**ALBIAN-CENOMANIAN FORAMINIFERA IN NORTHEASTERN
BRITISH COLUMBIA AND WESTERN ALBERTA:
PALEOECOLOGY AND INTEGRATION OF BIOSTRATIGRAPHY
WITH ALLOSTRATIGRAPHY**

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A thesis submitted to the Faculty of Graduate Studies in partial fulfillment of the
requirements for the degree of
Master of Science

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ABSTRACT

The Rocky Mountain foredeep in northeastern British Columbia and northwestern Alberta preserves an expanded Albian to Cenomanian interval in outcrop and subsurface that documents a nearly complete sea-level record of the Western Interior Sea at that time. Current foraminiferal subzonations that were based on multiple short stratigraphic intervals and are linked to lithostratigraphic frameworks make correlations to areas of less accommodation space to the east and south problematic. An extensive subsurface and outcrop database based on sedimentology and wireline logs in this region resulted recently in a new allostratigraphic framework that forms the basis for new biostratigraphic correlations. Micropaleontological analysis of a complete section at Deadhorse Meadows has led to a new foraminiferal zonation where faunal changes are linked to allostratigraphic surfaces. This zonation was tested in previously used outcrops and lateral faunal distribution correlates remarkably well to the new allomember architecture. Latest Albian faunas represent highstand and falling stage systems tracts, where maximum abundances occur in the middle of the deposits associated with maximum flooding intervals. Cenomanian strata also represent transgressive system tracts associated with the Greenhorn transgression.

Latest Albian foraminiferal assemblages in this region consist almost entirely of benthic agglutinated species controlled by cool, low salinity waters of the Mowry Sea. Distribution of morphotypes, related to feeding strategies indicate lower shoreface to marginal marine environments confirming lower paleosalinities and paleoenvironmental and paleogeographic interpretations based on sediment facies. Lowest Cenomanian strata are barren of foraminifera due to bottom water anoxia. An increase in the oxygen

minimum zone resulted in increased organic matter entering the water column during rapid transgression. As the basin deepened during continued Greenhorn transgression uncoiled and serial morphotypes began to colonize the mudstone dominated facies indicating normal marine paleosalinities and the return of bottom water oxygenation.

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INTRODUCTION

The sea-level history in the Western Canada Sedimentary Basin (WCSB) is associated with distinct macro- and micro- faunal assemblages. Paleontology has played an important role in paleogeographic and paleoecologic reconstructions of the WCSB. Macrofaunas such as molluscs are used as markers in regional correlation and have delivered a detailed zonation correlated with an absolute time scale (Warren and Stelck, 1969; Jeletzky, 1970, 1971a and 1971b). Macrofossils can be rare in Cretaceous marine rocks, in particular when work is based on core studies. In contrast, microfossils can be retrieved abundantly from core samples and have become a valuable correlation tool. The most detailed foraminiferal zonation for the WCSB originates in the foothills of British Columbia where expanded Rocky Mountain foredeep sections are associated with frequent faunal changes. The application of this detailed zonation with numerous subzones, however, has been problematic especially in condensed forebulge settings.

Recently a new allostratigraphic framework for Albian-Cenomanian strata has been proposed for western Alberta by Zhang (2006) and Roca (2007) who integrate these expanded foredeep outcrop sections with the subsurface of Alberta. The regional detailed correlation of strata that are bound by erosional surfaces requires a fresh look at the current biostratigraphic zones, which are limited to lithostratigraphic units. This study uses a multidisciplinary approach to address foraminiferal assemblages of the Rocky Mountain foredeep, integrating it with the new allostratigraphic framework and revisiting the region in northeast British Columbia where the original detailed zonation was created. Seven outcrops and three cores were studied in northeastern British Columbia and northwestern Alberta (Figure 1) in order to correlate foraminiferal assemblage changes

Figure 1. Location map of study area showing localities of sampled outcrops and wells with the Imperial Spirit River Well (Stritch et al. 1999) for reference. Green shaded areas are national parks and the grey shaded area represents the Peace River Arch structure.

with allostratigraphic surfaces and resolve application problems of the current zonation as proposed by Caldwell et al. (1978, 1993).

Foraminifera provide critical information for testing paleoceanographic and sequence stratigraphic models. This includes faunal relationships to e.g. paleosalinity, paleoproductivity, stratification of ancient water masses, and oxygenation (Eicher, 1975; Eicher and Diner, 1985; Leckie et al., 1991; Caldwell et al., 1993). A number of patterns of paleoecology and even evolutionary changes appear to correlate with fluctuations in water depth and sedimentation through the course of a depositional sequence (Brett, 1998). Until recently, there has been little attempt to meld foraminiferal paleoecology with sequence stratigraphy (allostratigraphy) and it has never been proposed for Western Canada. This study attempts to interpret the paleoenvironment of Albian-Cenomanian strata within an allostratigraphic model.

MATERIALS AND METHODS

This study is based on 236 micropaleontological samples from seven outcrops and three cores in northeastern British Columbia and northwestern Alberta. The study area includes outcrops from Moberly Lake Rd., Halfway River, Hasler Creek, Deadhorse Meadows, Mt. Belcourt, Nickerson Creek, and Sulphur River (figure 1 and table 1). Cores at 13-11-41-26W4, 10-33-34-5W5 and 8-20-44-3W5 were also studied (figure 1). These cores are kept at the Alberta Core Board in Alberta Canada.

Micropaleontology

The biostratigraphic framework was established on vertical and lateral distribution of foraminiferal assemblages. Foraminiferal analysis was based on outcrop and core

SECTION	COORDINATES
Deadhorse Meadows	54 deg 08'53'' N and 119 deg 53'24'' W
Sulphur River	53 deg 72'14'' N and 119 deg 03'33'' W
Nickerson Creek	54 deg 01'42'' N and 119 deg 28'06'' W
Mount Belcourt	54 deg 25'49'' N and 120 deg 27'36'' W
Hasler Creek	55 deg 33'40'' N and 121 deg 58'50'' W
Moberly Lake Rd	55 deg 54'30'' - 55 deg 55'30''N and 121 deg 55'00'' W
Halfway River	56 deg 13'45''N and 121 deg 29'00'' W

Table 1. Sections used in the study and locations.

samples, taken at variable intervals, depending on lithological boundaries, unusual characteristics of sediments, or other critical intervals. Samples for foraminiferal analysis were broken down according to the method described by Then and Dougherty (1983). Foraminifera were picked from the sand-size fraction ($>63\ \mu\text{m}$). Volumes of picked residues varied with foraminiferal abundance and the amount of material available; low abundance prohibited statistical analysis. Numerous samples were barren of foraminifera or had poorly preserved specimens. Total numbers of foraminifera are listed in the Appendix. Species were arranged in order of first appearance, followed by alphabetical order. Preservation of foraminifera was generally moderate to poor due to taphonomic processes such as crushing and fragmentation allowing in many cases genus identification only. Identification was based solely on original descriptions. Identified species were prepared and photographed under a binocular light microscope using a Sony Cyber-shot digital camera. Foraminiferal taxa were grouped into morphotypes according to Jones and Charnock (1985) for paleoenvironmental analysis.

Sedimentology

Sedimentological analysis is based on lithological description of cores and outcrops, which includes visual characteristics of sediments in terms of composition, grain size, sedimentary structure, trace fossils and fossil content. The allostratigraphic framework and core lithological descriptions were provided by Roca (2007).

Wireline well log correlations

Gamma ray and resistivity logs were used to establish correlations between cores in the British Columbia portion of the study to the Alberta portion where correlations

have been provided by Zhang (2006) and Roca (2007). Their established allostratigraphic framework and erosional surfaces were utilized in extending allostratigraphy into British Columbia. Well control covering the study interval in this region is much reduced due to thrusting and subsequent erosion. The regional wireline log cross-section in the British Columbia study area was constructed using Crosslog, the online digital database from Divestco Inc.

GEOLOGIC SETTING

Basin architecture

In the Early to Middle Jurassic the break-up of Pangea caused the northwestward movement of the North American Plate over the Farallon Plate creating an east-dipping subduction zone. This large scale, tectonically driven evolution was caused by loading of the continental lithosphere by plutonism, volcanism, accretion and lateral displacement of pericratonic and accreted terrains (Monger and Nokleberg, 1995). The static and dynamic loads caused subsidence on a large area of the craton and the formation of a foreland basin, which, combined with an eustatic sea-level highstand, culminated in the Cretaceous Western Interior Sea.

The Western Interior Sea developed between the Cordillera and the stable interior craton. At its maximum extent it was more than 6000 km long, stretching from the Arctic Ocean (Boreal Sea) to the Gulf of Mexico (Tethyan Sea) and up to 1600 km wide, extending from westernmost Ontario to central British Columbia (Leckie and Smith, 1992). Over the evolution of the basin, from the Middle Jurassic to the Middle Tertiary,

over six km of sediment was deposited along the western margin of the basin (Leckie and Smith, 1992). The sediment package tapers eastward in the WCSB, forming a wedge which covers the Precambrian crystalline basement of the North American craton (Price, 1994).

Tectonic events in the Cordillera largely controlled the supply of sediment to the foreland basin and significantly influenced accommodation space. During the latest Jurassic the first pulse of the Columbian Orogeny began with tectonic activity on the western margin of the basin (Stott, 1984). This resulted in an increased rate of sediment deposition in the expanding foreland basin that lasted until the end of the early Tertiary (Leckie et al., 1989). The development of a foredeep on the western edge of the basin allowed for the formation of a thick clastic wedge, composed primarily of sandstones, siltstones and shales. This thickened wedge records the most complete record of transgression and regression within the basin. As subsidence in the foredeep kept pace with sedimentation of marine and alluvial sediment, the development of an associated forebulge formed further east where condensed sections developed due to reduced sediment supply and subsidence (Kauffman and Caldwell, 1993). These hiatuses are often recognized by missing biostratigraphic zones (Caldwell et al., 1993; Schröder-Adams et al., 1996).

Relative sea-level history

Although regional and local tectonics largely controlled the source and rate of sedimentation within the WCSB, some accommodation space was supplied through eustatic sea-level changes (Jervey, 1992). Cretaceous strata within the WCSB were deposited in a series of nine major transgressive-regressive marine cycles (Kauffman

1977, 1984; Kauffman and Caldwell 1993). During the Albian (figure 2), the basin was influenced by two eustatic cycles, the Kiowa-Skull Creek and the basal transgressive phase of the Greenhorn Cycles (Kauffman, 1977). In the WCSB the global eustatic cycles were locally overprinted in the Albian by the Moosebar, Hulcross, Joli Fou and Mowry transgressions (Caldwell, 1984; Leckie and Smith, 1992). During times of maximum transgression (Joli Fou, Greenhorn and Niobrara), the northern and southern portions of the Western Interior Seaway were connected, allowing the northern Boreal waters to mix with southern Tethyan waters (Stelck, 1975). Deposition of the various strata within the Albian and Cenomanian was during a period of overall global eustatic sea-level rise, punctuated by several relative sea-level falls (Kauffman, 1977).

Early late Albian sea-level rise resulted in a narrow seaway connecting the Tethyan and Boreal seas, depositing the Joli Fou Formation. The succeeding lowstand terminated the Tethyan connection and deposited the Viking Formation which consists of marine sandstone and conglomerate throughout much of western to central Alberta. Along the western margin incised valleys were cut and subsequently infilled with estuarine sediments during sea-level rise (Leckie and Smith, 1992).

The subsequent transgression is associated with the Mowry Sea bringing cool, low salinity, Boreal watermasses and depositing the Westgate Formation (Bloch et al., 1993; Schröder-Adams et al., 1996). This transgression represents the beginning of the global eustatic Greenhorn cycle but is interrupted by several relative sea-level falls.

Figure 2. Global transgressive-regressive cycles and transgressive-regressive cycles in northwest Alberta of the WCSB during the Cretaceous (Aptian to Santonian) and radiometric ages at stage boundaries. Modified after Kauffman (1977) and Obradovich (1993).

Structure

Located in northeastern British Columbia and northwestern Alberta, the Peace River Arch is a significant northeast-trending Precambrian basement feature (Leckie et al., 1990) (figure 1), that has undergone several periods of uplift and subsidence during Phanerozoic time (Chen and Bergman, 1999). The block-faulted Peace River Arch was uplifted during the early Cambrian and remained a structural high until the Late Devonian (Cant, 1988; O'Connell et al., 1990). During the Mississippian, the arch began to subside and remained a topographic low until the Early Cretaceous (Cant, 1988; Leckie et al., 1990). During the latest Cretaceous and Tertiary, the arch again became a positive feature as a result of Laramide deformation farther west (Williams, 1958, Cant, 1988).

Lithostratigraphy

The Peace River area was first explored by Sir Alexander Mackenzie as early as 1792 (Stott, 1968). More detailed reports appeared in 1881 by George M. Dawson who named strata overlying the present day Notikewin Member the Fort St. John Shales (Stott, 1968). This was followed by Wickenden and Shaw (1943) who distinguished subdivisions such as Moosebar, Commotion, Hasler, Goodrich and Cruiser formations, creating the Fort St. John Group. As more subsurface data became available for correlation, Stott (1982) suggested removal of the name Commotion Formation and gave the Gates, Hulcross and Boulder Creek (members of the Commotion Formation) formation status. An extensive lithostratigraphic framework correlating outcrops of the Rocky Mountains with the subsurface of Alberta was proposed by Stott (1982). No major modifications have occurred since. Figure 3 illustrates the current stratigraphic nomenclature for the northeastern British Columbia Foothills, northwestern Alberta Peace

	Sikanni Chief River	Peace River Foothills	Peace River Plains	Central Alberta Plains
Cenom.	Dunvegan Formation	Dunvegan Formation	Dunvegan Formation	Belle Fourche Formation
	Sully Formation	Cruiser Formation	Shaftesbury Formation	Fish Scales Fm
Albian	Sikanni Formation	Goodrich Fm		Westgate Formation
	"Viking" marker bed	upper Hasler Fm "Viking" marker bed lower Hasler Fm		Viking Fm
	Buckinghamshire Formation	Boulder Creek Fm		Toll Four Fm
		Hulcross Fm	Peace River Fm Paddy Mb Cadotte Mb Harmon Mb	
	Bluesky Fm	Gates Fm	Spirit River Fm Notikewin Mb Falher Mb Wilrich Mb	Upper Mannville
A.	Gething Formation	Moosebar Fm	Bluesky Fm	Glaucconitic Sandstone
B.	?	Gething Formation	Gething Formation	Ostracode zone
		Cadomin Formation		Ellerslie

Figure 3. Regional stratigraphic nomenclature for the study area in northeast British Columbia and northwest Alberta. Modified from Stott (1982), Stelck and Koke (1987), Bloch et al. (1993) and Schröder-Adams and Pedersen (2003)

River Plains, central Alberta Plains and the Sikanni Chief River region to the north of the study area.

Lithostratigraphy is based on physical characteristics that are recognizable on a regional scale. However, basin-forming processes result in a laterally variable sediment package. As a result stratigraphic nomenclature differs from the northeastern British Columbia Foothills to northwestern Alberta Peace River Plains and to central Alberta Plains (figure 3). In the subsurface of the Peace River Plains, the Fort St. John Group (Albian to lower Cenomanian) consists of the Spirit River, Peace River and the Shaftesbury formations in ascending stratigraphic order (figure 3). The Spirit River Formation has been further subdivided into the Wilrich, Falher and Notikewin members, while the Harmon, Cadotte and Paddy members form the Peace River Formation. Farther to the east in the Central Alberta Plains the Albian to Cenomanian strata consists of the Mannville Group and the Lower Colorado Group. The Lower Colorado Group is then further divided into the Joli Fou, Viking, Westgate, Fish Scales and Belle Fourche formations.

In the foothills of northeastern British Columbia, the study area comprises the upper Albian to Cenomanian strata of the Hasler, Goodrich and Cruiser formations (figure 3). All three formations are equivalent to the Shaftesbury Formation of the Alberta Peace River Plains (Stelck and Leckie, 1990). The Shaftesbury Formation is in turn equivalent to the Westgate, Fish Scales and lower Belle Fourche formations of the Colorado Group (figure 2) (Warren and Stelck, 1969; Stelck and Leckie, 1990; Bloch et al., 1993).

Allostratigraphy

An allostratigraphic unit is a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities (NACSN, 1983, p. 865). Bounding discontinuities highlight important changes in depositional conditions. Thus they define allostratigraphic units in which depositional conditions were either fairly constant, or were progressively changing but without breaks (as in a sandier-upward succession). For this reason, allostratigraphic units are more natural subdivisions of the geological record for interpretive purposes than conventional lithostratigraphic units. A allostratigraphic framework of the Viking Formation in Alberta was originally proposed by Boreen and Walker (1991), who used well logs and cores to map three erosional surfaces in the Viking Formation in south-central Alberta (Willesden Green area). These erosion surfaces (Viking erosion surfaces VE2, VE3 and VE4), or bounding discontinuities, allowed the definition of five allomembers in the Willesden Green study area (Boreen and Walker, 1991). Roca (2007) and Zhang (2006) have expanded this work using a combined 47 outcrops, 223 cores and 2630 well logs to extend the allostratigraphic framework over large portions of western Alberta (figure 4). They also extended the framework to include allomembers from the underlying Joli Fou Formation up to the overlying Fish Scales Marker Bed. Figure 5 shows the differences between allostratigraphic and lithostratigraphic units. Allostratigraphic surfaces can best be identified in wireline log cross-sections, which are then extended into near-by outcrop. Often, the projected position of some surfaces in measured sections coincides with only subtle lithological change. Micropaleontological data can play an important role in supporting or disputing the position of these surfaces.

Figure 4. Allostratigraphic cross-section for western Alberta (Roca 2007). Erosional surfaces are labeled on the left and right margin of the cross-section and allomembers are labeled between erosional surfaces. Allomembers represent lithostratigraphic strata from the Viking and Westgate formations.

Figure 5. Differences in lithostratigraphy and allostratigraphy of the Lower Colorado Group (Roca, 2007). SB: sequence boundary, mfs: maximum flooding surface and fs: flooding surface.

This study integrates foraminiferal data with the allostratigraphic framework. Some outcrops from this study (Deadhorse Meadows, Nickerson Creek, Sulphur River, and cores 13-11-41-26W4, 10-33-34-5W5 and 8-20-44-3W5) coincide with sections used by Roca (2007). These outcrops are used to facilitate detailed correlations between faunal changes and allomembers. Samples for foraminiferal data for this study have been gathered from sections that are stratigraphically higher than the Viking erosive surface 3 (VE3), therefore this study will only use allomembers and surfaces above the VE3 surface (figure 4). These are allomembers VD, WA, WB, WC, FA and FB and associated erosional surfaces VE3, VE4, WE1, WE2, BFS, BFSM and FSU. This study extends the allostratigraphic model outside of Alberta and into northeast British Columbia using the existing well log data as a reference and starting point.

Foraminiferal Biostratigraphy

The presence of foraminifera in Cretaceous rocks in the WCSB is well known and Caldwell et al., (1978) proposed a comprehensive foraminiferal zonation for the WCSB. Numerous studies have been published describing Albian-Cenomanian age foraminifera throughout the American and Canadian portions of the Western Interior Basin. Excluding the endemic species that developed within the Western Interior Sea, the dominant agglutinated foraminiferal faunas of northeast British Columbia and northwest Alberta have more species in common with Cretaceous assemblages described from the Arctic slope of Alaska (Tappan, 1962) than with those of the Gulf Coast (Schröder-Adams et al., 1996; Stelck, 1991), suggesting a more continuous connection to the Boreal Sea.

The foraminiferal scheme has been correlated as much as possible to the molluscan zones outlined by Jeletzky (1968, 1970, 1971a, 1971b) for the Western Interior

of Canada (figure 6). In the Peace River and Sikanni Chief River areas, a number of foraminiferal studies have resulted in a detailed zonation for the Albian-Cenomanian of northeastern British Columbia (Wickenden, 1951; Stelck et al., 1956; Stelck, 1958; Sutherland and Stelck, 1972; Stelck 1975, 1991; Stelck et al., 2000; Stelck and Hedinger, 1983; Koke and Stelck, 1984, 1985; Stelck and Koke, 1987; Stelck and Leckie, 1990; Stritch and Schröder-Adams, 1999 and Schröder-Adams and Pedersen, 2003).

