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The Colorado Group in the Cold Lake Heavy Oil Area,
East-central Alberta: Biostratigraphy,
Paleoenvironments and Regional Correlations

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of
Master of Science

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ABSTRACT

The Colorado Group in the heavy oil area of Cold Lake, north-eastern Alberta represents a relatively condensed section of mudstone dominated sedimentation within the Western Interior Sea. Two long cores covering the entire Colorado Group provide a unique opportunity for a detailed multidisciplinary study in order to establish a biostratigraphic framework and to interpret paleoenvironmental changes in an area that has received attention only for its heavy-oil bearing Mannville Group. Regional stratigraphic wireline log correlations established broad geometries of the stratigraphic subdivisions, as established in the reference cores.

Five foraminiferal zones and nine subzones are recognized. Several intervals barren of foraminifera characterize the study area and reflect anoxic/dysoxic events. Paleoenvironmental interpretations are based on sedimentological, micropaleontological, paleoecological, nannofossil, geochemical (Rock Eval) data and log correlations. The Joli Fou Formation represents continuous transgression of the seaway after the Mannville unconformity. The Viking Formation in the Cold Lake area consists of a transgressive-regressive cycle. The Westgate Formation is characterized by intermittent dysoxic to anoxic benthic conditions. The Fish Scales Formation was deposited under anoxic bottom water conditions, which caused loss of all Albian foraminiferal fauna. The widespread bioclastic layer at the base of the Fish Scales Formation was deposited in relatively deep water during transgression following a sea-level lowstand at the end of the Albian. The bottom water continued to be inhospitable for benthic foraminifera during deposition of

the Belle Fourche Formation. During peak transgression of the Greenhorn Cycle, warm water of normal salinity from the Tethyan Sea entered the WCSB, bringing planktic foraminifera and nannofossils to the basin while causing anoxic bottom water. The Carlile Formation, which occurs in southern Alberta and southwest Saskatchewan, and represents the regressive phase of the Greenhorn Cycle, is absent at Cold Lake, modifying existing paleogeographic maps of the Middle to Late Turonian Western Interior Sea, with a possible shoreline south of the Cold Lake area. The Verger Member of the Niobrara Formation records initial transgression of the Niobrara Cycle and a dysoxic benthic environment. The Medicine Hat equivalent interval, which contains little sandstone compared to the counterpart in southern Alberta, was deposited during a slow sea-level drop and a following sea-level rise. The First White Specks Member records peak transgression of the Niobrara Cycle, in which the Tethyan watermass spreads into western Canada creating normal to low-salinity surface water and anoxic benthic environments.

The Cold Lake cores represent sedimentation in an area of low accommodation space distant to sources of coarse sediment. Signs of sea-level falls are subtle biological changes without pebble beds. Coarse components that are reworked during subsequent transgression in these fine sediments are bioclastic components.

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INTRODUCTION

The Cold Lake area, well known for one of the largest heavy oil deposits in North America with 100 billion bbl of heavy oil reserves, is located in east-central Alberta in close vicinity to the Saskatchewan border, stretching from Range 1W4 to 8W4 and from Township 53 to 68 (Fig 1).

Previous studies focused on the hydrocarbon productive Lower Cretaceous Mannville Group (e.g., Mattison, 1991; McCrimmon, 1996; Clack, 1968; McCrimmon and Arnott, 2002), but little attention was paid to the overlying shales of the Colorado Group in the Cold Lake area. Placement of the boundary between the Mannville and Colorado groups was studied by Mattison and Wall (1993). This study targets the overlying Colorado Group by combining micropaleontology, sedimentology and regional log correlations.

The study is based on two long cores provided by Imperial Oil Ltd. that cover the entire Colorado Group in the Cold Lake area and therefore provide excellent reference sections for a large interval of Cretaceous sedimentation in an area of limited data.

The main objectives are: a) to establish a biostratigraphic framework based on foraminifera for the Colorado Group in the Cold Lake Heavy Oil area, which will be correlated with the existing one of Caldwell et al. (1978) and other more recent studies; b) to interpret paleoenvironmental settings and define the relative sea-level history of the Western Interior Sea in this region; c) to produce a detailed correlation between wireline log signatures, sedimentology and micropaleontological assemblage changes to establish

a sequence stratigraphic framework; d) to compare foraminiferal response to paleoecological changes; and e) to test the recently proposed stratigraphy for the Upper Colorado Group that was established in the Sweetgrass Arch region, for the more northern Cold Lake region.

Figure 1. Location map of study area and the two reference cores in this study with major tectonic elements in western Canada (modified after Leckie and Smith, 1992; Mattison and Wall, 1993). Regional cross-sections are marked by A-A', B-B' and C-C'.

REGIONAL GEOLOGY

Geological Setting

The Western Canada Sedimentary Basin (WCSB) is the Canadian part of the western North America foreland basin, an elongate, asymmetric trough that developed between the eastern flanks of the Rocky Mountains and the stable interior platform of the North American craton. At its maximum extent, the foreland basin was more than 6000 km long, stretching from the Arctic Ocean (Boreal Sea) to the Gulf of Mexico (Tethyan Sea), and up to 1600 km wide, extending from westernmost Ontario to central British Columbia. Over 6 km of sediment was deposited along the western margin of the basin during its evolution from the Middle Jurassic to the Oligocene (Leckie and Smith, 1992). The sediment tapers northeastward in the WCSB, forming a wedge covering the Precambrian crystalline basement of the North American craton (Price, 1994).

The tectonic and stratigraphic history of the WCSB is closely related to the evolution of the Western Canada Cordillera. The depositional history of the WCSB can be divided into five cycles, each representing strata bounded by major unconformities or lithologic changes and corresponding to specific tectonic events in the Cordillera to the west (Leckie and Smith, 1992).

The Albian to Santonian Colorado Group was deposited during an approximately 25 to 30 million year period during the third cycle referred to above. Global sea level was high during this time, with specific sea-level maxima in the Late Albian, Early Turonian and Middle Santonian (Caldwell, 1984; Haq et al., 1987). Deposition at this time also

coincided with a regional tectonic downflexing of the North American craton (Lambeck et al., 1987). At times of highstands, warm Tethyan water from the proto-Gulf of Mexico (Tethyan Sea) mixed with the cooler Boreal water extending south from the Cretaceous Arctic Ocean to form a shallow epeiric seaway (Leckie et al., 1994) (Fig. 2).

The Colorado Group unconformably overlies the Mannville Group in the subsurface of central and southern Alberta and Saskatchewan (Fig. 3). It is overlain conformably to disconformably by the Milk River and Lea Park formations. Equivalent strata in the WCSB are the Alberta Group in the central and southern Foothills, the upper part of the Fort St. John Group and the lower part of the Smoky Group in the Northwest Plains, the Westgate and Belle Fourche members of the Ashville Formation and the Favel, Morden, and Niobrara formations in southern Manitoba. The Colorado Group and equivalent strata form an extensive eastward-tapering wedge of predominantly marine shales. Strata extend eastward for about 1100 km from southwestern Alberta, where it is about 700 m in thickness, to the Manitoba Escarpment, where it thins to 200 m. In northwestern Alberta, the Colorado Group exceeds 1200 m in thickness (Leckie et al. 1994). In the Cold Lake area of east-central Alberta, this stratigraphic package is about 180 m thick.

Major structural elements that influenced the late Cretaceous deposition within the WCSB include the Sweetgrass Arch in southeastern Alberta, the Peace River Arch in northwestern Alberta and northeastern British Columbia, and the Bowdoin Dome and Swift Current Platform in southern Saskatchewan. The Sweetgrass Arch was a positive structural feature during Laramide Orogeny and possibly during the Jurassic. In early Jurassic and late Cretaceous time this arch separated the Williston Basin, located in

a. Early Late Albian

b. Late Late Albian

c. Late Early Turonian

d. Late Late Turonian

e. Early Coniacian

f. Middle Santonian

Figure 2. Marine occupations during different stages from Late Albian to Late Santonian. The star indicates location of the Cold Lake area in this study (a-c: modified after Williams and Stelck, 1975; d-f: modified after Nielsen, 2002)

Figure 3. Stratigraphic chart showing the studied interval in the Cold Lake area and its correlations to nearby regions. Absolute ages in column 1 after Obradovich (1993); column 2 after McNeil and Caldwell (1981); columns 3 and 4 after Stott (1963, 1984); column 5 after Nielsen et al.(2003); column 6 after Simpson (1982).

Saskatchewan, Montana and North Dakota, from the Alberta Basin (Fig. 1). The Peace River Arch, uplifted during the Cambrian, started to subside during the Mississippian and remained a topographic low during the Early Cretaceous (Cant, 1988). By the middle to late Albian the arch started to rise and may have become a subtle high again by the late Turonian-early Santonian (Williams, 1958; Leckie et al., 1994).

History of Stratigraphic Nomenclature and Lithology

The Colorado Group consists predominantly of shale and mudstone interspersed with relatively thin sandstone and conglomerate beds. It appears to be uniform in composition and therefore remained largely undifferentiated until the early 1990's. Three wireline log markers and typical shale facies including the First and Second White Speckled Shales and Fish Scales zone have served for informal subdivision (Sanderson, 1946; Gleddie, 1949). Rudkin (1964) informally subdivided the Colorado Group into upper and lower subgroups, and drew the boundary at the base of the Fish Scales zone (Fig. 3). Bloch et al. (1993) differentiate the Upper Albian to Lower Turonian portion of the Colorado Group into the Westgate, Fish Scales, Belle Fourche, and Second White Specks formations. Nielsen et al. (2003) studied the upper Colorado Group in southeastern Alberta and southern Saskatchewan, and subdivided the strata above the Second White Specks Formation into the Carlile Formation and Niobrara Formation. These recent studies, in addition to earlier work on stratigraphy and biostratigraphy of the Colorado Group (e.g., Wickenden and Shaw, 1943; Stott, 1963, 1982; Simpson, 1982; Lang and McGugan, 1988), have resulted in a unified regional stratigraphic framework of the Colorado Group (Fig. 3).

Basal Colorado Sandstone

In southeastern Alberta and southern Saskatchewan, the basal unconformable contact between the Colorado Group and the underlying Mannville Group is generally represented by a thin conglomerate layer containing chert or intraformational shale clasts, which is named the Basal Colorado Sandstone. It is a thin (less than 1 m thick), sheet-like unit underlying the Joli Fou marine shales and overlying the non-marine Mannville Group (Banerjee, 1989). In central to western Alberta, the Basal Colorado Sandstone is absent and the Joli Fou Formation lies directly above the Mannville Group.

Joli Fou Formation

During the early Late Albian, relative sea level reached highstand, resulting in the Joli Fou Seaway, which connected the Boreal and Tethyan seas for a brief time (Stelck and Koke 1987; Fig. 2a). It is recorded in the strata of central Alberta as the Joli Fou Formation (Stritch and Schröder-Adams, 1999), which is comprised of a dark grey, noncalcareous, marine shale with a small proportion of interbedded fine- to medium-grained sandstone. Minor amounts of nodular phosphorite, bentonite, pelecypod coquinas and concretions of siderite, calcite and pyrite also occur. The Joli Fou Formation is extremely widespread, and is distributed throughout the subsurface. In parts of northwestern Alberta and northeastern British Columbia it is called Lower Hasler Formation. In western and central regions, the Joli Fou Formation disconformably overlies the Mannville Group and underlies the Viking Formation, disconformably in places. Southwestward, the Joli Fou passes laterally into the Bow Island Formation and is not known to occur in outcrop of the southern Rocky Mountain Foothills.

Viking Formation

The Tethyan connection of the Joli Fou Seaway was terminated by a major shallowing event depositing the sandstone-rich Viking Formation. Several sea-level lowstands may be present in the Viking Formation, with the major one being dated at 97 Ma (Leckie 1986). During these sea-level lowstands, incised valleys were cut and subsequently infilled with estuarine sediments during sea-level rise in areas, which form now the Sundance, Edson and Crystal oil pools of west-central Alberta (Leckie and Smith, 1992).

Westgate Formation

In the latest Albian, the Boreal Sea advanced southward, forming the Mowry Sea and depositing the shales of the Westgate Formation in central Alberta (Bloch et al. 1993; Fig. 2b). This transgression marks the beginning of the eustatic Greenhorn marine cycle (Caldwell, 1984).

The Westgate Formation is a mudstone-dominated interval with interbedded wave rippled, hummocky cross-stratified fine sandstones. Abundant benthic foraminifera and bioturbation suggest a well oxygenated distal environment with occasional storm influence (Schröder-Adams et al., 1996). Towards the top of the formation, a relative shallowing of the basin is indicated by a widespread coarsening upwards trend, an increase in foraminiferal species with coarse-grained, robust tests and an increase in bioturbation (Schröder-Adams et al., 1996).

Fish Scales Formation

The Fish Scales Formation, named by Bloch et al. (1993), includes strata

previously assigned to the zones referred to as Base of Fish Scales, Fish Scale Marker Bed, Fish Scale Sandstone and Fish Scale zone. It is a non-calcareous claystone to mudstone less than 20 m in thickness, which is generally well laminated, with abundant fish remains and algal cysts (Bloch et al., 1993). The base of the Fish Scales Formation is a thin, parallel or cross-laminated sandstone or pebble layer with abundant disarticulated fish and other vertebrate remains (Schröder-Adams et al., 1996), which is also known as the Fish Scales Zone. This sharp lithological contact with the underlying Westgate Formation and its equivalent strata is a basin-wide marker and is associated with the Albian/Cenomanian (Lower/Upper Cretaceous) boundary.

The Fish Scales Formation is characterized by high organic carbon contents and lack of benthic foraminifera, and is interpreted as representing deposition under anoxic bottom conditions. In Saskatchewan and Manitoba, the base of the Fish Scales Zone may represent a major hiatus with substages missing below and above (Caldwell et al., 1978), whereas in western Alberta, strata above and below the marker unit appear to be more conformable (Stelck and Armstrong, 1981).

Belle Fourche Formation

The contact between the Fish Scales and Belle Fourche formations is conformable and transitional. The Belle Fourche Formation is a westward-thickening wedge of non-calcareous to slightly-calcareous mudstone and siltstone (Bloch et al., 1993). In comparison to the Fish Scales Formation, the Belle Fourche Formation is bioturbated, contains several bentonite layers and coarsening-upward sandstones. In some cases, no change in sediment composition or texture is observed and the basal Belle Fourche may only be differentiated from the underlying Fish Scales Formation by a change in organic

matter type and abundance (Bloch et al., 1993).

In some places rare to common agglutinated foraminiferal species of low diversity mark the Belle Fourche Formation, indicating a slight and gradual improvement for benthic organisms during Belle Fourche time. The strongly fluctuating numbers of foraminiferal species indicate an unstable environment, and are interpreted to be a result of the breakdown of watermass stratification during storms (Schröder-Adams et al. 1996).

Second White Specks Formation

During the period between the latest Cenomanian to early Turonian, sea level in the Western Interior Seaway (WIS) reached a maximum and the Greenhorn Sea was formed (Kauffman, 1984; Schröder-Adams et al., 1996; Fig. 2c). During this period, the Second White Specks Formation was deposited. The formation is a calcareous claystone to siltstone in eastern and southern Alberta grading to a calcareous siltstone in northwest Alberta. The thickness of the Second White Specks Formation is generally less than 20 m in southern Alberta, but reaches up to 55 m in southeast Alberta (Bloch et al., 1993). The contact with the underlying Belle Fourche Formation is marked by a bed of coarse bioclastic debris 1 to 5 cm thick. A bentonite bed up to 20 cm thick and a calcite concretionary layer up to 30 cm thick commonly occur in association with this basal bioclastic layer. The shales of the Second White Specks Formation have high total organic carbon content, high hydrogen indices and high radioactivity on well logs. Ammonites, *Inoceramus*, bentonites, pyrite, calcite concretions and fish debris are common (Bloch et al., 1993; Schröder-Adams et al., 1996).

During latest Cenomanian to early Turonian sea-level highstand of the Greenhorn Cycle, warm Tethyan water of normal salinity entered the WCSB, which is indicated by

abundant planktic foraminifera and nannofossils. The total lack of benthic foraminifera in most locations, together with well-laminated, non-bioturbated sediments (Bloch et al., 1993; Schröder-Adams et al., 1996), indicates persistent bottom-water anoxia.

Carlile Formation

The Late Turonian Carlile Formation, recently proposed by Nielsen et al. (2003) for the Sweetgrass Arch region, represents the regressive part of the Greenhorn Cycle. It is non-calcareous shale with minor fine sandstone partings and a middle interval with abundant siderite concretions. The lower boundary is represented by a distinct lithological, microfaunal and floral change from the unconformably underlying calcareous shale of the Second White Specks Formation (Ridgley et al., 2001). The Carlile Formation is informally subdivided into a lower, middle and upper member. The lower unit is a homogenous platy to flaggy, non-calcareous, grey to bluish-grey, non-bioturbated shale changing gradually upwards to a slightly harder grey flaggy to slabby shale. The middle unit is characterized as a slightly bioturbated, silty grey shale with abundant 5-15 cm thick, isolated siderite concretions. The upper unit contains one to two intensively bioturbated, upward-coarsening intervals from silt to fine sandstone.

Niobrara Formation

The Coniacian to Santonian Niobrara Formation represents the transgressive part of the Niobrara Cycle. It unconformably overlies the Carlile Formation in most areas of southeastern Alberta and southern Saskatchewan. In central Saskatchewan, it directly overlies the Second White Specks Formation (Leckie et al., 1994; Schröder-Adams et al., 1996). The Niobrara Formation is characterized by partly calcareous to calcareous shale

with intervals of abundant bentonites and widespread fine-grain sandstones. This formation is subdivided in ascending order into the bentonite-rich Verger Member, the sandstone-rich Medicine Hat Member and the calcareous First White Specks Member (Nielsen et al. 2003). The basal Niobrara Formation is characterized by an interval rich in bentonites, which serves as criteria for boundary placement to the underlying Carlile Formation. The upper boundary with the overlying Milk River/Lea Park Formation is a sharp boundary separating dark, finely-laminated, calcareous shale of the First White Specks Member from intensely bioturbated, silty sandstones or siltstones.

