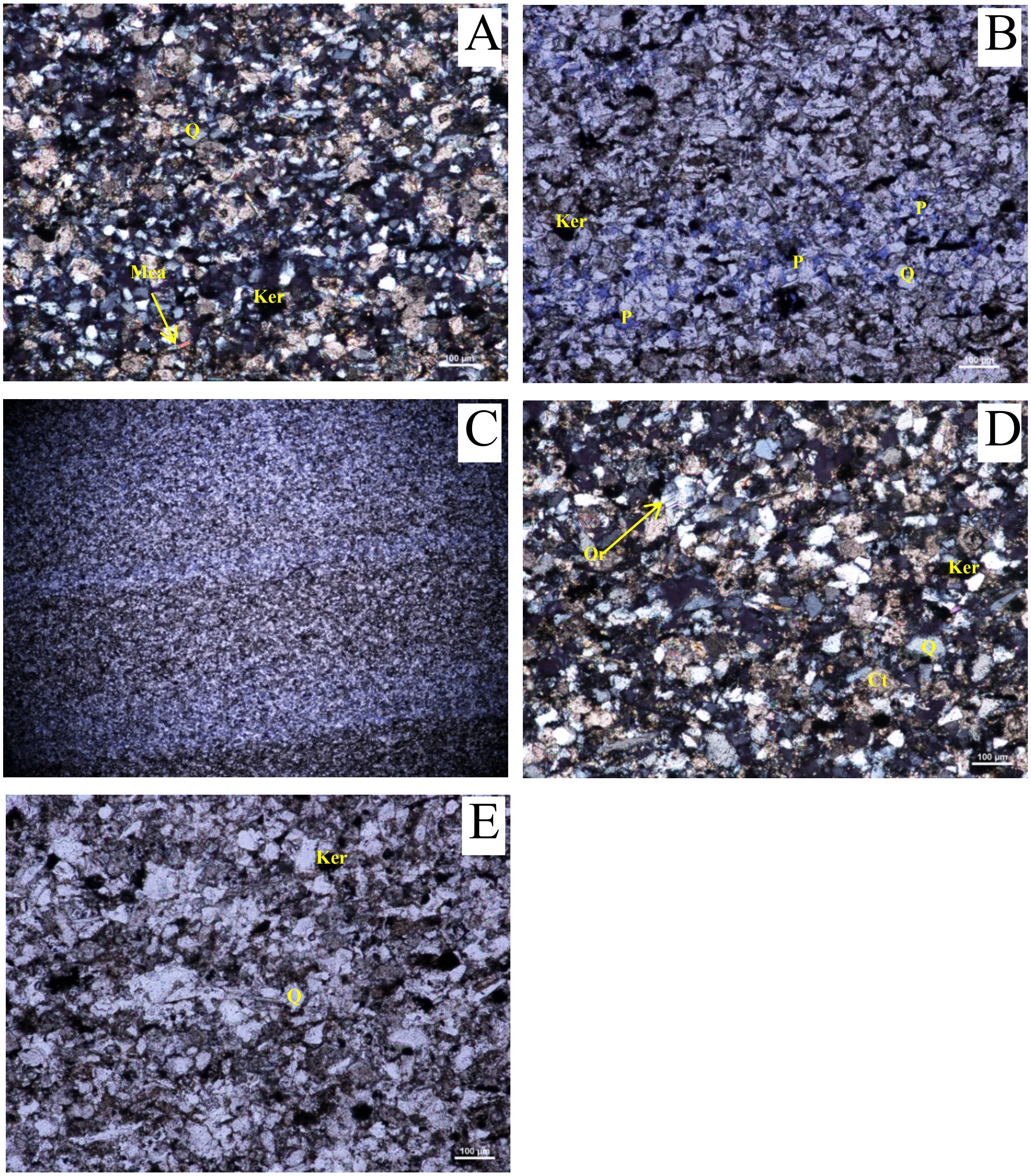


Figure 2-14: Facies4B (F4B): Plane parallel laminated sandstone. **A**. Quartz, mica, kerogen, pores, and cement in fine-grained sands under crossed polars. **B**. Under plane-polarized light. **C**. Fragment with pore space along plane parallel lamination under plane-polarized light.
Facies4C (F4C): Hummocky-cross stratified sandstone. **D**. Quartz, mica, kerogen, pores, and cement in fine-grained sands under crossed polars. **E**. Under plane-polarized light

Facies 4C (F4C): hummocky cross-stratified sandstone

The F4C thin section sample shows that the mineralogy consists of quartz (52%) and mica (9%). Quartz grains range in size from medium silt to fine sand. They are moderately sorted with angular roundness, and subhedral in shape. Cementation accounts for 21% around the quartz, which is considered as carbonate. Kerogen (7%) is isolated Porosity (4%) is observed by blue dye epoxy, and the rest is matrix. Very fine sand laminae are dominated by calcite and quartz. The contacts between grains range from point to line contacts. Features visible in thin section include planer to low angle lamination (Fig. 2-14).

Facies 5A (F5A): massive-appearing sandstone

The F5A thin section sample shows that the mineralogy consists of quartz (53%) and mica (7%). Quartz grains range in size from course silt to fine sand. They are well sorted with sub-angular roundness and subhedral to euhedral in shape. Cementation accounts for 19% around the quartz, which is considered as carbonate. Kerogen (10%) is isolated. Porosity (9%) is observed by blue dye epoxy, and the rest is matrix. The contacts between grains are concavo-convex contacts (Fig. 2-15).

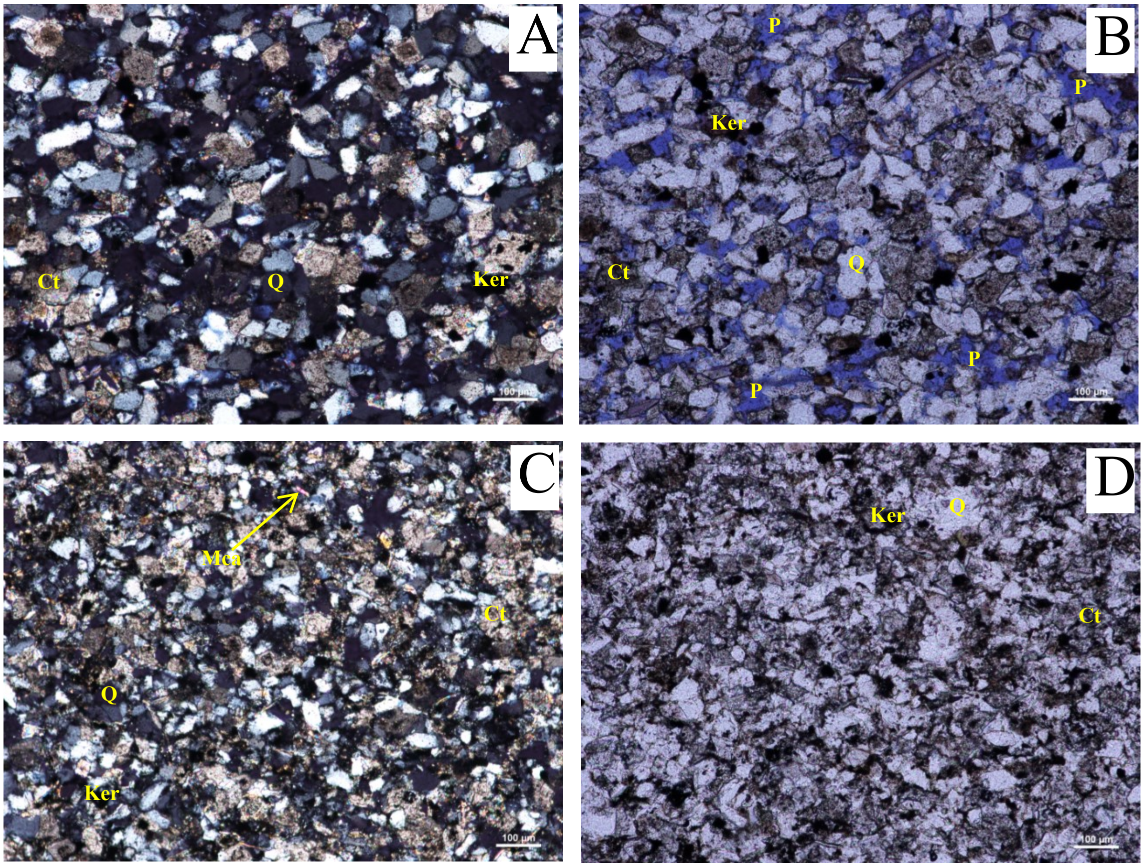


Figure 2-15: Facies5A (F5A): Massive-appearing sandstone. **A**. Quartz, mica, kerogen, pores, and cement in fine-grained sands under crossed polars. **B**. Under plane-polarized light.
Facies5B (F5B): Cryptobioturbated sandstone. **C**. Quartz, mica, kerogen, pores, and cement in fine-grained sands under crossed polars. **D**. Under plane-polarized light

Facies 5B (F5B): cryptobioturbated sandstone

The F5B thin section sample shows that the mineralogy consists of quartz (52%) and mica (8%). Quartz grains range in size from medium silt to fine sand. They are moderately sorted with angular roundness and subhedral to euhedral in shape. Cementation accounts for 21% around the quartz, which is considered as carbonate. Kerogen (7%) is isolated. Porosity (6%) is observed by blue dye epoxy, and the rest is matrix. The contacts between grains are line contacts (Fig. 2-15).

DISCUSSION

The Montney Formation in the study area is composed of fine- to very fine-grained sandstone interbedded with siltstone. The sedimentary facies described in this study were defined named Facies 1 through Facies 5, which provide sedimentological evidence as to the prevailing mechanism of sediment transport to the environment of deposition, including post-depositional modification. After initial deposition, sediments were reworked, and subsequently remobilized across shoreface to offshore. The depositional environment interpreted for the Montney Formation range from shoreface through offshore settings and deltaic conditions.

The sedimentary structures in the Montney Formation recorded from cores in the study area consists of plane to low-angle parallel lamination, combined flow ripples, climbing ripples, current ripples, hummocky cross-stratification, and convolute beddings. These structures were interpreted on the basis of the hydrodynamic processes prevalent during the process of these sedimentary structures. The sedimentary structures (e.g. plane parallel lamination and hummocky cross-stratification) suggest combined flow and wave-reworking. For example, hummocky cross-stratification is generated under oscillatory-dominant combined flow

Sedimentary deformational structures are result from wave loading (Pemberton and MacEachern, 2001; Zonneveld et al., 2010). Soft sedimentary deformation are commonly formed during a deformational event near or at the contemporary surface of unconsolidated sediments prior to, or soon after burial (Bhattacharya and Bandyopadhyay, 1998). These deformational structures are generally related to gravity acting upon the weak sediment, during or soon after deposition along the sediment surface (Collison, et al 2006). The occurrence of soft sediment deformation and convolute beddings in Facies 3B may provide evidence of penecontemporaneous event, or rapid deposition. However, Beranek and Mortensen, 2006; Ferri and Zonneveld, 2008 had interpreted some of the soft sediment deformation in the Montney Formation that may be related to initial terrane collision in the British Columbia/Yukon as part of a regional tectonism of Early to Middle Triassic.

The ichnofauna records in the study area are mostly associated with Facies 2, which is divided into Facies 2A and Facies 2B as *Cruziana* Ichnofacies. There are considerable diversity of trace fossils, which are *Asterosoma* (c), *Cylindrichnus* (r-m), *Diplocraterion* (r), *Helminthopsis* (m-c), *Palaeophycus* (r), *Arenicolites* (r), *Phycosiphon* (m-c), *Planolites* (c-a), *Rhizocorallium* (r), *Skolithos* (m-c), *Teichichnus* (m), and *fugichnia* (r). the escape traces (fugichnia) are common in some intervals of cores logged. *Phycosiphon* and *Helminthopsis* are the most pervasive and abundant in the study area. The limited numbers of suspension-feeding ichnofossils may indicate turbidity levels in the water column (Moslow and Pemberton, 1988; Gingras et al., 1998; Coates and MacEachern, 1999, 2000; Bann and Fielding, 2004; Hansen and MacEachern, 2007).

Pyrite in Facies 3A is related to post-depositional conditions. Pyrite is an important diagenetic mineral and their occurrence can provide evidence to define the diagenetic history of deposits (Hudson, 1982).

The observation of pores (dyed with blue) on the thin section indicate that the porosity may result from: 1) bioturbation enhancement from burrows; 2) organic matter dissolution during diagenesis; 3) artificial fracture along bedding planes during the logging. As reported by Pemberton and Gingras (2005), these unconventional reservoir can be increased by the activity of organisms.

CHAPTER III – THE INFLUENCE OF PERMEABILITY VALUES ON THE RESOURCE POTENTIAL OF MONTNEY FORMATION

INTRODUCTION

Permeability, the ability of the rock to allow the flow of fluid through the pores, is a crucial reservoir parameter. The permeability of a rock is controlled by grain size distribution, grain shape, packing, degree of sorting and cementation (Chehrazi and Rezaee, 2012).

The permeability analyses in the study are related to the overall textural heterogeneity, porosity, and ichnologic modification. As reported in Chapter II, the grain size of the Montney Formation sandstone ranges from fine to very fine. Due to the smaller grain size, the Montney Formation sandstones have a low permeability (Chehrazi and Rezaee, 2012). There is an exponential correlation between grain size and permeability.

Generally, permeability fabrics in flow media result from the lithofacies heterogeneities such as lamination, ichnologic modification, the arrangement and packing of grains, pore-throat distribution, and diagenetic modification (Gingras et al., 2005). The significant roles of bioturbation in reservoir media are: 1) ichnofossils maintain chemical characteristics which differ from the surrounding media; 2) ichnofossils modify pore-throat distribution; 3) ichnofossils serve as location of cementation and/or dissolution during early diagenesis; 4) ichnofossils provide permeability conduits which can enhance both horizontal and vertical permeability (Gingras et al., 2005).

