Cretaceous (Albian to Cenomanian) strata of Eagle Plain, Yukon:
Subsurface foraminiferal biostratigraphy, regional correlations and
paleoenvironments

by

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Abstract

The Eagle Plain, located in the northeastern Yukon Territory, Canada, forms a northern segment of the Cretaceous Western Interior Sea. Its preserved mid-Cretaceous strata document an active structural regime with sea-level fluctuations and changing sediment supply areas. The mid-Cretaceous rocks are unconformably underlain by either Paleozoic or younger Mesozoic formations. Recent paleontological evidence, including pollen, foraminifera and macrofossils from outcrop sections in the Eagle Plain, suggested that Albian to Cenomanian aged strata are preserved. This package includes the Whitestone River, Parkin, Fishing Branch, Burnthill Creek and Cody Creek formations.

This project tests new subsurface stratigraphy hypotheses by examining two continuous cores (Molar P-34 and Ellen C-24) and their benthic foraminiferal assemblages. It compares subsurface faunal changes with those obtained from outcrop samples by Haggart *et al* (2013) and integrates those to well log signatures that are used to establish the subsurface architecture. Three new biostratigraphic zones are recognized; the Early Albian *Gaudryina tailleuri* Zone in the lower Whitestone River Formation, the Middle to early Late Albian *Gaudryina canadensis* Zone in the Upper Whitestone River and sandstone member of the Parkin Formation, and the latest Albian *Miliammina manitobensis* Zone in the shale member of the Parkin Formation and lowermost Fishing Branch Formation. The biostratigraphic framework established in the subsurface correlates well with the fauna observed in outcrops. Foraminiferal assemblages are almost entirely dominated in both cores by agglutinated specimens that document a response to regionally recognized fluctuating sea-level changes during the Albian. Observations of foraminiferal morphogroups and their relative proportions allow for

paleoenvironmental reconstruction, including oxygen and nutrient conditions. The Ellen C-24 well represents a fully marine, well oxygenated proximal shelf deposited during the lower to early Late Albian Whitestone River Formation. The Molar P-34 well represents a deep water, offshore setting with increased accommodation space marked by sediment slumping, demonstrating a northwestward deepening of the basin. This interpretation is supported by the presence of abundant tubular suspension feeders which are less common in the Ellen C-24 well. In both settings a marked lithological change from mudstone to sandstone occurs between the Whitestone River and Parkin formations, corresponding to a distinct faunal changeover from rich to impoverished fauna.

The Whitestone River Formation documents Albian sea-level fluctuations of the Moosebar, Hulcross, Joli Fou and Mowry seas. These are distinguished from each other by faunal reductions that mark regressive phases and shifts in log signatures, and can be correlated to the northern Polar Sea and southern Western Interior Sea basins, as well as globally. The latest Albian disconformity is believed to occur in the terrestrial sandstones of the Fishing Branch Formation. While no unequivocal sedimentological evidence of this is recognized, foraminifera known from the latest Albian and late Cenomanian are found in the lower Fishing Branch Formation and Cody Creek Formation, respectively.

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1 Chapter: Introduction

The Cretaceous is marked by significant changes in sea level, paleogeography, paleotemperatures, and ocean chemistry (e.g., Hay, 2008; Friedrich *et al.*, 2012). One large scale effect of rising sea level was the flooding of the Western Interior of North America forming the Western Interior Sea (WIS), a basin that was connected through a series of smaller basins with the Sverdrup Basin spanning the Arctic Queen Elizabeth Islands (Figure 1). The Mackenzie region in northern Yukon and Northwest Territories formed the gateway between the Polar and Western Interior seas that allowed for paleoceanographic and faunal/floral exchange (Schröder-Adams, 2014). Due to a number of confounding factors including unconformities and limited faunal assemblages and age control, stratigraphic reconstructions of this northern region are still ongoing (e.g., Mountjoy, 1967; Mountjoy and Chamney, 1969; Norris, 1981a–d; Norris, 1982a; Dixon, 1992; Lane, 1998; Haggart *et al.*, 2013).

The Eagle Plain, situated in northeastern Yukon, is an intermontane region southwest of the Beaufort-Mackenzie Basin, and locally west of the Richardson Mountains (Figure 2). The Eagle Plain contains mid-Cretaceous strata resulting from the inundation of the Western Interior of North America. The stratal package is comprised of the Whitestone River Formation and the Eagle Plain Group. These units were first described by Martin (1959) and Mountjoy (1967), improved by Martin (1973) and Miall (1973) and formally described by Dixon (1992). The earlier descriptions were based on outcrop observations whereas Dixon (1992) incorporated outcrop with extensive wireline log correlations in order to establish subsurface stratal geometries. Lateral outcrop correlations in this area are difficult due to the limited surface exposures of these units on

Figure 1. Sedimentary basins of Western and Arctic Canada (from Schröder-Adams, 2014; modified after <http://www.aadnc-aandc.gc.ca>). The Eagle Plain is outlined in red.

Figure 2. Locality map indicating the Eagle Plain, Richardson Mountains and Peel Plateau.

Eagle Plain (Dixon, 1992; Haggart *et al.*, 2013). Formation thicknesses significantly diverge as a result of varying accommodation space and post-depositional compression during the latest Cretaceous and Tertiary (Lane, 1998).

Haggart *et al.* (2013) recently proposed a revised multi-fossil stratigraphic framework for the Eagle Plain Group and Whitestone River Formation, based on revised ages for outcrops of the Cretaceous formations. Several subsurface cores penetrating the Cretaceous strata and their log picks are integrated with the stratigraphic framework originally proposed by Dixon (1992); however, the foraminiferal assemblages from the Eagle Plain cores remain unstudied and are paramount for determining the biostratigraphic correlations between outcrops and subsurface. Foraminifera are useful biostratigraphic and paleoenvironmental indicators as they are found in almost every marine setting, are often abundant, speciose in some settings, and easily recoverable from sedimentary strata. Benthic foraminiferal tests can either be composed of calcium carbonate or constructed of agglutinated grains cemented together. Both test types are susceptible to different chemical or diagenetic processes that can lead to poor preservation or destruction, providing us under certain conditions with only poor quality, relict assemblages.

Establishing zonal markers allows for regional stratigraphic correlations to neighbouring areas (Figure 2), such as the Richardson Mountains (Fowler, 1985) to the northeast and Peel Plateau (Thomson *et al.*, 2011) to the east. The paleoenvironmental significance of assemblages, including their morphotype distribution (e.g., Berkeley *et al.*, 2007), refine our understanding of basin geometry, paleogeography and paleoecology.

This thesis addresses the following questions:

1. Does the foraminiferal biostratigraphic framework derived from this research based on two subsurface wells (Molar P-34 and Ellen C-24) of the Eagle Plain support the newly developed outcrop stratigraphy of the Whitestone River Formation and Eagle Plain Group proposed by Haggart *et al.* (2013)?
2. What do subsurface faunal assemblages contribute to the subsurface architecture of the Eagle Plain?
3. Can regional or global transgressive/regressive phases be recognized in wireline log signatures and do log shifts relate to faunal boundaries?
4. Do microfossil morphotype distribution patterns provide insight into the paleoecological parameters of this part of the northern Western Interior Sea?
5. How can the paleoenvironmental and paleogeographic history of the Cretaceous Eagle Plain basin be improved with benthic foraminiferal assemblages and what implications do those interpretations have on a larger regional scale?

2 Chapter: Geological Setting

The Eagle Plain (Figure 2) is located in northeastern Yukon near the Yukon/Northwest Territories border. It is an intermontane region west of the Richardson Mountains, covering approximately 13 600 km² (Dixon, 1992), that is bounded by the Ogilvie Mountains to the west and south, and the Dave Lord Mountains to the northwest (Haggart *et al.*, 2013). The basin contains over 5 km thick accumulations of Carboniferous to Permian strata separated from the overlying Cretaceous and Tertiary strata by a sub-Cretaceous unconformity (Figure 3; Rohr *et al.*, 2011; Dixon, 1997).

Foreland basin subsidence and sedimentation began in the Late Jurassic when regional compressional deformation was initiated (Mair *et al.*, 2006). Subsequent deposition into the basin was concentrated in low lying areas, such as the Richardson Trough to the east (Lane, 1998). Pre-upper Aptian sediments on the Eagle Plain were mostly removed by several phases of Early Cretaceous uplift and erosion (Dixon, 1993b).

Tectonism during late Aptian to early Albian times consisted of both compressive forces from the Cordilleran Orogeny and extensional forces from the emerging Canada Basin to the north, preceding a complex structural period (Dixon, 1993a). Marine sedimentation during the Aptian and Albian was sourced from the Canadian Shield to the east, with westward progradation (Hadlari *et al.*, 2014). Cenomanian to Campanian sediment is derived from the Cordillera to the south and west (Dixon, 1993a; Hadlari *et al.*, 2014). Post-Cretaceous strata are not observed on the Eagle Plain (Dixon, 1992).

Figure 3. Regional geologic setting of the Eagle Plain Group (modified after Haggart *et al.* (2013), Gordey and Makepeace (2003) and Norris (1984). The approximate outline of the Cretaceous Eagle Plain Basin is indicated by the red line.

The change in sediment provenance from the east to the south and west is due to the widespread Albian/Cenomanian unconformity (Dixon, 1993b; Thomson *et al.*, 2011). This unconformity is recorded in sediments throughout northwest and Arctic Canada and was likely the result of the cratonic extension of the Canada Basin breakup (Embry and Dixon, 1990; Dixon, 1993b). In the northern Yukon, this unconformity separates younger, weakly-cemented and more plastic strata from the underlying fractured and highly-indurated older strata (Dixon, 1993a). Jackson *et al.* (2010) identified a fluvial sandstone member within the Fishing Branch Formation in southern Eagle Plain and suggested that the base of this unit may represent the local expression of the latest Albian unconformity; however, Haggart *et al.* (2013) did not detect a long hiatus in the Eagle Plain Group. Instead, their multi-fossil evidence suggested that the unconformity was probably within the terrestrial Fishing Branch or Cody Creek formations, though believed the latter to be more likely.

The present day Eagle Plain is the result of latest Cretaceous to Tertiary compressional forces generated by the northward migration of the Cordilleran orogeny tectonic front (Dixon, 1993a). The development of the Ogilvie, Nahoni and Richardson mountains, and Keele Arch were associated with the extension of the Canada Basin. (Lane, 2010). The Richardson Mountains remain one of the few localities where earliest Cretaceous strata are preserved (Dixon and Jeletzky, 1991). The resulting north trending open anticlines and synclines of the Eagle Fold Belt (Figure 4) (Lane, 2010) are also observed to the North in the Beaufort-Mackenzie Basin (Dixon, 1993a). Compressional forces during the middle and late Miocene led to uplift and erosion forming unconformities in the Upper Cretaceous, above which little deformation is observed (Dixon and Dietrich, 1985).

Figure 4. Structural geology of the Eagle Plain (modified after Hannigan, 2014).

2.1 Litho- and Biostratigraphy

The lithostratigraphic nomenclature used in this study was chosen to allow for comparison with neighbouring regions including Richardson Mountains and Peel Plateau (Figure 5). Unit descriptions of Eagle Plain strata were originally proposed by Martin (1959) and Mountjoy (1967), improved by Martin (1973) and Miall (1973) and formally described by Dixon (1992). The ages of the formations in question were modified by Haggart *et al.* (2013) based on a multi-outcrop study and a multi-fossil approach (Figure 6). The following descriptions are based primarily on outcrop observations by Dixon (1992) and augmented with additional sedimentological and biostratigraphic information by Haggart *et al.* (2013). The Arctic Red Formation from the Richardson Mountains and Peel Plateau is included because it covers the thick Albian strata represented in this study by the Whitestone River Formation. Comparing these units allows for distinct faunal and sequence stratigraphic correlations.

2.1.1 Arctic Red Formation

The thick Arctic Red Formation is identified in the northern Richardson Mountains, Mackenzie Delta, Peel River (Figure 7) and Plateau region, and is stratigraphically correlative to the Whitestone River Formation of Eagle Plain. The unit rests unconformably on the Rat River Formation in the Richardson Mountains, and on the Martin House Formation on Peel Plateau to the southeast. The unit is generally lithologically consistent and comprises finely laminated, fissile shale with abundant concretion beds and minor mudstone, siltstone and sandstone interbeds. The fossil assemblage contains bivalves, *Inoceramus* fragments, rare ammonites, fish scales,

Figure 5. Regional stratigraphy including the Eagle Plain, Richardson Mountains and Peel Plateau, including recent revisions of stratigraphic nomenclature. The red arrow highlights the stratigraphic downwards shift of the Eagle Plain Group based on fossil evidence of Haggart *et al.* (2013).

Figure 6. Stratigraphic occurrence of pollen, foraminifera and macrofossil samples used by Haggart *et al.*, (2013) in order to establish biostratigraphic constraints on the Whitestone River Formation and Eagle Plains Group (based on Haggart *et al.*, (2013) and references therein).

Figure 7. Outcrop photograph of the Arctic Red Formation in the Peel River Canyon.

Photo courtesy of Claudia Schröder-Adams.

foraminifera and palynomorphs (Jeletzky, 1968, 1973; Mountjoy and Chamney, 1969; Chamney, 1978; Fowler, 1985; Thomson *et al.*, 2011). These fossil occurrences collectively suggest an early to late Albian age for the formation. In the Peel Plateau region along the Hume River a covered section in the uppermost part of the formation represents the latest Albian (Thompson *et al.*, 2011).

2.1.2 Whitestone River Formation

The Whitestone River Formation extends throughout the Eagle Plain. The formation rests unconformably on older strata, including the Porcupine (Jurassic) and the Tuttle, Jungle Creek and Hart (all Paleozoic) formations. The formation is composed of dominantly finely laminated grey shale and mudstone, with thinly interbedded siltstone and very fine-grained sandstone. Ironstone concretions occur throughout the unit, locally containing ammonites (Haggart *et al.*, 2013). The Whitestone River Formation is differentiated from the overlying units by the presence of common calcareous septarian nodules (Dixon, 1992). Along the Peel River where Dixon (1992) identified a reference outcrop for part of the formation, Haggart *et al.* (2013) described numerous 1 to 4 cm thick bentonite beds (Figure 8). Zircons picked from one of these bentonites gave a sensitive high-resolution ion microprobe (SHRIMP) age of 105.49 +/- 0.22 Ma (W.J. Davis, pers. comm., 2015), which falls in the early Late Albian (Gradstein *et al.*, 2012).

A sparse foraminiferal assemblage yielded Early to Mid-Albian species (Chamney, in Norford *et al.*, 1972; Wall, in Brideaux *et al.*, 1976; Fowler, 1986; McNeil, 2011; Haggart *et al.*, 2013). Ammonites collected by Haggart *et al.* (2013) suggest an age range of late Early to early Late Albian, and palynomorphs suggest an Albian age (McIntyre, 1987). Combined fossil evidence defines an Early to early Late Albian age for this formation (Haggart *et al.*, 2013).