Foraminiferal Biostratigraphy

Caldwell et al. (1978) established 10 foraminiferal zones and 11 subzones that span the late Albian to Santonian Colorado Group of western Canada (Fig. 4). This scheme then was redefined and refined by different authors based on studies of different areas in western Canada (e.g., Stelck and Koke, 1987; Stelck, 1991; Bloch et al., 1993; Schröder-Adams et al., 1998; Stritch and Schröder-Adams, 1999).

The basal *Haplophragmoides gigas* Zone was put forth by Wickenden (1932) and formally named by Caldwell et al. (1978), who did not subdivide this zone. In the Peace River district of northeastern British Columbia, Stelck and Koke (1987) and Stelck (1991) named seven subzones of the *H. gigas* Zone. However, only two of the subzones, those of *H. gigas gigas* and *H. gigas phaseolus*, have been recognized outside northeastern British Columbia (Caldwell et al., 1993). In the Canadian prairie region, this zone is widely identified as a biostratigraphic counterpart of the Joli Fou Formation and its equivalent (Caldwell et al., 1978, 1993). In addition, it may occupy the lower part of or the Viking

Figure 4. Foraminiferal zones and subzones of late Albian to Santonian stages and their relationship with sea-level change (modified after Caldwell et al., 1978)

STAGES	ZONES	SUBZONES	WCSB SEA LEVEL FALL RISE
SANTONIAN	<i>Globigerinelloides</i> sp.	<i>Heterohelix</i> cf. <i>reussi</i>	
		<i>Gavelinella henbesti</i>	
CONIACIAN	<i>Bullopore laevis</i>		Niobrara Cycle
	<i>Trochammina</i> sp.		
	<i>Pseudoclavulina</i> sp.		
TURONIAN	<i>Hedbergella loetterlei</i>	<i>Whiteinella aprica</i>	
		<i>Clavibergella simplex</i>	
CENOMANIAN	<i>Flabellamina gleddiei</i>	<i>Haplophragmoides spiritense</i>	Greenhorn Cycle
		<i>Ammobaculites pacalis</i>	
	<i>Verneuilinoides perplexus</i>	<i>Gaudryina irenensis</i>	
		<i>Ammobaculites gravenori</i>	
	<i>Textularia alcesensis</i>		
ALBIAN (part)	<i>Miliammina manitobensis</i>	<i>Haplophragmium swareni</i>	Mowry Sea
		<i>Haplophragmoides postis goodrichi</i>	
		<i>Verneuilina canadensis</i>	
	<i>Haplophragmoides gigas</i>		Joli Fou Sea

Figure 4

Formation in central and east-central Alberta (Stritch and Schröder-Adams, 1999, Figs. 6, 8).

In the foredeep of the Western Interior Basin in northeastern British Columbia, the late Late Albian *Miliammina manitobensis* Zone contains three subzones (Fig. 4). However, similar to the *H. gigas* Zone, only the basal *Verneuilina canadensis* Subzone is widespread throughout the WCSB (Caldwell et al., 1978, 1993). In the plains of western Saskatchewan and Alberta, this zone occurs in the Westgate Formation (Bloch et al., 1993; Caldwell et al., 1978). In central Alberta, the *M. manitobensis* Zone may range down into the Viking Formation, which underlies the Westgate Formation (Stritch and Schröder-Adams, 1999).

The *Textularia alcesensis* fauna has been found in the Peace River plains and Rocky Mountain foothills of northeastern British Columbia and northwestern Alberta, from the base of the Fish Scale Marker to the base of the Dunvegan Formation (Caldwell et al., 1978), and at Cadomin (Leckie et al., 2000). From central Alberta to the Manitoba Escarpment, the Fish Scales Formation, named by Bloch et al. (1993), is barren of foraminifera, and the *T. alcesensis* Zone is absent (Bloch et al., 1993; Schröder-Adams et al., 1996; McNeil and Caldwell, 1981). Where the zone occurs strata straddling the Albian/Cenomanian boundary seem to be better preserved.

The early Late Cenomanian *Verneulinoides perplexus* Zone has been found in the lower Kaskapau Formation of the Smoky River Group in the Peace River district of northeastern British Columbia and northwestern Alberta, where the zone is divided into two subzones: *Ammobaculites gravenori* and *Gaudryina irenensis* (Caldwell et al., 1978). Only a single zone can be distinguished farther east throughout the WCSB (Caldwell et

al., 1978). In the central and southern plains of Alberta and western Saskatchewan, this zone is found in the Belle Fourche Formation, and is characterized by rare to common agglutinated species of low diversity (Bloch et al., 1993; Schröder-Adams et al., 1996).

The Late Cenomanian to Early Turonian *Flabellamina gleddiei* Zone has been recognized only in the Peace River district of northeastern British Columbia and northwestern Alberta (Caldwell et al., 1978). In the other parts of the WCSB, this zone is absent. In central Saskatchewan the *Hedbergella loetterlei* Zone directly overlies the *Miliammina manitobensis* Zone, indicating a disconformity where the *F. gleddiei* and *V. perplexus* zones are missing (Caldwell et al., 1978).

The *Hedbergella loetterlei* Zone mainly composed of planktic foraminifera is one of the most widespread zones in the WCSB and represents a time when the seaway was at its widest extent. It is found in the upper part of the white-speckled shales that compose much of the middle Kaskapau Formation of the Smoky River Group in the Peace River district of northwestern Alberta and northeastern British Columbia and in the calcareous shales of the Vimy Member of the Blackstone Formation in the central and southern Rocky Mountain foothills of Alberta (Wall, 1967a; Caldwell et al., 1978). Across the plains of eastern Alberta and western Saskatchewan, the zone occurs mainly in the Second White Specks Formation (Wall, 1967a; North and Caldwell, 1975a; McNeil and Caldwell, 1981; Caldwell et al., 1978; Bloch et al., 1993). In eastern Saskatchewan and Manitoba, this zone occurs mainly in the Favel Formation (North and Caldwell, 1975a; McNeil and Caldwell, 1981; Caldwell et al., 1978) and can be subdivided into two subzones, the lower *Clavihedbergella simplex* Subzone and the upper *Whiteinella aprica* Subzone (Caldwell et al., 1978; McNeil and Caldwell, 1981). In Alberta and western

Saskatchewan, only the *W. aprica* Subzone has been found (North and Caldwell, 1975a; Caldwell et al., 1978; Bloch et al., 1993; Schröder-Adams et al., 1996). Caldwell et al. (1978) assign an Early Turonian age to the entire zone, whereas McNeil and Caldwell (1981) extend the age to early Middle Turonian.

The late Early to Middle Turonian *Pseudoclavulina* sp. Zone is to be found mainly in the Rocky Mountain foothills of Alberta and the Peace River district of northwestern Alberta (Wall, 1967b; Caldwell et al., 1978). The latest Turonian and/or Early Coniacian *Trochammina* sp. Zone is found in the central and southern Rocky Mountain foothills of Alberta (Wall, 1967b; Caldwell et al., 1978). East of the Rocky Mountain foothills, these two zones are poorly defined. In Saskatchewan and Manitoba, only some component species are found sparsely distributed in the Morden Formation and its equivalent upper Colorado Shale (North and Caldwell, 1975a; McNeil and Caldwell, 1981). McNeil and Caldwell (1981) assigned the assemblage to a single *Pseudoclavulina* sp. – *Trochammina* sp. Zone undifferentiated. Especially noted here is that both North and Caldwell (1975a) and McNeil and Caldwell (1981) reported planktic foraminiferal occurrences in the Morden Formation and its equivalent upper Colorado Shale in Manitoba and Saskatchewan. In southeastern Alberta and southwestern Saskatchewan, Nielsen (2002) assigned the *Pseudoclavulina* sp. Zone to the Carlile Formation and the *Trochammina* sp. Zone to the Verger Member of the Niobrara Formation, respectively. Elberdak (2004) suggests that the *Trochammina* sp. and *Pseudoclavulina* sp. zones cannot be clearly separated in southern Alberta and a single *Trochammina* sp. - *Pseudoclavulina* sp. Zone is assigned to the Carlile Formation and the lowest part of the Verger Member of the Niobrara Formation.

The Late Coniacian to Early Santonian *Bullopore laevis* Zone has been found throughout the Rocky Mountain foothills of Alberta. It can be traced eastwards throughout southern Alberta and southwestern Saskatchewan, below the top of the Alberta Shale (Wall, 1967c; Wickenden 1932; Caldwell et al., 1978). Nielsen (2002) assigned the *B. laevis* Zone to the interval from the upper part of the Verger Member to lower part of the Medicine Hat Member of the Niobrara Formation in southeastern Alberta and southwestern Saskatchewan. In southern Alberta, Elberdak (2004) subdivided the *B. laevis* Zone into three subzones: the lower *Marssonella oxycona* Subzone, the middle *Haplophragmoides bonanzaense* Subzone and the upper *Neobulimina canadensis* Subzone.

The *Globigerinelloides* sp. Zone is characterized by a mixed fauna composed of agglutinated, benthic calcareous and planktic foraminifera. In southern Alberta, it is associated with the interval from the middle part of the Medicine Hat Member to the First White-Speckled Member of the Niobrara Formation (Nielsen et al., 2003; Elberdak, 2004). In the southern Rocky Mountain foothills, southern Alberta, southernmost Manitoba, and probably other areas, it is divisible into two subzones, a lower *Gavelinella henbesti* Subzone and an upper *Heterohelix* cf. *reussi* Subzone (Caldwell et al., 1978; McNeil and Caldwell, 1981; Elberdak, 2004). In general, the *Globigerinelloides* sp. Zone spans Early to Late Santonian, but locally it may extend between Early Coniacian and Early Campanian (Caldwell et al., 1978). Therefore, as a marker of the top of the Colorado Group in central and southern Alberta and central and southern Saskatchewan, and an important regional marker throughout the WCSB, both the base and the top of the *Globigerinelloides* sp. Zone are diachronous. It is likely that the zonal elements form a

biofacies that moves with the white speckled lithofacies (Caldwell et al., 1978) and that in turn depends on variable paleoceanographic conditions.

Previous Work

Previous work on the Colorado Group in the Cold Lake area is scarce. Mattison and Wall (1993) examined the microfauna of the middle and upper subgroups of the Mannville Group and Joli Fou shales of the overlying Colorado Group. They found the diagnostic assemblage of the *Haplophragmoides gigas* fauna in Joli Fou shales. The microfauna (*H. gigas* and other foraminiferal species) and megafauna give evidence of a connection between the Boreal and Tethyan seas and an early Late Albian age (Stelck et al., 1956; Williams and Stelck 1975). Stancliffe and McIntyre (2003) studied stratigraphy and palynology of the Colorado Group and the overlying Lea Park Formation in the Cold Lake area utilizing one of the cores studied here. They subdivided the Colorado Group into six formations and one undefined unit based on wireline logs and palynomorphs. This study will draw stratigraphic comparisons with their work.

MATERIALS AND METHODS

Research is based on two long cores, ROB 5 at 7-8-65-3W4M and DDOB 5 at 3-7-65-3W4M, covering the Cretaceous Colorado Group in the Cold Lake area. A total of 120 core samples for ROB 5 and 118 core samples for DDOB 5 have been taken for foraminiferal and geochemistry analyses. Additional 60 and 56 samples respectively have been taken for nannofossil analysis performed by Jim Craig. This study is based on micropaleontology, lithology, petrophysics and geochemistry.

Micropaleontology

The biostratigraphic framework was established mainly based on micropaleontological analysis, which is based on the vertical and lateral distribution of foraminiferal assemblages. Foraminiferal analysis was based on core samples, taken at intervals of four to half meter, depending on lithological boundaries, unusual characteristics of sediments, or critical intervals. Samples for foraminiferal analysis were prepared according to the method described by Then and Dougherty (1983). Foraminifera were picked from the sand-size fraction ($>63\ \mu\text{m}$). Volumes of picked residues varied with foraminiferal concentration (abundance) in the residues; therefore a quantitative analysis was not possible. Numerous samples were barren of foraminifera or assemblages were poorly preserved. The foraminiferal fauna, ordered by first appearance datum, and estimation of relative abundances of fish remains, and bivalve shell prisms are listed in Appendix 1. Nannofossil data are listed in Appendix 2.

Sedimentology

Cores were lithologically described, including visual characteristics of sediments in terms of colour, composition, grain size, sedimentary structures, texture, trace fossils and bioturbation and fossil content.

Wireline well log correlations

Wireline logs of wells reflect changes of petrophysical characters, which are a function of rock composition, porosity, permeability, fluid contents, structure etc. Gamma-ray and resistivity logs were used to establish the correlations between cores in the Cold Lake area and on a regional scale. Responses were compared with sedimentology and micropaleontological assemblage changes based on the two key cores in the area. Three regional wireline log cross-sections were constructed using the digital database from International Database Corporation (iDc), Calgary: A-A' runs from the study area to the Bow Island Arch area in the south, where Nielsen (2002) and Nielsen et al. (2003) have establish a new stratigraphic framework of the upper Colorado Group; B-B' runs from Cold Lake westward to central Alberta; C-C' runs east southward to central Saskatchewan (Fig. 1).

Geochemistry

Rock-Eval Pyrolysis provides information about the total amount of organic carbon, source of organic matter in sediments and its state of maturity. In combination with micropaleontological and sedimentological data, it helps interpretation of the depositional history of the study area. In this study, Rock-Eval Pyrolysis was conducted on 94 samples from ROB5 using the standard procedure of the DELSI Rock-Eval II/TOC

apparatus (Espitalié et al., 1977) at the Geological Survey of Canada, Calgary. Rock-Eval Pyrolysis data are listed in Appendix 3. Information used in this study includes the amount of total organic carbon (TOC), the oxygen index (OI), and hydrogen index (HI).

RESULTS

Preservation of Cores

In the Cold Lake area, the Colorado Group consists mainly of grey to dark grey, non-calcareous to calcareous shale, with minor siltstones, very- to fine sandstones, bentonite layers, and bioclastic layers. Most intervals are poorly lithified, which is thought to be a result of shallow burial during approximately 100 million years after deposition in this region.

The two studied cores showed different status of preservation. Both cores were taken about 20 years ago (1984). The core of DDOB 5 was preserved in wax wraps shortly after coring. When unwrapped for this study, most parts of the core were still wet, the shale was soft, and there were little signs of weathering on the core (Fig. 5b). In contrast, the core of ROB 5 was preserved in plastic tubes and obviously had changed over years. The shale was dry, fragile with abundant cracks due to shrinking. Some parts of the core were covered by sulphur material, especially in bentonite-rich intervals. Different preservation might have influenced sedimentological descriptions of these cores, although similar lithologies were observed due to their close proximity. The following description results from observations in both cores

Joli Fou Formation

Lithology

The 28-34-m-thick Joli Fou Formation disconformably overlies oil sands of the

Grand Rapids Formation of the Mannville Group in the Cold Lake area. The contact between these two units is characterized by elements of the *Glossifungites* ichnofacies in the underlying siltstone of the Grand Rapids Formation (Fig. 5a). The Joli Fou Formation consists of dark grey, non-calcareous shale with a small proportion of siltstone interbeds and few bentonites. The formation can be roughly subdivided into two lithological units (Fig. 6a, 7a). The lower unit is about 13 m thick and contains a few glauconite-bearing silt beds and silt lenses that decrease upwards (Fig. 5b). The silt layers are grey-greenish in colour, up to 5 cm thick and moderately bioturbated. Trace fossils are dominated by *Planolites*. Inoceramids are common, especially in the lowest 6 meters (Fig. 5c). Fish remains are rare to absent in this interval.

The upper unit of the Joli Fou Formation is about 18 m thick and contains less silt layers with weak bioturbation in comparison with the lower unit. A few bentonite layers were observed near the top of the formation. Macrofossils are rare in this interval. Fish remains are common to abundant. Fish teeth are 1-2 cm long in average and exhibit little rounding.

Micropaleontology

Microfauna found in the Joli Fou Formation is characterized by an abundant and diverse agglutinated foraminiferal assemblage of the *Haplophragmoides gigas* Zone (Fig. 6a, Fig. 7a). Important elements include *Ammobaculites fragmentarius*, *Ammobaculites petilus*, *Ammobaculites tyrrelli*, *Ammobaculites whitneyi*, *Gaudryina canadensis*, *Gravellina chamneyi*, *Haplophragmoides gigas*, *Haplophragmoides postis*, *Haplophragmoides* cf. *collyra*, *Haplophragmoides kirki*, *Haplophragmoides linki*, *Haplophragmoides* sp., *Haplophragmoides cushmani*, *Haplophragmoides topogorukensis*,

Miliammina awunensis, and *Miliammina manitobensis*. Corresponding to the subtle lithological change, the foraminiferal assemblage of the upper unit of the formation shows differences from the lower unit. As a general trend, both foraminiferal diversity and abundance decrease upward (Fig.6a, Fig.7a).

Geochemistry

Total organic carbon (TOC) values range from 0.4% to 1.08%, with an average of 0.74 %. The average HI value is 19.2 mgHC/gOC, ranging from 14 to 24 mgHC/gOC. Organic matter in the Joli Fou Formation is of type III, indicating a terrestrial origin (Fig. 8a). From the lower unit to the upper unit of the formation, TOC values slightly increase from an average of 0.68% in the lower part to 0.78% in the upper part, and the average HI value increases from 17 to 20.7 mgHC/gOC, inferring a paleoenvironmental shift towards offshore conditions.

Wire-line log signatures

Changes in wire-line log signatures within the Joli Fou Formation are subtle, especially for those within the gamma-ray log. The contact with the underlying Grand Rapids Formation is characterized by a distinct increase in gamma-ray values and decrease of resistivity values (Fig. 6a). Near the top of the formation, several impure bentonite layers send gamma-ray values slightly higher than in the underlying unit. The lower unit of the formation consists of several bell-shaped resistivity signatures, whereas that of the upper unit is flat-to-funnel-shaped and characterized by lower readings. A significant decrease of resistivity and increase of sonic values mark the boundary between the lower and upper parts of the formation (Fig. 6a).