Contemporary ichnological research shows that the utility of ichnofossils exceeds palaeoenvironmetal and stratigraphic applications. Burrowing organisms alter the sedimentary fabric, resulting in differential permeabilities and porosities between the burrow and surrounding matrix (Meadow and Tait, 1989; Lee and Foster, 1991; Pierret et al., 1999, 2002; Gingras et al., 2002a, b; Bastardie et al., 2003). Since trace fossils alter the physical characteristics of porous media, they may provide flow conduits for the migration and production of fluids, including oil and gas (Gingras et al., 2004a; Pemberton and Gingras, 2005; Lemiski et al., 2011)

METHODS

Spot-Minipermeametry Testing

Spot-minipermeametry was conducted by using a Core Laboratories PDPK-400 Pressure-Decay Profile Permeameter on Montney Formation core from three wells (well 14-33-73-26w5, well 13-03-74-26w5, and well 16-14-73-26w5), and was tested on the flat surfaces of the core at core laboratory, Department of Earth Atmospheric Science, University of Alberta. Spot-permeability analysis required a flat surface for measurements. Slabbed core samples were selected from each facies in order to evaluate facies heterogeneity. Subsequently, spot-minipermeametry testing was conducted on all the facies (Chapter II). The measurements were conducted selectively, based on the sedimentary fabric.

The PDPK – 400 is a pressure decay system measures gas permeabilities from 0.001 millidarcy to greater than 30 Darcy and it consists of an air tank which supplies nitrogen to the probe assembly, the core rack which holds the samples, a monitor that displays measurement results, and a computer that stores data (Fig. 3-1). Four accurately calibrated volumes that are initially charged with nitrogen make up the probe assembly. These volumes are considered as the "tank supply". The permeameter controls comprise a probe regulator and tank supply, their respective gauges, and a firing button which initiates a permeability measurement.

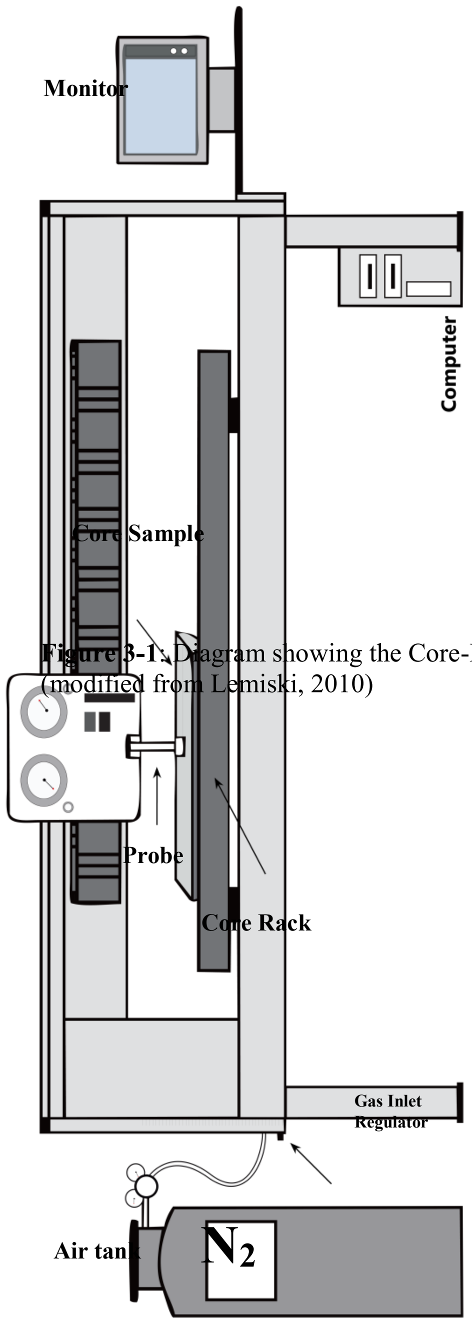


Figure 3-1: Diagram showing the Core-Laboratories PDPK-400 Pressure Decay Profile Permeamete (modified from Lemiski, 2010)

Spot-minipermeametry testing was carried out by placing the probe assembly and core rack in a desired location. To initiate a permeability measurement, the probe's rubber tip was then sealed against the sample using a pneumatic cylinder. Afterwards, the computer-controlled probe valve was opened, and the pressure in the tank and probe assembly was recorded as a function of time. The maximum time of a permeability measurement is generally set at 24 seconds; however, extreme accuracy and repetitiveness is required for low permeability data (Core Laboratories Instruments, 1996). Due to this reason, a maximum run time was 40 seconds during spot-minipermeametry testing of Montney Formation.

Permeameter experiments were conducted on burrows, burrow wall, and non-burrowed areas. Samples were taken from each of the facies identified with special emphasis on the productive zones. Based upon the result of spot-minipermeametry testing, the minimum and maximum data for each facies were discarded. The PDPK – 400 is an excellent device to provide precise permeability measurements. However, due to the limitation of sample selection, small pieces of the core were not examined.

MONTNEY FORMATION FACIES

In the study area, the Montney Formation ranges from 40-60 m thick. The following description of the Montney Formation in the study area is based upon detailed core descriptions, which are supplemented with sedimentological and ichnological characteristics and wireline log profiles. This paper uses the bioturbation index (BI) classification that was was modified by Droser & Bottjer (1986), (see Chapter II).

Herein, the Montney Formation strata are subdivided into six recurring facies and eleven subfacies. The details of facies analysis for Montney Formation depend on description of cores. Core analysis conducted on three cores, including well 14-33-73-26w5, well 13-03-74-26w5, and well 16-14-73-26w5 in the Puskwa Field (Table 1).

A summary of spot-minipermeametry results are presented in Table 4. The table contains three parts, including details of testing methods, permeability characteristics, and remarks. The remarks column indicates the corresponding permeability classification of each facies deserved in this study. The permeability values of each facies are shown within description of each facies. The descriptions of the permeability distributions for each facies are discussed below.

SPOT-MINIPERMEAMETRY RESULTS

Spot-minipermeametry results indicate that facies within the Montney Formation can be characterized by three permeability classification types, including:

1) Permeability Classification 1 (PC1): Extremely low permeability measurements commonly ranging from 0.02-0.3 md. These values are generally associated with Facies 1.
2) Permeability Classification 2 (PC2): Slightly higher permeability succession, resulting mainly from the primary sedimentary fabric Permeability Classification 2 typically occurs in Facies 2A, Facies 3, and Facies 4A generally ranging from 0.02 to 0.9 md.
3) Permeability Classification 3 (PC3): Well defined, and localized high permeability fields. Normally associated with ichnological heterogeneities. Unburrowed matrix permeability differs by more than two orders of magnitude when compared with burrow-associated permeability. Permeability with these characteristics is typically associated with Facies 2B, Facies 4B, Facies 4C, and Facies 5, generally ranging from 2 to 20 md.

Table 4: Permeability data of each facies

Facies	Permeability Characteristics	Remarks
Facies 1 Structureless Muddy Siltstone	• 0.02-0.3 md	• K Classification 1
Facies 2A Weakly Burrowed Silty Sandstone Interbedded with Silty Mudstone	• bioturbated silty sandstone: 0.2-1 md • matrix: 0.05-0.2 md • burrow permeability very slight increase compared with silty matrix	• K Classification 2
Facies 2B Moderately Burrowed Silty Sandstone Interbedded with Silty Mudstone	• bioturbated silt/sandstone: 0.2-8 md • matrix: 0.05-0.2 md	• K Classification 3 • Potential K-streak
Facies 3A Plane Parallel Laminated Silty Sandstone	• planar laminated sandstone: 0.05-1 md • values greater than 1 md also occur, however, these are rare	• K Classification 2
Facies 3B Loading Sedimentary Deformed Silty Sandstone	• deformational structure siltstone: 0.02-0.3md • plane laminated sandstone: 0.2-0.8md • values greater than 1 md also occur, however, these are extremely rare	• K Classification 2
Facies 3C Hummocky Cross-stratified Silty Sandstone	• sandstone: 0.1-0.8 md • values greater than 1 md also occur, however, these are rare	• K Classification 2
Facies 4A Sandstone with Silt Interlaminea	• muddy interval: 0.02-0.04 md • planar laminated sandstone: 0.2-0.9 md	• K Classification 2
Facies 4B Plane Parallel Laminated Sandstone	• 0.3-15 md • values greater than 1 md also seldom occur	• K Classification 3 • Potential K-streak
Facies 4C Hummocky Cross-stratified Sandstone	• 0.4-15 md • values greater than 1 md also seldom occur	• K Classification 3 • Potential K-streak
Facies 5A Massive-Appearing Sandstone	• massive sandstone: 1-20 md	• K Classification 3 • Potential K-streak
Facies 5B Cryptobioturbated Sandstone	• 0.8 to 8md • permeability values less than 1 md rare occur • permeability values greater than 10 md also rare occur	• K Classification 3 • Potential K-streak

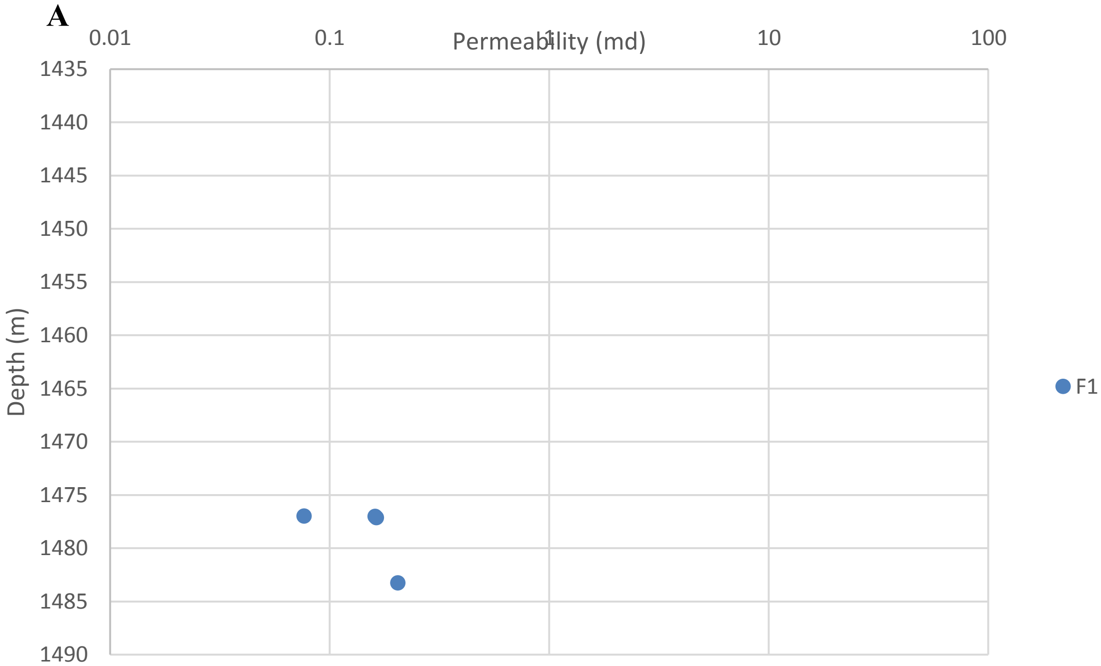
Facies 1 (F1): structureless muddy siltstone

Facies 1 consists of successions of dark grey muddy siltstones. None bioturbation were observed in this facies and the only observation is the planar bedding (rare). This facies exhibits permeability ranging from 0.02-0.3 md. Limited data is available (Fig.3-2). Permeability characteristics can be recognized as extremely low (K classification 1).

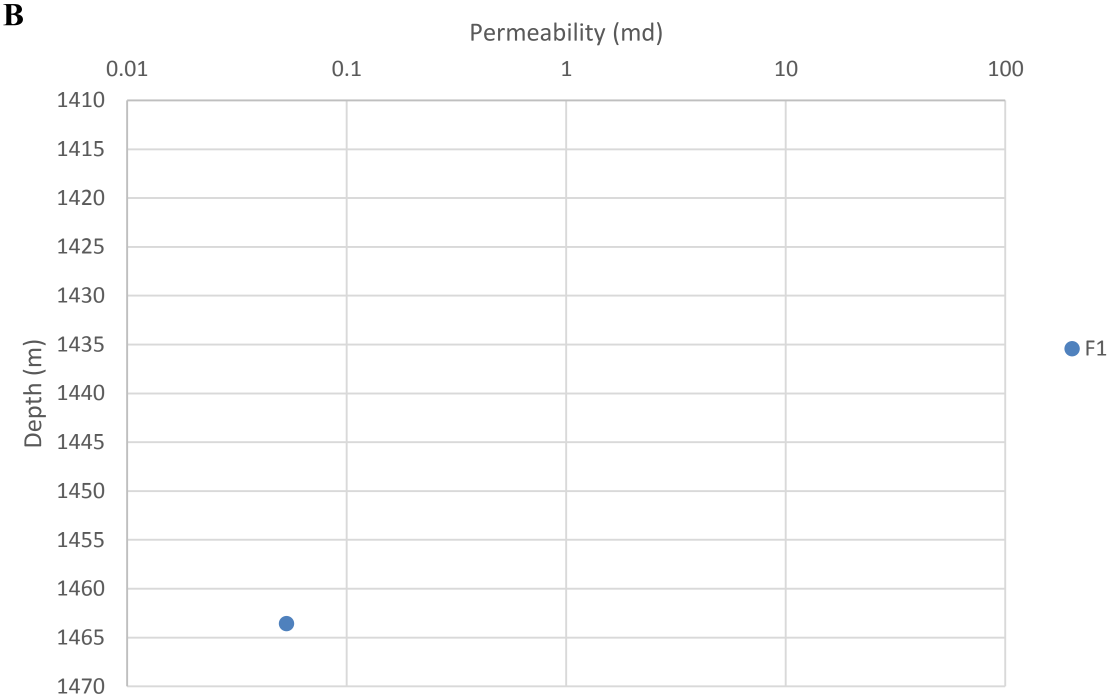
F1 Permeability Interpretation:

1) The finer grain-size leads to low permeability.
2) Limited data is due to sampling difficulties.