Figure 8. Outcrop photograph of the upper Whitestone River Formation exposed along the Peel River (locality A of Haggart *et al.*, 2013). Arrow points to the dated bentonite bed. Photo courtesy of Claudia Schröder-Adams.

2.1.3 Parkin Formation

The Parkin Formation extends throughout the Eagle Plain region and rests unconformably on the Whitestone River Formation (Dixon, 1992). The unit is separated into a lower sandstone member and an upper shale member. The upper member has a mudstone lithology, however, I retain the shale member designation originally proposed by Dixon (1992) and adopted by Haggart *et al.* (2013). The lower sandstone member is primarily coarse grained and contains channel conglomerates with chert pebbles, and is interpreted as fluvial to shoreface deposition (Jackson *et al.*, 2011). The upper member is dominated by dark gray to black mudstone interbedded with numerous siltstone and very fine-grained sandstone beds (Haggart *et al.*, 2013). This is interpreted as a shelf setting and part of an overall coarsening upward sequence transitioning into the overlying Fishing Branch Formation (Dixon, 1992). Jackson *et al.* (2010) identified a middle Parkin Formation sandstone member within the upper shale member in the southeast corner of Eagle Plain, which was interpreted as shallow-water mass transport deposits. The contact between the Parkin and Fishing Branch formations is exposed along the Fishing Branch River (Figure 9). Paleocurrent indicators in the lower sandstone member suggest that paleoflow was to the west (Jackson *et al.*, 2010).

Ammonite fragments indicate a Middle Albian age (Haggart, 2010) for the Parkin Formation. Lower in the formation, two ammonites were identified from the Middle Albian (Haggart *et al.*, 2013). A bivalve from the lower part of the formation was thought to represent a Middle to Late Albian age (Haggart *et al.*, 2013). Finally, foraminifera from the basal sandstone member of the Parkin Formation suggest an age range of Early to Middle Albian (McNeil, 2011), while palynomorphs from the same interval suggest a Middle Albian age (White, 2010). Combined evidence constrains the age of the Parkin Formation to the Middle to Late Albian (Haggart *et al.*, 2013).

Figure 9. Outcrop photograph of the upper Parkin Formation mudstones overlain by the sandstones of the lower Fishing Branch Formation exposed along the east side of the Fishing Branch River. Photo courtesy of Claudia Schröder-Adams.

2.1.4 Fishing Branch Formation

The Fishing Branch Formation extends throughout the Eagle Plain region and gradationally overlies the Parkin Formation (Figure 9). The unit consists of very fine to fine-grained massive to cross-stratified sandstone and siltstone with mudstone interbeds (Dixon, 1992; Haggart *et al.*, 2013). Wave and current ripples as well as hummocky cross-stratification suggests a storm dominated shelf setting. The increasing thickness of interbedded mudstone to the west and northwest suggests basin deepening in this direction (Dixon, 1992). Pollen, dinoflagellates and spores found in the formation suggest a nearshore marine environment for at least part of the unit (Haggart *et al.*, 2013).

Mudstone interbeds from the lowermost Fishing Branch Formation were sampled for foraminifera yielding a middle to late Albian age. Pollen, dinoflagellates and spores suggest a Middle Albian to Cenomanian age (Sweet, 2012). Bivalves from the lower part of the formation are coeval to Aptian-Albian bivalves from northern Alberta. The fossil evidence collectively suggests a middle to late Albian age for the unit (Haggart *et al.*, 2013).

2.1.5 Burnthill Creek Formation

The Burnthill Creek Formation extends throughout the Eagle Plain region and rests conformably on the Fishing Branch Formation. The unit consists of primarily dark gray to black mudstone (Figure 10) with fine silt laminae and thin sandstone interbeds that are more abundant in the upper unit. Fine- to medium-grained sandstone with common plant debris and orange oxidation suggest a transition to non-marine settings (Haggart *et al.*, 2013). This interpretation was confirmed by the presence of both marine and non-marine palynomorphs (Haggart *et al.*, 2013). Based on the above lithologies and

Figure 10. Outcrop photograph of the gray to black shale of the Burnthill Creek Formation exposed along Chance Creek. Photo courtesy of James Haggart.

faunas, a coastal plain marginal marine setting is suggested for this interval (Haggart *et al.*, 2013). This is also consistent with lacustrine deposits identified by Jackson (2012) in the southeastern part of the basin.

The sparse pollen assemblage from the lower Burnthill Creek Formation suggests an age range of Late Albian to Cenomanian (Haggart *et al.*, 2013).

2.1.6 Cody Creek Formation

The Cody Creek Formation extends throughout the Eagle Plain region and is expressed at the surface throughout much of the area. The unit gradationally overlies the Burnthill Creek Formation and changes in lithology from southeast to northwest. In the southeast the unit is primarily composed of interbedded fine- to medium-grained sandstone and mudstone which range from planar to trough-cross-stratified (Figure 11). Local channelized muddy siltstone, siltstone and sandstone were identified on the north bank of the Cody Creek Formation. Oxidized orange plant debris and mud clasts are abundant in several intervals. Ironstone concretions are present in siltstone intervals and are also oxidized orange to brown in colour. At the type locality in the West Parkin D-51 well, coarse-grained lithologies become increasingly interbedded with mudstone. The presence of hummocky cross stratification indicates an inner shelf and lower and middle shoreface setting (Dixon, 1992). To the south, palynomorphs and the lack of benthic foraminifera and amorphous kerogen, suggest a non-marine depositional environment for the Cody Creek Formation (Haggart *et al.*, 2013). Pollen assemblages provide only a coarse age range of Late Albian to Cenomanian to possibly Turonian for the Cody Creek Formation (Haggart *et al.*, 2013).

Figure 11. Outcrop photograph of the medium- to coarse-grained cross-stratified sandstone from the Cody Creek Formation exposed along Cody Creek, located in west-central Eagle Plain (see Figure 4). Photo courtesy of James Haggart.

3 Chapter: Materials and Methods

Microfossil and petrophysical data utilized in this study are based on two wells drilled on the Eagle Plain, Yukon. The Ellen C-24 well, containing the Porcupine River, Whitestone River, Parkin, Fishing Branch, Burnthill Creek and Cody Creek formations, is located centrally. The Molar P-34 well, containing the Tuttle, Whitestone River, Parkin and Fishing Branch formations, is to the northwest of Ellen C-24 (Figure 2). The microfossil assemblages from both wells were prepared from well cuttings by the Calgary office of the Geological Survey of Canada using the methods of Then and Dougherty (1983). Depth is shown in ft because original descriptions and sample intervals were made according to imperial units.

A total of 173 samples, representing 8650 ft collected at 50 ft intervals, were counted for foraminiferal abundance from Molar P-34. Detailed taxonomic identification was performed on 36 samples at approximately 200 ft intervals, with the number of samples examined increasing in sections of interest, such as formational contacts and intervals of accelerated faunal change. A total of 50 samples, representing 5000 ft at 100 ft intervals, were counted and taxonomically identified from Ellen C-24.

Picked specimens were identified, counted and photographed (Canon EOS Rebel T3i) using a binocular microscope (Olympus SZX9). Specimens were identified according to their test composition, morphology and aperture placement (Jones, 2014). A complete taxonomic list of all observed species was assembled (Appendix A) and illustrated (Figure 15, 16). Abundances were described as rare (1-3), few (3-9), common (10-24) or abundant (25+). Some specimens were poorly preserved, restricting identification to genus, while some samples were barren of foraminifera altogether. The

low abundance of foraminifera in some samples and the nature of the cuttings made it difficult to conduct statistical analyses. It is important to keep in mind that, since samples were acquired from well cuttings, while uncommon, it is possible for fragments of overlying younger rock or sediment to be included as the mixture rises through the well. This is caused by cuttings being forced to the surface with the drilling mud. For this reason the last appearance datums (LAD) of foraminifera are considered more reliable than first appearance datums (FAD), as it is impossible for older sediment to be included beyond the drilling point, but possible for younger overlying sediment to do so. However, liberty is taken to distinguish distinct intervals, within both cores, that are bounded by characteristic faunal changes which can then be linked to regional paleoenvironmental fluctuations that are, for example, sea level driven. In the absence of precise core samples, this approach provides the best attempt to integrate the subsurface paleoecology into a broader framework for the northern portion of Western Interior Sea.

Biostratigraphic comparisons between the Molar P-34 and Ellen C-24 wells were supported by log correlations (Chapter 4.1). Distinct faunal changes were linked to log shifts in a variety of log signatures. Log correlations were made using geoSCOUT (geoLOGIC, 2015). Sonic, gamma ray and deep resistivity well logs for both Molar P-34 and Ellen C-24 were utilized, as well for wells C-33, M-59, N-26 and D-51. Two log cross-sections were constructed (A to A' and B to B') (Fig. X) running northwest to southeast and west to east, respectively. These illustrate vertical changes in lithological and sediment character, and shed light on basin geometry.

The practical model for the determination of total organic carbon (TOC) from well logs as established by Passey *et al.* (1990) was applied in this study. The $\Delta\log R$

method used involves overlaying the sonic and resistivity logs at a scaling factor -50 $\mu\text{sec}/\text{ft}$, or -164 $\mu\text{sec}/\text{m}$, to 1 logarithmic resistivity cycle. The logs are horizontally aligned to form a baseline over a fine-grained interval, as indicated by high gamma ray, and non-source rock interval where sonic and resistivity logs overlay and track each other.

The separation between sonic and resistivity logs over non-reservoir intervals, with high gamma ray, is linearly related to the amount of TOC. Where thermal maturity data is available, or can be otherwise estimated, absolute TOC can be determined or estimated. Although thermal maturity is not available for the given cores, the vertical variability of organic matter can be established (Passey, 1990).

The age of the bentonite from the upper Whitestone River Formation was determined by Davis (pers. comm.) using isotope dilution thermal ionization mass spectrometry at the Geochronology Laboratory, Geological Survey of Canada in Ottawa. Zircons grains were recovered from the unconsolidated clay rich bentonite using a WilfleyTM table, density separation in methylene iodide and sorted by magnetic susceptibility using a GrantzTM isodynamic separator. Zircon fractions were prepared for analysis according to the annealing and chemical leaching technique (CATIMS) modified from the procedure described by Mattinson (2005). Zircon grains were selected under a binocular microscope and uranium and lead isotopic ratios were measured using a Triton mass spectrometer.

4 Chapter: Results

4.1 Well Logs

Two cross-sections on Eagle Plain were established for this study. Cross-sections A-A' and B-B' run from north-west to south-east, and west to east (Figure 12), respectively, and their well log correlations are represented in figures 13 and 14, respectively. Log signatures and stratigraphic boundaries originally described by Dixon (1992) were adopted for this study. Formational correlations were made by referencing type core sections (Table 1) and correlating log signatures at formational boundaries. The top of the Whitestone River Formation is used as the datum in order to illustrate basin geometry. Log correlations indicate the thickest Cretaceous sedimentary package is in the north-west region of the Eagle Plain, with considerable thinning to the south-east. This change in thickness is best illustrated with the reduction of the Whitestone River Formation from 5068 ft (1545 m) in Molar P-34 in the north-west to 484ft (147 m) in M-59 in the south-east (Figure 13).

The Whitestone River Formation is underlain by different strata at the various wells (Table 2). For M-59, C-23, D-51 and N-26, the contact between the Whitestone River Formation and the underlying formations is the sub-Cretaceous boundary, generally indicated by a positive shift in gamma ray relating to the fine-grained facies of the basal Whitestone River Formation. In P-34 and C-24, the lower contact of the Whitestone River Formation is not as well defined and the contact is marked by a negative shift in gamma ray and sonic, and a positive shift in resistivity.

Figure 12. Locality map of Eagle Plain with cross-sections A-A' and B-B' indicated.

Figure 13. Well log correlation of cross-section A-A' of wells P-34, C-24, C-33 and M-59 including gamma ray, sonic and resistivity logs. Notable depositional cycles within the Whitestone River Formation are indicated by numbers. WR – Whitestone River Formation; SS – sandstone member of the Parkin Formation; P – Parkin Formation; FB – Fishing Branch Formation; BC – Burnthill Creek Formation; CC – Cody Creek Formation.

Figure 14. Well log correlation of cross-section B-B' of wells N-26, D-51 and C-33 including gamma ray, sonic and resistivity logs. WR – Whitestone River Formation; SS – sandstone member of the Parkin Formation; Park – Parkin Formation; FB – Fishing Branch Formation; BC – Burnthill Creek Formation; CC – Cody Creek Formation.

Table 1. Well location of type sections for the Whitestone River and Eagle Plain Group formations

Formation	Well with type section	Latitude	Longitude
Cody Creek Formation	West Parkin D-51	66.269028	-137.434583
Burnthill Creek Formation	West Parkin D-51	66.269028	-137.434583
Fishing Branch Formation	West Parkin C-33	66.201111	-137.365556
Parkin Formation	West Parkin C-33	66.201111	-137.365556
Whitestone River Formation	Whitefish N-26	66.099722	-138.333333

Table 2. Formations underlying the Whitestone River Formation including age and lithology for P-34, C-24, M-59, C-23, D-51 and N-26.

Well	Formation below Whitestone River Formation	Age	Lithology
P-34	Porcupine Formation (Dixon, 1992)	Jurassic	Sandstone with mudstone interbeds
C-24	Tuttle Formation (Stott and Aitken, 1993)	Latest Devonian to Early Carboniferous	Sandstone
M-59	Jungle Creek Formation (Stott and Aitken, 1993)	Early to Middle Permian	Conglomerate to sandstone and carbonate
C-23/D-51/N-26	Hart Formation (Bamber and Waterhouse, 1971)	Mid-Carboniferous	Sandstone and carbonate

The contact between the Whitestone River Formation and the overlying sandstone member of the Parkin Formation is recognized by a sharp decrease in gamma ray and sonic with an increase in resistivity. The contact between the sandstone and upper shale members of the Parkin Formation is recognized by a sharp to consistent increase in gamma ray and sonic with a decrease in resistivity. The contact between the Parkin Formation and the Fishing Branch Formation is marked by a sharp decrease in gamma ray and sonic with an increase in resistivity. The contact between the Fishing Branch Formation and the Burnthill Creek Formation is marked by a sharp increase in gamma ray and sonic with a sharp decrease in resistivity. Lastly, the contact between the Burnthill Creek Formation and Cody Creek Formation is marked by a sharp decrease in gamma ray with a sharp increase in sonic and resistivity.