For Western Canada Caldwell et al. (1978, 1993) established three foraminiferal zones within the Albian Stage: the *Gaudryina nanushukensis* Zone, *Haplophragmoides gigas* Zone, and *Miliammina manitobensis* Zone (figure 6). Correlations with molluscan zones (Stelck and Koke, 1987; Caldwell et al., 1993) place the *Gaudryina nanushukensis* Zone within the early to middle Albian, the *Haplophragmoides gigas* Zone within the early late Albian, and the *Miliammina manitobensis* Zone within the late late Albian (figure 6). In northeastern British Columbia these three zones have their fullest expression and are subdivided into a number of subzones – six within the *Gaudryina nanushukensis* Zone (Caldwell et al. 1978), seven within the *Haplophragmoides gigas* Zone (Stelck and Koke, 1987; Stelck, 1991), and three within the *Miliammina manitobensis* Zone (Caldwell, 1978) (figure 6).

In the foredeep setting of the Peace River area, much of the refinement of the foraminiferal zonation has taken place within the Hasler, Goodrich and Cruiser formations. In the Peace River area, (northeastern British Columbia) in the lower part of the Hasler Formation, Koke and Stelck (1984, 1985) described the *Ammobaculites wenonahae* Subzone of the *Gaudryina nanushukensis* Zone in sections along the Halfway River just north of the Peace River. This subzone has also been recognized in the middle part of the Buckinghorse Formation by Schröder-Adams and Pedersen (2003) in the

Figure 6. Foraminiferal zones and subzones of Aptian to lower Cenomanian stages, macrofossil zones and their relationship with sea-level changes (modified after Schröder-Adams and Pedersen 2003).

Sikanni Chief River area. This subzone seems to have been retained only in the short segment of the foredeep of the basin northward from the Peace River to the southern end of the Mackenzie Mountains in the Northwest Territories (Caldwell et al. 1993).

Substantial refinement of the *Haplophragmoides gigas* Zone has resulted from analysis of Rocky Mountain foothills sections of northeastern British Columbia. In the Peace and Pine River valleys, the zone contains seven subzones (Stelck and Koke, 1987 and Stelck, 1991) whereas faunas farther east and south within the interior plains lack subzones (Caldwell et al., 1993). In the Canadian prairie region, the zone has been widely identified as the biostratigraphic counterpart of the Joli Fou Formation, and Koke and Stelck (1985) described the foraminifera of the Joli Fou equivalent in the lower Hasler Formation of the Peace River region. Stelck and Koke (1987) then showed that the zone should be extended through much of the upper Hasler Formation by describing a sequence of assemblages that are related to those of the Joli Fou equivalent.

In the outcrops studied the lowermost *Haplophragmoides uniorbis* Subzone is present in the Halfway River 3.5 km above the mouth of the Halfway River where the contact can be found with the underlying *Ammobaculites wenonahae* Subzone (Stelck, 1991). Stelck (1991) also found the uppermost 14 m of the *H. uniorbis* Subzone exposed in the Moberly Lake Road outcrop.

The *Haplophragmoides gigas gigas* Subzone has been recognized in two outcrops on the northern bank of the Peace River near the Halfway River and in the Moberly Lake Road outcrop. In the Moberly Lake Road outcrop the indicator species *Haplophragmoides gigas gigas* is absent and a smaller variety has been assigned to *H. gigas* (Stelck and Koke, 1987). The overlying *Haplophragmoides phaseolus* Subzone (originally name *Haplophragmoides gigas* ssp. A by Stelck and Koke, 1987; Stelck,

1991) is also based on a variety of *H. gigas* and has no clear cut boundary with the underlying *H. gigas gigas* Subzone (Stelck and Koke, 1987). Instead, *Kechenotiske* (a foraminiferal taxa) has been used as a marker for the top of the *H. gigas gigas* Subzone and is purely arbitrary (Stelck and Koke, 1987). The *Haplophragmoides phaseolus* Subzone has been recognized in the Moberly Lake road cuts and on the Halfway River north of the Peace River by Stelck and Koke (1987). The upper contact of this subzone has not been observed in outcrop and has been assumed to be transitional, as many foraminifera are common to the overlying *Reophax tundraensis* Subzone (Stelck and Koke, 1987).

The *Reophax tundraensis* Subzone has been recognized in the Moberly Lake road cuts in what Stelck and Koke (1987) have designated the “Viking” marker bed. The *R. tundraensis* Subzone has not been recognized in the Pine River valley 50 km south of the Peace River (Caldwell et al., 1993). Stelck and Koke (1987) also note that neither the lower or upper contact of this subzone has been observed in outcrop.

On Dokie Ridge, which represents the type section for the Hasler Formation, and Commotion Creek basal beds of the Hasler contain the *Trochammina depressa* Subzone indicating that only the upper part of the formation is represented at its type section (Stelck and Koke, 1987). Stelck and Koke (1987) also note that this is where the species *Haplophragmoides postis goodrichi*, forming a subzonal indicator of the overlying *Miliammina manitobensis* Zone, first appears. The top of the *Trochammina depressa* subzone is recognized in the Moberly Lake road cuts above the *Reophax tundraensis* Subzone. The lower contact of this unit is exposed in the Commotion Creek outcrop where Stelck and Koke (1987) suggest a conformable contact with the underlying

Boulder Creek Formation. The upper contact is exposed in the road cut on Moberly Lake Road where Stelck and Koke (1987) note no change in lithology.

On Dokie Ridge the *Trochammina depressa* Subzone is overlain by the *Trochammina umiatensis* Subzone with a total thickness of 90 m (Stelck and Koke, 1987). This subzone on Boulder Creek, Moberly Lake Road and Hasler Creek occurs below the “Viking grits”, which is not to be confused with the “Viking” marker bed.

On Hasler Creek above the *Trochammina depressa* Subzone and below the grit beds is the *Reophax troyeri* Subzone (Stelck and Koke, 1987). This subzone is absent in the Dokie Ridge section, poorly represented in a ditch in the Moberly Lake road cuts and has its most complete expression in the Hasler Creek outcrop (Stelck and Koke, 1987).

Like the *Haplophragmoides gigas* Zone, the *Miliammina manitobensis* Zone has its fullest expression in the foredeep of the WCSB in northeastern British Columbia, where it carries three diverse successive faunas; *Verneuilinoides canadensis*, *Haplophragmoides postis goodrichi* and *Haplophragmium swareni* (Caldwell et al., 1993). The *Miliammina manitobensis* Zone has been described from the upper parts of the Hasler and Buckinghorse formations (Stelck, 1975; Schröder-Adams and Pedersen, 2003), lower Sully Formation (Stelck and Hedinger, 1983), and the base of the Shaftesbury Formation (Nielsen, 1950; Stritch and Schröder-Adams, 1999). While the *Miliammina manitobensis* Zone is the most widespread Albian foraminiferal zone in western Canada only the *Verneuilina canadensis* Subzone can be identified east and south of British Columbia (Caldwell et al., 1978). The overlying *Haplophragmoides postis goodrichi* and *Haplophragmium swareni* Subzones have only been recognized in the foothills of northeastern British Columbia (Stelck and Hedinger, 1976).

In the Peace River area in northeastern British Columbia, where the *Miliammina manitobensis* Zone has its fullest expression, the zone is marked by an erosional base expressed as a thin pebble conglomerates. The pebble beds are the equivalent of the “Viking grits” (Stelck, 1975; Hein et al., 1986) in the Alberta plains and their base marks an unconformity that cuts across the Alberta foothills (Caldwell et al., 1993). This unconformity has removed the *Reophax troyeri* Subzone in the Moberly River area (Caldwell et al., 1993) and further south and east into Alberta the remainder of the *Haplophragmoides gigas* Zone has been removed to the extent that the *Miliammina manitobensis* Zone lies on older Albian beds (Caldwell et al., 1993).

The *Verneulinoides canadensis* Subzone was originally described by Stelck (1975) on the Sikanni Chief River in northeastern British Columbia. The *V. canadensis* Subzone is extremely widespread, having been recognized throughout the Western Interior of Canada and in adjacent parts of the United States (Caldwell et al. 1978). According to Sutherland and Stelck (1972) in the Moberly Lake roadcut the *Haplophragmoides postis goodrichi* Subzone lies above the *V. canadensis* Subzone which is not exposed in the Moberly Lake roadcut. Sutherland and Stelck (1972) found the *H. postis goodrichi* Subzone in the Goodrich sands within the Moberly Lake road cuts. However, Stritch and Schröder-Adams (1999) found that the *H. postis goodrichi* Subzone lies below the *V. canadensis* Subzone in the Spirit River well in northwest Alberta south of Peace River town. The uppermost subzone in the *Miliammina manitobensis* Zone was first described by Stelck and Hedinger (1983) in the lower Sully Formation, directly underlying the Fish-Scale Marker. The *Haplophragmium swareni* Subzone has since been recognized in the Sikanni Formation in the Sikanni Chief River area of British

Columbia (Schröder-Adams and Pederson, 2003) and in the Lower Sully Formation in the Liard Plateau (Jowett and Schröder-Adams, 2005).

The *Textularia alcesensis* Zone was first described by Stelck (1958) and straddles the Albian-Cenomanian boundary. It has been found in the Peace River plains and the Rocky Mountain foothills of northeastern British Columbia and northwestern Alberta, from the base of the Fish Scale Marker to the base of the Dunvegan Formation (Caldwell et al. 1978), and at Cadomin (Leckie et al., 2000). From central Alberta to the Manitoba Escarpment, the *T. alcesensis* Zone is absent and the end of the Albian is marked in these regions by a complete disappearance of benthic foraminifera in the lower Cenomanian Fish Scales Formation (McNeil and Caldwell, 1981; Bloch et al. 1993; Schröder-Adams et al., 1996).

The early Late Cenomanian *Verneulinoides perplexus* Zone has been divided into the *Ammobaculites gravenori* and *Gaudryina irenensis* subzones (Caldwell et al., 1978). Both subzones were originally described in the Kaskapau Formation in the Peace River area by Stelck and Wall (1954, 1955) and can be found in northeastern British Columbia and northwestern Alberta. Farther east in the WCSB in more condensed strata only a single zone can be distinguished (Caldwell et al., 1978, 1993) containing elements that are common to both subzones.

BIOSTRATIGRAPHIC CHALLENGES

Benthic foraminifera are employed widely as tools to determine biostratigraphic framework and to reconstruct paleoenvironments. Since the Cambrian, they have diversified along with other groups of the Kingdom Protista (Escalante and Ayala, 1996) and have been present in a wide range of environments, from shallow brackish waters to

the deepest parts of the ocean (Van der Zwaan et al., 1999). Their agglutinated or calcareous tests have allowed them good fossilization potential in a variety of diagenetic regimes, which in combination with their abundance makes them useful tools.

Planktonic foraminifera were rare in the Canadian Western Interior Sea, appearing only in the Late Cenomanian, Turonian and Santonian Stages, when Tethyan watermasses were widespread in the Western Interior Sea. In contrast, benthic foraminifera were relatively common, although their abundance was reduced by phases of bottom water anoxia. The Albian-Cenomanian strata in the WCSB contain an almost exclusive agglutinated benthic fauna, whereas calcareous benthic fauna have been found only sporadically (Stelck and Koke, 1987; Harrison, 1988; Stelck et al., 2000). Using the almost exclusive agglutinated benthic foraminifera as biostratigraphic markers and paleoenvironmental indicators presents a number of challenges.

Taphonomy is the fundamental problem of preservation and modification of the fossil assemblage. In general, the most significant post-mortem processes affecting preservation are transport and various modes of destruction (Murray and Alve, 1999). Transport of foraminiferal tests can lead to the loss of fragile tests or the introduction of allochthonous tests. Early diagenesis can cause the dissolution of calcareous tests from increased carboxylic acid in the pore water or disintegration of agglutinated tests from iron reduction utilizing iron present in foraminiferal cement (Hesse, 1984). The introduction of meteoric water during diagenesis can also lead to the dissolution of calcareous components due to the corrosive, low salinity nature of the water being introduced (Veizer, 2003). Burial diagenesis can also alter the foraminiferal assemblage. The increased temperature and pressure of burial can cause silicification, color alteration and distortion of tests making taxonomic placement difficult (McNeil et al., 1996).

An additional challenge working with agglutinated foraminifera is intraspecific variability hampering taxonomic placement of species. In order to create a useful biostratigraphic zonation key indicator foraminiferal species must be easily identifiable, widely distributed and have a short biostratigraphic range. Some authors have resorted to splitting resulting in short biostratigraphic ranges of species or subspecies. However, considering the high degree of taphonomic alteration to faunal elements within the WCSB great care must be taken that these variations represent truly different species and not just intraspecific variations, e.g. as response to substrate changes.

Figure 7 demonstrates possible intraspecific variability within the genus *Haplophragmoides*. Species 1-3 in the figure are easily recognizable and clearly defined species of *Haplophragmoides*. However, species 4-10 are believed to be representative specimens of *Haplophragmoides postis* (from a single sample) as defined by Stelck and Wall (1955). Subsequently some authors have subdivided the *H. postis* into a number of subspecies. It remains, however, unclear if each type represents a true evolutionary change or is a response to variations that are environmentally dependent. In modern agglutinated assemblages, intraspecific variability has frequently been observed as a response to substrate changes providing variable grains for test construction (Schröder, 1986).

Figure 7. Species 1. *Haplophragmoides postis goodrichi*, 2. *Haplophragmoides linki*, and 3. *Haplophragmoides multiplum* are well defined and easily identified taxonomically. Species 4-10 are all variations of *Haplophragmoides postis* found within the PR-2001-G3 sample from Moberly Lake Road. Note the various degree of distortion, overgrowth and silicification.

Figure 8. Legend for stratigraphic columns

RESULTS

Stratigraphic sections for outcrops and cores show foraminiferal sample locations, allostratigraphic surfaces and allomembers (Roca 2007) and facies. Foraminiferal faunas found in each section and core are subdivided into assemblages. Assemblage boundaries were defined on the basis of changes in foraminiferal abundance and species composition. Assemblage changes coincide with allostratigraphic erosional surfaces and will be described in relation to allomembers. All species are figured in Plates 1-5 and tables of actual counts are in the appendix. Foraminiferal species are exclusively agglutinated with the exception of one specimen found in the Mount Belcourt outcrop that had a calcareous test.

Individual facies are described by their sedimentary structures, ichnofossils, grain size and inferred depositional environment in table 2. The facies are fully marine sediments ranging from shelf to lower shoreface, with the exception of a coal bed in the Deadhorse Meadows outcrop.

Deadhorse Meadows

The Deadhorse Meadows outcrop lies in northwestern Alberta at 54 deg 08'53'' N and 119 deg 53'24'' W (figure 1 and table 1). The section can only be reached via helicopter and records an expanded section with the most complete coverage available for this study.

NO.	Facies	Texture	Sedimentary structures	Vertical Sequence	Degree of Bioturbation	Inferred Depositional Environment
I	Mudstone	Silt and clay	Mainly homogeneous and structureless, parallel laminations uncommon. Siderite concretions common.	None	None	Lower offshore to shelf
II	Siltstone interbedded w/ fine sandstone	Silt and very fine to fine sands	Siltstone structureless or laminated; Sands planar and laterally continuous. Siderite concretions common.	Gradual upwards coarsening	Uncommon <i>Skolithos Cruziana</i>	Lower offshore
III	Fine sandstone interbedded w/ siltstone	Fine to medium sands and silt	Sandstone beds 1-5 cm thick laterally continuous, often with starved or wave ripples. Beds coarsen upwards to medium sandstone, often hummocky cross-stratified. Commonly contains many coarsening upwards cycles.	Gradual upwards coarsening	Locally intense bioturbation In some sequences <i>Skolithos</i>	Upper offshore
IV	Fine sandstone	Fine to medium grained sand	Homogeneous and massive with uncommon medium grained beds. Rarely Cross-stratified.	Gradually upwards coarsening	Moderate to intense bioturbation <i>Skolithos</i>	Lower to middle shoreface
V	coal	lignite	Homogeneous 2 cm seam.	None	None	Swamp Marsh
VI	Lag & related facies	Medium sand to conglomerate	Quartz and chert pebbles up to 15 mm thick wave rippled or homogeneous, often containing gutter casts. Wood fragments, fish scales and bone fragments common to abundant.	None	Absent or intense <i>Skolithos</i>	Not applicable

Table 2. Six Facies (I to VI) are defined by their features of texture, stratification and ichnofossil content. The right column is the inferred depositional environment (after Clifton, 1986).

Lithology:

The section at Deadhorse Meadows comprises 420 m of strata from the VE4 to the FSU surface and the overlying Dunvegan Formation (figure 9). The outcrop lies unconformably on sandstone of Boulder Creek Formation (figure 10a) and consists predominately of dark grey platy mudstone interbedded with very fine 2-5 cm sandstone beds(facies II), with sporadic siderite concretions (figure 10b). Sandstone beds are laterally continuous, often forming small coarsening upwards sequences with wave or starved ripples. Coarsening upwards sequences are often followed by a medium to coarse grained bed that contains *Skolithos*, pebbles, chert, wood fragments and gutter casts (figure 11a). A 2 cm coal stringer, WE1 surface, is also present at 42 m (figure 11b).

From 95 m to 115 m the lithology consists of grey mudstone with continuously interbedded very fine sandstone with some bioturbation but mostly well laminated (facies II). Fish scales are present throughout this interval and become very abundant at the top (115 m) where *Inoceramus* fragments and pyritized wood (figure 12a) are present in an intensely bioturbated zone 20 cm thick.

Above 115 m the section consists mainly of dark grey platy mudstone (facies I) that contains siderite concretions. This siltstone lacks bioturbation even in the intervals that contain very fine to fine grained interbedded sandstone beds (facies III), often containing starved ripples. The overlying Dunvegan Formation lies unconformably above this interval (figure 12b).

Micropaleontology:

The foraminifera found in the Deadhorse Meadows section were subdivided into five assemblages, which were defined on the basis of changes in foraminiferal

Figure 9. Deadhorse Meadows section showing sample locations, erosional surfaces (Roca 2007), facies and foraminiferal zones. Refer to legend in figure 8. Allomembers above the FSU erosional surface have not been assigned and are therefore not labeled.

Figure 10. Deadhorse Meadows section: a. basal allomember WA lying unconformably over the Boulder Creek Formation b. dark grey mudstone with interbedded fine sandstone of allomember WB.

Figure 11. Deadhorse Meadows section: a. coarsening upwards sequence with a medium grained sandstone at the top of allomember WB b. 2 cm coal bed at WE1 surface indicated by the white arrow.

Figure 12. Deadhorse Meadows section: a. Pyritized wood fragment in allomember FB b. unconformable contact of Cruiser Formation with overlying Dunvegan Formation.

composition. Since the Deadhorse Meadows section covers a long stratigraphic interval and is nearly complete, it will serve as a reference section to establish foraminiferal zones that are then correlated to allomembers.

***Haplophragmoides postis goodrichi* Zone**

The lowest faunal zone in the Deadhorse Meadows outcrop falls within the WA allomember (figure 9) between the VE4 and WE1 surfaces spanning the interval from 0 m to 42 m below a 2 cm coal bed. The zone contains 18 species, of which,

Haplophragmoides postis goodrichi, is most abundant and unique to this zone.

Foraminiferal abundances within this interval range from 19 to 206 specimens per sample. Biostratigraphic ranges and species abundances for the Deadhorse Meadows section are in figure 13. The common (5-19 specimens) and abundant (>19 specimens) taxa are within this zone are listed below.

