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**CENOMANIAN TO SANTONIAN SEA-LEVEL HISTORY FROM A
PROXIMAL SETTING IN THE WESTERN CANADA SEDIMENTARY BASIN,
SOUTHERN ROCKY MOUNTAIN FOOTHILLS, ALBERTA:
SEDIMENTOLOGY, MICROPALAEONTOLOGY AND ORGANIC
GEOCHEMISTRY**

by

Barbara Elizabeth Medioli

**A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for a degree of
Masters of Science**

**Department of Earth Sciences
Carleton University
Ottawa, Ontario
©January, 1999**

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**CENOMANIAN TO SANTONIAN SEA-LEVEL HISTORY FROM A PROXIMAL
SETTING IN THE WESTERN CANADA SEDIMENTARY BASIN, SOUTHERN
ROCKY MOUNTAIN FOOTHILLS, ALBERTA: SEDIMENTOLOGY,
MICROPALAEONTOLOGY AND ORGANIC GEOCHEMISTRY**

submitted by Barbara Elizabeth Mediolli B.Sc.

(Hons. Earth Science and Biology CO-OP)

in partial fulfilment of the requirements for the degree of Master of Science

A handwritten signature in black ink, appearing to read 'Candia Schindler', written over a horizontal line.

Thesis supervisor

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Chair, Department of Earth Sciences

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January 15, 1999

ABSTRACT

The Cretaceous (Cenomanian-Santonian) Upper Alberta Group is exposed along the banks of Mill Creek, southwestern Alberta. The outcrop exposes a nearly complete section through the Blackstone, Cardium and Wapiabi formations and as such is proposed as a reference section for the southern Rocky Mountain Foothills. This outcrop records deposition in a western, proximal setting of the Western Canada Sedimentary Basin. Other authors have studied time-equivalent rocks of the subsurface Colorado Group, in detail, due to their hydrocarbon content.

The Cretaceous interval records sedimentation during the Greenhorn and Niobrara sea-level cycles. The Vimy Member of the Blackstone Formation records maximum highstand during the Greenhorn cycle while the Cardium Formation records sea-level lowstand during the Coniacian. The Thistle Member of the Wapiabi Formation represents the highstand deposits of the Niobrara Cycle and was deposited under slightly shallower conditions than the Vimy Member.

Paleoenvironments of each unit have been reconstructed using paleontological, sedimentological and organic geochemical data. The paleoenvironments range from shoreline during Cardium time to outer shelf (water depth ~100 m) during Vimy and Thistle times.

Foraminiferal assemblages are exclusively agglutinated, with the exception of those in the Vimy Member when conditions became deep and approached open marine to allow planktic foraminifera and nannofossils to prosper. Faunal changes through time are less pronounced at the Mill Creek location compared to distal parts of the basin. The more proximal position, characterized by shallow, increased energy conditions, prevented severe periods of bottom water anoxia and allowed shallow water assemblages, including species adaptable to lower salinities, to be sustained. Studies of concretions reveal, however, that anoxia was common within the sediment column and record the presence of fossil components not seen in the surrounding shales. Preferential taphonomy and carbonate dissolution may have also biased the foraminiferal assemblages by eliminating any calcareous components.

Organic geochemical results indicate that most of the organic matter in this system was of terrestrial origin and support a proximal setting.

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INTRODUCTION

The Western Canada Sedimentary Basin (WCSB) contains the largest reserve of hydrocarbons in Canada and, due to extensive exploration, it is one of the most well studied basins in the world. The Alberta Group (Albian to Santonian) includes both important source and reservoir rocks. Ten global sea-level cycles have been identified in the Cretaceous section (Figure 1) (Kauffman, 1977, 1984). The shales of the Alberta Group record three major marine transgressive cycles. The first of these, forming the Mowry Sea, was a southward inundation of the Boreal Sea while the other two cycles (Greenhorn and Niobrara) reflect times when the warm southern waters of the Tethyan Sea met the cooler, northern waters of the Boreal Sea (Caldwell *et al.*, 1993). During times of sea-level lowstand, coarser sediments that characterise the reservoir rocks of the Colorado Group, were deposited (Leckie and Smith, 1992); these include the Cardium Formation of this study. During transgression and sea-level highstands shales were deposited and these make up most of the Alberta and Colorado groups. In this study, the sedimentology, paleontology and organic geochemistry of the Greenhorn (Latest Albian to Middle Turonian) and Niobrara (Middle Turonian to Late Santonian) cycles are investigated in detail.

The sedimentology of the WCSB has been studied extensively. Its paleogeography, in connection with sea-level history, has been divided into distinct periods mostly based on macrofaunal assemblages (Kauffman, 1977; 1984; Jeletzky, 1977). Macrofossil assemblages have allowed regional and

Figure 1. Transgressive-regressive couplets and cycles in the southern interior plains of Canada. Modified after Kauffman (1977) - global T-R cycles; Caldwell (1984) - T-R couplets; and Obradovich (1993) ages at stage boundaries.

temporal correlations to be made while microfossil zones tend to be less confined in time and space (Jeletzky, 1968; 1971; 1977; Kauffman, 1969; 1977; 1984; Wall and Germundson, 1961; 1963). Through the use of micropaleontological assemblages, the paleoecology, paleogeography and sea-level history of the deeper, more distal parts of the basin have been refined. The paleoecology of more proximal parts of the basin has been studied in detail in the northern foothills and in the Peace River area by Stelck and Wall (1954; 1955), Stelck *et al.* (1956; 1958), Stelck and Leckie (1990a; b), Stelck and Koke (1987), Stelck (1975; 1991) and Koke and Stelck (1984; 1985). In the southern foothills data are more limited (Wall, 1967a, b, c).

Purpose of this Study:

The primary purpose of this investigation is to establish a reference section for the Upper Alberta Group in the southern foothills of Alberta so that correlations between the subsurface Colorado Group and the Alberta Group outcrop may be readily made. The Mill Creek location was chosen because of the almost continuous exposure of the Upper Alberta Group, spanning approximately 12 million years of sedimentation (Wall, 1967a; Obradovich, 1993) in a proximal setting (Stott, 1963) on the western margin of the WCSB. This section was previously studied by Wall (1967a) who did not characterise the lithological nature of the outcrop but rather focused on microfaunal data. In this study, lithological, paleontological and organic geochemical properties of the Upper Alberta Group strata are reported. Secondly, these parameters are

used to attempt to reconstruct the paleoenvironmental change and sea-level history, as recorded through time, at this proximal location on the western margin of the WCSB.

Location of the Study Area:

The study area is located in southwestern Alberta (Figure 2) and is exposed along the Mill Creek gorge, located about 20 km southwest of Pincher Creek in Sec. 12 & 13, Twp. 5, R. 2 W 5. The outcrop is situated within the structurally deformed zone of the Rocky Mountain Foothills and structural thickening of the shales poses potential problems for correlation of strata with other areas.

GEOLOGICAL SETTING

The WCSB is centered on the Canadian Interior Plains. The basin's western margins are defined by major faults in the Rocky Mountain Foothills; eastward it extends to the Canadian Shield. The WCSB extends from the Arctic Ocean in the north, southward into the mid-western states of the United States where it becomes the Western Interior Basin, south of the international border (Porter et al., 1982; Leckie and Smith, 1992; Stott, 1984).

In the WCSB, sediments have been accumulating since Proterozoic times. Sloss (1963) established six major regional transgressive/regressive sequences for the North American continent. These first order sea-level sequences are well recognized in the WCSB and of these sequences, only the

Figure 2. Map showing the location of the study area (*). The outcrop is located about 20 km southwest of the town of Pincher Creek, in the Southern Rocky Mountain Foothills.

Upper Zuni sequence (Upper Cretaceous to Tertiary) is of interest to this study (Leckie, 1989).

During the latest Jurassic time 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 deposition of sediment, in the ever-expanding foreland basin, that lasted until the end of the early Tertiary (Leckie, 1989). On the western margin of the WCSB, the development of a foredeep basin allowed the formation of a thick clastic wedge, composed primarily of sandstones, siltstones and shales, and recorded repeated cycles of transgression and regression. Some of these cycles can be tied to eustatic sea-level fluctuations while others were associated with more local tectonic events that occurred to the west, in the ever-rising Cordilleran fold and thrust belt (Leckie, 1989). Late Cretaceous sediments record the last northward transgressions of the Tethyan Sea. During the Turonian and the Santonian the Tethyan and Boreal seas merged to form the Western Interior Seaway that flooded most of the cratonic interior of North America (Williams and Stelck, 1975; Kauffman, 1977; Stott, 1984; Leckie and Smith, 1992). The Western Interior Seaway was a shallow, epicontinental sea, estimated to be no more than 500 metres deep during the Turonian highstand (Asquith, 1970; Hay *et al.*, 1993), whose closest modern analogue would be a shelf environment on a passive margin. Deep-water facies are preserved in the Interior Plains while more proximal facies are easily observed in the Alberta foothills (Stott, 1984; Wall, 1967a).

Deposition of organic matter, coupled with the necessary burial and tectonic conditions, promoted the formation of large quantities of hydrocarbons in this basin (Podruski *et al.*, 1988). The Upper Alberta and Colorado groups (Late Cenomanian-Santonian) contain the Cardium Sandstone, the richest oil-producing facies known in the Cretaceous strata of this basin, while the Lower Colorado Group contains such hydrocarbon reservoirs as the Barons, Viking and Bow Island formations (Podruski *et al.*, 1988). Basinward, the Upper Colorado Group also contains the Second White Specks Formation (Bloch *et al.*, 1993) and the Medicine Hat Formation in the Sweetgrass Arch area (Hankel *et al.*, 1989; Schröder-Adams *et al.*, 1997; 1998) which are also major hydrocarbon reservoirs.

Stratigraphic Nomenclature

The studied section exposes an almost complete section of the Late Cretaceous (Late Cenomanian to Santonian) Alberta Group (Figure 3). The Alberta Group is composed predominantly of black shale units. In the study area two shale units are exposed: the lower Blackstone Formation and the upper Wapiabi Formation separated by sandstones of the Cardium Formation. Lithological names of age-equivalent rocks in the foothills Alberta Group and the plains Colorado Group vary from region to region. Inconsistencies in naming units are partly due to facies changes, associated with distance from shoreline, within this large basin. Throughout this work southern foothills terminology will be used (Stott, 1962; 1963) and this is applied to all Alberta Group outcrops south of the Bow River. Formational and member ages are

Figure 3. Stratigraphic correlation chart of the Blaimore, Mannville, Fort St. John and Colorado Groups in the Western Canada Sedimentary Basin (Ages after Obradovich, 1993).

based on macrofossil fauna from throughout the WCSB (Stott, 1962; 1963; 1984; Wall and Germundson, 1961; 1963; Mellon and Wall, 1967).

The Blackstone Formation (Late Cenomanian-Turonian) is exposed along the Rocky Mountain Foothills. The base of this unit is diachronous throughout the foothills, reflecting a southward inundation of the Boreal Sea onto the North American continent (Stott, 1963; Wall, 1967a). In the northern plains the Colorado Group sits conformably over the Lower Cretaceous Mannville Group while in the central and southern plains and foothills, the Colorado Group (and its equivalent the Alberta Group) lie unconformably over the Blairmore and Mannville groups (Mellon and Wall, 1963; Norris, 1993). The Blackstone Formation consists of four shales which are, in ascending order, the Sunkay, Vimy, Haven and Opabin members. This formation is overlain by the Cardium Formation which in turn is overlain by the Wapiabi Formation, consisting of the Muskiki, Marshybank, Dowling, Thistle and Hanson members (Figure 4).

The Sunkay Member is of late Albian to Cenomanian age (Stott, 1963). It is equivalent to the Westgate, Fish Scales, Barons and Belle Fourche formations in the plains and the Cruiser, Dunvegan and lower Kaskapau formations in the central (between the Bow and Peace Rivers) and northern foothills (north of the Peace River) (Bloch *et al.*, 1993). The Early Turonian Vimy Member (Stott, 1963) of the Alberta Group is equivalent to the Second White Specks Formation of the plains and to the Kaskapau Formation in the central foothills (Bloch *et al.*, 1993). The Haven Member of the Blackstone Formation

Figure 4. Stratigraphy of the Upper Alberta Group in the southern Alberta Foothills (after Stott, 1963).

is of Middle Turonian age (Stott, 1963) and is equivalent to the lower unnamed shales of the Colorado Group in the plains and the Kaskapau Formation in the central foothills (Bloch *et al.*, 1993). The Opabin Member of the Alberta Group is a Middle Turonian shale (Stott, 1963) that is equivalent to the lower undifferentiated Colorado Group in the plains and the Upper Kaskapau Formation in the central foothills (Bloch *et al.*, 1993). The Coniacian Cardium Formation is found extensively across the western margins of the WCSB (Plint, 1990; 1991; Plint *et al.*, 1990). The Muskiki Member of the Wapiabi Formation is of Latest Coniacian to Earliest Santonian age (Plint, 1990; 1991; Plint *et al.*, 1990) and is equivalent to the undifferentiated shales overlying the Cardium Formation in the plains. The Marshybank Member is of Early Santonian age and is equivalent to undifferentiated Colorado Shales in the plains (Plint, 1990; 1991; Plint *et al.*, 1990) while the Dowling member is Early to Middle Santonian (Stott, 1963) and is equivalent to the Medicine Hat Formation over the Sweetgrass Arch and the undifferentiated shales of the Colorado Group in the plains (Schröder-Adams *et al.*, 1997). The Thistle Member is of Mid- to Late Santonian age (Stott, 1963) and is known as the First White Speckled Shale in the plains. The Hanson Member is of latest Santonian age (Stott, 1963) and in the plains its equivalents are the Lea Park and Milk River Formations.

Biostratigraphic nomenclature

Micropaleontological studies have been carried out throughout the Cretaceous strata of the WCSB. Although foraminiferal ranges are not as age-diagnostic as those of ammonite and mollusc taxa, foraminifera tend to be more

widespread and are easier to recover from small subsurface core samples. For this reason detailed foraminiferal biozones are extremely useful in the subsurface (Figure 5). The Colorado Group has recently been extensively re-investigated to describe shale units which remained formally undescribed until recently (Bloch *et al.*, 1993; Schröder-Adams *et al.*, 1996). Wall (1967a) established foraminiferal zones for the Rocky Mountain Foothills and his work remains the only published literature for the southern foothills. In the northern foothills (especially around the Peace River area) detailed foraminiferal zonations were established by Stelck (1975; 1991), Stelck and Hedinger (1983), Stelck and Wall (1954; 1955), Stelck *et al.* (1956; 1958), Stelck and Koke (1987), Koke and Stelck (1984, 1985) and Caldwell *et al.* (1978; 1993). Tappan (1957; 1962) established foraminiferal biostratigraphy for the Alaskan slope. In the southern plains of Alberta and Saskatchewan, a foraminiferal biostratigraphic framework was established by North and Caldwell (1975a, b), McNeil and Caldwell (1981), Bloch *et al.* (1993) and Schröder-Adams *et al.* (1996).

No nannofossil biozones exist for the northern portion of the Western Interior Seaway. Macrofossil zones are extensive in the basin and offer better time constraints than foraminiferal zones (Jeletzky, 1968; 1971; 1977; Wall and Germundson, 1961; 1963; Kauffman, 1969; 1977; 1984).

Stratigraphic Units (this study)	Stage	(Wall, 1967a)	(Caldwell et al., 1978) (Bloch et al., 1993)	(North & Caldwell, 1964) (Caldwell et al., 1978)	(McNeil & Caldwell, 1981)
ALBERTA GROUP	CAMPANIAN	Rocky Mountain Foothills	Southern Alberta Plains	Saskatchewan	Manitoba Escarpment
		<i>Trochammina</i> <i>absolonensis</i>	<i>Haplophragmoides</i> <i>kiki</i>	<i>Haplophragmoides</i> <i>kiki</i>	<i>Trochammina</i> <i>absolonensis</i>
		Upper Pelagic			
		<i>Atoma</i> <i>inoides</i> <i>hannasili</i>	<i>Globgerinelloides</i> sp.	<i>Globgerinelloides</i> sp.	<i>Globgerinelloides</i> sp.
		<i>Brachycythere</i> <i>Bullopora</i>			
	SANTONIAN	<i>Trochammina</i> sp.	<i>Trochammina</i> sp.		<i>Trochammina</i> sp.
	CONIACIAN	<i>Pseudobulavulina</i> sp.	<i>Pseudobulavulina</i> sp.		<i>Pseudobulavulina</i> sp.
	TURONIAN	Lower pelagic microfauna	<i>Hedbergella</i> <i>loetterlei</i>	<i>Hedbergella</i> <i>loetterlei</i>	<i>Hedbergella</i> <i>loetterlei</i>
	CENOMANIAN	<i>Verneuilinoides</i> <i>kansasensis</i>	<i>Verneuilinoides</i> <i>perplexus</i>	<i>Verneuilinoides</i> <i>perplexus</i>	<i>Verneuilinoides</i> <i>perplexus</i>
			Barren	Barren	
	ALBIAN	<i>Millammina</i> <i>manitobensis</i>	<i>Millammina</i> <i>manitobensis</i>	<i>Millammina</i> <i>manitobensis</i>	<i>Millammina</i> <i>manitobensis</i>

Figure 5. Correlation of foraminiferal biozones across the Western Canada Sedimentary Basin. (*Verneuilinoides kansasensis* is placed in synonymy with *Verneuilinoides perplexus*. The *Brachycythere-Bullopora* is a combined ostracod and foraminiferal biozone).

METHODS

A preliminary field excursion was conducted in 1996 to establish the feasibility of using this section for this investigation. During the following summer of 1997 I returned to the outcrop and during the course of a three-week field season I measured and described the entire section of Upper Alberta Group sediments exposed along Mill Creek. The measured section includes sedimentological information including lithology, structural disturbances, mineralogy (where discernible), sedimentary structures and presence of macrofossils and trace fossils. Sampling was completed at regular intervals (every 2-5 m) with increased frequency near lithological boundaries and significant bentonite and macrofossil beds. Concretionary layers were sampled where encountered and studied in detail. Concretions were selected based on their size (generally less than 30 cm long axis) and completeness.

Concretions were slabbed and thin-sectioned. Thin sections were not covered to allow for later staining with Alizarin Red S and Potassium ferrocyanide. Standard petrography and photography were performed on unstained and stained thin sections. Thin sections were also examined via cathodoluminescence (CL). Selected sections were coated with Au-Pd and viewed under the SEM. XRD analysis was performed on three samples pertaining to sample 395.07 m. Carbonate bomb runs were conducted, on both concretionary samples and on their shale host rocks, according to the method described by Muller and Gastner (1971). CO₂ partial pressure readings were taken at 15 seconds, 5 minutes, 10 minutes and 15 minutes. Fast-reacting

carbonate was assumed to be all calcite and slow-reacting carbonate was assumed to be siderite since no dolomite was seen in thin sections.

Rock classification was modified from Potter *et al.* (1980) and Tucker (1982). Fine-grained, clay-rich rocks were subdivided into siltstones and shales with silt percentages estimated in the field.

Micropaleontological samples were processed by a modified method after Wall (1967a). Samples were crushed and then repeatedly frozen, in detergent, overnight and thawed rapidly in the microwave. Most samples disaggregated quickly by this method. Samples that did not respond to this treatment were further processed in a 30% hydrogen peroxide bath to remove organic matter and further disaggregate rock particles. Residues were washed, over a 63 μm sieve, under tap water to remove unreacted reagents. The residues were then dried in an oven and size-fractioned. Foraminifera were picked for identification. Volumes of picked residues varied with foraminiferal abundances. Foraminiferal populations and faunal preservation varied widely from sample to sample therefore numerical analysis was not feasible. Foraminifera were identified to at least the family level, with most specimens being identified to either the genus or species level. In addition to foraminiferal data, estimates of bivalve fragments, fish remains and other organic particles are included in Appendix 1.

Electron micrograph images and elemental analyses of foraminiferal tests were carried out on a JOEL 6400 scanning electron microscope (SEM) at the Carleton University Research Facility for Electron Microscopy. Picked

foraminiferal specimens were mounted onto SEM stubs and coated with Au/Pd. Thin-sectioned foraminifera were mounted, in epoxy, in brass rings. Tests were sanded down using fine sand papers and then polished. Ultrasound cleaning was done to remove residual epoxy from the tests. The mounted foraminifera were then carbon-coated for analysis.

Nannofossil samples were prepared and examined by Jim Craig, paleontological consultant (Bragg Creek, Alberta). These samples were processed according to the method described by Barss and Williams (1973). Data were collected from 200 views per slide using a light microscope. Nannofossil abundances are listed in Appendix 2.

Macrofossils were collected in the field. Specimens were sent to the Geological Survey of Canada in Vancouver, for identification by Dr. Jim Haggart. The specimens were entered into a permanent collection in Vancouver. Identifications are listed in Appendix 3.

Rock-Eval pyrolysis was performed at the Geological Survey of Canada (Calgary) on a DELSI Rock-Eval II/TOC apparatus. Samples were pulverized and processed according to the standards laid out in Peters (1986), Espitalié *et al.* (1977) and Macauley *et al.*, (1985). Organic geochemical data are listed in Appendix 4.

RESULTS

Lithological Descriptions

Stratigraphic measurements from this study differ from those of Wall (1967a) who did not include a stratigraphic column of his measurements. It has, therefore, not been possible to reconcile these differences. Some of these differences may be due to the structurally disturbed nature of the outcrop while others may be due to the difficulty in distinguishing between some members in outcrop. The measurements for each member are listed in Table 1.

The concretions mentioned below can be divided into two types: a) concretionary layers occurring predominantly in the Blackstone Formation, and b) concretions occurring in the Wapiabi Formation. Concretionary layers are beds of coarser-grained siliciclastics than the background sediment (typically silt-sized particles) and have been cemented with calcite, late in their depositional history. Concretions are oblate or discoidal in shape and are distinct entities that can be extracted from the background shales.