Figure 5. a) *Glossifungites* ichnofacies in the Grand Rapids siltstone below the unconformable contact with the Joli Fou Formation (ROB 5, 323.5 –323.6 m); b) the uppermost Grand Rapids Formation and lowermost Joli Fou Formation. Note the rippled base and top of the uppermost siltbeds (arrow-pointed). (DDOB 5, 321.5--324.2 m); c) Concentrated bivalve shells in dark grey shale in the lower part of the Joli Fou Formation (ROB 5, 321 m).

Figure 5

Figure 6. a) Stratigraphy, log signatures, lithology, hydrogen index (HI) and TOC values and biostratigraphic ranges of foraminiferal species of the Joli Fou, Viking, and Westgate formations at ROB 5; b) Stratigraphy, log signatures, lithology, hydrogen index and TOC values, biostratigraphic ranges of foraminiferal species, and nannofossil occurrences of the Fish Scales, Belle Fourche, Second White Specks and Niobrara formations at ROB 5. The Carlile Formation is missing in this core.

Figure 6a

Figure 6b

Figure 7. a) Stratigraphy, lithology, and biostratigraphic ranges of foraminiferal species of the Joli Fou, Viking, and Westgate formations at DDOB 5; b) Stratigraphy, biostratigraphic ranges of foraminiferal species, and nannofossil occurrences of the Fish Scales, Belle Fourche, Second White Specks and Niobrara formations at DDOB 5. The Carlile Formation is missing in this core.

DDOB 5
3-7-65-3W4

Figure 7a

Figure 7b

Figure 8. Hydrogen Index/Oxygen Index plots for formations of the Colorado Group at ROB 5. Arrows point towards top of section. a) Joli Fou Formation, Viking Formation and Westgate Formation; b) Fish Scales Formation and Belle Fourche Formation; c) Second White Formation; d) First White Formation

HI refers to hydrogen index; OI refers to oxygen index.

Figure 8

Figure 8

Viking Formation

Lithology

The Viking Formation is about 6 m thick in ROB5 and 5 m in DDOB 5. The basal formation is a dark grey to black shale with rare, strongly bioturbated silt beds up to 2 cm in thickness. These differ from the dark grey shale with few non-bioturbated silt laminae (2-3mm thick) of the underlying upper Joli Fou Formation. The upper boundary of the Viking Formation is marked by a relatively sharp contact between bioturbated siltstone and dark grey shale of the Westgate Formation. The Viking Formation is composed of several fining upward cycles. In each cycle, the proportion of silt beds decreases whereas the proportion of dark grey shale increases upward. However, the overall trend in the formation is coarsening-upward (Fig. 9a). Near the top of the formation, the sand grain-size reaches fine sand grade. Moderate to strong bioturbation was observed throughout the interval (Figs. 9a, b), in which horizontal traces are identified as *Planolites* and *Chondrites*. Only few primary sedimentary structures remained preserved. Some silt beds show scours at the base but no pebbles on surfaces (Fig. 9a). Some silt beds exhibit horizontal lamination. Microscopic examination of the prepared samples reveals common to rare fish remains in this formation.

Micropaleontology

The foraminiferal assemblage of the Viking Formation is characterized by agglutinated species of moderate abundance and high diversity. About 24 species have been identified in the Viking formation including *Gaudryina canadensis*, *Pseudobolivina variana*, *Haplophragmoides postis* and *Miliammina manitobensis*. A foraminiferal

change marks the base of the Viking formation (Figs. 6a, 7a). Another faunal change occurs within the formation. The lower faunal includes *Gaudryina canadensis*, *Saccamina lathrami*, *Haplophragmoides postis*, *Miliammina manitobensis*, *Miliammina ischina*, *Trochammina depressa*, *Trochammina rainwateri* in common; the upper faunal is characterized by loss of *Trochammina depressa*, *Haplophragmoides postis*, *Haplophragmoides cushmani*, *Pseudobolivina variana*, and occurrence of *Trochammina rutherfordi*, *Reophax troyeri*, *Psamminopelta bowsheri*, *Glomospira glomerosa*. This change takes place at two meters below the top, and corresponds to the lithological change where the fine sandy interval overlies the silty interval (Figs. 6a, 7a). Incoming species are *Trochammina rutherfordi*, and others.

Geochemistry

The organic material in the Viking Formation is of terrestrial origin (type III, Fig. 8a). TOC values narrowly range from 0.27% to 0.76% with an average of 0.64%. The average HI value is 24.9 mgHC/gOC, with a range of 18-39.2 mgHC/gOC (Fig. 7a).

Wire-line log signatures

The overall signatures of both gamma and resistivity logs of the Viking Formation in the Cold Lake area tend to be funnel-shaped (Fig. 6a). Therefore, the contact with the overlying Westgate Formation can be easily picked with an obvious decrease in resistivity values and a sharp increase of gamma-ray readings. However, the basal contact with the Joli Fou Formation is usually gradational, making it difficult to determine its position with wire-line logs.

Figure 9. DDOB 5, 287.5—290.6 m. Moderately to heavily bioturbated siltstone and fine sandstone intervals in the Viking Formation: a) overall view. Note the scour bases (arrow-pointed); and b) detail, *Planolites* (arrow-pointed).

Westgate Formation

Lithology

The Westgate Formation is about 50 m thick. The basal contact with the underlying Viking Formation is characterized by the disappearance of siltstone. The top contact with the overlying Fish Scales Formation is marked by a bioclastic bed mainly composed of phosphatic fish remains (Fig 6a, 7a).

The Westgate Formation is heterolithic, comprised of several coarsening-upward units from interbedded shale to siltstone to very fine sandstone. The siltstones and sandstones, mainly concentrated in the middle part of the formation, are greyish, highly bioturbated, coarsening-upwards to very fine and fine sandstones, siderite-cemented and parallel-laminated in some cases (Fig. 10a). Siderite concretions are also common in the middle part (Fig. 10c). Shales are grey to dark grey, non-bioturbated to weakly bioturbated, and may contain bioturbated silt laminae, especially in the middle part of the formation. Identifiable trace fossils include *Planolites* and *Chondrites* (Fig. 10b). Fish remains are rare to absent in the formation.

Micropaleontology

The Westgate Formation contains agglutinated foraminiferal taxa of moderate abundance and species richness. The assemblage contains common specimens of *Gaudryina canadensis*, *Gaudryina irenensis*, *Haplophragmoides* cf. *kirki*, *Haplophragmoides gilberti*, *Haplophragmoides postis*, *Miliammina manitobensis*, *Miliammina ischnia*, *Uvigerinammina manitobensis*, *Pseudobolivina variana*, *Arenobulimina paynei*, *Arenobulimina* sp., *Trochammina rutherfordi*, *Verneuilina*

Canadensis and *Verneuilina* sp. This composition is typical for the *Verneuilina canadensis* Subzone of the *Miliammina canadensis* Zone of latest Albian age (Caldwell et al., 1978). Foraminiferal distribution is not continuous, but corresponds to coarser and bioturbated intervals (Fig. 6a, 7a), whereas shale dominated strata are barren of microfossils. Near the top of the formation, radiolaria become common.

Geochemistry

Similar to the previous two formations, the Westgate Formation is characterized by terrestrial organic matter (type III) (Fig. 6a), whereas total amounts have increased (average 1.15%, ranging from 0.3% to 2.36%), which results in a higher gamma reading of the mud line, especially in the lower shaly interval. The HI values range from 21 mgHC/gOC to 61 mgHC/gOC, with an average of 35.3 mgHC/gOC. TOC values in the sandy intervals are remarkably lower than in the surrounding shaly intervals (Fig. 6a) while HI values remain the same.

Wire-line log signatures

The contact between the Westgate and the underlying Viking formation is marked by a sharp increase of gamma-ray values and an obvious decrease of resistivity values. Within the Westgate Formation, log responses are variable, reflecting a heterogeneous lithology, but the logs can be subdivided into a shaly lower part with high gamma-ray and relatively low resistivity, and an upper sandy part with low gamma-ray and relatively high resistivity. The spontaneous potential curve responds to the sandstone intervals with a symmetric hummocky shape (Fig. 6a)

Figure 10. a) Coarsening-upward fine sandstone in the Westgate Formation. Note the parallel lamination as pointed to by arrow. (DDOB 5, 266.5-267.65 m); b) *Planolites* (*Pl.*) and *Chondrites* (*Ch.*) on shale plane surface. (DDOB 5, 276.2 m); c) siderite concretion (DDOB 5, 260.2 m).

Fish Scales Formation

Lithology

The Fish Scales Formation is about six metres thick. The base is marked by a 2-3 cm thick bed of bioclastic conglomerate. The bed is lenticularly bedded with sharp contacts to the underlying and overlying shales. The basal contact shows sole marks with a relief of 1-2 mm (Fig.11a). The framework occupies about 85% of the rock volume and is comprised mainly of fish teeth, bones, scales, and minor bentonite clasts. No siliciclastic grain was found in the sand-sized fraction of the bed. Grainsize is of medium sand size, moderately sorted, and grain-supported. The fish debris shows little sign of rounding, particularly smaller grains such as teeth and spines. The rest of the formation is black to brownish grey, non-bioturbated, well laminated shale containing laminae of concentrated fish scales. After years of exposure to the air, the shale was covered by sulphur on core surfaces and in fractures, indicating weathering of initially sulphur-rich sediment. Especially in the upper part of the formation, the amount of sulphur increases considerably (Fig 11b).

Micropaleontology

The Fish Scales Formation is barren of foraminifera and no macrofossil was found.

Geochemistry

Organic matter of the Fish Scales Formation is of terrestrial origin (type III, Figs. 6b, 8b). TOC and HI curves show a considerable increase from the underlying Westgate

a.

Figure 11. a) Bioclastic conglomerate at base of the Fish Scales Formation. Note the relief of the basal surface. (DDOB 5, 236m); b) Increasing-upward sulphur on “weathered” core surfaces in the Fish Scales Formation. (ROB 5, 232-235 m).

b.

Formation but remain variable throughout the Fish Scales Formation (Figs. 6a, 8b). TOC values average 2.82%, ranging from 1.89% to 4.95%; HI values range from 53 mgHC/gOC to 132 mgHC/gOC, with an average of 79.4 mgHC/gOC.

Wire-line log signatures

Regionally, the contact between the Fish Scales Formation and the underlying Westgate Formation is characterized by an increase in the gamma-ray and resistivity responses (Figs. 18, 19), although the changes are not as prominent in the Cold Lake area (Fig. 6b). Generally, both gamma-ray and resistivity values of the formation remain higher than those of the underlying and overlying strata. The increase seems to be caused by the increased phosphate material in the fish bonebed and shale, and can be observed in other fish-remain-enriched intervals. The top of the Fish Scales Formation is marked by a decrease in gamma-ray readings, indicating decrease of fish remain content and/or organic matter content. The resistivity response continuously decreases into the overlying Belle Fourche Formation.

Belle Fourche Formation

Lithology

The Belle Fourche Formation is about 28 m thick and is comprised of non-to-slightly calcareous shale, thin siltstone beds and bentonites (Fig. 6b, Fig 7b). On the weathered cores, the contact to the underlying Fish Scales Formation is marked by an abrupt decrease in sulphur (Fig. 11b) and a decrease in fish remains. The formation overall coarsens upward, and is comprised of four stacked smaller coarsening-upward cycles expressed by an upwards increasing number of silt beds (Figs. 6b, 7b). The lowest 10 metres are dominated by grey to brownish/grey claystone with pyrite concretions (Fig.

12b). A 20- cm-thick iron concretion was observed in ROB 5. Shale intervals are non-laminated. The siltstones in the upper part of the formation are mostly lenses and thin interbeds within grey shale (Fig. 12d). Horizontal-lamination and ripple cross-lamination are common in silty intervals. The siltstones and shales are sparsely bioturbated by *Planolites*. Several medium grained sandstone beds occur in the upper part of the formation. These are millimetres to centimetres thick, sharp-based, and cross-bedded. Near the top of the formation, the siltstone beds are more concentrated and ratios of siltstone to shale exceed 1:1 (Fig. 7b). In the silty section of ROB 5 a small scale (4 cm thick) slump structure on a syndepositional fault is overlain by chaotic deposits of claystone and ripped clumps of medium sandstone (Fig. 12a). This might indicate a subaqueous slump event and subsequent redeposition on a slope (Collinson and Thompson, 1988). The upper part of the formation is also characterized by abundant sideritic concretionary horizons and discrete concretions. Occurrence of these siderites is associated with siltstone beds; hence, an increasing-upward trend is obvious. Pyrite concretions were not observed in silty intervals. Associated with the increased silt beds, fish remains (bones and teeth) become abundant towards the top of the formation. Unlike those from the Fish Scales Formation, the teeth and bones from the Belle Fourche Formation are rounded and fractured, indicating longer periods of transport and abrasion before deposition.

The Belle Fourche Formation contains several bentonite layers. Among them, a 30 cm thick bentonite is a regional lithological marker called “X” bentonite (Fig., 6b, 7b; Fig. 12c). In southern Alberta and Northern Montana, the “X” bentonite separates essentially non-calcareous shale below from non-calcareous to highly calcareous shale

Figure 12. Sedimentary features of the Belle Fourche Formation. a) Slump structure (ROB 5, 208.6 m). b) Pyrite concretions in black shale. (DDOB 5, 219.2 m). c) "X" bentonite layer marked by a bracket (DDOB 5, 205.9—208 m). d) Silt lenses and thin beds interbedded with grey shale. Note the sparse *Planolites* (ROB 5, 208--208.15 m). Diameter of cores is about 7.1cm; length of core boxes: about 75 cm.

above (Ridgley et al., 2001). In the Cold Lake area, only a thin interval close to the top of the Belle Fourche Formation is highly calcareous (Fig. 6b).

Micropaleontology

No complete foraminiferal specimen was observed from samples of the Belle Fourche Formation (Fig. 6b, 7b). However, fragments of agglutinated foraminifera have been found in one sample from ROB 5 (sample #17). Slight bioturbation in this interval indicates oxygenized bottom water conditions for benthic organisms. However, no benthic foraminifera occur. The lack of foraminifera might suggest poor preservation of fragile species as also observed in the younger Niobrara Formation. Samples from this formation were examined for nannofossil occurrences but were found barren (Fig. 6b). The lowest two metres contain abundant radiolaria.

Geochemistry

TOC values for the Belle Fourche Formation range from 1.46 % to 4.49% with an average of 2.56%, increasing upsection. HI values are variable from 88 mgHC/gOC to 297 mgHC/gOC with an average of 176.2 mgHC/gOC. HI values show higher values at the base and top of the formation (Fig. 6b), indicating a change in the organic matter source.

Wire-line log signatures

The contact between the Belle Fourche Formation and the underlying Fish Scales Formation is marked on log expression by decreasing gamma-ray and resistivity values (Fig. 6b; Fig. 11a, b). The gamma-ray and resistivity curves of the formation are characterized by several funnel shaped log responses separated by those of bentonites and

shale intervals.

Second White Specks Formation

Lithology

The Second White Specks Formation is about six metre thick in both ROB 5 and DDOB 5 of the Cold Lake area. The basal contact with the underlying Belle Fourche Formation is marked by a 2-cm-thick bioclastic layer, parallel-laminated, calcareous fine sandstone with abundant coarse sand-sized fish remains of mainly teeth (Fig. 13a). Fish debris comprises about 50% of the rock volume, and show little evidence of abrasion. The bioclastic layer has a sharp boundary to the overlying black calcareous shale. The formation is dominated by dark grey to black, finely laminated, non-bioturbated calcareous shale. Fish remains are common to abundant in the shale, particularly in the lowest two metres. Shells of the inoceramid *Mytiloides labiatus* Schlötheim and the ammonite *Watinoceras reesidei* Warren are common (Fig. 13b), which indicate an Early Turonian age (Caldwell et al., 1978; Jeletzky, 1971). White specks are visible on some shale samples. Near the top of the formation, a bentonite layer and a calcareous concretion occur.

Micropaleontology

The Second White Specks Formation is characterized by a planktic foraminiferal assemblage of the *Whiteinella aprica* Subzone of the *Heterohelix loetterlei* Zone. Representative taxa of the older *Clavhedbergella simplex* Subzone were not found. Instead a mixed calcareous benthic and planktic foraminiferal fauna was observed near the base of the formation in ROB 5, where the benthic taxon *Neobulimina albertensis*

Figure 13. a) Bioclastic layer at base of the Second White Specks Formation. Note the lamination shown by the terraces on the core. (DDOB 5, 202 m).

b) *Watinoceras reesidei* and *Mytiloides labiatus* in calcareous shale of the Second White Specks Formation. (DDOB 5, 195.4-195.5 m).

occurs. The most abundant and frequently occurring species of the *Whiteinella aprica* Subzone are of planktic nature and include *Hedbergella delrioensis*, *Hedbergella loetterlei*, *Hedbergella planispira*, and *Heterohelix globulosa*. Less common species include *Hedbergella amabilis*, *Hedbergella portsdownensis*, *Heterohelix moremani*, and *Whiteinella aprica*.

The formation is characterized by abundant nannofossils. A total of 38 species were identified and the assemblage suggests a Lower to Middle Turonian age (pers. comm., J. Craig, 2003; 2004).

Geochemistry

The Second White Specks Formation is characterized by high TOC values that average 8.20%, ranging from 3.75% to 11.04%. HI values average 409.9 mgHC/OC, with a range of 200 mgHC/OC to 490 mgHC/OC. The base of the formation is marked by a sharp TOC and HI increase from the underlying Belle Fourche Formation (Fig. 6b). The organic matter of most of the Second White Specks Formation is type II (marine) derived. However, samples from the lowest two metres contain more organic elements of terrestrial origin (Fig. 8c).

Wire-line log signatures

In the Cold Lake area, the Second White Specks Formation is distinguished from its underlying and overlying strata by high resistivity and highly fluctuating gamma-ray readings (Fig. 6b). The contact with the underlying Belle Fourche Formation is marked by increased gamma-ray and resistivity values as a response to the basal bioclastic layers. The upper part of the formation has lower gamma-ray readings, with minor increases to

higher values. The 5 cm bentonite in ROB 5 near the top of the formation is represented by an indistinct gamma-ray increase and resistivity decrease (Fig. 6b).