A



B



C

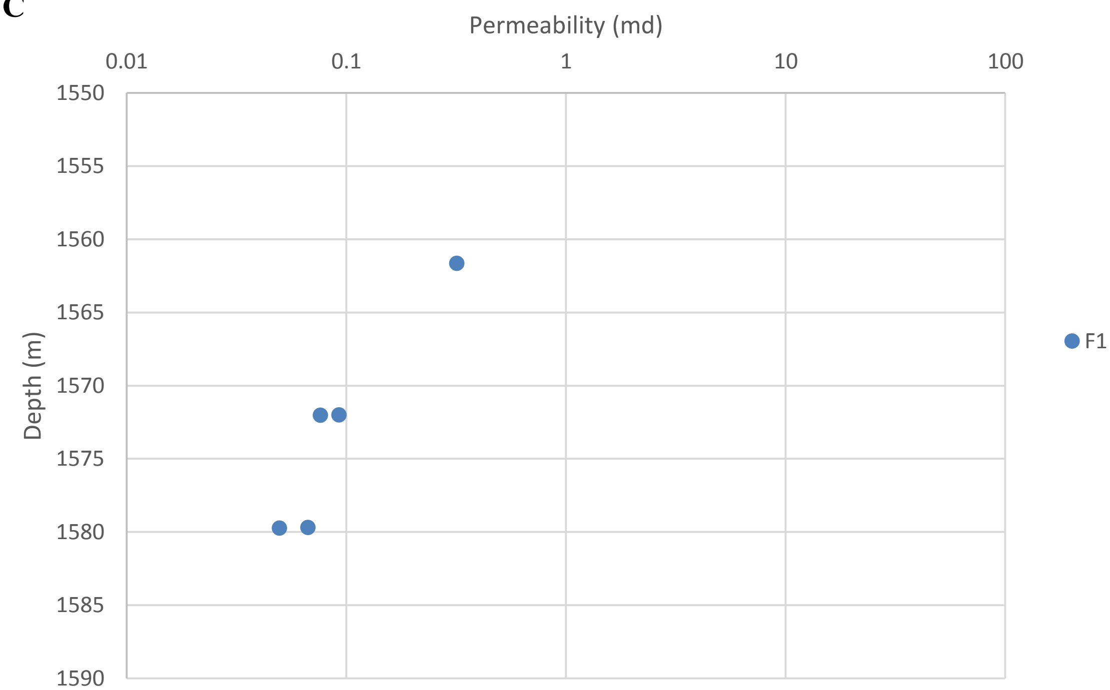


Figure 3-2: Permeability measurements for F1 in well 14-33-73-26w5 (A), well 13-03-74-26w5 (B), and well 16-14-73-26w5 (C).

Facies 2A (F2A): weakly burrowed silty sandstone interbedded with siltstone

Facies 2A comprises regularly alternating (millimeter- to centimeter-thick) fine- to very fine-grained sandstone and siltstone, and interbedded siltstones. Due to the sporadic distribution of trace fossils and small burrow diameter (generally < 4 mm), slight differences in permeability occur between burrows and unburrow media. Within F2A, unburrowed silty laminae present low permeability values ranging from 0.05-0.2 md, whereas bioturbated silty sandstone exhibit permeability ranging from 0.2-1 md (Fig.3-3). Permeability characteristics can be recognized as K Classification 2.

Facies 2B (F2B): moderately burrowed silty sandstone interbedded with siltstone

Facies 2B comprises of regularly alternating (millimeter- to centimeter-thick) fine to very fine-grained sandstone and siltstone, and interbedded siltstone. Trace fossils are sporadically distributed and small burrow diameter (generally < 5 mm), and differences in permeability are observed between burrow and unburrowed media. Within F2B, unburrowed silty laminae present low permeabilities ranging from 0.05-0.2 md, whereas bioturbated silty sandstone exhibits permeabilities ranging from 0.2-8 md (Fig.3-3). Permeability values of F2B have a narrower range than F2A (Fig.3-3). Permeability characteristics can be recognized as highly contrasting permeability (K Classification 3).

F2 permeability interpretation:

1) Burrows may increase local pore volume and improve connectivity that are particularly important in enhancing permeabilities.

2) Bioturbation may have the potential to increase isotropy by destroying sedimentary laminae.

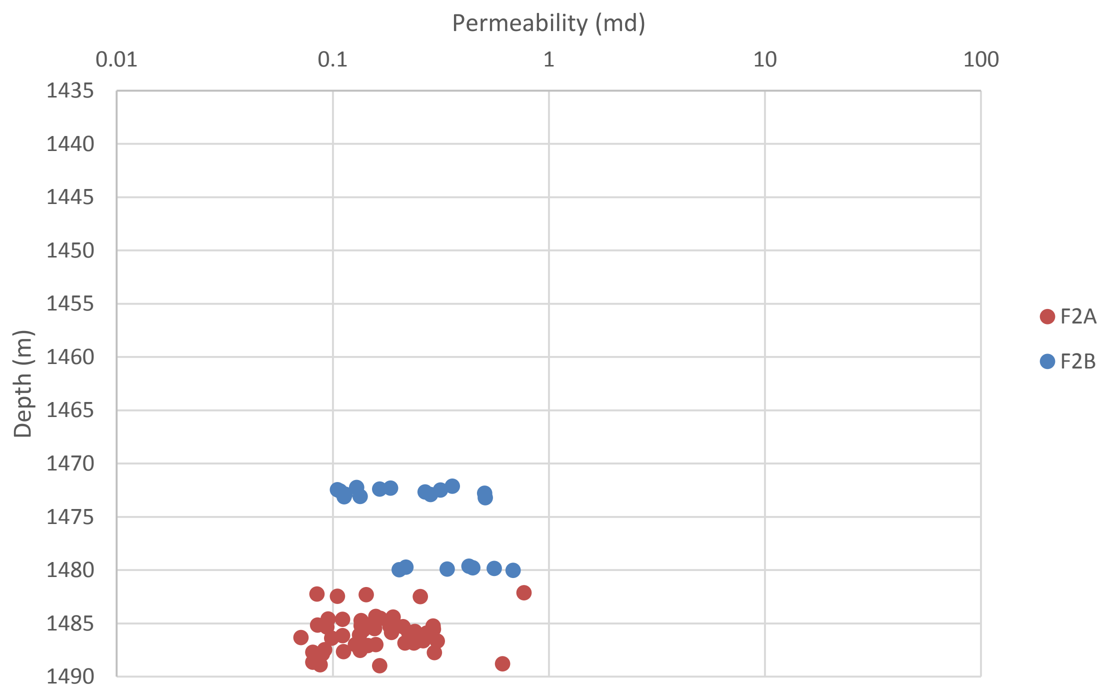


Figure 3-3: Permeability measurements for F2 in well 14-33-73-26w5

Facies 3A (F3A): plane parallel laminated silty sandstone

Facies 3A consists of well sorted, upper very fine-grained to lower fine-grained sandstone with 30-40% siltstone laminae. Due to the volumetric importance of this facies, numerous permeability measurements were taken. Within F3A, siltstone bed exhibits permeability ranging from 0.02-0.4 md, whereas planar laminated sandstone beds display permeability ranging from 0.05-1 md (Fg.3-4). Values greater than 1 md commonly occur in well 14-33-73-26w5. Higher permeability values (> 10 md) rarely occur (Fig.3-3). With very low bioturbation, the impact of trace fossils on permeability can be ignored. Due to the low contrast in permeability fields, this facies is K Classification 2.

Facies 3B (F3B): loading sedimentary deformed silty sandstone

Facies 3B comprises interbedded fine to very fine-grained sandstone and siltstone. Within F3B, deformed siltstone beds exhibit permeabilities ranging from 0.02-0.3 md, whereas planar laminated sandstones display permeability ranging from 0.2-0.8 md (Fig.3-4). Values greater than 1 md rarely occur. Higher permeability values (> 10 md) were not measured during test. With very low degree of bioturbation, the impact of trace fossils on permeability values is minimal. This Facies is also recognized as K Classification 2.

Facies 3C (F3C): hummocky cross-stratified silty sandstone

Facies 3C comprises regularly alternating fine to very fine-grained sandstone, siltstone, and silty sandstone. Within F3C, siltstone beds exhibit permeabilities ranging from 0.02-0.4 md, whereas cross-laminated sandstone display permeability ranging from

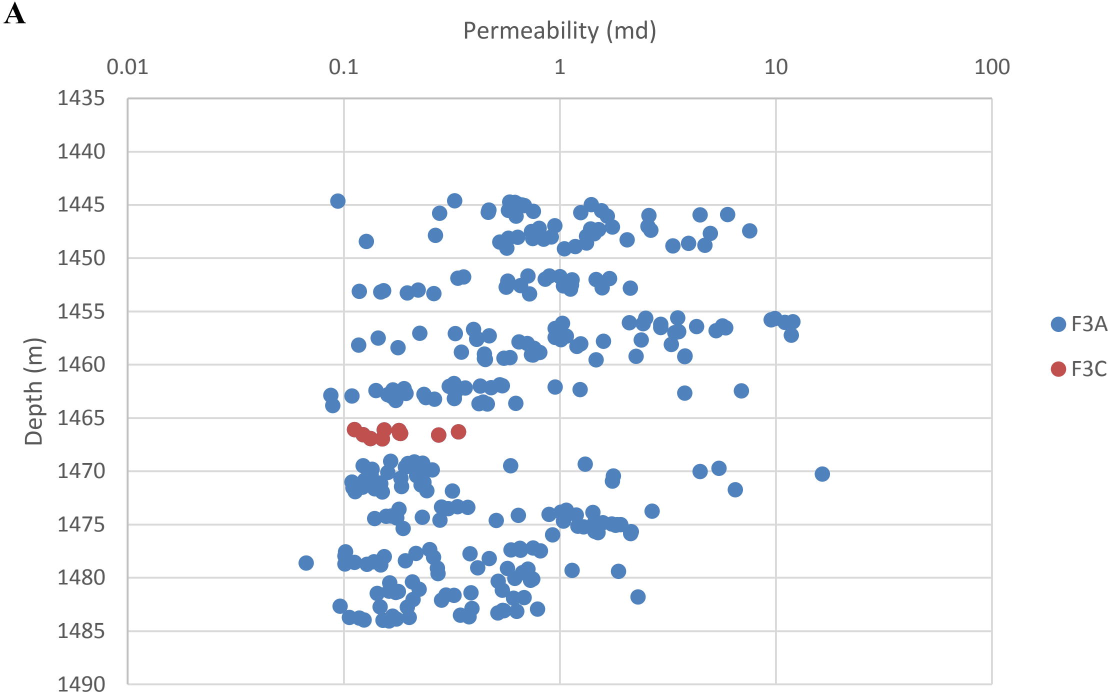
0.1-0.8 md (Fig.3-4). Values greater than 1 md occur in well 13-03-74-26w5 and well 16-14-73-26w5. The permeability values (> 10 md) rarely occur in well 16-14-73-26w5. This Facies is also recognized as K Classification 2.

F3A, F3B, and F3C, all display permeability values that have a wide range. The chart showing F3 (Fig.3-4) permeabilities shows an increasing-upward permeability trend.

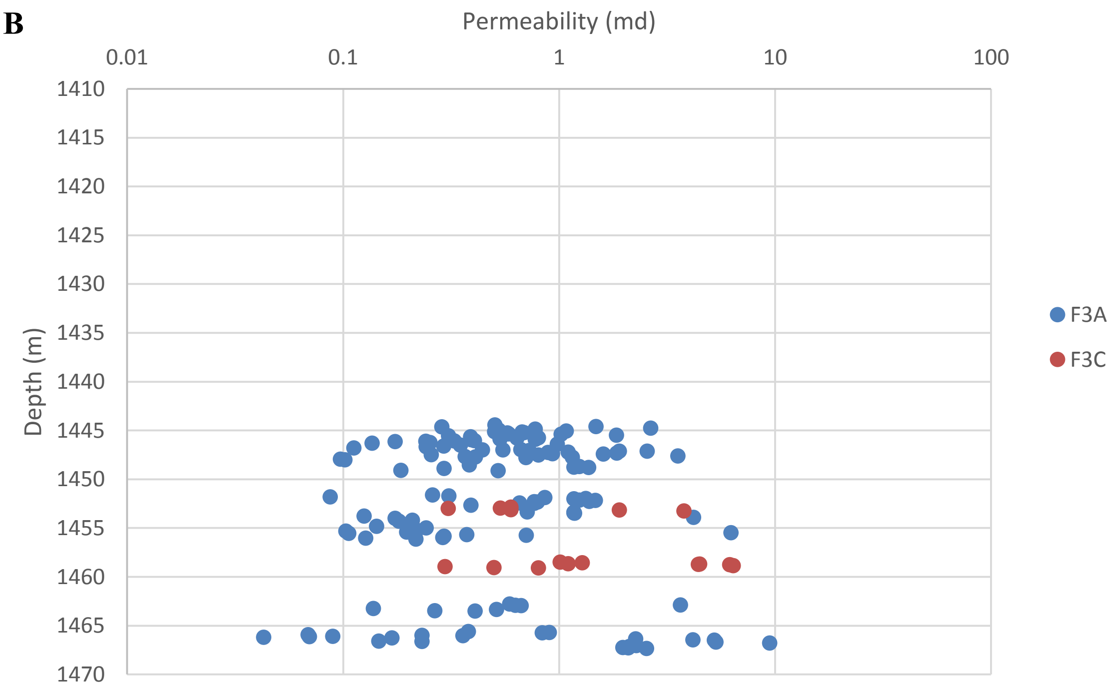
F3 permeability interpretation:

1) Permeability values higher than 10 md may result from poor cementation based on petrographic analysis (page 61, Table 2).
2) Based on the core observation, grain size is increasing from the bottom (F3A) to top (F3C) (Table 2, page 61). Minor coarsening-upward grain size influence permeability values increasing-upward.
3) Burial compacting may also influence the permeability trends, and this would suggest some early cementation, thereby preserving a shallow-burial porosity profile.
4) The influence of bioturbation on permeability values is minimal.
5) Macro-pore is also the observation in the core (Chapter II page 32). This may be produce higher permeability measurements.