Crowsnest Formation

The Albian Crowsnest Formation is equivalent to the upper part of the Blairmore Group (Norris, 1993) and is an isolated package of volcanic rocks that only outcrops in the southern Foothills of Alberta, south of the Oldman River (Mellon and Wall, 1967). On geological maps of the Beaver Mines area (Norris, 1993), this unit is not placed within the Blairmore Group although it is recognized to interfinger with the Mill Creek Formation of the Blairmore Group (Leckie and Krystinik, 1995; Adair and Burwash, 1996). Stratigraphers have,

Member/ Formation	Wall (1967a) measurements	Thicknesses from this study
Sunkay Member	80 ft. (24 m)	14 m
Vimy Member	260 ft. (79 m)	31m
Haven Member	160 ft. (48 m)(with Opabin Member)	38 m
Haven Member (repeated)	--	31.5 m
Opabin Member	160 ft. (48 m) with Haven Member	29 m
Opabin Member (repeated)	--	9 m
Cardium Formation	Not reported	10 m
Muskiki Member	183 ft. (53 m)	17 m
Marshybank Member	160 ft. (48 m)	29 m
Dowling Member	297 ft. (89 m)	21.3 m
Thistle Member	505 ft. (151 m)	39.8 m
Hanson Member	435 ft. (130 m)	--

Table 1. Comparison of stratigraphic thickness measured in this study versus those reported by Wall (1967a).

however, decided that the unit is a distinct, mappable unit and have therefore raised it to formational status. The Crowsnest Formation is age-equivalent to the Bow Island and Viking Formations of the Colorado Group (Mellon and Wall, 1967). Measurement of the studied section was arbitrarily begun at a prominent pebble conglomerate located 14 m below the Blairmore Group/Sunkay Member contact.

The Crowsnest Formation consists of interbedded upward-fining matrix-supported pebble agglomerates and bentonites. The agglomeratic beds tend to have irregular to scoured bottom contacts and resemble pyroclastic flows (Norris, 1993). Within this unit there are also clay-rich, rubbly, green and maroon, laminated mud beds with pebbles. These beds are disturbed in this outcrop and bedding is difficult to follow laterally due to its pinch-and-swell structure. The thickness of this unit was not determined at Mill Creek. At Mill Creek the topmost bed of the Crowsnest Formation is a fault breccia that occurs along a fault separating it from the overlying unit.

No fossils were visible in the measured Crowsnest Formation of the section although plant impressions were visible stratigraphically below the measured section and pollen was reported from within this unit and from the interfingering Blairmore Group (Mellon and Wall, 1963; 1967).

Blackstone Formation, Sunkay Member

At Mill Creek, the Sunkay Member overlies the Blairmore Group unconformably. The unit is extensively structurally disturbed and a true

thickness cannot be assessed. At this particular location the unit was estimated to be 14 m thick.

The Sunkay Member is made up of dark gray, interbedded non-calcareous shales and slightly to moderately calcareous siltstones (Figure 6a & 6b). Rusty weathering is diagnostic of this unit in outcrop. Shales are fissile although they tend to crumble as the amount of silt and the degree of structural deformation increases. Shales are interbedded with 1 to 2 cm thick siltstone. The Sunkay Member contains an uppermost shale layer overlain by a 7 cm granular- to pebble-sized, lag of disarticulated skeletal fish debris. A gray calcareous shale bed of the Vimy Member overlies the Sunkay Member along a fault plane, occurring along a structurally thickened bentonite that forms the base of the overlying Vimy Member (Figure 7).

Bioturbation is negligible to low in the exposed Sunkay Member at the Mill Creek outcrop. This unit appears to be barren of macrofossils. Concretions are absent from the Sunkay Member and no oil odour or shows are associated with this unit.

Vimy Member

The Vimy Member is well exposed along Mill Creek and is 40.3 m thick with parts of the unit being structurally disturbed. A minor shear zone also occurs at 58.4 m.

The lower boundary of the Vimy Member is faulted at Mill Creek. The basal Vimy Member is marked by a thick (1.9 m), regionally-correlative bentonite unit overlain by slightly calcareous fissile shales (Bloch *et al.*, 1993).

Figure 6a. Sunkay Member of the Blackstone Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Blackstone Formation SUNKAY MEMBER

HI(mg HC/g C_{org}) **TOC**

(wt. %)

**ENVIRONMENTAL
INTERPRETATION**

- Shallow water environment (near 50 m water depth)
- Sublittoral zone
- Dysoxic bottom conditions
- Low energy conditions

Figure 6b. Legend of symbols used on all sections.

Figure 7. Contact between the Sunkay and Vimy Members. The lithology of these units is distinctly different. The Sunkay Member contains black rubbly shales while the overlying Vimy Member is composed of whitish grey weathering, platy shales.

Figure 8. Outcrop photo of the Upper Vimy Member . Small shears are found throughout this part of the unit.

These shales grade into the grayish-white weathering, fissile calcareous shales interbedded with silty shales and siltstones (Figures 8, 9) that characterize the Vimy Member in the Rocky Mountain Foothills (Stott, 1963). Some of the siltstones at Mill Creek contain abundant fecal pellets (Goodman, 1951; Wall, 1967a) and this gives them the “white speckled” appearance (J. Craig, pers. comm., 1998). Graded millimetre-thick siltstone laminae, containing broken, randomly oriented macrofossil fragments, occur in the middle of this member (Figure 10). Shales contain impressions of intact ammonites and bivalves (Figure 11). At least twelve bentonites, ranging from 1 mm to 15 cm thick, occur within the Vimy Member (Figure 12).

This member contains siltstone beds of concretionary limestone that pinch and swell. These have cross-laminae and ripple-structures. Fresh surfaces give off strong hydrocarbon odours. Carbonate bomb runs indicate these beds contain up to 11% calcite. Thin sections reveal that these beds are composed of calcite-cemented silt-sized quartz and feldspar grains together with sparsely distributed calcitic grains.

The contact between the Vimy and Haven members is gradational between the more calcareous shales of the Vimy and the non-calcareous shales of the Haven, and has been placed at 63 m (Figure 9).

Bioturbation is minimal in most of the Vimy. Small fragments of disarticulated skeletal fish debris are also abundant in the Vimy Member occurring mostly on the tops of rippled siltstone beds.

Figure 9. Vimy Member of the Blackstone Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Blackstone Formation VIMY MEMBER

Benthic Foraminifera Abundances (Absolute Number)

Planktic Foraminifera Abundances (Absolute Number)

Calcareous Nannofossil Abundances

(Absolute Number)

HI

(mg HC/g C_{org})

TOC

(wt. %)

ENVIRONMENTAL INTERPRETATION

- ≈ 100 m water depth
- Sublittoral to outer shelfal
- Dysoxic to anoxic bottom conditions
- Moderate energy conditions with storm surges

Figure 10. Storm bed in the Vimy Member at 42.14 m. Note the rippled surface of this silt bed contains large quantities of fossil hash composed predominantly of broken ammonite and *Inoceramus* shells.

Figure 11. Fossil horizons such as this one at 42.10 m are common throughout the Vimy Member. Typically the fossil assemblages are dominated by ammonites and *Inoceramus* casts.

Figure 12. Bentonites are abundant in the Upper Vimy Member. These bentonites are often structurally thickened and vary in thickness laterally. Bentonites range from millimetre-scale to a few centimetres in thickness.

Figure 13. Close up of shale beds in the Vimy Member (~40m). Note the platy nature of the shales.

Haven Member

At Mill Creek the Haven Member is 36 m thick. Figures 14 and 15 show the exposure of this member at Mill Creek. The calcareous shales of the Vimy Member grade into the non-calcareous, rusty shales of the Haven Member (Figure 16). Thus it is difficult to specify a lowermost boundary for this unit based on lithology. The upper contact coincides with the top of a coarsening-upward cycle (Figure 14). The overlying Opabin Member is differentiated from the Haven by the presence of siderite concretions (Stott, 1963).

Overall the Haven Member comprises a series of coarsening-upward sequences of interbedded shales, silty shales and rippled siltstones (Figures 17, 18). The dark gray shales are fissile and interbedded with ~10% siltstones. The siltstone interbeds are generally 1-3 cm thick and some are concretionary or cemented with calcite similar to those of the Vimy Member. The siltstones can be internally parallel-laminated while the concretionary layers tend to be rippled. As a whole the member coarsens upward in cycles. Fish debris layers occur generally on the top surfaces of rippled siltstone beds (Figure 19, 20). At 73.30 m, a coarsening-upward cycle ends with a very fine sandstone bed. Concretions occur and in places make up ~30% of the rock outcrop. Concretion frequency increases upsection. Fresh surfaces of concretionary layers, when broken, give off a hydrocarbon odour. Nine 1-2 cm thick bentonites occur in the middle to upper parts of this unit and numerous mm-scale bentonites are dispersed throughout.

Figure 14. Haven Member of the Blackstone Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Blackstone Formation HAVEN MEMBER

SAMPLES (m)

Benthic Foraminiferal Abundances

(Absolute numbers)

**ENVIRONMENTAL³²
INTERPRETATION**

- Shallow water conditions
- Sublittoral
- Dysoxic to somewhat oxic bottom conditions
- Moderately high energy conditions
- Overall upward shallowing sequence

Figure 15. Repeated part of the Haven Member of the Blackstone Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Blackstone Formation HAVEN MEMBER (REPEATED)

HI

(mg HC/g C_{org})

TOC

(wt. %)

ENVIRONMENTAL INTERPRETATION

- Shallow water (<100 m)
- Sublittoral
- Proximal to nearshore
- Oxic bottom conditions
- Overall upward shallowing sequence in the bottom part of this unit
- Upper part of sequence is an upward fining sequence
- Moderate to high energy conditions indicated by rippled sandstone beds

Figure 16. Outcrop of the Lower Haven Member. Contact is indicated by arrow.

Figure 17. Typical centimetre thick siltstone beds are interbedded with thin shale beds in the Haven Member. Silt stone beds are wavy with little internal lamination.

Figure 18. Rippled sandstone bed at 81 m in the Haven Member. Fish debris occurs on the surface of the ripples.

Figure 19. Close up of interbedded shales and siltstones in the Haven Member. Note the pinch and swell nature of some of the beds.

Figure 20. (Above) Interbedded siltstone and rippled sandstone beds in the repeated Haven Member (at 257 m).

Figure 21. (Left) Cardium Formation outcrop from base of unit (arrow). Note the thick sandstone beds are hummocky cross-stratified.

This unit is heavily bioturbated and horizontal burrows are common to abundant in some places resulting in a more crumbly texture. Macrofossils are scarce and are mostly concentrated near the lower contact with the Vimy Member.

Opabin Member

The thickness of the Opabin Member at Mill Creek is difficult to estimate due to the structural deformation and thrusting that affected in the upper part of the member. Underlying the disturbed intervals are 29 m of undisturbed outcrop from the lower Opabin Member.

The base of this unit is placed at the base of the first siderite concretionary layer occurring at the top of a coarsening-upward cycle in the Haven Member. The top of the unit is extremely structurally disturbed and a covered interval follows (Figure 22). However, the Opabin outcrops again as a repeat of 9 m further upstream (Figure 23).

The Opabin Member is, overall, a coarsening-upward shale to fine sand unit. Shales are non-calcareous and are characteristically rusty due to extensive weathering and the presence of iron in the system. Fresh surfaces reveal dark gray, rubbly, silty shales that are interbedded with siltstones and contain siderite concretions. These siltstones are 1 to 2 cm thick and beds commonly have rippled tops although they tend to show no internal lamination. The shales in the lower part of this unit are only moderately bioturbated. The unit coarsens upward into sandstone beds near the contact with the overlying Cardium Formation. It contains abundant siderite concretions throughout and

Figure 22. Opabin Member of the Blackstone Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Blackstone Formation

OPABIN MEMBER

HI
(mg HC/g C_{org})

TOC
(wt. %)

ENVIRONMENTAL INTERPRETATION

- Shallow water (between 50-100 m water depth)
- Sublittoral
- Oxidic bottom conditions
- Energy conditions are moderate to low

Figure 23. Repeated part of the Opabin Member of the Blackstone Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Blackstone Formation OPABIN MEMBER (REPEATED)

ENVIRONMENTAL INTERPRETATION

- Shallow water reaching ≈ 50 m near top of unit
- Nearshore sublittoral
- Upward shallowing sequence
- High energy conditions
- Oxidic bottom conditions

rare dolomite concretions (that were not sampled) in the lower part of the unit. The sandstones are heavily bioturbated.

The Opabin Member is easily distinguished from the underlying Haven Member due to its distinct siderite concretions. These concretions occur both as distinct oblate forms, occurring along bedding-parallel horizons, and as continuous concretionary layers. Siderite concretions are more common towards the top of the unit, towards the Cardium sandstones. Fresh surfaces in these concretions give off heavy hydrocarbon odour. Dolomite concretions also occur, though less commonly than siderite concretions, near the structurally disturbed top of the lower part of this unit, and were not sampled.

Macrofossils are scarce in the Opabin Member at this particular locale although ammonites occur rarely. Disarticulated skeletal fish debris is seen infrequently on bedding surfaces.

Cardium Formation

The Cardium Formation is extensive along the western margin of the WCSB (Plint, 1990; 1991; Walker, 1983; 1988). In the southern foothills of Alberta it is represented by laterally extensive sandstone units (Walker, 1983; 1988). At Mill Creek, the Cardium Formation is 10.2 metres thick. Wall (1967a) did not report a thickness for this unit (Table 1).

The underlying Opabin Member coarsens upward into this sandstone, unit forming a relatively gradational contact (Figure 21) . The Cardium Formation (Figure 24) is composed of a clean, white, fine to medium-grained quartz sandstone whose weathered surface is buff-coloured. Some coarse-

Figure 24. Cardium Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

CARDIUM FORMATION

ENVIRONMENTAL INTERPRETATION

- Shallow water (≤ 50 m)
- Shorline/nearshore
- Oxidic bottom conditions
- High energy/turbulent conditions

grained sandstone beds are interbedded with siderite near the top of the unit (Figure 25, 26). Beds are generally 3 to > 50 cm thick and show hummocky cross-stratification. Overall the unit coarsens upward, culminating in a pebbly to granular sandstone bed (Figure 27). This unit is not well exposed and is difficult to follow laterally due to the orientation of bedding in the outcrop. The upper contact of the Cardium occurs at the top of a siderite concretion layer that is very poorly exposed. Above this horizon the sandy siltstones and shales of the Muskiki Member of the Wapiabi Formation prevail.

The Cardium Formation contains large (diameters >50 cm), spherical to oblate, siderite concretions in the lower part, with more laterally continuous siderite layers in the upper part of the unit. These concretions are persistent throughout the unit and most abundant at the top of the unit.

Bioturbation is very intense in the Cardium Formation and ichnofossils can be seen both on bedding surfaces and cross-cutting bedding.

Wapiabi Formation, Muskiki Member

This member is poorly exposed along structural strike with extensive, scree covering much of the outcrop, but it is estimated to be 19 metres thick. The lower contact between the Cardium and Wapiabi formations is difficult to discern as much of it is covered. Below the contact sandstones predominate and above the contact siltstones and shales make up the majority of the rock. The contact is placed at the top of a continuous siderite concretion layer. The Muskiki Member is composed of non-calcareous, rusty-weathered, dark gray interbeds of siltstones and silty shales (Figure 28, 29). The Muskiki can be

Figure 25. (Above) Rippled sandstone beds within the Cardium Formation (307 m).

Figure 26. (Left) Siderite layers are interbedded with sandstones in the Upper Cardium Formation (316 m).

Figure 27. Mud clast/pebble conglomerate layer at the top of the Cardium Formation (316.7 m). This bed is interpreted to be a transgressive lag deposit.

Figure 28. Close up of the interbedded siltstones and thin shale beds in the Muskiki Member. Beds are rubbly and weather a rusty colour.

Figure 29. Muskiki Member of the Wapiabi Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Wapiabi Formation MUSKIKI MEMBER

HI
(mg HC/g C_{org})

TOC
(wt. %)

ENVIRONMENTAL INTERPRETATION

- Very shallow water
- Sublittoral/Nearshore
- High energy conditions
- Fairly oxic bottom conditions

summarized as a basal, fining-upward sequence of siltstones and silty shales that then coarsens upward into siltstones with minor fine sandstone interbeds occurring in places (Figure 29). Beds tend to show no internal lamination due to extensive bioturbation and as a result appear very rubbly to crumbly. Some siltstone beds appear to be wave ripple-laminated. The upper contact of the Muskiki Member with the Marshybank Member is gradational and has been placed at the top of the uppermost coarsening-upward cycle.

Layers of siderite concretions occur parallel to bedding throughout this member. No hydrocarbon staining is noted in association with these concretions. Concretions contained abundant framboidal pyrite as seen under the SEM.

This member is heavily bioturbated resulting in a very crumbly appearance. No macrofauna were recovered.

Marshybank Member

At Mill Creek the Marshybank Member is poorly exposed with a measured thickness of 28.8 metres. The Marshybank Member gradationally overlies the Muskiki Member. The Marshybank Member (Figure 30) begins above the uppermost sandstone bed associated with the last coarsening-upward cycle of the Muskiki Member. It is composed chiefly of non-calcareous black shale and shaly siltstone interbeds that coarsen upward near its base and then remain silty throughout the rest of the unit. These shales and shaly siltstones are typically rusty due to weathering. Interbeds are thin (0.5 to 2 cm thick) and siltstones make up 35-40% of the rock. Millimetre-thick shale

Figure 30. Marshybank Member of the Wapiabi Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Wapiabi Formation

MARSHYBANK MEMBER

SAMPLES (m)

Benthic Foraminiferal Abundances

(Absolute numbers)

HI
(mg HC/g C_{org})

TOC
(wt. %)

**ENVIRONMENTAL
INTERPRETATION**

- Shallow water (between 50-100 m maximum)
- Nearshore to proximal sublittoral
- Oxic to dysoxic bottom conditions
- Moderate energy conditions

laminae tend to be rubbly although they become platier upsection. Silt content increases upsection. Four widely separated thin (mm-scale) bentonites occur in the member. Siltstone beds tend to be lenticular or wave ripple-laminated. The upper contact of this member is gradational with the overlying Dowling Member and is placed at the base of the first siderite concretions of the Dowling Member.

Small limestone concretions (8-15 cm diameter) occur in layers parallel to bedding. Near the top of the member concretionary limestone layers are seen. No hydrocarbon staining was observed.

Bioturbation is intense at the base of this unit and decreases upward to moderate in the upper parts of the member. Macrofossils are rare in the Marshybank although some *Inoceramus* were found at 347.2 metres. Fish debris is absent from this member.

Dowling Member

The Dowling is not very well exposed along Mill Creek and is 21.3 metres thick. Its lower contact with the Marshybank Member is gradational and is placed at the first appearance of abundant concretion horizons. The Dowling Member is composed of interbedded non-calcareous, black shales and silty shales that coarsen upward into sandstone beds (Figure 31). These beds are non-calcareous black shales and siltstones with only moderate rusty weathering. Shales make up ~80% of the lower part of this member and break concoidally with no internal laminations visible. Upsection, beds become more massive and shales give way to siltstone beds. Interbeds of grayish-white, non-calcareous, rubbly, silty shale begin about half-way through the member and by

Figure 31. Dowling Member of the Wapiabi Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Wapiabi Formation

DOWLING MEMBER

HI
(mg HC/g C_{org})

TOC
(wt. %)

ENVIRONMENTAL INTERPRETATION

- Water shallowing upsection
- Proximal sublittoral setting
- Overall upward shallowing sequence
- Oxic to dysoxic bottom conditions
- Moderate to high energy conditions

376 m the unit is very silty (60%). At 381.3 m siltstone becomes interbedded with centimetre-thick, lenticular beds of very fine, rubbly sandstone. Three bentonites (~5 cm thick) occur in the Dowling Member. The upper contact of the Dowling Member is gradational with the Thistle Member and is placed at the first appearance of bentonite beds that are abundant in the overlying unit; it coincides with the disappearance of sandbeds.

The Dowling Member contains abundant small (10-15 cm diameter), round, limestone concretions that occur in layers parallel to bedding near the base of the unit. The concretions become more abundant upsection and show evidence of siderite composition (rusty outer rind). The concretions increase in size (diameter 30-40 cm) upsection. Thin rusty concretionary layers (1 to 2 cm thick) with high limestone content (determined to be up to 30 % from carbonate bomb runs) begin around the middle of the unit and persist through to the top of the unit. Hydrocarbon odour is given off from fresh siderite concretionary surfaces above 380.75 m.

The shales of the Dowling Member are non-bioturbated near the base of this unit but further upsection horizontal burrows occur at 375.53 m and at 379.44 m. Bioturbation becomes heavy in the upper part of the member. *Inoceramus* casts have been recovered from concretions in this part of the section. Within shale beds, cross-sectional views of calcitic *Inoceramus* prisms are also visible.

Thistle Member

The Thistle Member is well exposed along Mill Creek and is 39.8 metres thick. The Thistle Member has a gradational contact with the underlying Dowling Member and is distinguished from it by the abundance of bentonites (Figure 32). This unit characteristically weathers a grayish white. At Mill Creek the Thistle Member is non-calcareous to slightly calcareous. The Thistle Member is a coarsening-upward silty shale unit. Shaly siltstone and siltstone are interbedded with layers containing large, oblate concretions which locally constitute up to 10% of the rock. Shales tend to be fissile to rubbly while siltstone beds are both wave ripple-laminated and parallel-laminated (Figures 33, 34, 35). This unit contains twenty-three bentonite beds ranging from mm-scale to tens of centimetres thick. Many of these bentonites are graded and their frequency increases upsection with the thickest bentonites occurring in the lower part of the section. Near the top of the section some fine sandstone beds are interbedded with fine siltstone and shale beds containing large *Inoceramus* prisms. The upper contact with the overlying Hanson Member of the Belly River Formation is gradational. It is marked by the upward disappearance of concretions and the reappearance of rusty weathered shales.

Siderite concretions occur along horizons and vary from small- (6-8 cm diameter) to medium-sized (25-30 cm diameter). The concretions contain calcite and strong hydrocarbon odours are released from fresh surfaces. Siderite concretions dominate the lower part of this member while limestone

Figure 32. Thistle Member of the Wapiabi Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Wapiabi Formation THISTLE MEMBER

Benthic Foraminiferal Abundances

HI(mg HC/g C_{org}) **TOC**

(wt. %)

ENVIRONMENTAL INTERPRETATION

- Shallow water with a maximum depth of <100 m
- Sublittoral inner shelf?
- Oxic bottom conditions
- Moderate to high energy conditions

Figure 33. Outcrop photo of the Thistle Member starting at ~385m. Note the whitish grey colour of the weathered shales that distinguishes this unit from the underlying Dowling Member. The unit contains numerous millimetre- to centimetre-thick bentonites.

Figure 34. Interbeds of siltstone and shale in the Thistle Member (402 m).

Figure 35. Parallel laminated shales interbedded with rippled siltstone in the Thistle Member at 417 m.

Figure 36. *Inoceramus* prisms within shale interbeds of the Hanson Member.

concretions are more abundant in the upper parts. Limestone concretionary layers (1-2 cm thick) pinch and swell and contain hydrocarbon stains.