Niobrara Formation

In the Cold Lake area, the Niobrara Formation unconformably overlies the Second White Specks Formation. Paleontological and petrophysical data suggest that the Carlile Formation is missing as discussed later. In southeastern Alberta and southwestern Saskatchewan the Niobrara Formation is subdivided into three members (Nielsen et al, 2003). Equivalent strata to the Verger, Medicine Hat and First White Specks members were identified in the Cold Lake area, although with some lithological and faunal variation as compared to the type sections further south.

Verger Member

Lithology

The Verger Member is about four metres thick in the Cold Lake area. The contact to the unconformably underlying Second White Specks Formation is characterized in the pristine core by a sharp lithological change from strongly calcareous, dark grey shale to non-calcareous, black shale containing *Inoceramus* and ammonites. In the ROB 5 core, the black shale gradates into dark grey shale with increasing upward sulphur content on core surfaces. This trend is then truncated by a thin (ca. 10 cm) calcareous, dark grey shale (Fig. 14). Similar cycles frequently occur in the overlying Medicine Hat equivalent interval. The upper part of the member is grey shale with minor silt content and weak bioturbation.

Figure 14. Lithological features of the upper Second White Specks Formation and lower Verger Member. Features in the Second White Specks Formation as shown include a calcareous concretion (a) and a bentonite layer (b); features of the Verger Member include black shale and an interval with increasing upward sulphur content.

Micropaleontology

The foraminiferal assemblage of the Verger Member is characterized by low species richness and low to moderate abundance. Minute, poorly preserved agglutinated foraminifera dominate the four-metre interval. Dominant species are *Dorothia* sp., *Haplophragmoides crickmayi*, *Haplophragmoides howardense*, *Reophax* cf. *troyeri*, and *Ammobaculites tyrrelli* being typical components of the *Haplophragmoides bonanzaense* Subzone of the *Bullopore laevis* Zone. The Late Turonian *Trochammina* sp./*Pseudoclavulina* sp. Zone is missing indicating a hiatus.

Nannofossils are nearly absent from the entire member, except from the calcareous shale in the middle of the section (Fig. 6b). *Kampnerius magnificus* was identified and is known to range from the Coniacian to the Maastrichtian (Craig, per. comm., 2003), thus it provides evidence for the disconformity above the Lower to Middle Turonian Second White Specks Formation where the Late Turonian Carlile Formation is missing in the Cold Lake area.

Geochemistry

TOC values from the Verger Member demonstrate variable organic matter content ranging from 3.06 % to 7.17%, with an average of 5.37%. The TOC values show a decreasing trend upsection (Fig. 6b). HI values range from 223 mgHC/gOC to 313 mgHC/gOC. The Hydrogen Index/Oxygen Index Plot reveals a mixed origin of the organic material in the Verger Member, with nearly equal proportions of marine and terrestrially derived components (Fig. 8d).

Wire-line log signatures

Even though the Verger Member is thin in the Cold Lake area, this interval can be identified and traced on wire-line logs with its high gamma-ray and low resistivity responses (Figs. 6b; 18-21). On gamma-ray log, the contact with the underlying Second White Specks Formation is marked by a sharp increase in most wells whereas the top boundary is marked by a sharp decrease of gamma-ray values.

Medicine Hat equivalent

Lithology

The thickness of the strata equivalent to Medicine Hat Member is highly variable in the Cold Lake area, with a maximum of ca. 25 m in the southern part of the area and thinning northwards. In some wells, particularly in the northern part of the Cold Lake area, the member is absent. The Medicine Hat equivalent in ROB 5 and DDOB 5 is about 21 metres thick. It overlies the Verger Member, possibly disconformably, with interbedded non-calcareous shale and calcareous shale, silty shale with fine silt laminae and lenses. The term “Medicine Hat equivalent” instead of the Medicine Hat Member is used in the Cold Lake area because this interval is dominantly shale and lacks distinctive sandstone beds as defined over the Sweetgrass Arch (Nielsen et al., 2003). Upwards, the proportion of silt laminae and calcareous shale decreases, accompanied by an increase of bioturbation to an interval of several 0.5-3 cm thick bentonite layers and calcareous shale interbeds. The cycles of non-calcareous shale free of sulphur to non-calcareous shale with increasing sulphur content upwards to calcareous shale as described above occur frequently in the lower and upper part of the member in the weathered core of ROB 5. Tracefossils are dominated by *Chondrites*. Shells of *Inoceramus* rarely occur in the

member, but near the top fish remains become abundant

Micropaleontology

The microfauna of the Medicine Hat equivalent interval at Cold Lake is characterized by mixed agglutinated, benthic calcareous and planktic foraminiferal assemblages. Non-calcareous shale is dominated by agglutinated foraminifera, with *Pseudobolivina rollaensis*, *Dorothia smokyensis*, *Dorothia* sp., *Trochammina* sp. forming the most abundant and continuously distributed taxa. Calcareous shale is characterized by planktic and benthic calcareous species. The calcareous shale within the lowermost Medicine Hat equivalent strata is dominated by *Hedbergella delrioensis* and *Heterohelix globulosa*. Upwards, benthic calcareous specimens of *Neobulimina albertensis*, *Neobulimina canadensis*, *Gavellinella henbesti*, and *Gavellinella* cf. *talaria* dominate, with the presence of agglutinated and planktic species. The benthic environmental indicator species *N. albertensis* drops out in the middle part of the Medicine Hat equivalent, and returns near top of this interval associated with agglutinated species (Fig. 6b).

Nannofossils mainly occur in calcareous intervals of the lowermost and uppermost parts of the section. They are absent from non-calcareous shale, which mainly occupies the middle part (Fig. 6b). *Marthasterites simplex* and *M. furcatus* make their first appearance in the lowest part of the section. The former is known to range from the Late Turonian to the Santonian. In western Canada, the *Marthasterites* clan (being made up of *M. furcatus* and *M. simplex*) seems to arrive in the Santonian, hence a Santonian age is proposed for this interval (Craig, pers. comm., 2004).

Geochemistry

TOC values of the Medicine Hat equivalent strata average 2.73%, ranging from 1.53-5.77%; HI values range from 90 to 412 mgHC/gOC, with an average of 210.4 mgHC/gOC. Calcareous shale has higher TOC and HI values than non-calcareous shale, causing fluctuation of TOC and HI values in the lower part of the section, with a general decreasing trend upwards. Above the bentonites, TOC and HI values significantly increase. Consequently, the Hydrogen Index/Oxygen Index plot shows a type II-type III-type II path through the section (Fig. 8d).

Wire-line log signatures

In the Cold Lake area, the Medicine Hat Member equivalent is distinguished from the surrounding strata by its relatively low gamma-ray response. The lower boundary with the underlying Verger Member is marked by a sharp or gradual drop in gamma-ray values. In most wells at Cold Lake, the upper boundary to the First White Specks Member is rather transitional, with gradually increasing gamma-ray readings upsection. The boundary is picked at a peak on the gamma-ray response, which corresponds to a peak on resistivity log. Based on data from the ROB 5 and DDOB 5, these peaks reflect a fish-scale-rich shale interval at the top of the Medicine Hat equivalent, and correlate with the lithological change from non-calcareous shale to calcareous shale.

First White Specks Member

Lithology

Like the underlying Medicine Hat equivalent, the thickness of the First White Specks Member is variable, from ca. 60 m in the south, to less than 10 metres in some

wells in the north. It unconformably underlies the Campanian Lea Park Formation or Quaternary glacial drifts. A thin bioclastic layer was recognized from a sample at the basal boundary of the member. It contains a flood of fish remains and abundant quartz sand grains. The fish remains exhibit no sign of abrasion; the quartz grains are subrounded to angular. The member is characterized by dark grey, calcareous shale throughout, which differs from the underlying Medicine Hat equivalent composed of interbedded non-calcareous and calcareous shale. The member is not completely cored from ROB 5 and DDOB 5 thus the upper boundary of the member was not observed. The calcareous shale is laminated and essentially not bioturbated. White speckled lenses and laminae composed of nannofossils are common. Three bentonite layers, each less than one centimetre thick, appear within a two-metre interval near the middle of the member (Fig. 6b; 7b; Fig. 15a). Few shells of *Inoceramus* were observed. Fish remains are common in the cored First White Specks Member, particularly below the bentonites. Dolomitic and calcareous concretions were also observed (Fig. 15b).

Micropaleontology

Microfauna of the First White Specks Member is characterized by mixed agglutinated, calcareous benthic, and planktic foraminiferal assemblages. Planktic species such as *Globigerinelloides messinae*, *G. bentonensis*, *Hedbergella delrioensis*, and *Heterohelix globulosa* dominate the interval below the bentonites, with minor occurrences of the agglutinated taxon *Miliammina* sp. and calcareous benthic species *Neobulimina albertensis*. The interval above the bentonites is dominated by agglutinated foraminifera such as *Pseudobolivina rollaensis*, *Trochammina* sp., *Haplophragmoides* sp., with decreased diversity and abundance.

Figure 15. Sedimentary features of the First White Specks Formation: a) Three thin bentonite layers (arrow-pointed). (ROB 5, 151.6-156.8 m). b) A calcareous concretion marked by a bracket. (DDOB 5, 153-156.6 m).

All samples from the First White Specks Member contain nannofossils (Fig. 6b, Fig. 7b), in contrast to the underlying Medicine Hat equivalent, in which only certain intervals contain nannofossils. Age-diagnostic species include *Rucinolithus hayi* and *Marthasterites simplex*. The former is known to range from the Santonian into the Campanian; the latter ranges from the Late Turonian to the Santonian (Craig, per. comm., 2003). Thus, a Santonian age is suggested for the First White Specks Member.

Geochemistry

From the upper part of the Medicine Hat to the lower part of the First White Specks members, the trends of the TOC and HI curves resemble the gamma-ray log curve (Fig. 6b), implying the high radiation is mainly caused by high content of organic matter. Average TOC of the measured lowest 10 metres of the member is 6.74%, with a narrow range of 6.39 to 7.12%. HI averages 433.3 mgHC/gOC, ranging from 408 to 497 mgHC/gOC. A Hydrogen Index/Oxygen Index plot indicates terrestrial origin (type II) of the organic material (Fig. 8d).

Wire-line log signatures

In the Cold Lake area, the boundary between the First White Specks Member and the underlying Medicine Hat equivalent strata is marked by a peak in gamma-ray response (Fig. 6b). In ROB 5, a subtle increase of resistivity readings at the boundary seems to respond to the bioclastic layer, however, it does not hold as a regional marker (Figs. 18-21).

The First White Specks Member regionally unconformably underlies the Milk River/Lea Park formations (Leckie et al., 1994). In the Cold Lake area, the expression of the unconformity greatly varies between different localities/wells. In the southern part of

the area, the API values of the gamma-ray logs slightly decrease over the boundary. With increasing missing strata of the First White Specks Member in the northern part, the drop of API values can be distinct and sharp (Fig. 19).

Log Correlations

Three cross-sections have been established in this study (Fig. 1). The cross-section A-A' is running from north-eastern to east-central Alberta, the cross-section B-B' from central to east-central Alberta including the entire Colorado Group and the cross-section C-C' from east-central Alberta to central Saskatchewan including the upper Colorado Group (the Fish Scales Formation and above).

Because the cross-sections go far beyond the Cold Lake area, where reference cores are located, log signatures of stratigraphic boundaries described and/or illustrated by different authors working on different areas are adopted in this study. Log picks for the lower Colorado Group (Joli Fou Formation—Westgate Formation) were based on: Leckie et al. (1994); Reinson et al. (1994); Stritch and Schröder-Adams (1999); Bloch et al. (1993). Log picks for the Fish Scales Formation to the Second White Specks Formation were based on: Ridgley et al. (2001); Bloch et al (1993); Schröder-Adams et al. (1996); Leckie et al. (1994). Log picks for the Carlile Formation to the Niobrara Formation were based on: Nielsen et al. (2003); Nielsen (2002); Ridgley et al. (2001); Leckie et al. (1994).

Results of the correlations are illustrated in figures 16 to 21. Cross-section A-A' shows that the Colorado Group drastically thins from the Sweetgrass Arch in southern Alberta to the Cold Lake area in east-central Alberta (Figs. 16-19). The Viking Formation thickens and coarsens southward. On the Sweetgrass Arch, the Joli Fou and Viking

formations are replaced by the coarse-grained Bow Island Formation (Figs. 16, 17). The Fish Scales and Belle Fourche formations thin northward. The latter loses its main sandstone beds of the upper part in the range between the Sweetgrass Arch and the Cold Lake area, where the Second White Specks Formation thickens (Figs. 18, 19). The Carlile Formation, which developed well on the Sweetgrass Arch, sharply thins near the edge of the arch, and finally pinches out just south of the Cold Lake area (Figs. 1, 18, 19).

Thinning of the Carlile Formation and the Verger Member of the Niobrara Formation forms a main factor in the wedge geometry of the Upper Colorado Group. The sandstones developing in the Medicine Hat and First White Specks members on the Sweetgrass Arch pinch out toward the north wing of the arch. In some of the wells in the Cold Lake area and further north, the Colorado Group is incised and infilled with Cenozoic deposits (Figs. 16-19).

The west-east cross-section B-B' shows that the Colorado Group and its subunits thicken gently westward from Cold Lake (Fig. 20). However, more significant increases in thickness takes place further west beyond the reach of this cross section where the Colorado Group in the foothills becomes up to 1250 m thick (Fig. 20. 2 in Leckie et al., 1994).

Cross section C-C' reveals that the Upper Colorado Group thins toward central Saskatchewan (Fig. 21). The Fish Scales Formation is very thin, and the Carlile Formation is absent throughout the cross-section. The Verger Member and the Medicine Hat equivalent thin and disappear toward central Saskatchewan, resulting in the Santonian First White Specks Member overlying the Middle Turonian Second White Specks Formation.

Figure 16. Cross-section A-A': a south-north resistivity log cross-section of the Lower Colorado Group from south-eastern to east-central Alberta. For location of cross-section see figure 1.

A

A'

50

Erosion
Surface
Westgate F

Viking Fm.

Joli Fou Fm.

Datum

Mannvil

A'

Figure 16

Figure 17. Cross-section A-A': a south-north gamma-ray log cross-section of the Lower Colorado Group from south-eastern to east-central Alberta. For location of cross-section see figure 1.

A'

Figure 17

Figure 18. Cross-section A-A': a south-north resistivity log cross-section of the Upper Colorado Group from south-eastern to east-central Alberta. For location of cross-section see figure 1.

A

A'

Figure 18

Figure 19. Cross-section A-A': a south-north gamma-ray log cross-section of the Upper Colorado Group from south-eastern to east-central Alberta. For location of cross-section see figure 1.

Figure 19

Figure 20. Cross-section B-B': a west-east resistivity and gamma-ray log cross-section of the Colorado Group from central to eastern Alberta. For location of cross-section see figure 1.

Figure 21. Cross-section C-C': a northwest-southeast resistivity and gamma-ray log cross-section of the Upper Colorado Group from east-central Alberta to central Saskatchewan. For location of cross-section see figure 1.

05-18W4 7-32-05-17W4 7-4-05-10W4 1-17-05-18W4 7-13-05-14W4 5-27-05-13W4 7-7-05-12W4 3-6-05-11W4 11-17-05-10W4 9-16-05-09W4 10-30-05-08W4 11-30-05-07W4 8-11-05-06W4 11-14-05-05W4 6-11-05-04W4 12-5-05-03W4 13-11-05-02W4 5-11-05-01W4

Figure 20

Figure 21

DISCUSSION

Biostratigraphy

Haplophragmoides gigas Zone

In the Cold Lake area, the entire Joli Fou Formation and most of the Viking Formation fall in the *Haplophragmoides gigas* Zone. Koke and Stelck (1985), Stelck and Koke (1987), and Stelck (1991) described and subdivided this zone into seven subzones in northeastern British Columbia. They are, in descending order: *Haplophragmoides uniorbis*, *H. gigas gigas*, *H. gigas phaseolus*, *Reophax tundraensis*, *Trochammina depressa*, *T. umiatensis*, and *Reophax troyeri* subzones. Gulioy (1967) proposed two subzones of *Ammomarginulina asperata* and *Miliammina sproulei* within the Joli Fou Formation for eastern Saskatchewan, whereas North and Caldwell (1975a) recognized two distinct faunas named assemblages IIa and IIb from Saskatchewan. These faunal assemblages are equivalent to the *H. gigas gigas* and *H. gigas phaseolus* subzones, respectively (Caldwell et al. 1993). In northwestern Alberta, elements of the uppermost *Reophax troyeri* Subzone have been recognized by Stelck and Leckie (1990) from the Paddy Member of the Peace River Formation.

In Cold Lake area, the Joli Fou and Viking formations fall in the *Haplophragmoides gigas* Zone. Four microfaunal assemblages corresponding to the *H. gigas gigas*, *H. gigas phaseolus*, *T. depressa* and *R. troyeri* subzones are recognized. The contact between the *H. gigas gigas* Subzone and the overlying *H. gigas phaseolus* Subzone is marked by the disappearance of *Haplophragmoides gigas* (sensu stricto)

(Caldwell et al., 1993), as shown in Figure 7a. In addition, the disappearance of species enriched in the *H. gigas gigas* Subzone, such as *Gaudryina canadensis*, *Ammobaculoides whitneyi*, and *Haplophragmoides postis*, and appearance of *Miliammina* differentiate the two subzones in the study area. These two subzones, with 14 genera and 20 species and 9 genera and 16 species respectively, are less diverse in the Cold Lake area in comparison to northeastern British Columbia, where the subzones comprise 25 genera and 46 species and 21 genera and 35 species, respectively (Caldwell et al., 1993). However, the Joli Fou and Viking formations are still the most diverse interval of the Colorado Group in the study area.

The contact between the *H. gigas phaseolus* and *T. depressa* subzones marks the Joli Fou/Viking boundary (Fig. 6a, 7a). The *T. depressa* Subzone is characterized by several species of *Trochammina* (Stelck and Koke, 1987; Fig. 6a), including the high-spired, globular-chambered *Trochammina umiatensis* (plate IV, figs. 7a, b). However, the separate *T. umiatensis* Subzone cannot be recognized from these two cores. The *T. depressa* Subzone shows lower abundances, but similar species richness than the underlying subzones (Fig. 22).