The Whitestone River Formation is examined in greater detail due to the prevalence of foraminifera observed in this study and Haggart *et al.* (2013). Five discrete depositional cycles are observed in Molar P-34 in the Whitestone River Formation (Figure 13). Depositional cycle 1 is characterised by a backstepping gamma ray signature. Depositional cycle 2 is characterised by a forestepping gamma ray signature with a negative peak in sonic and a very notable peak in resistivity. Depositional cycle 3 is characterised by moderately stable gamma ray, sonic and supported by resistivity logs. Depositional cycle 4 is characterised by stable gamma ray with a decrease in sonic and an increase in resistivity signatures, with a significant separation between sonic and resistivity. Depositional cycle 5 is characterised by a backstepping gamma ray signature and positive spikes in the sonic log. These depositional cycles are later linked to large-scale transgressive/regressive cycles that are observed basin-wide (Caldwell *et al.*, 1993; Schröder-Adams *et al.*, 2014) and globally (Gradstein *et al.*, 2012).

4.2 Organic Matter

Application of the $\Delta\log R$ method to the Molar P-34 and Ellen C-24 wells reveals several key trends formed by the separation between sonic and resistivity logs (Figure 13). These intervals include, 1) an elevated organic matter content in the upper Whitestone River Formation relative to the lower section and 2) elevated and moderate upward enrichment in organic matter in the Parkin Formation above the sandstone member. The triangular separation in the lower Whitestone River Formation of Molar P-34 and the sandstone member of the Parkin Formation are disregarded as they correspond to coarse-grained intervals as suggested by low gamma ray. Certain intervals, such as that within the Fishing Branch Formation, demonstrate small intervals enriched in organic matter corresponding to high gamma ray. Finally, within the examined wells, Molar P-34 is significantly more enriched in organic matter when compared to Ellen C-24.

4.3 Foraminiferal Data

Faunal data was acquired from both Molar P-34 and Ellen C-24 and are discussed in the following chapters with reference to their abundance, biostratigraphic significance, and paleoecological implications. Identified foraminifera are illustrated in Figure 15 (Plate 1) and Figure 16 (Plate 2) and counts are presented in Appendix B.

The taphonomic influences on the composition of the foraminiferal assemblages can have important consequences for their interpretation, e.g., post depositional destruction of foraminiferal tests can skew the observed assemblage. Calcareous tests in particular are prone to being damaged or removed completely by dissolution when porewaters become acidic (e.g., Murray, 1989; Schröder-Adams and Van Rooyen, 2011).

Plate 1 (see page 53)

1. *Bathysiphon brosgei* Tappan, 1957. Ellen C-24 sample 3500 – 3600 ft.
2. *Bathysiphon vitta* Nauss, 1947. Ellen C-24 sample 3500 – 3600 ft.
3. *Saccamina alexanderi* (Loeblich and Tappan), 1950. Ellen C-24 sample 4500 – 4600 ft.
4. *Saccamina lathrami* Tappan, 1960. Ellen C-24 sample 4000 – 4100 ft.
5. *Hippocrepina barksdalei* (Tappan), 1957. Molar P-34 sample 1250 – 1300 ft.
6. *Glomospira corona* Cushman and Jarvis, 1928. Ellen C-24 sample 4200 – 4300 ft.
7. *Glomospirella gaultina* (Berthelin), 1980. Ellen C-24 sample 3300 – 3400 ft.
8. *Ammodiscus rotalarius* Loeblich and Tappan, 1949. Ellen C-24 sample 4700 – 4800 ft.
9. *Reophax fuscus* Chamney, 1978. Ellen C-24 sample 3500 – 3600 ft.
10. *Reophax incompta* Loeblich and Tappan, 1946. Ellen C-24 sample 4000 – 4100 ft.
11. *Reophax troyeri* Tappan, 1960. Ellen C-24 sample 4700 – 4800 ft.
12. *Reophax suevica* Franke, 1936. Molar P-34 sample 7700 – 7750 ft.
13. *Reophax vasiformis* Chamney, 1978. Ellen C-24 sample 4000 – 4100 ft.
14. *Psamminopelta bowsheri* Tappan, 1957. Molar P-34 sample 2850 – 2900 ft.
15. *Miliammina manitobensis* Wickenden, 1932. Molar P-34 sample 600 – 650 ft.
16. *Haplophragmoides canui* Cushman, 1930. Molar P-34 sample 7700-7750 ft.
17. *Haplophragmoides linki* Nauss, 1947. Ellen C-34 sample 4000 – 4100 ft.
18. *Haplophragmoides peelensis* Chamney, 1978. Ellen C-24 sample 4400 – 4500 ft.
19. *Haplophragmoides spissum* Stelck and Wall, 1956. Ellen C-24 sample 4200 – 4300 ft.
20. *Haplophragmoides topagorukensis* Tappan, 1957. Ellen C-24 sample 4300–4400 ft.
21. *Haplophragmoides yukonensis* Chamney, 1978. Ellen C-24 sample 4000– 4100 ft.
22. *Evolutinella multiplum* Stelck and Wall, 1956. Ellen C-24 sample 4600 – 4700 ft.
23. *Ammobaculites alaskensis* Tappan, 1962. Molar P-34 sample 7700 – 7750 ft.
24. *Ammobaculites fragmentarius* Tappan, 1962. Molar P-34 sample 2600 – 2650 ft.
25. *Ammobaculites wenonahae* Tappan, 1960. Ellen C-24 sample 4400 – 4500 ft.
26. *Spiroplectamina ammovitrea* Tappan, 1940. Ellen C-24 sample 3400 – 3500 ft.
27. *Textularia gravenori* Stelck and Wall, 1955. Ellen C-24 sample 300 – 400 ft.
28. *Textularia topagorukensis* Tappa, 1957. Ellen C-24 sample 3900 – 4000 ft.
29. *Trochamina eilete* Tappan, 1957. a – umbilical view; b – spiral view. Molar P-34 sample 5800 – 5850 ft.
30. *Trochamina gryci* Tappan, 1962. a – umbilical view; b – spiral view. Molar P-34 sample 7700 – 7750 ft.
31. *Trochamina rainwateri* Cushman and Applin, 1946. a – umbilical view; b – spiral view. Ellen C-24 sample 4200 – 4300 ft.
32. *Trochamina rutherfordi* Stelck and Wall, 1955. a – spiral view; b – umbilical view. Ellen C-24 sample 4400 – 4500 ft.
33. *Trochamina umiatensis* Tappan, 1957. a – spiral view; b – umbilical view. Ellen C-24 sample 4200 – 4300 ft.
34. *Gaudryina barrowensis* Tappan, 1960. Ellen C-24 sample 4400 – 4500 ft.

Figure 15. Plate 1

Plate 2 (see page 55)

1. *Gaudryina canadensis* Cushman, McNeil and Caldwell, 1981. Ellen C-24 sample 3300 – 3400 ft.
2. *Gaudryina dyscrita* Tappan, 1962. Molar P-34 sample 7700 – 7750 ft.
3. *Gaudryina nanushukensis* Tappan, 1951. Ellen C-24 sample 3300 – 3400 ft.
4. *Gaudryina stotti* Chamney, 1978. Ellen C-24 sample 3300 – 3400 ft.
5. *Gaudryina tailleuri* (Tappan) 1957. Ellen C-24 sample 4300 – 4400 ft.
6. *Tritaxia solea* Chamney, 1978. Ellen C-24 sample 4000 – 4100 ft.
7. *Uvigerinammina manitobensis* (Wickenden), 1932. Molar P-34 sample 2600 – 2650 ft.
8. *Verneulinoides canadensis* (Cushman), 1927. Ellen C-24 sample 3300 – 3400 ft.
9. *Dentalina ectadia* Loeblich and Tappan, 1950. Molar P-34 sample 7700 – 7750 ft.
10. *Paleopolymorphina vagina* (Terquem), 1864. Molar P-34 sample 7700 – 7750 ft.
11. *Lenticulina macrodisca* (Reuss), 1863. Ellen C-24 sample 3600 – 3700 ft.
12. *Marginulinopsis collinsi* Mellon and Wall, 1956. Ellen C-24 sample 4900 – 5000 ft.
13. *Marginulinopsis jonesi* (Reuss), 1863. Ellen C-24 sample 3600 – 3700 ft.
14. *Saracenaria projectura* Stelck and Wall, 1956. Ellen C-24 sample 3900 – 4000 ft.
15. *Oolina* sp. Ellen C-24 sample 200 – 300 ft.
16. *Anomalinoides* sp. a – spiral view; b – umbilical view. Ellen C-24 sample 4200 – 4300 ft.
17. *Gavelinella awunensis* Tappan, 1960. a – umbilical view; b – spiral view. Ellen C-24 sample 4300 – 4400 ft.
18. *Astacolus* cf. *grata* (Reuss), 1863. Ellen C-24 sample 0 – 100 ft.

Figure 16. Plate 2

A similar phenomena can occur with agglutinated tests where iron from the test's cement is leached to produce pyrite, resulting in degradation of the consolidating cement leading to disaggregation (Schröder-Adams and McNeil, 1994). The dominance of agglutinated taxa in the examined assemblages of the two studied wells indicates that they are highly modified, relict faunas. Pyritized rods present in greater abundance in the lower Whitestone River Formation indicates that sulphur reduction processes took place (Berner *et al.*, 1985).

4.3.1 Foraminiferal Abundance

4.3.1.1 Foraminiferal Abundance of the Molar P-34 Well

The Cretaceous foraminiferal data (Figure 15, Figure 16; Appendix B) derived from the Molar P-34 well indicates a distal basin position. The 173 samples studied from this well yielded 27 foraminiferal species, representing 19 genera. Foraminiferal abundance trends (Figure 17) are compared to the depositional cycles of the Whitestone River Formation and overlying formations (Figure 13). Correlations are presented in ascending order with the numbered intervals in brackets (Figure 17). Samples below the sub-Cretaceous boundary show high to low foraminiferal numbers clearly distinct in composition from the Whitestone River assemblage (faunal interval 0). Faunal interval 1, corresponding to moderately stable high gamma ray, is characterized by low abundance. Faunal interval 2, with steadily decreasing gamma ray, produced only rare foraminifera. Faunal interval 3, corresponding to moderately stable gamma ray and slightly increased organic matter, shows an abundance increase in foraminifera to common levels. Faunal intervals 4 and 5, characterized by stable high gamma ray and further increased organic matter, correspond to the maximum observed abundances. Faunal interval 6, spanning the

Molar P-34

Figure 17. Abundance expressed as number of specimens of foraminifera throughout the Molar P-34 well. Numbered vertical black bars represent faunal intervals linking foraminiferal abundance to well logs in

Figure 13. SS. mb – sandstone member of the Parkin Formation; PR – Porcupine River Formation.

contact between the Whitestone River Formation and basal sandstone member of the Parkin Formation, is marked by a sharp decrease in foraminiferal abundance. The sandstone member experiences a repopulation event correlating to an increase in gamma ray, suggesting a decrease in grain size (6). The faunal intervals 7 and 8 of the overlying formations including the mudstone member of the Parkin Formation (7) and Fishing Branch Formation (8) do not see a recovery in foraminiferal numbers.

4.3.1.2 Foraminiferal Abundance of Ellen C-24 Well

The reduced thickness of the Cretaceous suite in the Ellen C-24 well relative to Molar P-34 well suggests a more proximal basin position. A total of 50 samples yielded 40 foraminiferal species, representing 22 genera. Abundance changes (Figure 18) are compared to depositional cycles as identified on the logs (Figure 13). Faunal interval 1, with high gamma ray, has the maximum foraminiferal abundance. Faunal interval 2, with stable high gamma ray, shows moderately abundant numbers. Faunal interval 3 is characterized by fluctuating foraminiferal numbers and coinciding fluctuating gamma ray values, in addition to a general increase in sonic. Strong fluctuating numbers continue in faunal intervals 4 and 5 corresponding to stable high gamma ray and resistivity with slightly lower sonic. Faunal interval 6, encompassing the Parkin, Fishing Branch and Burnthill Creek formations, is nearly barren with only 1 specimen recovered from the Parkin Formation. Log signatures from this interval are variable. Within faunal interval 7, only rare occurrences appear in the Cody Creek Formation.

Ellen C-24

Figure 18. Abundance expressed as number of specimens of foraminifera throughout the Ellen C-24 well. Numbered black bars represent faunal intervals linking foraminiferal abundance to well logs in Figure 13. Ss. mb – sandstone member of the Parkin Formation.

4.3.2 Biostratigraphy

Foraminiferal zones in this study are established based on marker species, with preference given to dominant taxa. Effort was made to choose zonal markers with short stratigraphic ranges and the potential for correlation with the WIS and Canadian Arctic. Biozones describe discrete stratigraphic intervals as an assemblage marked by the stratigraphic range of one or multiple taxa with clearly expressed limits (Hedberg, 1976). The particularly long range of *Bathysiphon* is artificial due to the lack of distinctive morphologies of this tubular genus prohibiting species identifications.

4.3.2.1 Molar P-34 Biostratigraphy

Stratigraphic occurrences of the foraminiferal taxa are shown in Figure 19. Basal samples (7700 - 7750 ft) represent strata of the Jurassic Porcupine River Formation. The assemblage consists of *Ammobaculites alaskensis*, *Dentalina ectadia*, *Gaudryina dyscrita*, *Haplophragmoides canui*, *Paleopolymorphina vagina* and *Reophax suevica*. A similar assemblage is described from Jurassic aged strata from the North Slope of Alaska by Tappan (1962). The Cretaceous assemblage is dominated by agglutinated species with minor calcareous occurrences. Three foraminiferal zones - *Gaudryina tailleuri*, *Gaudryina canadensis* and *Miliammina manitobensis* - were established based on dominant and marker species spanning the Whitestone River, Parkin and Fishing Branch formations (Figure 19).

The *Gaudryina tailleuri* Zone (7650 to 5400 ft) directly overlies the Jurassic assemblage and is identified by its zonal indicator and extends through the lower part of the Whitestone River Formation. The dominant taxa include *Gaudryina tailleuri*, *Trochammina eilete*, *Hippocrepina barksdalei*, *Bathysiphon* sp., *Reophax* sp.,

Figure 19. Foraminiferal faunal distribution for the Molar P-34 well. P – Porcupine River Formation. SS – sandstone member of the Parkin Formation; Park – Parkin Formation; Fishing – Fishing Branch Formation; J. – Jurassic; Cen – Cenomanian; *G. tailleuri* – *Gaudryina tailleuri*; *G. canadensis* – *Gaudryina canadensis*; *M. man.* – *Miliammina manitobensis*.

Saccamina lathrami and *Uvigerinamina* sp. *G. tailleuri* and *T. eilete* are both diagnostic of the Early Albian as determined by Tappan (1962) and Sliter (1981) who studied the North Slope of Alaska and the Arctic Islands, respectively.