Bioturbation is moderate throughout this unit with siltstones showing more bioturbation than shales. Vertical burrows are visible in some limestone layers. Ammonite and *Inoceramus* casts occur within concretions throughout this member. *Inoceramus* prisms are also commonly dispersed within shale beds.

Hanson Member

This unit is well exposed along Mill Creek. Only the basal 14.5 metres of the unit were measured. The base of the Hansen Member is gradational with the underlying Thistle Member of the Wapiabi Formation and is placed at the upward disappearance of bentonites and the reappearance of rusty weathering dark gray shales and silty shales (Figure 36, 37). This unit has a non-calcareous shaly lithology. Interbeds of shales (70%) and silty shales to siltstones (30%) are very finely parallel-laminated. Rare mm-thick bentonites occur in the base of the Hanson Member. Shales are fissile with some parallel- to rippled-laminated siltstone interbeds. Near the top of the measured section shales become more rubbly and contain larger quantities of siltstone. Mud drapes occur on rippled siltstone bedding surfaces. The upper contact of this unit is not included in this study.

Concretions occur in this unit although they are not very common in the measured section; they are extremely pervasive above the measured section.

Figure 37. Hanson Member of the Wapiabi Formation: micropaleontological and organic geochemical results are plotted against lithology and paleoenvironmental interpretation. Refer to figure 6b for detailed legend.

Wapiabi Formation

HANSON MEMBER

HI
(mg HC/g C_{org})

TOC
(wt. %)

ENVIRONMENTAL INTERPRETATION

- Shallow water (>50 m but less than 100 m)
- Proximal sublittoral setting
- Dysoxic bottom conditions
- Moderate to low energy conditions

Fresh concretionary surfaces release strong hydrocarbon odours and frequently break along fossil casts.

Bioturbation is moderate to somewhat heavy on bedding surfaces in the Hanson siltstones. Near the top of the measured section bioturbation drops to negligible. *Inoceramus* prisms are common throughout this unit. Many concretions contain ammonite and *Inoceramus* casts in the upper part of the measured section and above the measured section. Disarticulated skeletal fish remains are seen on bedding surfaces.

Lithological Description of Concretions

Concretions were studied to get a better understanding of the burial history and the conditions under which sediments were deposited. In this study, at times faunal components, that are no longer present in the host rock shales, are preserved within the concretions.

Fossil content

Many concretions found *in situ* contained complete body fossils of ammonites and *Inoceramus*. Thin sections of concretionary layers in the Vimy and Haven members revealed abundant phosphatic fish debris and calcareous foraminifera (Figure 38). Concretions, from the Dowling and Thistle members, contain both calcareous and agglutinated foraminifera (Figure 38). Concretions also contain abundant fish debris, bryozoans, gastropods, ostracods and infilled burrows (Figure 38). Foraminifera are infilled with framboidal pyrite and tests are well preserved internally and externally. Gastropod and ostracod shells are easily identifiable although recrystallization (and in some cases replacement) of

Figure 38. Photomicrographs of fossil material found within siderite concretions a) agglutinated foraminiferal test, probably *Ammobaculites* (450X); b) cluster of calcareous foraminiferal tests (450X); c) planktic foraminiferal test (*Heterohelix* sp.) (820X); d) unidentified ostracod shell (45X); e) gastropod shell (45X); f) bryozoan remains (450X); and g) fish debris within a sideritic matrix (45X).

the original material has occurred. Similar observations were made by Ludvigson *et al.* (1994) in Greenhorn-aged concretions from the eastern margins of the WIS.

Description

Concretionary layers are associated with the sediments of the Blackstone Formation and frequently show cross bedding and ripple lamination on their weathered surfaces. On fresh surfaces, however, the layers appeared completely crystalline. Commonly these beds are associated with storm deposits that contain abundant fossil debris. In thin section these are revealed to be predominantly composed of silt-sized grains of quartz and feldspars within a calcitic cement. Only minor amounts of pyrite are present in these layers and iron is otherwise poor (Appendix 5). Hydrocarbon volatiles are generally abundant, especially where these layers are cut by sets of calcite fractures.

Concretions are easily identified in the field due to their characteristic rusty, ellipsoidal to discoidal appearance. When a fresh surface is examined in the field it is difficult to identify any grains unless fossil fragments are present in the concretion. Concretions are composed of microcrystalline siderite with calcitic cements containing various amounts of iron. The concretions also contain significant concentrations of detrital sediments, frequently in zones, derived from the surrounding shale host rocks. Framboidal pyrite is also abundant in these concretions. Grains of both Fe-free calcite and Fe-rich calcite (identified by the characteristic polygonal cracking when stained) are seen within the framework of many concretions. Replacement calcite rims are seen

around quartz grains in the uppermost part of the section. Concretions are also very rich in hydrocarbons and when slabbed give off a strong hydrocarbon odour.

Analytical Results of Concretion Studies

Cathodoluminescence

Cathodoluminescence (CL) and fluorescence microscopy were performed on all thin sections except for samples 364.25 m (Marshybank Member) and 413.50 m (Thistle Member) which had been coated for scanning electron microscopy. Sample 392.41 (Thistle Member) showed some correlation between mineral luminescence under CL and mineral zonation of calcite grains. The areas of the thin section that were richer in pyrite and thereby poorer in carbonate minerals did not luminesce while zones very rich in carbonate matrix showed bright luminescence. Calcite veins also luminesced and showed zoning outward. All other thin sections contained disseminated luminescent carbonate grains. These grains were generally ~1% of the whole rock and could not be subdivided into any meaningful groupings.

Scanning Electron Microscopy

Two thin sections were studied under the scanning electron microscope (SEM): 364.25 m (Marshybank Member) and 413.50 m (Thistle Member). These samples were chosen because of their fossil content and their fine-grained matrix. The texture of sample 364.25 m was studied and revealed randomly oriented clay particles with framboidal pyrite growing between the platelets. Elemental Spectral Detection (ESD) analysis of the matrix revealed

that the primary composition of matrix is calcite and siderite. Silt-sized grains are predominantly quartz and clays are present. The shell of a gastropod within this concretion has been altered and is rich in barium (Appendix 5).

Sample 413.50 m (Thistle Member) contains agglutinated foraminifera. ESD analysis revealed that the tests are composed primarily of quartz and are infilled with pyrite. The surrounding sediments are composed of calcite and clay minerals (Appendix 5). SEM microscopy also revealed that this concretion formed before compaction of its host sediment, because the clay minerals are randomly oriented within the carbonate matrix.

XRD Analysis

XRD analysis was conducted only on one suite of concretionary samples, sample 384.66 m (Dowling Member) (see Appendix 5). An inner and an outer concretion sample were run as well as one for the surrounding host sediment. The shale was found to be composed primarily of quartz, muscovite and albite. The inner and outer concretion showed very similar spectra representing a mineral composition of quartz, calcite and siderite. The inner sample also showed a manganese peak which may be diagnostic of concretionary formation in anoxic conditions (Coleman, 1993). Unfortunately, due to problems with the XRD equipment, no more suites of samples could be run thus limiting data interpretation significantly.

Carbonate Bomb

Carbonate bomb data were run on all concretions and their host shales (Appendix 5). Shales, with the exception of sample 92.27 m (Haven Member),

contained little to no carbonate at all. Concretions contain between 30.6 % and 67.6 % total carbonate. In almost all samples the carbonate was more than 50% calcite with the remaining fraction composed of siderite.

Micropaleontology

All foraminiferal counts are in Appendix 1. Foraminiferal abundances are plotted against the lithology in Figures 5, 6, 13, 14, 21, 22, 23, 29, 30, 31, 32 and 36. Plates I and II show the most common taxa from this section.

No age assignments have been made based on the micropaleontological data due to the poor preservation of the assemblages and lack of key index species.

Blackstone Formation, Sunkay Member

The foraminiferal assemblages of the Sunkay Member have moderate species diversity and low abundance (Figure 6). In addition, these agglutinated faunae are poorly preserved and are highly pyritized. The assemblage includes *Verneuilinoides perplexus* (the index species for this member), *Trochammina* spp., *Verneuilinoides* spp., *Ammobaculites* spp., *Haplophragmoides* spp., *Spiroplectammina* spp., *Ammobaculites albertensis*, *Ammobaculites fragmentarius*, *Ammomarginulina lorangerae*, *Dorothia* spp., *Gaudryina spiritensis*, *Haplophragmoides crickmayi*, *Haplophragmoides rota*, *Miliammina* spp., *Trochammina rutherfordi* and *Verneuilina canadensis*.

Disarticulated fish debris is rare but present throughout the Sunkay Member. Rare individual and well rounded *Inoceramus* prisms are also present.

Vimy Member

The Vimy Member is characterized by a mixed agglutinated benthic and planktic foraminiferal fauna (Figure 9). The Vimy Member, by definition, begins with the first occurrence of planktic foraminifera, which occurs at 32.77 m at Mill Creek. Planktic foraminifera are less common in the basal part, dominate the middle part of the unit and slowly diminish in abundance towards the top of the unit. The planktic foraminifera consist primarily of *Hedbergella loetterlei* and *Hedbergella delrioensis* with rare occurrences of *Heterohelix globulosa* and *Heterohelix* spp. The abundance of agglutinated forms is reduced compared to the underlying Sunkay and the overlying Haven members but the species diversity remains moderate. The dominant agglutinated components of these assemblages are *Ammomarginulina* spp., *Haplophragmoides* spp., *Trochammina* spp., and *Verneuilinoides* spp. The planktic assemblage is diagnostic of the Turonian Greenhorn highstand throughout the basin (Schröder-Adams *et al.*, 1996).

Nannofossil identifications were provided by Jim Craig (Consultant, Bragg Creek, Alberta). Nannofossils are abundant in the lower Vimy Member and Appendix 2 lists the species by sample. Extensive evidence of carbonate dissolution in the upper Vimy samples was observed and therefore the lack of nannofossil remains may be biased by taphonomic processes (J. Craig, pers.

comm, 1998). Nannofossils first appear subsequent to planktic foraminifera at 34.46 m and their abundances peak at 35.03 m and to a lesser degree at 44.24 m. The last nannofossil appearance is at 47.50 m. Nannofossil assemblages are dominated by environmentally stress-resistant species such as *Biscutum constans*, *Eiffellithus turriseiffeli*, *Prediscosphaera cretacea*, *Watznaueria barnesae* and *Zygodiscus diplogrammus*. This assemblage is diagnostic of the Turonian age (Doeven, 1983). The nannofossils from these strata are characteristic of the Second White Specks Formation in the Interior Plains (Schröder-Adams *et al.*, 1996).

Haven Member

The Haven Member contains an agglutinated foraminiferal assemblage (Figure 14). In the lower part of this member the assemblage has moderate species diversity and low abundances while the assemblage in the upper (repeated part) Haven Member has a much higher species diversity and abundance. This assemblage is dominated by *Ammobaculites albertensis*, *Ammobaculites* spp., *Haplophragmoides* spp., *Spiroplectammina ammovitrea*, *Gaudryina spiritensis*, *Verneuilinoides* spp. and *Trochammina* spp. Less abundant components include *Spiroplectammina* spp., *Ammomarginulina* spp. *Ammobaculites fragmentarius*, *Haplophragmoides crickmayi*, and *Haplophragmoides rota*. A concretionary layer was sampled at 98.2 m and yielded an anomalously low foraminiferal population.

In the repeated section of the Haven Member agglutinated foraminiferal populations are highly diverse and very abundant (Figure 15). This exposure

also does not correspond well with the *Pseudoclavulina* sp. Zone designated for this time interval by Wall (1967a). The assemblage is dominated by *Ammobaculites* spp., *Ammobaculites fragmentarius*, *Ammobaculites albertensis*, *Ammomarginulina* spp., *Haplophragmoides crickmayi*, *Haplophragmoides* spp., *Spiroplectammina* spp., *Trochammina* spp., *Textularia* spp., *Verneuilioides* spp., *Verneuilioides bearpawensis* and *Verneuulina* spp. *Trochammina rutherfordi*, *Trochammina wettereii*, *Verneuulina canadensis*, *Dorothia* spp. and *Spiroplectammina ammovitrea* are also present in low number.

Opabin Member

The Opabin Member contains an abundant foraminiferal assemblage with a high species diversity. The upper part of this member (in the non-repeated part of the section) contains the highest number of foraminifera per sample in the section (Figure 22). The dominant taxa are *Ammobaculites fragmentarius*, *Dorothia* spp., *Gaudryina spiritensis*, *Haplophragmoides* spp., *Spiroplectammina* spp., *Trochammina* spp. and *Verneuilioides* spp. More minor components of this assemblage include *Trochammina rutherfordi*, *Verneuilioides bearpawensis*, *Textularia* spp., *Spiroplectammina ammovitrea*, *Reophax* spp., *Haplophragmoides crickmayi*, *Haplophragmoides howardense* and *Ammobaculites albertensis*.

The upper part of the Opabin Member is exposed just below the Cardium Formation and consists of upward coarsening cycles of shaly silt and sand beds. The species diversity of the foraminiferal assemblages decreases

upsection in these cycles (Figure 23). In the upper part of the Opabin Member (within the repeated section) the foraminiferal assemblages are dominated by *Ammobaculites* spp., *Haplophragmoides* spp., *Spiroplectammia* spp., *Trochammia* spp. and other unidentified specimens of the family ATAXOPHRAGMIIDAE. Minor components of the assemblage include *Spiroplectammia ammovitrea*, *Verneuilina* spp., *Verneuilinoides bearpawensis*, *Trochammia wettereii*, *Dorothia* spp. and *Ammobaculites albertensis*.

Cardium Formation

The sandstones of the Cardium Formation contain an impoverished agglutinated foraminiferal assemblage (Figure 24) including coarse-grained tests of *Ammobaculites*, *Trochammia*, *Verneuilinoides*, *Reophax* and *Textularia*, and other unidentified taxa of the families ATAXOPHRAGMIIDAE and LITUOLIDAE.

Wapiabi Formation, Muskiki Member

The Muskiki Member begins with a small upward-fining sequence followed by an overall upward-coarsening trend. In this member the foraminiferal species diversity and abundance decrease with increased grain size (Figure 29). The entirely agglutinated assemblage is dominated by the genera *Ammobaculites*, *Haplophragmoides*, *Trochammia* and *Verneuilinoides*, and other unidentified taxa of the families ATAXOPHRAGMIIDAE and LITUOLIDAE. Less abundant components of this fauna include

Ammobaculites albertensis, *Ammobaculites fragmentarius*, *Spiroplectammina* spp., *Verneuilina canadensis* and *Textularia* spp.

Marshybank Member

Species diversity is moderate and the foraminiferal abundances decrease in abundance upsection within the Marshybank Member (Figure 30). This unit is dominated by the family ATAXOPHRAGMIIDAE, with the genera *Ammobaculites* spp., *Haplophragmoides* spp., *Spiroplectammina* spp., *Trochammina* spp., *Textularia* spp., *Verneuilina* spp., *Verneulinoides* spp. and *Verneulinoides bearpawensis* being the most common. Less abundant but persistent components of this assemblage include *Ammobaculites albertensis*, *Ammobaculites fragmentarius*, *Dorothia* spp., *Spiroplectammina ammovitrea* and LITUOLIDAE. The highest abundance of foraminifera occurs at the base of this unit at 335.4 m.

Dowling Member

The microfaunal assemblages of the Dowling Member are composed of benthic agglutinated foraminifera. The species abundance is low and decreases upsection, through the overall upward-coarsening cycle, and culminates with the lowest number of foraminifera just below sandstone beds (Figure 31). The unit is dominated by unidentified taxa of the family ATAXOPHRAGMIIDAE, as well as by the species of the genera *Ammobaculites*, *Haplophragmoides*, and *Trochammina*. Also present in lesser numbers are *Verneulinoides* spp., *Verneuilina* spp., *Spiroplectammina* spp. and *Ammobaculites albertensis*.

Thistle Member

In this study no calcareous benthic foraminifera were found in the sediments of the Thistle member. The benthic agglutinated assemblage displays a high species diversity, and abundances in the Thistle Member are highest within the Wapiabi Formation members (Figure 32). Peak abundances occur in the middle of upward-coarsening cycles where shale beds are common (at 427.9 m and 431.3 m). The benthic agglutinated assemblage is dominated by *Ammobaculites* spp., *Haplophragmoides* spp., *Spiroplectamina* spp., *Trochammina* spp. and *Verneuilinoides* spp. Less common, but still persistent, in the Thistle Member are *Verneuilinoides bearpawensis*, *Verneuilina* spp., *Textularia* spp., *Spiroplectamina ammovitrea*, *Haplophragmoides crickmayi*, *Ammomarginulina lorangerae*, *Ammobaculites fragmentarius* and *Ammobaculites albertensis* as well as unidentified foraminifera belonging to the families ATAXOPHRAGMIIDAE and LITUOLIDAE. No planktic foraminifera were found in the shale samples but some pyrite-infilled *Heterohelix* were found within carbonate concretions from this unit at 387.27 and 413.50 m.

Samples prepared for nannofossils were barren and showed extensive evidence of carbonate dissolution (J. Craig, pers. comm., 1998).

Hanson Member

The samples from the Hanson Member yielded only benthic agglutinated foraminifera (Figure 37). The species diversity was moderate and the abundances were relatively low. These assemblages are dominated by

Ammobaculites spp., *Haplophragmoides* spp., *Trochammina* spp., *Spiroplectammina* spp. and *Textularia* spp. Also present in the assemblages were *Spiroplectammina ammovitrea*, *Ammobaculites fragmentarius*, *Ammobaculites albertensis*, *Verneuilina* spp., *Ammomarginulina lorangerae* and *Verneuilinoides bearpawensis*. The entire Hanson Member was not sampled, therefore no real trends can be seen from these samples.

Macropaleontology

The Vimy Member of the Blackstone Formation contains abundant beds containing macrofossils. Macrofossil identifications were provided by Jim Haggert of the Geological Survey of Canada (Vancouver). The most common individuals in these layers are *Collignonicerias woolgari*, *Mytiloides* sp., and *Mytiloides sybhercynicus* suggesting an age of early Middle Turonian for the Vimy Member. This age is confirmed by the presence of the *Hedbergella loetterlei* Zone. The macrofauna of the Opabin Member indicates an age of late Middle to Late Turonian and typically consists of *Plesiacanthoceras wyomingense* and *Collignonicerias woolgari*. *Cremnoceramus* sp. is found in the Dowling Member and is indicative of the Coniacian to Early Santonian. The Thistle Member yielded scaphitid ammonites that are indicative of the Late Cretaceous such as *Scaphites ventricosus* (J. Haggart, pers. comm., 1998). These taxa are illustrated on Plates III and IV. Appendix 3 contains a summary of the macrofossil data.

Geochemistry

Organic geochemical analysis was carried out on 35 samples distributed over the entire section. Inverse relationships exist between coarsening-upward cycles and total organic carbon (TOC) and hydrogen index (HI) values (Figure 39). Peak TOC and HI values (3.72 weight % and 409.0 mg HC/g C_{org}, respectively) occur in the Vimy Member at 35.03 m. This corresponds with the peak in nannofossil abundance. A second, smaller peak occurs in the Vimy Member at 57.66 m with a TOC value of 2.12 weight % and HI equal to 351 mg HC/g C_{org}. This second peak coincides with a sharp decrease in both benthic agglutinated and planktic foraminifera as well as nannofossil populations. A third minor peak is seen in the Thistle Member at 429.60 m. The TOC, at this height, is 1.48 weight % and the HI measures 205.50 mg HC/g C_{org}. This peak corresponds to a peak in benthic agglutinated foraminiferal fauna while nannofossils are absent (probably due to carbonate dissolution). All other organic geochemical data measure low TOC values (between 0.11 and 1.15 weight %) and low HI values (between 33.5 and 158.5 mg HC/g C_{org}).

Hydrogen Index vs. Oxygen Index plots reveal the types of organic carbon within the rock (Figure 40). The majority of the organic matter at Mill Creek is Type III (terrestrially derived). The organic matter in the Vimy Member, however, is a mixture of Type II and Type III indicating that varying amounts of both terrestrial and marine organics were deposited in this area during this time.

T_{max} values vary between 428°C and 443°C. A continuous section should have a similar burial history therefore one would not expect such a large

Figure 39. Complete measured section at Mill Creek: lithology is plotted against organic geochemical results. Refer to figure 6b for detailed legend.

HI

(mg HC/g Corg)

TOC

(wt %)

variation in Tmax values. Therefore these variations must be due to differences in the type of organic matter present in the rocks. The lower Tmax values occur in the Vimy Member where Type II, or more marine type, organic matter is present. Most of the Tmax values are around 435°C and indicate that the rocks were buried deep enough to be on the threshold of the oil window (Peters, 1986; Hunt, 1996).

The PI values for the Vimy Member are between 0.1 and 0.4 and this implies that rocks just to the west were mature source rocks (Figure 41). PI values for the rest of the section are generally below 0.1 with the exception of samples 97-40, 97-63 and 97-73 which all coincide with silt beds whose fresh surfaces give off a strong hydrocarbon smell. These beds probably represent preferred fluid pathways.

DISCUSSION

Taphonomy

Carbonate Dissolution

A discussion on the taphonomic grade of the fossil assemblages is necessary in order to follow the paleoenvironmental reconstruction discussed later in the text. It would appear that selective preservation has left a dominantly agglutinated foraminiferal fauna during times of sea-level highstand and these are quite different from what is found in the more eastern parts of the basin where planktic and benthic agglutinated foraminifera occur together with a minor calcareous benthic component (McNeil and Caldwell, 1981; Bloch *et al.*,

Figure 40. Hydrogen Index vs. Oxygen Index values indicate the type of organic matter present in each member of the Upper Colorado Group at Mill Creek. Most of the values fall within Type II organic matter, dominantly terrestrial in origin but the Vimy Member samples are a combination of Type II and Type III organic matter, indicating a mixture of marine and terrestrial organic matter.

Figure 41. Production Index (PI) vs. Maximum Temperature (Tmax) show how samples plot with respect to the Oil Window. Most samples plot well outside the oil window and are undermature. The samples plotting close to the oil window are from the Vimy Member.