The uppermost Viking Formation, as heavily bioturbated, thin fine sandstone beds expressed, contains a foraminiferal assemblage that shows some affinity with the overlying *Miliammina manitobensis* Zone. This fauna may belong to the *R. troyeri* Subzone though it is missing several species found in abundance in northeastern British Columbia (Stelck and Koke, 1987). As also observed in southern Alberta by Stritch and Schröder-Adams (1999) the faunal turnover is taking place within Viking strata.

Figure 22. Variation of abundances and species richness of foraminifera and nannofossils in different foraminiferal zones and subzones in ROB 5. For legends see figures 6a, 6b, 7a, 7b.

Figure 22

Miliammina manitobensis Zone

In the Rocky Mountain Foothills of northeastern British Columbia, the *Miliammina manitobensis* Zone is divided into three subzones, of which only the lowest *Verneuilina canadensis* Subzone can be recognized across the plains of Alberta and Saskatchewan (Caldwell et al., 1978). It was suggested that a disconformity denoted by the Fish Scale Marker may contribute to the missing of the upper two subzones of *Haplophragmoides postis goodrichi* and *Haplopragmium swareni* throughout the plains and the foothills belt in Alberta (Caldwell et al., 1978; North and Caldwell, 1975a). However, Schröder-Adams et al. (1996), Bloch et al. (1993), and Stritch and Schröder-Adams (1999) report index species of both subzones, i.e., *H. postis goodrichi* and *H. swareni*, recovered from the Westgate Formation in central and northwestern Alberta and Saskatchewan. These index species are not mutually exclusive in many plains areas and may occur together with *Verneuilina canadensis* (for example, 413.2m of CMS Vanscoy 11-16-35-8W3, Appendix 6b, Schröder-Adams et al., 1996). The stratigraphically distinct occurrences of index species forming the three subzones in northeast British Columbia are not repeated in the Alberta Basin.

In the Cold Lake area, the *M. manitobensis* Zone occupies the entire Westgate Formation. It is characterized by discontinuous vertical species distribution and several barren intervals (Fig. 6a, 7a). Foraminiferal occurrences and increased number of species seem to be associated with coarser and bioturbated intervals (Fig. 22). Subtle faunal change occurs approximately halfway through the Westgate Formation, immediately above a major coarsening-upward sequence. The change is marked by disappearance of *Verneuilina canadensis*, *Pseudobolivina variana*, *Uvigerinammina manitobensis*, and

reappearance of *Arenobulimina paynei* and *Trochammina rutherfordi*. However, this change is so subtle that no subdivision is proposed. Hence, a single subzone of *Verneuilina canadensis* is assigned for the entire Westgate Formation.

Hedbergella loetterlei Zone

In the study area, the *Hedbergella loetterlei* Zone occupies the entire Second White Specks Formation and only the *Whiteinella aprica* Subzone is present, as the case in Alberta and western and central Saskatchewan. The fauna is exclusively composed of planktic foraminifera, except near the base of the zone, where the dysoxia-tolerant benthic species *Neobulimina albertensis* is present (West et al., 1998). The presence of molluscs *Mytiloides labiatus* and *Watinoceras reesidei* indicates an Early Turonian age of the subzone. The overlying *Pseudoclavulina* sp./*Trochammina* sp. Zone is not recognized at Cold Lake indicating the absence of the Carlile Formation.

Bullopore laevis Zone

Elberdak (2004) proposes a subdivision of the *Bullopore laevis* Zone based on his biostratigraphic study in central and southeastern Alberta. The zone spans the entire Verger Member and lowermost Medicine Hat Member of the Niobrara Formation and consists of the *Marssonella oxycona*, *Haplophragmoides bonanzaense*, and *Neobulimina canadensis* subzones. In the Cold Lake area the index species of the *B. laevis* Zone is absent, and only the *H. bonanzaense* and *N. canadensis* subzones are present indicating that the lowermost part of the Verger Member might also be missing.

The *H. bonanzaense* Subzone is composed of agglutinated foraminifera and occupies the entire Verger Member. Taxa from *Haplophragmoides* and *Dorothyia* make

up most of the fauna. An obvious trend within the subzone is an upward decrease in both species richness and abundance.

The *N. canadensis* Subzone spans the lower part of the Medicine Hat Member and consists of a mixed agglutinated, calcareous benthic and planktic fauna. Important species include *Heterohelix globulosa*, *Hedbergella delrioensis*, *Hedbergella loetterlei*, *Neobulimina albertensis*, *Neobulimina canadensis*, *Gavelinella henbesti*, and *Gavelinella* cf. *henbesti*. The upper boundary of the subzone is marked by the disappearance of *N. canadensis*.

Globigerinelloides sp. Zone

Recent work by Elberdak (2004) suggests that the *Globigerinelloides* sp. Zone is divisible in southern Alberta and spans a large part of the Medicine Hat Member and the entire First White Specks Member, with the *Gavelinella henbesti* Subzone occupying the underlying Medicine Hat Member and the *Heterohelix* cf. *reussi* Subzone characterizing the overlying First White Specks Member of the Niobara Formation.

In the Cold Lake area, the *Globigerinelloides* sp. Zone is equally divisible. The underlying *G. henbesti* Subzone occupies the Medicine Hat equivalent strata. In addition to the zonal indicator this subzone is characterized by an agglutinated foraminiferal assemblage. The most common species include *Dorothia* sp., *Dorothia smokyensis*, *Pseudobolivina rollaensis*, and *Haplophragmoides howardense*. In contrast to the southern area, planktic taxa are not present.

The *Heterohelix* cf. *reussi* Subzone is associated with the First White Specks Member. The fauna is dominated by planktic taxa including *Globigerinelloides*, *Heterohelix*, and *Hedbergella*. Agglutinated foraminifera are present toward the top of

the cores.

Comparison with the Stratigraphic Framework Proposed by Stancliffe and McIntyre (2003)

Based on palynology data, Stancliffe and McIntyre (2003) subdivided the strata in the Cold Lake area, utilizing among others core ROB 5. Thus, a direct comparison between results of these two studies can be readily made (Fig. 23).

The comparison reveals considerable differences between stratigraphic subdivisions of the Upper Colorado Group. Stancliffe and McIntyre (2003) used the nomenclature of Bloch et al. (1993) for the Westgate, Fish Scales, Belle Fourche and Second White Specks formations, but the new nomenclature of Nielsen et al. (2003) for the Carlile and Niobrara formations was not available. The contact between the Fish Scales and Belle Fourche formations is usually transitional, though the former contains abundant fish remains in shale (Bloch et al., 1993). This fish-remain-rich interval is “in the lower part” of the Fish Scales Formation defined by Stancliffe and McIntyre (2003) for the Cold Lake area, and is approximately the entire Fish Scales Formation in this study (Fig. 23).

Stancliffe and McIntyre included the so-called Second White Specks Sandstone into the Second White Specks Formation, which forms the upper Belle Fourche Formation after Bloch et al. (1993).

Stancliffe and McIntyre (2003) proposed that the uppermost shales of the cores such as ROB 5 are of early Campanian age and consequently assigned them to the Lea Park Formation. However, the *Globigerinelloides* sp. Zone reveals a Santonian age for this interval (Caldwell et al., 1978). Occurrences of nannofossil species *Rucinolithus hayi*

Figure 23. A comparison between stratigraphic subdivisions of ROB 5 by Stancliffe and McIntyre (2003) and this study. For legends see figures 6a, 6b, 7a, 7b.

Figure 23

and *Marthasterites simplex* also support a Santonian age. In addition, lithological features of this interval, such as calcareous shale, visible white specks make the interval unlike the Lea Park Formation. In this study following Nielsen et al. (2003) and Elberdak (2004), this interval is assigned to the First White Specks Member of the Niobrara Formation.

Paleoenvironments

The Colorado Group was deposited during Late Albian to Santonian when sea level was globally high (Haq et al., 1987; Cant and Stockmal, 1989; Schröder-Adams et al., 1996). As a result, the group is dominated by fine-grained deposits and appears uniform in composition. However, previous studies on the Colorado Group not only stratigraphically subdivided, but also revealed vertical and lateral paleoenvironmental changes in this shale dominated section (e.g. Bloch et al., 1993; Schröder-Adams et al., 1996; Stritch and Schröder-Adams, 1999; Nielson, 2002).

Integrated sedimentological, geochemical, and micropaleontological data are proven to be effective in interpretation of the dynamic paleoenvironments of the Colorado Group. With this approach, Schröder-Adams et al. (1996) discussed vertical and lateral environmental changes of a portion of the Colorado Group from the Late Albian Westgate Formation to the Middle Turonian Second White Specks Formation of the WCSB; Nielsen (2002) studied paleoenvironments of the Upper Turonian to Santonian Carlile and Niobrara formations.

Particularly, micropaleontological data can play an important role in environmental interpretations of shale dominated sections. Microorganisms are sensitive to environmental changes and are good indicators of paleocological variations. Planktic

microfossils provide environmental information such as salinity and temperature of the upper water column, whereas benthic microfossils are used to analyse benthic ecological parameters such as substrate features, water depth, oxygenation, salinity, nutrient availability, and energy (Boltovskoy et al., 1991).

Previous studies show that morphological features of foraminifera respond to physical environments (e.g. Carpenter, 1856; Chamney, 1976; Brouwer, 1965; Butt, 1981). Different approaches have been developed to group foraminifera based on various morphological aspects considered as paleoenvironmental indicators. Generally but not absolutely, morphological groups defined in most studies so far only include taxonomy levels no lower than genus (e.g. Murray, 1973; Chamney, 1976). Instead of establishing or using foraminiferal morphogroups, this study simply applies results of previous studies to paleoenvironmental interpretations on a generic level. Table 1 is a summary of paleoenvironments, life positions and feeding strategies of different foraminiferal genera occurring within the Colorado Group of the Cold Lake area.

The Joli Fou Seaway

In the early Late Albian, relative sea level peaked during the Kiowa-Skull Creek Cycle, and allowed the southern and northern arms of the WIS to connect for the first time, resulting in the Joli Fou Seaway (Williams and Stelck, 1975; Kauffman, 1984; Stott, 1984; Stelck and Koke, 1987) (Fig. 2a). During this period, the cool temperate Boreal water advanced as far south as south-central Colorado, USA (Kauffman, 1984). The Hasler Formation in the Peace River district of northeastern British Columbia represents a thick sedimentary package deposited in the high accommodation setting of the foredeep.

Table 1. Paleoecology of different foraminiferal genera

Genus	Paleoenvironments optimum conditions/ morphological response in adverse conditions	Life position	Feeding strategy	Reference *
<i>Saccammina</i>	Normal marine and hypersaline conditions where nutrient source is favourable; not common in the deeper slope environments	Infaunal/ Epifaunal	Passive deposit feeders	1,2
<i>Miliammina</i>	Shallow, hyposaline (marsh, low-delta complex)	Infaunal	Detrital/bacterial	1,2
<i>Psamminopelta</i>	Hyposaline			1
<i>Glomospira</i>		Epifaunal	Active deposit- feeders	1,2
<i>Glomospirella</i>	“Dual” environment such as a high rate of fresh-water runoff and then a return to more favourable conditions			1,2
<i>Ammodiscus</i>	Slope to shelf; thicker and coarser forms indicate nearshore and thinner more siliceous tests indicate deeper and low energy marine environments	Epifaunal	Active deposit- feeders	1,2
<i>Bathysiphon</i>	Deeper, normal marine. A much shorter, parallel-sided, thicker- and-coarser walled, tube chamber may indicate paralic environments	Erect	Primarily suspension- feeders	1,2
<i>Trochammina</i>	Paralic; quite tolerant to hyposaline conditions	Epifaunal (attached)	Herbivores	1,2
<i>Haplophragmoides</i>	Normal marine of the shelf-slope contact (approx. 130 m). / Fairly tolerant to hyposaline conditions. Involute tests with coarser wall could indicate shallow, paralic conditions; evolute tests with translucent, thin wall could indicate a normal marine environment with a low level of energy in deeper slopes.	Epifaunal	Active herbivores, detritivores	1,2
<i>Verneuilinoides</i>	Tolerant normal marine; most common in the moderate energy paleoenvironments			1
<i>Verneulina</i>	Tolerant normal marine; slightly lower energy level than <i>Verneuilinoides</i>			1

Genus	Paleoenvironments optimum conditions/ morphological response in adverse conditions	Life position	Feeding strategy	Reference *
<i>Gaudryina</i>	General normal marine; slightly lower energy level than <i>Verneuilinoides</i>	Infaunal		1
<i>Gravellina</i>	Tolerant to less favourable normal marine			1
<i>Textularia</i>	Normal marine with relatively moderate energy level/ coarser test wall indicates higher energy level and greater amounts of silica cement indicate lower energy level	Infaunal	Detrital/ Bacterial scavengers	1, 2
<i>Ammobaculites</i>	Normal marine, from nearshore, shallow shelf to slope	Infaunal		1,2
<i>Reophax</i>	All normal marine environments of the shelf and slope. / Not tolerant to environmental changes; thicker, coarser test wall may indicate prodelta environments	Infaunal		1,2
<i>Ammobaculoides</i>	Normal marine, stable environments			1
<i>Pseudobolivina</i> , <i>Uvigerinamina</i>	Optimum, normal marine conditions			1
<i>Gavelinella</i>		Epifaunal/ shallow infaunal		4
<i>Neobulimina</i>	Tolerant to dysoxic conditions	Infaunal		4
<i>Heterohelix</i>	Epicontinental sea (<100m)	Planktic		3, 5
<i>Hedbergella</i>	Shallow water (<100m)	Planktic		3, 5
<i>Globigerinoides</i>	Shallow water (<100m), more open sea	Planktic		3, 5

* 1 refers to Chamney (1976); 2 refers to Jones and Charnock (1985); 3 refers to Leckie (1987); 4 refers to West et al. (1998); 5 refers to Leckie et al. (1998).

In contrast, the Cold Lake area represents a low accommodation setting, where the history of the WIS is documented in a much more condensed section. However, paleoenvironmental changes of the Joli Fou Seaway through time are also reflected by changing sedimentary, geochemical, and micropaleontological features. Comparison between foraminiferal genera and their associated sea-level interpretations between northeastern British Columbia and the Cold Lake area shows certain similarities and differences during Joli Fou time (Fig. 24).

Joli Fou Formation

The Joli Fou Formation represents offshore marine conditions (Fig. 24). The sample (#59) immediately above the Grand Rapids/Joli Fou unconformity in ROB 5 contains no foraminifera, which is consistent with observations of Mattison and Wall (1993) studying the same area. Benthic communities became slowly established during initial transgression after the lowstand that caused the unconformity. The *H. gigas gigas* Subzone in the lower part of the formation carries large forms of *Haplophragmoides*, such as *H. gigas*, *H. postis*, *H. collyra*, *Haplophragmoides* cf. *yukonensis*, and *Haplophragmoides* sp. A (plate I, figs. 20a, 20b; plate II, figs. 4, 5, 6a, 6b, 14a, 14b). The large test size may indicate cold water and a Boreal origin (Koke and Stelck, 1985). The subzone is dominated by genera of *Gaudryina*, *Ammobaculites* and *Haplophragmoides*. Relatively high abundance and species richness indicate a healthy, well circulated, and oxygenated, benthic environment of normal salinity. Chamney (1976) suggested the water depth of 130 m (i.e. shelf/slope boundary) as the most abundant occurrence of agglutinated foraminifera in normal marine. The *H. gigas gigas* Subzone in Cold Lake seems to have been deposited in the offshore transitional zone, below normal wave base

and above storm wave base. This is supported by the dominant dark grey shale, moderate to strong bioturbation of *Planolites*, and the erosional base and top surfaces of silt beds (Fig. 5).

Species richness in the *H. gigas phaseolus* Subzone decreases towards the top of the Joli Fou Formation (Figs. 6a, 7a, 22). The epifaunal taxon *Haplophragmoides* dominates this section accompanied by reduced numbers of the infaunal genus *Ammobaculites* and absence of the infaunal genus *Gaudryina* (Figs. 6a, 7a, 23, Table 1). Leckie et al. (1998) showed that with abundant organic matter supply oxygen is depleted from pore waters in sediment due to excess organic matter, which leads to a dominance of epifaunal taxa. In the Cold Lake region the change in foraminiferal composition between the two subzones might suggest similar environmental conditions on the seafloor. This situation could deteriorate to anoxia locally, leading to foraminiferal barren intervals as observed in the upper Joli Fou Formation (Figs. 6a, 25).

Viking Formation

There is no sedimentary evidence for an unconformity and/or sequence boundary between the Joli Fou and Viking formations in the two cores. However, an unconformity, which represents a significant sea-level fluctuation between the Joli Fou and Viking formations (Fig. 25), is supported by the following evidence. First, according to the sequence stratigraphic model by Reinson et al. (1994) for the Viking Formation in central Alberta, the formation consists of two principle sequences: the lower progradational succession (HST) and the upper transgressive succession (TST). Eastward, the HST thins out and the TST overlies directly the Joli Fou Formation (Reinson et al., 1994, figs. 11, 12, 15). The Cold Lake area is located east from the zero (erosional) edge of the HST

Figure 24. Biostratigraphic and sequence stratigraphic correlation between northeastern British Columbia and the Cold Lake area to show the Joli Fou/Viking unconformity in the Cold Lake area.

LST—lowstand system tract; TST—transgressive system tract; HST—highstand system tract; R-regression; T-transgression

Figure 25. Comprehensive features of the formations in the Colorado Group related to paleoenvironments and sea level changes.

Figure 25

(west-east cross-section K-K' after Reinson et al., 1994, fig. 11). Comparison of gamma-ray signatures of the Joli Fou and Viking formations between their and this study would suggest that the HST is missing in the Cold Lake region (Figs. 20). Second, the regressive *R. tundraensis* Subzone in northeastern British Columbia (Fig. 24) sits across the base of the "Viking marker-bed" (Stelck and Koke, 1987). The lack of this subzone also supports the depositional discontinuity in the Cold Lake area.