The *Gaudryina canadensis* Zone (5400 to 2100 ft) is identified by *Gaudryina canadensis* and *Ammobaculites fragmentarius*, and extends through the upper Whitestone River Formation and lowermost Parkin Formation. The dominant taxa include *G. canadensis*, *Ammobaculites fragmentarius*, *H. barksdalei*, *Bathysiphon* sp., *Haplophragmoides topagorukensis*, *Gavelinella awunensis*, *Trochammina umiatensis*, *Trochammina rainwateri*, *Uvigerinamina manitobensis*, *Ammobaculites wenonahae*, *Psamminopelta bowsheri* and *Ammodiscus rotalarius*. *G. canadensis*, *A. fragmentarius*, *P. bowsheri*, *Gavelinella awunensis*, *Trochammina umiatensis* and *Ammobaculites wenonahae* are diagnostic of the Middle to early Late Albian as determined by Tappan (1962). The interval at 2600 ft, marking the sandstone member of the Parkin Formation, is characterized by six last appearance datums (LADs) in addition to a major abundance loss from 51 specimens in the uppermost sample of the Whitestone River Formation to eight individuals in the lowermost sample of the Parkin Formation. Five species including *A. fragmentarius*, *H. topagorukensis*, *H. yukonensis*, *Gaudryina barrowensis* and *T. umiatensis* completely disappear. In contrast, other species return within the basal sandstone member of the Parkin Formation after a brief absence, including *Saccamina lathrami*, *H. barksdalei*, *P. bowsheri*, *G. canadensis* and *T. rutherfordi*.

The *Miliammina manitobensis* Zone (2100 to 1300 ft) extends through the upper Parkin and lower Fishing Branch formations. The dominant assemblage includes *Miliammina manitobensis*, *Haplophragmoides* sp., *H. barksdalei* and *S. lathrami*. *M.*

manitobensis is diagnostic of the latest Albian and is commonly found within the Western Interior Sea (Caldwell *et al.*, 1978), and was recently described from time equivalent deposits in the Sverdrup Basin (Schröder-Adams *et al.*, 2014).

4.3.2.2 Ellen C-24 Biostratigraphy

Two foraminiferal zones - *Gaudryina tailleuri* and *Gaudryina canadensis* - were established based on dominant and marker species spanning the Whitestone River Formation (Figure 20). Assemblages are dominated by agglutinated forms with minor calcareous occurrences. The sparse foraminiferal occurrences in strata above the Whitestone River Formation at this locality did not allow the establishment of any additional biozones. The *G. tailleuri* Zone is identified by its zonal marker taxon and extends through the lower part of the Whitestone River Formation. The dominant assemblage includes *G. tailleuri*, *H. topagorukensis*, *Haplophragmoides linki*, *Haplophragmoides peelensis*, *Bathysiphon vita*, *Bathysiphon* sp., *Reophax troyeri*, *Saccamina lathrami*, *Ammobaculites wenonahae*, *Gaudryina nanushukensis* and *Textularia topagorukensis*. From this assemblage, *G. tailleuri* is diagnostic of the Early Albian (Tappan, 1962; Sliter, 1981). This taxon, and several of other Albian species were found in the lowermost most samples of the Ellen C-24 suite (Figure 20) associated with the uppermost Devonian to lowermost Carboniferous Tuttle Formation. This occurrence is interpreted as the result of upwell contamination during drilling.

The *Gaudryina canadensis* Zone is identified by the presence *G. canadensis* and *Verneuilinoides canadensis*, and extends through the upper Whitestone River Formation. While *G. canadensis* occurs in the uppermost sample of the underlying *G. tailleuri* Zone, more weight is given to the last occurrence of *G. tailleuri* in defining the zonal boundary

for reasons discussed in Chapter 3. The dominant assemblage includes *G. canadensis*, *H. topagorukensis*, *Bathysiphon vitta*, *Bathysiphon* sp., *Reophax troyeri*, *S. lathrami*, *A. wenonahae*, *Gaudryina stotti* and *V. canadensis*. From this assemblage, *G. canadensis* and *V. canadensis* are diagnostic of the Middle to early Late Albian (Tappan, 1962; Thomson *et al.*, 2011).

The sparse taxa above the sharp faunal loss at the contact between Whitestone River and Parkin formations includes taxa such as *Bathysiphon* sp., *Haplophragmoides* sp., *Reophax* sp., *Oolina* sp. and *Trochammina* sp. The poor preservation of these specimens did not permit species level identification of biostratigraphic indicators. A rare occurrence of *Textularia gravenori* was identified in the upper Cody Creek Formation suggesting a Cenomanian age. This species was also observed in the upper Cenomanian portion of the Trevor Formation on the Peel Plateau (Thomson *et al.*, 2011) and in the Cenomanian strata of the more southern Western Interior Sea (e.g., Stelck and Wall, 1955). Occurrences of this taxon in Alaska are in the early Turonian (Tappan, 1962).

Several LADs occur within the upper part of the Whitestone River Formation at approximately 3600 ft. A total of nine species are lost coinciding with a decrease from 84 to 27 individuals. The second and most significant LADs occurs at 3300 ft where 18 of 23 remaining species are lost, with a complete loss of 65 foraminifera counted in the uppermost sample of the Whitestone River Formation.

4.3.3 Faunal Changes

The study of modern depositional environments and the foraminiferal ecosystems they foster provides an analog with which to reconstruct environmental conditions of past

environments based on fossil foraminiferal assemblages (e.g. Nagy, 1992; Tyszk, 1994; Reolid *et al.*, 2008). Composition of modern and fossil foraminiferal communities are controlled by primarily oxygen and nutrient levels (Jorissen *et al.*, 1995). This model, TROX (TRophic OXygen; Jorissen *et al.* (1995)), demonstrates the distribution of foraminifera with respect to oxygen and nutrient levels, at the water sediment interface and within the upper sediment layer. It demonstrates that under oxygen-rich and oligotrophic conditions epifaunal forms dominate and that infaunal forms are hindered by low levels of organic matter below the water-sediment interface (Figure 21). As nutrient levels increase to mesotrophic and eutrophic conditions, oxygen becomes increasingly depleted at the water-sediment interface and more so in pore waters. These conditions are reflected by a gradual increase in shallow and eventually deep infaunal forms which are adapted to low oxygen conditions and able to burrow down to find food (Jorissen *et al.*, 1995; Reolid *et al.*, 2008). Species are separated into infauna or epifaunal according to a study by Reolid *et al.* (2008).

Four faunal categories are identified:

1. Oligotrophic and intermittently dysoxic. An assemblage dominated by the tubular suspension feeder *Bathysiphon* has been interpreted as indicative for an oligotrophic and intermittently dysoxic environment located near the middle to lower slope, in deeper water conditions (Koutsoukos and Hart, 1990; Schönfeld, 2001).
2. Dysoxic to anoxic. Assemblages dominated by the epifaunal species *Trochammina* are associated with oxygen depleted benthic environments (Gooday *et al.*, 2000).

Figure 21. Schematic representation of the Trophic Oxygen model (TROX Model; Jorissen *et al.*, 1995). The model demonstrates the distribution of foraminifera with respect to oxygen and nutrient levels, at the water sediment interface and within sediment. Morphotype illustrations reflect species from this study (after Koho (2008)).

3. Oxygen-rich. Dominance of epifaunal species is linked to oxygen-rich and oligotrophic conditions (Jorissen *et al.*, 1995).

4) Oxygen-poor and meso- to eutrophic. Dominance of infaunal species is linked to oxygen-poor and mesotrophic to eutrophic environments (Jorissen *et al.*, 1995).

Peak assemblages in this study are dominated by very high numbers of *Bathysiphon*, which may be overrepresented due to multiple fragments possibly belonging to the same individual. Therefore, relative abundances of species from the other categories are plotted without *Bathysiphon* counts in order to better interpret faunal trends.

4.3.3.1 Faunal Changes in Molar P-34

Data from the Molar P-34 well exhibits seven intervals marked by faunal changes (Figure 22), discussed here in ascending depth. The five stratigraphically lowest intervals cover the Whitestone River Formation. Interval 1 contains seven foraminiferal specimens, mostly epifaunal taxa, three of them suspension feeders, and only one infaunal specimen. Interval 2 is also characterized by rare specimens of mainly suspension feeders, with rare epifaunal and infaunal taxa. These scarce low abundance assemblages do not permit meaningful interpretations. Interval 3 is initially dominated by infauna, mostly *G. tailleuri*, with a lesser epifaunal component dominated by *Trochammina*. Moving up the interval, the assemblage becomes increasingly dominated by *Bathysiphon*. Species richness in this interval remains generally stable though

Figure 22. Foraminiferal variations for Molar P-34 including *Trochammina*, *Bathysiphon*, other epifaunal, infauna, foraminiferal abundance and species richness. *Percent *Bathysiphon* represents the proportion from the total assemblage, whereas percent *Trochammina*, other epifaunal and infauna exclude *Bathysiphon* from the total. J. – Jurassic; Por – Porcupine River Formation; SS – sandstone member of the Parkin Formation; Fishing Br. – Fishing Branch Formation; *G. tailleuri* – *Gaudryina tailleuri*; *G. canadensis* – *Gaudryina canadensis*; *M. manitobensis*. – *Miliammina manitobensis*.

decreases in association with declining abundance in the uppermost interval. Interval 4 exhibits the most significant increase in both abundance and species richness among all intervals. While abundance consistently increases throughout the interval, species richness peaks at 4000 ft. The peak in species numbers corresponds to an increase in infauna, represented by *Reophax*, with few specimens of the epifaunal genus *Trochammina*. The abundance of *Bathysiphon* increases moving up section with a peak at 3200 ft. Infauna increases significantly above this interval, represented by *Ammobaculites* and to a lesser extent *Gaudryina*, in association with an increase in species richness. Interval 5 is characterized by an increase in epifaunal taxa, including *Haplophragmoides*, *Hippocrepina*, *Trochammina* and *Saccammina*. The top of this interval shows a significant loss in abundance of all species. Interval 6, related to the sandstone member of the Parkin Formation, becomes gradually dominated by epifauna. Interval 7, covering the shale member of the Parkin Formation and the lower Fishing Branch Formation, contains only sporadic occurrences of rare foraminifera which are entirely epifaunal, including *Bathysiphon*, *Saccammina*, *Haplophragmoides* and *Hippocrepina*. Species richness is marginally higher in the upper interval.

4.3.3.2 Faunal Changes in Ellen C-24

Ellen C-24 exhibits seven intervals of discrete faunal changes (Figure 23). The lower five intervals cover the Whitestone River Formation. Intervals 1 to 3 are marked by common to abundant foraminifera and consists of approximately two-thirds epifaunal taxa, represented by *Haplophragmoides*, *Bathysiphon*, *Trochammina* and *Saccammina*, and one-third infauna, represented by *Reophax*, *Gaudryina* and *Ammobaculites*. Despite slight abundance variations the assemblage remains relatively constant. *Bathysiphon*

Figure 23. Foraminiferal variations for Ellen C-24 including *Trochammina*, *Bathysiphon*, other epifaunal, infauna, foraminiferal abundance and species richness. *Percent *Bathysiphon* represents the proportion from the total assemblage, whereas percent *Trochammina*, other epifaunal and infauna exclude *Bathysiphon* from the total. D-C – latest Devonian to earliest Carboniferous; Tut. – Tuttle Formation; SS – sandstone member of the Parkin Formation; Park. – Parkin Formation; FB – Fishing Branch Formation; BC – Burnthill Creek Formation; *G. tailleuri* – *Gaudryina tailleuri*; *G. canadensis* – *Gaudryina canadensis*.

increases towards the top of interval 3 and peaks in the lowermost Interval 4. Interval 4 is also marked by an increase in infauna corresponding to an abundance decrease. Interval 5 exhibits the complete loss of benthic foraminifera at approximately 3300 ft. Interval 6, covering the Parkin, Fishing Branch and Burnthill Creek formations, host only one occurrence of *Reophax* within the shale member of the Parkin Formation. Interval 7 represents the Cody Creek Formation and contains only sporadic occurrences of rare foraminifera, mostly at its base and top.

4.3.4 Biostratigraphic Comparison of the Molar P-34 and Ellen C-24 Wells

Reliable biostratigraphic correlations can be drawn between the Molar P-34 and Ellen C-24 wells based on the fact that, both wells share the same faunal zones in the lower (*G. tailleuri*) and upper (*G. canadensis*) Whitestone River Formation (Figure 24). Nineteen taxa are shared by both wells including most common species, e.g., *Ammobaculites wenonahae*, *Ammobaculites fragmentarius*, *Haplophragmoides topagorukensis*, *Gaudryina barrowensis*, *Hippocrepina barksdalei*, *Haplophragmoides yukonensis* and *Trochammina umiatensis*, among others. Despite the condensed section of the Whitestone River Formation in the Ellen C-24 well relative to the Molar P-34 well, both assemblages show similar faunal compositions. Notable differences include: 1) Ellen C-24 has high species abundance and diversity in both faunal zones, whereas those parameters peak in the *G. canadensis* zone of Molar P-34; and 2) the abundance of the tubular suspension feeder *Bathysiphon* is higher in the Molar P-34 well in both zones. The sandstone member of the Parkin Formation marks a significant loss of foraminifera in both wells. Of note is that in the Ellen C-24 well, the broad sample resolution places

Figure 24. Well log and biostratigraphic correlation between the Molar P-34 and Ellen C-24 wells with ranges of selected foraminifera indicated. The solid correlations lines represent formational contacts and the dotted correlation line within the Whitestone River Formation indicates a level of several first appearances of species. J. – Jurassic; D-C – latest Devonian to earliest Carboniferous; SS – sandstone member of the Parkin Formation; Fishing Br./FB – Fishing Branch Formation; BC – Burnthill Creek Formation; *V. canadensis* – *Verneuilinoides canadensis*.

the LADs within the sandstone member, whereas in Molar P-34 the LADs occur at the member's base.

Faunal correlations above the Whitestone River Formation are not possible due to the impoverished fauna at both localities. Here, well log correlation marked by clear boundary signals are relied upon. The latest Albian indicator species *Miliammina manitobensis* was only found in the Molar P-34 well within the shale member of the Parkin Formation and lowermost Fishing Branch Formation corresponding to a barren section in the Ellen C-24 well.

5 Chapter: Discussion

5.1 Comparison between surface and subsurface foraminiferal assemblages

Recent revisions made to the stratigraphic framework of the Whitestone River Formation and Eagle Plain Group by Haggart *et al.* (2013) were based on outcrop studies. Because complete formations are not generally found in outcrop on the Eagle Plain, type sections for these formations were chosen from well logs and subsequent correlations throughout the Eagle Plain were based on well logs (Dixon, 1992). This study integrates the recent stratigraphic framework of Haggart *et al.* (2013) with subsurface foraminiferal evidence obtained here from the Molar P-34 and the Ellen C-24 wells, amended by petrophysical signatures.