1993; Schröder-Adams *et al.*, 1996; Simpson, 1975) and in foothills outcrops north of Mill Creek (C. Schröder-Adams, pers. comm., 1998; Wall, 1967a). The absence of calcareous benthic forms, however, cannot be assumed to be solely due to their absence at the time of sediment deposition but rather may be due to differential taphonomy. Selective preservation of foraminifera has been studied by Berger and Soutar (1970), Brandt (1989), Murray and Alve (1994) and Sidner and McKee (1975). The reasons for the absence of calcareous benthic and planktic foraminifera, and nannofossils from the Wapiabi Formation are believed to be threefold: 1) the study of nannofossils revealed signs of carbonate dissolution in both the Vimy and Thistle members (J. Craig, pers. comm, 1998). In foraminiferal samples, *Inoceramus* prisms were observed to be rounded rather than angular, which is interpreted as a sign of carbonate dissolution. These prisms are large objects with a low surface area to volume ratio. Smaller carbonate particles with much higher surface area to volume ratios, therefore, may have been completely dissolved thus biasing the fossil faunal content. Furthermore, planktic foraminifera were found within carbonate concretions (formed very early in the burial history of the sediment) in the Thistle Member but are absent from processed shale samples. 2) In addition, Wall (1967a) reports small numbers (1-9 for most genera, occasionally 10-99) of calcareous benthic and planktic foraminifera from both the Thistle Member and the Hanson Member, yet in this study none were recovered. Since calcareous specimens are rare and possibly occur in distinct concentration layers formed by currents (Brennan-Alpert, 1998), they could be easily missed during sample

collection. Conversely, this may be due to a "lumping" effect in Wall's (1967a) data presentation since all his individual sample data are not present but rather combined into one large data set for the entire member. 3) Finally, according to Hodgkinson (1991) strong concentrations (i.e. >10%) of hydrogen peroxide can destroy calcareous tests in highly pyritized samples. The planktic foraminifera found within the Thistle concretions are all completely infilled with pyrite and pyritized agglutinated foraminifera are common within the shale samples. Therefore if calcareous forms were present it is likely they were destroyed during processing since samples were placed in a 30% hydrogen peroxide bath. However, even if samples were reprocessed, the results would still have to be considered in conjunction with 2), the statistical probability of finding such low concentrations of calcareous benthics.

In addition, bioturbation can cause a taphonomic bias by eliminating calcareous foraminifera more readily than agglutinated foraminifera. This is because the calcareous foraminifera are more easily digested by other organisms (Berger and Soutar, 1970).

Elemental analysis of selected foraminifera indicate that a number of diagenetic processes have been at work in the Mill Creek section. The organic cement between grains is completely replaced with silica or iron oxides while the tests are usually infilled with iron oxides (indicative of anoxic sediment conditions) (Berner, 1970; Davis *et al.*, 1988; Stelck and Wall, 1955; Hedley, 1963). Calcareous planktic foraminifera are also infilled with pyrite (see Appendix 6). Most agglutinated foraminifera are highly silicified, strengthening

the test and enhancing its preservation potential. The presence of iron oxides, however, can weaken the test due to their chemical reaction potential (Hodgkinson, 1991).

It is also essential to remember that the faunal assemblage is biased by the robustness of the original tests (Denne and Sen Gupta, 1989). In moderately high to high energy conditions delicate tests may be transported and broken long before they have a chance to fossilize (Kaminski and Schröder, 1987). This is especially true in proximal settings where currents and storms may disrupt the sediment periodically. The tests seen in this study are all quite robust and may indicate that more delicate forms have been destroyed before fossilisation.

Concretionary layers

The mechanism by which concretions are formed is still highly controversial and many models have been put forward to explain the early formation of carbonate concretions in mudrocks (Bloch, 1990; Coleman, 1993; Gautier, 1982; Mozley, 1989 & 1996; Sellés-Martínez, 1996).

The concretionary layers, mostly found in the Vimy Member, are believed to have been deposited in a somewhat oxic environment. These layers were probably deposited near storm wave base since they are frequently associated with graded silt beds interpreted to be storm deposits. Concretionary layers are typically composed of silt-sized particles sandwiched between less permeable shales. In fact, these units are not true concretions but rather were "concretionized" subsequent to deposition and compaction (clay platelets are

aligned in a preferential plane when viewed under the SEM). Their coarser grain size allowed for preferential fluid flow through them thus cementing detrital grains together with calcite (J. Bloch, pers. comm., 1998). This system is relatively poor in iron, unlike the overlying formation, thus deposition probably occurred under more oxic conditions because iron is only deposited in reducing conditions. These concretionary layers behaved brittlely during the deformation of the foothills zone and as a consequence are cut by numerous sets of Fe-free calcite veins that must have been emplaced post-diagenetically.

Concretions

The concretions found in the Wapiabi Formation are “true” concretions. They contain an abundance of siderite and pyrite that is indicative of an anaerobic, microbially-mediated formational process. The abundance of pyrite is especially indicative of oxidation of organic matter under anoxic conditions within the sediment (Bloch, 1990). When organic-rich sediment undergoes sulphate reduction to produce dissolved HS^- , subsequent oxidation of organic matter proceeds via the following pathway:

Bicarbonate ions are thus produced on the surface of organic matter and encourage carbonate precipitation to nucleate preferentially around it. Similar pathways have been proposed by Coleman (1993) for iron reduction leading to the formation of microbially-mediated siderite:

In this reaction Fe_2^+ is released and able to bind with bicarbonate ions to produce siderite.

These reactions are thought to have occurred very shortly after deposition (Coleman, 1993), within the top few centimetres of the sediment, with siderite forming prior to compaction of sediment. When viewed under the SEM, some of the incorporated clays, in concretions, are randomly oriented, as they would be before compaction and deep burial. Once formed, the concretions appear to have been essentially unaltered diagenetically due to the impermeable nature of their siderite matrix.

It is interesting that calcite cements show multiple compositions that appear gradational in some places and distinct in others. These calcite cements indicate an increase in iron abundance through time and may also indicate increased anoxia at depth, during burial and compaction of sediments. Neither calcareous nor agglutinated foraminiferal tests, from within the shales, show similar iron enrichments or multiple stages of calcite cement development.

Paleoenvironment

This discussion on paleoenvironments begins with an overview of the different components that affected the measured section through time, and then follows with a discussion of the individual environments, by member.

Paleoecology and water depth

In reconstructing paleoenvironments of a sequence of rock, one often attempts to use modern analogues to interpret ancient conditions, or “the present is the key to the past”. During the Cretaceous global sea-level was

significantly higher than present and no polar ice caps existed. As a result, epicontinental seaways were common. Unfortunately no modern analogue exist (Hay *et al.*, 1993), however, the sediments in this study were deposited in a shallow, shelfal setting which can be compared to similar, modern environments (Hay *et al.*, 1993). Paleoecological information on ancient foraminifera is scarce if available at all and many Cretaceous workers in the WCSB have made inferences about ancient assemblages by comparing them to the recent (Stelck *et al.*, 1955; 1956; Stelck and Wall, 1954; 1955; Stelck, 1975; Stelck and Hedinger, 1983; Tappan, 1962; Leckie, 1987). As a consequence, it makes sense in this study to also base any paleoecological reconstructions on what is known about living representatives of the same genera, as well as on interpretations of other Cretaceous assemblages.

Murray (1973) discussed the ecology of living benthic foraminifera. He characterized the preferred living conditions of certain modern genera whose ancient counterparts occur in the assemblages at Mill Creek. These genera, however, may have a broader bathymetric range under favourable modern ecological circumstances. Murray indicate that *Trochammina* can be subdivided into two major groups: a) those that prefer hyposaline to hypersaline conditions in the intertidal to tidal marshes, and b) those that inhabit normal marine conditions from the shelf into bathyal depths. He reported that *Ammobaculites* prefer hyposaline conditions found in marshes, lagoons and the inner shelf while both *Textularia* and *Gaudryina* are shelf to upper bathyal forms that are typically found between 50 and 640 m water depth and these

observations are confirmed, for the Cretaceous, by Stelck (1975). Murray (1973) suggested that at shallow, inner shelf water depths (0-150 m) *Reophax* and *Saccamina* are common. *Miliammina* is associated with hyposaline to hypersaline conditions in marshes and estuaries. Figure 42 shows the preferred water depths of selected modern foraminifera which have ancient counterparts that are rare to dominant in the Mill Creek assemblages. Haig (1979a, b) reported that in the mid-Cretaceous of Australia, hyposaline, epicontinental seaway deposits contain the genera *Saccamina*, *Reophax*, *Miliammina*, *Haplophragmoides*, *Ammobaculites*, *Textularia*, *Pseudobolivina*, *Trochammina*, *Gaudryina*, *Verneuilina* and *Verneulinoides*, which agrees well with modern generic counterparts in shallow shelfal settings. Sliter and Baker (1972) reported on the bathymetric preferences of Cretaceous foraminifera in the La Jolla Basin, California. Most of their genera are calcareous but they report that *Gaudryina*, *Trochammina*, *Haplophragmoides* and *Spiroplectammina* are common in his inner-shelf fauna. His outer-shelf fauna includes the agglutinated genera *Gaudryina*, *Spiroplectammina*, *Dorothia* and *Trochammina*. Stelck and Wall (1955) reported that *Dorothia* is considered a shallow water genus and Stelck *et al.* (1958) report that the genera *Tritaxia*, *Trochammina* and *Saccamina* are indicative of shallow marine conditions. It is also important to note that the coarsely agglutinated nature of some foraminiferal tests is indicative of shallow water conditions (Stelck *et al.*, 1956; 1958; Tappan, 1962), a feature seen throughout the samples in this study. The absence of calcareous benthic foraminifera is

Figure 42. Bathymetric preferences of modern foraminiferal genera according to Murray (1973). Shaded area represents an overlap zone of preference for all genera and is interpreted at the range of water depths for the studied section.

believed to be due to fresher than normal marine salinities that reduced the amount of CaCO_3 in the water column (Tappan, 1962), as well as being indicative of cool water conditions (Stelck and Wall, 1955). Since we do not know much about the other common genera we can only assume that their preferred depth ranges overlap those of the known genera. Figure 42 shows that the sequence most likely was deposited water depths oscillated between 50 and 100 m. This corresponds to an inner shelf setting (Tappan, 1962), with assemblages containing and/or dominated by *Miliammina* and *Trochammina* indicative of shallower water depths, while assemblages containing abundant *Textularia* and *Gaudryina* should be indicative of deeper water depths. Similar interpretations are reported by Stelck (1975), Stelck and Hedinger (1983) and Stelck and Wall (1955) in the Albian-Cenomanian of northern Alberta.

Foraminifera are most abundant in the middle of upward-coarsening cycles and diminish as the sediment coarsens into sand-sized grains (figures 14, 23, 31 and 43). This corresponds with what Stelck and Wall (1955) found in the Lower Cretaceous of the Peace River Area and by Tappan (1962) in the Cretaceous of the Alaskan Slope. This may be due to three factors: a) with a relative drop in sea level, coastal erosion and therefore sediment input increases and foraminiferal populations are diluted at the top of each cycle; b) with progradation, coarser sediments are deposited further offshore and foraminifera prefer finer sediment grains for test agglutination; and c) generally coarser sediment grains prevail where higher energy conditions occur which also bring more oxygenation to the bottom. This makes for a less hospitable

living environment due to higher turbidity conditions, and it lowers preservation potential significantly.

Energy conditions

Based on lithological (dominance of shale and siltstone with some sandstone beds) and sedimentological evidence (bedforms are indicative of moderate to low energy conditions with occasional high energy conditions) (Figure 43), it would appear that the water depth was always ~50 m or more (i.e. below fairweather wave base) and perhaps even below storm wave base throughout the section, with the exception of the Cardium Formation which was deposited under the shallowest water conditions. If the water depths were extremely shallow (0-10 m) one would expect to see only a few genera present in any given sample (Tappan, 1962), therefore water depths were probably deeper and conditions were shelfal. This is demonstrated by the presence of mixed fine clastic materials (clays and silts) with only minor sand beds present sporadically through the section. Furthermore sediments were probably deposited at some distance from their source given that offshore surface currents kept planktic foraminiferal and nannofossil tests from being washed shoreward.

Salinity

Euryhaline foraminifera, although capable of thriving under normal marine salinity conditions, are at an advantage over stenohaline genera at times of variable salinity conditions. Figure 44 shows the range of tolerance for selected recent genera (Murray, 1973) which are also found in the Mill Creek

Figure 43. Complete measured section at Mill Creek: micropaleontological and organic geochemical results are plotted against lithology and interpreted sea-level curve. In foraminiferal abundances, closed circles indicated purely agglutinated assemblages while open circles indicate mixed planktic and benthic agglutinated assemblages. Refer to figure 6b for detailed legend.

HI
(mg HC/g Corg)

TOC
(wt %)

Relative Sea Level⁹⁶
← Fall Rise →

Figure 44. Salinity preferences of modern foraminiferal genera according to Murray (1973). Shaded area represents a range of "normal" marine salinities.

assemblages. When salinity varies, euryhaline genera tend to increase in abundance or even dominate the assemblage, depending on the severity of the salinity changes (Murray, 1973; Tappan, 1962). The modern analogue would suggest that euryhaline forms seen in the Mill Creek section are *Trochammina*, *Ammobaculites* and *Miliammina*. High numbers of these genera therefore, signal oscillations in salinity, though it cannot be discerned if these changes are increases or decreases in salinity. The likelihood, however, of above normal salinity under inner shelf conditions is remote. It would appear that the increase in these forms mainly signals increased freshwater input that probably resulted in a brackish water column. Small test size of these euryhaline forms is also interpreted as an indication of lower than normal salinities (Tappan, 1962) and most of the foraminifera in this study are quite small (between 63-125 μm , with most in the smaller end of this range). Furthermore for the Thistle and Hanson members, the lack of calcareous benthic foraminifera may be indicative of fresher than normal marine conditions that inhibit the precipitation of calcium carbonate tests in favour of chitinous tests that do not fossilize well (Tappan, 1962).

Water stratification

The lack of modern analogues for the Western Interior Seaway (WIS) makes a paleoenvironmental reconstruction problematic (Hay *et al.*, 1993). Many modern oceanographic analogues have been put forth to represent different aspects of this basin. The circulation of the WIS, during the Late Cretaceous, has been studied and modelled extensively. Recent models by

Sageman and Bina (1997) and Slingerland *et al.* (1996) have explored mixing processes between the cool Boreal waters and the warmer waters of the Tethys. It has been postulated that this would have resulted in extensive basinwide watermass stratification (Hay *et al.*, 1993; Jewell, 1993; Kyser *et al.*, 1993). This type of stratification is thought to lead to bottom water anoxia during periods of peak transgression and highstand. The idea of freshwater input, from terrestrial sources in more proximal settings, has been suggested as a means of forming either a freshwater or a brackish water lid that would also cause bottom anoxia in parts of the basin (Kauffman, 1977; Hay *et al.*, 1993; Slingerland *et al.*, 1996). Eicher and Diner (1985) have proposed a variation on the freshwater lid model in which stratification occurs during periods of high precipitation but during dry periods vertical mixing increases in more proximal zones and permits benthic organisms to thrive. They related these periods of increased vertical mixing of the water column with global highstands and maximum inundation of continental landmasses, which created large volumes of hypersaline waters in arid, low latitude areas. These hypersaline waters would sink and cause nutrient-laden waters to upwell and mixing would also occur. For the most part, however, these models have not been rigorously tested against existing sedimentological, biostratigraphic and geochemical data that could confirm or discard their results. The idea of a freshwater or brackish lid in the proximal parts of the basin is not confirmed by the data from this study. Such lids are assumed to lead to bottom anoxia but, in this proximal setting, anoxia is not seen in the fossil record although periods of extensive dysoxia are

interpreted for the Sunkay and Vimy members. Instead, freshwater input may have resulted in periods (for example during the deposition of the Thistle Member) during which the entire water column became brackish thus allowing euryhaline genera to survive and prosper at the exclusion of calcareous benthic foraminifera. In addition, watermass stratification did not occur in this proximal setting because of the turbidity and turbulence that is associated with shallow water, shelf settings.

In distal parts of the WIS water mass stratification was interpreted as the cause of the purely planktic foraminiferal assemblage associated with the sea-level highstands in the Turonian and the Santonian (Frerichs, 1980; Douglas, 1972; Stelck and Wall, 1954; Stelck *et al.*, 1956; McNeil and Caldwell, 1981; West *et al.*, 1998; Leckie *et al.*, 1998 and Leckie, 1987). At Mill Creek, a mixed agglutinated and planktic foraminiferal fauna exists in the Vimy Member while the assemblages in the Thistle Member are completely agglutinated. This is indicative that no true watermass stratification formed on these more proximal shelf settings. If watermass stratification formed then the agglutinated benthic fauna could not have survived much less thrived. Conditions may have oscillated from dominantly dysoxic to periodically more oxic conditions allowing the benthic communities to establish and survive the periods of dysoxia. These findings are similar to those described by Eicher and Diner (1985) in the Cretaceous Greenhorn Sea of Wyoming and Colorado. Disruption of watermass stratification in the proximal setting was probably due to five conditions: a) the shallower water depth, as compared to the deeper, more

eastern parts of the basin, did not permit true watermass stratification of Boreal and Tethyan waters to form due to the higher energy conditions along the margin; b) along the shallow margin, freshwater input mixed with marine waters to produce a brackish water column; c) although energy levels were not high, they were high enough to periodically disrupt any dysoxia that may have built up, thus never letting the bottom become fully anoxic; d) compared to the more distal parts of the basin, sediment input was high, which kept the sediment-water interface oxic, thus permitting moderate to rich, benthic agglutinated foraminiferal faunae to flourish during much of the studied interval, while a few centimetres into the bottom sediments were anoxic and concretions formed (especially true during deposition of the Haven, Marshybank, Dowling and Thistle members); and e) high clastic input and shallow conditions kept planktic foraminifera out, which kept surface production down, thus not overloading the bottom sediments with organic matter to oxidize. During the deposition of the Sunkay, Haven and Opabin members, the Boreal and Tethyan seas were not joined (Kauffman, 1984; Kauffman and Caldwell, 1993), thus true water mass stratification is not interpreted to have formed. The same can be said for the Cardium Formation and the Muskiki, Marshybank, Dowling and Hanson members. The idea of a freshwater lid has been proposed by Slingerland *et al.* (1996) but this does not fit with the data from this proximal setting as previously discussed. The area was under boreal influence and only benthic agglutinated foraminifera were present in these cooler waters (Stelck and Wall, 1954; 1955). The preservation of dominantly agglutinated assemblages is generally

indicative of either very deep waters, below the calcium compensation depth, or cooler waters in which calcareous foraminifera do not preserve well (Boersma, 1978). If the sediments were in fact deposited on an inner shelf then the watermass must have been relatively cool, which agrees with the ideas of Wall (1967a); Stelck and Wall (1954; 1955); Stelck *et al.* (1956; 1958) of a boreally influenced watermass.

Geochemical data indicates that organic carbon in this suite of rocks is both terrigenous and marine in origin (Hunt, 1996; Peters, 1986) which supports a shallow, inner shelf, depositional setting for the Upper Colorado Group at Mill Creek.

Sea Level History

On a shallow, relatively flat shelf, changes in relative sea level need not be extreme in order to be dramatically recorded in the rock record. During the Greenhorn and Niobara highstands, however, sea-level has been estimated to have risen up to 300 m (Kauffman and Caldwell, 1993). At this section, therefore, the changes in RSL were largely controlled by changes in terrestrial and coastal processes (rate of clastic input, location and gradient of streams) and Cordilleran uplift. Changes in RSL, however, are interpreted to have been smaller in this proximal setting than in more distal parts of the basin. For this section, the deepest water depth estimates are interpreted to be around 100 m for the Vimy Member and slightly less than 100 m for the Thistle Member (discussed in next section). Shallowest water depths occurred during the deposition of the Cardium Formation which was deposited very close to shore,

probably at close to 50 m or less water depth since hummocky cross-stratification forms between fairweather wave base and storm wave base depth (Walker, 1983; 1988; Krause and Nelson, 1984; 1991). The difference between these maximum and minimum water depth values is only around 50 m, significantly less than the estimates for the distal parts of the basin. Sediment input and Cordilleran uprise probably played a large role in controlling the differences in RSL change between the proximal and distal settings.

Paleoenvironmental and Sea-level History Interpretations

Blackstone Formation, Sunkay Member

The Sunkay Member (Figure 6) is interpreted to represent a shallow (<50 m), inner sublittoral setting of an epicontinental sea. The water was probably somewhat turbid with a rock composition of mixed shales and siltstones, and rather cool since it was of boreal origin (Wall, 1967a). The salinity is interpreted as subnormal or brackish based on the presence of *Miliammina* and other euryhaline foraminifera (Figure 45a) (Wall, 1967a). The bottom surface sediments were probably dysoxic because: 1) the benthic foraminiferal populations and diversities are low (<50 specimens per sample); and 2) pyrite is common in the Sunkay Member and is diagnostic of anoxic to highly dysoxic conditions within the bottom sediments (Berner, 1970; Davis *et al.*, 1988; Dean and Arthur, 1989). Bioturbation is absent from the Sunkay Member, further confirming the anoxic nature of the sediments. The organic matter in the Sunkay Member is of type III, or of terrestrial origin, which supports the interpretation of a proximal, nearshore setting (Hunt, 1996; Peters, 1986).

Opabin Member

(d)

Cardium Formation

(e)

Muskiki Member

(f)

Figure 45. These pie graphs show the generic make up of the assemblages associated with each stratigraphic member/formation in this study: (Blackstone Formation) (a) the Sunkay Member; (b) the Vimy Member; (c) the Haven Member; (d) the Opabin Member; (e) the Cardium Formation; (Wapiabi Formation) (f) the Muskiki Member; (g) the Marshybank Member; (h) the Dowling Member; (i) the Thistle Member; and (j) Hanson Member. Euryhaline genera are underlined.

Vimy Member

The paleoenvironment of the Vimy Member is indicative of a trend towards more open marine conditions with planktic foraminifera and nannofossils present (Figure 9). This member is interpreted as being deposited at the minimum depth that permits planktic foraminifera to invade (Leckie, 1987) while remaining shallow enough to keep bottom water conditions somewhat oxygenated and thus permitting benthic foraminifera to persist in reduced numbers. Bioturbation is low and bedding tends to be fairly platy also indicating that bottom sediments were somewhat oxic to periodically dysoxic. The presence of planktic foraminifera and nannofossils in the basal sediments records a rapid deepening to approximately 100 m water depth. This is considered the depth at which plankton begin to invade surface waters (Leckie, 1987). There may have also been, however, strong onshore currents bringing planktic foraminifera into a shallower, more turbid environment where benthic foraminifera still persisted. These currents also may have been responsible for keeping bottom waters mixing with surface waters and breaking up anoxia (Figure 45b). The presence of broken macrofossil shell horizons is interpreted as storm beds deposited under a waning flow. The organic matter in the Vimy Member is a mix of Type II and III indicating that organic carbon was derived from both marine and terrestrial sources (Hunt, 1996; Peters, 1986). Benthic foraminifera occur in reduced numbers, with *Inoceramus* assemblages, which are believed to have been opportunistic taxa that inhabited poorly oxygenated environments (Saltzman and Barron, 1982; MacLeod and Hoppe, 1992). The

energy conditions in the Vimy Member were probably relatively calm most of the time since planktic foraminifera thrived and the dominant bed forms in the Vimy Member are platy, well laminated shales. Occasionally high energy storm events brought in coarser, siltier sediments and deposited them in storm beds which were rippled.