A


Permeability (md)
0.01
0.1
1
10
100
Depth (m)
1435
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
F3A
F3C

B


Permeability (md)
0.01
0.1
1
10
100
Depth (m)
1410
1415
1420
1425
1430
1435
1440
1445
1450
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1460
1465
1470
F3A
F3C

C

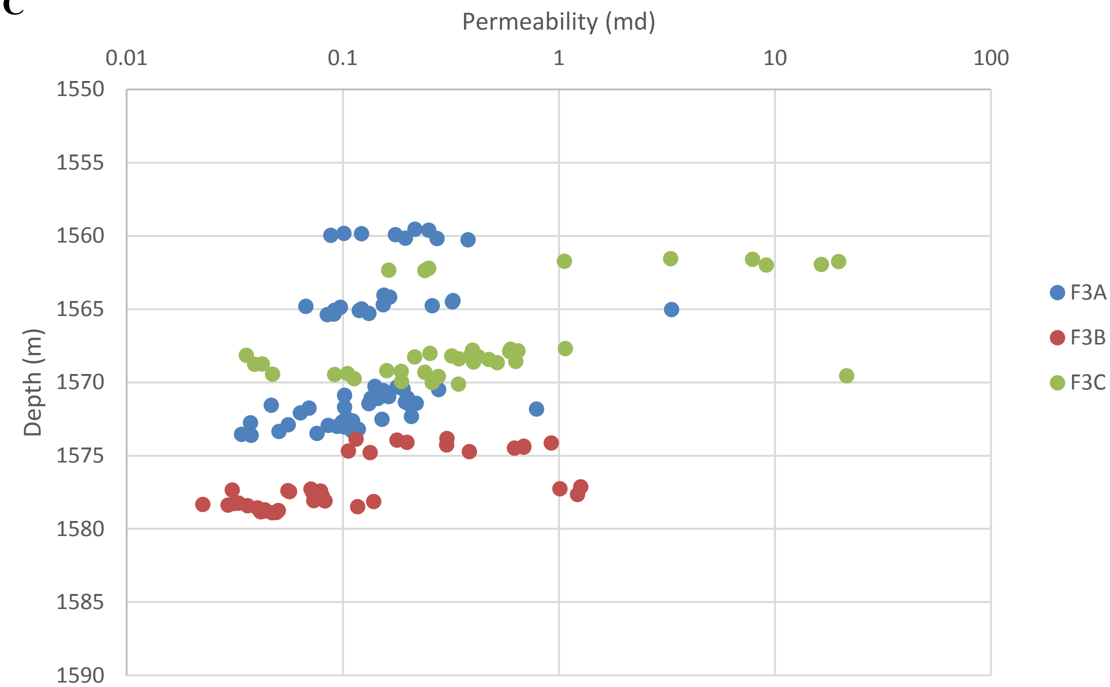


Figure 3-4: Permeability measurements for F3 in well 14-33-73-26w5 (A), well 13-03-74-26w5 (B), and well 16-14-73-26w5 (C).

Facies 4A (F4A): sandstone with silty interlaminae

Facies 4A consists of alternating (millimeter to centimeter thick) fine to very fine-grained sandstone and siltstone. Within F4A, cemented silty laminae measured ranges from 0.02 md to 0.4 md, whereas interbedded sandstones exhibit permeability ranging from 0.2-0.9 md (Fig.3-5). The permeability values (> 10 md) are sporadically observed in well in well 14-33-73-26w5. With very low degrees of bioturbation, the impact of bioturbation on permeability distributions can be ignored. Permeability characteristics can be recognized as slightly contrasting permeability (K Classification 2).

Facies 4B (F4B): plane parallel laminated sandstone

This facies consists of well sorted, fine to very fine-grained sandstones. Within F4B, sandstones exhibit permeability ranging from 0.3-15 md (Fig.3-5). Values greater than 1 md commonly occur in well 13-03-74-26w5 and well 16-14-73-26w5. Higher permeabilities (>10 md) rarely occur in well 13-03-74-26w5 and well 16-14-73-26w5. Permeability characteristics can be recognized as highly contrasting permeability (K classification 3). Due to relatively high permeability values, this facies is considered as a possible gas reservoir flow conduit.

Facies 4C (F4C): hummocky cross-stratified (HCS) sandstone

This facies consists of well sorted, fine to very fine-grained sandstones. Within F4D, sandstone exhibits permeabilities ranging between 0.4-15 md (Fig.3-5). Values greater than 1 md also commonly occur in well 14-33-73-26w5, well 13-03-74-26w5, and well 16-

14-73-26w5. Higher permeability values (> 10 md) rarely occur in well 13-03-74-26w5 and well 16-14-73-26w5. Permeability characteristics can be recognized as highly contrasting permeability (K classification 3). Due to relatively high permeability values, this facies to represent a flow unit.

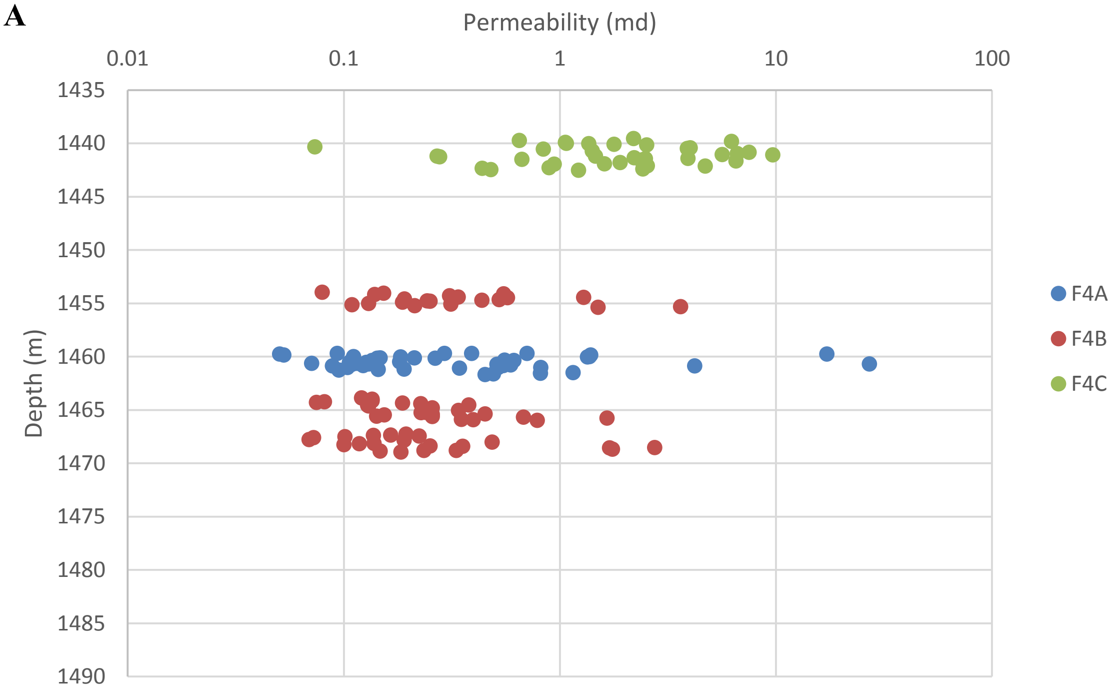
F4A, F4B, and F4C, all display permeability values that have a relatively narrow range. The chart showing F4 (Fig.3-5) permeabilities show a very mild increasing-upward permeability trend.

F4 permeability interpretation:

1) Lithologic homogeneity of F4B and F4C contributes to the narrow range in the chart.
2) Permeability values higher than 10 md of F4B and F4C may result from poor cementation of the sandstones. This is evidenced by petrographic analysis (Chapter II Fig2-14).
3) Based on the core observation, grain size is increasing from the bottom (F4A) to top (F4C) (Chapter II Petrography, Table 2, page 61). Increasing-upward permeability values may be impacted by minor coarsening-upward grain size.
4) Burial compaction may also influence the permeability trends, and this would suggest some early cementation, thereby preserving a shallow-burial porosity profile.
5) The influence of bioturbation can be ignored due to the absence of ichnofossils observation.

6) Outlying data points (> 10 md) may be influence by local fractures or poor permeameter seal.

A



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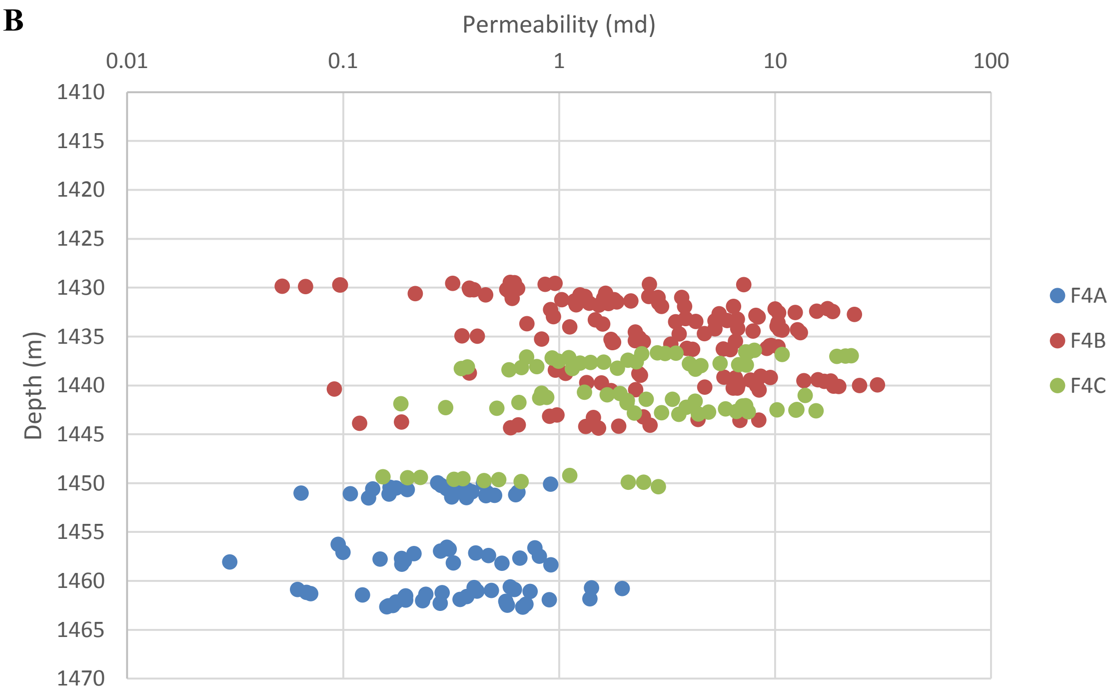

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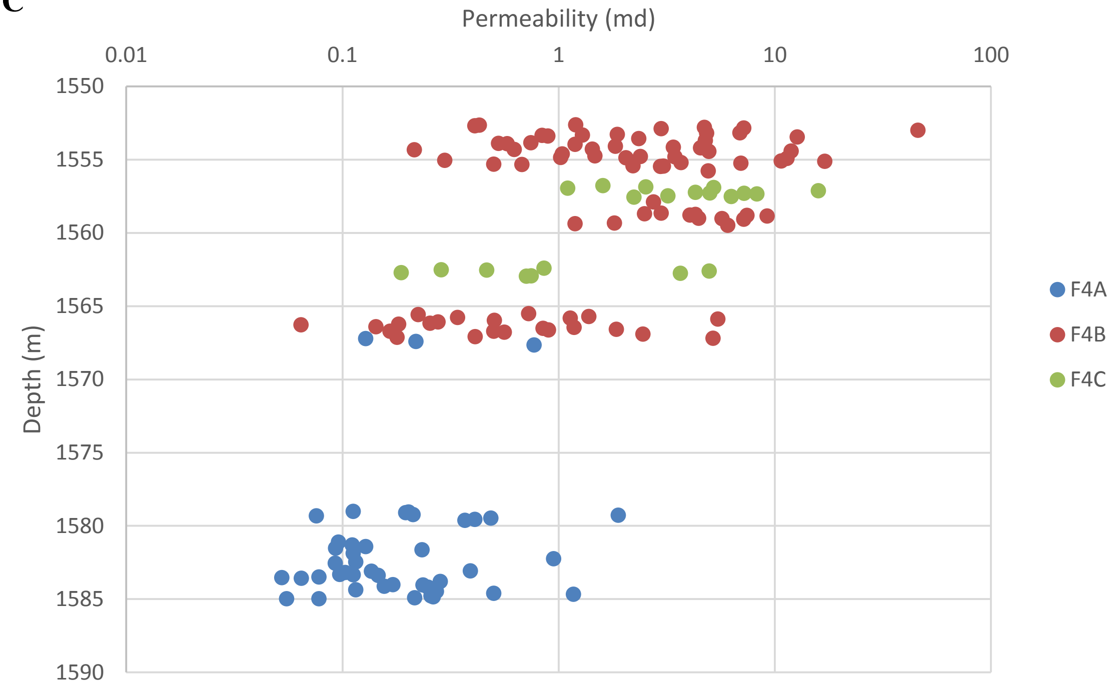


Figure 3-5: Permeability measurements for F4 in well 14-33-73-26w5 (A), well 13-03-74-26w5 (B), and well 16-14-73-26w5 (C).