The most notable difference between outcrop and subsurface foraminiferal assemblages was the inferior preservation and overall sparser assemblages in outcrop (Haggart *et al.*, 2013). Formations exposed in outcrop or sampled in wells would have undergone similar depositional and diagenetic histories, suggesting that the main difference would be mechanical and chemical weathering from subaerial exposure.

In terms of assemblage composition, outcrop samples (Haggart *et al.*, 2013) and subsurface samples share a total of eight taxa from the lower to upper Albian Whitestone River Formation and eleven taxa from the uppermost Albian Parkin Formation. The shared taxa include *Ammobaculites fragmentarius*, *Haplophragmoides topagorukensis*, *Gaudryina nanushukensis*, *Ammobaculites wenonahae*, *Textularia topagorukensis*, *Verneuilinoides borealis*, *Gaudryina barrowensis*, *Gaudryina tailleuri*, *Gaudryina canadensis*, *Saccamina alexanderi* and *Hippocrepina barksdalei*. In both outcrop and subsurface, foraminiferal assemblages are richest in the Whitestone River Formation.

Outcrops of the Parkin Formation only yielded an impoverished fauna; those outcrops were located in the central part of the Eagle Plain (Haggart *et al.*, 2013) and have a high degree of correspondence to the faunal data of the nearby Ellen C-24 well. The significant faunal loss within the upper Albian sandstone member of the Parkin Formation is equally recognized in outcrop and subsurface. The reoccurrence of foraminifera in the upper Albian Parkin Formation above the sandstone member and uppermost Albian Fishing Branch Formation is recognized in outcrop along the Fishing Branch River (loc. C, Haggart *et al.*, 2013). In the subsurface species only reappear in the Molar well. Both localities fall within the western and northwestern portions, respectively, representing more distal settings (Dixon, 1992).

5.2 Stratigraphic Re-evaluation of the Whitestone River Formation and Eagle Plain Group

Integration of the SHRIMP zircon age of 105.49 +/- 0.22 Ma (W.J. Davis, pers. comm., 2015) from a bentonite in the upper Whitestone River Formation leads to a revision of the age of this formation and the Eagle Plain Group (Figure 25). This bentonite age moves the upper Whitestone River Formation into the early Late Albian using the timescale by Gradstein *et al.* (2012). The Early to Middle Albian boundary is placed at 110.8 Ma, the Middle to Late Albian boundary at 107.6 Ma and the Late Albian to Cenomanian boundary at 100.5 Ma (Gradstein *et al.*, 2012) giving the late Albian a long duration. The top of the Whitestone River Formation was moved by Haggart *et al.* (2013) into the Middle Albian to accommodate macrofossil ages, whereas the bentonite age of 105.49 +/- 0.22 Ma places the top into the early Late Albian (Figure 25).

Figure 25. Stratigraphic revision of the Whitestone River Formation and Eagle Plain Group based on biostratigraphy from this study and a U-Pb zircon date compared to the stratigraphy established by Haggart *et al.* (2013). Burnthill Ck – Burnthill Creek Formation.

Moving the uppermost Whitestone River Formation into the lower Upper Albian pushes the inferred fossil age ranges as suggested by Haggart *et al.*, (2013) for this unit and the Parkin Formation to their upper limit. By doing so, the Parkin Formation remains within the middle to upper Albian. However, this boundary change inferred from a single new geochronological age conflicts with some biostratigraphic data, including the age ranges for ammonites and foraminiferal assemblages from the top of the basal sandstone member of the Parkin Formation (Haggart *et al.*, 2010). For example, the ammonites, *Cleogastrolites aberrans* Jeletzky, *Cleoniceras* aff. *subbaylei* Spath and *Gastrolites kingi* McLearn range into the Middle Albian (Haggart *et al.*, 2010). The same authors report a foraminiferal assemblage including *Bathysiphon vitta*, *Reophax troyeri*, *Haplophragmoides yukonensis*, *Ammobaculites petilus*, *Gaudryina nanushukensis*, and *Gaudryina tailleuri* was identified by Haggart *et al.* (2013) in mudstone interbeds from the lower Parkin Formation previously assigned an Early to Middle Albian age range by McNeil (2011). While most taxa from the latter assemblage are observed from the Middle to early Late Albian by other workers (e.g., Tappan, 1962; Chamney, 1978; Caldwell *et al.* 1978), *G. tailleuri* appears to be out of place as it is regarded as an early to middle Albian species (Tappan, 1962). This extended range of *G. tailleuri* in outcrop might be explained by either taxonomic uncertainty due to poor preservation or a novel adaptation of the taxon to favourable paleoecological conditions extending its biostratigraphic range; both subjects would require further study.

Foraminifera from the Molar P-34 and Ellen C-24 wells that integrate well with the revised formational boundary ages reported here (Figure 24). The presence of the zonal markers *G. tailleuri* of Early Albian age, and *G. canadensis* of Middle to early Late

Albian age, confines the age of the Whitestone River Formation and basal sandstone member of the Parkin Formation. The presence of the *M. manitobensis* Zone in the upper Parkin and lower Fishing Branch formations confirms a latest Albian age and the position of the Albian/Cenomanian boundary at least above the last occurrence of *M. manitobensis*. The presence of *Textularia gravenori* within the Cody Creek Formation supports a late Cenomanian age.

5.3 Biostratigraphic Comparisons to Regional Frameworks

The dominance of Albian agglutinated assemblages in the Eagle Plain compares well to the dominance of agglutinated assemblages observed throughout the WIS during the mid-Cretaceous (Caldwell *et al.*, 1993) including the Manitoba Escarpment (McNeil and Caldwell, 1981), the Interior Plains (e.g., Caldwell *et al.*, 1978; Stritch *et al.*, 1999), the Liard Basin (Jowett and Schröder-Adams, 2005), the Peel Plateau (Thomson *et al.*, 2011) and the Beaufort-Mackenzie Basin (McNeil, 1996).

The *Gaudryina tailleuri* Zone is correlated to the same zone in equivalent aged strata in the North Slope of Alaska (Tappan, 1962), and the Ellef Ringnes and Amund Ringnes islands (Sliter, 1981) in the Sverdrup Basin. *Trochammina eilete* is another important biostratigraphic indicator and is part of this zone. Sliter (1981) pointed out that *G. tailleuri* alone reaches down into the Late Jurassic (Ramsay, 1970; Souaya, 1976), but the entire assemblage zone is assigned to the Early Albian. Schröder-Adams *et al.* (2014) studied the Aptian/Albian Christopher Formation on Axel Heiberg Island and assigned the *Quadriformina albertensis* Zone to the Aptian part of this formation (Figure 26). On the Peel Plateau the *Q. albertensis* Zone was defined for the lower Albian interval (Thomson *et al.*, 2011). This zone was not discovered in the studied cores, although it has

Stage		Jowett et al. 2004, 2007 Liard Basin	This study Eagle Plain	Thomson et al. 2011 Peel Plateau	Tappan, 1962 Arctic Slope of Alaska	McNeil, 1996 & 1997a Beaufort- Mackenzie Area	Schröder-Adams et al. (2014) Axel Heiberg Is.
Camp. Sant. Con.						<i>Glaphyrammina semicompressa</i>	<i>Glaphyrammina semicompressa</i>
Turonian				<i>Pseudoclavulina hastata</i>	<i>Pseudoclavulina hastata</i> - <i>Neobulimina canadensis</i>		<i>Dorothia smokyensis</i> - <i>Evolutinella boundaryensis</i>
Cenomanian	Late					<i>Trochammina superstes</i>	<i>Trochammina rutherfordi</i>
		Unzoned		<i>Gaudryina irenensis</i>	<i>Gaudryina irenensis</i> - <i>Trochammina rutherfordi</i>		
	Early	<i>Textularia alcesensis</i>		fish debris			<i>Gaudryina irinensis</i>
Albian	Late	<i>Miliammina manitobensis</i> <i>Haplophragmium swareni</i>	<i>Miliammina manitobensis</i>				<i>Miliammina manitobensis</i>
		<i>Bathysiphon- A. fragmentarius assemblage</i> <i>Ammomarginulina assemblage</i> <i>Ammobaculites wenonahe</i>	<i>Gaudryina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Verneuilinoides borealis</i>	<i>Verneuilinoides borealis</i>	<i>Haplophragmoides gigas</i> - <i>Gaudryina canadensis</i>
	Middle	<i>Ammobaculites</i> sp.					<i>Evolutinella multiplum</i>
	Early	<i>Haplophragmoides multiplum</i> <i>Verneuilinoides cummingensis</i>	<i>Gaudryina tailleuri</i>	<i>Quadrиморфина albertensis</i>	<i>Gaudryina tailleuri</i>	<i>Quadrиморфина albertensis</i>	<i>Verneuilinoides borealis</i>
Aptian	Late						<i>Quadrиморфина albertensis</i>
							barren

Figure 26. Foraminiferal biostratigraphic frameworks from the Liard Basin, Peel Plateau, Richardson Mountains, North Slope of Alaska, Beaufort-Mackenzie Area and Axel Heiberg Island (modified from Schröder-Adams *et al.*, (2014)).

to be noted that *Q. albertensis* is a minute calcareous species easily removed by taphonomic processes. In the Richardson Mountains, *G. tailleuri* was identified ranging from the latest Hauterivian to the Barremian associated with the Mount Goodenough Formation and from the lower Albian Arctic Red Formation, though it is not recognized as a formal zone in either formation. This confirms the long biostratigraphic range of this zonal marker. Common faunal elements of the *G. tailleuri* Zone amongst all these localities, including *Ammodiscus rotalarius*, *H. topagorukensis*, and *H. barksdalei*, points towards an Albian rather than an Aptian age.

The *Gaudryina canadensis* Zone is correlated to the time-equivalent *Verneuilinoides borealis* Zone from the North Slope of Alaska (Tappan, 1962) and the Beaufort-Mackenzie area (McNeil, 1996, 1997). *G. canadensis* is also a zonal indicator for equivalent aged strata from Peel Plateau (Thomson *et al.*, 2011), though the lower boundary was placed in the late Middle Albian rather than at the Early/Middle Albian contact as proposed here. The *G. canadensis* Zone from Eagle Plain correlates to the same zone on Axel Heiberg Island (Schröder-Adams *et al.*, 2014), though there the Middle Albian is represented by the *Evolutinella multiplum* Zone. The *G. canadensis* Zone from the Eagle Plain shares a number of taxa with the aforementioned time equivalent zones, including *A. fragmentarius*, *A. wenonahae*, *H. topagorukensis* and *A. rotalarius*.

The *Miliammina manitobensis* Zone is identified in the Interior Plains (Caldwell *et al.*, 1978), Liard Basin (Jowett, 2004; Jowett *et al.*, 2007) and the Sverdrup Basin (Schröder-Adams, 2014). On the Eagle Plain *M. manitobensis* is rare, but together with species such as *S. lathrami* and *H. barksdalei* provide an important marker for the latest

Albian.

Biostratigraphic correlations confirm the interconnectedness of the Western Interior Sea to the Polar Sea (Schröder-Adams, 2014) as the result of a major transgression that took place during the Aptian (Embry and Beauchamp, 2008) inundating the North American continent and reaching as far south as Alberta (Jeletzky, 1975; Williams and Stelck, 1975; Caldwell *et al.*, 1993; Schröder-Adams *et al.*, 2014). Whereas distal marine Aptian deposits are preserved, for example, in the Sverdrup Basin (Schröder-Adams *et al.*, 2014) and the Banks Basin (Miall, 1979), transgressive proximal deposits are mapped in the Liard Basin (Leckie *et al.*, 1991) and Mackenzie Plain (Dixon, 1999). For the Eagle Plain, Dixon (1993b) suggested that pre-upper Aptian sediments were mostly removed by several phases of early Cretaceous uplift and erosion. However, it is still unknown whether upper Aptian sediments are preserved on Eagle Plain. Log correlations of the base of the Whitestone River Formation, in addition to the basal foraminiferal assemblage encountered in the Ellen well, point to an Albian age of the lowermost preserved Cretaceous strata (Figure 23).

5.4 Paleogeography and Foraminiferal Response

The original Eagle Plain basin subsurface framework by Dixon (1992) suggested an outer shelf to slope setting for the Molar P-34 well and a proximal- to middle shelf setting for the Ellen C-24 well. These interpretations, based on lithofacies and subsurface formational geometries, can now be confirmed with subsurface faunal data.

The faunal changes and variations in the Whitestone River Formation and Eagle Plain Group document a response to fluctuating sea level and resulting changes in paleoenvironment and paleogeography. Paleoecological conditions are inferred based on key fossil indicators by using the methodology of Murray *et al.* (2011) who calibrated

well studied modern foraminiferal assemblages with fossil assemblages. Chosen parameters include the relative abundance of deep water indicators such as the genus *Bathysiphon*, low oxygen resistant taxa such as *Trochammina*, and increased nutrient availability represented by a dominance of infaunal over epifaunal taxa (Jorissen *et al.*, 1995).

In the Molar P-34 well data, the overall high proportion of *Bathysiphon*, a tubular, erect species preferring quiet water habitats, within the Whitestone River Formation, is characteristic of outer shelf to slope settings (Nagy *et al.*, 1995; Murray, 2011). The increased proportion of *Trochammina*, in addition to increased infauna and preserved organic matter, suggests diminished benthic oxygen conditions (Jorissen *et al.*, 1995; Gooday *et al.*, 2000; Reolid *et al.*, 2007) and the presence of the oxygen minimum zone (e.g., Ifrim *et al.*, 2011) related to the outer shelf locality of Molar P-34 well. Those conditions are, in turn, reflected in the low abundance of foraminifera within the early Albian *G. tailleuri* Zone.

In contrast, the lower proportion of *Bathysiphon* at the Ellen C-24 well, in association with a higher proportion of epifauna, is indicative of a proximal-to middle shelf setting. The dominance of epifauna in the well (Figure 21), often comprising up to two-thirds of the assemblage, suggests well oxygenated bottom waters and an oligotrophic setting. This progressive decrease in bottom water oxygen concentrations moving towards the slope is consistent with observations of foraminiferal assemblages is similar to extant assemblages on shelf to slope settings of the Barents and northern North seas (Nagy *et al.*, 2010).