Haven Member

The Haven Member was deposited during the terminal regression of the Greenhorn Cycle. The foraminiferal assemblages in the Haven Member are suggestive of a cool, shallower water paleoenvironment than the Vimy Member. Water depth is estimated to have been between 50 and 100 m. This nearshore setting probably contained somewhat turbid water conditions indicated by the presence of silt and even some fine sands within this unit (Figures 14 and 15). Similarly the energy conditions were moderately elevated as observed from some rippled sandstones. Salinity was probably subnormal or brackish as euryhaline genera dominated the assemblages (Figure 45c) and no calcareous forms are present. Bottom oxygen levels were reduced to dysoxic while within the sediments anoxia occurred. This is further supported by the presence of only a small benthic foraminiferal population coupled with horizontal borrows but no vertical burrowing. Concretions are not common in this unit and may not have formed due to either oxidizing conditions in the sediments or due to the low organic carbon weight percents that characterized this member. The organic carbon in this system was of terrestrial origin.

Opabin Member

The Opabin Member was deposited during the continuing regressive event that ended the Greenhorn cycle. The unit coarsens upward indicating shallowing water conditions (from less than 100 m to about 50 m) and increased turbidity through time. This unit is interpreted to have been deposited in a cool, shallow water, sublittoral shelf environment (Figures 22 and 23). The salinity of this unit is again interpreted as brackish due to the dominance of euryhaline foraminifera and the lack of calcareous benthic foraminifera (Figure 45d) is indicative of a boreally-influenced water mass (Caldwell *et al.*, 1978). The sediments are only moderately bioturbated indicating a somewhat oxic to dysoxic sediment-water interface. Anoxia is interpreted to have occurred within the sediment column where siderite concretions formed. With the drop in sea-level that occurred towards the top of the member, shallower water depths seem to have brought more oxygen to the bottom as suggested by abundant benthic agglutinated foraminiferal populations and intense bioturbation. Energy conditions seem to have changed radically through time, from very low energy, quiescent conditions, with predominantly shale lithologies in the lower Opabin Member, to quite high energy conditions near the contact with the Cardium Formation where thin rippled sandstone beds are present. Water conditions remained under boreal influence and were therefore relatively cool (Wall, 1967a; Caldwell *et al.*, 1978).

Cardium Formation

The Cardium Formation was deposited during the maximum lowstand of the Coniacian (Plint, 1990; 1991). The foraminiferal assemblages seen in this unit are typical of brackish marine conditions (Wright and Walker, 1981). Wall (1967a) interpreted this unit as a lagoonal deposit. The coarse nature of this sandstone unit, however, indicates a shoreface depositional setting (maximum 50 m water depth), with high energy, shoreline conditions prevailing (Walker 1983, 1988). The occurrence of hummocky cross-stratification favours this coastal, offshore environmental interpretation and suggests that this unit was deposited below fairweather wave base but above storm wave base, under high energy conditions (Figure 24) (Walker *et al.*, 1983; Walker 1983; 1988; Krause, 1983; Krause and Nelson, 1984; 1991). These sands contain large quantities of coal fragments, also indicative of nearshore conditions. The environment is characterized by high freshwater input since all the benthic foraminifera are brackish water indicators (Figure 45e). Abundant oxygen at the sediment-water interface is indicated by high diversity and abundant trace fossil assemblages. The formation of siderite concretions, however, indicates highly dysoxic to anoxic conditions within the sediments, especially towards the top of the unit.

Wapiabi Formation, Muskiki Member

The Muskiki Member was deposited during the transgression that marks the beginning of the Niobrara Cycle. This unit was deposited under shallow water conditions (< 50 m) with fairly high energy conditions prevailing, indicated

by the high percentage of sand still present throughout this unit (Figure 29). The water conditions were somewhat brackish during this time and benthic foraminiferal assemblages are dominated by euryhaline forms (Figure 45f). In addition, calcareous forms are completely absent, probably because the waters were quite cool. This unit is interpreted to have been deposited in fairly oxygenated conditions as a result of a high energy system. This is further substantiated by the intense bioturbation associated with this member. However, the presence of siderite indicates that below the water-sediment interface conditions were anoxic.

Marshybank Member

The Marshybank Member was deposited during the continued transgression of the Niobrara Cycle. This shaly unit was deposited in deeper water than the silty Muskiki Member and energy conditions, although still somewhat turbulent, were much lower than the underlying member. The unit is predominantly shale and siltstone (Figure 30). The foraminiferal assemblage is indicative of a shallow water, inner shelf environment. The salinity of the seaway at Marshybank time remained brackish with euryhaline foraminifera dominating the assemblage (Figure 45g). At the time of deposition of the sediments near the base of this unit, oxygen levels are interpreted to have been high since bioturbation is intense. Bottom oxygen levels decreased through time and become dysoxic towards the top of the unit where the benthic foraminiferal populations are small and bioturbation is significantly reduced.

Dowling Member

At Mill Creek, the Dowling Member does not represent a deepening as it does elsewhere in the foothills (Wall, 1967a). Instead, the Dowling Member has an overall coarsening-upward cycle that culminates in thin, sandstone beds (Figure 31). This local shallowing is interpreted as a change from a more distal to a more proximal sediment source in the area. The water depth appears to have shallowed from 100 to about 50 m (indicated by the presence of sand beds at the top of the unit), with moderate energy conditions. Salinity was probably brackish with euryhaline genera dominating and no calcareous forms present (Figure 45h). Within the bottom sediments anoxia was common and concretions formed. Oxygen levels were low when sediments at the base of this unit were deposited and increased near the top of the unit where oxygenation is indicated by relatively large benthic foraminiferal populations and horizontal burrows.

Thistle Member

The Thistle Member was deposited during a renewed deepening resulting in the highstand deposits of the Niobrara cycle. The water depth during Thistle time was not as deep as during the Vimy time since benthic agglutinated foraminifera dominate the assemblage. The water depth, however, would have been close to 100 m although less than depths found in the Vimy Member (Figure 32). The water conditions were probably turbid and cool. The large number of bentonites that characterize the Thistle Member (Figure 32) may have also kept planktic foraminifera from invading this proximal

setting due to the increased water column turbidity and silica content that must have resulted. The small number of calcareous planktic foraminifera observed within concretions suggest near normal salinities for the Thistle Member. The lack of calcareous benthic foraminifera, however, suggests lower than normal salinity on the bottom and within the sediments (Figure 45i), therefore the planktic foraminifera found within the concretions are interpreted to have been washed in by onshore currents. The sediment-water interface was oxic, permitting large benthic agglutinated foraminiferal populations, with periodic dysoxic conditions permitting *Inoceramus* to inhabit the bottom. Within the sediments, periods of anoxia occurred during shale deposition and these conditions permitted microbially-mediated concretions to form. Siltstone layers were bioturbated and vertical burrows through these probably allowed oxygen to penetrate somewhat deeper into the sediment column for distinct periods of time. No concretions are associated with these layers. Energy conditions were moderate and at times high enough to deposit some sand beds within this unit.

Hanson Member

The part of the Hanson Member investigated in this study was deposited under similar conditions to the Thistle Member (Figures 37 and 44j). The large difference in stratigraphic thickness between this study and Wall (1967a) could be due to part of the Hanson Member being included in the Thistle Member by Wall. This is substantiated by the similarity of the foraminiferal assemblages in these two units (Figure 45i and j).

Comparison with established foraminiferal biozones

The foraminiferal data obtained during this study differs greatly from that reported by Wall (1967a) and from established biozones for the Rocky Mountain Foothills. Possible reasons for these differences have already been mentioned in the taphonomic discussion. These data also differ greatly from what is observed in the more distal parts of the basin (Figure 44).

Verneuilinoides kansasensis Microfauna

Table 2 lists the major faunal elements of Wall's (1967a) *Verneuilinoides kansasensis* zone (*V. kansasensis* has been placed into synonymy with *V. perplexus*). This biozone is found at Mill Creek, and corresponds well with the previously described microfauna for the uppermost strata of the Sunkay Member. The only major element of Wall's assemblage not seen in the Mill Creek assemblage is *Haplophragmoides howardense*.

In the more distal parts of the basin the Belle Fourche Formation is characterised by a low diversity, agglutinated foraminiferal assemblage (Bloch *et al.*, 1993). The assemblage is somewhat similar to what is observed at Mill Creek and also belongs to the *Verneuilinoides perplexus* biozone.

Lower Pelagic Microfauna

Wall (1967a) named the assemblage he found in the Vimy Member the Lower Pelagic Microfauna. Table 3 shows the major components of Wall's fauna and what is found at Mill Creek. The two faunae are very similar except that in the present study benthic agglutinated foraminifera are also found within assemblages. This probably indicates that the depositional environment of the

***Verneuilinoides kansasensis** Microfauna**

Wall (1967a) faunal components	Faunal components this study
Agglutinated foraminifera	Agglutinated foraminifera
<i>Trochammina rutherfordi</i>	<i>Trochammina rutherfordi</i>
<i>Verneuilinoides kansasensis</i>	<i>Verneuilinoides perplexus</i>
<i>Haplophragmoides</i> spp.	<i>Haplophragmoides</i> spp.
<i>Trochammina</i> spp.	<i>Trochammina</i> spp.
<i>Haplophragmoides howardense</i>	<i>Ammobaculites</i> spp.
	<i>Spiroplectammina</i> spp.
	<i>Ammobaculites albertensis</i>
	<i>Ammobaculites fragmentarius</i>
	<i>Ammomarginulina lorangerae</i>
	<i>Dorothia</i> spp.
	<i>Gaudryina spiritensis</i>
	<i>Haplophragmoides crickmayi</i>
	<i>Haplophragmoides rota</i>
	<i>Miliammina</i> spp.
	<i>Verneuilinoides</i> spp.
	<i>Verneuilina canadensis</i>

Table 2. Comparison of the major microfaunal components for the Upper Sunkay Member (Middle Cenomanian) as reported by Wall (1967a) vs. the major components found in this study. (**Verneuilinoides kansasensis* has been placed in synonymy with *V. perplexus*).

Lower Pelagic Microfauna

Wall (1967a) faunal components	Faunal components this study
Planktic foraminifera	Planktic foraminifera
<i>Heterohelix globulosa</i>	<i>Heterohelix globulosa</i>
<i>Hedbergella delrioensis</i>	<i>Hedbergella delrioensis</i>
<i>Hedbergella loetterlei</i>	<i>Hedbergella loetterlei</i>
<i>Heterohelix</i> sp. 1	<i>Heterohelix</i> spp.
	Agglutinated foraminifera
	<i>Ammomarginulina lorangerae</i>
	<i>Ammomarginulina</i> spp.
	<i>Gaudryina</i> spp.
	<i>Haplophragmoides</i> spp.
	<i>Trochammina</i> spp.
	<i>Verneuilinoides</i> spp.

Table 3. Comparison of the major microfaunal components for the lower half to two thirds of the Vimy Member (Early Turonian) as reported by Wall (1967a) vs. the major components found in this study.

Vimy Member at Mill Creek was shallower than that found elsewhere in the foothills because it could still sustain a benthic agglutinated fauna, therefore bottom anoxia was not fully developed. Similar results are reported from the Vimy Member by Brennan-Alpert (1998) for the foothills outcrop at Highwood River.

The Second White Specks Formation, in the more distal parts of the basin, is characterised by a completely pelagic fauna that defines the *Hedbergella loetterei* Zone. The typical foothills and plains species for this zone are *Hedbergella loetterei*, *Hedbergella amabilis*, *Hedbergella delrioensis*, *Hedbergella portsdownensis*, *Whiteinella aprica* and *Heterohelix globulosa* (Bloch *et al.*, 1993). The species diversity and abundances in this study are significantly reduced compared with those found in the distal parts of the basin by McNeil and Caldwell (1981) in the Manitoba Escarpment and by Schröder-Adams *et al.*, (1996) in the Alberta and Saskatchewan plains.

***Pseudoclavulina* sp. Microfauna**

Table 4 indicates the major elements of the *Pseudoclavulina* sp. microfauna. According to Wall (1967a) this fauna is found in the shales of the Upper Blackstone Formation (Haven and Opabin members) which he did not differentiate at Mill Creek. Certain elements of this microfauna are present in both the Haven and the Opabin members but the index species, *Pseudoclavulina* sp. *, was not found in this study. The Haven Member contains *Dorothia* spp., *Trochammina* sp., *Verneuilioides* sp. and

***Pseudoclavulina* sp. Microfauna**

Wall (1967a) faunal components	Faunal components this study
	Haven:
Agglutinated foraminifera	Agglutinated foraminifera
<i>Haplophragmoides bonanzaense</i>	<i>Ammobaculites albertensis</i>
<i>Haplophragmoides howardense</i>	<i>Ammobaculites</i> spp.
<i>Haplophragmoides howardense manifestum</i>	<i>Ammobaculites fragmentarius</i>
<i>Dorothia</i> sp. 1	<i>Ammomarginulina</i> spp.
<i>Pseudoclavulina</i> sp. 1	<i>Haplophragmoides crickmayi</i>
	<i>Haplophragmoides</i> spp.
	<i>Spiroplectammina ammovitrea</i>
	<i>Textularia</i> spp.
	<i>Trochammina</i> spp.
	<i>Verneulinoides</i> spp.
	Opabin:
	<i>Ammobaculites fragmentarius</i>
	<i>Ammobaculites</i> spp.
	<i>Dorothia</i> spp.
	<i>Gaudryina spiritensis</i>
	<i>Haplophragmoides</i> spp.
	<i>Spiroplectammina</i> spp.
	<i>Trochammina</i> spp.
	<i>Verneulinoides</i> spp.

Table 4. Comparison of the major microfaunal components for the Haven/Opabin members (early Late Turonian) reported by Wall (1967a) vs. the major components found in this study.

Haplophragmoides spp. The fauna of the Opabin Member includes *Haplophragmoides howardense* and *Dorothia* spp.

The more distal basin-equivalent microfauna for the *Pseudoclavulina* sp. Microfauna is the *Trochammina* sp.-*Pseudoclavulina* sp. Zone which combines this biozone with Wall's (1967a) *Trochammina* sp. 1 Microfauna (McNeil and Caldwell, 1981). This zone is present in the southern Alberta plains but is completely absent from central Saskatchewan where a large regional unconformity spans this time period (McNeil and Caldwell, 1981). In the Manitoba escarpment, the *Trochammina* sp.-*Pseudoclavulina* sp. Zone also occurs. The fauna at Mill Creek does not correspond well with either of these biozones since the zonal indicators are missing.

Cardium Formation Microfauna

Wall (1967a) does not designate a microfauna for the Cardium Formation but reports the occurrence of *Reophax* sp.1, *Haplophragmoides crickmayi*, *Haplophragmoides howardense*, *Ammobaculites* sp. cf. *A. fragmentarius*, *Spiroplectammina semicomplanata*, *Trochammina* spp., *Verneuillinoidea bearpawensis* and *Dorothia smokyensis*. In this study, *Ammobaculites* spp., *Reophax* spp., *Textularia* spp., *Trochammina* spp. and *Verneuillinoidea* spp. are reported from the Cardium Formation. This fauna does not differ greatly from Wall's findings and is interpreted to represent very shallow, perhaps brackish, water conditions (Wall, 1967a; Wright and Walker, 1981). A comparison between Wall's finding and those from this study are in Table 5.

Cardium Microfauna

Wall (1967a) faunal components	Faunal components this study
Agglutinated foraminifera	Agglutinated foraminifera
<i>Reophax</i> sp. 1	<i>Ammobaculites</i> spp.
<i>Haplophragmoides crickmayi</i>	<i>Reophax</i> spp.
<i>Haplophragmoides howardense</i>	<i>Textularia</i> spp.
<i>Ammobaculites</i> sp. cf. <i>A. fragmentarius</i>	<i>Trochammina</i> spp.
<i>Spiroplectammina semicomplanata</i>	<i>Verneuilinoides</i> spp.
<i>Trochammina</i> spp.	
<i>Verneuilinoides bearpawensis</i>	
<i>Dorothia smokyensis</i>	

Table 5. Comparison of the major microfaunal components for the Cardium Formation (Latest Turonian-Early Coniacian) as reported by Wall (1967a) vs. the major components found in this study.

This unit represents a shoreface deposit and, therefore, does not occur in the distal parts of the basin. The time-equivalent rocks in the distal basin, however, belong to the *Trochammina* sp.-*Pseudoclavulina* sp. Microzone and this is to be expected since this facies is very different.

***Trochammina* sp. 1 Microfauna**

This microfauna is found in the Muskiki Member of the Wapiabi Formation. The main components of this fauna, as reported by Wall (1967a), are listed in Table 6. Wall found two calcareous benthic foraminifera within this fauna but no such elements are reported from this study. Furthermore Wall's agglutinated fauna differs greatly from that found in this study. Although some genera are in common, no species correspondance exists between Wall's findings and those of this study.

This microfauna is combined with the *Pseudoclavulina* sp. Microfauna in the distal parts of the basin.

***Brachycythere-Bullopura* Microfauna**

The *Brachycythere-Bullopura* Microfauna is the most diverse of all the microfaunae described by Wall (1967a) and it contains a large diversity of both agglutinated and calcareous benthic foraminifera, as well as abundant ostracodes. Table 7 compares Wall's findings with those of this study. In this study, no calcareous benthic foraminifera were found in the shales belonging to this biozone (Upper Dowling to Lower Thistle members). There are, however, elements in common between this microfauna and the foraminifera found, in this study, at the Mill Creek location. These include *Haplophragmoides*

***Trochammina* sp.1 Microfauna**

Wall (1967a) faunal components	Faunal components this study
Agglutinated foraminifera	Agglutinated foraminifera
<i>Reophax</i> sp. 1	<i>Ammobaculites</i> spp.
<i>Haplophragmoides howardense</i>	<i>Ammobaculites albertensis</i>
<i>Haplophragmoides howardense manifestum</i>	<i>Ammobaculites fragmentarius</i>
<i>Ammobaculites</i> sp. 1	<i>Haplophragmoides</i> spp.
<i>Spiroplectammina semicomplanata</i>	<i>Spiroplectammina ammovitrea</i>
<i>Pseudobolivina rollaensis</i>	<i>Textularia</i> spp.
<i>Trochammina</i> sp. 1	<i>Trochammina</i> spp.
<i>Dorothia smokyensis</i>	<i>Verneuilina canadensis</i>
<i>Dorothia</i> sp. 1	<i>Verneulinoides</i> spp.
Calcareous foraminifera	
<i>Quinqueloculina sphaera</i>	
<i>Guembelitra</i> sp.	

Table 6. Comparison of the major microfaunal components for the Muskiki Member (Early Coniacian) as reported by Wall (1967a) vs. the major components found in this study.

Brachycythere-Bullopore Microfauna

Wall (1967a) faunal components	Faunal components this study
Agglutinated foraminifera	Agglutinated foraminifera
<i>Bathysiphon vitta</i>	<i>Ammobaculites</i> spp.
<i>Saccammina</i> sp. cf. <i>S. alexanderi</i>	<i>Ammobaculites fragmentarius</i>
<i>Ammodiscus</i> sp. 2	<i>Ammobaculites albertensis</i>
<i>Reophax</i> sp. 1	<i>Ammomarginulina lorangerae</i>
<i>Reophax</i> sp. 2	<i>Dorothia</i> sp.
<i>Reophax</i> sp. 3 (uncommon)	<i>Haplophragmoides howardense</i>
<i>Haplophragmoides crickmayi</i>	<i>Haplophragmoides</i> spp.
<i>Haplophragmoides howardense</i>	<i>Haplophragmoides crickmayi</i>
<i>Ammobaculites</i> sp. cf. <i>A. fragmentarius</i>	<i>Spiroplectammina</i> spp.
<i>Ammobaculites</i> sp. 2	<i>Spiroplectammina ammovitrea</i>
<i>Flabellamina magna</i>	<i>Textularia</i> spp.
<i>Coscinophragma</i> ? <i>codyensis</i>	<i>Trochammina</i> spp.
<i>Spiroplectammina semicomplanata</i>	<i>Verneuilinoides</i> spp.
<i>Dorothia smokyensis</i>	<i>Verneuilinoides bearpawensis</i>
	<i>Verneuilina</i> spp.
Calcareous foraminifera	
<i>Marsonella oxycona</i>	
<i>Dentalina summitensis</i> (uncommon)	
<i>Dentalina</i> sp. 1 (uncommon)	
<i>Bullopore laevis</i>	
<i>Bolivina elkensis</i>	
<i>Bolivina</i> sp. 1 (uncommon)	
<i>Valvulineria</i> sp. cf. <i>V. umbilicata</i>	
<i>Valvulineria</i> sp. 1 (uncommon)	
<i>Guembelitra</i> sp. (uncommon)	
<i>Praeglobotruncana</i> sp. 1	
<i>Pullenia</i> ? sp.	
<i>Anomalinoides herbesti</i>	
<i>Anomalinoides talaria</i>	
<i>Anomalinoides</i> ? sp. 1 (uncommon)	
<i>Reinholdella</i> ? sp.	

Table 7. Comparison of the major microfaunal components for the Upper Dowling to lower Thistle Members (Early Santonian) as reported by Wall (1967a) vs. the major components found in this study.

crickmayi, *Haplophragmoides howardense*, *Ammobaculites fragmentarius* and *Dorothia* sp.

Three of the foothills biozones, the *Brachyocythere-Bullopore*, *Anomalinoidea henbesti* and Upper Pelagic microfaunas, are combined to form the *Globigerinelloidea* sp. Zone in the plains. This biozone is characterised by a high species diversity and abundance for both planktic and benthic, calcareous and agglutinated foraminifera (Caldwell *et al.*, 1978; McNeil and Caldwell, 1981). This mixed benthic and agglutinated fauna partly corresponds with what is seen in the Mill Creek section where agglutinated foraminifera prevail. The lack of calcareous benthic and planktic foraminifera, however, make these proximal and distal faunas significantly different and is probably a reflection of the very different paleoenvironmental conditions that prevailed in shallow vs. deep water facies.