Haplophragmoides postis goodrichi, *Ammobaculites fragmentarius*, *Ammobaculites tyrrelli*, *Miliammina sproulei*, *Saccammina alexanderi*, *Trochammina rutherfordi* and *Miliammina manitobensis*

***Trochammina umiatensis* Zone**

The second faunal zone (figure 13) appears above the coal bed at 42 m and ranges to a glauconitic medium grained sandstone containing small pebbles at 64 m and corresponds to allomember WB between the WE1 and WE2 surfaces (figure 9). The species *Haplophragmoides postis goodrichi* and *Trochammina rutherfordi* that were abundant below are no longer present in this interval. *Trochammina umiatensis* is designated as the indicator species due to its first appearance and abundance in allomember WB. This zone contains 16 different species with foraminiferal

Figure 13. range and abundance chart of foraminiferal species for Deadhorse Meadows outcrop.

abundance ranging from 4 to 60 specimens per sample (figure 13). Common and abundant taxa include

Trochammina umiatensis, *Ammobaculites fragmentarius*, *Ammobaculites tyrrelli*, *Miliammina manitobensis*, *Verneuilina Canadensis*, *Psammosphaera* spp. and *Haplophragmoides postis*

***Haplophragmium swareni* Zone**

The third zone follows a barren interval from 64 m to 71 m and ranges from 71 m to 94 m. This zone is associated with allomembers WC and FA and falls between the WE2 and FSMB surfaces (figure 9). The species *Haplophragmium swareni* first appears in this zone and is given indicator status, while *Trochammina umiatensis* is no longer present (figure 13). This assemblage contains 18 species with abundance ranging from 8 to 74 specimens per sample. Common and abundant taxa in this assemblage include: *Ammobaculites fragmentarius*, *Ammobaculites tyrrelli*, *Saccammina alexanderi*, *Miliammina manitobensis* and *Reophax minuta*.

***Verneuilinoides perplexus* Zone**

***Ammobaculites gravenori* Subzone**

The interval from 94 m to 134 m (associated with allomember FB) has two coarsening upwards cycles with abundant fish scales, intense bioturbation, wave rippled fine sandstones, but is barren of foraminifera. The incoming foraminiferal zone falls above the allomembers defined by Roca (2007) but is associated with the *Ammobaculites gravenori* Subzone of the *Verneuilinoides perplexus* Zone. This subzone occurs from 134 m to 227 m and contains five species. Abundances range from 4 to 40 specimens per sample (figure 13). The common and abundant taxa include:

Saccamina alexanderi, *Verneulinoides perplexus* and *Reophax spp.*

***Verneulinoides perplexus* Zone**

***Gaudryina irenensis* Subzone**

The youngest strata contains *Gaudryina irenensis*, the upper subzonal marker of the *Verneulinoides perplexus* Zone. This subzone occurs from 227 m to 345 m where the section becomes barren up to the Dunvegan Formation that unconformably overlies the study interval. There are eight species present within this assemblage and total abundances range from 2 to 44 specimens per sample (figure 13). The common and abundant taxa include:

Ammobaculites gravenori, *Gaudryina irenensis*, *Saccamina alexanderi*,
Verneulinoides perplexus, *Reophax spp.* and *Trochammina rutherfordi*

Nickerson Creek

The Nickerson Creek outcrop lies southeast of Deadhorse Meadows at 54 deg 01'42'' N and 119 deg 28'06'' W (figure 1 and table 1). This section lies 24 km northwest of Grande Cache, Alberta off Highway 40. It can be reached by four-wheel-drive vehicle off a logging road just northwest of Grande Cache.

Lithology:

The Nickerson Creek outcrop is a 105 m section (figure 14) and spans the interval from the VE4 surface at the base of the WA allomember to the FB allomember (figure 15). The basal four meters of this section is medium to coarse grained sandstone (facies IV) with symmetrical wave ripples. The remaining 100 m are mudstone with abundant

Figure 14. Stratigraphic section of Nickerson Creek with location of foraminiferal samples, allostratigraphic surfaces (Roca, 2007), facies and foraminiferal zones (refer to legend: figure 8).

Figure 15. Outcrop photo of the Nickerson Creek locality showing the unconformable contact between Viking Formation and the over-lying allomembers above the VE4 surface.

very fine grained 2-5 cm thick sandstone beds (facies II), showing coarsening upwards cycles to very fine grained sandstone.

Micropaleontology:

Samples taken in the Nickerson Creek outcrop lie between the VE4 and the WE2 surfaces. The *Haplophragmoides postis goodrichi* assemblage occurs in the coarse interval between the VE4 and the WE1 surfaces (figure 14). The *Haplophragmoides postis goodrichi* assemblage contains ten different species with *Haplophragmoides postis goodrichi* being the dominant species. Foraminiferal species abundances range from 17 and 91 specimens. The *Trochammina umiatensis* assemblage occurs from 17 m to 33 m (figure 14) and contains 18 different species with abundances of 41 and 90 specimens. Foraminiferal abundance and ranges are shown in figure 16.

Sulphur River

The Sulphur River outcrop is southeast of Nickerson Creek at 53 deg 72'14'' N and 119 deg 03'33'' W (figure 1 and table 1) and is 32 km southwest of Grande Cache, Alberta.

Lithology:

The Sulphur River outcrop is a 108 m long section (figure 17) of allomembers VD, WA, WB, WC and FB (figure 18). The basal eight meters (VD) are fine to medium grained cross-stratified sandstone (facies IV) with a thin 10-15 cm conglomeratic bed at the top, representing the VE4 surface (figure 17). From 8 to 20 m the section consists of four coarsening upwards cycles grading from mudstone to very fine grained sandstone

Figure 16 Range and abundance charts of foraminiferal species for Nickerson Creek and Sulphur River outcrops

Figure 17. Stratigraphic section of the Sulphur River section with location of foraminiferal samples, allostratigraphic surfaces (Roca 2007), facies and foraminiferal zones. Refer to legend: figure 8.

Figure 18. Outcrop photograph at the Sulphur River section showing allomembers VD, WA, WB, WC and FB (from Roca, 2007).

(facies II to III). The remaining section is mostly siltstone with interbedded very fine grained sandstone beds (1-4cm) that often coarsen upwards (facies II).

Micropaleontology:

The *Haplophragmoides postis goodrichi* assemblage occurs in allomember WA from eight to 15 m lying between VE4 and WE1 (figure 17). The assemblage contains 13 species but is 53% dominated by *Haplophragmoides postis goodrichi*. The *Trochammina umiatensis* assemblage occurs from 15 m to 55 m (figure 17). The *Trochammina umiatensis* assemblage contains 21 species including *Ammobaculites fragmentarius*, *Ammobaculites tyrrelli*, *Miliammina manitobensis*, and *Verneulinoides canadensis*. Foraminiferal abundance and biostratigraphic ranges are shown in figure 16.

Mount Belcourt

The Mount Belcourt outcrop lies northeast British Columbia at 54 deg 25'49'' N and 120 deg 27'36'' W on the north facing slope of Mt. Belcourt (figure 1 and table 1). This outcrop can only be reached via helicopter.

Lithology:

The 315 m thick Mount Belcourt section (figure 19) includes strata of allomembers VD, WA and WB that are overlain by the Goodrich Formation (figure 20a). The outcrop sits unconformably over the Boulder Creek Formation (figure 20b) and consists predominately of dark grey, parallel laminated mudstone (figure 21a) interbedded with laterally continuous very fine grained 2-5 cm thick sandstone beds (facies II; figure 21b), with sporadic siderite concretions. Sandstone beds often form small coarsening upwards sequences, from mudstone to fine sandstone, (figure 21b) with

Figure 19. Stratigraphic section of the outcrop at Mount Belcourt with location of foraminiferal samples, allostratigraphic surfaces, facies and foraminiferal zones (refer to legend: figure 8).

Figure 20. Outcrop photos of Mt. Belcourt. a) Spectacular outcrop exposure of allomembers VD, WA and WB lying between the Boulder Creek and Goodrich formations. b) Conglomerate unconformity with 8 cm of relief between Boulder Creek Formation and the VD allomember at the base of the Mt. Belcourt outcrop.

Figure 21. Outcrop photos of Mt Belcourt. a) Parallel lamination in dark grey siltstone seen in a streambed in allomember WA. b) Laterally continuous very fine sandstone beds with coarsening upwards cycles in the WB allomember.

wave rippled tops. Bioturbation is absent within the fine and coarse intervals of the outcrop or cannot be identified due to lack of sediment contrast.

Inoceramus shells are present in the basal nine meters of section (figure 22a) followed by a 30 m covered interval. Abundant very fine grained sandstone beds containing coarsening upwards cycles are prevalent through the remaining section (facies III). Coarsening upwards cycles culminate in medium grained, hummocky cross-stratified sandstone (facies III) at 95 m and 116 m. Mudstone intervals in-between coarse cycles show parallel lamination (facies I and II). A number of small 2-4 cm thick bentonites are present above 225 m and become increasingly common near the top of the section with increasing sandstone content. The Goodrich Formation unconformably overlies allomember WB (figure 22b).

Micropaleontology:

***Haplophragmoides multiplum* Zone**

The *Haplophragmoides multiplum* Zone is stratigraphically the lowest zone present in the study area. It occurs in the VD allomember between the VE3 and VE4 surfaces (figure 4). *Haplophragmoides multiplum* is a subzonal marker of the *Gaudryina nanushukensis* Zone, and associated with the Middle Albian Hulcross/Harmon formations after the zonation proposed by Caldwell et al. (1978). Within the studied stratigraphic interval its last appearance datum occurs consistently within the allomember VD and therefore has been chosen here as a zonal marker despite its first appearance datum in the Middle Albian. The *Haplophragmoides multiplum* Zone is recognized in the Moberly Lake Road, Halfway River and Mount Belcourt outcrops. Species occurring commonly (5-19 specimens) and abundantly (>19 specimens) are listed below.

Figure 22. Outcrop photos of Mt. Belcourt. a) impression of an *Inoceramus* shell in the lower VD allomember. b) Unconformity between the WB allomember and Goodrich Formation.

Haplophragmoides multiplum, *Ammobaculites fragmentarius*, *Ammobaculites tyrrelli*, *Miliammina sproulei*, *Psamminopelta bowsleri*, *Trochammina rutherfordi* and *Haplophragmoides postis*

The *Haplophragmoides multiplum* Zone, allomember VD, spans the interval from 0 m to 55 m. The assemblage contains 19 foraminiferal species with abundances ranging from 9 to 40 specimens per sample (figure 23). *Inoceramus* prisms are common in this interval with peak abundance at eight meters. At this location the only calcareous foraminiferal taxon present within the study was identified as *Lenticulina macrodisca*.

The interval from 65 m to 230 m (allomember WA) contains common foraminiferal elements including *Verneuilina canadensis*, *Miliammina manitobensis*, *Ammobaculites fragmentarius* and *Ammobaculites tyrrelli* but no biostratigraphically useful maker species. Within this interval, *Inoceramus* prisms, fish scales and framboidal pyrite are common. A total of 15 foraminiferal species are present and abundances range from 2-25 specimens per sample (figure 23).

Above a barren interval, at 265m the *Trochammina umiatensis* assemblage is present. The assemblage ranges to the top of the section where the coarser sandstones of the Goodrich Formation appear. The *Trochammina umiatensis* assemblage contains nine species including *Verneuilina canadensis*, *Bathysiphon brosgiei*, *Gravellina chamneyi*, and *Trochammina umiatensis*. Foraminiferal abundances range from 6 to 14 specimens per sample (figure 23).

Hasler Creek

The Hasler Creek outcrop lies at 55 deg 33'40'' N and 121 deg 58'50'' W in British Columbia on the east bank of Hasler Creek southwest of Chetwynd (figure 1 and

Figure 23. Range and abundance chart of foraminiferal species at Mount Belcourt

table 1). This outcrop is reached by a service road off Highway 97 that runs south along Hasler Creek.

Lithology:

The 85 m thick Hasler Creek section (figure 24) includes strata of allomembers WB and WC (figure 25a). The initial 80 m contains laterally continuous very fine to fine grained sandstone beds 2-5 cm thick interbedded with dark grey mudstone (facies III), with sporadic siderite concretions. Sandstone beds often form coarsening upwards sequences with wave rippled tops (figure 25b). Bioturbation is very abundant within the section and is especially visible in the coarser sandstone intervals.

The upper five meters of section coarsens to medium grained sandstone with pebble beds present (facies IV). The basal meter is unconformable and is represented by a coarse to very coarse grained conglomeratic unit that fines upwards to fine grained sandstone. This unit has abundant *Skolithos* burrows and cross-stratification. The overlying sandstone is well indurated and forms a cliff at the top of the outcrop.

Micropaleontology:

The Hasler Creek section contains 17 foraminiferal species (figure 26). Despite common bioturbation foraminiferal abundance within the section was low and preservation was poor. No indicator species of the newly established zonation were present to allow assemblage placement. However species present, such as *Verneuilina canadensis*, *Miliammina manitobensis*, and *Haplophragmoides postis* are elements common to the *Trochammina umiatensis* and *Haplophragmium swareni* assemblages suggesting placement within these two units. Log correlations (see wireline

Figure 24. Stratigraphic section of the Hasler Creek outcrop with location of foraminiferal samples, allostratigraphic surfaces, facies and foraminiferal zones (refer to legend: figure 8).

Figure 25. Outcrop photos of Hasler Creek. a) Outcrop exposure of allomembers WB and WC. b) Wave ripples in fine sandstone in allomember WB.

log correlations) aided to place the outcrop in the WB and WC allomembers, which contain the *Trochammina umiatensis* and *Haplophragmium swareni* assemblages. Foraminiferal abundances varied from 2 to 47 specimens per sample (figure 26).

Moberly Lake Road

The Moberly Lake Road outcrop consists of a number of small road cuts on Highway 29 along Moberly Lake at 55 deg 54'30'' - 55 deg 55'30''N and 121 deg 55'00'' W in British Columbia (figure 1 and table 1). The outcrops lie on the east side of the road just north of Moberly Lake. Dip measurements, where available, varied from 2-5 degrees. Due to the large length of covered intervals between road cuts the overall thickness might be overestimated. A change to horizontal beds or other structural changes might have lengthened the section.

Lithology:

The 850 m Moberly Lake Road outcrop consists of eight small outcrops (figure 27) that make up 60 m of section; the remaining 790 m are covered. Despite the unfavourable representation this outcrop was included for two reasons: 1) it represents a long stratigraphic interval from the VE3 surface to the FSU surface (figure 27); and 2) this outcrop forms part of the base for the original foraminiferal subzonation (Sutherland and Stelck, 1972; Koke and Stelck, 1984, 1985; Stelck and Koke, 1987). This outcrop includes the upper Viking, Hasler, Goodrich and Cruiser formations covering the VD, WA, WB, WC, FA and FB allomembers. Starting at the north end of the section (stratigraphically oldest) the lowest two outcrops, a and b, (figure 28 a, b) which are separated by a covered interval of 21 m, consist predominately of dark grey mudstone

Figure 27. Stratigraphic section of the Moberly Lake Road outcrop with location of foraminiferal samples, allostratigraphic surfaces, facies and foraminiferal zones. Letters refer to different outcrops (refer to legend: figure 8).

Figure 28. Outcrop photos of the Moberly Lake Road section. a) northern most outcrop (a in figure 27) representing allomember VD. b) second outcrop (b in figure 27) moving south containing allomembers WA and WB.

interbedded with 2-5 cm thick very fine sandstone (facies II). Sandstones are bioturbated with increasing bioturbation upsection and are wave rippled in the upper portion of outcrop b.

Following a covered interval of 56 m, the third outcrop, c, (figure 29 a) consists of ten meters of fine grained 4-20 cm thick sandstone interbedded with mudstone (facies III). Siderite concretions and bioturbation are abundant within this section. The uppermost meter of the outcrop is mudstone (facies I).

From 97 m to 365 m only seven meters of outcrop are exposed (figure 27) as two small outcrops; d and e (figure 27). Outcrop d is two meters of mudstone (facies I) and outcrop e is five meters of a black mudstone (facies I) (figure 29 b). At 365 m, outcrop f (figure 27), contains seven meters of very fine to fine grained 5 to 25 cm thick sandstones with mudstone interbeds (facies III) (figure 30a). Sandstones are hummocky cross-stratified (figure 30b), current rippled (figure 31a) and show minor bioturbation.

Outcrops g and h (figure 27) follow a 422 m covered interval. Outcrops f (figure 31b) and g consist predominantly of very fine to fine grained sandstone with interbedded mudstone (facies III). A conglomeratic lag (facies VI) with chert pebbles and fish scales is present at 815 m (figure 31b). Gamma Ray readings (figure 32) show a sharp spike just above this lag which is tentatively correlated with the Fish Scales Marker Bed (BFSM). The lag is overlain by mudstone (facies I). Following 15 m of covered interval the section coarsens upwards to fine grained sandstone (facies III) with common bioturbation.

Micropaleontology:

The *Haplophragmoides multiplum* assemblage (VD allomember) is present in outcrop a (figure 27). The assemblage is very diverse containing 20 foraminiferal species

Figure 29. Outcrop photos of the Moberly Lake Road section. a) outcrop c in figure 27; fine sandstone interbedded with siltstone coarsening upwards to medium grained sandstone containing allomembers WB and WC. b) Dark fine grained interval at 295 m (e in figure 27) in allomember WC.

Figure 30. Outcrop photos of the Moberly Lake Road section. a. Outcrop f in figure 27 showing very fine to fine grained 5 to 25 cm thick sandstones with mudstone interbeds in allomember FA . b. Hummocky cross-stratification in fine sandstone in allomember FA in outcrop f of figure 27.

Figure 31. Outcrop photos of the Moberly Lake Road section. a) Asymmetrical wave ripples in outcrop f (figure 27) in allomember FA . b) Allomembers FA and FB in outcrop g (figure 27) and Fish Scales Marker Bed (FSMB major flooding surface Roca 2007).

Figure 32. Section of outcrop along Moberly Lake Road containing a highly radioactive pebble bed that is tentatively correlated with the Fish Scale Marker Bed or FSMB in Roca (2007) .

with abundances ranging from 17 to 102 specimens per sample. Three meters of the *Haplophragmoides postis goodrichi* assemblage is present in the lower portion of outcrop b (figure 27). This short interval contains the species *Trochammina rutherfordi*, a species that occurs in both the *Haplophragmoides multiplum* and *Haplophragmoides postis goodrichi* assemblages. Neither indicator species, *Haplophragmoides multiplum* or *Haplophragmoides postis goodrichi* are present (figure 33) however wireline logs (see wireline log correlation) place this interval in the WA allomember (*Haplophragmoides postis goodrichi* assemblage). This interval contains 12 foraminiferal species with abundances ranging from 28 to 82 specimens per sample (figure 33).

The *Trochammina umiatensis* assemblage (allomember WB) starts at 30 m and continues to 95 m (figure 27 outcrops b & c). The assemblage contains 18 foraminiferal species with abundances ranging from 4 to 84 specimens per sample (figure 33). The *Haplophragmium swareni* assemblage (allomember WC) is present in outcrops c and d in the interval from the sandstone at 95 m to the small black mudstone at 295 m (figure 27). The assemblage contains 19 foraminiferal species with abundances ranging from 3 to 14 specimens per sample (figure 33).

Foraminiferal samples from 236 m to 815 m (figure 27) were mostly barren. Three samples did contain a few foraminifera but specimens belonged to common long ranging taxa making placement impossible (figure 33). Above the Fish Scales Marker Bed (BFSM), the FB allomember is barren (figure 27). The remaining ten meters of section (outcrop h) represents the *Gaudryina irenensis* Subzone of the *Verneuilinoides perplexus* Zone.

Figure 33. range and abundance chart of foraminiferal species for Moberly Lake Road outcrop with different outcrops labeled (see figure 26).

rare (1-4)
common (5-19)
abundant (>19)

Halfway River

The outcrop at Halfway River sits on the east bank of the river just north of Highway 29 at 56 deg 13'45''N and 121 deg 29'00'' W in British Columbia (figure 1 and table 1). The outcrop is situated north of the bridge on Highway 29 where it crosses the Halfway River.

Lithology:

The Halfway River outcrop is a 15 m section (figure 34) that consists of 5 to 15 cm thick very fine to fine grained sandstone with interbedded mudstone (facies III) with abundant siderite nodules (Figure 35). At five meters minor bioturbation is present and symmetrical wave ripples are present in a 12 cm fine to medium grained sandstone. From 10 m to 12 m the section consists of fine grained sandstone (facies IV) with a 14 cm coarse grained sandstone within it followed by three meters of dark grey mudstone (facies I).