These slope to proximal shelf conditions are maintained throughout the Whitestone River Formation and are consistent with paleogeographic reconstructions by

Blakey (Blakey, 2016) of open marine conditions during the Early to early Late Albian for this locality (Figure 27A). Open marine conditions also reached the Peel Plateau (Thomson *et al.*, 2011) and the Richardson Mountains (Fowler, 1985) where distal marine sediments of the Arctic Red Formation were deposited. During the latest Albian, the increasing proximal conditions, as witnessed by the sandstones of the Fishing Branch Formation, support a nearshore position on Blakey's latest Albian reconstruction (Figure 27B). The mainly terrestrial deposits of the Cenomanian Cody Creek Formation (Haggart *et al.*, 2013) relate to a land-locked position on Blakey's middle Cenomanian paleogeographic map (Figure 27C). During the Turonian the northern seaway constricted (Figure 27D), supporting the eastward movement of the paleoshoreline, as witnessed by eastward prograding shoreface deposits of the Turonian Trevor Formation on the Peel Plateau (Thomson *et al.*, 2011).

Within the Whitestone River Formation, four distinct faunal associations can be correlated to major Albian transgressive-regressive cycles including, in ascending order, the Moosebar, Hulcross, Joli Fou and Mowry sea-level cycles (Figure 27). These cycles were mainly established based on cores and outcrops from the southern parts of the Canadian WIS (Caldwell *et al.*, 1978, 1993). These regional transgressive-regressive cycles are equivalent to contemporaneous major global sea level cycles (e.g. Gradstein *et al.*, 2012) as suggested by Schröder-Adams (2014). Shared faunal elements with Eagle Plain faunas support the linkage between these regions. Cycle boundaries are clearly marked by notable shifts in logs and by phases of faunal reduction (Figure 28), pointing towards regressive phases. After each shallowing event foraminiferal communities gradually recovered. The largest number of first appearances of species takes place in the Joli Fou sequence, a time known to relate to the seaway that connects the Polar Sea to the

Figure 27. Paleogeographic maps of the Eagle Plain (Dixon, 1992; Haggart *et al.*, 2013; this study - square), Richardson Mountains (Fowler, 1985 - star) and Peel Plateau (Thompson *et al.*, 2011 - circle) during the Early Albian, Late Albian, Middle Cenomanian and Late Turonian. Paleogeographic maps courtesy of © Ron Blakey, Colorado Plateau Geosystems, Inc.

Figure 28. Faunal and well log signature for Molar P-34 and Ellen C-24 wells established in this study in relation to Albian transgressive-regressive cycles for the WIS (Caldwell *et al.*, 1993). J. – Jurassic; D-C – latest Devonian to earliest Carboniferous; SS – sandstone member of the Parkin Formation; Fishing Br./FB – Fishing Branch Formation; BC – Burnthill Creek Formation; CC – Cody Creek Formation.

North with the Tethyan Sea to the south (e.g., Williams and Stelck, 1975).

A complete loss of foraminifera occurs at the boundary between the Whitestone River Formation and the sandstone member of the Parkin Formation. The basal fluvial to shoreface sandstones of the Parkin Formation (Haggart *et al.*, 2013) mark the end of the Joli Fou Sea. Jeletzky (1971) described a restricted western embayment setting as part of the WIS overlapping with the Eagle Plain region, possibly not favourable for benthic fauna. In addition, inhospitable benthic conditions might have been reinforced by a warming climate towards the end of the Albian (e.g., Erba, 2004). A humid climate with increased precipitation might have caused an influx of freshwater that formed a freshwater lid and intensified stratification (e.g., Schlanger and Jenkyns, 1976; Hay *et al.*, 1993). Inferred increased nutrient runoff and its preservation is recorded in the upper Parkin Formation by the $\Delta\log R$ signatures. Benthic depleted oxygen conditions are also confirmed by pyrite nodules (Berner *et al.*, 1985) within the Parkin Formation (Haggart *et al.*, 2013).

Repopulation after this barren interval is only noticed in the Molar P-34 well, where after this boundary the genus *Trochammina* - known for its adaptability to dysoxic benthic conditions in modern settings - dominates the assemblage, (Reolid *et al.*, 2014). The Ellen C-24 well remains barren of foraminifera throughout the latest Albian.

The latest Albian disconformity, recognized throughout northwestern Canada and the Arctic (Dixon, 1993), remains elusive within the Eagle Plain. On Peel Plateau the disconformity is identified by paleosol development at the base of the Slater River Formation (Thomson *et al.*, 2011). Haggart *et al.* (2013) suggested the unconformity likely occurs within the terrestrial Fishing Branch or Cody Creek formations, though

those authors believe the latter to be more likely. Jackson *et al.* (2010) described a fluvial sandstone member, representing a disconformity, within the Fishing Branch Formation in southern Eagle Plain and interpreted the base of that unit as a local expression of the latest Albian disconformity.

This core study adds some additional evidence to the the position of the disconformity. Foraminifera known from the latest Albian are identified in the lower Fishing Branch Formation. Late Cenomanian faunal elements were retrieved from marine mudstone interbeds of the Cody Creek Formation. If the Fishing Branch Formation occupies the latest Albian, it is unlikely that the entire Burnthill Creek Formation can also be regarded as being of latest Albian age. Therefore, the Albian/Cenomanian disconformity is more likely to be within the upper Fishing Branch Formation, contra Haggart *et al.* (2013).

5.5 Regional Correlations between Arctic Basins

The goal of this chapter is to discuss the Aptian to Cenomanian history of the Canadian Arctic from the Liard Basin in the south to the Sverdrup Basin in the north (Figure 29).

Aptian

Middle Aptian: During the middle Aptian, a major transgression deposited the marine mudstones of the Christopher Formation in the Sverdrup (Tozer, 1960), Banks (Miall, 1979) and Anderson (Yorath *et al.*, 1975) basins. During late Aptian to early Albian time, extensional and compressional tectonics resulted in the formation of a foredeep, east of the Cordilleran orogeny, resulting in formation of the WIS (Dixon,

Figure 29. Major events of the Canadian Arctic from the Liard Basin (Jowett, 2004; Jowett and Schröder-Adams, 2005), Eagle Plain (this study), Peel Plateau (Mountjoy and Chamney, 1969; Thomson *et al.*, 2011), Beaufort Mackenzie (McNeil, 1996) and Sverdrup basins (Schröder-Adams, 2014).

1993a). Marine mudstone deposition spanned a region from the Sverdrup Basin to the Beaufort-Mackenzie Basin (Dixon, 1999) and progressed southward through Peel Plateau (Mountjoy and Chamney, 1969), Richardson Mountains (Mountjoy and Chamney, 1969), Eagle Plain (Mountjoy, 1967) and Liard Basin (Leckie *et al.*, 1991; Jowett and Schröder-Adams, 2005), and finally reached the foothills of Alberta (Scott, 1984). The Torok and Fortress Mountain formations from the northern slope of Alaska are contemporaneous with this phase of widespread transgression (Bird, 1985; Detterman *et al.*, 1975).

Albian

The Albian is associated with several global transgressive-regressive cycles (Gradstein *et al.*, 2012) which are also represented in the Sverdrup Basin (Schröder-Adams, 2014) and the WIS (Kauffman, 1969). The Early Albian transgression associated with the Moosebar Sea coincides with cooler climates, as suggested by the wide occurrence of glendonites (calcite pseudomorphs) in the Arctic (Kemper, 1987; Schröder-Adams *et al.*, 2014; Herrle *et al.*, 2015). Glendonite formation requires not only cool, but also alkaline, waters which may have been responsible for the wide preservation of calcareous foraminifera during this period. These have been identified in the Sverdrup Basin (Wall, 1983; Sliter, 1981; Schröder-Adams *et al.*, 2014), the Beaufort-Mackenzie Area (McNeil, 1996), Peel River (Mountjoy and Chamney, 1969; Chamney 1978), Peel Plateau (Thompson *et al.*, 2011), Eagle Plain (this study), Liard Basin (Jowett and Schröder-Adams, 2005) and the southernmost extent of the WIS in the Interior Plains of Canada (Caldwell *et al.*, 1978). Calcareous foraminifera in northern Canada are rare after the Early Albian.

The Middle Albian is marked by the transgression of the Hulcross Sea, originally

recognized from the Interior Plains of Alberta and British Columbia (Caldwell *et al.*, 1978), through to the Sverdrup Basin (Schröder-Adams, 2014), formed in response to a global sea level rise (Gradstein *et al.*, 2012). These transgressions coincided with a global temperature increase (Erba, 2004) and marked the initiation of dominantly agglutinated foraminiferal assemblages from the WIS to the Sverdrup Basin (Caldwell *et al.*, 1978; Schröder-Adams, 2014).

The early Late Albian is marked by the regionally recognized transgression of the Joli Fou Sea and was associated with a short lived, cooler period during an overall warming trend (Erba, 2004). The Joli Fou transgression inundated the WIS southward, eventually forming a seaway with a connection to the Tethyan Ocean (Williams and Stelck, 1975). Increased oceanographic circulation brought well oxygenated bottom waters which, together with an influx of nutrients, nourished widespread rich foraminiferal assemblages (Caldwell *et al.*, 1978; Jowett and Schröder-Adams, 2005; this study) within the WIS including the Eagle Plain and Sverdrup Basin (Sliter 1981; Schröder-Adams *et al.*, 2014).

The latest Albian saw a renewed transgression namely the Mowry Sea (Caldwell *et al.*, 1978), however, the Eagle Plain region represents a shallow embayment of the northern WIS south of a significantly restricted passageway to the Polar Sea. The latest Albian impoverished fauna was a result of those restricted marine conditions. Schröder-Adams (2014) even suggested a short-lived complete closure of the connection between the WIS and Polar Sea towards the end of the Albian. On Axel Heiberg Island, the Albian/Cenomanian boundary is expressed as a paleosol (Schröder-Adams *et al.*, 2014), as it is on the Peel Plateau (Thomson *et al.*, 2011). This event is globally recognized as a

major regression (Gradstein *et al.*, 2012).

Cenomanian

The early Cenomanian age experienced two transgressive-regressive cycles (Gradstein *et al.*, 2012) marked by renewed marine shale deposition in many parts of the Sverdrup Basin and WIS. While foraminifera are present in the Sverdrup Basin (Schröder-Adams *et al.*, 2014), impoverished assemblages are found in the Beaufort Mackenzie Basin (McNeil, 1996), Peel Plateau (Mountjoy and Chamney, 1969; Thomson *et al.*, 2011), Eagle Plain (McNeil, 2011), and Liard Basin (Jowett and Schröder-Adams, 2005), especially as recorded higher in section. Temperatures reached a maximum during the latest Cenomanian and earliest Turonian, causing the global Oceanic Anoxic Event 2 (OAE 2) (e.g., Arthur *et al.*, 1988; Hayes *et al.*, 1989), now also firmly recognized in the Canadian Arctic (Pugh *et al.*, 2014; Lenniger *et al.*, 2014; Herrle *et al.*, 2015).

6 Chapter: Conclusion

1. Biostratigraphic analysis based on benthic foraminiferal assemblages covering Cretaceous strata of the Molar P-34 and Ellen C-24 wells of the Eagle Plain, Yukon Territory, confirms for the most part the recently proposed revised stratigraphic framework by Haggart *et al.* (2013), who took a multi-fossil approach using outcrop faunal data of the same region.
2. Based on faunal evidence, the Whitestone River Formation spans a maximum age of Early Albian to early Late Albian.
3. Three foraminiferal zones are identified from the Molar P-34 and Ellen C-24 wells. The Early Albian *Gaudryina tailleuri* Zone spans the lower Whitestone River Formation. The Middle to early Late Albian *Gaudryina canadensis* Zone occurs in the Upper Whitestone River and sandstone member of the overlying Parkin Formation. The latest Albian *Miliammina manitobensis* Zone occurs in the shale member of the Parkin Formation and lowermost Fishing Branch Formation.
4. An age of 105.49 +/- 0.22 Ma measured on a bentonite sampled within the upper Whitestone River Formation from outcrop correlates well with the presence of the *G. canadensis* Zone in the upper Whitestone River Formation and basal sandstone member of the Parkin Formation. The presence of the latest Albian *M. manitobensis* Zone in the upper Parkin Formation suggests a minimum age of early to mid-Late Albian for the contact between the Whitestone River and Parkin formations.
5. Observations of foraminiferal morphogroups and their relative proportions have allowed for paleoenvironmental reconstruction, as well as oxygen and nutrient conditions. In the Molar P-34 well, an increased abundance of tubular suspension

feeders within the Whitestone River Formation suggest an oligotrophic-to-mesotrophic middle/outer shelf, or possibly a slope setting. In the Ellen C-24 well log, rarer suspension feeders and dominant epifauna indicate a more proximal shelf setting that was generally well oxygenated. This interpretation confirms the larger accommodation space to the northwest as seen in the significantly thicker Albian strata in Molar when compared to the Ellen C-24 well.

6. The complete microfaunal loss within the Late Albian is associated with an unconformity as manifested in the basal sandstone of the Parkin Formation. The lack of repopulation, particularly in the Ellen C-24 well locality, may have been related to inhospitable conditions such as benthic anoxia, loss of marine conditions, or other unknown taphonomic processes during early burial of the specimens. The loss of foraminifera occurs earlier at this locality than in the Western Interior Sea to the south, where it is more closely associated with the Albian/Cenomanian disconformity. The regionally recognized latest Albian disconformity is believed to occur within the Fishing Branch Formation.
7. Within the Whitestone River Formation, four distinct faunal associations can be correlated to major Albian transgressive-regressive cycles, including, in ascending order, the Moosebar, Hulcross, Joli Fou and Mowry sea-level cycles. Cycle boundaries are clearly marked by notable shifts in logs and by phases of faunal reduction pointing towards regressive phases. These transgressive-regressive events are globally recognized.
8. Cretaceous strata of the Eagle Plain undergo a complex tectonic, oceanographic, and ecological history as part of regional scale changes also reflected in the Western Interior Seaway and the Sverdrup Basin.

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Appendix A

TAXONOMIC LIST OF FORAMINIFERA

The following is a list of each species observed in this study including the original reference followed by more recent descriptions where applicable.

Family ASTRORHIZIDAE Brady, 1881

Genus *Bathysiphon* Sars, 1872

Bathysiphon brosgiei Tappan 1957

Plate 1, Figure 1

Bathysiphon brosgiei Tappan, 1957. United States National Museum, Bulletin no. 215, p. 202, Plate 65, figures 1-5.

Bathysiphon brosgiei Tappan, 1962. USGS Professional Paper 236-C, p. 128, Plate 29, figures 1-5.

Bathysiphon brosgiei Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 1-2.

Occurrence. Whitestone River Formation.

Bathysiphon vitta Nauss, 1947

Plate 1, Figure 2

Bathysiphon vitta, Nauss, 1947, Jour. Paleontology, v. 21, no. 4, p. 334, Plate 48, figure 4.

Bathysiphon vitta, Tappan, 1962. USGS Professional Paper 236-C, p. 128, Plate 29, figures 6-8.

Occurrence. Whitestone River Formation.