***Anomalinoidea henbesti* Microfauna**

This biozone is reported to occur in the beds of the Upper Thistle and Lower Hanson members. Wall's (1967a) microfauna consists of mixed planktic and benthic, calcareous and agglutinated, foraminifera. No planktic or calcareous benthic foraminifera were found in the shale samples in this study. Sparse planktic foraminifera were found within concretions and appear to correspond with those reported by Wall. Table 8 compares this microfauna with the foraminiferal assemblages found in the Upper Thistle and Lower Hanson strata. The agglutinated foraminifera in these samples differ significantly from

***Anomalinoides henbesti* Microfauna**

Wall (1967a) faunal components	Faunal components this study
Agglutinated foraminifera	Agglutinated foraminifera
<i>Saccamina</i> sp. cf. <i>S. alexanderi</i>	<i>Ammobaculites</i> spp.
<i>Reophax pepperensis</i> (uncommon)	<i>Ammobaculites fragmentarius</i>
<i>Reophax</i> sp. 4 (uncommon)	<i>Ammobaculites albertensis</i>
<i>Haplophragmoides</i> sp. 2 (abundant)	<i>Ammomarginulina lorangerae</i>
<i>Pseudobolivina rollaensis</i>	<i>Haplophragmoides crickmayi</i>
<i>Pseudobolivina</i> sp. 1 (common)	<i>Haplophragmoides</i> spp.
<i>Trochammina</i> sp. 2 (abundant)	<i>Pseudobolivina rollaensis</i>
<i>Uvigerinammina</i> ? sp. 1	<i>Spiroplectammina</i> spp.
<i>Dorothia glabrata</i> (common)	<i>Spiroplectammina ammovitrea</i>
Calcareous foraminifera	<i>Textularia</i> spp.
<i>Nodosaria</i> sp. 1 (common)	<i>Trochammina</i> spp.
<i>Nodosaria</i> sp. 2 (uncommon)	<i>Verneuilinoides</i> spp.
<i>Frondicularia</i> sp. cf. <i>F. greybullensis</i> (uncommon)	<i>Verneuilinoides bearpawensis</i>
<i>Neobulimina</i> sp. (common)	<i>Verneuilina</i> spp.
<i>Bolivina</i> sp. cf. <i>B. elkensis</i>	
<i>Bolivina</i> sp. 1	
<i>Heterohelix globulosa</i>	
<i>Heterohelix</i> sp. cf. <i>H. reussi</i>	
<i>Heterohelix</i> sp. 1	
<i>Hedbergella delrioensis</i>	
<i>Praeglobotruncana</i> sp. 1	
<i>Anomalinoides henbesti</i>	
<i>Reinholdella</i> ? sp.	

Table 8. Comparison of the major microfaunal components for the Upper Thistle to Lower Hanson members (Middle Santonian) as reported by Wall (1967a) vs. the major components found in this study.

those reported by Wall (1967a). The common elements between these faunae are *Reophax* spp., *Pseudobolivina rollaensis* and *Trochammina* spp.

Refer to the previous discussion on the *Brachyocythere-Bullopore* Microfauna in the foothills versus the plains.

Upper Pelagic Microfauna

Wall (1967a) reported an Upper Pelagic Microfauna in the beds belonging to the Hanson Member. This fauna contains both benthic (calcareous and agglutinated) and planktic foraminifera. It does not correspond with the fauna found in the Hanson Member of this study, however, Wall may have combined the Thistle and Hanson members from this study into one unit. Table 9 shows the very different major elements from Wall's microfauna compared to the assemblage observed in this study. The only elements in common between the two are *Trochammina* spp. and *Haplophragmoides* spp.

This microfauna is combined with the *Globigerinelloides* sp. Zone in the plains and therefore comparisons between this biozone and the *Brachyocythere-Bullopore* Microfauna are valid here as well.

CONCLUSIONS

The Upper Colorado Group (late Cenomanian-Santonian) is exposed along Mill Creek in the Southern Rocky Mountain Foothills and will serve as a reference section for this interval in this southern, proximal setting of the WCSB. A detailed multidisciplinary study of this Upper Cretaceous interval resulted in the following conclusions:

Upper Pelagic Microfauna

Wall (1967a) faunal components	Faunal components this study
Agglutinated foraminifera	Agglutinated foraminifera
<i>Reophax</i> sp. 4	<i>Ammobaculites</i> spp.
<i>Haplophragmoides</i> sp. 2	<i>Ammobaculites albertensis</i>
<i>Trochammina</i> sp. 2	<i>Ammobaculites fragmentarius</i>
Calcareous foraminifera	<i>Ammomarginulina lorangerae</i>
<i>Neobulimina</i> sp.	<i>Haplophragmoides</i> spp.
<i>Bolivina</i> sp. cf. <i>B. elkensis</i>	<i>Spiroplectammina</i> spp.
<i>Bolivina</i> sp. 1	<i>Spiroplectammina ammovitrea</i>
Planktic foraminifera	<i>Textularia</i> spp.
<i>Heterohelix globulosa</i>	<i>Trochammina</i> spp.
<i>Heterohelix</i> sp. cf. <i>H. reussi</i>	<i>Verneuilina</i> spp.
<i>Heterohelix</i> sp. 1	<i>Verneuilinoides bearpawensis</i>
<i>Hedbergella delrioensis</i>	<i>Verneuilinoides bearpawensis</i>
<i>Praeglobotruncana</i> sp. cf. <i>P. coarctata</i>	
<i>Praeglobotruncana</i> sp. 1	

Table 9. Comparison of the major microfaunal components for the Hason Member (Late Santonian) as reported by Wall (1967a) vs. the major components found in this study.

1. The Mill Creek section spans the Upper Alberta Group including, in ascending order, the Sunkay, Vimy, Haven and Opabin members of the Blackstone Formation, the Cardium Formation and the Wapiabi Formation consisting of the Muskiki, Marshybank, Dowling, Thistle and Hanson members. The succession unconformably overlies the Crowsnest Member of the Mill Creek Formation, Blairmore Group and Belly River Group (not measured). Upper Alberta Group sediments were deposited during the Greenhorn and Niobrara sea-level cycles. These third order cycles were overprinted by changes in relative sea-level.
2. The sediments at this location represent deposition in a shallow (50-100 m depth), inner shelf environment. Bottom waters ranged from oxic to dysoxic in this proximal location as indicated by the abundant and diverse benthic, agglutinated foraminiferal faunae throughout most the section.
3. TOC and HI values indicate that most of the organic matter accumulated in this proximal setting was of terrigenous origin with a mixed marine and terrigenous origin for organic matter in the Vimy Member. The peak accumulations of organic matter occurred during deposition of the Vimy Member and this corresponds with a peak in nannofossil abundance. With increased sediment input and oxygen levels organic matter was oxidized rather than preserved in the sediment.
4. PI and Tmax values indicate that the sediments are undermature, however, anomalous Tmax values correspond to silt layers that possibly acted as

hydrocarbon conduits during hydrocarbon migration from more mature source rocks to the west (J. Bloch, pers. comm. 1998).

5. Benthic foraminiferal faunae do not change significantly from member to member or formation to formation, indicating that some of the paleoenvironmental conditions (salinity, O_2 , turbidity) during this period did not change significantly in the proximal setting. Water depth, however, changed significantly, in the proximal setting, during the Greenhorn and Niobrara sea-level cycles. The RSL changes are interpreted to have been less dramatic than in the basin due to tectonic uplift and high sediment input.
6. Variations in foraminiferal abundances reflect changes in sediment size. Agglutinated foraminifera are more abundant in shaly and silty intervals and decrease in abundance towards the tops of upward-coarsening cycles due to changes in energy conditions and sediment size.
7. The faunal components of this study are not diverse enough to create any biozones and do not correspond to biozones for the Rocky Mountain Foothills or the established biozones for more distal parts of the WCSB during this interval. The facies and biostratigraphic changes observed in the proximal setting reflect changes in sedimentation patterns rather than water mass stratification. This is in sharp contrast to the distal parts of the basin where faunal changes reflect fluctuations in Boreal and Tethyan watermass stratification rather than changes in sedimentation.
8. Taphonomy probably played a large role in the preservation of original foraminiferal populations. Due to anoxic conditions within the sediment,

calcareous foraminifera may have been readily pyritized and then dissolved during the diagenetic history of the area thus biasing the fossil record in favour of a benthic agglutinated fauna.

FORAMINIFERAL REFERENCE LIST

Ammobaculites albertensis Stelck and Wall, 1954, p. 18-19, pl. 1, fig. 21-22

Ammobaculites fragmentarius Cushman 1927, p. 130, pl. 1, fig. 8
MacNeil and Caldwell, 1981, p. 156, pl. 12, fig. 6-7

Ammobaculites spp.

Ammomarginulina lorangerae Stelck and Wall, 1955, p. 34-35, pl. 1, fig. 13, 27

Ammomarginulina spp.

Bathysiphon spp.

Coscinophragma ? codyensis ? Fox, 1954, p. 113-114, pl. 25, fig. 1-4
Wall, 1967a, p. 60-61, pl. 7, fig. 8-13

Dorothia smokyensis Wall, 1960, p. 23-25, pl. 4, fig. 22-28
Wall, 1967a, p. 81-82, pl. 11, fig. 25-28

Dorothia spp.

Flabellamina spp.

Gaudryina spiritensis Stelck and Wall, 1955, p. 43-44, p. 2, fig. 9-10; p. 3., fig. 3-8
Wall, 1967a, p. 140, pl. 1, fig. 16-19

Gaudryina spp.

Haplophragmoides bonanzaense Stelck and Wall, 1954, p. 24, pl. 2, fig. 10 a-b
Wall, 1967a, p. 48-49, pl. 4, fig. 1-2

Haplophragmoides crickmayi Stelck and Wall, 1954, p. 10, 12, 13;
Stelck and Wall, 1955, p. 47-49, pl. 2, fig. 22-23
Wall, 1967a, p. 49-50, pl. 8, fig. 12-15, pl. 10, fig. 18-19

Haplophragmoides hendersonense Stelck and Wall, 1954, p. 25-2, pl. 1, fig. 20, pl. 2 fig. 5-6

Haplophragmoides howardense Stelck and Wall, 1954, p. 25-26, pl. 1, fig. 20, pl. 2, fig. 5-6
Wall, 1967a, p. 50-51, pl. 4, fig. 5-7, pl. 5, fig. 6-9, pl. 10, fig. 16-17

Haplophragmoides sp. cf. *H. rota* Nauss, 1947, p. 339, pl. 49, fig. 1a-b, 3a-b

Tappan, 1962, p. 134, pl. 31, fig. 16-18
 Wall, 1967a, p. 52-53, pl. 14, fig. 5-8

Haplophragmoides spp.

Hedbergella delrioensis Carsey, 1926, p. 43
 Tappan, 1940, p. 121, pl. 19, fig. 11 a-c
 Stelck and Wall, 1954, p. 21-22, pl. 2, fig. 21-22
 Wall, 1967a, p. 105-106, pl. 3, fig. 1-12, pl. 13, fig. 13-21

Hedbergella loetterlei (*Globigerina loetterlei* Nauss) 1947, p. 336-337, p. 49,
 fig. 11 a-c
 McNeil and Caldwell, 1981, p. 250, pl. 19, fig. 3-10c

Hedbergella spp.

Heterohelix globulosa (*Textularia globulosa* Ehrenberg) 1840, p. 135, pl. 4, fig.
 1b, 2b, 4b, 5b, 7b, 8b
 McNeil and Caldwell, 1981, p. 250, pl. 20, fig. 1-4

Miliammina spp.

Pseudobolivina rollaensis Stelck and Wall, 1954, p. 30-31, pl. 1, fig. 17
 Stelck and Wall, 1955, p. 55, pl. 2, fig. 34-35
 Wall, 1960, p. 21-22, pl. 4, fig. 16-19
 Wall, 1967a, p. 65-66, pl. 4, fig. 20-23, pl. 7, fig. 21-26

Pseudobolivina spp.

Reinholdella sp.? Wall, 1967a, p. 116, pl. 6, fig. 34-39

Reophax incompta Loeblich and Tappan, 1946., p. 242, pl. 35, fig. 1a-b, text
 fig. 1
 McNeil and Caldwell, 1981, p. 138, pl. 9, fig. 19-20

Reophax sp. 3 cf. Wall, 1967a, p. 45-46, pl. 7, fig. 3

Reophax sp. cf. *R. troyeri* Chamney, 1969, p. 22-23, pl. 4, fig. 2-4
 Stelck, 1975, pl. 1, fig. 19-20, 23

Reophax spp.

Saccammina alexanderi Loeblich and Tappan, 1950, p. 5, pl. 1, fig. 1-2
 Wall, 1967a, p. 40-41, pl. 8, fig. 16-17, pl. 14, fig. 17-18

Saccammina spp.

Spiroplectammina ammovitrea Tappan, 1940, p. 97, pl. 14, fig. 13
Eicher, 1967, p. 177, pl. 18, fig. 8

Spiroplectammina sp. cf. *S. mordensis* Wickenden, 1932, p. 86, pl. 1, fig. 4a-b
Cushman, 1946, p. 28, pl. 6, fig. 4
Tappan, 1962, p. 140, pl. 33, fig. 6

Spiroplectammina semicomplanata Carsey, 1926, p. 25, pl. 3, fig. 4
Wall, 1967, p. 62-63, pl. 5, fig. 22-29

Spiroplectammina sp. c. f. *S.* sp. 1 Wall 1967a

Spiroplectammina spp.

Textularia gravenori ? Stelck and Wall, 1955, p. 55, pl. 2, fig. 3
Tappan, 1962, p. 141, pl. 33, fig. 1-17

Textularia topagukensis ? Tappan, 1957, p. 205, pl. 4, fig. 5a-b, 6
Stelck, 1975, pl. 3, fig. 22-23

Textularia spp.

Tritaxia spiritensis Stelck and Wall, 1954, p. 31-32, pl. 2, fig. 12-14

Tritaxia spp.

Trochammina rainwateri Cushman and Applin, 1946, p. 75, pl. 13, fig. 9
McNeil and Caldwell, 1981, pl. 164, pl. 13, fig. 11, 12c
Bloch *et al.*, 1993, pl. 1, fig. 7-8

Trochammina ribstonensis Wickenden, 1932, p. 90-91, pl. 1, fig. 12a-c
Cushman, 1946, p. 50, pl. 15, fig. 9a-c
Wall, 1960, p. 26-17, pl. 5, fig. 10-12
Tappan, 1962, p. 154-155, pl. 39, fig. 16-17
Wall, 1967a, p. 67-68, pl. 10, fig. 20-25

Trochammina rutherfordi Stelck and Wall, 1955, p. 56-57, pl. 1, fig. 11-12
North and Caldwell, 1975, pl. 3, fig. 1

Trochammina wettereii Stelck and Wall, 1955, p. 59-60, pl. 2, fig. 1-3, 6
Stelck and Hedinger, 1983, pl. 2, fig. 19-20, 33-34

Trochammina spp.

Uvigerinammina spp.

Verneuilina canadensis Cushman, 1927, p. 131, pl. 1, fig. 11
McNeil and Caldwell, 1981, pl. 14, fig. 3

Verneuilina spp.

Verneuilinoides bearpawensis Wickenden, 1932, p. 87, pl. 1, fig. 8
Cushman, 1946, p. 31, pl. 7, fig. 4-6
Wall, 1967a, p. 75-76, pl. 4, fig. 31-34, pl. 5, fig. 21, pl. 14, fig. 13-15

Verneuilinoides perplexus (*Verneuilina perplexa* Loeblich), 1946, p. 138, pl. 22, fig. 14-16)
Stelck and Wall, 1955, p. 60-61, pl. 2, fig. 40-41
McNeil and Caldwell, 1981, p. 172, pl. 14, fig. 4-6b
Verneuilinoides kansasensis conspecific with *V. perplexus*

Verneuilinoides spp.

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Plate I Foraminifera

1. *Hedbergella delrioensis*, Vimy Member (Sample 97-23), 69X
2. *Hedbergella delrioensis*, Vimy Member (Sample 97-23), 140X
3. *Trochammina wettereii*, Vimy Member (Sample 97-19), 125X
4. *Trochammina* sp., Haven Member (Sample 97-46), 225X
5. *Trochammina rutherfordi*, Haven Member (Sample 97-46), 300X
6. *Haplophragmoides crickmayi*, Opabin Member (Sample 97-63), 210X
7. *Haplophragmoides crickmayi*, Opabin Member (Sample 97-67), 190X
8. *Hedbergella delrioensis* (?), Haven Member (Sample 97-69), 225X
9. *Haplophragmoides* sp., Haven Member (Sample 97-69), 210X
10. *Haplophragmoides crickmayi*, Haven Member (Sample 97-76), 205X
11. Unidentified, Haven Member (Sample 97-79), 200X
12. *Haplophragmoides rota*, Opabin Member (Sample 97-86), 110X
13. *Haplophragmoides howardense*, Muskiki Member (Sample 97-96), 180X
14. *Ammomarginulina lorangerae* (?), Muskiki Member (Sample 97-98), 205X
15. *Trochammina rutherfordi*, Muskiki Member (Sample 97-102), 145X
16. *Haplophragmoides crickmayi*, Thistle Member (Sample 97-144), 210X
17. *Trochammina ribstonensis* (?), Thistle Member (Sample 97-144), 230X
18. *Trochammina* sp., Thistle Member (Sample 97-89), 200X
19. *Trochammina rutherfordi* (?), Haven Member (Sample 97-40), 140X

Plate II Foraminifera

1. *Pseudobolivina* sp., Haven Member (Sample 97-34), 180X
2. *Ammomarginulina* sp., Haven Member (Sample 97-34), 95X
3. *Dorothia* sp., Opabin Member (Sample 97-55), 165X
4. *Textularia* sp., Opabin Member (Sample 97-63), 170X
5. *Ammobaculites* sp. cf. *A. fragmentarius*, Opabin Member (Sample 97-63), 185X
6. *Pseudobolivina* sp., Opabin Member (Sample 97-63), 180X
7. *Verneuilinoides* sp. (?), Opabin Member (Sample 97-65), 60X
8. *Dorothia* sp., Opabin Member (Sample 97-65), 185X
9. *Gaudryina* sp. (?), Haven Member (Sample 97-69), 160X
10. *Haplophragmoides howardense*, Haven Member (Sample 97-70), 210X
11. *Ammomarginulina lorangerae*, Haven Member (Sample 97-70), 165X
12. *Ammobaculites* sp., Opabin Member (Sample 97-84), 185X
13. *Ammobaculites albertensis* (?), Marshybank Member (Sample 97-109), 175X
14. *Gaudryina* sp. (?), Marshybank Member (Sample 97-111), 200X
15. *Verneuilinoides bearpawensis* (?), Marshybank Member (Sample 97-112), 205X
16. *Ammobaculites fragmentarius*, Thistle Member (Sample 97-144), 180X
17. Unidentified, Thistle Member (Sample 97-139), 155X
18. *Spiroplectamina* sp. (?), Muskiki Member (Sample 97-101), 95X
19. *Ammobaculites* sp., Dowling Member (Sample 97-115), 190X
20. *Verneuilina* sp., Dowling Member (Sample 97-127), 150X

Plate III Macrofossil

1. *Collignoniceras woollgari* (Mantell) (?)
Blackstone Formation, Vimy Member.
2. *Collignoniceras woollgari* (Mantell)
Blackstone Formation, Vimy Member, structurally disturbed interval, float.
3. *Mytiloides sybhercynicus* (Seitz) (?)
Blackstone Formation, Vimy Member
4. *Collignoniceras woollgari* (Mantell) (?)
Blackstone Formation, Opabin Member
5. *Plesiacanthoceras wyomingense* (Reagan) (?)
Blackstone Formation, Opabin Member
6. Scaphitid ammonite
Wapiabi Formation, Thistle(?) Member, float
7. *Cremnoceramus* sp.
Wapiabi Formation, Dowling(?) Member, float

1a

2a

1b

2b

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Plate IV Macrofossil

- 1a, b. *Scaphites ventricosus* (Meek & Hayden)
Wapiabi Formation, Thistle Member, float
- 2a, b. Scaphitid (?) Ammonite
Wapiabi Formation, Thistle(?) Member
- 3. *Mytiloides (?) hercynicus* (Petrascheck)
Blackstone Formation, Vimy Member.