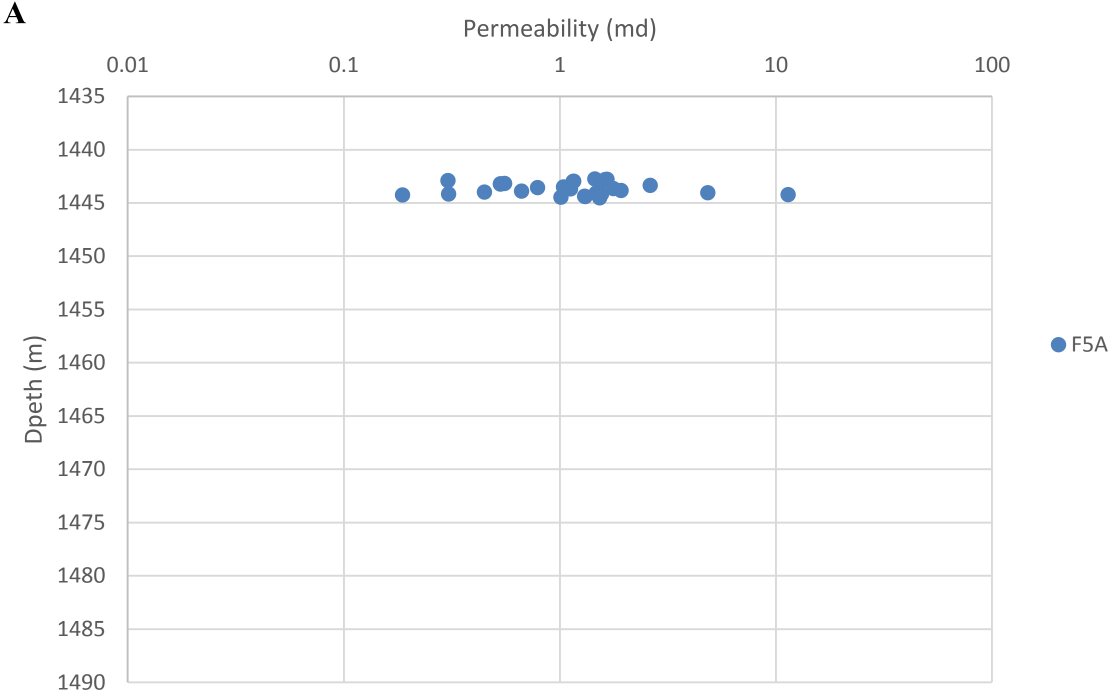
Facies 5A (F5A): massive-appearing sandstone

Facies 5A consists of fine-grained sandstone. Within F5A, sandstones display permeability ranging from 0.3-20 md (Fig.3-6). Permeability measurements (>1 md) commonly occur in well 14-33-73-26w5, well 13-03-74-26w5, and well 16-14-73-26w5. Higher permeability values (>10 md) rarely occur in well 16-14-73-26w5. Permeability characteristics can be recognized as high permeability (K Classification 3). Due to relatively high permeability values, this facies is considered as a possible reservoir flow conduit.

F5A permeability interpretation:

1) High value (>10 md) may due to poor cementation and presence of kerogen which is recognized under microscopy during petrographic analysis (Chapter II Fig2-15).
2) Burial compaction may also influence the permeability trends, and this would suggest some early cementation, thereby preserving a shallow-burial porosity profile.
3) The influence of bioturbation can be ignored.

A


Permeability (md)
0.01
0.1
1
10
100
1435
1440
1445
1450
1455
1460
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1470
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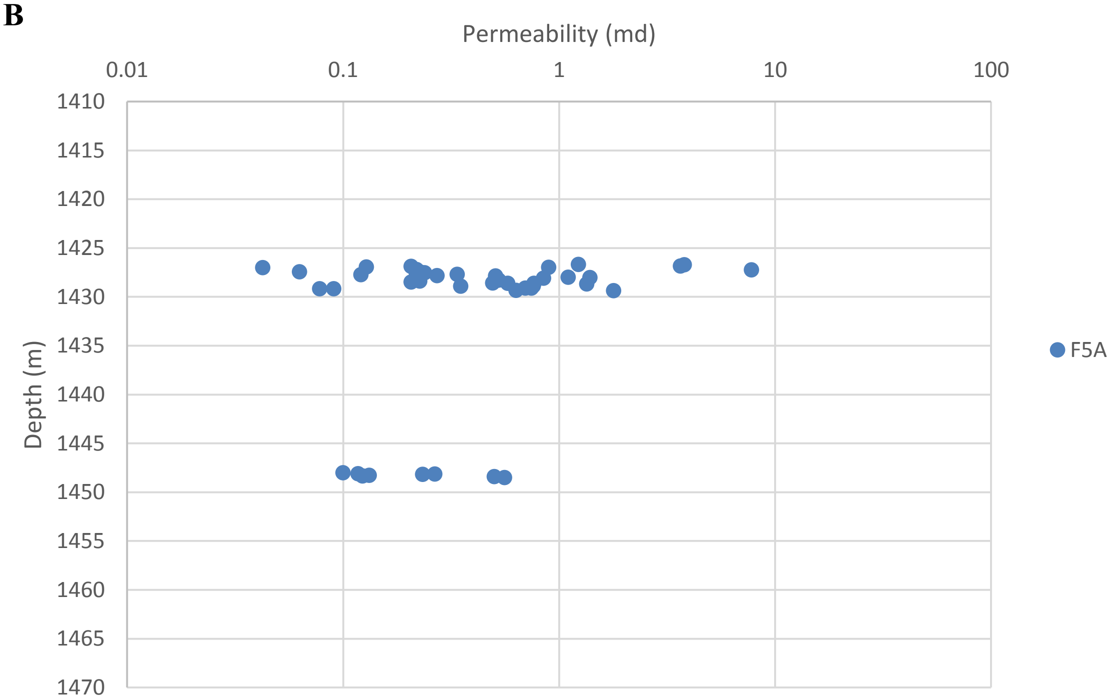
1480
1485
1490
Dpeth (m)
F5A

B


Permeability (md)
0.01
0.1
1
10
100
1410
1415
1420
1425
1430
1435
1440
1445
1450
1455
1460
1465
1470
Depth (m)
F5A

C

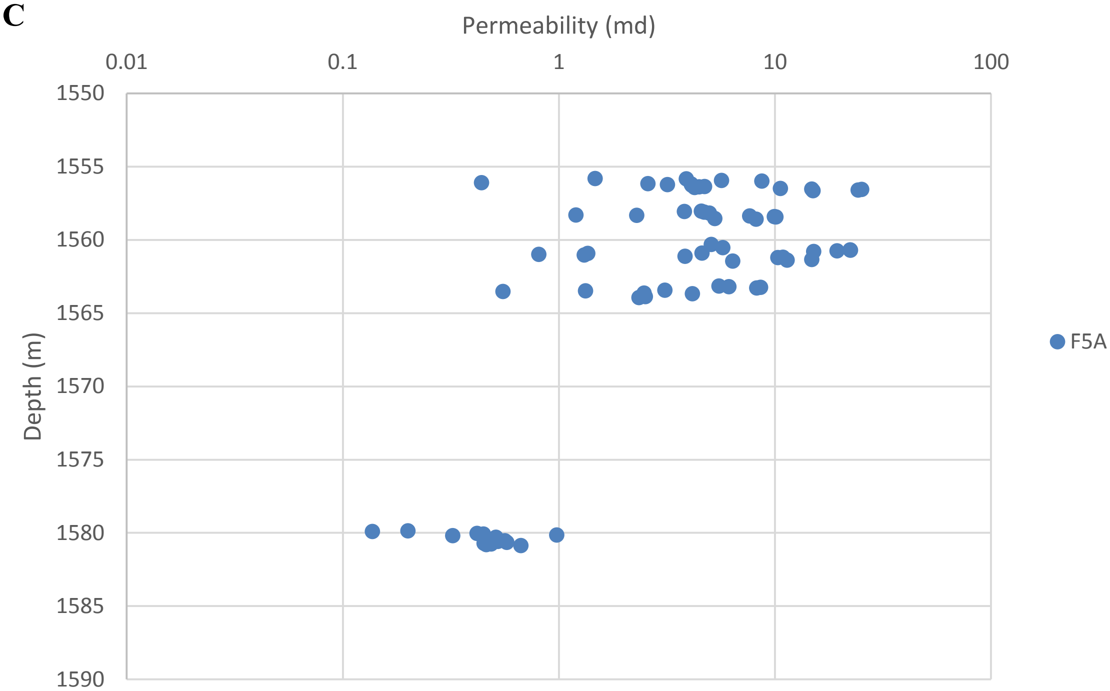


Figure 3-6: Permeability measurements of F5A in well 14-33-73-26w5 (A), well 13-03-74-26w5 (B), and well 16-14-73-26w5 (C).

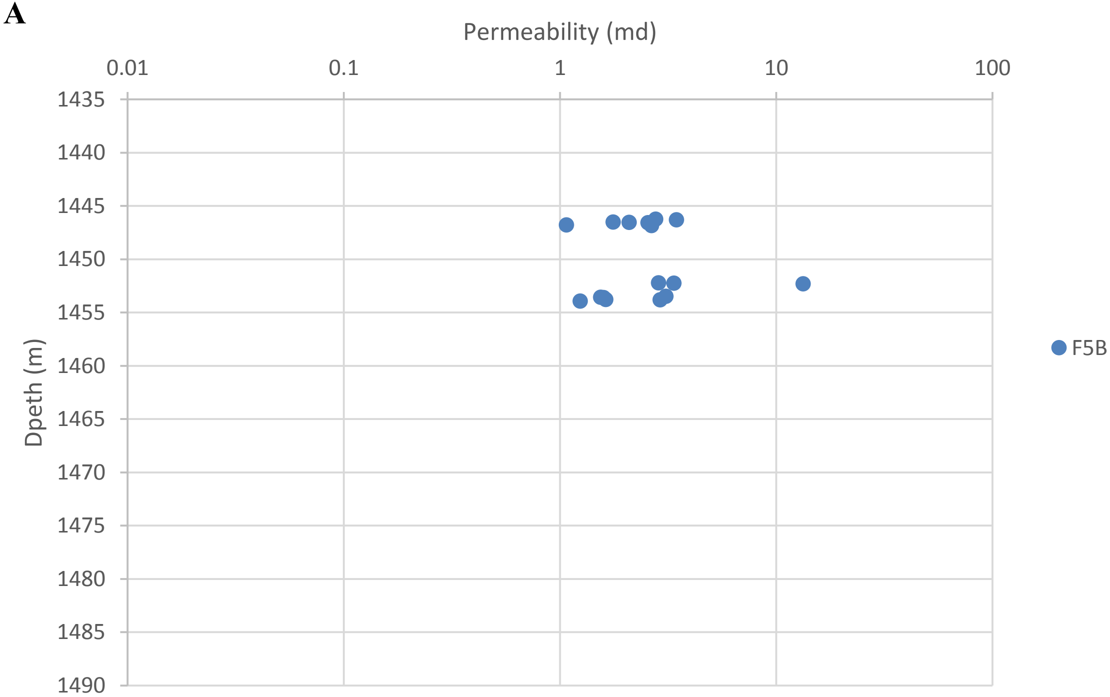
Facies 5B (F5B): cryptobioturbated sandstone

Facies 5B consists of very fine to fine-grained sandstone. Within F5B, cryptobioturbated sandstones exhibit permeability ranging from 0.8 – 8 md (Fig.3-7). The permeability values (> 1 md) commonly occur with a narrow range in well 14-33-73-26w5, well 13-03-74-26w5, and well 16-14-73-26w5. Permeability characteristics can be recognized as highly contrasting permeability (K classification 3). Due to relatively high permeability values, this facies is considered as a possible gas reservoir flow conduit.

F5B permeability interpretation:

1) The narrow range of permeability data of F5B may be result from lithologic homogeneity, in association with cryptobioturbation.
2) Cryptic bioturbation may alter the distribution of grain sizes, resulting in increased homogeneity and isotropy.