Family SACCAMMINIDAE Brady, 1884

Genus *Saccamina* Sars, 1869

Saccamina alexanderi (Loeblich and Tappan) 1950

Plate 1, Figure 3

Saccamina alexanderi (Loeblich and Tappan); Eicher, 1960. Peabody Museum of Natural History Bulletin no. 15, p.55, Plate 3, figures 1, 2.

Saccamina alexanderi (Thompson), 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 7-8.

Occurrence. Whitestone River Formation.

Saccamina lathrami Tappan 1960

Plate 1, Figure 4

Saccamina lathrami Tappan, 1960. American Association of Petroleum Geologists, Bulletin vol. 44, no. 3, p. 289, Plate 4, figures 1, 2.

Saccamina lathrami Tappan, 1962. USGS Professional Paper 236-C, p. 129, Plate 29, figures 9-12.

Saccamina lathrami Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 9-10.

Occurrence. Whitestone River, Parkin and Fishing Branch formations.

Family HYPERAMMINIDAE Eimer and Fickert, 1899

Genus *Hippocrepina* Parker in Dawson, 1860

Hippocrepina barksdalei (Tappan) 1957

Plate 1, Figure 5

Hyperaminoides barksdalei (Tappan), 1962. USGS Professional Paper 236-C, p. 129, Plate 29, figures 21-27.

Hippocrepina barksdalei Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 9, Plate 1, figures 10-11.

Occurrence. Whitestone River, Parkin and Fishing Branch formations.

Family AMMODISCIDAE Reuss, 1862

Genus *Glomospira* Rzehak, 1888

Glomospira corona Cushman and Jarvis 1928

Plate 1, Figure 6

Glomospira corona Cushman and Jarvis; Tappan, 1962. USGS Professional Paper 236-C, p. 130, Plate 29, figures 13-16.

Glomospira corona Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 11-12.

Occurrence. Whitestone River Formation.

Genus *Glomospirella* Plummer, 1945

Glomospirella gaultina (Berthelin) 1880

Plate 1, Figure 7

Glomospirella gaultina Tappan, 1962. USGS Professional Paper 236-C, p. 130, Plate 29, figures 17-20.

Occurrence. Whitestone River Formation.

Genus *Ammodiscus* Reuss, 1862

Ammodiscus rotalarius Loeblich and Tappan 1949

Plate 1, Figure 8

Ammodiscus rotalarius Loeblich and Tappan; Tappan, 1962. USGS Professional Paper

236-C, p. 131, Plate 30, figures 5-8.

Ammodiscus rotalarius Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 13-14.

Occurrence. Whitestone River Formation.

Family HORMOSINIDAE Haeckel, 1894

Genus *Reophax* de Montfort, 1808

Reophax fuscus Chamney 1978

Plate 1, Figure 9

Reophax fuscus Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 11, Plate 2, figures 4-7.

Reophax fuscus Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 15-16.

Occurrence. Whitestone River Formation.

Reophax incompta Loeblich and Tappan 1946

Plate 1, Figure 10

Reophax incompta Loeblich and Tappan; Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 11, Plate 2, figures 1-3.

Reophax incompta Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 17-18.

Occurrence. Whitestone River Formation.

Reophax troyeri Tappan 1960

Plate 1, Figure 11

Reophax troyeri Loeblich and Tappan; Tappan, 1962. USGS Professional Paper 236-C,

p. 133, Plate 30, figures 11-13.

Occurrence. Whitestone River Formation.

Reophax suevica Franke 1936

Plate 1, Figure 12

Reophax suevica Tappan, 1962. USGS Professional Paper 236-B, p. 37, Plate 7, figures 7-10.

Occurrence. Porcupine River Formation.

Reophax vasiformis Chamney 1978

Plate 1, Figure 13

Reophax vasiformis Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 10-11, Plate 1, figures 12-14.

Reophax vasiformis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 23-24.

Occurrence. Whitestone River Formation.

Family RZEHAKINIDAE Cushman, 1933

Genus *Psamminopelta* Tappan, 1957

Psamminopelta bowsheri Tappan 1957

Plate 1, Figure 14

Psamminopelta bowsheri Tappan, 1962. USGS Professional Paper 236-C, p. 157, Plate 37, figures 11-22.

Psamminopelta bowsheri Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 25-26.

Occurrence. Whitestone River and Parkin formations.

Genus *Miliammina* Heron-Allen and Earland, 1930

Miliammina manitobensis Wickenden 1932

Plate 1, Figure 15

Miliammina manitobensis Tappan, 1962. USGS Professional Paper 236-C, p. 160, Plate 36, figures 12-18.

Occurrence. Parkin and Fishing Branch formations.

Family LITUOLIDAE de Blainville, 1825

Genus *Haplophragmoides* Cushman, 1910

Haplophragmoides canui Cushman 1930

Plate 1, Figure 16

Haplophragmoides canui Tappan, 1962. USGS Professional Paper 236-B, p. 42, Plate 9, figures 11-15.

Occurrence. Porcupine River Formation.

Haplophragmoides linki Nauss 1947

Plate 1, Figure 17

Haplophragmoides linki McNeil and Caldwell, 1981. Geological Association of Canada, Special Paper no. 21, p. 153, Plate 11, figure 11.

Haplophragmoides linki Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 33-34.

Occurrence. Whitestone River Formation.

Haplophragmoides peelensis Chamney 1978

Plate 1, Figure 18

Haplophragmoides peelensis Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 13, Plate 3, figures 4,5.

Haplophragmoides peelensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 1, figures 35-36.

Occurrence. Whitestone River Formation.

Haplophragmoides spissum Stelck and Wall 1956

Plate 1, Figure 19

Haplophragmoides spissum Stelck and Wall, 1956. Research Council of Alberta, Report no. 75, p. 39, Plate 4, figures 27, 28.

Haplophragmoides cf. *H. spissum* Stelck and Wall; Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 14, Plate 3, figure 8.

Haplophragmoides spissum Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 3-4.

Occurrence. Whitestone River Formation.

Haplophragmoides topagorukensis Tappan 1957

Plate 1, Figure 20

Haplophragmoides topagorukensis Tappan, 1962. USGS Professional Paper 236-C, p.135, Plate 31, figures 1-15.

Haplophragmoides topagorukensis Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 11, Plate 3, figures 1-3.

Haplophragmoides topagorukensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 5-6.

Occurrence. Whitestone River Formation.

Haplophragmoides yukonensis Chamney 1978

Plate 1, Figure 21

Haplophragmoides yukonensis Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 13, Plate 2, figures 8, 9.

Haplophragmoides yukonensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 7-8.

Occurrence. Whitestone River Formation.

Genus *Evolutinella* Myatlyuk, 1971

Evolutinella multiplum Stelck and Wall, 1956

Plate 1, Figure 22

Haplophragmoides multiplum Wall, 1983. Bulletin of Canadian Petroleum Geology 31, 246–281.

Occurrence. Whitestone River Formation.

Genus *Ammobaculites* Cushman, 1910

Ammobaculites alaskensis Tappan 1960

Plate 1, Figure 23

Ammobaculites alaskensis Tappan, 1962. USGS Professional Paper 236-B, p. 43, Plate 12, figures 1-10.

Occurrence. Porcupine River Formation.

Ammobaculites fragmentarius Tappan 1962

Plate 1, Figure 24

Ammobaculites wenonahae Tappan, 1962. USGS Professional Paper 236-C, p. 136, Plate

32, figures 9-11.

Occurrence. Whitestone River Formation.

Ammobaculites wenonahae Tappan 1960

Plate 1, Figure 25

Ammobaculites wenonahae Tappan, 1962. USGS Professional Paper 236-C, p. 138, Plate 32, figures 1-7.

Ammobaculites wenonahae Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 9-10.

Occurrence. Whitestone River Formation.

Family TEXTULARIIDAE Ehrenberg, 1838

Genus *Spiroplectammina* Cushman, 1927

Spiroplectammina ammovitrea Tappan 1940

Plate 1, Figure 26

Spiroplectammina ammovitrea Tappan, 1962. USGS Professional Paper 236-C, p. 139, Plate 33, figure 4.

Occurrence. Whitestone River Formation.

Genus *Textularia* Defrance, 1824

Textularia gravenori Stelck and Wall 1955

Plate 1, Figure 27

Textularia gravenori Stelck and Wall; Tappan, 1962. USGS Professional Paper 236-C, p. 141, Plate 33, figures 16, 17.

Textularia gravenori Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 23-24.

Occurrence. Whitestone River Formation.

Textularia topagorukensis Tappan 1957

Plate 1, Figure 28

Textularia topagorukensis Tappan 1962. USGS Professional Paper 236-C, p. 141, Plate 33, figures 7-11.

Textularia topagorukensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 25-26.

Occurrence. Cody Creek Formation.

Family TROCHAMMINIDAE Schwager, 1877

Genus *Trochammina* Parker and Jones, 1859

Trochammina eilete Tappan 1957

Plate 1, Figure 29

Trochammina eilete Tappan, 1962. USGS Professional Paper 236-C, p. 153, Plate 38, figures 9-10.

Occurrence. Whitestone River Formation.

Trochammina gryci Tappan 1962

Plate 1, Figure 30

Trochammina gryci, 1962. USGS Professional Paper 236-B, p. 50, Plate 14, figures 12-14.

Occurrence. Porcupine River Formation.

Trochammina rainwateri Cushman and Applin 1946

Plate 1, Figure 31

Trochammina rainwateri Cushman and Applin; McNeil and Caldwell, 1981. Geological Association of Canada, Special Paper no. 21, p. 169, Plate 13, figures 11,12.

Trochammina rainwateri Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 39-41.

Occurrence. Whitestone River and Parkin formations.

Trochammina rutherfordi Stelck and Wall 1955

Plate 1, Figure 32

Trochammina rutherfordi Stelck and Wall, 1955. Research Council of Alberta, Report no. 70, p. 56-57, Plate 1, figures 11,12.

Trochammina rutherfordi Stelck and Wall; McNeil and Caldwell, 1981. Geological Association of Canada, Special Paper no. 21, p. 171, Plate 14, figure 2.

Trochammina rutherfordi Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 3, figures 7-9.

Occurrence. Whitestone River and Parkin formations.

Trochammina umiatensis Tappan 1957

Plate 1, Figure 33

Trochammina umiatensis Tappan, 1962. USGS Professional Paper 236-C, p. 156, Plate 38, figures 5-8.

Trochammina umiatensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 10-12.

Occurrence. Whitestone River Formation.

Family ATAXOPHRAGMIIDEA Schwager, 1877

Genus *Gaudryina* d'Orbigny, 1839

Gaudryina barrowensis Tappan 1960

Plate 1, Figure 34

Gaudryina barrowensis Tappan, 1962. USGS Professional Paper 236-C, p. 156, Plate 34, figures 16-18.

Occurrence. Whitestone River Formation.

Gaudryina canadensis Cushman 1943

Plate 2, Figure 1

Gaudryina canadensis Cushman, McNeil and Caldwell, 1981. Geological Association of Canada, Special Paper 21, p. 175, Plate 14, figures 10,11.

Gaudryina canadensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 2, figures 16-17.

Occurrence. Whitestone River and Parkin formations.

Gaudryina dyscrita Tappan 1962

Plate 2, Figure 2

Gaudryina dyscrita Tappan, 1962. USGS Professional Paper 236-B, p. 47, Plate 13, figures 17-18.

Occurrence. Porcupine River Formation.

Gaudryina nanushukensis Tappan 1951

Plate 2, Figure 3

Gaudryina nanushukensis Tappan; Sliter, 1981. Geological Survey of Canada, Bulletin 300, p. 57, Plate 11, figures 13-15,17.

Gaudryina nanushukensis Thompson, 2011. Palaeogeography, Palaeoclimatology,

Palaeoecology 302, Plate 3, figures 20-21.

Occurrence. Whitestone River Formation.

Gaudryina stotti Chamney 1978

Plate 2, Figure 4

Gaudryina stotti Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 20, Plate 4, figures 6-8.

Gaudryina stotti Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 3, figures 22-23.

Occurrence. Whitestone River Formation.

Gaudryina tailleuri (Tappan) 1957

Plate 2, Figure 5

Gaudryina tailleuri (Tappan) 1962. USGS Professional Paper 236-C, p. 149, Plate 35, figures 8-16.

Gaudryina tailleuri Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 3, figures 24-25.

Occurrence. Whitestone River Formation.

Genus *Tritaxia* Reuss, 1860

Tritaxia solea Chamney 1978

Plate 2, Figure 6

Tritaxia solea Chamney, 1978. Geological Survey of Canada, Bulletin no. 253, p. 15, Plate 3, figures 19-21.

Tritaxia solea Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 3, figures 26-28.

Occurrence. Whitestone River Formation.

Genus *Uvigerinammina* Majzon, 1943

Uvigerinammina manitobensis (Wickenden) 1932

Plate 2, Figure 7

Uvigerinammina manitobensis (Wickenden); McNeil and Caldwell, 1981. Geological Association of Canada, Special Paper no. 21, p. 179, Plate 14, figures 15-18.

Uvigerinammina manitobensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 3, figures 31-32.

Occurrence. Parkin and Fishing Branch formations.

Genus *Verneuilioides* Loeblich and Tappan, 1949

Verneuilioides canadensis (Cushman) 1927

Plate 2, Figure 8

Verneuiliina canadensis Cushman; McNeil and Caldwell, 1981. Geological Association of Canada, Special Paper no. 21, p. 175, Plate 14, figure 3.

Verneuilioides canadensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 3, figures 33-34.

Occurrence. Whitestone River Formation.

Calcareous Foraminifera

Family NODOSARIIDAE Ehrenberg, 1838

Genus *Dentalina* d'Orbigny, 1826

Dentalina ectadia Loeblich and Tappan 1950

Plate 2, Figure 9

Dentalina ectadia Tappan, 1962. USGS Professional Paper 236-B, p. 66, Plate 13, figures 3-5.

Occurrence. Porcupine River Formation.

Family POLYMORPHINIDAE d'Orbigny, 1838

Genus *Paleopolymorphina* Cushman and Ozawa, 1930

Paleopolymorphina vagina (Terquem) 1864

Plate 2, Figure 10

Paleopolymorphina vagina Tappan, 1962. USGS Professional Paper 236-B, p. 83, Plate 28, figures 20-21.

Occurrence. Porcupine River Formation.

Genus *Lenticulina* Lamarck, 1804

Lenticulina macrodisca (Reuss), 1863

Plate 2, Figure 11

Lenticulina macrodisca Tappan, 1962. USGS Professional Paper 236-C, p. 162, Plate 40, figures 5-8.

Occurrence. Whitestone River Formation.

Genus *Marginulinopsis* Silvestri, 1904

Marginulinopsis collinsi Mellon and Wall, 1956

Plate 2, Figure 12

Marginulinopsis collinsi Tappan, 1962. USGS Professional Paper 236-C, p. 166, Plate 42, figures 10-15.