Appendix 1
Foraminiferal assemblages by Member

Sample Number	1	2	3	4	5	6
Stratigraphic Height (m)	21.2	23.1	22.5	24.9	32.2	32.7
Genus & Species						
Ataxophragmiidae	1					
<i>Ammobaculites albertensis</i>		5				
<i>Ammobaculites fragmentarius</i>		2				
<i>Ammobaculites</i> spp.	2		2		4	
<i>Ammomarginulina lorangerae</i>	3					
<i>Dorothyia smokyensis</i>			1			
<i>Dorothyia</i> spp.	2			1	1	
<i>Gaudryina spiritensis</i>	3				1	
<i>Gaudryina</i> spp.		1				
<i>Haplophragmoides crickmayi</i>	1		1			
<i>Haplophragmoides rota</i>	1	1				
<i>Haplophragmoides</i> spp.	3	3	1	1	3	
<i>Miliammina manitobensis</i>		1				
<i>Miliammina</i> spp.		1				
<i>Pseudobolivina rollaensis</i>		1				
<i>Reophax incompta</i> ?		2				
<i>Reophax</i> spp.		1				
<i>Spiroplectammina ammovitrea</i>	1	1				
<i>Spiroplectammina</i> spp.	4	4			2	
<i>Textularia</i> spp.	1	1				
<i>Trochammina rainwateri</i>					1	
<i>Trochammina ribstonensis</i>		2				
<i>Trochammina rutherfordi</i>	1		2			
<i>Trochammina</i> spp.	5	6		1	2	
<i>Uvigerinammina</i> spp.		1	3			
<i>Verneuilina canadensis</i>	3	1				
<i>Verneuilina</i> spp.					4	
<i>Verneuilinoides perplexus</i>					1	
<i>Verneuilinoides</i> spp.	1	4			3	
Unidentified agglutinated	3	4	1	5	4	
TOTAL	35	42	11	8	26	0
Total Benthic	35	42	11	8	26	0
Total Planktic	0	0	0	0	0	0
Percent Benthic	100	100	100	100	100	N/A
Percent Planktic	0	0	0	0	0	N/A
Fish debris	P		R		P	P
Plant Material					P	
Glaucinite						
Coal						
<i>Inoceramus</i> prisms	R					

Sample Number	9	11	12	13	17	18	19	23	25	27	28	30B	31A
Stratigraphic Height (m)	32.8	32.8	34.5	35	39.1	39.4	40.5	44.2	47.5	51.6	57.7	62.5	65.2
Genus & Species													
<i>Ammobaculites albertensis</i>	1												3
<i>Ammobaculites</i> spp.			1	1					1	1			4
<i>Ammomarginulina lorangerae</i>			1		1					1			1
<i>Ammomarginulina</i> spp.	1	1		2					3	2			
<i>Dorothia</i> spp.				1									
<i>Gaudryina spiritensis</i>			1	1						2			
<i>Gaudryina</i> spp.										1			
<i>Haplophragmoides crickmayi</i>			1										
<i>Haplophragmoides rota</i>									1				2
<i>Haplophragmoides</i> spp.		7	2	2	1							1	
<i>Hedbergella delrioensis</i>							24	11		2		2	
<i>Hedbergella lotterlei</i>							32	4		4		1	
<i>Hedbergella</i> spp.	5			1		1	22	5		2	1		
<i>Heterohelix globulosa</i>						1							
<i>Heterohelix</i> spp.						1	3	2					
<i>Reophax</i> spp.			2										
<i>Reophax</i> sp. ?							4						
<i>Reinholdella</i> sp. ?	1	1		1									
<i>Saccamina</i> sp. ?			1										1
<i>Saccamina</i> sp. cf <i>S. alexanderi</i>											1		
<i>Saccamina alexanderi</i>													2
<i>Spiroplectammina ammovitrea</i>													1
<i>Spiroplectammina</i> spp.	1		1	2			1	1	1	2		1	1
<i>Spiroplectammina</i> sp. 1 (Wall'67)				1									
<i>Tritaxia spiritensis</i>			2						1				
<i>Trochammina rutherfordi</i>	1			1	1								
<i>Trochammina</i> spp.		4	2	3	2	3	6	3	5	4			3
<i>Verneuilina canadensis</i>	1								1			1	
<i>Verneuilina</i> spp.			1				1						1
<i>Verneulinoides bearpawensis</i>			1	2									1
<i>Verneulinoides perplexus</i>							1						
<i>Verneulinoides</i> spp.	2				2	1	5						1
Unidentified agglutinated	1	4	6	2	2	1	9	2	4		3	1	6
Unidentified calcareous	3	4								3		2	
TOTAL	17	21	22	20	9	8	108	28	17	24	5	9	27
Total Benthic	12	21	22	19	9	5	27	6	17	16	4	6	27
Total Planktic	5	0	0	1	0	3	81	22	0	8	1	3	0
Percent Benthic	71	100	100	95	100	63	25	21	100	67	80	67	100
Percent Planktic	29	0	0	5	0	38	75	79	0	33	20	33	0
Fish debris													
Plant Material			C	R	P								
Glauconite				R									
Coal				P									
<i>Inoceramus</i> prisms	P	P		P	A	P	P	A		P	R		
Algal cyst					R					R			

Sample Number	31C	34	38	40	42	44	46	47	52
Stratigraphic Height (m)	66.4	67.8	69.1	76.6	78.8	84.3	91.7	94.7	98.2
Genus & Species									
Ataxophragmiidae			3		1				
<i>Ammobaculites albertensis</i>	1	10	2	3	1	2	5	7	
<i>Ammobaculites fragmentarius</i>		1	2				2	4	
<i>Ammobaculites</i> spp.		6		2		2	8	7	1
<i>Ammomarginulina lorangerae</i>			2	5	3				
<i>Ammomarginulina</i> spp.	1	1			1	1	2	7	
<i>Dorothyia</i> spp.			4				4		1
<i>Gaudryina spiritensis</i>		1	3				2	4	
<i>Gaudryina</i> spp.	1	2							
<i>Haplophragmoides crickmayi</i>		2		3			3	2	
<i>Haplophragmoides hendersonense</i>								1	
<i>Haplophragmoides rota</i>		1		1			3	3	
<i>Haplophragmoides</i> spp.		3			1	1	4	11	
Lituolidae				1				4	
<i>Miliammina</i> spp.								1	
<i>Pseudobolivina rollaensis</i>				1		2			
<i>Reophax</i> sp.3 Wall'67		1							
<i>Reophax</i> sp. ?			1						1
<i>Saccammina</i> sp. ?			1						
<i>Saccammina</i> sp. cf. <i>S. alexanderi</i>				1					
<i>Spiroplectammina ammovitrea</i>	1	2		3			4	2	
<i>Spiroplectammina</i> sp. cf. <i>S. mordensis</i>								1	
<i>Spiroplectammina</i> spp.		4	2				1	8	
<i>Textularia</i> spp.			1					1	
<i>Textularia topagukensis</i> ?				1					
<i>Tritaxia spiritensis</i>		1							
<i>Trochammina ribstonensis</i>							3		
<i>Trochammina rutherfordi</i>					1		2	7	
<i>Trochammina</i> spp.	8	6	5	4	3		11	14	
<i>Trochammina wettleri</i>							2		
<i>Uvigerinammina</i> spp.			1					1	
<i>Verneuilina canadensis</i>								1	
<i>Verneuilina</i> spp.	1		2	2					
<i>Verneuilinoides bearpawensis</i>	1		1				2		
<i>Verneuilinoides perplexus</i>				2					
<i>Verneuilinoides</i> sp. cf. <i>V. perplexus</i>								1	
<i>Verneuilinoides</i> spp.	1	2	1	4	1		2	4	
Unidentified agglutinated	3	3	4	2		2	9	10	2
TOTAL	18	46	35	35	12	10	69	101	5
Total Benthic	18	46	35	35	12	10	69	101	5
Total Planktic	0	0	0	0	0	0	0	0	0
Percent Benthic	100	100	100	100	100	100	100	100	100
Percent Planktic	0	0	0	0	0	0	0	0	0
Fish debris								R	
Plant Material								R	
Glauconite									
Coal							R	R	
<i>Inoceramus</i> prisms	P		P						

Sample Number	67	69	70	71	74	76	79	80	83
Stratigraphic Height (m)	246.9	247.1	248.6	250.5	254.4	256.5	260.2	262.1	270.3
Genus & Species									
Ataxophragmiidae			3	3	12	12	11	18	11
<i>Ammobaculites albertensis</i>	3		2	9	13	16	11	6	2
<i>Ammobaculites fragmentarius</i>	1	4	7	3	21	7	14	10	5
<i>Ammobaculites</i> spp.	2	4	6	12	23	23	36	26	17
<i>Ammomarginulina</i> spp.		6	5	4	13	9	3	1	3
<i>Bathysiphon</i> sp. ?						1			
<i>Dorothia</i> spp.	1	2	6	1	2		4	3	3
<i>Flabellammina</i> sp. ?					2	1			
<i>Gaudryina spiritensis</i>		3	5	1	5	1	2	9	6
<i>Haplophragmoides bonanzaense</i>				1					
<i>Haplophragmoides crickmayi</i>	4	1	5	6	7	3	4	6	5
<i>Haplophragmoides howardense</i>	1			1	1	1		3	2
<i>Haplophragmoides rota</i>			3						1
<i>Haplophragmoides</i> spp.	4	7	11	20	54	22	39	30	32
Lituolidae					2	7	10	11	5
<i>Pseudobolivina</i> sp. cf. <i>P. rollaensis</i>		2							
<i>Pseudobolivina</i> spp.	1		1		1				
<i>Reophax</i> spp.				1					
<i>Reophax</i> sp. ?			3				1	1	
<i>Spiroplectammina ammovitrea</i>		3	2	2	2	3	8	7	6
<i>Spiroplectammina</i> spp.	1	2	9	8	22	8	19	19	11
<i>Spiroplectammina semicomplanata</i>						1	1	2	
<i>Textularia</i> spp.	5	1	4	3	9	2	3	5	6
<i>Tritaxia spiritensis</i>								8	
<i>Tritaxia</i> spp.			2	2	2		4		1
<i>Trochammina rutherfordi</i>	2		6	5	1			5	7
<i>Trochammina</i> spp.	1	4	16	10		46	54	45	35
<i>Trochammina wetterei</i>		1	5	10		3	9	3	9
<i>Uvigerinammina</i> spp.			1		43				
<i>Verneuilina canadensis</i>		1			4	1		6	2
<i>Verneuilina</i> spp.		1	5	4	7	3	5	14	11
<i>Verneuilinoides bearpawensis</i>	1	1	1	2	2	3	6	13	4
<i>Verneuilinoides</i> spp.		6	9	4	17	7	17	13	10
Unidentified agglutinated	2	9	14	17	25	15	31	11	20
TOTAL	29	58	131	129	290	195	292	275	214
Total Benthic	29	58	131	129	290	195	292	275	214
Total Planktic	0	0	0	0	0	0	0	0	0
Percent Benthic	100	100	100	100	100	100	100	100	100
Percent Planktic	0	0	0	0	0	0	0	0	0
Fish debris									
Plant Material									
Glauconite									
Coal		P		P			P		
<i>Inoceramus</i> prisms	A		A	A					

Sample Number	55	60	63	65	66
Stratigraphic Height (m)	104.6	114.8	119.2	125.1	128.6
Genus & Species					
Ataxophragmiidae	2	1	2	16	2
<i>Ammobaculites albertensis</i>		6	10	5	4
<i>Ammobaculites fragmentarius</i>	3	11	6	21	4
<i>Ammobaculites</i> spp.		6	12	9	1
<i>Ammomarginulina lorangerae</i>		1	4		
<i>Ammomarginulina</i> spp.	5	6		4	
<i>Coscinophragma ? codyensis ?</i>		1			
<i>Dorothia smokyensis</i>				1	
<i>Dorothia</i> spp.	5	10	5	7	1
<i>Flabellamina</i> sp. ?			1		
<i>Gaudryina spiritensis</i>	2	5	10	3	
<i>Haplophragmoides crickmayi</i>	3	6	4	6	4
<i>Haplophragmoides howardense</i>	1	3	6	5	6
<i>Haplophragmoides rota</i>	1			5	1
<i>Haplophragmoides</i> spp.	8	5	10	26	6
Lituolidae					1
<i>Miliammina</i> spp.					1
<i>Pseudobolivina rollaensis</i>		2			
<i>Pseudobolivina</i> spp.			3		
<i>Reophax</i> spp.	3	4	4	3	
<i>Reophax</i> sp. cf. <i>R. troyeri</i> ?	1				
<i>Spiroplectammina ammovitrea</i>	11	4	1	6	
<i>Spiroplectammina</i> sp. cf. <i>S. mordensis</i>	1				
<i>Spiroplectammina</i> spp.	4	12	12	15	
<i>Spiroplectammina semicomplanata</i>		2		1	
<i>Textularia</i> spp.	6	9	8	8	
<i>Textularia gravenori</i> ?	2				
<i>Tritaxia</i> spp.	3	7	5		
<i>Trochammina rutherfordi</i>	6	7	10		3
<i>Trochammina</i> spp.	15	25	32	22	2
<i>Trochammina wetterei</i>		1	7	3	
<i>Verneuilina canadensis</i>			5		
<i>Verneuilina</i> spp.	3	5	4	8	
<i>Verneuilinoides bearpawensis</i>	3	8	9	1	
<i>Verneuilinoides</i> sp. cf. <i>V. perplexus</i>		2			
<i>Verneuilinoides</i> spp.	14	16	17	20	3
Unidentified agglutinated	17	22	26	12	1
TOTAL	119	187	213	207	40
Total Benthic	119	187	213	207	40
Total Planktic	0	0	0	0	0
Percent Benthic	100	100	100	100	100
Percent Planktic	0	0	0	0	0
Fish debris					
Plant Material					
Glauconite					
Coal	P				
<i>Inoceramus</i> prisms					

Sample Number	86	88	89	90	91
Stratigraphic Height (m)	277.3	300.9	303.3	305.9	307.2
Genus & Species					
Ataxophragmiidae	8	2	10	5	
<i>Ammobaculites albertensis</i>	5		1	2	
<i>Ammobaculites fragmentarius</i>	5			1	
<i>Ammobaculites</i> spp.	14	1	9	5	
<i>Ammomarginulina</i> spp.	1				
<i>Dorothyia</i> spp.	6		3		
<i>Gaudryina spiritensis</i>	2		1		
<i>Haplophragmoides crickmayi</i>	4		1		
<i>Haplophragmoides rota</i>				1	
<i>Haplophragmoides</i> spp.	13		18		
Lituolidae	11			1	
<i>Saccamina alexandrei</i>	1				
<i>Spiroplectammina ammovitrea</i>	6		3	1	
<i>Spiroplectammina</i> spp.	9		5		1
<i>Textularia</i> spp.	1				1
<i>Tritaxia</i> spp.	1				1
<i>Trochammina rainwateri</i>	3				
<i>Trochammina rutherfordi</i>	4				1
<i>Trochammina</i> spp.	32	1	26	2	
<i>Trochammina wettleri</i>	10		4		
<i>Verneuilina canadensis</i>	2		2		
<i>Verneuilina</i> spp.	9		7		
<i>Verneulinoides bearpawensis</i>	9		7		
<i>Verneulinoides</i> spp.	6		4		
Unidentified agglutinated	16		10	1	
TOTAL	178	4	111	19	4
Total Benthic	178	4	111	19	4
Total Planktic	0	0	0	0	0
Percent Benthic	100	100	100	100	100
Percent Planktic	0	0	0	0	0
Fish debris					
Plant Material					
Glauconite					
Coal					
<i>Inoceramus</i> prisms					

Sample Number	02	03	04	05	107
Stratigraphic Height (m)	309.9	312.6	315.3	316.7	316.7
Genus & Species					
Ataxophragmiidae					1
<i>Ammobaculites</i> spp.			2		1
Lituolidae	1				
<i>Reophax</i> sp. ?				1	
<i>Textularia</i> spp.				1	
<i>Trochammina</i> spp.			3		4
<i>Verneuilinoides</i> spp.	1			1	2
Unidentified agglutinated		1			
TOTAL	2	1	5	3	8
Fish debris					
Plant Material					
Glauconite					
Coal			R	R	
<i>Inoceramus</i> prisms					

Sample Number	98	98	98	100
Stratigraphic Height (m)	320.7	326.1	331.5	334.2
Genus & Species				
Ataxophragmiidae	7	8	6	8
<i>Ammobaculites albertensis</i>		7	2	1
<i>Ammobaculites fragmentarius</i>	3		4	2
<i>Ammobaculites</i> spp.		7	10	4
<i>Ammomarginulina lorangerae</i>		1	1	
<i>Dorothyia</i> spp.	1		2	2
<i>Gaudryina spiritensis</i>		1		
<i>Haplophragmoides crickmayi</i>		1		
<i>Haplophragmoides rota</i>	1	2		1
<i>Haplophragmoides</i> spp.	1	6	10	5
Lituolidae	6	4	2	2
<i>Spiroplectammina ammovitrea</i>	1		1	2
<i>Spiroplectammina</i> spp.		7	5	3
<i>Textularia</i> spp.	1	3	2	
<i>Tritaxia spiritensis</i>				1
<i>Tritaxia</i> spp.				1
<i>Trochammina</i> spp.	1	15	13	9
<i>Trochammina wettereii</i>		1		
<i>Uvigerinammina</i> spp.	1			
<i>Verneuilina canadensis</i>		2	2	3
<i>Verneuilina</i> spp.		3		1
<i>Verneuilinoides bearpawensis</i>		1	2	2
<i>Verneuilinoides</i> sp. cf. <i>V. perplexus</i>	1			
<i>Verneuilinoides</i> spp.		4	6	7
Unidentified agglutinated	4	9	4	2
TOTAL	28	82	72	56
Total Benthics	28	82	72	56
Total Planktics	0	0	0	0
Percent Benthics	100	100	100	100
Percent Planktics	0	0	0	0
Fish debris				
Plant Material				
Glaucinite				
Coal				R
<i>Inoceramus</i> prisms				

Sample Number	101	102	103	105	107	109	111	112
Stratigraphic Height (m)	335.4	336.9	339.4	344.5	349.5	354.7	359.9	362.5
Genus & Species								
Ataxophragmiidae	9	5	1	3		1		1
<i>Ammobaculites albertensis</i>	2	1		3	3		2	
<i>Ammobaculites fragmentarius</i>	4		2	1	3			2
<i>Ammobaculites</i> spp.	11	4		6	2	2	1	8
<i>Ammomarginulina lorangerae</i>	2	1						
<i>Ammomarginulina</i> sp.	1							
<i>Dorothyia</i> spp.	3	3	1	3			2	
<i>Gaudryina spiritensis</i>	4	2				1		
<i>Haplophragmoides chickmayi</i>				1		3		4
<i>Haplophragmoides rota</i>							1	
<i>Haplophragmoides</i> spp.	12	8	4	7	7	12	2	12
Lituolidae	1	2	2	1		1		
<i>Miliammina</i> sp. ?								1
<i>Reophax</i> sp. ?	1							
<i>Spiroplectammina ammovitrea</i>	4			1	1	4		
<i>Spiroplectammina</i> spp.	12	4	3	3	2	1	2	3
<i>Textularia</i> spp.	9	3		1	1	1	2	
<i>Tritaxia spiritensis</i>	1							
<i>Tritaxia</i> spp.	3			1		1		
<i>Trochammina</i> spp.	10	10	9	12	14	8	4	6
<i>Trochammina wetterei</i>		1						
<i>Verneuilina canadensis</i>	3	2		1				
<i>Verneuilina</i> spp.	9	5			3			5
<i>Verneuilinoides bearpawensis</i>	8	4		1	2			
<i>Verneuilinoides</i> spp.	11	6	2	3	5	1		3
Unidentified agglutinated	6	5		1	5	5	2	6
TOTAL	126	66	24	49	48	41	18	51
Total Benthics	126	66	24	49	48	41	18	51
Total Planktics	0	0	0	0	0	0	0	0
Percent Benthics	100	100	100	100	100	100	100	100
Percent Planktics	0	0	0	0	0	0	0	0
Fish debris								
Plant Material								
Glauconite					R			
Coal		R						
<i>Inoceramus</i> prisms					P			

Sample Number	116	117	119	188	122
Stratigraphic Height (m)	367.7	370.3	375.5	379.4	383.4
Genus & Species					
Ataxophragmiidae	9	1	1		1
<i>Ammobaculites albertensis</i>	2	1	2		2
<i>Ammobaculites fragmentarius</i>		3			
<i>Ammobaculites</i> spp.	10	7	4	3	8
<i>Ammomarginulina lorangerae</i>		1			
<i>Bathysiphon</i> sp. ?	1				
<i>Dorothia</i> sp. 1 (Wall'67)		1			
<i>Dorothia</i> spp.	1	2			
<i>Gaudryina spiritensis</i>	3				1
<i>Haplophragmoides crickmayi</i>		2			
<i>Haplophragmoides howardense</i>		2			
<i>Haplophragmoides</i> spp.	17	6	4		5
Lituolidae	1	2			1
<i>Spiroplectammina ammovitrea</i>	4				2
<i>Spiroplectammina</i> spp.	5	3	1		4
<i>Textularia</i> spp.	1				1
<i>Tritaxia spiritensis</i>			1		
<i>Trochammina</i> spp.	19	8	3		9
<i>Trochammina wetterei</i>		1			
<i>Verneuilina canadensis</i>	2				
<i>Verneuilina</i> spp.	10		2		
<i>Verneuilinoides bearpawensis</i>	1		1		1
<i>Verneuilinoides</i> spp.	9	1	1		4
Unidentified agglutinated	2	5	1		3
TOTAL	97	46	21	3	42
Total Benthics	97	46	21	3	42
Total Planktics	0	0	0	0	0
Percent Benthics	100	100	100	100	100
Percent Planktics	0	0	0	0	0
Fish debris					
Plant Material					
Glauconite					
Coal	P	R	R	R	P
<i>Inoceramus</i> prisms		R			

Sample Number	124	125	126	128	127	131	135	139	142	144	148
Stratigraphic Height (m)	388.6	391.2	392.5	393.8	396	406	412.4	419.3	424.4	427.9	431.3
Genus & Species											
Ataxophragmiidae	2	3	1		3	5	1	5		8	7
<i>Ammobaculites albertensis</i>	3	1			2		3	2	3	1	6
<i>Ammobaculites fragmentarius</i>	6	4			8		2	10	2	11	24
<i>Ammobaculites</i> spp.	11	5	6	9	15	14	8	17	6	34	34
<i>Ammomarginulina lorangerae</i>	1	1	1	1	3	1	1	4		3	
<i>Dorothia smokyensis</i>			1		1						
<i>Dorothia</i> sp. 1 (Wall'67)	1										
<i>Dorothia</i> spp.						1	1	3			5
<i>Gaudryina spiritensis</i>	1					1				2	1
<i>Haplophragmoides crickmayi</i>		1			1	2	1	2	3	5	3
<i>Haplophragmoides rota</i>											2
<i>Haplophragmoides</i> spp.	13	11	5	7	11	17	15	29	11	36	65
Lituolidae		1	1		2	1		4	1	2	1
<i>Pseudobolivina rollaensis</i>									1		
<i>Pseudobolivina</i> spp.									4		
<i>Reophax</i> spp.										2	
<i>Reophax</i> sp. ?											1
<i>Saccamina</i> sp.						1					
<i>Spiroplectammina ammovitrea</i>	5	2					2	4		7	3
<i>Spiroplectammina</i> spp.	5	6	1	4	3	5	1	6	6	25	29
<i>Textularia</i> spp.	3			2	1	1	1	1		8	8
<i>Tritaxia spiritensis</i>					1		2				5
<i>Tritaxia</i> spp.				1			1				
<i>Trochammina ribstonensis</i>											1
<i>Trochammina</i> spp.	15	16	11	16	24	25	26	29	5	43	39
<i>Trochammina wetterei</i>			1	1	1	5		3	3	8	
<i>Verneuilina</i> spp.	3	3	2	1	5	3	2	2	3	3	6
<i>Verneulinoides bearpawensis</i>	7	5	2	1	1	6		4		8	7
<i>Verneulinoides</i> sp. cf. <i>V. perplexus</i>											4
<i>Verneulinoides</i> spp.	5	6	1	1	3	10	6	8	3	20	19
Unidentified agglutinated	3	7	4	4	5	8	4	6	1	8	7
TOTAL	84	72	37	48	90	106	77	139	52	234	277
Total Benthics	84	72	37	48	90	106	77	139	52	234	277
Total Planktics	0	0	0	0	0	0	0	0	0	0	0
Percent Benthics	100	100	100	100	100	100	100	100	100	100	100
Percent Planktics	0	0	0	0	0	0	0	0	0	0	0
Fish debris											
Plant Material											
Glauconite											
Coal	P	P		P		P				P	
<i>Inoceramus</i> prisms								C		C	