The Viking Formation in the Cold Lake area consists of a transgressive-regressive cycle. The *T. depressa* Subzone represents the transgressive phase; the *R. troyeri* Subzone represents the regressive phase (Fig. 24). Average size of the foraminifera recovered from this formation decreases significantly from the underlying Joli Fou Formation (Plate IV). This may be caused by decreased water depth at Viking time. Many foraminiferal species have been reported to decrease in size in response to depth decrease (Boltovskoy et al., 1991, Table 1). Shallowing during Viking time is supported by the frequent rippled siltstone and very fine sandstone beds in the formation. Foraminifera of the Viking Formation responded to the substrate change from the underlying Joli Fou Formation with coarser test walls (Plate IV). In addition, the dominance of genera such as *Haplophragmoides*, *Trochammina*, and *Miliammina* indicates a somewhat brackish environment (Table 1). This further implies the Cold Lake area was dominated or strongly influenced by Boreal waters of reduced salinity or local freshwater influence during the latest stage of the Joli Fou Seaway. Intensive bioturbation, and equal abundance of epifaunal and infaunal foraminifera, suggest a well oxygenated benthic environment with sufficient food supply. Low TOC and HI values suggest terrestrial origin of primary organic matter, high oxygenation rates, and/or increased

sedimentation rates.

The Mowry Sea –the Greenhorn Sea-Level Cycle

Westgate Formation

Following the lowstand of the Viking time, a major transgression marking the base of the latest Albian Westgate Formation initiated the Mowry Sea as well as the Greenhorn Cycle, which extended from Wyoming to the Arctic and from the Rocky Mountain Foothills to eastern Manitoba (Stelck, 1975; Williams and Stelck, 1975; Beaumont, 1984; Leckie and Reinson, 1993) (Fig. 2b).

In many areas of the WCSB, the Westgate Formation is characterized by moderately to well-oxygenated benthic environments in a shallow, wave-influenced sea of inner neritic to possibly middle neritic water depth (Schröder-Adams et al., 1996). In the Cold Lake area, however, the Westgate Formation is characterized by intermittent absences of agglutinated foraminifera. Several barren intervals correspond to non-bioturbated or weakly bioturbated shale intervals (Fig. 25), indicating intermittent dysoxic to anoxic benthic conditions. The coarser intervals with moderate to intensive bioturbation and parallel lamination represent oxygenated benthic environments with higher energy levels. They can be traced laterally for long distances (Figs. 16, 17, 20), hence are considered as products of relative sea-level drop (Fig. 25). At deeper times the basin in the Cold Lake region became stagnant whereas a drop in sea level brought the benthic zone above the oxygenation level, and benthic fauna colonized again. This scenario is not limited to the Cold Lake area, since Schröder-Adams et al. (1996) reported foraminifera-barren shale intervals in the Westgate Formation of central and east-central Alberta as well. During the transgressive phase corresponding to the lowest six metres of

the formation, however, the benthic water was well oxygenated, resulting in foraminiferal content of moderate species richness in the muddy sediment (Fig. 25). Agglutinated foraminifera responded in test grain size to their substrate. Sandy to silty substrates support coarse grained foraminiferal assemblages, whereas fine substrates in the lower part of the formation have a fine grained fauna.

The microfaunal assemblage in the Westgate Formation is characterized by dominance of hyposaline-tolerant foraminiferal taxa, such as *Miliammina*, *Trochammina*, and *Haplophragmoides*. This is consistent with the paleogeography of the Mowry Sea, in which the basin closed to the Tethys in the south and hence became increasingly affected by the Boreal Sea, which is considered to have been more brackish and cooler (Williams and Stelck, 1975).

Fish Scales Formation

A 2-3 cm thick conglomerate consisting of fish remains marks the Albian-Cenomanian boundary and separates the Fish Scales Formation from the underlying Westgate Formation (Fig. 25). The origin of this bonebed is still under discussion. Leckie et al. (1992) proposed two hypotheses: evidence in support of a deep water origin includes: a) the basal phosphatic-rich bed is widespread in the WCSB; b) the fishbed contains very rare to no extra-basinal material; and c) fish bones, especially fish teeth are poorly rounded. However, Leckie et al. (1992) also proposed an alternative interpretation suggesting that the fish-hash conglomerate represents a lag deposit overlying a marine disconformity. The later explanation is consistent with interpretations of biostratigraphic data. The uppermost Albian to lower Cenomanian *Textularia alcesensis* Zone, described by Stelck et al. (1958), is absent over a broad area of the WCSB (North and Caldwell,

1975; Caldwell et al., 1978; Bloch et al.; 1993; Schröder-Adams et al., 1996). If this bed represents a disconformity related to a sea-level lowstand, the location of Cold Lake was far removed from coarse clastic input. Instead fish remains form the coarse-grained fraction and the bioclastic conglomerate might represent a relatively long period of reworking and deposition during subsequent transgression. The organic debris was concentrated when *terrestrial clastic material* was trapped in estuaries and coastal zones (Leckie et al., 1992).

The Albian/Cenomanian boundary records drastic environmental changes indicated by loss of benthic fauna, including foraminifera, and increased organic-matter content. Anoxic bottom-water conditions dominated early Cenomanian time when the Fish Scales Formation was deposited. Density stratification, resulted from either the incomplete mixing of Tethyan and Boreal waters, or the introduction of a meteoric, low-density surface watermass, may account for the anoxia (Kauffman, 1975; Arthur et al., 1985, 1987; Schröder-Adams et al., 1996). Increased freshwater flux which produced a brackish water lid in the stratified water column leads to an interpretation of climate change across the Albian/Cenomanian boundary (Schröder-Adams et al, 1996). The abundant sulphur on the weathered core indicates an initially sulphate-rich sediment. A sediment with abundant sulphide and phosphate is consistent with elevated concentrations of preserved organic material (Leckie et al., 1992).

In contrast to other areas in the WCSB (e. g. Bloch et al., 1993; Schröder-Adams et al., 1996; Elberdak, 2004), TOC and HI values from the Fish Scales Formation at Cold Lake are relatively low and organic matter is mainly of type III (Figs. 6b, 8b). Associated with the organic matter features, the gamma log readings are lower than in other areas,

making the log signatures at the Albian/Cenomanian boundary not as distinct in the Cold Lake area (Figs. 16-21). Low productivity of pelagic algae may account for the low TOC and HI values in the Cold Lake area.

Belle Fourche Formation

The contact between the Belle Fourche Formation and the underlying Fish Scales Formation is conformable and transitional, and discerned by decreased concentration of fish scales and disappearance of sulphur on weathered cores. There is a significant increase in HI values at the base of the Belle Fourche Formation as seen as a distinct trend toward type II on the OI-HI diagram (Figs. 6b, 8b), indicating increased productivity of planktic fauna and/or flora. A slight improvement in condition for benthic organism is indicated by bioturbation and poorly preserved agglutinated foraminifera in the lower part of the formation (Fig. 25). Although bioturbation remains in the upper part, samples are found barren of foraminifera, except one sample (ROB5, #17) which contains 2 fragments of agglutinated foraminiferal specimens. This indicates stressful benthic environments. Increased siltstone and sandstone content indicates shallowing and a sediment source, which is consistent with the development of the Dunvegan Delta in northwestern Alberta (Bhattacharya and Walker, 1991). Above the “X” bentonite, however, increasing TOC and HI values, a shift toward type II organic matter on the HI-OI diagram, and a thin calcareous shale interval suggest a sea-level rise during early Late Cenomanian (Figs. 8b, 25). In southeastern Saskatchewan and southern Alberta, nannofossil and planktic foraminifera have been found from the uppermost part of the Belle Fourche Formation (Schröder-Adams et al., 1996), indicating initial arrival of the warm Tethyan waters across the Canada/US border.

During the middle Cenomanian, cold and low-salinity waters of Boreal origin continued to dominate the WIS (Eicher and Diner, 1985; Cadrin, 1992, Caldwell et al., 1993). The density stratification of the water column may have continued to exist to some extent. However, the lowering of sea level during the middle Cenomanian lowstand may destabilize the stratified water column by reducing water depth (Schröder-Adams et al., 1996). In addition, storms could further break the watermass stratification and briefly increase oxygen levels at the sediment/water interface, resulting in strongly fluctuating abundances of agglutinated foraminifera in most parts of the WCSB (Schröder-Adams et al., 1996). At Cold Lake, and possibly in southeast Alberta (Elberdak, 2004), the effect of storms was abated, probably by greater water depth in the area, resulting in weak bioturbation and absence of foraminifera. In early Late Cenomanian, sea-level rose again and Tethyan sea water intruded intermittently into the southern part of the WCSB.

Second White Specks Formation

In the study area, the latest Cenomanian to early Turonian Second White Specks Formation disconformably overlies the Belle Fourche Formation. This disconformity represents a sea-level lowstand followed by transgression (Fig. 25). The basal bioclastic layer was a product of submarine erosion during transgression. This layer differs from the fish bonebed at the base of the Fish Scales Formation in composition and sedimentary structures, perhaps indicating different origins of the two bioclastic layers.

The transgression led to an interior seaway of maximum width and widespread incursion of the warm Tethyan waters into the WCSB (Fig. 2c; North and Caldwell, 1975a, b; Caldwell et al., 1978; Kauffman, 1977, 1984; Eicher and Diner, 1985; Haq et al., 1988; Kauffman and Caldwell, 1993; Schröder-Adams et al., 1996). The *Hedbergella*

loetterlei Zone is divisible into two subzones in Manitoba and eastern Saskatchewan, whereas only the upper *Whiteinella aprica* subzone exists in Alberta and western Saskatchewan (Caldwell et al., 1978). Lithologies of the Second White Specks Formation and equivalent strata also vary regionally. The formation mainly consists of calcareous shale in most parts of the WSCB whereas chalky shales are limited to the south and southeastern regions (Kauffman, 1984; Nielsen, 2002). Warm Tethyan waters of normal salinity brought planktic foraminifera and nannofossils. The distribution pattern of the planktic species (Eicher and Diner, 1985) and their diachronous occurrence let Caldwell et al. (1993) suggest a circulation model in which the Tethyan water mass intruded into the WCSB along the eastern platform of the Western Interior Seaway spilling slowly westwards. The abundance of pelagic organisms, coupled with widespread bottom water anoxia, resulted in high TOC values of dominantly Type II organic matter (Figs. 6b, 8c). Hay et al. (1993) suggest that the mixing of Boreal and Tethyan watermasses created an oxygen-depleted intermediate body of water. The incursion of the oxygen-poor waters into Canada may have caused the widespread anoxic benthic waters. The high productivity of pelagic organisms strengthened the anoxia.

The thin, rippled nannofossil-bearing lamination indicates unidirectional bottom currents in the seaway. However, the bottom water anoxia is indicated by lack of benthic foraminifera in most parts of the Second White Specks Formation and the well laminated, non-bioturbated sediments. The bivalve *Inoceramus* is abundant throughout the Second White Specks Formation. Inoceramids are epifaunal suspension feeders and very tolerant to different conditions, including anoxia. Their dominance in benthic fauna is another indicator of anoxic benthic condition.

At Cold Lake, the bottom water conditions were less stressful during the first stage of the transgression. A benthic foraminiferal fauna composed of a single species *Neobulimina albertensis* was found immediately above the basal bioclastic layer (Fig. 6b). *N. albertensis* is known to be infaunal and low-oxygen tolerant (West et al., 1998). The dominance of this species in the benthic foraminiferal assemblage indicates a low-oxygen benthic condition. This situation is not isolated. A benthic assemblage consisting of agglutinated and calcareous foraminiferal species, including *N. albertensis*, was found in eastern Alberta (Elberdak, 2004); in the United States, a lower Turonian zone, rich in benthic species, was described from the Great Plains and the Black Mesa Basin in Arizona, by Eicher and Worstell (1970) and Leckie et al. (1991), respectively. The presence of the benthic foraminiferal assemblage may suggest that at the beginning of marine transgression, the bottom water condition was somehow hospitable due to shallower water depth and/or stronger current/wave activities. This interpretation is supported by the fact that the organic matter in the lowest one metre of the Second White Specks Formation is mainly of terrestrial origin (Figs. 6b, 8c).

The remaining foraminiferal assemblage of the Second White Specks Formation is dominated by planktic *Heterohelix* and *Hedbergella*. Both genera are shallow water dwelling (<100m) and belong to the Epicontinental Sea Fauna (Leckie et al., 1987). They tolerate eutrophic environments, lower salinity and temperatures. The dominance of these two genera throughout the Second White Specks Formation is consistent with the theory that the water body in the WCSB during latest Cenomanian and early Turonian was a mixture of Boreal and Tethyan watermasses (Hay et al., 1993). A possible alternative interpretation is that the surface water was diluted by freshwater input. Deeper-dwelling,

salinity-sensitive keeled planktic foraminifera are not found north of the Canada/USA border.

Carlile/Cardium /Morden Formation

Deposition of the Second White Specks Formation was terminated by the regressive phase of the Greenhorn Cycle (Schröder-Adams et al., 1996; Ridgley et al., 2001; Nielsen, 2002). In southern Alberta and southwest Saskatchewan, the regressive phase was recorded in the Carlile Formation, which is characterized by non-calcareous, non-bioturbated to bioturbated shale with lenticular sand beds in the upper unit, siderite concretions in the middle unit, low TOC of terrestrial origin, lack of nannofossils, and presence of the benthic foraminiferal assemblage of *Pseudoclavulina* sp. Zone assigned to the middle and upper units of the formation (Nielsen, 2002). The overall sequence of the Carlile Formation reflects a shallowing seaway during the Late Turonian. In the Manitoba Escarpment, the Morden Formation of Late Turonian age is composed of dark-grey to black, blocky, non-calcareous shale. It carries the *Pseudoclavulina* sp.-*Trochammina* sp. Zone microfauna, which consists of a mixed foraminiferal assemblage of benthic and planktic species (North and Caldwell, 1975; McNeil and Caldwell, 1981). No obvious shallowing of sea level has been revealed from this formation. However, a disconformity between the Favel Formation and Morden Shale has been indicated (McNeil and Caldwell, 1981; Schröder-Adams et al., 2000). In the southern Foothills, the sea-level drop after the Greenhorn maximum transgression is recorded by the change in organic-matter type to Type III, the disappearance of planktic foraminifera and nannofossils, and the introduction of coarse-grained clastics, eventually culminating in the deposition of Cardium sandstones and conglomerates (Wall, 1967b; Schröder-Adams

et al., 1996).

In the study area, the Carlile Formation and its equivalents are missing, causing the Coniacian-Santonian Niobrara Formation to overly directly the Lower Turonian Second White Specks Formation. The south-north cross-section along the west side of the Alberta/Saskatchewan border reveals that the Carlile Formation pinches out around Township 53 (Figs. 17, 18). Northwest-southeast cross-sections show that the Carlile Formation and equivalents are missing in large area of western-central Saskatchewan, and in central Saskatchewan, where the Santonian First White Specks Member of the Niobrara Formation overlies directly the Second White Specks Formation (Fig. 19; Fig. 7 of Schröder-Adams et al., 1996). This implies that the shoreline during the Late Turonian was south and west from the Cold Lake area (Fig. 26).

The Niobrara Cycle

In the study area, the Niobrara Formation represents the Niobrara transgressive-regressive cycle, which includes in ascending order the Verger Member, Medicine Hat equivalent, and First White Specks Member.

Verger Member

In southern Alberta, two subzones of the *Bullopore laevis* Zone have been recognized from the Verger Member: the lower *Marssonella oxycona* Subzone and the upper *Haplophragmoides bonanzaense* Subzone (Elberdak, 2004). In the Cold Lake area, only the *H. bonanzaense* Subzone is found, which implies returning marine influence to this area in the Late Coniacian. Detection of the unconformity between the Verger Member and the underlying Second White Specks Formation is supported by

Figure 26. Marine shoreline distribution during the late Late Turonian. Modified after Nielsen, 2002

micropaleontological and nannofossil analysis, and regional log correlations. No lithological evidence such as pebble beds is found for the depositional hiatus between early Turonian and Coniacian sediments.

The paleoenvironment of the Verger Member in the Cold Lake area is characterized by offshore, low energy, dysoxic bottom water, and prevalence of Boreally-derived watermasses with occasional Tethyan Sea influence. The initial sea-level rise was quick, indicated by the black shale immediately overlying the Verger/Second White Specks disconformity. Black shale, together with moderate TOC values, nearly equal proportions of marine and terrestrially derived organic components, essentially lack of silt or sand beds, and a foraminiferal assemblage of low abundance and species richness dominated by hyposaline-tolerant, epifaunal *Haplophragmoides* reflect a quiet, benthic environment of low oxygen levels. Influence from the Tethyan watermass is indicated by calcareous shale containing nannofossils (figs. 6b, 25).

Medicine Hat equivalent

The lower part of the Medicine Hat equivalent in the Cold Lake area represents continued transgression following the deposition of the Verger Member, with stronger control of the Tethyan waters. This is consistent with paleoenvironments in southern Alberta and southwestern Saskatchewan (Nielsen, 2002; Elberdak, 2004). Calcareous shale intervals containing nannofossils and planktic foraminifera are found in the lower part of this interval (Figs. 6b, 25). Benthic water continued to be dysoxic, indicated by low abundance and low numbers of benthic foraminiferal species, and dominance of *Neobulimina albertensis* and *N. canadensis* (Figs. 6b). However, a slight improvement in benthic conditions can be observed by decreasing TOC values, a slow shift of organic

matter type toward Type III, and increased bioturbation in the shale (Figs. 6b, 7b, 8d). Due to low energy, possibly increased distance to the shoreline and sediment sources, the interval contains only a small amount of silty sediments.

Within the upper Medicine Hat equivalent strata, the benthic environment was further improved while sea level slightly dropped (Fig. 25). Improved benthic conditions brought benthic foraminiferal faunas of higher abundance and species richness when compared to the interval below, and led to medium to strong bioturbation (Figs. 6b, 7b, 25). Influence of Tethyan water decreased, leading to absence of nannofossils and planktic foraminifera in this interval, which corresponds to decreasing TOC values and further shift of the organic matter type to Type III (Figs. 6b, 8d).