Micropaleontology:

The *Haplophragmoides multiplum* assemblage is present in the basal five meters of section (allomember VD) and ends at a fine grained sandstone bed that is 12 cm thick (figure 34). This assemblage contains 18 foraminiferal species and has foraminiferal abundances from 14 to 53 specimens per sample (figure 36). The *Haplophragmoides postis goodrichi* assemblage occurs in the final ten meters of the section (allomember WA) and contains 22 foraminiferal species and abundances from 29 to 184 specimens per sample (figure 36). This outcrop contains the most diverse *Haplophragmoides postis goodrichi* assemblage with the study with *Ammobaculites fragmentarius*, *Ammobaculites*

Figure 34. Stratigraphic section of the Halfway river outcrop with location of foraminiferal samples, allostratigraphic surfaces, facies and foraminiferal zones (refer to legend: figure 8).

Figure 35. Outcrop of the Halfway River section containing allomembers VD and WA featuring mudstone with interbedded very fine to fine grained sandstone.

Figure 36. Range and abundance chart of foraminiferal species for Halfway River.

tyrrelli, *Psammosphaera* spp., *Haplophragmoides* spp., *Reophax vasiformis*, *Reophax troyeri*, *Trochammina rutherfordi*, *Gravellina chamneyi*, *Haplophragmoides postis goodrichi*, *Verneuilina canadensis*, and *Haplophragmoides postis* all being common.

Cores

The allostratigraphic framework by Roca (2007), which is the basis for my correlations, is mainly based on subsurface stratigraphic correlations. Therefore three cores were sampled for foraminifera that are located in Roca's southern study area (figure 1) in an attempt to: a) extend biostratigraphic correlations from outcrops into the subsurface; and b) test the lower Viking allomembers below surface VE3 for foraminiferal content that is represented in one of the cores. Unfortunately, samples were either barren or contained low foraminiferal counts that were poorly preserved. For documentation purpose results are included.

Core 10-33-34-5W5

Lithology:

Core 10-33-34-5W5 is 52 m long and comprises an interval from the VE4 to the BFSM surfaces (figure 37). The lowest 12 m of this section consists of medium to coarse grained cross-stratified sandstone with minor mudstone interbeds (facies I, II and IV). Multiple pebble beds are found within the cross-stratified sandstone as well as minor bioturbation. Mudstone intervals contain abundant pyrite. A finer interval of mudstone with scattered fine to medium sandstone (facies I and II) is present from 12 m to the BFSM erosional surface at 44 m (figure 37). Fish scales are present throughout this interval and become increasingly abundant higher in the section. A coarsening upwards

Figure 37. Stratigraphic section of the 10-33-34-5W5 core with location of foraminiferal samples, allostratigraphic surfaces and facies (refer to legend: figure 8). No foraminiferal zones are recognized in this core.

and then fining upwards cycle is represented from 44 m to the top of the core. This very fine to medium grained sandstone interval with mudstone interbeds (facies II) contains abundant fish scales and wave ripples.

Micropaleontology:

Of the 23 samples obtained from the 10-33-34-5W5 core only two yielded rare foraminifera (figure 38). Due to poor preservation and long biostratigraphic ranges of the species present, no zone was assigned. The taxa *Ammobaculites*, *Trochammina*, *Miliammina*, *Gravellina chamneyi* and *Haplophragmoides* were identified.

Core 13-11-41-26W4

Lithology:

Core 13-11-41-26W4 is 23 m long and ranges from the VE3 surface to the WA allomember (figure 39). The basal four meters of core is a mudstone capped by a 20 cm coarse sandstone bed. This interval contains four pebble beds, two of which represent erosional surfaces (Figure 39). The remaining 19 m of core is a mudstone (facies I) with a few 2-4 cm thick sandstone beds.

Micropaleontology:

Due to poor preservation and long biostratigraphic ranges of the species present, no assemblage was assigned between the VE3 and VE4 surfaces. The *Trochammina umiatensis* assemblage is present above the VE4 surface in the WC allomember and also contains the species *Verneuilina canadensis*, *Miliammina manitobensis*, *Ammobaculites fragmentarius* and *Ammobaculites tyrrelli* (figure 38).

Figure 38. Range and abundance of foraminiferal species in cores 13-11-41-26W4, 10-33-34-5W5
8-20-44-3W5

Figure 39. Stratigraphic section of the 13-11-41-26W4 core with location of foraminiferal samples, allostratigraphic surfaces (Roca, 2007), facies and foraminiferal zones (refer to legend: figure 8).

Core 8-20-44-3W5

Lithology:

Core 8-20-44-3W5 covers 58 m representing strata from the VE3 surface to the WB allomember (figure 40). The lower 25 m is a medium grained sandstone (facies IV) with three pebble beds at the top, containing the VE3 and VE4 surfaces (fig 40). A mudstone containing very fine to fine wave rippled sandstones (facies I and II) persist from 25 m to 49 m. At 49 m a four meter coarsening upwards cycle begins that ends in a 45cm medium sand bed with a pebble bed on top (facies III and VI). The remaining five meters of section becomes a finer grained mudstone (facies II).

Micropaleontology:

Of the 26 samples from the core 17 were barren of foraminifera. Due to poor preservation and long biostratigraphic ranges of the species present, no assemblage was assigned. The common species *Ammobaculites fragmentarius*, *Haplophragmoides postis*, *Miliammina manitobensis* and *Verneuilina canadensis* were present. Foraminiferal abundance and biostratigraphic ranges are shown in figure 38.

Wireline log correlations

The shallow marine rocks of the Albian-Cenomanian strata were deposited during numerous transgressive-regressive events and hence the stratigraphic succession is punctuated by widely recognizable marine transgressive or flooding surfaces which can be readily identified and correlated in outcrop and subsurface. Because allostratigraphic

Figure 40. Stratigraphic section of the 8-20-44-3W5 core with location of foraminiferal samples, allostratigraphic surfaces (Roca, 2007) and facies (refer to legend: figure 8). no foraminiferal zones were identified.

units are defined on the basis of mappable surfaces and are independent of the lithology between the bounding surfaces, an allostratigraphic approach is particularly well-suited to rock units that undergo major lateral variation in facies.

An initial allostratigraphic division of the Viking Formation was presented by Boreen and Walker (1991), who recognized numerous regionally traceable erosional surfaces on which Zhang (2006) and Roca (2007) have built their comprehensive allostratigraphic framework for western Alberta. The purpose of wireline log correlations of this study is to provide an extension of the allostratigraphic framework from western Alberta presented by Zhang (2006) and Roca (2007) to northeastern British Columbia in order to integrate the most western outcrops studied here. Until recently, the lack of a regional stratigraphic framework has made it difficult to relate extended, fine-grained strata of the Rocky Mountain foredeep to coeval rocks in other parts of the basin. The allostratigraphic framework presented by Zhang (2006) and Roca (2007) and extended in this study, allow for detailed correlation of individual depositional units in the subsurface and into outcrop. Such a framework is an essential prerequisite to a workable biostratigraphic framework and a comprehensive paleoenvironmental interpretation. It has to be pointed out that the number of wells that preserve the study interval is reduced in the British Columbia area. This results in large distances between wells giving in turn less confidence to correlations.

Figure 41 uses the complete reference section at Deadhorse Meadows and correlates its flooding surfaces to the nearest well log at 11-3-62-12-12W6 providing a reference for gamma ray and resistivity responses as proposed by Roca (2007). A NW-SE and E-W cross-section is presented here (figure 42) that utilizes the erosional surfaces of Roca (2007) and Zhang (2006). The NW-SE cross-section (figure 43) starts just north

Figure 41. Allostratigraphic surfaces in the Deadhorse Meadows outcrop and well 11-3-62-12W6 (left curve is gamma ray log and right curve is resistivity) showing correlation of surfaces from outcrop into the subsurface (after Roca, 2007).

Figure 42. Black dots are wells used to create the NW-SE (blue line) and the east-west (green line) cross-sections. Red dots are outcrops from this study; 1: Halfway River, 2: Moberly Lake Road, 3: Hasler Creek, 4: Mount Belcourt, 5: Deadhorse Meadows.

Figure 43. Cross-section SE-NW (blue line from figure 42) connecting established allostratigraphic framework of Roca (2007) with northeast British Columbia. Red curves represent gamma logs and black curves represent resistivity.

of the Deadhorse Meadows outcrop at well 11-3-62-12W6, part of Zhang's (2006) study, and heads northwest into British Columbia to the Moberly Lake Road outcrop. The E-W cross-section (figure 44) also starts in Zhang's (2006) framework at well 6-3-76-13W6 and moves west to the Moberly Lake Road outcrop.

The very distinct gamma-ray kick of the Fish Scale Marker Bed, widely recognized in the entire WCSB, has been used as a datum and cross-sections have been flattened on this surface. On gamma-ray curves flooding surfaces appear as a distinct increase in gamma radiation, and on resistivity curves as a decrease in electrical resistance values.

Broadly speaking, the VD, WA, WB, WC, FA and FB allomembers in British Columbia form a wedge that is thickest in the northwest and gradually thins eastward and southward to the Alberta-British Columbia border (figures 43 and 44). In western Alberta Roca (2007) and Zhang (2006) shows similar gradual thinning of strata to the south and east. On a regional scale Leckie et al. (1994) show a similar wedge formed by the Colorado Group that is thickest in the north and west and thins south and east throughout Alberta.

Log correlations in the British Columbia portion of this study support the micropaleontological framework for the Halfway River, Hasler Creek and Mount Belcourt outcrops. Erosional surfaces from nearby log correlations coincide with foraminiferal assemblage changes from these outcrops. In addition, allomember stratigraphy is in agreement with the sequence of foraminiferal zones (figures 43 and 44).

The Moberly Lake Road section, however, presents problems. Allostratigraphic correlations of the 16-20-79-25W6 (Hudson Bay et al. Moberly) well indicate a thickness of 310 m, whereas the total thickness of the Moberly Lake Road outcrops, only five

Figure 44. Cross-section W-E (green line from figure 42) connecting established allostratigraphic framework of Zhang (2006) with northeast British Columbia. Red curves represent gamma logs and the black curves represent resistivity.

kilometres northwest, was calculated to be 850 m (figure 43 and 44) by assuming a consistent dip angle throughout all covered intervals. Foraminiferal indicator taxa and their corresponding allomembers in the initial 130 m (sections a-d in figure 27) correlate well with surfaces extended from the Hudson Bay et al. Moberly 16-20-79-25W6 well. This interval is followed by 660 m of section, of which, only six meters are exposed introducing much uncertainty. The remaining 60 m of section (g & h from figure 27) are more confidently placed in the vicinity of the Fish Scale Marker Bed. This position is supported by high gamma readings followed by a barren interval (allomember FB) changing into the *Verneuilinoides perplexus* Zone. It seems plausible that the Moberly Lake Road section contains a fault with repeated section and/or that the shallowly dipping strata become horizontal in the covered interval making section thicknesses inaccurate.

DISCUSSION

A biostratigraphic zonal scheme using allostratigraphy

One of the main objectives of this study is the establishment of a foraminiferal zonal scheme in relation to the newly developed allostratigraphic framework in western Alberta and northeastern British Columbia. The extensive allostratigraphic framework proposed by Zhang (2006) and Roca (2007) has provided a physical stratigraphy linking the subsurface to outcrop in western Alberta. Previously, biostratigraphic work was integrated with lithostratigraphy, a methodology that resulted in numerous conflicting stratigraphic frameworks coupled with biostratigraphic subzones that had only localized relevance. Foraminiferal data gathered shows that, within the study area, each foraminiferal assemblage (distinctive enough to have biostratigraphic value and therefore receiving zonal status) is found in a body of strata (allomember) bound by unconformities. In addition, the discovery of the complete section at Deadhorse Meadows and the sequential reoccurrence of its foraminiferal zones in near and distant outcrops provided confidence in establishing a new zonation. Figure 45 contrasts the existing zonation after Caldwell et al. (1993) with the one of this study where zones are correlated to allomembers. Figure 46 shows the schematic cross-section of allomember subsurface geometry in a NW-SE direction as developed by Roca (2007). Each allomember is now correlated with an index species. The reasoning for creating this new zonation and moving away from the existing one is discussed below.

Figure 45. Left diagram shows the current foraminiferal zonation (Caldwell et al. 1993) along with the outcrops used to create the subzonation in northeast British Columbia. The right diagram shows foraminiferal zones from this study along with selected outcrops from the study.

Figure 46. Schematic NW/SE cross-section from northwestern British Columbia to western Alberta showing the sequence of allomembers bounded by erosional surfaces and the distribution of foraminiferal zones. Modified from Roca 2007. See figure 4 for position of cross-section. See figure 4 for position of cross-section.

Lithostratigraphic vs. allostratigraphic biostratigraphy

The current foraminiferal zonation after Caldwell et al. (1978, 1993) has been based on the concept of lithostratigraphy and a multitude of outcrops, which at the time were not allostratigraphically correlated. Figure 45 shows the current foraminiferal zonation and the sections used by Stelck et al. (1956, 1958), Sutherland and Stelck (1972), Stelck (1975, 1991, 2000), Stelck and Hedinger (1983), Koke and Stelck (1984, 1985) and Stelck and Koke (1987) to create that zonation in contrast to the new zonation using allomembers. Utilized outcrops for the new zonation include some of the short intervals of the previous authors that were revisited in addition to the newly discovered extensive reference section at Deadhorse Meadows (figure 45).

An important finding of this study is the difference in thickness of the Hasler interval in the Peace River area as determined by use of allostratigraphic correlations. Stelck and Koke (1987) and Stelck (1991) proposed a thickness of 530 m for the Hasler Formation based on the Hudson Bay et al. Moberly 16-20-79-25W6 well. Lithostratigraphically, their Hasler interval ranges from the top of the Boulder Creek Formation (“Cadotte” equivalent) to the base of the Goodrich Sandstone (Fig. 4 in Stelck and Koke, 1987). Using wireline logs (figures 43 and 44) this study has determined that the thickness of the Hudson Bay et al. Moberly 16-20-79-25W6 well is 310 m covering the interval from the VE3 to FSMB surfaces. In terms of lithostratigraphy this interval represents the very top of the Boulder Creek, Hasler, Goodrich and lower Cruiser formations representing a larger lithostratigraphic interval. Equivalent lithostratigraphic units in the subsurface would include in ascending order the uppermost Viking and Westgate formations (figure 5).

The Sun et al. Chetwynd 14-20-77-23W6 well lies 65 km southeast of the Hudson Bay et al. Moberly 16-20-79-25W6 well where Stelck and Koke (1987) and Stelck (1991) calculated 230 m of Hasler Formation. Using the allostratigraphic surfaces the Chetwynd 14-20-77-23W6 well (figures 43 and 44) I interpret 300 m of strata from the VE3 surface to the FSMB surface. While Stelck and Koke (1987) and Stelck (1991) show a doubling of the thickness of the Hasler over 65 km from the Chetwynd 14-20-77-23W6 well (230 m) to the Hudson Bay et al. Moberly 16-20-79-25W6 well (530 m), this study shows only a 10 m increase in thickness over the 65 km. Approximately 30 km west of the Moberly Lake Road section Stott (1982) recognized 265 m of Hasler shale in the type section at Dokie Ridge where he measured from the top of the Boulder Creek Formation to the base of the Goodrich Formation. Considering the wireline log data from this study and the thickness of the Hasler given by Stott (1982) it seems likely that Stelck and Koke (1987) and Stelck (1991) have overestimated the thickness of the Hasler shale in the Hudson Bay et al. Moberly 16-20-79-25W6 well.

The foraminiferal zonation after Caldwell et al. (1993) shows two zones and ten subzones (figure 45) within the Hasler and Goodrich formations in the Peace River area. In looking at the outcrops used in the current zonation (figure 45) it can be seen that none show a great degree of stratigraphic completeness. In fact, many of the subzones are only partially represented in outcrop and boundaries have been placed arbitrarily. For example Stelck and Koke (1987) state that the *Haplophragmoides phaseolus* Subzone has no clear boundary with the underlying *H. gigas gigas* Subzone. Another complication with the existing subzonal scheme stems from the use of subspecies such as *Haplophragmoides gigas gigas* and *H. gigas phaseolus* formerly introduced as *H. gigas* ssp. A (Stelck and

Koke, 1987). These subzones are based on intraspecific variability that could easily be a response to changing facies and therefore have no biostratigraphic significance.

Despite resampling the Moberly Lake and Halfway River outcrops the subzones of the *Haplophragmoides gigas* Zone including the *H. uniorbis*, *H. gigas gigas*, *H. gigas phaseolus*, *Reophax tundraensis*, *Trochammina depressa* and *Roephax troyeri* could not be recognized. Some of these species were found, but neither with distinctive abundance nor range to justify zonal status.

While faunal elements found within this study are similar to *Miliammina manitobensis* Zone after Caldwell et al. (1978, 1993) some changes have been made. This study creates zones in reference to allomembers and purposefully does not use the species *Miliammina manitobensis* as an indicator species because of its long biostratigraphic range (figure 47). Figure 45 shows the zones from this study in stratigraphic order.

***Haplophragmoides multiplum* Zone**

The *Haplophragmoides multiplum* Zone is a thin zone associated with allomember VD between the VE3 and VE4 erosional surfaces (figure 46). In the northern portion of the study area this zone is recognized in the Mount Belcourt, Moberly Lake Road and Halfway River outcrops. Roca's (2007) schematic allomember cross-section from the Deadhorse Meadows to the Fall Creek region (figures 1 and 4) indicates the presence of allomember VD in the NW and SE, but being eroded or non-deposited over the forebulge. Micropaleontological analysis of several Fall Creek outcrops (pers. comm. Schröder-Adams, 2007) supports the presence of *H. multiplum* in allomember VD. The identification of this species at this interval in a previously described Fall Creek outcrop originally led to the incorrect identification of the Middle Albian Hulcross/Harmon

Figure 47. Biostratigraphic range of some key species in the Albian and Cenomanian strata of western Canada and allostratigraphic members. Ranges after Caldwell et al. 1978, 1993; this study and allomembers after Roca (2007).

stratigraphic interval at this location (Leckie et al., 2000). At the time, this biostratigraphic call was based on the zonation of Caldwell et al. (1993) who associated this subzonal index for the Harmon /Hulcross transgression. Integration with Roca's allostratigraphic framework now shows the association with allomember VD extending the range of *H. multiplum* from the Middle Albian to the early late Albian Viking Formation (allomember VD)

***Haplophragmoides postis goodrichi* Zone**

The *Haplophragmoides postis goodrichi* Zone is recognized only in the northern portion of the study area and pinches out southward towards the forebulge (fig 46). This zone lies between the VE4 and WE1 erosional surfaces and is recognized by the abundant and dominating occurrence of *Haplophragmoides postis goodrichi*, which is present only within the WA allomember. This zone is recognized in the Halfway River, Deadhorse Meadows, Nickerson Creek, Moberly Lake Road and Sulphur River outcrops, all northern sections in the study area. In the current zonation by Caldwell et al. (1978, 1993)

Haplophragmoides postis goodrichi is the middle of three subzones in the *Miliammina manitobensis* Zone (figures 6 and 45). Originally, Sutherland and Stelck (1972) described this subzone in the Moberly Lake Road outcrop and placed it on top of the *Verneuilina canadensis* Subzone. As shown in figure 45 this study places the *Haplophragmoides postis goodrichi* Zone stratigraphically lower and below the *Verneuilina canadensis* Subzone. This confirms observations by Stritch and Schröder-Adams (1999) who also placed the *Haplophragmoides postis goodrichi* Subzone below the *Verneuilina canadensis* Subzone in the Spirit River 12-20-78-6W6 well near Peace River Town. Allomember WA is not present in the southern region of Fall Creek (figure 46),

confirmed by the absence of the *H. postis goodrichi* Zone in the Fall Creek outcrops (pers. comm, Schröder-Adams, 2007).

***Trochammina umiatensis* Zone**

The *Trochammina umiatensis* Zone is recognized throughout the entire study area and lies between the WE1 and WE2 erosional surfaces associated with allomember WB (figures 46). This zone is recognized in the Deadhorse Meadows, Nickerson Creek, Sulphur River, Mount Belcourt, Moberly Lake Road and core 13-11-41-26W4.