A



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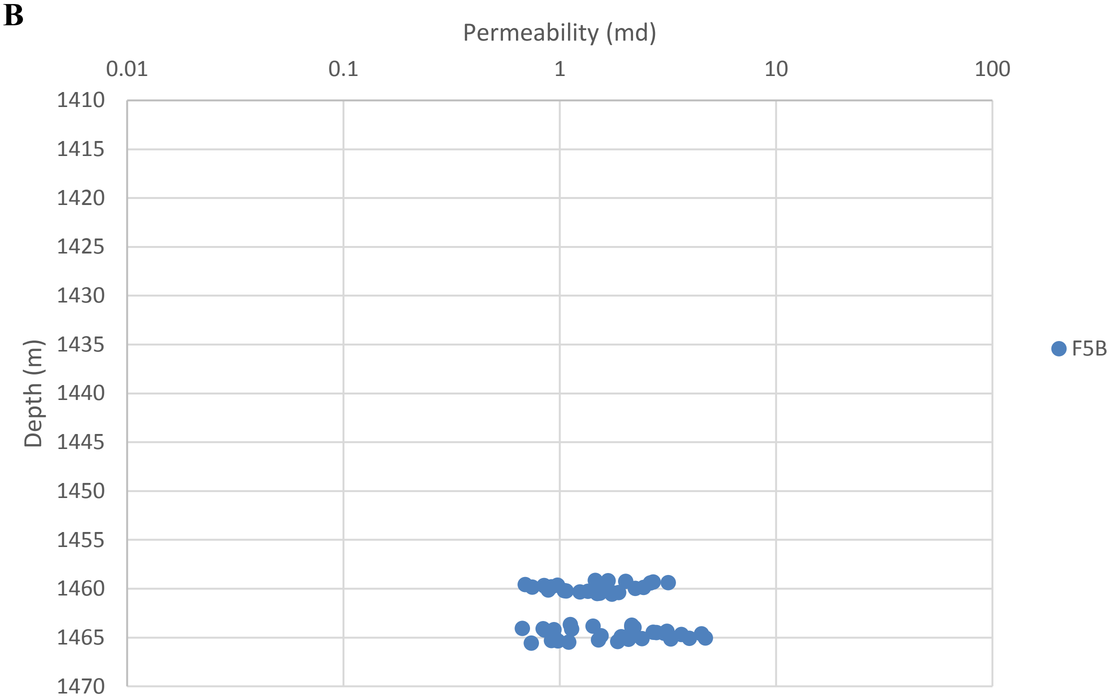

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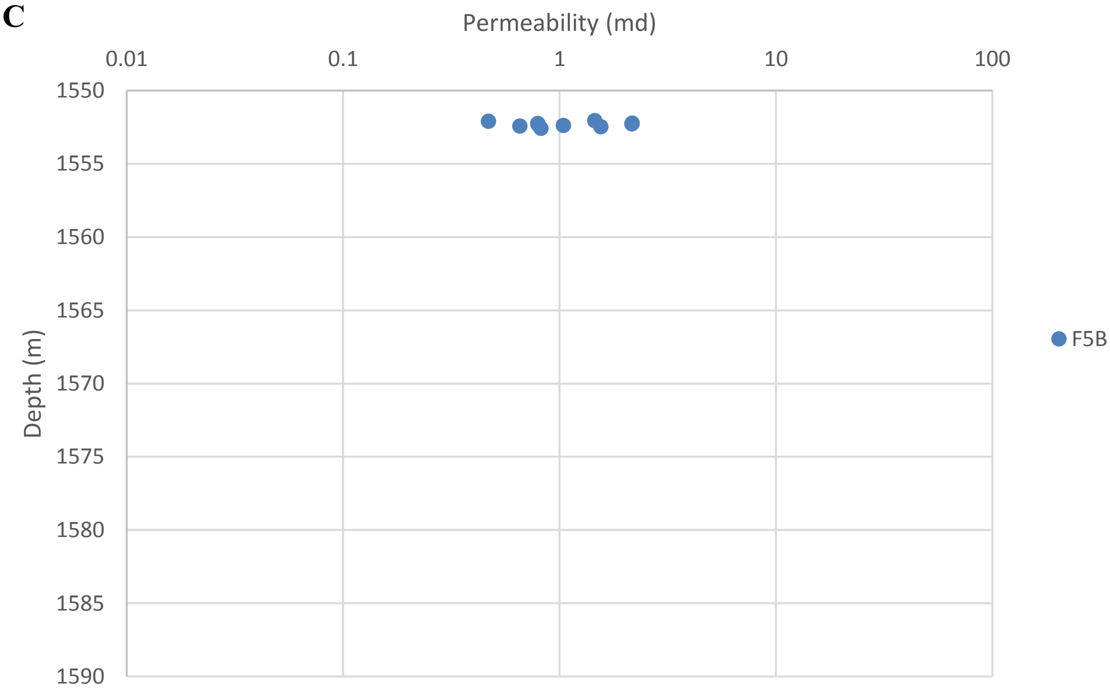

Figure 3-7: Permeability measurements of F5B in well 14-33-73-26w5 (A), well 13-03-74-26w5 (B), and well 16-14-73-26w5 (C).

Reservoir Characteristics – porosity and permeability relationship

Porosity, dependent on grain texture, is determined by grain size, grain shape, grain orientation, roundness, sorting, packing, and chemical composition. Porosity is controlled by the distribution of pore-throats and the pore structure. Low porosity values can be considered as evidence of a combination of lithologic heterogeneity, mineral alternation, and diagenesis in the Montney Formation. In fact, the porosity of the Montney Formation meets the tight gas reservoir classification standard of Haines et al. (2006), ranging from 2% - 10%. Relatively higher porosity (10-20%) were collected from core plug data. Because the Montney Formation in the study area is unconventional reservoir, porosity ranging from 10-20% is recognized modest for tight gas reservoir. Also, relatively higher porosity in the Montney Formation is associated with bedding plane fractures.

The permeability of sedimentary rocks, depending on effective porosity, is controlled by grain shape, grain size distribution, degree of sorting and cementation (Chehrazi and Rezaee, 2012). The results of permeability analyses are related to the overall heterogeneity, porosity, and ichnologic modification.

Generally, in flow media the distribution of porosity and permeability fabrics principally indicate the heterogeneities of lithofacies, e.g. lamination, ichnofabrics, the arrangement and packing of grains, local alteration of grains, random pore-throat distribution, or diagenetic modification of rock fabric (Gingras et al., 2005). The implication of the porosity and permeability is in relation to the fact that smaller porosity have smaller permeability values because smaller pores and smaller pore throats may constrain the fluid flow (Chehrazi and Rezaee, 2012).

The relationships between porosity and permeability are shown in Fig. 3-8, Fig. 3-9, and Fig. 3-10 for three cores, respectively. Porosity is directly proportional to permeability for mini-permeametry. Compared with plug data, the core data present the similar relation of porosity and permeability, which is shown in APPENDIX page 136-138. The trends of porosity and permeability relation from mini-permeametry data is also similar comparable with core data, as well as plug data (Fig.3-8 to 3-10). The similar trends of porosity and permeability are shown in Facies 1, Facies 3, Facies 4, and Facies 5A, whereas, Facies 2 and Facies 5B present more variable trends.

Porosity and Permeability Relation Interpretation:

1) The core permeability results provides strongly supporting to mini-permeametry results.
2) The excellent distribution of date indicate that there are few anomalous data points measured.
3) Similar trends for Facies 1, Facies 3, Facies 4, and Facies 5A may suggest that intergranular pore is the main type of pore for these facies. There is evidence by petrographic analysis in Chapter II (Fig. 2-14 and Fig. 2-15)
4) More variable trends for Facies 2 and Facies 5B may indicate that the distribution of pore is disturbed by burrows, resulting in increased homogeneity and isotropy.

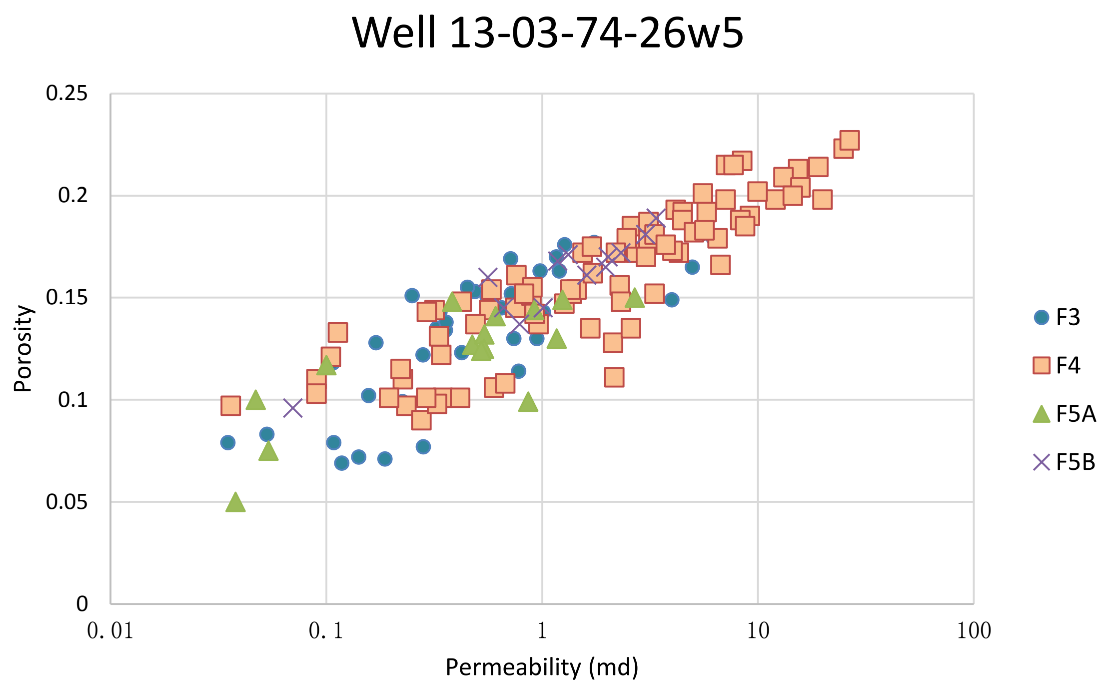

Figure 3-8: Relationship of porosity and permeability value in well 13-03-74-26w5.

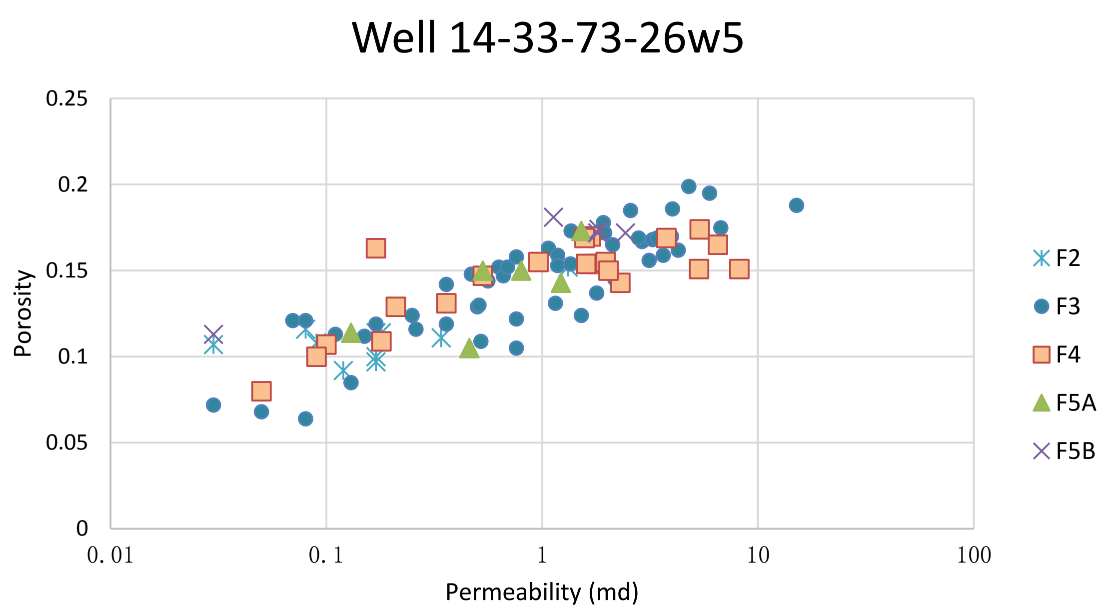

Figure 3-9: Relationship of porosity and permeability value in well 14-33-73-26w5.

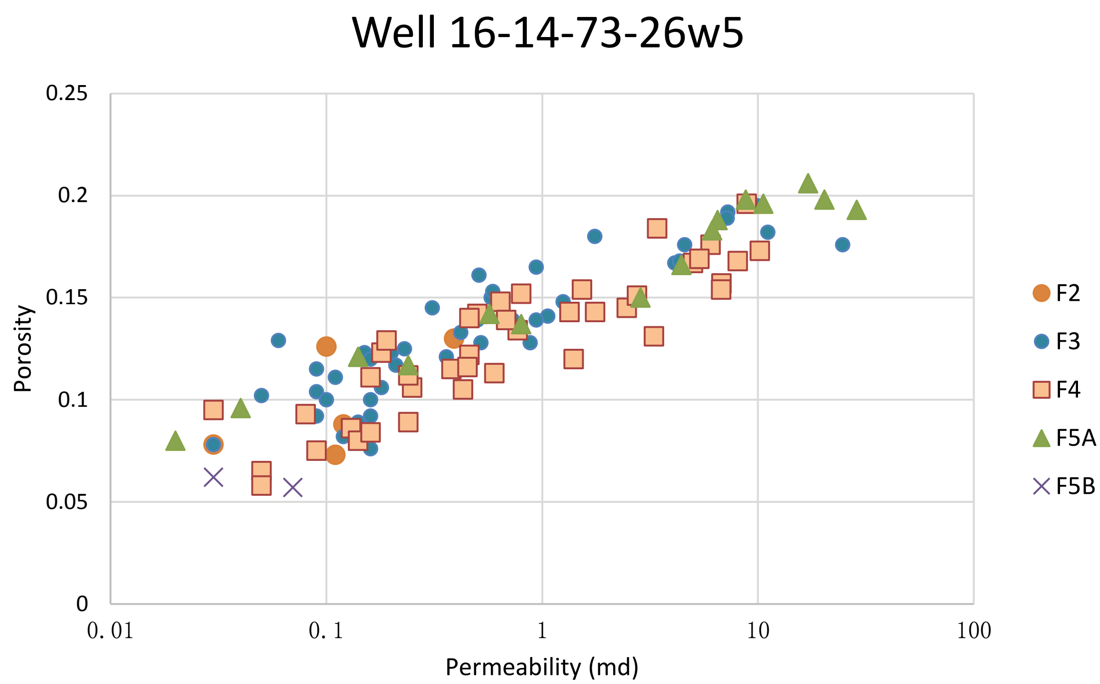

Figure 3-10: Relationship of porosity and permeability value in well 16-14-73-26w5.

DISCUSSION

As the petroleum industry strive to provide energy to the world with increasing demand, decreasing conventional hydrocarbon reservoirs production rates has indicated a visible challenge. The unconventional reservoirs have become economically selection for petroleum industry (Law and Curtis, 2002). Study of fine-grained, low permeability intervals has demonstrated that these strata may also contain volumes of hydrocarbons (e.g. Odedra et al., 2005; Hovikoski et al., 2008). These reserve volumes such as Montney Formation that have caught the attention of petroleum industry toward fine-grained, low permeability intervals. Nevertheless, the characteristics of unconventional reservoirs maintain poorly understood and multiple challenge for development.