Above the bentonite layers, which represent a volcanic ashfall event, sea level rose again, indicated by return of calcareous shale containing nannofossils, elevated TOC, and increased organic matter towards Type II. The close association between the bentonite occurrences and sea-level change points towards the link between relative sea level and volcanic activity related to Cordilleran tectonics (Leckie and Smith, 1992; Bally and Snelson, 1980; Nielsen, 2002).

First White Specks Member

The calcareous shale with visible “specks” of the First White Specks Member abruptly replaces non-calcareous shale of the Medicine Hat equivalent (Figs. 6b, 7b). At DDOB 5, a thin bioclastic layer was recognized (Fig. 7b). This thin layer may represent a brief sea-level fall bringing submarine erosion to the area. The warm, normal-marine Tethyan watermass proceeded to the Canadian part of the WIS during peak transgression of the Niobrara Cycle (Fig. 2f).

In southern Alberta and southwestern Saskatchewan, the Sweetgrass Arch influenced the depositional environments of the Medicine Hat and First White Specks members (Arnott et al., 1995; Hankel et al., 1989; Schröder-Adams et al., 1998; Nielsen, 2002). Sandstones deposited in the mainly calcareous shale interval. Agglutinated foraminifera dominated the microfaunal assemblage, whereas planktic foraminifera and nannofossils are limited to some intervals (Schröder-Adams et al., 1998; Nielsen, 2002; Elberdak, 2004).

In the Cold Lake area, the influence of the Sweetgrass Arch did not exist. The First White Specks Member consists of calcareous shale throughout, with a few bentonite layers and calcareous/dolomitic concretions. Nannofossils prevail throughout the member. The foraminiferal assemblage is characterized by dominance of planktic species. *Heterohelix* and *Hedbergella* are shallow-dwelling planktic genera and are tolerant to low-salinity environments (Leckie et al., 1987). *Globigerinelloides* is characteristic of more open marine pelagic environments and indicate the establishment of normal marine conditions coinciding with peak transgression (West et al., 1998). Absence of benthic foraminifera in large parts of the member, together with dominance of *Neobulimina*, and abundant inoceramids in the member suggest anoxic to dysoxic bottom water condition. High TOC with mainly marine origin (type II) coincides with high productivity of nannofossils (Fig. 6b). Occurrence of agglutinated foraminifera near the top of the core of ROB 5 may represent the beginning of the regressive phase of the Niobrara Cycle (Fig. 25)

Comparison of the Greenhorn and Niobrara Cycles

A comparison is made in this study between the Cenomanian-Turonian Greenhorn

Cycle and the Coniacian-Santonian Niobrara Cycle, both second-order cycles (Haq et al., 1987, 1988), in respect to lithology, sedimentology, log signature, geochemistry, micropaleontology and sea-level change in the Cold Lake area (Fig. 27). A number of similarities between the two cycles become apparent despite representing different times of the WIS history. Thus a cycle model could be established as follows.

The cycle begins with a rapid transgression of the Boreal watermass. Benthic environments become stressful for agglutinated foraminifera. Benthic anoxia/dysoxia leads to high TOC values. After a short period of relief, benthic conditions return to inhospitable during continued sea-level rise. This is followed by a brief lowstand and subsequent transgression, accompanied by submarine erosion. Then sea-level highstand is reached and the warm, normal-marine Tethyan waters widely enter into the basin, bringing planktic foraminiferal assemblages and abundant nannofossils. The benthic environment is dominated by anoxia, which prevents agglutinated foraminifera from colonizing. During final regression, benthic conditions are improving, indicated by the return of agglutinated foraminifera.

Figure 27. A comparison of the Greenhorn Cycle and Niobrara Cycle. For lithological symbols see figures 6a, 6b, 7a, 7b.

Figure 27

CONCLUSIONS

Cores that cover the entire Cretaceous Colorado Group in the heavy oil area near Cold Lake, Alberta, proved that a multidisciplinary approach using sedimentology, geochemistry, micropaleontology, nannofossils, and wireline logs are effective in a study of shale-dominated basins. The following conclusions are drawn from this work:

1. The Joli Fou Formation, forming the lowest part of the Colorado Group, represents continuous transgression of the WIS, which deposited dark grey, non-calcareous shale with a small proportion of siltstone interbeds and few bentonites. Two foraminiferal subzones of the *Haplophragmoides gigas* Zone represent two substages and a subtle environmental change from an oxygenated, occasionally storm influenced offshore transition zone to a deeper shelf environment with abundant food supply during the transgression.

2. The Viking Formation in the Cold Lake area consists of a transgressive-regressive cycle. The subzones of *T. depressa* and *R. troyeri* of the *H. gigas* Zone represent the transgressive and regressive phases, respectively. The study area was dominated by waters from the Boreal Sea during the late stage of the Joli Fou Seaway, and a shallower and well oxygenated benthic environment with sufficient food supply.

3. The *Miliammina manitobensis* Zone occupies the entire Westgate Formation and is characterized by several barren intervals, indicating intermittent dysoxic to anoxic benthic conditions due to a stagnant water column. The *M. manitobensis* Zone is not divisible in the study area. The lack of the upper two subzones of *Haplophragmoides*

postis goodrichi and *Haplopragmium swareni*, as defined in northeast British Columbia, over a large area of the WCSB may suggest the subzones are facies dependent in where they were first defined and the more condensed nature of Westgate sedimentation in areas of reduced accommodation space.

4. The widespread bioclastic layer at the base of the Fish Scales Formation was deposited in relatively deep water during a sudden transgression following a sea-level lowstand at the end of the Albian. The deposition of the Fish Scales Formation is characterized by anoxic bottom water conditions, which was caused by density stratification in the water column that prohibited the development of benthic assemblages.

5. The benthic environment was slightly improved during deposition of the Belle Fourche Formation as indicated by slight bioturbation. However, benthic foraminiferal assemblages were not supported in the Cold Lake area. The upper part of the Belle Fourche Formation records sea-level rise and initial influence of the southern Tethyan Sea.

6. A bioclastic layer at the base of the Second White Specks Formation records another sea-level drop near the base of the Turonian followed by transgression and submarine erosion. Incursion of warm water of normal salinity from the Tethyan Sea brings planktic foraminifera and nannofossils to the basin. Mixture of the two watermasses from north and south created an oxygen-depleted body, and an anoxic benthic environment. However, the dysoxic bottom water during the initial transgression in the Cold Lake area allowed a short term survival of the tolerant *Neobulimina albertensis*.

7. The Carlile Formation which records the regressive phase of the Greenhorn

Cycle is missing in the Cold Lake area, causing the Niobrara Formation to overly directly the Second White Specks Formation extending the disconformity, as documented in central Saskatchewan, into Alberta.

8. The Verger Member records initial transgression of the Niobrara Cycle. The paleoenvironment in the Cold Lake area is featured by offshore, low energy, dysoxic bottom water, mainly Boreally derived with occasional Tethyan influence.

9. The Medicine Hat equivalent interval was deposited during a slow sea-level drop and a following sea-level rise. Short periods of high sea level allowed northward incursions of the Tethyan Sea.

10. Unlike southern Alberta, the Sweetgrass Arch had no influence on the Cold Lake area during the Santonian. Therefore Medicine Hat sandstones were not found.

11. The *Haplophragmoides bonanzaense* and *Neobulimina canadensis* subzones, recently defined by Elberdak (2004) in southern Alberta, were recognized from the Verger Member and lower part of Medicine Hat equivalent interval of the Niobrara Formation. This extends the stratigraphic significance of these two subzones to a relatively broad area.

12. Similarities of the Greenhorn and Niobrara cycles in respect to lithology, sedimentology, geophysics, geochemistry, and micropaleontology imply that in addition to global sea-level change, the sedimentary cycles in the WIS are related to relative sea level connected with repeated plate tectonic movement in the Cordillera.

SYSTEMATICS

Family ASTRORHIZIDAE Brady, 1881

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

Bathysiphon brosgiei Tappan, 1957

Bathysiphon brosgiei Tappan, 1957, United States National Museum, Bulletin N. 215, p. 202, pl. 65, figs. 1-5

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

Bathysipon vitta Nauss, 1947

Bathysipon vitta Nauss, 1947, Journal of Paleontology, v. 21, no. 4, p. 334, pl. 48, fig. 4

Bathysipon vitta Nauss. Tappan, 1962, United States Geological Survey, Prof. Paper 236-C, pl. 29, figs. 6-8

Genus *Hippocrepina* Parker, 1870

Hippocrepina sp.

Family SACCAMMINIDAE Brady, 1884

Genus *Saccamina* M. Sars in Carpenter, 1869

Saccamina alexanderi (Loeblich and Tappan), 1950

Proteonina alexanderi Loeblich and Tappan, 1950, University of Kansas Paleontological

Contributions, Protozoa, art. 3, p. 5, pl. 1, figs. 1, 2

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

Saccammina lathrami Tappan, 1960

Saccammina lathrami Tappan, 1960, Bulletin of the American Association of Petroleum
Geologists, p. 289, pl. 1, figs. 1, 2

Saccammina sp. cf. *S. lathrami* Tappan. Sutherland and Stelck, 1972, Bulletin of
Canadian Petroleum Geology, p. 559, pl. 1, fig. 5

Saccammina globosa Crespin, 1963

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

Family AMMODISCIDAE Reuss, 1862

Genus *Ammodiscus* Reuss, 1862

Ammodiscus kiowensis Loeblich and Tappan, 1950

Ammodiscus kiowensis Loeblich and Tappan, 1950, University of Kansas Paleontological
Contributions, Protozoa, art. 3, p. 5-6, pl. 1, figs. 3a, b

Ammodiscus kiowensis Loeblich and Tappan. Stelck and Wall, in Stelck et al., 1956,
Research Council of Alberta Report 75, p. 25, pl. 5, figs. 16, 17

Genus *Glomospira* Rzehak, 1885

Glomospira reata Eicher, 1960

Glomospira reata Eicher, 1960, Peabody Museum of Natural History, Bulletin, n. 15, p. 56-57, pl. 3 figs. 4a, b, 5

Glomospira reata Eicher. Stelck and Leckie, 1990, Canadian Journal of Earth Sciences, pl. 1, figs. 5-8

Glomospira corona Cushman and Jarvis, 1928

Glomospira corona Cushman and Jarvis, 1928, Contrib. Cushman Lab. Foram. Research, v. 4, pt. 4, pls. 12-14

Glomospira glomerosa Eicher, 1960

Glomospira glomerosa, Eicher, 1960, Peabody Museum of Natural History, Bulletin. 15, p. 56, pl. 3, fig. 6

Glomospira glomerosa, Eicher, 1960. McNeil and Caldwell, 1981, Geological Association of Canada, Special Paper no. 21, p. 138, pl. 9, figs. 18a, b

Glomospira tortuosa Eicher, 1960

Glomospira tortuosa Eicher, 1960, Peabody Museum of Natural History, Bulletin. 15, p. 57, pl. 3, figs. 8a-b

Family HORMOSINIDAE Haeckel, 1894

Genus *Reophax* de Montfort, 1808

Reophax troyeri Tappan, 1960

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

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

Reophax sp.

Family RZEHAKINIDAE Cushman, 1933

Genus *Miliammina* Hero-Allen and Earland, 1930

Miliammina awunensis Tappan, 1957

Miliammina awunensis Tappan, 1957, United States National Museum, Bulletin, no. 215,
p. 210, pl. 67, figs. 19-21

Miliammina awunensis Tappan. Stelck and Koke, 1987, Canadian Journal of Earth
Sciences, v. 24, pl. 2, figs. 23, 24

Miliammina inflata Eicher, 1960

Miliammina inflata Eicher, 1960, Peabody Museum of Natural History, Bulletin 15, p.
70-71, pl. 5, figs. 13-14

Miliammina inflata Eicher. Stelck and Koke, 1987, Canadian Journal of Earth Sciences, v.
24, pl. 2, figs. 21, 22

Miliammina ischnia Tappan, 1957

Miliammina ischnia Tappan, 1957, United States National Museum, Bulletin 215, p. 211,
pl. 67, figs. 25-26

Miliammina ischnia Tappan. North and Caldwell, 1975, Geological Survey of Canada
Paper 74-38, pl. 1, figs. 16a, b

Miliammina manitobensis Wickenden, 1932

Miliammina manitobensis Wickenden, 1932, Royal Society of Canada Transactions, 3rd
Serial, v. 26, sec. 4, p. 90, pl. 1, figs. 11a-c

Miliammina manitobensis Wickenden. North and Caldwell, 1975, Geological Survey of
Canada Paper 74-38, pl. 1, figs. 12a-14b

Miliammina sproulei Nauss, 1947

Miliammina sproulei Nauss, 1947, Journal of Paleontology v. 21, no. 4, p. 339, pl. 48,
figs. 13a-b

Miliammina sproulei Nauss, Koke and Stelck, 1985, Canadian Journal of Earth Sciences,
v. 22, pl. 2, figs. 2, 3, 7, 8

Genus *Psamminopelta* Tappan, 1957

Psamminopelta bowsheri Tappan, 1957

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

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

Family HAPLOPHRAGMOIDIDAE Maync, 1952

Genus *Haplophragmoides* Cushman, 1910

Haplophragmoides bonanzaense Stelck and Wall, 1954

Haplophragmoides bonanzaense Stelck and Wall, 1954. Research Council of Alberta,
Report 68, p. 38, fig. 10

Haplophragmoides collyra Nauss, 1947

Haplophragmoides collyra Nauss, 1947, Journal of Paleontology, v. 21, no. 4, p. 337-338,
pl. 49, figs. 2a, b, 5

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

Haplophragmoides gigas Cushman, 1927

Haplophragmoides gigas Cushman, 1927, Transaction of the Royal Society of Canada,
ser. 3, v. 21, sec. 4, p. 129-130, pl. 1, fig. 5

Haplophragmoides gigas Cushman. Koke and Stelck, 1985, Canadian Journal of Earth
Sciences, v. 22, pl. 2, figs. 10-14

Haplophragmoides gigas minor Nauss, 1947

Haplophragmoides gigas minor Nauss, 1947, Journal of Paleontology, v. 21, p. 338, pl.
49, figs. 10a, b

Haplophragmoides gigas minor Nauss. Stelck and Wall, in Stelck and et al., 1956,

Alberta Research Council Report 75, p. 35-36, pl. 2, figs. 29, 30

Haplophragmoides gilberti Eicher, 1965

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

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

Haplophragmoides hendersonense Stelck and Wall, 1954

Haplophragmoides hendersonense Stelck and Wall, 1954. Research Council of Alberta, Report 68, p. 38, fig. 4

Haplophragmoides howardense Stelck and Wall, 1954

Haplophragmoides howardense Stelck and Wall, 1954, Research Council of Alberta, Report 68, p. 38, figs. 5, 6

Haplophragmoides howardense Stelck and Wall. Wall, 1967, Research Council of Alberta, Bulletin 20, p. 147, figs. 5-7; p. 148, figs. 6-9

Haplophragmoides howardense manifestum Stelck and Wall, 1954

Haplophragmoides howardense manifestum Stelck and Wall, 1954, Research Council of Alberta, Report 68, p. 37., figs. 3, 4, 5, 18; p. 38, figs. 1, 2

Haplophragmoides howardense manifestum Stelck and Wall. Wall, 1967, Research Council of Alberta, Bulletin 20, p. 160, figs. 12, 13

Haplophragmoides cf. kirki Wickenden, 1932

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

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

Haplophragmoides linki Nauss, 1947

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

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

Haplophragmoides postis Stelck and Wall, 1956

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

Haplophragmoides postis goodrich Sutherland and Stelck, 1972

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

Haplophragmoides spiritense Stelck and Wall, 1954

Haplophragmoides spiritense Stelck and Wall, 1954, Research Council of Alberta,

Report 68, p. 38, figs. 7-9

Haplophragmoides topagorukensis Tappan, 1957

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

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

Haplophragmoides cf. *yukonensis* Chamney, 1978

Haplophragmoides yukonensis Chamney, 1978, Geological Survey of Canada, Bulletin
253, p. 13, pl. 2, figs. 8,9

Haplophragmoides yukonensis Chamney. Stelck, 1991, Canadian Journal of Earth
Sciences, v. 28, pl. 2, figs. 36-39

Family LITUOLIDAE de Blainville, 1827

Genus *Ammobaculites* Cushman, 1910

Ammobaculites fragmentarius Cushman, 1927

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

Ammobaculites fragmentarius Cushman. North and Caldwell, 1975, Geological Survey
of Canada Paper 74-38, pl. 2, figs. 2-5

Ammobaculites humei Nauss, 1947

Ammobaculites humei Nauss, 1947, Journal of paleontology, v. 21, no. 4, p. 333, pl. 48,
fig. 1

Ammobaculites pacalis Stelck and Wall, 1954

Ammobaculites pacalis Stelck and Wall, 1954, Research Council of Alberta, Report 68, p.
37, fig. 19

Ammobaculites petilus Eicher, 1960

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

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

Ammobaculites tyrrelli Nauss, 1947

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

Ammobaculites tyrrelli Nauss. North and Caldwell, 1975, Geological Survey of Canada
Paper 74-38, pl. 2, figs. 8, 9

Genus *Ammomarginulina* Wiesner, 1931

Ammomarginulina asperata Guliov, 1966

Ammomarginulina asperata Guliov, 1966, Contributions of the Cushman Foundation for
Foraminiferal Research, p. 142-143, pl. 12, figs. 6-9

Family SPIROPLECTAMMINIDAE

Genus *Ammobaculoides* Plummer, 1932*Ammobaculoides whitneyi* (Cushman and Alexander), 1932

Spiroplectammina whitneyi Cushman and Alexander, 1932, Contributions to the
Cushman Laboratory of Foraminiferal Research, v. 6, no. 1, p. 8, pl. 2, figs,
12a, b

Ammobaculoides whitneyi (Cushman and Alexander). North and Caldwell, 1975,
Geological Survey of Canada Paper 74-38, pl. 2, fig. 12

Family TEXTULARIIDAE Ehrenberg, 1838

Genus *Spiroplectammina* Cushman, 1927*Spiroplectammina semicomplanata* (Carsey), 1926

Textularia semicomplanata Carsey, 1926, University of Texas Bulletin 2612, p. 25, pl. 3,
fig. 4

Spiroplectammina semicomplanata (Carsey), McNeil and Caldwell, 1981, Geological
Association of Canada, Special Paper No. 21, p. 157, pl. 15, fig. 15

Spiroplectammina mordenensis Wickenden, 1932

Spiroplectammina mordenensis Wickenden, 1932, Trans. Royal Soc. Canada, ser. 3, v.
26, sec. 4, pl. 1, fig. 4

Genus *Textularia* DeFrance, 1824

Textularia topagorukensis Tappan, 1957

Textularia topagorukensis Tappan, 1957, United States National Museum, Bulletin No.