Occurrence. Whitestone River Formation.

Marginulinopsis jonesi (Reuss), 1863

Plate 2, Figure 13

Marginulinopsis jonesi Tappan, 1962. USGS Professional Paper 236-C, p. 167, Plate 42, figures 1-6.

Occurrence. Whitestone River Formation.

Genus *Saracenaha* Defrance, 1824

Saracenaria projectura Stelck and Wall 1956

Plate 2, Figure 14

Saracenaria projectura Stelck and Wall; Tappan, 1962. USGS Professional Paper 236-C, p. 164, Plate 41, figures 9-14.

Saracenaria projectura Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 4, figures 9-10.

Occurrence. Whitestone River Formation.

Family GLANDULININAE Reuss, 1860

Genus *Oolina* d'Orbigny, 1839

Oolina sp.

Plate 2, Figure 15

Occurrence. Whitestone River Formation.

Family ANOMALINIDAE Cushman, 1927

Genus *Anomalinoides* Brotzen, 1942

Anomalinoides sp.

Plate 2, Figure 16

Anomalinoides sp. Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 4, figures 13-14.

Occurrence. Whitestone River Formation.

Genus *Gavelinella* Brotzen, 1942

Gavelinella awunensis Tappan, 1960

Plate 2, Figure 17

Gavelinella awunensis Tappan, 1962. USGS Professional Paper 236-C, p. 197, Plate 56, figures 1-7.

Gavelinella awenensis Thompson, 2011. Palaeogeography, Palaeoclimatology, Palaeoecology 302, Plate 4, figures 21-22.

Occurrence. Whitestone River Formation.

Genus *Astacolus* Montfort, 1808

Astacolus cf. *grata* (Reuss), 1863

Plate 2, Figure 18

Vaginulinopsis grata (Reuss) Tappan, 1962. USGS Professional Paper 236-C, p. 179, Plate 46, figures 6-7.

Occurrence. Cody Creek Formation.

Appendix B - Foraminiferal Counts

Molar P-34

Sample Interval (ft)	250 - 300	400 - 450	500 - 550	600 - 650	850 - 900	1250 - 1300	1650 - 1700	1850 - 1900	2050 - 2100	2250 - 2300	2500 - 2550	2600 - 2650	2750 - 2800	2850 - 2900	3200 - 3250	3550 - 3600	3750 - 3800
Foraminiferal species																	
<i>Bathysiphon</i> sp.	1	3	1	1	1					4			10	27	111	110	62
<i>Saccammina lathrami</i>		1				3		5	2			2	1	1	12		
<i>Spiropectammina</i> sp.	1	1															
<i>Haplophragmoides</i> sp.		1		2				1	2			1					
<i>Hippocrepina barksdalei</i>				3	4	4		1			1	10	3	1	7		
<i>Psamminopelta bowsheri</i>				2						2				1			
<i>Miliammina manitobensis</i>				1				1									
<i>Saccammina</i> sp.			1				2										
<i>Reophax</i> sp.								1									
<i>Ammodiscus</i> sp.									1			1	1				
<i>Gavelinella awunensis</i>									4	3	1	1				1	
<i>Anomalinoidea</i> sp.									1								
<i>Haplophragmoides topagorukensis</i>												7	34	17		2	
<i>Haplophragmoides yukonensis</i>												3					
<i>Trochammina rainwateri</i>									8			8	3	7			
<i>Trochammina rutherfordi</i>									4			1	1				
<i>Uvigerinamina manitobensis</i>								3	5	1		1					
<i>Uvigerinamina</i> sp.																	
<i>Trochammina</i> sp.												3	1				
<i>Trochammina umiatensis</i>												2	1	2		1	
<i>Ammobaculites fragmentarius</i>												2	29	63			
<i>Gaudryina barroensis</i>												1			1		2
<i>Ammodiscus rotalarius</i>													1	3			
<i>Gaudryina canadensis</i>									7				2	11			
<i>Haplophragmoides linki</i>														2			
<i>Ammobaculites wenonahae</i>														3			
<i>Verneuilinoides canadensis</i>															1		
<i>Reophax troyeri</i>															1		
<i>Oolina</i> sp.																	
<i>Gaudryina tailleuri</i>																	
<i>Haplophragmoides</i> sp.																	
<i>Saccammina alexanderi</i>																	
<i>Trochammina eilete</i>																	
<i>Ammobaculites</i> sp.																	
<i>Gaudryina</i> sp.																	
<i>Haplophragmoides canui</i>																	
<i>Gaudryina dyscrita</i>																	
<i>Ammobaculites alaskensis</i>																	
<i>Reophax suevica</i>																	
<i>Trochammina gryci</i>																	
<i>Dentalina ectadia</i>																	
<i>Paleopolymorphina vagina</i>																	

Sample Interval (ft)	4000 - 4050	4250 - 4300	4450 - 4500	4600 - 4650	4700 - 4750	4800 - 4850	5050 - 5100	5350 - 5400	5600 - 5650	5800 - 5850	6150 - 6200	6350 - 6400	6500 - 6550	6800 - 6850	7050 - 7100	7200 - 7250	7550 - 7600	7650 - 7700	7700 - 7750
Foraminiferal species																			
<i>Bathysiphon</i> sp.	17	18	8	5	7	15	8	4	3	2			2	1		3			6
<i>Saccammina lathrami</i>			1	5			3	3	2										
<i>Spiropectammina</i> sp.																			
<i>Haplophragmoides</i> sp.				2	1			2	2							1	1		
<i>Hippocrepina barksdalei</i>	1	1					1	3	6		1				1		2		
<i>Psamminopelta bowsheri</i>				2															
<i>Miliammina manitobensis</i>																			
<i>Saccammina</i> sp.							1												
<i>Reophax</i> sp.	5							2	5		2					1			11
<i>Ammodiscus</i> sp.																			
<i>Gavelinella awunensis</i>	1																		
<i>Anomalinoides</i> sp.																			
<i>Haplophragmoides topagorukensis</i>	2		6	4			2												
<i>Haplophragmoides yukonensis</i>				1															
<i>Trochammina rainwateri</i>								1											
<i>Trochammina rutherfordi</i>																			
<i>Uvigerinamina manitobensis</i>																			
<i>Uvigerinamina</i> sp.							7		1	7	1								
<i>Trochammina</i> sp.	1					1		1	3					1		2	1	1	
<i>Trochammina umiatensis</i>																			
<i>Ammobaculites fragmentarius</i>							8												
<i>Gaudryina barroensis</i>																			
<i>Ammodiscus rotalarius</i>																			
<i>Gaudryina canadensis</i>																			
<i>Haplophragmoides linki</i>																			
<i>Ammobaculites wenonahae</i>																			
<i>Verneuilinoides canadensis</i>																			
<i>Reophax troyeri</i>					1	2	1												
<i>Oolina</i> sp.	1	2									1								
<i>Gaudryina tailleuri</i>										4					1				
<i>Haplophragmoides</i> sp.																			1
<i>Saccammina alexanderi</i>																			
<i>Trochammina eilete</i>									4		1								
<i>Ammobaculites</i> sp.							1						1						
<i>Gaudryina</i> sp.																			2
<i>Haplophragmoides canui</i>																			43
<i>Gaudryina dyscrita</i>																			8
<i>Ammobaculites alaskensis</i>																			3
<i>Reophax suevica</i>																			2
<i>Trochammina gryci</i>																			1
<i>Dentalina ectadia</i>																			3
<i>Paleopolymorphina vagina</i>																			1

Ellen C-24

Sample Interval (ft)	0- 100	100 - 200	200 - 300	300 - 400	400 - 500	500 - 600	600 - 700	700 - 800	890	900- 1000	1000 - 1100	1100 - 1200	1200 - 1300	1300 - 1400	1400 - 1500	1500 - 1550	1600 - 1700	1700 - 1800	1800 - 1900	1900 - 2000	2000 - 2100	2100 - 2200	2200 - 2300	2300 - 2400	2400 - 2500	2500 - 2600	2600 - 2700
Foraminiferal species																											
<i>Haplophragmoides topagorukensis</i>																											
<i>Astacolus cf. grata</i>	1																										
<i>Bathysiphon</i> sp.																1	1										
<i>Haplophragmoides</i> sp.	1	2			2								1	1		1											
<i>Trochammina rutherfordi</i>																											
<i>Oolina</i> sp.			1																								
<i>Textularia gravenori</i>				1																							
<i>Trochammina</i> sp.	1	1										1															
<i>Reophax vasiformis</i>																											
<i>Bathysiphon brosegi</i>																											
<i>Haplophragmoides yukonensis</i>																											
<i>Trochammina umiatensis</i>																											
<i>Reophax troyeri</i>																											
<i>Saccammina lathrami</i>																											
<i>Saccammina alexanderi</i>																											
<i>Saccammina</i> sp.																											
<i>Glomospirella gaultina</i>																											
<i>Ammodiscus rotalarius</i>																											
<i>Ammobaculites wenonahae</i>																											
<i>Hippocrepina barksdalei</i>																											
<i>Gaudryina stotti</i>																											
<i>Gaudryina barroensis</i>																											
<i>Gaudryina</i> sp.		1																									
<i>Gaudryina nanushukensis</i>																											
<i>Gaudryina canadensis</i>																											
<i>Verneulinoides canadensis</i>																											
<i>Spiroplectamina ammovitrea</i>																											
<i>Psamminopelta bowsheri</i>																											
<i>Bathysiphon vitta</i>																											
<i>Gavelinella</i> sp.																											
<i>Reophax fuscus</i>																											
<i>Reophax</i> sp.																											
<i>Ammobaculites fragmentarius</i>																											
<i>Haplophragmoides linki</i>																											
<i>Ammodiscus</i> sp.																											
<i>Gavelinella awunensis</i>																											
<i>Haplophragmoides peelensis</i>																											
<i>Anomalinoides</i> sp.																											
<i>Marginulinopsis jonesi</i>																											
<i>Lenticulina macrodisca</i>																											
<i>Textularia topagorukensis</i>																											
<i>Oolina</i> sp.																											
<i>Saracenaria projectura</i>																											
<i>Reophax incompta</i>																											
<i>Tritaxia solea</i>																											
<i>Gaudryina tailleuri</i>																											
<i>Trochammina rainwateri</i>																											
<i>Haplophragmoides spissum</i>																											
<i>Glomospira corona</i>																											
<i>Evolutinella multiplum</i>																											
<i>Marginulinopsis collinsi</i>																											

Sample Interval (ft)	2700 - 2800	2800 - 2900	2900 - 3000	3000 - 3100	3100 - 3200	3200 - 3300	3300 - 3400	3400 - 3500	3500 - 3600	3600 - 3700	3700 - 3800	3800 - 3900	3900 - 4000	4000 - 4100	4100 - 4200	4200 - 4300	4300 - 4400	4400 - 4500	4500 - 4600	4600 - 4700	4700 - 4800	4800 - 4900	4900 - 5000
Foraminiferal species																							
<i>Haplophragmoides topagorukensis</i>							15	34	2	17	10	1	10	9	3	9	9	12	11	4	12	16	7
<i>Astacolus</i> cf. <i>grata</i>																							
<i>Bathysiphon</i> sp.							1	3	1	23		10	9	5	10	5	3	6			7	8	
<i>Haplophragmoides</i> sp.							7	4		5	2	2		3	1	5	4		7	4	1	4	
<i>Trochammina rutherfordi</i>							3			2	1	1	1	4	2	1	1	1	2	3	4	2	
<i>Oolina</i> sp.																1		1		1			
<i>Textularia gravenori</i>																							
<i>Trochammina</i> sp.							1			1		1	1		1			1					
<i>Reophax vasiformis</i>								2	1	1	1		1	3	2				2	1	5	2	
<i>Bathysiphon brosegi</i>							1		1		5		3	2					1	5	1		
<i>Haplophragmoides yukonensis</i>							3	1		1			2	2					1				
<i>Trochammina umiatensis</i>							2	1			1	1		3	2	4	3		1			2	
<i>Reophax troyeri</i>							4	5	3	3	2			4	1	6	2	5	4	2	8	5	4
<i>Saccammina lathrami</i>							7	4	3	4	6	1	2	8	2	8	13	5	1	5	10	2	1
<i>Saccammina alexanderi</i>							1						1	1	4	1	1		1	2	3		
<i>Saccammina</i> sp.							1															1	
<i>Glomospirella gaultina</i>							2		1														
<i>Ammodiscus rotalarius</i>							1	1								1	1	1			5		1
<i>Ammobaculites wenonahae</i>							2	5	1	2	3		4	2	3	5	2	4		2	5	3	1
<i>Hippocrepina barksdalei</i>							1	1					1	1		1					1		
<i>Gaudryina stotti</i>							5	7		3	1	1	1	4	1	2	2	2					
<i>Gaudryina barroensis</i>							2	3		5		2							1			1	
<i>Gaudryina</i> sp.							1																
<i>Gaudryina nanushukensis</i>							1	3	4		1	1					7	5	4	2	9	2	1
<i>Gaudryina canadensis</i>							2	5	3	2	1	1	2	1	1								
<i>Verneulinoides canadensis</i>							2	4	2	2	1	1	1										
<i>Spiroplectamina ammovitrea</i>							1																
<i>Psammionopelta bowsheri</i>							1							1				1					
<i>Bathysiphon vitta</i>									3	4	11	14	6	4	6	2		4	1	4	5	2	
<i>Gavelinella</i> sp.									1		1	1						1	4				
<i>Reophax fuscus</i>									1	1													
<i>Reophax</i> sp.		1								1											1		
<i>Ammobaculites fragmentarius</i>										1	1												
<i>Haplophragmoides linki</i>										1	1			4	4	6	7	4	6	2	3	4	1
<i>Ammodiscus</i> sp.										1				1			1		1				
<i>Gavelinella awunensis</i>										1	1		1				1						
<i>Haplophragmoides peelensis</i>										4			5					5	5	5	2	5	1
<i>Anomalinoidea</i> sp.										2					2	1		1					
<i>Marginulinopsis jonesi</i>										2									2			1	
<i>Lenticulina macrodisca</i>											1												
<i>Textularia topagorukensis</i>													2	1		2		3	3	2	9	2	
<i>Oolina</i> sp.													1										
<i>Saracenaria projectura</i>													1										
<i>Reophax incompta</i>														3									
<i>Tritaxia solea</i>														2				1					
<i>Gaudryina tailleuri</i>															2	2	2			1		1	
<i>Trochammina rainwateri</i>															1	2	1	2				1	
<i>Haplophragmoides spissum</i>																2				1			
<i>Glomospira corona</i>																2				1	1	2	1
<i>Evolutinella multiplum</i>																				1			
<i>Marginulinopsis collinsi</i>																							1