Sample Number	147	148	149	150
Stratigraphic Height (m)	438.2	441.7	445.1	448.6
Genus & Species				
Ataxophragmiidae			5	1
<i>Ammobaculites albertensis</i>	1	3	2	
<i>Ammobaculites fragmentarius</i>	1	3	7	3
<i>Ammobaculites</i> spp.	11	7	7	6
<i>Ammomarginulina lorangerae</i>	1	2	1	
<i>Ammomarginulina</i> sp.	1			
<i>Dorothia</i> spp.			2	
<i>Gaudryina spiritensis</i>			1	
<i>Haplophragmoides crickmayi</i>				1
<i>Haplophragmoides</i> spp.	13	9	10	11
Lituolidae		1		
<i>Pseudobolivina rollaensis</i>	1			
<i>Spiroplectammina ammovitrea</i>	1		1	3
<i>Spiroplectammina</i> spp.	2	2	4	4
<i>Textularia</i> spp.		4	4	
<i>Trochammina</i> spp.	9	5	16	8
<i>Trochammina wettereii</i>				1
<i>Verneuilina</i> spp.	2	1	2	1
<i>Verneuilinoides bearpawensis</i>	1			2
<i>Verneuilinoides</i> spp.	1	1	8	3
Unidentified agglutinated	2	2	4	2
TOTAL	47	40	74	46
Total Benthics	47	40	74	46
Total Planktics	0	0	0	0
Percent Benthics	100	100	100	100
Percent Planktics	0	0	0	0
Fish debris				
Plant Material				
Glauconite				
Coal	R		R	R
<i>Inoceramus</i> prisms		A	C	P

Appendix 2
Nannofossil assemblages

 

Appendix 3
Macrofossil assemblages and occurrences

Fossils	Age	Stratigraphic height	Formation/ Member
<i>Collignonicerias woollgari</i>	early Middle Turonian ?	37.87 m	Vimy Member
<i>Mytiloides</i> sp.	Turonian	38.49 m	Vimy Member
<i>Mytiloides sybhercynicus</i> ?	early Middle Turonian ?	40.05m	Vimy Member
<i>Mytiloides sybhercynicus</i>	early Middle Turonian	39.61 m	Vimy Member
<i>Collignonicerias woollgari</i> juvenile			
<i>Collignonicerias woollgari</i>	early Middle Turonian	39.70 m	Vimy Member
<i>Mytiloides sybhercynicus</i>	Middle Turonian ?	41.27 m	Vimy Member
<i>Plesiakanthoceras wyomingense</i>	late Middle Turonian	floaters	Vimy Member
<i>Collignonicerias woollgari</i>	early Middle Turonian	50.44 m	Vimy Member
<i>Plesiakanthoceras wyomingense</i>	Lite Middle Turonian ?	128.61 m	Opabin Member
<i>Collignonicerias woollgari</i>	Late Turonian	128.63 m	Opabin Member
<i>Collignonicerias woollgari</i>	Lite Middle Turonian	128.80 m	Opabin Member
<i>Cremnoceramus</i> sp.	Coniacian to Early Santonian	367.71 m	Dowling Member
Scaphitid ammonite	Turonian to Santonian	388.90 m	Thistle Member
<i>Scaphites ventricosus</i>	Late Coniacian to Early Santonian	floaters	Thistle Member
Scaphitid ammonite	Late Cretaceous ?	floaters	Thistle Member

Appendix 4

Geochemical Data

Mill Creek Cretaceous Samples

DEPTH (m)	SAMPLE ID.	QTY (mg)	TMAX (°C)	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
20.48	97-4 SUNKAY	100.55	433.00	0.21	1.81	0.15	0.10	12.00	0.16	1.14	158.50	12.00
32.77	97-9 VIMY	99.95	432.00	0.14	1.87	0.29	0.07	3.01	0.17	0.53	355.00	54.00
35.03	97-13 VIMY	100.60	428.50	1.01	15.23	0.95	0.06	16.34	1.35	3.72	409.00	25.00
42.14	97-22 VIMY	99.95	430.50	0.12	0.59	0.25	0.17	2.49	0.06	0.24	248.50	105.00
57.66	97-28 VIMY	99.95	428.00	0.85	7.45	0.43	0.11	17.45	0.69	2.12	351.00	19.50
67.44	97-33 HAVEN	100.10	431.00	0.32	2.54	1.10	0.11	2.33	0.24	1.81	140.00	60.50
68.27	97-35 HAVEN	100.25	438.50	0.02	0.65	0.04	0.03	18.79	0.05	0.94	68.00	3.50
76.62	97-40 HAVEN	100.65	434.50	0.17	0.54	0.14	0.24	4.76	0.06	0.51	106.50	26.50
84.34	97-44 HAVEN	100.00	427.50	0.15	1.13	0.19	0.12	6.08	0.10	0.89	126.50	20.50
94.71	97-47 HAVEN	100.30	429.50	0.14	1.30	0.33	0.10	3.98	0.12	0.85	152.00	37.50
109.99	97-59 OPABIN	100.25	440.50	0.05	0.62	0.58	0.07	1.07	0.05	1.03	59.50	55.50
114.76	97-60 OPABIN	99.95	443.50	0.04	0.37	0.38	0.09	0.97	0.03	0.72	50.00	52.00
119.18	97-63 OPABIN	99.85	439.00	0.11	0.39	0.20	0.22	1.89	0.04	0.59	65.50	34.50
125.05	97-65 OPABIN	99.95	440.00	0.04	0.37	0.26	0.09	1.45	0.03	0.73	50.50	34.50
253.51	97-73 HAVEN	99.90	431.50	0.17	0.96	0.36	0.15	2.70	0.09	0.65	147.50	54.00
267.74	97-82 OPABIN	100.50	436.50	0.04	0.68	0.07	0.05	10.43	0.06	0.93	72.50	6.50
277.46	97-86 OPABIN	100.15	438.50	0.03	0.38	0.19	0.06	2.03	0.03	0.60	63.00	31.50
298.56	97-87 OPABIN	100.10	439.00	0.02	0.71	0.12	0.03	6.13	0.06	0.87	80.50	12.50
305.85	97-90 OPABIN	101.00	403.50	0.00	0.01	0.31	0.00	0.16	0.00	0.11	45.00	276.50
316.65	97-95 CARDIUM	100.10	435.00	0.01	0.15	0.47	0.06	0.32	0.01	0.33	46.00	144.50
320.71	97-96 MUSKIKI	100.15	443.00	0.00	0.21	0.44	0.00	0.48	0.01	0.62	33.50	70.00
331.51	97-99 MUSKIKI	100.25	439.50	0.01	0.33	0.32	0.03	1.04	0.02	0.64	51.50	49.50
336.91	97-102 MUSKIKI	100.30	439.50	0.05	0.55	0.39	0.09	1.40	0.05	0.73	74.50	53.00
341.95	97-104 MUSKIKI	100.40	435.50	0.02	0.49	0.01	0.04	12.75	0.04	0.61	80.50	1.50
357.28	97-110 MUSKIKI	100.30	427.50	0.22	1.54	0.23	0.13	6.91	0.15	1.03	149.00	21.00
367.71	97-115 MARSHYBANK	99.65	433.50	0.12	1.27	0.36	0.09	3.58	0.11	1.03	123.00	34.00
383.36	97-122 THISTLE	100.70	434.50	0.02	0.54	0.00	0.04	0.00	0.04	0.57	93.00	0.00
391.18	97-125 THISTLE	100.35	435.50	0.07	0.79	0.39	0.08	2.06	0.07	0.77	102.00	50.00
396.82	97-128 THISTLE	100.30	436.00	0.06	1.06	0.20	0.05	5.28	0.09	1.04	101.50	18.50
403.72	97-130 THISTLE	99.85	432.50	0.12	1.44	0.12	0.08	12.40	0.13	1.02	140.50	11.00
414.07	97-136 THISTLE	100.20	434.00	0.05	1.14	0.43	0.04	2.67	0.09	1.15	98.50	36.50
420.97	97-140 THISTLE	100.15	437.50	0.04	0.67	0.51	0.06	1.34	0.06	0.89	75.00	56.00
429.6	97-145 THISTLE	100.05	430.00	0.28	3.05	0.46	0.09	6.67	0.28	1.48	205.50	30.50
438.23	97-147 HANSON	100.00	431.00	0.19	1.82	0.30	0.10	6.42	0.17	1.20	151.50	24.00
445.13	97-149 HANSON	100.05	431.00	0.05	0.74	0.55	0.06	1.37	0.06	0.90	82.00	60.50

Appendix 5
Geochemical Data from Concretions

Sample Number	Type	Bomb #	15 sec	5 min	10 min	15 min	Total XCO3	Total CaCO3	Total FeCO3	Total Silici.
Standard	STD	2	155	155	155	155	100.0	100.0	0.0	0.0
Standard	STD	3	176	175	175	175	100.0	100.0	0.0	0.0
Standard	STD	2	160	160	160	160	100.0	100.0	0.0	0.0
Standard	STD	3	170	170	170	170	100.0	100.0	0.0	0.0
Average	AVG	2	157.5	157.5	157.5	157.5	N/A	N/A	N/A	N/A
Average	AVG	3	173	172.5	172.5	172.5	N/A	N/A	N/A	N/A
30.40	S	2	0	29	29	32	20.3	0.0	20.3	79.7
49.12	S	3	19	39	54	60	34.7	11.0	23.7	65.3
76.60	S	2	34	44	46	47	29.8	21.6	8.3	70.2
95.12	S	3	90	107	109	109	63.0	52.0	11.0	37.0
102.62	S	2	0	0	0	0	0.0	0.0	0.0	100.0
371.07	S	3	11	19	24	24	13.9	6.4	7.5	86.1
395.07	S	2	0	0	0	0	0.0	0.0	0.0	100.0
398.07	S	3	25	25	25	25	14.5	14.5	0.0	85.5
Standard	STD	2	160	157	N/A	N/A	100.0	100.0	0.0	0.0
Standard	STD	3	170	170	N/A	N/A	100.0	100.0	0.0	0.0
399.57	S	2	0	0	N/A	N/A	0.0	0.0	0.0	100.0
404	S	3	24	25	N/A	N/A	14.7	14.1	0.6	85.3
423	S	2	0	0	N/A	N/A	0.0	0.0	0.0	100.0
425.23	S	3	29	30	N/A	N/A	17.6	17.1	0.6	82.4
30.40	C	2	38	46	46	49	30.6	23.8	6.9	69.4
49.12	C	3	130	151	151	154	90.6	76.5	14.1	9.4
76.60	C	2	55	64	75	75	46.9	34.4	12.5	53.1
95.12	C	3	31	39	41	42	24.7	18.2	6.5	75.3
102.62	C - I	2	50	67	70	73	45.6	31.3	14.4	54.4
102.62	C - O	3	49	65	70	73	42.9	28.8	14.1	57.1
371.57	C	2	50	64	66	69	43.1	31.3	11.9	56.9
395.07	C	2	44	68	76	74	46.3	27.5	18.8	53.8
395.07	C - I	3	34	65	68	71	41.8	20.0	21.8	58.2
398.07	C - O	3	41	50	53	55	32.4	24.1	8.2	67.6
Standard	STD	2	160	160	N/A	N/A	100.0	100.0	0.0	0.0
Standard	STD	3	172	172	N/A	N/A	100.0	100.0	0.0	0.0
Standard	STD	2	166	163	162	161	100.0	100.0	0.0	0.0
Standard	STD	3	182	180	178	178	100.0	100.0	0.0	0.0
Standard	STD	2	160	158	158	158	100.0	100.0	0.0	0.0
Standard	STD	3	174	172	172	171	100.0	100.0	0.0	0.0
Standard	STD	2	162	162	152	141	100.0	100.0	0.0	0.0
Standard	STD	3	168	166	166	166	100.0	100.0	0.0	0.0
Average	AVG	2	163	160.5	160	159.5	100.0	100.0	0.0	0.0
Average	AVG	3	174.67	172.67	172	171.67	100.0	100.0	0.0	0.0
399.57	C - I	2	0	40	48	53	32.5	0.0	32.5	67.5
399.57	C - O	3	22	55	54	56	32.1	12.6	19.5	67.9
404	C	2	60	74	85	85	52.1	36.8	15.3	47.9
423	C	3	59	74	76	80	45.8	33.8	12.0	54.2
425.23	C	3	90	112	115	118	67.6	51.5	16.0	32.4
Standard	STD	2	170	170	170	N/A	100.0		0.0	0.0
Standard	STD	3	172	172	N/A	N/A	100.0		0.0	0.0

Figure A5-1 Spot scan ESD spectrum of framboidal pyrite infilling foraminiferal test in Sample 423 m.

Figure A5-2 Spot scan ESD spectrum of a foraminiferal test outer wall in Sample 423 m.

Figure A5-3 Spot scan ESD spectrum of the sediment matrix around framboidal pyrite-infilled foraminifera in Sample 423 m.

Figure A5-4 Spot scan ESD spectrum of matrix infilling a gastropod shell in Sample 371.07 m.

Figure A5-5 Spot scan ESD spectrum the shell of a gastropod in Sample 371.07 m.

Figure A5-6 Spot scan ESD spectrum of the matrix surrounding a gastropod shell in Sample 371.07 m.

Figure A5-7 Area scan ESD spectrum of the outer matrix surrounding a gastropod shell in Sample 371.07 m.

Figure A5-8 XRD spectrum of inner concretion of Sample 395.07 m.

Angle [°2 θ]	d-value a1 [Å]	d-value a2 [Å]	Peak width [°2 θ]	Peak int [counts]	Back. int [counts]	Rel. int [%]	Signif.
17.765	4.4437	4.4546	0.320	38	24	2.5	1.20
20.475	4.3279	4.3406	0.220	86	24	5.7	1.01
20.785	4.2459	4.2564	0.180	132	24	12.0	2.20
22.540	3.8984	3.9080	0.140	123	24	6.1	1.93
23.205	3.8300	3.8395	0.200	132	24	8.7	1.27
23.665	3.7566	3.7659	0.120	35	24	2.3	0.89
24.895	3.5737	3.5825	0.250	119	24	7.9	0.83
25.855	3.4393	3.4477	0.140	350	24	23.1	3.59
26.565	3.3424	3.3496	0.140	625	24	41.3	9.73
28.100	3.1730	3.1808	0.260	52	24	3.4	0.83
28.765	3.1011	3.1088	0.260	216	24	14.3	2.84
29.550	3.0175	3.0249	0.140	1313	24	100.0	16.10
31.565	2.8324	2.8373	0.060	228	24	15.1	1.20
32.045	2.7928	2.7977	0.060	459	24	30.3	1.24
32.305	2.7689	2.7737	0.160	246	24	16.3	0.76
32.865	2.7214	2.7261	0.160	123	24	8.1	1.41
33.140	2.7010	2.7077	0.140	202	24	13.3	3.03
34.175	2.6216	2.6280	0.090	106	24	7.0	0.90
36.150	2.4827	2.4889	0.160	161	24	10.7	2.57
36.640	2.4507	2.4567	0.100	92	24	6.1	0.83
38.510	2.3358	2.3416	0.320	25	24	1.7	1.07
39.550	2.2751	2.2807	0.100	190	24	12.6	1.76
40.120	2.2457	2.2513	0.240	76	24	5.0	2.84
40.365	2.2065	2.2119	0.240	55	24	3.6	2.58
42.565	2.1222	2.1275	0.090	149	24	9.0	0.75
43.020	2.1018	2.1069	0.140	189	24	7.1	1.77
43.335	2.0863	2.0914	0.120	144	24	9.5	2.22
44.240	2.0545	2.0596	0.140	46	24	3.1	1.69

Table A5-9 Peaks and d-spacing for XRD spectrum of inner concretion of Sample 395.07 m.

numbering different from Figures? Table B-1?

Figure A5-10 XRD spectrum of outer concretion of Sample 395.07 m.

A5-9, 2

Angle [°2θ]	d-value d1 [Å]	d-value d2 [Å]	Peak width [°2θ]	Peak int [counts]	Back. int [counts]	Rel. int [%]	Signif.
17.565	4.4437	4.4546	0.320	38	24	2.5	1.20
20.475	4.3259	4.3406	0.080	86	24	5.7	1.01
20.725	4.2459	4.2564	0.100	162	24	12.0	2.20
22.640	3.8984	3.9000	0.140	123	24	6.1	1.93
23.225	3.8320	3.8395	0.060	132	24	8.7	1.27
23.665	3.7566	3.7659	0.120	35	24	2.3	0.89
24.895	3.5737	3.5825	0.030	119	24	7.9	0.83
25.355	3.4393	3.4477	0.140	350	24	23.1	5.59
25.655	3.3424	3.3486	0.140	625	24	41.3	9.73
26.120	3.1730	3.1808	0.050	52	24	3.4	0.83
26.765	3.1011	3.1068	0.060	216	24	14.3	2.84
29.550	3.0175	3.0249	0.140	1513	24	100.0	15.16
31.535	2.8324	2.8373	0.060	228	24	15.1	1.20
32.845	2.7903	2.7977	0.060	458	24	30.3	1.24
33.325	2.7639	2.7757	0.160	246	24	16.3	0.76
32.555	2.7214	2.7281	0.160	123	24	8.1	1.41
33.140	2.7010	2.7077	0.140	202	24	13.3	3.03
34.175	2.6216	2.6280	0.060	105	24	7.0	0.90
35.150	2.4827	2.4889	0.160	161	24	10.7	2.57
35.640	2.4507	2.4567	0.100	92	24	6.1	0.83
38.510	2.3359	2.3416	0.320	25	24	1.7	1.07
37.552	2.2751	2.2827	0.100	190	24	12.6	1.76
40.120	2.2457	2.2513	0.240	76	24	5.0	2.84
43.365	2.2065	2.2119	0.240	55	24	3.6	2.58
42.565	2.1222	2.1275	0.090	149	24	9.6	0.75
45.020	2.1018	2.1069	0.140	108	24	7.1	1.77
45.335	2.0563	2.0614	0.120	144	24	9.5	2.22
44.240	2.0545	2.0596	0.140	46	24	3.1	1.69

Table B-2 Peaks and d-spacing for XRD spectrum of outer concretion of Sample 395.07 m.

Figure A5-12 XRD spectrum of shale host rock for Sample 395.07 m.

A5-10, 2

Angle [°2 θ]	d-value d_1 [Å]	d-value d_2 [Å]	Peak width [°2 θ]	Peak int [counts]	Back. int [counts]	Rel. int [%]	Signif.
9.935	9.8891	9.9135	0.200	71	19	2.4	0.77
12.575	7.8534	7.8529	0.320	61	13	2.7	1.61
17.825	4.9721	4.9543	0.400	32	16	1.1	1.05
19.892	4.4683	4.4712	0.150	128	22	4.3	2.52
23.942	4.2389	4.2494	0.150	1076	25	36.5	3.81
25.305	3.8165	3.5254	0.400	59	42	2.0	1.61
26.720	3.3336	3.3416	0.200	2948	42	100.0	15.11
28.042	3.1796	3.1675	0.150	67	44	2.3	1.39
31.042	2.8785	2.8859	0.150	72	44	2.5	3.78
34.658	2.5846	2.5909	0.100	74	37	2.5	1.00
35.815	2.5578	2.5633	0.100	71	40	2.4	1.00
36.638	2.4513	2.4573	0.150	296	30	10.0	2.25
37.820	2.3781	2.3839	0.400	25	30	1.0	0.64
39.555	2.2760	2.2816	0.200	225	30	7.6	4.49
40.395	2.2311	2.2366	0.150	90	30	3.1	1.16
42.545	2.1232	2.1284	0.200	174	29	5.9	3.88
45.892	1.9763	1.9812	0.150	83	30	2.8	1.13
49.190	1.8968	1.8915	0.300	6	22	0.2	0.79
50.250	1.8149	1.8193	0.250	202	22	9.6	10.43
54.935	1.6700	1.6742	0.100	117	28	4.0	1.00
55.420	1.6566	1.6626	0.100	55	30	1.9	1.00

Table B-3 Peaks and d-spacing for XRD spectrum of shale host rock of Sample 395.07 m.

Appendix 6
Elemental Analysis Data from Foraminifera

Sample #	Print out #	Image #
MC97-19	MC1-61	1June_61.tif
MC91-31	MC1-59	1June_59.tif
MC97-36	MC1-60	1June_60.tif
MC97-66	MC1-62	1June_62.tif
MC97-66	MC1-63	1June_63.tif

Filename	Voltage	Label name	Elements	Description
1june1	15 kV	mc66a1	S, Fe	bright areas
1june2	15 kV	mc66a2	S, Fe	bright areas
1june3	15 kV	mc66a3	Al	contamination
1june4	15 kV	mc66a4	Al	contamination
1june5	20 kV	mc66a5	Si	inside test
1june6	20 kV	mc66a6	Si	inside test
1june7	20 kV	mc66a7	Si	edge outside test
1june8	20 kV	mc66a8	Si, K	outside test
1june9	20 kV	mc66a9	Si	very edge test
1june10	20 kV	mc66b1	Fe, minor S	big bright round patch
1june11	20 kV	mc66b2	Fe, minor S, Si, Al, P	big bright round patch
1june12	20 kV	mc66b3	Fe, + Si, Al, minor P, S	greyish mottled
1june13	20 kV	mc66b4	Si	inside test
1june14	20 kV	mc66b5	Si	outside test
1june15	20 kV	mc31-1	Ca	light coloured grain
1june16	20 kV	mc31-2	Si, K, Al, minor Ca	other light grain
1june17	20 kV	mc31-3	Si	central clast
1june18	20 kV	mc31-4	Si	outside clast
1june19	20 kV	mc36-1	Ca	infill light
1june20	20 kV	mc36-2	Si	grey clasts
1june21	20 kV	mc36-3	Si, Ca, S	white edge bit
1june22	20 kV	mc19-1	Si, Ti	darkish area
1june23	20 kV	mc19-2	Ca	infill centre
1june24	20 kV	mc19-3	Ca	outside test
1june25	20 kV	mc19-4	Ca	inside chamber

X-RAY: 0 - 20 keV
Live: 100s Preset: 100s Remaining: 0s
Real: 127s 21% Dead

FS= 4K
MEM1:mc19-1
4.506 keV 9.6 >
ch 235= 1290 cts

6"

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