The Lower Triassic Montney Formation of Western Alberta, Canada, has been recognized as an important hydrocarbon producer since the late 1950's. Contemporary ichnological research has revealed that the use of ichnofossils exceeds palaeo-environmental and stratigraphic application. Organisms burrowing and alter the characteristics of sedimentary structures, resulting in differential permeabilities and porosities between the burrow and surrounding matrix (Meadow and Tait, 1989; Lee and Foster, 1991; Pierret et al., 1999, 2002; Gingras et al., 2002a, b; Bastardie et al., 2003). Since trace fossils alter the characteristics of sedimentary structures for porous media, they may provide flow conduits for the migration and production of oil and gas (Gingras et al., 2004a; Pemberton and Gingras, 2005; Lemiski et al., 2011). For instance, the Montney Formation has been considered for the primary unconventional gas exploration. These unconventional gas reservoirs in such volumes are descripted as very fine-grained, low permeability successions.

Spot-minipermeametry testing for the Montney Formation has provided the insight on identification the controls on reservoir quality and potential storativity. The results show that the lowest permeability facies are Facies 1 and are associated with very fine-grained siltstone. Permeability characteristics can be recognized as K classification 1. The highest permeability values are demonstrated in F2B, F4B, F4C, and F5 are considered as possible gas flow conduits, whereas, slight permeability value enhancement are exhibit in F2A, F3, and F4A. Corresponding to lithology and bioturbation, the permeability values indicates that burrows make contributions to potential storativity. The sedimentary structures may also induce the enhancement of permeability values. However, the permeability values attributable to facies from this method might be inaccurate due to carbonate cementation (dolomite and calcite). Bioturbated sandstones, regarded as fluid flow conduits, are significant unconventional reservoirs. In order to maximize production, the bioturbated sandstones should be regarded. All these data demonstrate that sandstone associated with sedimentary structures and bioturbated heterolithically bedded intervals make contributions to the storativity and provide flow conduits.

Some researches show the similar results. As Davies et al. stated (1997), Porosity and permeability in siliciclastic facies of the Montney showed a lower porosity and permeability distribution compared with dolimitized coquinas. This study also illustrated that the porosities in the 25-30% and permeability in 10 to near 1000 md occur in the best reservoir quality. Zonneveld and Gingras (2012) indicated the role of bioturbation in permeability in the Upper Montney Formation, Northeastern British Columbia. The permeability values of their study are one to two orders higher in the burrowed media than in the laminated intervals. For example, permeability values of planar laminated siltstone range from 0.04 to 0.08 md, whereas, permeability values of biogenically siltstone range from 0.2 to 1.0 md. All these results are indicative that ichnological analyses are importance to assess Montney Formation and other unconventional reservoirs.

In the past, bioturbation was regarded as having a negative impact on permeability. This point derives from poorly sorting induced by the biogenic disturbing, resulting in permeability reduction. However, not all bioturbation is detrimental to the permeability values. Pemberton and Gingras (2005) have shown five classification and characterizations of biogenically enhanced permeability. Additionally, several examples are reported for bioturbation-enhanced permeability (e.g., Dawson, 1978; Gingras et al., 1999; 2004a; McKinley et al., 2004; Pemberton and Gingras, 2005; Gingras et al., 2007). However, there are no papers that analyze the ichnological influences on the Montney shale.

CHAPTER IV— CONCLUSION

This thesis investigates the sedimentological characteristics, ichnological characteristics, and the results of thin section analyses and permeability measurements of the Lower Triassic Montney Formation in the Western Canadian Sedimentary Basin in British Columbia and Alberta. In order to better understand the lithological characteristics and reservoir quality of the Montney Formation, three cores were descripted from the Puskwa field. In the study area, the Montney Formation includes mudstones, siltstones, and bioturbated fine to very fine-grained sandstones. This study contributes to the palaeo-environmental interpretation of Montney Formation, and sedimentological assessment of reservoir properties.

Chapter II identifies facies classification based upon sedimentological and ichnological characteristics. Based on sedimentological and ichnological characteristics, the Montney Formation were identified in five facies, and eleven subfacies with high resolution. F1 is muddy siltstone with rarely plane beddings. F2 is sandstone with variable bioturbation intensities (BI=0-5). Plane parallel to low angle lamination and hummocky cross stratification are the common sedimentary structures in Facies 3 and Facies 4. Load casts, convolute bedding, and micro-faults are commonly observed in silty facies (Facies 3). Combined flow ripple seldom occur in Facies 4. Facies 5 is massive-appearing sandstone with very rare plane bedding.

Ichnogenera that are recognized include *Asterosoma* (c), *Cylindrichnus* (r-m), *Diplocraterion* (r), *Helminthopsis* (m-c), *Palaeophycus* (r), *Arenicolites* (r), *Phycosiphon* (m-c), *Planolites* (c-a), *Rhizocorallium* (r), *Skolithos* (m-c), *Teichichnus* (m), and *fugichnia* (r), which are observed in Facies 2. Cryptic bioturbation occur in Facies 5B. The ichnofossils have overall low bioturbation intensity. Most of trace fossils occur within or at the bottom of the event beds and are small in size. The ichnofauna primarily comprises deposit-feeding structures and grazing structures, as well as suspension-feeding structures.

Physical sedimentary structures and biogenic features indicate that the setting is characterized by rapid deposition and storm/wave reworking, and as well as post-storm quiescence in shoreface environment.

There are two facies association can be defined in the study area depend on description and interpretation of cores. Facies Association 1 has an upward-coarsening succession and is interpreted to shoreface environment. The shoreface succession comprises F2B (silty sandstone with moderate bioturbation), F4 (plane parallel laminated sandstone) and F4C (hummocky cross-stratified sandstone). Facies Association 2 can be classified as river influence shoreface, including F1 (siltstone), F2A (weakly bioturbated silty sandstone), F3A (plane parallel laminated silty sandstone), F4A (sandstone with silt interlaminae), F3B (loading sedimentary deformed silty sandstone), F3C (hummocky cross-stratified silty sandstone), and F5A (massive-apparently sandstone), and F5B (cryptobioturbated sandstone).

Integrating geological observations to smaller-scale petrographic analyses provides a better understanding of the composition, mineralogy; and helps identify the units with the best reservoir properties. The results of thin sections exhibit percentage of minerals, kerogen, and pores of sandstone facies (Facies 4 and Facies 5).

Depend on the observation of thin section under the microscopy, the intergranular pores are the main type of the pore. The coarser sandstone facies have a relatively higher porosity (Chapter II, Table 2 and 3). The reason may be due to the poor cementation (Chapter II, Table 2 and 3).

Chapter III presents the result of permeametry for each facies. Spot-minipermeametry is used to measure permeability. Spot-minipermeametry measurement can be important data to compare with core data and plug data in order to assessment of reservoir properties and their distributions.

Spot-minipermeametry was conducted on each facies using a Core Laboratories PDPK-400 Pressure-Decay Profile Permeameter. The results show that the lowest permeability facies are Facies 1 and are associated with very fine-grained siltstone. Permeability characteristics can be recognized as K Classification 1. The highest permeability values are demonstrated in F2B, F4B, F4C, and F5 are considered as Potential K-streak; whereas, slight permeability value enhancement are exhibit in F2A, F3, and F4A.

There is a relationship between porosity and permeability shown in plug data, core data, and spot-minipermeametry data. Porosity is directly proportional to permeability for mini-permeametry. Similar trend of porosity and permeability relation display by plug data, core data, and spot-minipermeametry. Facies 1, Facies 3, Facies 4, and Facies 5A with the same trends may suggest that grain size is the main impact factor and intergranular pore is the main type of pore for these facies. Whereas, more variable trends for Facies 2 and Facies 5B may indicate that the distribution of pore is disturbed by burrows.

With continuous rising of the global energy demand, the unconventional reservoirs in Montney Formation will become more and more significant. Under careful observation, the sedimentological and ichnological characteristics can be used to interpret the palaeo-environment. Assessing the economic importance of the Lower Triassic Montney

Formation unconventional reservoirs in Western Canadian Sedimentary Basin will spearpoint further studies and provide understanding the influence of ichnology.

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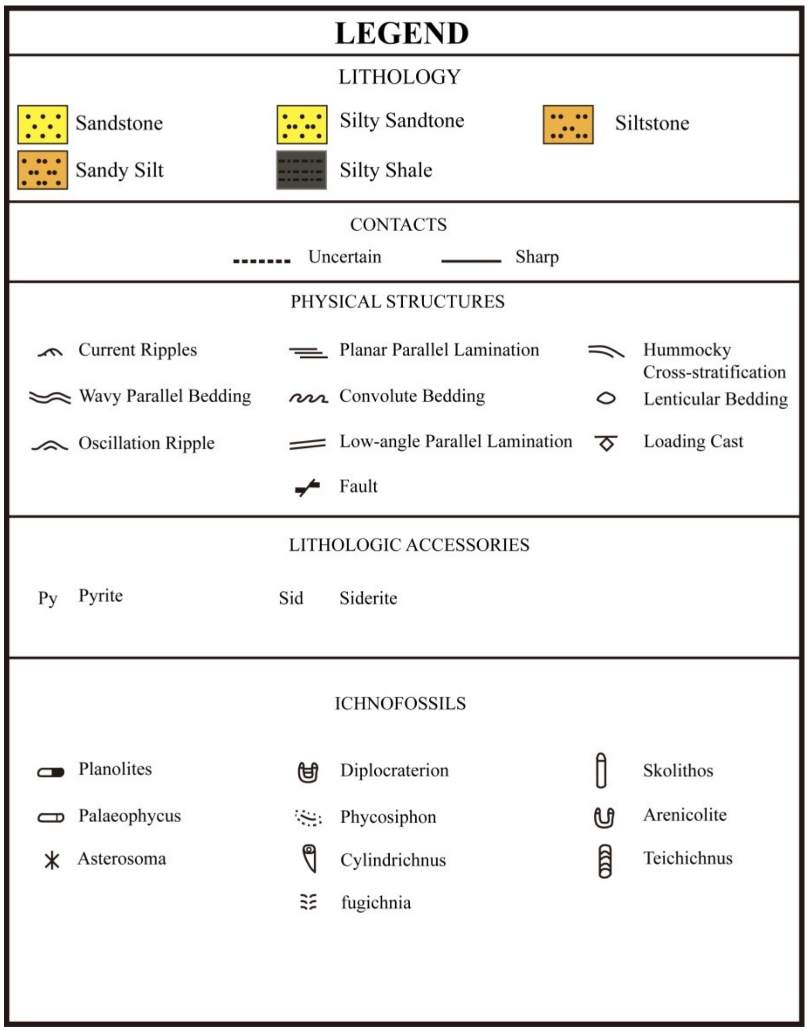
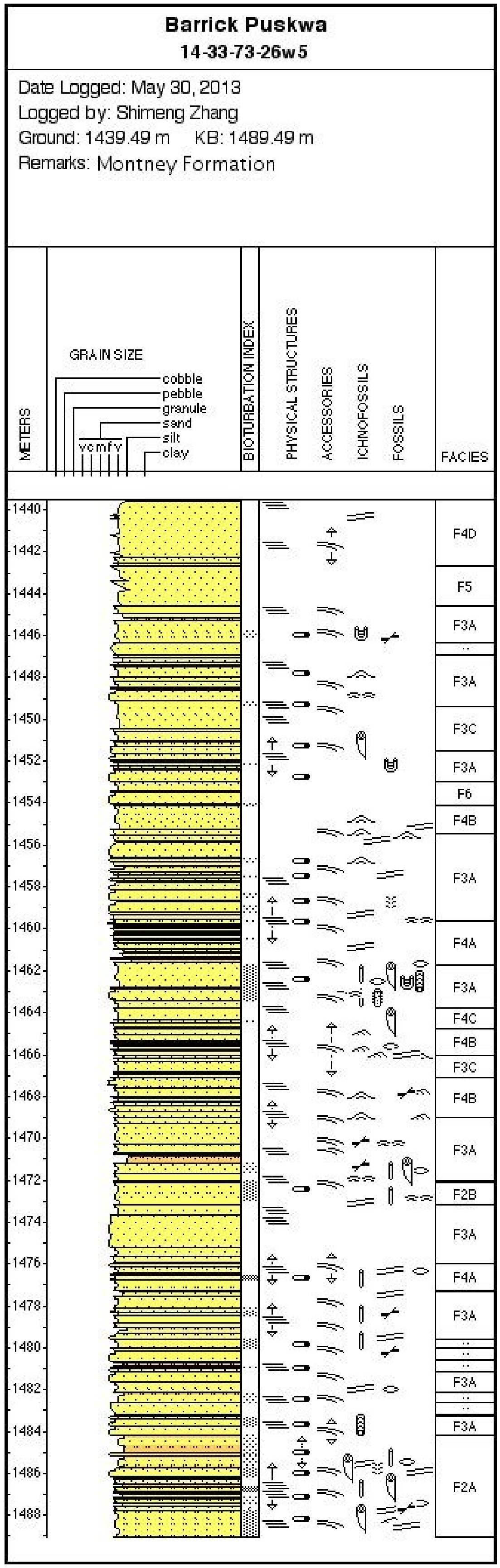
APPENDIX