Trochammina umiatensis has been used as a zonal marker here because it only occurs in the WB allomember where *H. postis goodrichi* disappears (figure 47) and its consistent occurrence in nearly all outcrops. The zonation of Caldwell et al. (1993) also recognized this species as a subzonal index where it was found in the Moberly Lake and Hasler Creek localities.

***Haplophragmium swareni* Zone**

The *Haplophragmium swareni* Zone is recognized in the northern portion of the study area in the interval from the WE2 surface to the BFSM surface (figure 46). This zone corresponds to the WC and FA allomembers. It is only represented in the Deadhorse Meadows and Moberly Lake Road outcrops. Large abundances of this species have been recognized farther north in the upper Buckinghorse Formation (Schröder-Adams et al., 2003), Sikanni and lower Sully formations (Stelck and Hedinger, 1983; Schröder-Adams pers. comm., 2007). This species was also used by Caldwell et al., (1978, 1993) where it takes the highest subzone of the *Miliammina manitobensis* Zone (figure 45). In the southern portion of the study area the condensed nature of the strata

produce an assemblage that has common elements of the *Trochammina umiatensis* and *Haplophragmium swareni* zones (WB and WC allomembers) (figure 46) .

In western Alberta the *Textularia alcesensis* Zone (found above the *H. swareni* Subzone of Caldwell et al. 1993) has been found locally in the interval straddling the Fish Scale Marker Bed (Stelck et al., 1958; Caldwell et al., 1978; Leckie et al., 2000) but is absent over most of the WCSB (Bloch et al., 1993). The *T. alcesensis* was not encountered in this study despite being originally recognized in the Peace River area. It might represent a facies related occurrence.

***Verneuilina canadensis* Zone**

The *Verneuilina canadensis* Zone is recognized southeast of the forebulge between the WE1 and BFSM erosional surfaces (figure 46) where it encompasses both the WB and the WC allomembers. *V. canadensis* was found in cores 13-11-41-26W4 and 8-20-44-3W5 and in the Fall Creek sections (Schröder-Adams, pers. comm. 2007) in the same allomembers. The original foraminiferal zonation by Caldwell et al. (1978, 1993) agrees that east of the foredeep the three part subdivision of the *Miliammina manitobensis* Zone (figure 6) is replaced by a single subzone of *V. canadensis*, which contains elements of the *Trochammina umiatensis* and *Haplophragmium swareni* zones.

***Verneuilinoides perplexus* Zone**

The allostratigraphic model (Roca 2007) reaches up to the FSU erosional surface above the Fish Scale Marker Bed. The FB allomember, bound by these two surfaces, is barren of foraminifera throughout the entire study interval, a well documented fact by Schröder-Adams et al. (1996) who described the disappearance of all Albian species at

the base of the Fish Scales Formation in central and southern Alberta. Above FSU, outside of the allostratigraphic framework and further up within the Cenomanian, the *Verneuilinoides perplexus* Zone is present within the Moberly Lake Road and Deadhorse Meadows outcrops. This zone follows the original zonation created by Caldwell et al. (1978, 1993) with its two subzonations recognized in the study area (figure 46). In the Deadhorse Meadows section both the *Ammobaculites gravenori* and *Gaudryina irenensis* subzones are present. In the Moberly Lake Road section only the *Gaudryina irenensis* Subzone is recognized.

Foraminifera as paleoenvironmental proxies in sequence stratigraphy

The integration of biostratigraphy with allostratigraphy in this study has proven superior over the integration with lithostratigraphy. Other authors have integrated their paleontological data with the more widely used method of sequence stratigraphy, a methodology that uses cyclic and genetically related stratal units resulting from sea-level change, and have also considered it as superior over lithostratigraphy (Brett, 1995; Abbott and Carter, 1997 and Brett, 1998). Given that many fossils are facies controlled, sequence stratigraphy becomes a tool for predicting the distribution of fossils in space and time. Thus, it is not only patterns of the first and last occurrence of species that can be understood, but also changes in the abundance, species composition, paleoecological attributes and taphonomic features. By using the succession of sequence system tracts, their distribution through time and their lateral correlation, a wealth of patterns at higher stratigraphic resolution can be studied with time-environment analysis.

The processes of sea-level, climate, and sediment supply fluctuation have strong biological impacts, controlling spatial distribution of organisms at a variety of scales and

influencing patterns of immigration, origination, and extinction (Bennett, 1990; Rey et al., 1993). Bathymetric and sedimentologic factors with associated parameters, in particular, exert major controls on the distribution patterns of marine benthic organisms. Because paleoecological changes in shallow marine settings are closely correlated with fluctuations in sea level and sedimentation, one may predict many relationships between fossil distributional patterns and depositional sequences.

Sequence stratigraphy in respect to paleobiological patterns has received increasing attention in recent years (Brett, 1995, 1998; Holland, 1999; Rey et al., 1993; Scarponi and Kowalewski, 2007). Table 3 shows a summary of important relationships between fauna and sequences observed by Rey et al., (1993), Scarponi and Kowalewski, (2007) and this study. In marine-shelf environments it is sometimes difficult to distinguish the different system tracts of a depositional sequence (Vail et al., 1984, 1987; Posamentier and Vail, 1988; Sarg, 1988). This is particularly true when dealing with homogeneous lithology and intermittent data. For shallow shelf settings, preservation of lowstand systems tracts are typically restricted or absent, and depositional sequences consist of genetically related transgressive and highstand deposits, bounded by erosional lowstand unconformities (Baum and Vail, 1988).

In identifying system tracts this study uses micropaleontological data and lithological observations and compares those to results by Scarponi and Kowalewski (2007) and Rey et al. (1993). Both authors observe under oxygenated marine conditions a higher number of species in the transgressive systems tract (TST) representing the colonization phase as favourable ecological conditions develop. In contrast, the highstand systems tract (HST) is characterized by reduced species richness due to domination of a few taxa.

STUDY	ENVIRONMENT	SYSTEMS TRACT	FAUNAL PATTERNS
Scarponi & Kowalewski 2007	Shallow marine	HST	Low species richness and dominance of most common species
		TST	High species richness and most abundant species less dominant Species richness decreases upwards within sequences from TST to HST Turnover across sequences is negligible compared to variation between different systems tracts
Rey et al. 1993	Shallow marine	HST	Low species richness, maximum concentration in middle of deposit,
		TST	High species richness, maximum concentration in middle of deposit, gradual colonization at first, then rapid
		LST	Robust test morphology, lowest diversity
This Study	Shallow marine	HST/FSST	Low diversity and dominance of most common species, maximum concentration in middle of deposit, low turnover
		TST	Sequence is barren
		LST	No preservation

Table 3. Summary of important relationships between fauna and sequences observed by; Rey et al., 1993; Scarponi and Kowalewski, 2007 and this study. LST: lowstand systems tract; TST: transgressive systems tract; HST: highstand systems tract; FSST: falling stage systems tract.

On sedimentological basis my measured sections do not give evidence for the preservation of lowstand systems tract (LST) or TST. These mainly preserve in incised valley fills, which are not present within measured strata. Therefore assemblages described here might represent primarily HST and possibly falling stage systems tracts (FSST). Generally, numbers of species do not show a significant change between allomembers suggesting the preservation of the same sea-level phase, namely the HST, in most allomembers. Scarponi and Kowalewski (2007) and Rey et al. (1993) found an average of 19 species for their HST, a number comparable to numbers found in this study (Table 4). In terms of foraminiferal abundance Rey et al. (1993) observed maximum concentrations in the middle deposits of the TST and HST. In the Deadhorse Meadows outcrop for example peak foraminiferal abundances for allomembers WA, WB, WC and FA also occur in the middle of the deposit in a relatively fine grained mudstone. If only HST and possible FSST are preserved, physical sedimentological evidence indicating sequence boundaries should be expected in measured sections where the LST and TST are missing. Where in some instances these boundaries are pronounced as e.g. the presence of a coal bed or a pebble bed, others are not obvious. In these cases, foraminiferal assemblage changes give the most convincing evidence for a basin paleoecological change related to sea level.

The lowest Cenomanian strata require further discussion. All Albian foraminifera disappear within the FB allomember and the section remains barren. Benthic foraminifera only reappear in strata above the FSU surface. The lack of benthic species in correlative strata to FB has previously been interpreted as the result of anoxic bottom water conditions (Schröder-Adams et al., 1996). Rey et al., (1993) has seen similar faunal successions within sequences in anoxic basins where the TST lacks foraminifera and the

Allomember	Species richness	Dominant genera
	3-13 species	<i>Saccamina</i> <i>Bathysiphon</i>
FB	Barren	NA
FA	12 species	<i>Ammobaculites</i> <i>Miliammina</i>
WC	3-17 species	<i>Ammobaculites</i> <i>Miliammina</i>
WB	9-21 species	<i>Ammobaculites</i> <i>Trochammina</i> <i>Miliammina</i>
WA	10-22 species	<i>Haplophragmoides</i> <i>Ammobaculites</i>
VD	17-20 species	<i>Ammobaculites</i> <i>Trochammina</i>

Table 4. Foraminiferal species richness (variable number of species results from multiple outcrops) and dominant genera for allomembers and depositional sequences.

following HST shows recolonization and diversification. Similarities between both studies support the interpretation of the FB allomember as being the TST representing the anoxic phase (see discussion below). In the HST (strata above FSU) foraminifera start to colonize the seafloor starting with primitive, one chambered forms such as the genus *Saccamina* and tubular taxa such as *Bathysiphon* followed by more sophisticated building plans. The tubular tests of *Bathysiphon*, living erect on the seafloor, also indicate a deeper and low energy paleoenvironment.

As discussed above, foraminiferal evidence suggests the predominant preservation of HST tracks in the recorded strata. This is in agreement with the sequence stratigraphic interpretation based on the new allostratigraphic framework that suggests that each allomember associated with Albian sediments represent the HST/FSST (Roca, pers. comm., 2007).

Paleoshorelines

Foraminiferal diversity is dependant on numerous ecological factors. Marginal marine environments generally have a reduced number of species that can tolerate extreme conditions often associated with these environments. Therefore interpretations of fossil assemblages cannot be decoupled from paleogeographic reconstructions and ancient shoreline positions. The fossil record of marginal marine environments suggests that such settings tend to be represented by relatively fewer taxa e.g. (Baumbach, 1977; Kowalewski et al., 2002) dominated by opportunistic species with intermittently explosive population growths. Studying the allomember WA and its foraminifera in various outcrops makes this point. In the southeastern outcrops of Sulphur River and Nickerson Creek the species richness is 13 and 10 respectively. The allomember WA in

these two outcrops is almost exclusively dominated by *Haplophragmoides postis goodrichi* making up 50 to 67 percent respectively of all specimens. Moving northwest, abundance of *H. postis goodrichi* peaks at the Deadhorse Meadows outcrop increasing to 80 percent of all specimens despite a slightly higher total number of 18 species. North of Deadhorse Meadows species richness increases to 22 species but with decreasing dominance. Paleogeographic maps by Roca (pers. comm. 2007) indicate that during deposition of WA the paleoshoreline was close to the Deadhorse Meadows, Nickerson Creek and Sulphur River outcrops. This is supported by a coal bed at the WE1 surface (WE1 forms the upper boundary of allomember WA) at Deadhorse Meadows indicating a nearshore marsh environment. The increase in species richness and greater evenness of species (loss of dominance of *Haplophragmoides postis goodrichi*) at Halfway River suggests a more seaward position for WA in the northwest or at least more fully marine conditions.

Use of morphotypes

Paleoenvironmental data of the past several million years have recorded an impressive record of sea-level rise and fall that is preserved in both strata of continental margins and isotopes of deep-sea carbonates (Tibert and Leckie, 2004). To identify comparable patterns with fossil assemblages we often rely on proxy data that compare the Recent with the Past.

The abundance and well known ecological preferences of different morphotypes in modern agglutinated foraminifera are the basis for the following interpretations. Jones and Charnock (1985) highlighted the potential to make paleoecological inferences using

modern agglutinated foraminifera that are differentiated into morphogroups based on their different test morphologies, life position and associated feeding strategies. I have adopted this approach to facilitate comparison of Recent with Cretaceous taxa for paleoenvironmental reconstructions. Table 5 is modified from Jones and Charnock (1985) by combining their morphotypes, feeding strategies, life positions and ecological requirements with genera found in this study. Using this data one can make a number of paleoenvironmental interpretations.

Paleobathymetry

Paleontologic data frequently provides a far more sensitive gauge of relative water depth than do sedimentologic features (Brett, 1998). Throughout evolution specific organisms tend to be conservative with respect to their preferred depth ranges. Hence, most genera and families seem to have occupied similar bathymetric zones for millions of years (Boucott, 1990; Aberhan, 1994).

The breakdown of foraminifera based on generic morphologies in selected outcrops is shown in figures 48a, b and c. Figure 49 is modified from Jones and Charnock (1985) and shows the breakdown of relative proportions of morphotypes in neritic environments from marsh to outer shelf. Foraminiferal test morphologies are subdivided into planispiral, serial/uncoiling, quinqueloculine and trochospiral. When applying this model to the Western Interior Sea, it is important to keep in mind its unusual paleoecology related to e.g. basin restriction, prevailing relative shallow bathymetry and lowered salinities. Furthermore, the Cretaceous marine settings cannot be discussed without taking anoxic events into account (Jenkyns, 1980). These factors and their widespread influence throughout the basin may have overprinted the distribution of

Genus	Morphotype	Paleoenvironments	Life position	Feeding Strategy
<i>Saccamina</i>	Unioocular	Normal marine and hypersaline conditions where nutrient source is favorable; not common in the deeper slope environment	Infaunal/Epifaunal	Passive deposit feeders
<i>Miliammina</i>	Quinqueloculine	Shallow, hyposaline (marsh, low-delta complex)	Infaunal	Detrital/bacterial
<i>Psamminopelta</i>	Coiled	Hyposaline		
<i>Ammodiscus</i>	Planispiral	Slope to shelf; thicker coarser forms indicate nearshore and thinner more siliceous tests indicate deeper and low energy marine environments	Epifaunal	Active deposit feeders
<i>Bathysiphon</i>	Uncoiled	Deeper, normal marine. A shorter, parallel-sided, thicker and coarser walled, tube chamber may indicate paralic environments	Erect	Primarily suspension feeders
<i>Trochammina</i>	Trochospiral	Paralic: quite tolerant of hyposaline conditions	Epifaunal	Herbivores
<i>Haplophragmoides</i>	Planispiral	Normal marine of the shelf-slope contact. Fairly tolerant to hyposaline conditions. Involute tests with coarser wall could indicate shallow, paralic conditions: evolute tests with translucent, thin wall could indicate a normal marine environment with a low level of energy in deeper slopes.	Epifaunal	Active herbivores, detritivores
<i>Verneuilinoides</i>	Triserial	Tolerant normal marine	Infaunal	detritivores
<i>Verneuilina</i>	Triserial	Tolerant normal marine	Infaunal	detritivores
<i>Gaudryina</i>	Quadroserial	General normal marine	Infaunal	detritivores

Table 5. Paleoenvironment, life position, and feeding strategy of foraminera genera based on morphotypes. Modified from Chamney (1976) and Jones and Charnock (1985).

<i>Gravellina</i>	Serial	Tolerant to less favorable normal marine	Infaunal	detrivores
<i>Textularia</i>	Biserial	Normal marine with relatively moderate energy level/ coarser test wall indicates higher energy level and greater amounts of silica cement indicate lower energy level	Infaunal	Detrital/ bacterial scavengers
<i>Ammobaculites</i>	Coiled, later stage uncoiled	Normal marine to hyposaline, from nearshore, to shallow shelf to slope	Infaunal	Detrital/ bacterial scavengers
<i>Reophax</i>	uniserial	All normal marine environments of the shelf and slope. Not tolerant to environmental changes.	Infaunal	Detrital/ bacterial scavengers

Table 5 continued

Figure 48a. Foraminiferal morphotypes shown as a percentage of entire sample with erosional surfaces labeled on the left and allomembers labeled on right.

Figure 48b. Foraminiferal morphotypes shown as a percentage of entire sample with erosional surfaces labeled on the left and allomembers on the right.

Figure 48c. Foraminiferal morphotypes shown as a percentage of entire sample with erosional surfaces labeled on the left and allomembers on the right.

ENVIRONMENT	Outer Shelf	Inner Shelf	Marginal	Marsh		
MORPHOTYPE PROPORTIONS	Planispiral	Planispiral	Planispiral	Planispiral		
		Serial/ Uncoiling			Quinque- loculine	Quinque- loculine
	Trochospiral		Trochospiral	Trochospiral		

Figure 49. Relative abundances of morphotypes in neritic environments modified from Jones and Charnock (1985).

morphotypes resulting in less distinctive trends when compared with open oceanic settings.

Nevertheless, a changing dominance in test morphologies can be best observed in the reference section at Deadhorse Meadows (figure 48 a). The lowest allomember WA contains dominantly planispiral and to a lesser degree quinqueloculine and trochospiral morphotypes. This combination indicates a marginal marine environment (figure 49 and 50), also supported by the nearly monospecific assemblage of the *Haplophragmoides postis goodrichi* Zone in this allomember as discussed above. Paleoshoreline maps by Roca (2007) also indicate that during WA time the shoreline was near the Deadhorse Meadows locality. In contrast, the WA allomember in Halfway River contains more uncoiling/serial morphotypes (figure 48c) that suggest a deeper marine setting further northwest of Deadhorse Meadows. The middle allomembers (WB, WC, FA) show a dominance of uncoiling and quinqueloculine forms suggesting a slightly deeper paleoenvironment from marginal to inner shelf settings (figure 49 and 50). The upper portion of the section that falls within the Cenomanian is mainly characterized by serial and uncoiled foraminiferal tests with a distinct decrease in other morphotypes (figure 48a) pointing towards offshore conditions (figure 49 and 50). For example, suspension feeders that are uncoiled (table 5) require lower energy conditions. At this time, paleoecology changes with the onset of the Greenhorn Transgression (Kauffman, 1977) (figure 2). Due to the incompleteness of the other outcrops morphotype distributions are more difficult to interpret (figures 48a, b and c).

Paleoenvironmental analysis of sedimentological facies (table 2) agrees with paleontological interpretations based on foraminifera and their morphotypes. Outcrops

ALLOMEMBER	VD	WA (SOUTH)	WA (NORTH)	WB	WC	FA	Lower Cenomanian
ENVIRONMENT	Inner Shelf	Marginal	Inner Shelf	Inner shelf to marginal	Inner shelf to marginal	Inner shelf to marginal	Outer Shelf
MORPHOTYPE PROPORTIONS	Planispiral	Planispiral	Planispiral	Planispiral	Planispiral	Planispiral	Planispiral
	Serial/ Uncoiling		Serial/ Uncoiling	Serial/ Uncoiling	Serial/ Uncoiling	Serial/ Uncoiling	Serial/ Uncoiling
		Quinque- loculine					
		Trochospiral		Trochospiral	Trochospiral	Trochospiral	
	Trochospiral		Trochospiral	Quinque- loculine	Quinque- loculine		

Figure 50. Relative abundances of morphotypes in allomembers and environments. Modified from Jones and Charnock (1985).

contain sheet-like sandstones often showing current ripples and fine to medium grained hummocky cross-stratified sandstone (facies II & III from table 2) agreeing with the inner shelf setting interpretation of the middle allomembers. The FB allomember is barren of foraminifera in all outcrops making paleontological based estimates of paleobathymetry difficult. At Deadhorse Meadows where the full allomember is preserved the section consists of a platy grey mudstone, abundant fish scales and minor very fine sandstone beds that are parallel laminated or contain starved ripples. These features indicate an environment below fair weather wave base, an offshore shelf environment. Above the FB allomember the facies becomes mudstone rich with occasional coarser storm beds. These features are characteristic of shallow marine environments in the lower shoreface setting (Clifton, 1986). The overall deepening from shoreface to upper and lower offshore regions (table 2) triggers the morphological change in foraminiferal faunas to uniserial and uncoiled morphotypes, which is the most pronounced foraminiferal change within the studied interval.

Paleosalinity

The Albian to Cenomanian foraminiferal species identified in this study show an affinity to Boreal agglutinated assemblages of the Albian Tuktu and Grandstand formations of northern Alaska, described by Tappan (1962), Berquist (1966), and Sliter (1979). Particularly the Albian Mowry Sea which was dominated by a cool, low salinity watermass of Boreal affinity (Stelck, 1975; Schröder-Adams et al., 1996; Stritch and Schröder-Adams, 1999) that resulted in an assemblage dominated by agglutinated foraminifera. In modern settings agglutinated assemblages are indicative of hyposaline

conditions in shallow water settings and in deepest waters that fall below the Calcium Compensation Depth.

Reduced salinities during the restricted phases of the Western Interior Sea may account for the abundance of the quinqueloculine morphotype (e.g. the genus *Miliammina*) which according to Jones and Charnock (1985) should be most common in marsh and marginal marine environments (figure 49). Numerous studies of Recent and fossil assemblages use the quinqueloculine morphotype as a proxy for reduced salinity environments (Scott et al., 1980; Culver et al., 1996; Tibert and Leckie, 2004). In this study the quinqueloculine morphotype is dominant in the WB, WC and FA allomembers (table 4), suggesting reduced salinities during the deposition of these allomembers.

Lower Cenomanian anoxia

Benthic communities may signal bottom-water oxygen levels (Sageman, 1989) and help to identify oxygen depletion events. The end of the Albian is marked by a widespread disappearance of Albian foraminiferal species within the Canadian portion of the Western Interior Sea. This horizon is marked by a bioclastic conglomerate or sandstone followed by a claystone to mudstone interval rich in phosphatic debris (Leckie et al., 1992; 2000; Bloch et al., 1999). Although no total organic carbon content was measured in the studied sections, in southern and central Alberta a clear increase is reported at this horizon (Bloch et al., 1999). The high gamma ray signature of the Fish Scale Marker Bed (BFSM) makes it an important wireline log marker throughout the basin. The concentration of phosphatic material often related to fish debris depends on local sedimentation rates. The bioclastic component of this bed in the Rocky Mountain foothills with high clastic input is strongly diluted compared to regions in the eastern

basin where bonebeds develop. In this study the BFSM and the overlying FB allomember are present at the Moberly Lake Road (figure 27) and the Deadhorse Meadows outcrops (figure 9). The FSMB in the Moberly Lake Road section is a pebble conglomerate with a high gamma ray signal immediately above, but poor in phosphatic debris. At Deadhorse Meadows this horizon is a medium grained sandstone containing abundant plant debris. Fish scales are a visible component throughout this interval. Immediately above the BFSM both sections are fine grained mudstones with no bioturbation or foraminifera.

The widespread disappearance of all foraminifera at the end of the Albian requires an explanation. Previous authors have hypothesized a stratified water column that is established through the Early Cenomanian sea-level rise by bringing Tethyan and Boreal derived watermasses together (Hay, 1989; Hay et al., 1993). The difficulty with this theory is the lack of typical pelagic Tethyan derived microfossils in these early Cenomanian deposits (Schröder-Adams et al., 1996). It also has been suggested that episodes of widespread anoxia are typically associated with transgressions resulting in an increased influx of organic matter such as refractory wood and plant material. During the early Cenomanian the northern portion of the Western Interior Sea does not show evidence for pelagic organic carbon. Nannofossils and planktic foraminifera only entered during late Cenomanian/Turonian time when Tethyan waters became more prevalent in the North (Bloch et al., 1999). Diverse dinoflagellate communities in surface waters, however, survived the Albian/Cenomanian boundary suggesting that surface waters remained productive during deposition of the Lower Cenomanian Fish Scales Formation (Bloch et al., 1999). Hydrogen Index values vary depending on localities indicating a mixed source of organic matter with mainly terrestrial derived organic matter in the northwest (Bloch et al., 1999) close to the study area. In any case, decomposition of this

increased amount of organic matter through bacterial oxidation caused oxygen depleted waters (Kauffman, 1981; Hallam, 1992; Wignall, 1994). Where this oxygen minimum zone reaches the sediment/water interface the benthic community will be negatively affected (Jenkyns, 1980). Leckie et al. (1992) found abundant amorphous organic matter above the FSMB, which has been linked to marine transgression and anoxic bottom waters. Algal cysts are abundant within the FB allomember, and commonly occur in organic-rich marine shales, deposited under anoxic conditions (Leckie et al., 1992).

Black, bituminous shales are globally widespread throughout Cretaceous oceans. These stem from oceanic anoxic events that were short-lived periods of increased organic carbon burial, measured in distinct carbon isotope excursions (e.g. Jenkyns, 1980; Leckie et al., 2002 and references therein). Figure 51 roughly positions the Cretaceous lithostratigraphic units of the western margin of the Canadian Western Interior Sea onto a Cretaceous timescale comparing formational boundaries to eustatic sea-level cycles and variations in $\delta^{13}\text{C}$. The loss of all benthic foraminifera at the Albian-Cenomanian boundary in the Western Interior Sea, dated at 98-99 Ma (Obradovich, 1993) just falls slightly later than the Anoxic Event OAE1d, also called the Breistroffer Event (figure 51). This oceanic anoxic event developed mainly in the eastern and western Tethys approximately 99.5 Ma ago (Leckie et al., 2002). It is believed to be triggered by a series of events such as tectonics, global warming, rising sea level, resulting in flooding of coastal plain areas, changes in ocean circulation and increasing watermass stratification. These extraordinary changes continued throughout the Upper Cretaceous and culminated in the globally spread OAE2 (Bonarelli event) marking the Cenomanian/Turonian boundary. Cretaceous open oceanic sediments such as deposited in the Tethyan Ocean were rich in pelagic carbonate, which differs to the Western Interior Sea during

Figure 51. Summary of major geochemical, tectonic and sea level events associated with mid-Cretaceous oceanic anoxic events (OAEs) (from Leckie et al., 2002). Peace River foothills strata (Stott, 1982) showing the Fish Scale Marker Bed (FSMB) in comparison to global sea-level.

Albian/early Cenomanian time where clastic sedimentation prevailed in a shallow foreland basin. Therefore, direct comparisons are difficult. Consequently, for the above-discussed reasons rapid rising sea levels during early Cenomanian time flooding coastal areas rich with organic matter seems to be the most plausible explanation for the cause of depleted oxygen bottom waters in this epicontinental sea.

Application beyond the study area

In the studied outcrops foraminiferal assemblage changes have been shown to correlate with sequence stratigraphic units. This integration resulted in a newly proposed biostratigraphic framework. The question remains if this framework is useful when applied to subsurface strata further east in the basin, for example in forebulge areas where unconformities are common and in regions removed from the westerly derived sediment source. Recently, subsurface well log correlations have resulted in an allostratigraphic framework for the Cenomanian to Turonian interval for the Rocky Mountain Foothills to southwestern Saskatchewan (Tyagi et al., 2007). This demonstrates that allostratigraphic surfaces can be pulled from the foredeep east to condensed forebulge in Saskatchewan.

Figure 52 gives a rough comparison between the overall changes in numbers of agglutinated species of the Deadhorse Meadows section and well 11-36-22-1W2 in eastern Saskatchewan, which was studied by Schröder-Adams et al. (1996). While the interval of the Westgate and Belle Fourche formations in Saskatchewan are condensed to less than half the thickness of Deadhorse Meadows (allomembers WA to FC), broad similarities can be seen. The peak foraminiferal abundance in the western WA allomember has no representation further east as shown in the allostratigraphic framework (figure 46) and is not correlated here. Further up in the section, as one

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observes abundance fluctuations associated with sequence boundaries (e.g. WE2) at Deadhorse Meadows, one can also detect those within the Westgate Formation in Saskatchewan. The widely recognized BFSM and its associated faunal change are clearly recorded in both localities. Final correlations between these patterns require further integration of allostratigraphic and micropaleontological work. Basin-wide correlative trends might suggest an eustatic signal that has influenced the Western Interior Sea (Plint and Kreitner, 2007) and its foraminiferal faunal development.

CONCLUSIONS

Late Albian to Cenomanian strata in the Rocky Mountain foredeep were studied in seven outcrops addressing micropaleontology, lithostratigraphy and allostratigraphy. The following conclusions are drawn from this study:

1- The original foraminiferal zonation after Caldwell et al. (1993) for Northeastern British Columbia has been revised as a result of integration with recently developed regional allostratigraphic framework after Roca (2007). A new zonation of six foraminiferal zones has been proposed. These include in ascending order:

- a) The *Haplophragmoides multiplum* Zone recognized in the VD allomember between the VE3 and VE4 surfaces.
- b) The *Haplophragmoides postis goodrichi* Zone is present only in the northern portion of the study area in the WA allomember between the VE4 and WE1 surfaces.
- c) The *Trochammina umiatensis* Zone is recognized in the WB allomember between the WE1 and WE2 surfaces.
- d) The *Haplophragmium swareni* Zone is present in the WC and FA allomembers between the WE2 and FSMB surfaces.
- e) The *Verneuilina canadensis* Zone is recognized in the southern portion of the study area in the WB and WC allomembers between the WE1 and FSMB surfaces.
- f) The *Verneuilinoides perplexus* Zone which lies outside the allostratigraphic framework of Roca (2007) and Zhang (2006) follows the original zonation created by Caldwell et al. (1978, 1993) and contains both the *Ammobaculites gravenori* and *Gaudryina irenensis* subzones.

- 2- The new zonal indicators are chosen for their laterally consistent occurrence within their retrospective allomember, their short biostratigraphic range and their easily recognizable morphology.
- 3- The allostratigraphic framework for Albian-Cenomanian strata created by Roca (2007) and Zhang (2006) in western Alberta has been extended to northeastern British Columbia in order to integrate studied outcrops. Log correlations to the Peace River area of British Columbia indicate an overestimation in the previously assumed thickness of the Hasler Formation.
- 4- Foraminiferal assemblage changes correlate with allostratigraphic erosional surfaces throughout the study area and new zonations coincide with allomembers.
- 5- The FB allomember represents the lowest Cenomanian and is barren of foraminifera. The interval represents an anoxic event possibly due to rapid transgression resulting in increased input of organic matter extending the oxygen minimum zone.
- 6- The reference section at Deadhorse Meadows preserves mainly HST/FSST. All sequences show relatively low species richness with peak abundances occurring in the middle of the sequence.
7. Vertical and lateral distribution of foraminiferal morphotypes correlate to sedimentary facies developments, paleosalinities and paleoshoreline positions making them useful paleoenvironmental indicators. Albian sediments and their faunal communities represent lower shoreface to marginal marine settings. Deepening to lower offshore settings takes place above the BFSM within the lowest Cenomanian associated with the Greenhorn transgression.

8- Close integration of biostratigraphic boundaries and faunal changes with allostratigraphy has resulted in refined positions of erosional surfaces that had the most impact on the paleoecological setting and with that the recognition of system tracts.

SYSTEMATICS

Each species is listed with its original reference in addition to one, often more recent publication that figures the species. Species occurrences are based on lithostratigraphic units and allomembers after Roca (2007).

AGGULTINATED FORAMINIFERA

Family ASTRORHIZIDAE Brady, 1881

Genus *Bathysiphon* M. Sars in G. O. Sars, 1872

Bathysiphon brosgiei Tappan, 1957

Plate 1, figures 1, 2

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

Bathysiphon brosgiei Tappan, Stelck and Koke, 1987, Canadian Journal of Earth Sciences v. 24, pl. 1, figs. 1-3.

Occurrence. This species is recognized in the Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou, Viking and Westgate formations of the Colorado Group. In this study it is recognized in allomembers VD, WA, WB, WC and FA after (Roca, 2007). *B. brosgiei* was originally described from the Topagoruk and Fortress Mountain formations of Alaska.

Family SACCAMMINIDAE Brady, 1884

Genus *Psammosphaera* Schultze, 1875

Psammospaera sp.

Plate 1, figure 3

Saccammina alexanderi (Loeblich and Tappan), 1950

Plate 1, figure 4

Porteonina alexanderi Loeblich and Tappan, 1950. University of Kansas Paleontological Contributions, Protozoa, art. 3, p. 5, pl. 1, figs. 1, 2.

Saccammina alexanderi (Loeblich and Tappan), Eicher, 1960, Peabody Museum of Natural History, Bulletin, no. 15, p. 55, pl. 3, figs. 1, 2.

Occurrence. This species is recognized in the Moosebar, Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou, Viking and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB, WC and FA after (Roca, 2007). *S. alexanderi* was originally described from the Lower Cretaceous Kiowa Shale, of Kansas.

Saccammina globosa Crespin, 1963

Plate 1, figure 5

Saccammina globosa Crespin, 1963. Australia, Department of Natural Development, Bureau of Mineral Resources, Geology and Geophysics, Bulletin 66, p. 21, pl. 1 figs. 13-17.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Westgate Formation of the Colorado Group. It is

recognized in allomembers VD, WA and WB after (Roca, 2007). *S. globosa* was originally described from the Cretaceous of Australia.

Remarks. The globular shape of *S. globosa* separates it from *S. alexanderi*.

Family AMMODISCIDAE Ruess, 1862

Genus *Ammodiscus* Reuss, 1862

Ammodiscus mangusi Tappan, 1957

Plate 1, figure 6

Ammodiscus mangusi Tappan, 1957, United States National Museum, Bulletin no. 215, p. 203, pl. 65, figs. 15-14.

Ammodiscus mangusi Tappan, Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, pl. 1, figs. 20-21.

Occurrence. This species is recognized in the upper Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. It is recognized in allomember WB after (Roca, 2007). *A. mangusi* was originally described in the Topagoruk and Fortress Mountain formations of Alaska

Family HORMOSINIDAE Haeckel, 1894

Genus *Reophax* de Montfort, 1808

Reophax minuta Tappan, 1940

Plate 1, figures 7, 8

Reophax minuta Tappan 1940, Journal of Paleontology. v. 14, p. 94, pl. 14, fig 4.

Reophax minuta Tappan, Stelck and Hedinger 1983, Canadian Journal of Earth Sciences v. 20, no. 8, p. 1248-1259, pl. 1, fig. 17-18.

Occurrence. This species is recognized in the Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Westgate Formation of the Colorado Group. It is recognized in allomembers WB, WC and FA after (Roca, 2007). *R. minuta* was originally described from the Lower Cretaceous Washita Group.

Reophax texanus Cushman and Waters, 1928

Plate 1, figure 9

Reophax texanus Cushman and Waters, 1928, Journal of Paleontology, vol. 2, no. 4, p 367, pl. 1, fig 9-11.

Reophax texanus Cushman and Waters, Stelck and Hedinger 1983, Canadian Journal of Earth Sciences v. 20, no. 8, p 1248-1259, pl. 1, fig. 7.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. It is recognized in allomember WC after (Roca, 2007). *R. texanus* was originally described in the Cisco Group Sutton County, Texas.

Reophax troyeri Tappan, 1960

Plate 1, figures 10, 11

Reophax troyeri Tappan, 1960, American Association of Petroleum Geologists Bulletin, v. 44, no. 3, p. 291, pl. 1, figs. 10-12.

Reophax troyeri Tappan, Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, pl. 1, figs. 20-24.

Occurrence. This species occurs in the Hasler, Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB, WC and FA after (Roca, 2007). This tason was originally described from the Middle Albian Topagoruk Formation, northern Alaska.

Remarks. This species has a small to medium test with a very distinct neck. It can be readily distinguished from *Ammobaculites fragmentarius* by its smaller size and more uniform test.

Reophax vasiformis Chamney, 1978

Plate 1, figures 12, 13

Reophax vasiformis Chamney, 1978, Geological Survey of Canada, Bulletin 253, p. 10-11, pl. 1, figs. 12-14.

Reophax vasiformis Chamney, Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, pl. 1, figs. 17-19.

Occurrence. This species is recognized in the Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB after (Roca, 2007). This species was originally described from the Middle to Upper Albian Arctic Red Formation, Yukon Territory.

Family RZEHAKINIDAE Cushman, 1933

Genus *Miliammina* Heron-Allen and Earland, 1930

Miliammina manitobensis Wickenden, 1932

Plate 1, figures 16-19

Miliammina manitobensis Wickenden, 1932, Royal Society of Canada Transactions,3rd Serial, v. 26, sec. 4. p. 90, pl. 1 figs. 11a-c.*Miliammina manitobensis* Wickenden, North and Caldwell, 1975a, Geological Survey of

Canada Paper 74-38, pl. 1, figs. 12a-14b.

Occurrence. This species occurs in the Moosebar, Harmon, Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB, WC and FA from (Roca, 2007). *M. manitobensis* was originally described from the Upper Albian Ashville Formation in Manitoba, and later was recognized by Nauss (1947) in the Lower Albian Loydminster Formation in central Alberta.

Remarks. *M. manitobensis* is very common throughout the Albian across the entire basin. The test varies gradationally from elongate to oval. The aperture in some specimens is formed by the end of the final tubular chamber; in others, the chamber is constricted at or near its end to form a neck, variable in length.

Miliammina sproulei Nauss, 1947

Plate 2, figures 1, 2

Miliammina sproulei Nauss, 1947, Journal of Paleontology v. 21, no. 4, p. 339, pl. 48,

figs. 13a-b.

Miliammina sproulei Nauss, Koke and Stelck, 1985, Canadian Journal of Earth Sciences

v. 22, pl. 2, figs. 2, 3, 7, 8.

Occurrence. This species occurs in the Moosebar, Harmon, Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA and WB after (Roca, 2007). *M. sproulei* was originally recorded in the Lower Albian Cummings Formation in the Vermilion area of Alberta.

Remarks. The narrow elongate test distinguishes *M. sproulei* from *M. manitobensis*

Genus *Psamminopelta* Tappan, 1957

Genus *Psamminopelta bowsheri* Tappan, 1957

Plate 2, figure 3

Genus *Psamminopelta bowsheri* Tappan, 1957, United States National Museum, Bulletin no. 215, p. 211, pl. 67, figs. 11-18.

Genus *Psamminopelta bowsheri* Tappan, Sutherland and Stelck, 1972, Bulletin of Canadian Petroleum Geology, v. 20, no. 3, p. 566-567, pl. 2, figs. 14-17, pl. 3, figs. 1-4.

Occurrence. This species occurs in the Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB, WC and FA after (Roca, 2007). *P. bowsheri* was originally reported from the northern Alaskan Albian succession of the Torok, Tuktu, Topagoruk and Grandstand formations.

Remarks. The paratypes encompassed a wide range of sizes. Specimens of this study also vary in size and are ovate to lenticular.

Family LITUOLIDAE de Blainville, 1825

Genus *Haplophragmoides* Cushman, 1910

Haplophragmoides collyra Nauss, 1947

Plate 2, figures 4, 5

Haplophragmoides collyra Nauss, 1947, Journal of Paleontology v. 21, p. 337, pl. 49, figs. 2, 5.

Haplophragmoides collyra Nauss, Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, p. 1248-1259, pl. 2, figs. 34-36.

Occurrence. This species is recognized in the Cruiser Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. *H. collyra* was first described in the Late Cretaceous Lloydminster shale.

Haplophragmoides gigas Cushman, 1927

Plate 2, figures 6, 7

Haplophragmoides gigas Cushman, 1927, Royal Society of Canada, Transactions ser. 3, v. 21, pl. 2, p. 129, fig. 5.

Haplophragmoides gigas Cushman, Stelck and Koke, 1986, Canadian Journal of Earth Sciences v. 24, p. 2254-2278, pl. 3, figs 5-6.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is

recognized in allomember VD from (Roca, 2007). *H. gigas* was first found in the upper Cretaceous in the British Petroleum Well No. #13 at 1921-1929 feet interval.

Remarks. This species is known to have a wide range in size.

Haplophragmoides gilberti Eicher, 1965

Plate 2, figures 8, 9

Haplophragmoides gilberti Eicher, 1965, Journal of Paleontology v. 39, no. 5, p. 894, pl. 103, figs. 11, 13, 14.

Haplophragmoides gilberti Eicher, Sutherland and Stelck, 1972, Bulletin of Canadian Petroleum Geology, v. 20, p. 567-568, pl. 3, figs, 8-9.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomember WA after (Roca, 2007). *H. gilberti* was originally described from the Cenomanian Graneros shale in Colorado.