LEGEND



14-33-73-26w5



Barrick Puskwa
14-33-73-26w5
Date Logged: May 30, 2013
Logged by: Shimeng Zhang
Ground: 1439.49 m KB: 1489.49 m
Remarks: Montney Formation
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
vc m f vf
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
FACIES
1440
1442
1444
1446
1448
1450
1452
1454
1456
1458
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1462
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1486
1488
F4D
F5
F3A
F3A
F3C
F3A
F6
F4B
F3A
F4A
F3A
F4C
F4B
F3C
F4B
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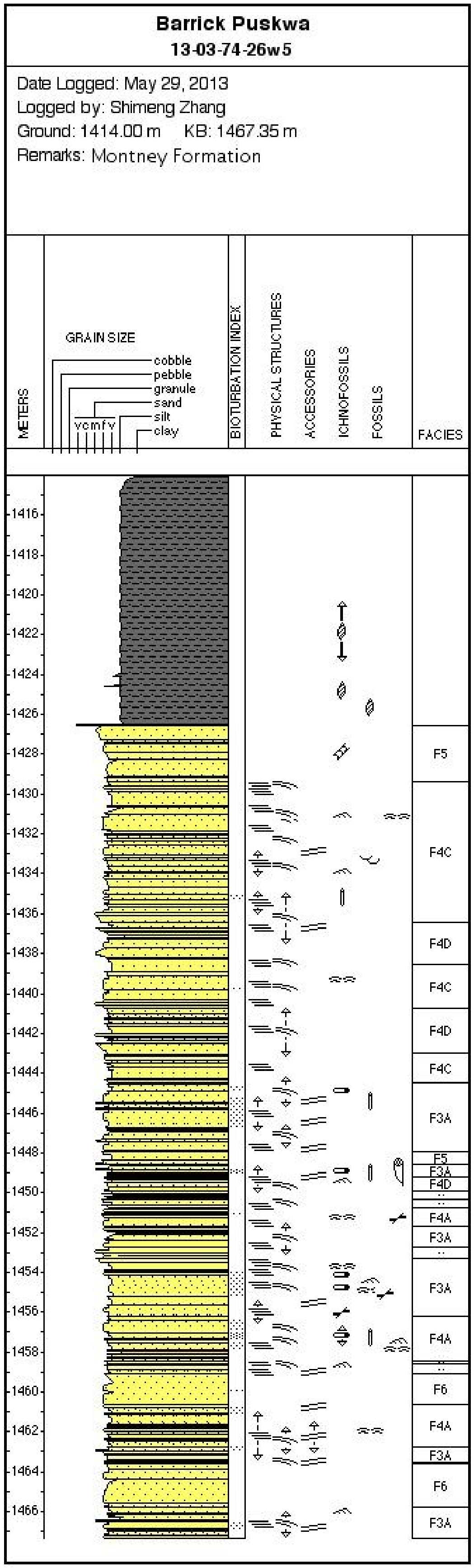
F3A
F4A
F3A
F3A
F3A
F2A

13-03-74-26w5



Barrick Puskwa
13-03-74-26w5
Date Logged: May 29, 2013
Logged by: Shimeng Zhang
Ground: 1414.00 m KB: 1467.35 m
Remarks: Montney Formation
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
vcmfvf
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
FACIES
1416
1418
1420
1422
1424
1426
1428
1430
1432
1434
1436
1438
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1442
1444
1446
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1450
1452
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1456
1458
1460
1462
1464
1466
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F4C
F4D
F4C
F4D
F4C
F3A
F5
F3A
F4D
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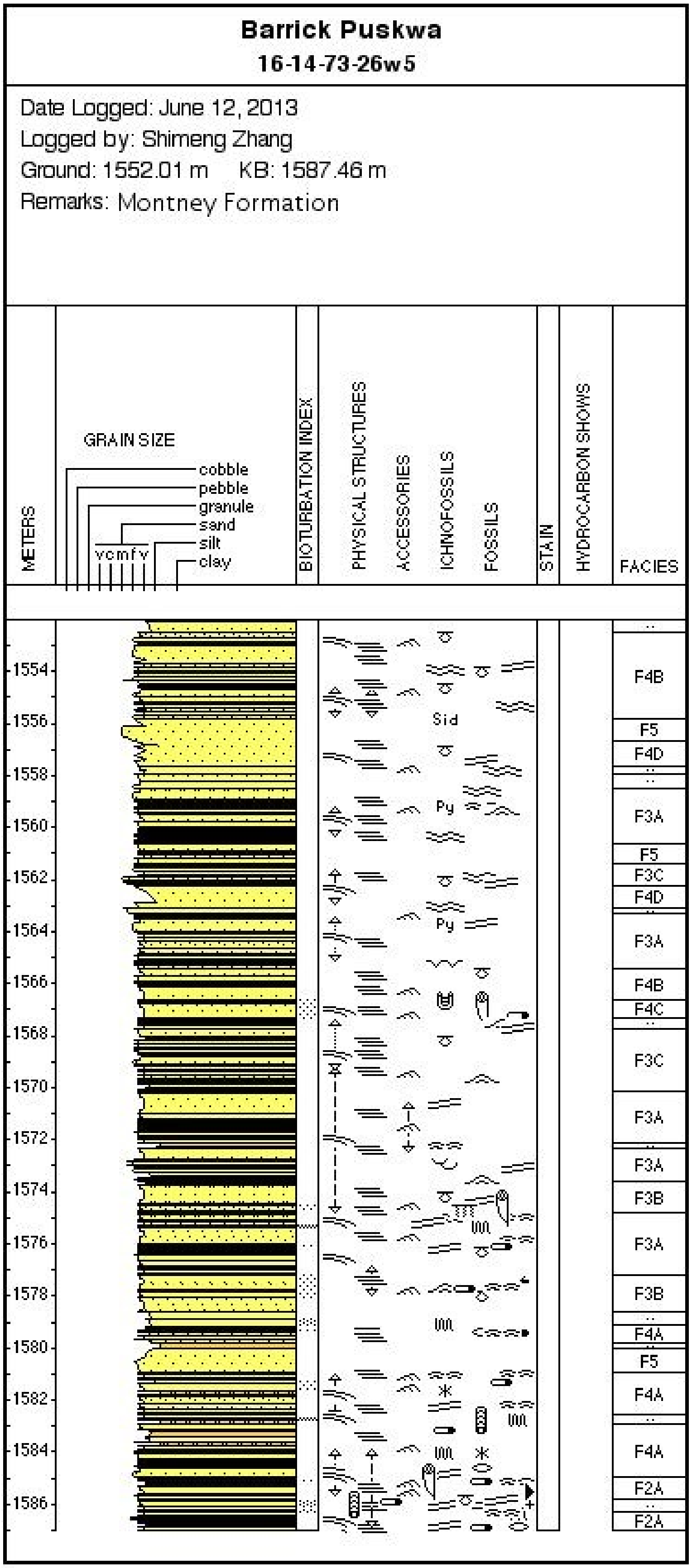
F4A
F3A
F6
F3A

16-14-73-26w5



Barrick Puskwa
16-14-73-26w5
Date Logged: June 12, 2013
Logged by: Shimeng Zhang
Ground: 1552.01 m KB: 1587.46 m
Remarks: Montney Formation
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
vcmfv
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
STAIN
HYDROCARBON SHOWS
FACIES
1554
1556
1558
1560
1562
1564
1566
1568
1570
1572
1574
1576
1578
1580
1582
1584
1586
Sid
Py
Py
F4B
F5
F4D
F3A
F5
F3C
F4D
F3A
F4B
F4C
F3C
F3A
F3A
F3B
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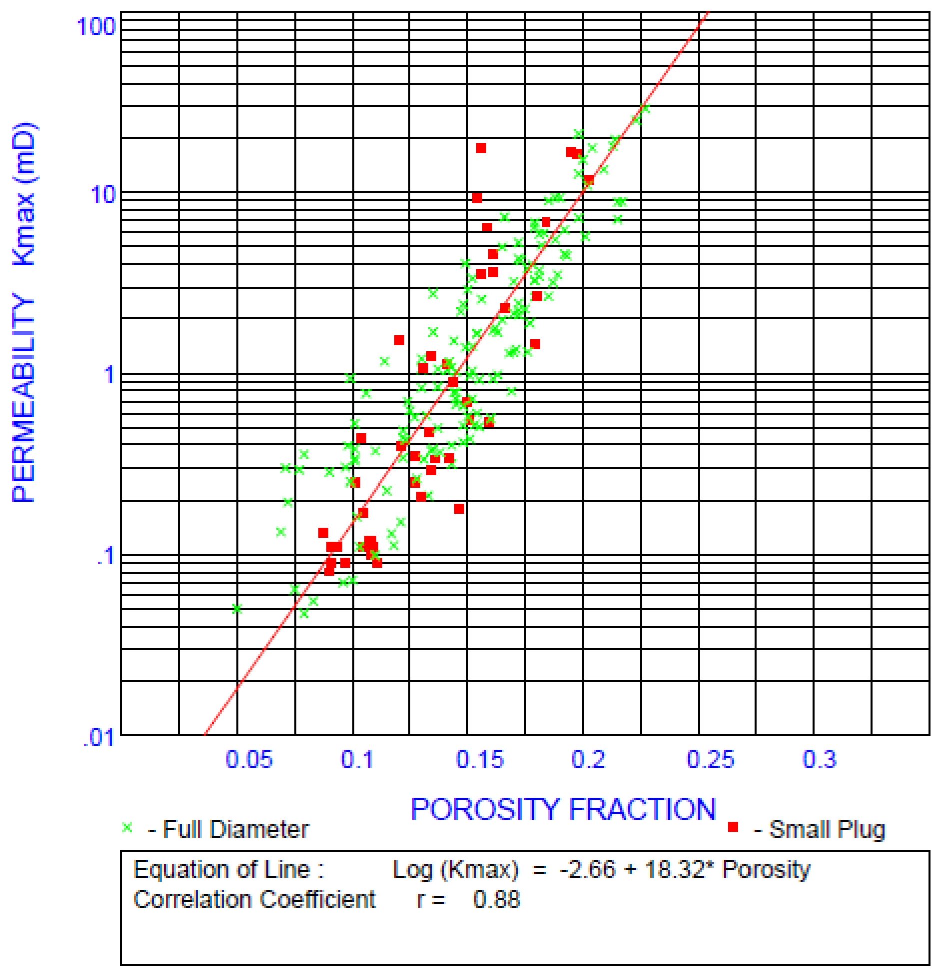
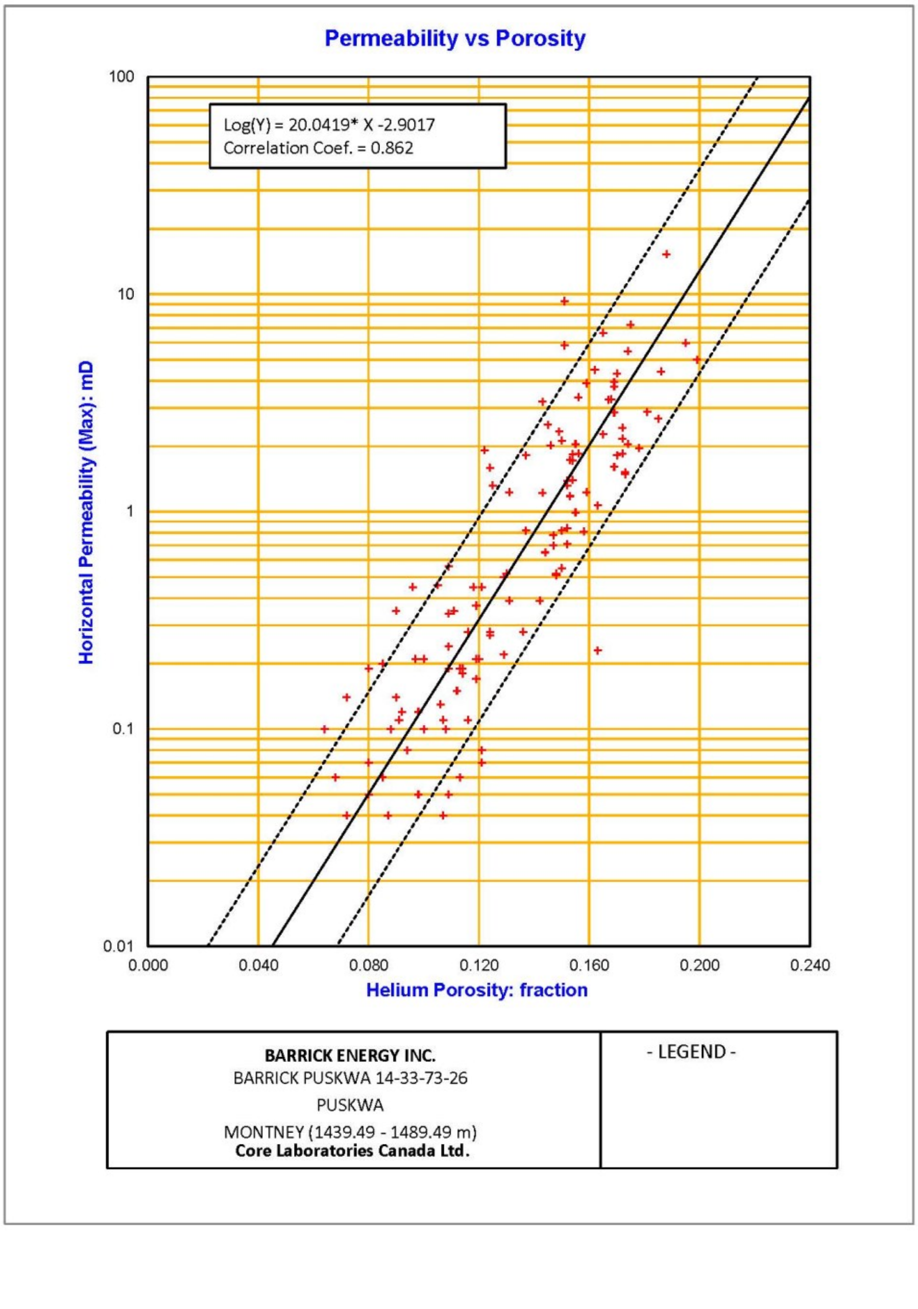
F2A

Porosity and permeability correlation in well 13-03-74-26w5



Porosity and permeability correlation in well 14-33-73-26w5



Porosity and permeability correlation in well 16-14-73-26w5