Haplophragmoides kirki Wickenden, 1932

Plate 2, figures 10, 11

Haplophragmoides kirki Wickenden, 1932, Transactions of the Royal Society of Canada, ser. 3, v. 26. sec. 4, p. 85, pl. 1 figs. 1a-c.

Haplophragmoides kirki Wickenden, McNeil and Caldwell, 1981, Geological Association of Canada, Special Paper no. 21, p. 152, pl. 11, figs. 10a-b.

Occurrence. This species is recognized in the Cruiser Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Belle Fourche Formation of the Colorado Group. *H. kirki* was originally described from the Campanian Bearpaw Formation in Alberta

Haplophragmoides linki Nauss, 1947

Plate 2, figures 12, 13

Haplophragmoides linki Nauss, 1947, Journal of Paleontology, v. 21, no. 4, p. 339, pl. 49, figs. 7a, b.

Haplophragmoides linki Nauss, North and Caldwell, 1975a, Geological Survey of Canada Paper 74-38 pl. 1, figs. 17a, b.

Occurrence. This species occurs in the Moosebar, Harmon, Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB, WC after (Roca, 2007). *H. linki* was originally described from the Lloydminster Member of the Cantaur Formation in the Vermilion area of Alberta.

Haplophragmoides multiplum Stelck and Wall, 1956

Plate 2, figures 14-17

Haplophragmoides multiplum Stelck and Wall, in Stelck et al., 1956, Research Council of Alberta, Report no. 75, p. 37-38, pl. 4, figs. 14-16.

Haplophragmoides multiplum Stelck and Wall, Eicher, 1960, Peabody Museum of Natural History, Bulletin, no. 15, p. 58-59, pl. 3, fig. 12.

Occurrence. This species occurs in the Harmon and Hasler formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou Formation of the Colorado Group. It is recognized in allomember VD after (Roca, 2007). *H. multiplum* was originally described from the Harmon Formation of northeastern British Columbia.

Remarks. *H. multiplum* makes a good indicator for the VD allomember because it is easily recognized, has a short range and is abundant in the VD allomember. *H. multiplum* is easily recognized by its small, planispiral test, with at least three whorls of chambers with twelve in the ultimate whorl. *H. multiplum* is a subzonal marker in the Albian *Gaudryina nanushukensis* Zone (Caldwell et al., 1978, 1993) in the Harmon/Hulcross Formation. Its presence in the VD allomember (Viking Formation) and paucity above it make it a good indicator for the VD allomember.

Haplophragmoides postis Stelck and Wall, 1956

Plate 2, figures 18-21; Plate 3, 1-4

Haplophragmoides postis Stelck and Wall, in Stelck et al., 1956, Research Council of Alberta, Report no. 75, p. 38, pl. 4, figs. 23-24.

Haplophragmoides postis Stelck and Wall, Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, pl. 2, figs. 15-21, 26-30.

Occurrence. This species occurs in the Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado

Group. It is recognized in allomembers VD, WA, WB, WC and FA after (Roca, 2007). *H. postis* was originally reported from the Early Albian Gates Formation of northeastern British Columbia, but has since been recognized in the Upper Albian.

Remarks. A lot of variability exists within *H. postis*. Sutures are distinct and range from nearly straight to slightly sigmoidal. Seven to ten chambers are usually visible in the ultimate whorl. This species can be distinguished by medium sized tests that are evolute with chambers that are approximately the same size.

Haplophragmoides postis goodrichi Sutherland and Stelck, 1972

Plate 3, figures 5, 6

Haplophragmoides postis goodrichi Sutherland and Stelck, 1972, Bulletin of Canadian Petroleum Geology, p. 570, pl. 3, figures 13-15.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. It is recognized in allomember WA after (Roca, 2007). *H. postis goodrichi* was originally described from the Upper Albian Goodrich Formation of northeastern British Columbia.

Remarks. *H. postis goodrichi* differs from *H. postis* by being less evolute and having strongly inflated chambers that increase rapidly in size. The number of chambers varies from seven to ten in the ultimate whorl with two to two and a half whorls being visible. This species makes a good indicator for the WA allomember because it is easily identifiable and only occurs in the WA allomember. It also occurs in great numbers especially in near nearshore deposits.

Haplophragmoides topagorukensis Tappan, 1957

Plate 3, figures 7, 8

Haplophragmoides topagorukensis Tappan, 1957, United States National Museum, Bulletin 215, pl. 203, pl. 65, figs. 15-25.

Haplophragmoides topagorukensis Tappan, Sutherland and Stelck, 1972, Bulletin of Canadian Petroleum Geology, p. 570-571, pl. 3, figs. 10-12.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Westgate Formation of the Colorado Group. It is recognized in allomember WC after (Roca, 2007). *H. topagorukensis* was originally described from the Albian Torok, Topagoruk, and Grandstand formations in northern Alaska.

Genus *Haplophragmium* Reuss, 1860

Haplophragmium swareni Stelck and Hedinger, 1976

Plate 4, figures 7, 8

Haplophragmium swareni Stelck and Hedinger, 1976, Journal of Foraminiferal Research, vol 6, no. 2, p. 137, pl. 1, figs 8-11.

Occurrence. This species is recognized in the Goodrich Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. It is recognized in allomembers WC and FA after (Roca, 2007). *H. swareni* was originally described from the Sully Formation on the Sikanni Chief River in northeastern British Columbia and has been extended by Schröder-Adams and Pedersen (2003) into the Buckinghorse Formation.

Remarks. *H. swareni* is used as an indicator species for the *Haplophragmium swareni* Zone (allomembers WC and FA). This species occurs only in this interval and is easily identified. It consists of a streptospirally or trochospirally coiled portion (6-10 chambers) and a later rectilinear portion with 5 or 6 chambers.

Genus *Ammobaculites* Cushman, 1910

Ammobaculites fragmentarius Cushman, 1927

Plate 3, figures 11-14

Ammobaculites fragmentarius Cushman, 1927a, Royal Society of Canada Transactions, 3RD serial, v. 21, sec. 4, p. 130, pl. 1, fig. 8.

Ammobaculites fragmentarius Cushman, Stelck, Wall, Bahan, and Martin, 1956, Alberta Research Council Report no. 75, p. 21-22, pl. 5, figs. 18-19.

Occurrence. This species is recognized in the Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers VD, WA, WB, WC and FA after (Roca, 2007). *A. fragmentarius* was originally described from unnamed Cretaceous rocks of Alberta.

Remarks. This species is easily distinguished by its tapering nature in the uniserial portion of the test. *A. fragmentarius* is common throughout the entire Albian in the Western Interior.

Ammobaculites gravenori Stelck and Wall, 1955

Plate 3, figures 9, 10

Ammobaculites gravenori Stelck and Wall, 1955, Research Council Report., Edmonton, Alberta, no. 68, p 65, pl. 1, figs 1-3.

Occurrence. This species is recognized in the Cruiser Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. *A. gravenori* was first described from the Imperial Oil Limited Spirit River test hole A-337-1 in the Kaskapau Formation

Remarks. This species is similar to *A. tyrrelli* but is distinguished by having a more involute coiled portion. It is also a subzonal marker in the *Verneuilioides perplexus* Zone of Caldwell et al., (1978, 1993).

Ammobaculites petilus Eicher, 1960

Plate 3, figure 15, 16

Ammobaculites petilus Eicher, 1960, Peabody Museum of Natural History, Bulletin 15, p. 62-63, pl. 4, figs. 2a, b, 6.

Ammobaculites petilus Eicher, North and Caldwell, 1975a, Geological Survey of Canada Paper 74-38, pl. 2, figs. 6, 7.

Occurrence. This species occurs in the Cruiser Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Belle Fourche Formation of the Colorado Group. It is recognized in allomembers WA and WB after (Roca, 2007). *A. petilus* was originally described from the Upper Albian Thermopolis Shale, Wyoming.

Remarks. *A. petilus* differs from *A. tyrrelli* principally in being much more slender with less inflated chambers and having a smaller coil often with more chambers.

Ammobaculites tyrrelli Nauss, 1947

Plate 3, figures 17, 18; Plate 4, figures 1, 2

Ammobaculites tyrrelli Nauss, 1947, Journal of Paleontology v. 21, no 4, p. 333, pl. 48, fig. 2.

Ammobaculites tyrrelli Stelck and Wall, in Stelck et al., 1956, Research Council of Alberta Report no. 75, p. 23, pl. 5, fig. 20.

Occurrence. This species occurs in the Hasler and Goodrich formations of the Ft. St.

John Group of northwestern Alberta and northeastern British Columbia. In

central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado

Group. It is recognized in allomembers VD, WA, WB, WC and FA after (Roca,

2007). *A.tyrrelli* (*sensu stricto*) was originally described from the Lloydminster

Shale in the Vermilion area of Alberta.

Remarks. I include *Ammobaculites tyrrelli jolifouensis* Stelck and Wall in this category as the specimens quite closely resemble *A. tyrrelli*. Also included in this category is *A. humei* Nauss which has a similar stratigraphic range. Nauss described the difference between *A. tyrrelli* and *A. humei* as the latter having more coarse grains in the test and a pyriform last chamber. These differences may be the result of differing substrates and preservation.

Ammobaculites wenonahae Tappan, 1960

Plate 4, figures 3, 4

Ammobaculites wenonahae Tappan, 1960, American Association of Petroleum

Geologists Bulletin, v. 44, no. 3, p. 291. pl. 1, figs. 3-6.

Ammobaculites wenonahae Tappan, Koke and Stelck, 1984, Canadian Society of Petroleum Geologists Memoir 9, pl. 1, figs. 33-35.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomember VD after (Roca, 2007). *A. wenonahae* was initially described from the Middle Albian Topagoruk and Upper Albian Grandstand formations, northern Alaska.

Remarks. *A. wenonahae* differs from *A. fragmentarius* Cushman in being two to three times as large with chambers proportionally broader, lower and more closely appressed.

Family TEXTULARIOPSIDAE Loeblich and Tappan, 1982

Genus *Textulariopsis* Banner and Pereira, 1981

Textulariopsis minuta (Berthelin), 1880

Plate 4, figure 11

Textulariopsis minuta (Berthelin), Stelck and Hedinger, 1983, Canadian Journal of Earth Sciences v. 20, pl. 2, figs. 9-10.

Textulariopsis minuta (Berthelin), Stelck and Koke, 1987, Canadian Journal of Earth Sciences v. 24, pl. 4, figs. 26-27.

Occurrence. This species occurs in the Hasler Formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. It is recognized in allomembers WA and WB after (Roca, 2007).

Remarks. The original reference was unavailable for this species. *T. minuta* may have been placed originally in one of a number of genera including *Textularia*, *Bigenerina* or *Vulvulina*.

Family TROCHAMMINIDAE Schwager, 1877

Genus *Trochammina* Parker and Jones, 1859

Trochammina rutherfordi Stelck and Wall, 1955

Plate 4, figures 12, 13

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

Trochammina rutherfordi Stelck and Wall, North and Caldwell, 1975a, Geological Survey of Canada Paper 74-38, pl. 67, figs. 27-29.

Occurrence. This species was recognized in the Hasler, Goodrich and Cruiser formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Westgate and Belle Fourche formations of the Colorado Group. It is recognized in allomembers VD and WA after (Roca, 2007). *T. rutherfordi* was originally described from the Cenomanian Kaskapau Formation in northwestern Alberta.

Remarks. *T. rutherfordi* can be recognized by its trochoid test with three whorls and six chambers in the ultimate whorl.

Trochammina umiatensis Tappan, 1957

Plate 4, figures 14, 15

Trochammina umiatensis Tappan, 1957, United States National Museum, Bulletin no. 215, p. 214, pl. 67, figs. 27-29.

Trochammina umiatensis Tappan, Sutherland and Stelck, 1972, Bulletin of Canadian Petroleum Geology v. 20, p. 575, pl. 5, figs. 1-4.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Westgate Formation of the Colorado Group. It is recognized in allomember WB after (Roca, 2007). *T. umiatensis* was originally described from the Upper Albian Grandstand Formation, northern Alaska.

Remarks. *T. umiatensis* is an indicator species of the *Trochammina umiatensis* Zone (allomember WB) and is easily recognized by having a trochoid test with chambers that are inflated and subglobular, few in number, increasing rapidly in size, and only four or five chambers in each whorl.

Family VERNEUILINIDAE Cushman, 1911

Genus *Verneuilinoides* Loeblich and Tappan, 1949

Verneuilinoides borealis Tappan, 1957

Plate 4, figure 16

Verneuilinoides borealis Tappan, 1957, United States National Museum, Bulletin no. 215, p. 206, pl. 66, figs. 10-18.

Verneuilinoides borealis Tappan, Sliter, 1981, Geological Survey of Canada Bulletin 300, p. 57, pl. 11, figs. 11, 16.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it

occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomember VD after (Roca, 2007). *V. borealis* was originally recognized in the Albian Torok, Topagoruk, and Grandstand formations, northern Alaska.

Remarks. This species is extremely variable in size, degree of flaring, and coarseness of texture

Verneuilinoides fischeri Tappan, 1957

Plate 4, figure 17, 18

Verneuilinoides fischeri Tappan, 1957, U. S. National Museum Bulletin, Washington D. C., no. 215, p. 145, pl. 66, figs 23-28.

Occurrence. This species is recognized in the Hasler Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. It is recognized in allomember VD from (Roca, 2007). *V. fischeri* was first described from the Upper Cretaceous Ignek formation, Alaska.

Verneuilinoides perplexus Stelck and Wall, 1955

Plate,4 figures 19, 20

Verneuilinoides perplexus Stelck and Wall, 1955, Alberta Research Council, Report no. 68, p. 10 pl. 2, figs 40, 41.

Occurrence. This species is recognized in the Cruiser Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Belle Fourche Formation of the Colorado Group. *V.*

perplexus was first described from the Upper Cretaceous, upper Cenomanian, lowermost part of the Kaskapau formation

Remarks. This species is a zonal marker in Caldwell et al., (1978, 1993) and this study.

It is distinguished by having a triserial test with five volutions that increases rapidly in size with the final volution comprising at least one-third of the length of the test.

Genus *Gaudryina* d'Orbigny, 1839

Gaudryina canadensis Cushman, 1943

Plate 5, figure 1

Gaudryina canadensis Cushman, 1943, Contrib. Cushman Laboratory for Foraminiferal Research, v. 19, pt. 2, p. 28, pl. 6, figs. 7-8.

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

Occurrence. This species is recognized in the Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomember WB and WC after (Roca, 2007). *G. canadensis* was originally described from the subsurface of Alberta.

Gaudryina irenensis Stelck and Wall, 1955

Plate 5, figures 2, 3

Gaudryina irenensis Stelck and Wall, 1955, Research Council of Alberta, Report 68, p. 208, pl. 66, figs. 19-22.

Gaudryina irenesis Stelck and Wall, McNeil and Caldwell, 1981, Geological Association of Canada Special Paper 21, p. 177, pl. 14, figs. 8-9.

Occurrence. This species is recognized in the Cruiser Formation of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. *G. irenensis* was originally described upper Cenomanian in the lower part of the Kaskapau Formation.

Remarks. *G. irenensis* is a subzonal marker in the *Verneuilioides perlexus* Zone of Caldwell et al., (1978, 1993). It is similar to *G. hectori* Nauss however, it was a stouter triserial portion and does not become biserial until rather late in its development.

Genus *Verneuilina* d'Orbigny, 1839

Verneuilina canadensis Cushman, 1927

Plate 5, figures 4-7

Verneuilina canadensis Cushman, 1927a, Transactions of the Royal Society of Canada ser. 3, v. 21, sec. 4, p. 131, pl. 1, fig. 11.

Verneuilina canadensis Cushman, McNeil and Caldwell, 1981, Geological Association of Canada Special Paper 21, p. 175, pl. 14, fig. 3.

Occurrence. This species is recognized in the Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Westgate Formation of the Colorado Group. It is recognized in allomembers WA, WB and WC after (Roca, 2007). *V. canadensis* was originally described from the subsurface of Alberta, uncertain formation.

Remarks. *V. canadensis* has only been recorded from the Western Interior of North America. It is recognized as a subzonal marker in Caldwell et al., (1978, 1993) and as a zonal marker of the WB and WC allomembers in the southern portion of this study. This species makes a good indicator species due to its short biostratigraphic range, its ease of identification and abundance.

Family GLOBOTEXTULARIIDAE Cushman, 1927b

Genus *Gravellina* Brönnimann, 1933

Gravellina chamneyi Stelck, 1975

Plate 5, figures 8, 9

Gravellina chamneyi Stelck, 1975, Geological Association of Canada Special Paper 13, p. 267-268, pl. 3, figs. 27, 28, 37-44.

Gravellina chamneyi Stelck, Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, pl. 4, figs. 30, 31, 34-36.

Occurrence. This species is recognized in the Hasler and Goodrich formations of the Ft. St. John Group of northwestern Alberta and northeastern British Columbia. In central Alberta it occurs in the Joli Fou and Westgate formations of the Colorado Group. It is recognized in allomembers WB and WC after (Roca, 2007). *G. chamneyi* was originally described from the upper Buckinghorse shale (Upper Albian) in northeastern British Columbia.

CALCAREOUS FORAMINIFERA

Family NODOSARIIDAE Ehrenberg, 1838

Genus *Lenticulina* Larmack, 1804

Lenticulina macrodisca Tappan, 1960

Plate 5, figures 10, 11

Lenticulina macrodisca Tappan, 1960, American Association of Petroleum

Geologists Bulletin vol. 44, no. 3, pl. 1 figs 16-19.

Lenticulina macrodisca Tappan, Stelck et al., 2000, Canadian Journal of Earth Science

vol. 37 pl. 1, fig. 10.5.

Occurrence. This species was only found in this study with a single occurrence. It appears in the Hasler Formation in the Deadhorse Meadows outcrop in British Columbia in allomember VD. Stelck, et al., 2000 found this species in the upper Viking of Giroux Lake, Alberta, a correlative stratigraphic interval to allomember VD. *L. macrodisca* was originally described from the Albian Topagoruk Formation in Alaska.

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PLATES

PLATE 1

Agglutinated taxa:

Figures 1, 2. *Bathysipon brosgei* Tappan. X40, 1 Hasler Creek PR-2006-C6, side view; 2 Deadhorse Meadows DHM-15-04, side view.

Figure 3. *Psammospaera* sp. X40, Hasler Creek PR-2006-15, side view.

Figure 4. *Saccamina alexanderi* Loeblich and Tappan. X40, Halfway River PR-2006-D10.

Figure 5. *Saccamina globosa* Crespin. X40, Moberly Lake Rd. PR-2006-F4, side view.

Figure 6. *Ammodiscus mangusi* Tappan. X40, Moberly Lake Rd. PR-2006-F3, side view.

Figures 7, 8. *Reophax minuta* Tappan. X40, 7 Deadhorse Meadows DHM-34-04, side view; 8 Halfway River PR-2006-D9, side view.

Figure 9. *Reophax texanus* Cushman and Waters. X40, Moberly Lake Rd. PR-2001-J3, side view.

Figures 10, 11. *Reophax troyeri* Tappan. X40, 10 Moberly Lake Rd. PR-2001-H11, side view; 11 Mt. Belcourt Belct-7, side view.

Figures 12, 13. *Reophax vasiformis* Chamney. X40, 12 Moberly Lake Rd, PR-2001-H9, side view; 13 Moberly Lake Rd, PR-2001-H4, side view.

Figures 14-19. *Miliammina manitobensis* Wickenden, X40, 14 and 15 Deadhorse Meadows DHM-13-04, opposite sides; 16 and 17 Hasler Creek PR-2006-C9, opposite sides; 18 and 19 Hasler Creek PR-2006-C19, opposite sides.

PLATE 2

Figures 1, 2. *Miliammina sproulei* Nauss. X40, 1 Nickerson Creek NC-6-04, side view; 2 Deadhorse Meadows DHM-34-04, side view.

Figure 3. *Psamminopelta bowsheri*. X40, Hasler Creek PR-2006-15, side view.

Figures 4, 5. *Haplophragmoides collyra* Nauss. X40, Halfway River, PR-2006-D9, opposite side views.

Figures 6, 7. *Haplophragmoides gigas* Cushman. X40. Moberly Lake Rd. PR-2001-G3, opposite side views.

Figures 8, 9. *Haplophragmoides gilberti* Eicher. X40, Moberly Lake Rd. PR-2006-G3, opposite side views.

Figures 10, 11. *Haplophragmoides kirki* Wickenden. X40, Moberly Lake Rd. PR-2001-H2, opposite side views.

Figures 12, 13. *Haplophragmoides linki* Nauss. X40, Moberly Lake Rd. PR-2006-F3, opposite side views.

Figures 14-17. *Haplophragmoides multiplum* Stelck and Wall. X40, 14, 15; Moberly Lake Rd. PR-2006-F4, opposite side views; 16, 17; Mt. Belcourt Belct-7, opposite side views.

Figures 18-21. *Haplophragmoides postis* Stelck and Wall. X40, 18, 19; Moberly Lake Rd, PR-2001-H9, opposite side views; 20, 21; Moberly Lake Rd, PR-2001-H4, opposite side views.

PLATE 3

Figures 1-4, *Haplophragmoides postis* Stelck and Wall X40, 1, 2 Moberly Lake Rd. PR-2001-J1, opposite side views; 3, 4 Deadhorse Meadows DHM-30-04, opposite side views.

Figures 5, 6. *Haplophragmoides postis goodrichi* Sutherland and Stelck X40, Deadhorse Meadows, DHM-9-04, opposite side views.

Figures 7, 8. *Haplophragmoides topagorukensis* Tappan X40, Nickerson Creek, NC-4-06, opposite side views.

Figures 9, 10. *Ammobaculites gravenori* Stelck and Wall X40, Deadhorse Meadows, PR-2006-I10, opposite side views.

Figures 11-14. *Ammobaculites fragmentarius* Cushman X40, 11, 12 Deadhorse Meadows DHM-21-04, opposite side views; 13, 14 Halfway River, PR-2006-D7, opposite side views.

Figures 15, 16. *Ammobaculites petilus* Eicher X40, Halfway River, PR-2006-D10, opposite side views.

Figures 17, 18. *Ammobaculites tyrrelli* Nauss X40, Deadhorse Meadows, DHM-23-04, opposite side views.

PLATE 4

Figures 1, 2. *Ammobaculites tyrrelli* Nauss X40, Halfway River, PR-2006-D5
opposite side views.

Figures 3, 4. *Ammobaculites wenonahae* Tappan X40, Sulphur River, SR-6-04, opposite
side view.

Figures 5-10. *Haplophragmium swareni* Stelck and Hedinger X40, 5, 6 Moberly Lake
Rd. PR-2006-F3, opposite side view; 7, 8 Deadhorse Meadows, DHM-33-04,
opposite side views; 9, 10, Deadhorse Meadows DHM-32-04, opposite side
views.

Figure 11, *Textulariopsis minuta* Berthelin X40, Deadhorse Meadows, DHM-7-04.

Figures 12, 13. *Trochammina rutherfordi* Stelck and Wall X40, Sulphur River, SR-5-04,
12 spiral view, 13 umbilical view.

Figures 14, 15. *Trochammina umiatensis* Tappan X40, Sulphur River, SR-6-04, 14,
umbilical view, 15 spiral view.

Figure 16. *Verneuilinoides borealis* Tappan X40, Nickerson Creek, NC-1-06.

Figures 17, 18. *Verneuilinoides fischeri* Tappan X40, Moberly Lake Rd. PR-2006-F3,
opposite side views.

Figures 19, 20. *Verneuilinoides perplexus* Loeblich X40, Deadhorse Meadows, PR-
2006-13, opposite side views.

PLATE 5

Figures 1. *Gaudryina canadensis* Cushman X40, Moberly Lake Rd. PR-2001-G4, opposite side views.

Figures 2, 3. *Gaudryina irenensis* Stelck and Wall X40 Deadhorse Meadows, PR-2006-I17, opposite side views.

Figures 4-7. *Verneuilina canadensis* Cushman X40, 4,5. Moberly Lake Rd. PR-200-H7, opposite side views; 6. Deadhorse Meadows, DHM-15-04; 7. Moberly Lake Rd. PR-2001-G3.

Figures 8, 9. *Gravellina chamneyi* Stelck X40, Hasler Creek, PR-2006-C6, opposite side views.

Calcareous taxa:

Figures 10, 11. *Lenticulina macrodisca* (Reuss) Tappan X40 Mt. Belcourt, Belct 9, opposite side views.

APPENDIX

8-20-44-3W5
 S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> sp.	<i>Ammobaculites</i> tyrelli	<i>Millammina</i> sp.	<i>Psammilopelta bowsheri</i>	<i>Psammospira</i> sp.	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Verneuilinoides</i> sp.	<i>Trochammina</i> sp.	<i>Gravellina chamneyi</i>	<i>Millammina manitobensis</i>	<i>Verneuilina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Trochammina umlatensis</i>	SUM OF FORAMS
133						1		1			1	1					0
132										2			1				4
131								1				1					4
130								1		1							3
129						1											1
WE1																	0
128	1					1	1			1							4
124																	0
126																	0
125																	0
124		1				1							1				4
123																	0
122																	0
121																	0
120						3											3
119																	0
118																	0
117																	0
115																	0
115																	0
114	2					1						2			3		8
113																	0
112					1						1	1	2		1		6
111																	0
110																	0
VE4																	0
109																	0
108																	0
VE3																	0

10-33-34-5W5
S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> spc.	<i>Ammobaculites tyrelli</i>	<i>Milliammina</i> spc.	<i>Psammionopelta bowsheri</i>	<i>Psammospheera</i> spc.	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Verneuilinoides</i> spc.	<i>Trochammina</i> spc.	<i>Gravelina chamey</i>	<i>Milliammina manitobensis</i>	<i>Verneuilina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Trochammina umlatensis</i>	SUM OF FORAMS
107																	0
106																	0
105																	0
104																	0
103																	0
BFS										1					2		3
102																	0
101																	0
100																	0
99																	0
98																	0
97																	0
96																	0
95		1		2							2				3		8
93																	0
92																	0
91																	0
90																	0
88																	0
87																	0
86																	0
85																	0
84																	0
83																	0
VE4																	0

13-11-41-26W4
S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> sp.	<i>Ammobaculites</i> tyrelli	<i>Miliammina</i> sp.	<i>Psammimopelta bowsheri</i>	<i>Psammospheera</i> sp.	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Verneuilinoides</i> sp.	<i>Trochammina</i> sp.	<i>Gravellina channeyi</i>	<i>Miliammina manitobensis</i>	<i>Verneuilina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Trochammina umlatensis</i>	SUM OF FORAMS
48	3	4	5		1	2					1	2	2			5	20
47									1								0
46				2		1					1						5
42																	0
41																	0
VE4																	0
40	1												2				3
39																	0
VE3																	0

Hasler Creek S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> spc.	<i>Ammobaculites tyrelli</i>	<i>Bathysiphon brosgel</i>	<i>Hapliphragmoides multipum</i>	<i>Hapliphragmoides</i> spc.	<i>Miliammina</i> spc.	<i>Pammosphaera</i> spc.	<i>Reophax troyeri</i>	<i>Reophax vasiformis</i>	<i>Saccammina alexanderi</i>	<i>Verneuilinoides borealis</i>	<i>Trochammina</i> spc.	<i>Textulariopsis minuta</i>	<i>Gravellina chamneyi</i>	<i>Hapliphragmoides linki</i>	<i>Miliammina manitobensis</i>	<i>Verneuilina canadensis</i>	<i>Hapliphragmoides postis</i>	<i>Reophax minuta</i>	Unidentified foram fragments	Fish remains	Algal cysts	Framboidal pyrite	Inoceramus prisms	SUM OF FORAMS
PR-2006 C23		1						3										4								8
WE2																										
PR-2006 C22	1		1	1				1										3							R	7
PR-2006 C21			1	2														3		1						7
PR-2006 C20			2	2					2									1		1						8
PR-2006 C19			4															8	5	10						27
PR-2006 C18	1		2			3		5	3		1						4		5							24
PR-2006 C17			4	2				2								1		5	5					R		19
PR-2006 C16	7	4	7	3				4	2		3						4	2	11							47
PR-2006 C15	1		3			5											1		4							14
PR-2006 C14				1				2			4			1			5	4	7							25
PR-2006 C13	2					2											1		5							10
PR-2006 C12			1	1													3	1	8							14
PR-2006 C11		2	3					2	1								3	2	4							17
PR-2006 C10	3	4	6	1				2			2		3						9							30
PR-2006 C9	2	2		1						1							3		6							15
PR-2006 C8		3	1						2	2	2							2								12
PR-2006 C7	5	4	7	1															6	2						25
PR-2006 C6			3	2		1		1		3		2							5							17
PR-2006 C5	4	2	3								2					1			2							14
PR-2006 C4	1	4	3	1			1						8								R					18
PR-2006 C3																1	1									2
PR-2006 C2	2	1	1	1				1					3													9
PR-2006 C1			3					1			2								2							8

Mount Belcourt										S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)																			
Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> spc.	<i>Ammobaculites tyrelli</i>	<i>Bathysiphon brosgel</i>	<i>Haplophragmoides multiplex</i>	<i>Haplophragmoides</i> spc.	<i>Miliammina</i> spc.	<i>Miliammina sproulei</i>	<i>Psammisphaera bowsher</i>	<i>Psammisphaera</i> spc.	<i>Reophax troyeri</i>	<i>Reophax vasiformis</i>	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Verneuilinoides borealis</i>	<i>Reophax</i> spc.	<i>Textulariopsis minuta</i>	<i>Gravellina chamneyi</i>	<i>Haplophragmoides linki</i>	<i>Miliammina mantibensis</i>	<i>Verneuilina canadensis</i>	<i>Trochammina umlatensis</i>	<i>Reophax minuta</i>	Unidentified foram fragments	Fish remains	Algal cysts	Framboidal pyrite	Inoceramus prisms	SUM OF FORAMS
PR-2006-J22													3												R		R		0
PR-2006-J21				3																									6
PR-2006-J20				3				3											2	1	1	4	C				R	R	14
PR-2006-J19			1						4				1								5	3							14
WE1																													
PR-2006-J18																													0
PR-2006-J17																													0
PR-2006-J16	1			2									2					2						R					7
PR-2006-J15																				2					R		R		0
PR-2006-J14																					5	3				R			14
PR-2006-J13						1																							0
PR-2006-J12				5																									14
PR-2006-J11																													0
PR-2006-J10	1								1				2				2										A	A	6
PR-2006-J9				2																							A	A	2
PR-2006-J8	3		4	1	2																	1		S	R				11
PR-2006-J7																													0
PR-2006-J6	3	4				4		2			5									4	3		A		R		R		25
PR-2006-J5													1						1										2
PR-2006-J4				1			1		1				3										2						8
VE4																													
PR-2006-J3			3			1																							
PR-2006-J2	7	3		1	3	4					2	6									1		S		S		R		27
Belct-10	1				1				1						3														6
PR-2006-J1					3	1			1					4															9
Belct-9	5	2			4			2	2				1	22						1	1		C				F		40
Belct-8	3			1			2	3							1	4													14
Belct-7						3	3	4	4	2					3														19
VE3																													

Nickerson Creek		S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)																																	
Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> spc.	<i>Ammobaculites tyrelli</i>	<i>Bathysiphon brosgel</i>	<i>Haplophragmoides</i> spc.	<i>Miliammina</i> spc.	<i>Miliammina sproulei</i>	<i>Psammolinopelta bowsleri</i>	<i>Psammospiraera</i> spc.	<i>Reophax troyeri</i>	<i>Reophax vasiformis</i>	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Verneulinoides</i> spc.	<i>Haplophragmoides gigas</i>	<i>Trochammina</i> spc.	<i>Reophax</i> spc.	<i>Saccammina Globosa</i>	<i>Gravellina chameyi</i>	<i>Haplophragmoides linki</i>	<i>Haplophragmoides postis goodrichi</i>	<i>Miliammina mantibensis</i>	<i>Verneuilina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Trochammina umiatensis</i>	<i>Reophax minuta</i>	<i>Haplophragmoides topagorukensis</i>	Unidentified foram fragments	Fish remains	Algal cysts	Framboidal pyrite	Inoceramus prisms	SUM OF FORAMS	
NC-5-06																																			0
WE2																																			0
NC-4-06	9	6	2					1	3			3			1	4			2	3		14	7			13	12	2	1	A				90	
NC-3-06	3	12	2						4		4	4				1			1			1	4			5							A	41	
WE1																																			0
NC-2-06		2	1						1		1					9	2				61	9								1	A			91	
NC-1-06		2	4								1					1	1				5	2	1											17	
VE4																																			0

Sulphur River S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> spc.	<i>Ammobaculites tyrelli</i>	<i>Bathysiphon brosgel</i>	<i>Haplophragmoides</i> spc.	<i>Miliammina</i> spc.	<i>Miliammina sproulei</i>	<i>Psammionopelta bowsher</i>	<i>Psammospira</i> spc.	<i>Reophax troyer</i>	<i>Reophax vasiformis</i>	<i>Saccammina alexander</i>	<i>Trochammina rutherfordi</i>	<i>Verneuilinoides</i> spc.	<i>Haplophragmoides gigas</i>	<i>Trochammina</i> spc.	<i>Reophax</i> spc.	<i>Saccammina Globosa</i>	<i>Gravellina chamneyi</i>	<i>Haplophragmoides linki</i>	<i>Haplophragmoides postis goodrichi</i>	<i>Miliammina manitobensis</i>	<i>Verneuilina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Trochammina umlatensis</i>	<i>Reophax minuta</i>	<i>Haplophragmoides topagorukensis</i>	Unidentified foram fragments	Fish remains	Algal cysts	Framboidal pyrite	Inoceramus prisms	SUM OF FORAMS
SR-9-04																																		0
BFS																																		0
SR-8-04																																		0
WE2																																		0
SR-7-04																																		0
SR-6-04	1	12	1	11	3	5	3	5	3	3	3	2					3		7				15	13		4	21	6						118
SR-5-04	16	27	10	2			7	1	7	2	2	3		4	3		2		6			22	9		29	38								190
WE1																																		0
SR-2-04	7	3	5				9		7	5	4		29				3				111	12	10		6									211
VE4																																		0

Halfway River S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> spc.	<i>Ammobaculites tyrrelli</i>	<i>Bathysiphon brosgel</i>	<i>Haplophragmoides multipilum</i>	<i>Haplophragmoides</i> spc.	<i>Miliammina</i> spc.	<i>Miliammina sproulei</i>	<i>Psammimnopolis bowsheri</i>	<i>Psammospira</i> spc.	<i>Reophax troyeri</i>	<i>Reophax vasiformis</i>	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Verneulinoides borealis</i>	<i>Trochammina</i> spc.	<i>Textulariopsis minuta</i>	<i>Gravellina chamneyi</i>	<i>Haplophragmoides linki</i>	<i>Haplophragmoides gilberti</i>	<i>Haplophragmoides postis goodrichi</i>	<i>Miliammina manitobensis</i>	<i>Verneullina canadensis</i>	<i>Gaudryina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Reophax minuta</i>	<i>Ammobaculites petilus</i>	Unidentified foram fragments	Fish remains	Algal cysts	Framboidal pyrite	Inoceramus prisms	SUM OF FORAMS	
PR-2006-D11	27	49	27			3	1			5	8	3	2	13			3																	175
PR-2006-D10	17	29	20			11		4	1	4	4	11	3	15				16																184
PR-2006-D9	14	9	6						2	5		4		18			1																	83
PR-2006-D8	5	1	3			1						2	1					1																29
VE4																																		
PR-2006-D7	9	6	4	3	1			3				2		18	2				2															53
PR-2006-D6	8	1	1		3	3								4	1				1				2					2						25
PR-2006-D5	5	1	2					1				3		6																R				22
PR-2006-D4	2	1			4									9	1				1				1											21
PR-2006-D3	5	3	1	3	3	2			1			1		8	4	5			1				2						R					37
PR-2006-D2	2		1		2			1						4									4											14
PR-2006-D1	1		2				3			3				9					2															20

Deadhorse Meadows

S single; R rare (2-8); C common (9-19); A abundant (20-199); F flood (>200)

Sample #	<i>Ammobaculites fragmentarius</i>	<i>Ammobaculites</i> sp.	<i>Ammobaculites tyrrelli</i>	<i>Bathysiphon brasieri</i>	<i>Haplophragmoides</i> sp.	<i>Millammina</i> sp.	<i>Millammina sproulei</i>	<i>Psammimopeltis bowsheri</i>	<i>Psammospira</i> sp.	<i>Reophax troyeri</i>	<i>Reophax vasiformis</i>	<i>Saccammina alexanderi</i>	<i>Trochammina rutherfordi</i>	<i>Trochammina</i> sp.	<i>Reophax</i> sp.	<i>Textulariopsis minuta</i>	<i>Ammodiscus marginatus</i>	<i>Gravellina chamneyi</i>	<i>Haplophragmoides linki</i>	<i>Haplophragmoides postis goodrichi</i>	<i>Millammina maritobensis</i>	<i>Veneuilina canadensis</i>	<i>Haplophragmoides postis</i>	<i>Trochammina umiliensis</i>	<i>Haplophragmoides swireni</i>	<i>Reophax minuta</i>	<i>Haplophragmoides kirkii</i>	<i>Veneuilinoides perplexus</i>	<i>Ammobaculites gravenori</i>	<i>Gaudryina lenensis</i>	Unidentified foram fragments	Fish remains	Algal cysts	Framboidal pyrite	Inoceramus prisms	SUM OF FORAMS	
PR-2006-13																																					0
PR-2006-14																																					0
DHM-43-04																																					0
PR-2006-15																																					0
PR-2006-16																																					0
DHM-44-04																																					0
PR-2006-17																																					0
DHM-46-04				4	7	2				1		9	16	1	2															4		1				3	
DHM-45-04				2		3						4	4																	3						15	
DHM-47-04	10			2	3							4	4		3								4					6	5	2						43	
PR-2006-18												3																	1								4
PR-2006-19																																					0
DHM-42-04												1		2																3						6	
PR-2006-12												1																	1								2
PR-2006-11				2															2										1								10
PR-2006-10	6			2	2							3						3	1									5		1						20	
PR-2006-9				2											5														3							R	7
DHM-41-04																																					0
DHM-40-04	7			3	3					2	3	9		5	7																1					40	
PR-2006-8																															1						0
DHM-39-04				2								2																	1	2							9
PR-2006-7						4																															4
FSU																																					0
DHM-38-04																																					0
DHM-37-04																																					0
PR-2006-6																																					0
PR-2006-5																																					0
BF3M																																					0
DHM-34-04	9	17	5		2		1	7			1	5									10					17											74
PR-2006-4				2																	4				2	1										R	11
DHM-33-04	1				1				1				1								4																8
BF3																																					0
DHM-31-04	6	5	2	2	4		1	3												5					2	2										34	
DHM-30-04	4	4						1						2					1		3	2	2													19	
DHM-28-04	7	5		4	2		3	2	2			4						1		4					1											36	
PR-2006-3																																					0
PR-2006-2																																					0
DHM-27-04																																					0
WE2																																					0
DHM-26-04																				2			1	1												4	
DHM-23-04	3	2	1		1		3														1				6		1									18	
DHM-22-04	7	11	4		3		1			1										1	1	11	3	3	14											60	
DHM-21-04	5	3	4	2	6			1		1										2							2									29	
DHM-16-04	6	4	4									1								3																34	
DHM-15-04	4		6	1	1		1	1											1	1	2	2													32		
DHM-13-04	4	9	2						5			1							1		2	7	5													36	
PR-2006-1	3			2	2							2									2															11	
WE1																																					0
DHM-8-04	1	3			4	2		1					8	1							25															45	
DHM-7-04	3		3	1				1		1			3	5		1																				66	
DHM-9-04	6	4	1		8								14	2							161	10														206	
DHM-5-04	2		5		2				2			1	6	3							42															63	
DHM-4-04	3	2	2		1				1			2	4	1		1					8	3														28	
DHM-3-04		3								3	1	3	1	3							3	2														24	
DHM-2-04				2	3		6	1				3	3																							18	
DHM-1-04				1	3	3	2	1	2			2	5																							19	
WE3																																					0

[illegible]