215, p. 205, pl. 66, figs. 8, 9

Textularia topagorukensis Tappan. Stelck, 1975, Geological Association of Canada

Special Paper no. 13, pl. 3, figs. 22, 23

Textularia sp.

Genus *Pseudobolivina* Wiesner, 1931

Pseudobolivina rollaensis (Stelck and Wall), 1954

Textularia rollaensis Stelck and Wall, 1954, Research Council of Alberta, Report 68, p.

30, pl. 1, fig. 17

Pseudobolivina rollaensis (Stelck and Wall). North and Caldwell, 1975, Geological

Survey of Canada, Paper 74-38, p.25, pl. 7, fig. 10

Pseudobolivina variana (Eicher), 1960

Bimonilina variana Eicher, 1960, Peabody Museum of Natural History, Bulletin 15, p. 67,

pl. 4, figs. 15-19

Pseudobolivina variana (Eicher). Eicher, 1965, Journal of Paleontology v. 39, p. 897, pl.

104, fig. 8

Family TEXTULARIOPSIDAE Loeblich and Tappan, 1982

Genus *Textulariopsis* Banner and Pereira, 1981

Textulariopsis minuta (Berthelin), 1880

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

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

Family TROCHAMMINIDAE Schwager, 1877

Genus *Trochammina* Parker and Jones, 1859

Trochammina depressa Lozo, 1944

Trochammina depressa Lozo, 1944, American Midland Naturalist v. 31 n. 3, p. 552, pl. 2, figs. 4, 5

Trochammina depressa Lozo. Koke and Stelck, 1985, Canadian Journal of Earth Sciences v. 22, pl. 4, figs. 6-8

Trochammina rainwateri Cushman and Applin, 1946

Trochammina rainwateri Cushman and Applin, 1946, Cushman Laboratory for Foraminiferal Research, Cont. v. 22, no. 3, p. 75, pl. 13, fig. 9

Trochammina rainwateri Cushman and Applin. Bloch et al., 1993, Bulletin of Canadian Petroleum Geology, v. 41, pl. 1, figs., 7,8

Trochammina rutherfordi Stelck and Wall, 1955

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

Trochammina rutherfordi Stelck and Wall. North and Caldwell, 1975, Geological Survey of Canada Paper 74-389, pl. 3, fig. 1

Trochammina umiatensis Tappan, 1957

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

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

Trochammina wetteri Stelck and Wall, 1955

Trochammina wetteri Stelck and Wall, 1955, Research Council of Alberta, Report no. 70, p. 59-60, pl. 2, figs. 1-3, 6

Trochammina wetteri Stelck and Wall. Stelck and Hedinger, 1983. Canadian Journal of Earth Sciences, v. 20, po. 2, figs. 19-20, 33, 34

Family VERNEUILINIDAE Cushman, 1911

Genus *Verneulinoides* Loeblich and Tappan, 1949

Verneulinoides sp.

Genus *Gaudryina* d'Orbigny, 1839

Gaudryina canadensis Cushman, 1943

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

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

Gaudryina irenensis Stelck and Wall, 1955

Gaudryina irenensis Stelck and Wall, 1955, Research Council of Alberta, Report 68, p. 42-43, pl. 2, figs. 4, 5

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

Gaudryina tailleuri (Tappan), 1957

Verneuilinoides tailleuri Tappan, 1957, United States National Museum, Bulletin 215, p. 208, pl. 66, figs. 19-22

Gaudryina tailleuri (Tappan). Tappan, 1962, United States Geological Survey Professional Paper 236-C, p. 149, pl. 35, figs. 8-16

Genus *Verneuilina* d'Orbigny, 1839

Verneuilina canadensis Cushman, 1927

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

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

Genus *Uvigerinammmina* Majzon, 1943

Uvigerinammina manitobensis (Wickenden), 1932

Tritaxia manitobensis Wickenden, 1932, Trans. Royal Soc. Canada, ser. 3, v. 26, sec. 4,
pl. 1, fig. 10

Uvigerinammina manitobensis (Wickenden). McNeil and Caldwell, 1981, The
Geological Survey of Canada, Special Paper No. 21, p. 173, pl. 14, figs. 15-18

Family ATAXOPHRAGMIIDAE Schwager, 1877

Genus *Arenobulimina* Cushman, 1927

Arenobulimina paynei Tappan, 1957

Arenobulimina paynei Tappan, 1957, United States National Museum, Bulletin 215, p.
208, pl. 67, figs. 1-4

Arenobulimina paynei Tappan. North and Caldwell, 1975, Geological Survey of Canada
Paper 74-38, p. 3, figs. 16, 17

Family EGGERELLIDAE Cushman, 1937

Genus *Dorothia* Plummer, 1931

Dorothia smokyensis Wall, 1960

Dorothia smokyensis Wall, 1960, Research Council of Alberta, Bulletin 6, p.23-25, pl. 4,
figs. 22-28

Dorothia smokyensis Wall. McNeil and Caldwell, 1981, The Geological Survey of
Canada, Special Paper No. 21, p. 180, pl. 15, fig. 5

Dorothia sp.

Family GLOBOTEXTULARIIDAE Cushman, 1927

Genus *Gravellina* Brönniamann, 1933

Gravellina chamneyi Stelck, 1975

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

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

Family DISCORBIDAE Ehrenberg, 1838

Genus *Discorbis* Lamarck, 1804

Discorbis cf. *norrisi* Mellon and Wall, 1956

Discorbis norrisi Mellon and Wall, 1956, Research Council of Alberta, Report no. 72, p.
15, pl. 2, figs. 9-11

Family QUADRIMORPHINIDAE Saidova, 1981

Genus *Quadrिमorphina* Finlay, 1939

Quadrिमorphina albertensis Mellon and Wall, 1956

Quadrिमorphina albertensis Mellon and Wall, 1956, Research Council of Alberta,
Report no. 72, p. 24-25, pl. 2, figs. 12-14

Family TRRILINIDAE Cushman, 1927

Genus *Neobulimina* Cushman and Wickenden, 1928

Neobulimina albertensis (Stelck and Wall), 1954

Güembelitra cretacea Cushman var. *albertensis* Stelck and Wall, 1954, Research

Council of Alberta, Report 68, p. 23, pl. 2, figs. 19

Neobulimina albertensis (Stelck and Wall). North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 11a, b, 14

Neobulimina albertensis (Stelck and Wall). McNeil and Caldwell, 1981, The Geological Survey of Canada, Special Paper No. 21, p. 221, pl. 18, figs. 2, 3

Family HETEROHELICIDAE Cushman, 1927

Genus *Heterohelix* Ehrenberg, 1843

Heterohelix globulosa (Ehrenberg), 1840

Textularia globulosa Ehrenberg, 1840, K. Akad. Wiss. Berlin, Physik. Abh. (1838), p. 135, pl. 4, figs. 1b, 2b, 4b, 5b, 7b, 8b

Heterohelix globulosa (Ehrenberg). McNeil and Caldwell, 1981, The Geological Survey of Canada, Special Paper No. 21, p. 236, pl. 19, figs. 1, 2

Heterohelix globulosa (Ehrenberg). North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 8a, b

Heterohelix moremani (Cushman), 1938

Heterohelix moremani (Cushman). North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 9a-c

Heterohelix cf. *reussi* (Cushman),

Heterohelix cf. *reussi* (Cushman). Wall, 1967, Research Council of Alberta, Bulletin 6, p. 164, pl. 13, figs. 22-27

Family PLANOMALINIDAE Bolli, Boeblich, and Tappan, 1957

Genus *Globigerinelloides* Cushman and Ten Dam, 1948

Globigerinelloides messinae (Bröennimann), 1952

Globigerinelloides messinae (Bröennimann). North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 12a-c

Globigerinelloides bentonensis (Morrow), 1934

Globigerinelloides bentonensis (Morrow). North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 13a-c

Family ROTALIPORIDAE Sigal, 1958

Genus *Hedbergella* Bröennimann and Brown, 1958

Hedbergella amabilis Loeblich and Tappan, 1961

Hedbergella amabilis Loeblich and Tappan, 1961, Micropaleontology, v. 7, no. 3, p. 274, pl. 3, figs. 1-10

Hedbergella amabilis Loeblich and Tappan. North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 15a-c

Hedbergella delrioensis (Carsey), 1926

Hedbergella delrioensis (Carsey). North and Caldwell, 1975, Geological Survey of

Canada, Paper 74-38, p.19, pl. 4, figs. 16a-c, 18a-c

Hedbergella delrioensis (Carsey). McNeil and Caldwell, 1981, The Geological Survey of Canada, Special Paper No. 21, p. 251, pl. 20, figs. 5a-c, 6a-c

Hedbergella loetterlei (Nauss), 1947

Globigerina loetterlei Nauss, 1947, Journal of Paleontology, v. 21, no.4, p. 336-337, pl. 49, figs. 11a-c

Hedbergella loetterlei (Nauss). North and Caldwell, 1975, Geological Survey of Canada, Paper 74-38, p.19, pl. 4, figs. 17a-c

Hedbergella planispira (Tappan), 1940

Globigerina planispira Tappan, 1940, Journal of Paleontology, v. 14, p. 122, pl. 19, figs. 12a-c

Hedbergella planispira (Tappan). McNeil and Caldwell, 1981, The Geological Survey of Canada, Special Paper No. 21, p. 251, pl. 20, figs. 7a-c, 8a-c

Hedbergella portdownensis (Williams-Mitchell), 1948

Globigerina portdownensis Williams-Mitchell, 1948, Proc. Geol. Assoc., v. 59, pt. 2, p. 26, pl. 8, fig. 4

Hedbergella portdownensis (Williams-Mitchell). McNeil and Caldwell, 1981, The Geological Survey of Canada, Special Paper No. 21, p. 251, pl. 20, figs. 9a-c, 10a-c

Family MARGINOTRUNCANIDAE Pessagno, 1967

Genus *Whiteinella* Pessagno, 1967*Whiteinella aprica* (Loeblich and Tappan), 1961

Ticinella aprica Loeblich and Tappan, 1961, Micropaleontology, v. 7, no. 3, p. 292, p. 4,
figs. 14-16

Whiteinella aprica (Loeblich and Tappan). North and Caldwell, 1975, Geological Survey
of Canada, Paper 74-38, p.21, pl. 5, figs. 6a-c, 7a-c

Family GLOBOTRUNCANIDAE Brotzen, 1942

Genus *Archaeoglobigerina* Pessagno, 1967*Archaeoglobigerina* sp.

Family ANOMALINIDAE Cushman, 1927

Genus *Gavelinella* Brotzen, 1942*Gavelinella henbesti* (Plummer), 1936

Anomalina henbesti Plummer, 1936, Journal of Paleontology, vol.10, no.4, p. 290-291, pl.
5, figs. 7-10

Anomalinoides henbesti (Plummer). Wall, 1967, Research Council of Alberta, Bulletin 6,
p. 164, pl. 13, figs. 22-27

Gavelinella cf. *talaria* (Nauss), 1947

Anomalinoides talaria (Nauss). Wall, 1967, Research Council of Alberta, Bulletin 6, p.
168, pl. 15, figs. 7-12

Gavelinella talaria (Nauss). North and Caldwell, 1975, Geological Survey of Canada,
Paper 74-38, p.21, pl. 12, figs. 2a-c, 3

REFERENCES

- Arthur, M. A., Dean, W. E. and Schlanger, S. O. 1987. The Cenomanian-Turonian Oceanic Anoxic Event, II. Paleooceanographic controls on organic-matter production and preservation. *In* Marine petroleum source rocks (eds Brooks, J. & Fleet, A. J.), Geological Society, Special Publication 26, 401 – 420
- Arthur, M. A., Dean, W. E., Pollastro, R. M., Claypool, G. E. and Scholle, P. A. 1985. Comparative geochemical and mineralogical studies of two cyclic transgressive pelagic limestone units, Cretaceous western interior basin, U. S. In Fine - grained deposits and biofacies of the Cretaceous Western Interior Seaway : evidence of cyclic sedimentary processes (eds Pratt, L. M., Kauffman, E. G. and Zelt, F. B.), Society of Economic Paleontologists and Mineralogists, 1985 midyear meeting, Golden, CO, Field Trip Guidebook 9, 16 – 27.
- Bally, A. W. and Snelson, S., 1980, Realms of subsidence. *In*: Facts and principles of world petroleum occurrence (Ed. Miall, A. D.), Memoir - Canadian Society of Petroleum Geologists, no.6, pp.9-75
- Banerjee, I. 1989. Tidal sandsheet origin of the transgressive Basal Colorado Sandstone (Albian): a subsurface study of the Cessford, southern Alberta. *Bulletin of Canadian Petroleum Geology*, v 37, p. 1-17
- Beaumont, E. A. 1984. Retrogradational shelf sedimentation : Lower Cretaceous Viking Formation, central Alberta. *In* Siliciclastic shelf sediments (eds Tillman, R. W. and Siemers, C. T.), Society of Economic Paleontologists and Mineralogists, Special Publication 34, 163 – 177.
- Bhattacharya, J. and Walker, R. G. 1991a. Allostratigraphic subdivision of the Upper Cretaceous Dunvegan, Shaftesbury and Kaskapau formations in the northwestern Alberta subsurface. *Bulletin of Canadian Petroleum Geology* 39, 145 – 164.
- Bloch, J., Schröder-Adams, C. J., Leckie, D. A., McIntyre, D. J., Craig, J. and Staniland, M. 1993. Revised stratigraphy of the lower Colorado Group (Albian to Turonian),

- western Canada. *Bulletin of Canadian Petroleum Geology* 41, 325 – 348.
- Boltovskoy, E., Scott, D. B., Medioli, F. S., 1991, Morphological variations of benthic foraminiferal tests in response to changes in ecological parameters: a review. *Journal of Paleontology*, vol.65, no.2, pp.175-185
- Brady, H. B., 1881. Notes on some of the reticularian Rhizopoda of the Challenger expedition. Part III. 1. Classification. 2. Further notes on new species. 3. Note on *Biloculina* mud. *Quarterly Journal of Microscopical Science*, new ser. 21: 31-71
- Brady, H. B., 1884. Report on the foraminifera dredged by H. M. S. Challenger, during the years 1873-1876, in Report on the scientific results of the voyage of the H. M. S. Challenger during the years 1873-1876, *Zoology*, vol. 9
- Brouwer, J., 1965, Agglutinated foraminiferal faunas from turbiditic sequences. I+II. *Proceedings Koninklijke Nederlandse Akademie van Wetenschappen, B*. vol. 69, no. 5, p. 309-334
- Butt, A., 1981, Depositional environments of the Upper Cretaceous rocks in the northern part of the Eastern Alps. Cushman Foundation for Foraminiferal Research, Special Pub. No. 20, p. 1-121
- Cadrin, A. A. J. 1992. Geochemistry and paleoenvironmental reconstruction of the Cretaceous Greenhorn Cyclothem in the Western Interior Basin of Canada. Unpublished Ph. D. thesis, University of Saskatchewan, Saskatoon, 191 pp.
- Caldwell, W. G. E. and North B. R. 1984. Cretaceous stage boundaries in the southern Interior Plains of Canada. *Bulletin of the Geological Society of Denmark* 33, 57 – 69
- Caldwell, W. G. E., Diner, R., Eicher, D. L., Fowler, S. P., North, B. R., Stelck, C. R. and von Holdt Wilhelm, L. 1993. Foraminiferal biostratigraphy of Cretaceous marine cyclothem. *In* Evolution of the Western Interior Basin (eds Caldwell, W. G. E. & Kauffman, E. G.), Geological Association of Canada, Special Paper 39, 477 – 520.
- Caldwell, W. G. E., North, B. R., Stelck, C. R. & Wall, J. H. 1978. A foraminiferal zonal scheme for the Cretaceous System in the Interior Plains of Canada. *In* Western and

- Arctic Canadian biostratigraphy (eds Stelck, C. R. & Chatterton, B. D. E.), Geological Association of Canada, Special Paper 18, 495 – 575.
- Cant, D. and Stockmal, G. S., 1989. Stratigraphy of the Alberta foreland basin; an interpretation in terms of Cordilleran tectonics. Geological Survey of Canada, Program with Abstracts, vol.1989, pp.9
- Cant, D., 1988, Regional structure and development of the Peace River Arch, Alberta: A Paleozoic failed rift system? *Bulletin of Canadian Petroleum Geology*, vol. 36, p. 284-295
- Carpenter, W. B., 1856, Researches in the foraminifera. Royal Society of London, philosophical Transactions, 146, p. 547-569
- Carsey, D. O., 1926. Foraminifera of the Cretaceous of central Texas. University of Texas Bulletin 2612, 56pp
- Chamney, T. P., 1976, Foraminiferal morphogroup symbol for palaeoenvironmental interpretation of drill cutting samples; Arctic America, Albian continental margin. 1st Int. Symp. On Benthonic Foraminifera of Continental Margins, Part B, pp. 585-624
- Chamney, T. P., 1978. Albian foraminifera of the Yukon Territory. Geological Survey of Canada, Bulletin 253, 62p.
- Clack, W. J. F., 1968, Sedimentology of the Mannville Group in the Cold Lake area, Alberta. *Bulletin of Canadian Petroleum Geology*, vol.16, no.2, pp.204-205
- Collinson, D. J. and Thompson, D. B., 1989. Sedimentary structures, 2nd Edition, p.156-157
- Crespin, I., 1963. Lower Cretaceous arenaceous Foraminifera of Australia. Australia, Department of Natural Development, Bureau of Mineral Resources, Geology and Geophysics, Bulletin 66, 69pp.
- Cushman, J. A. and Applin, E. R., 1946. Some foraminifera of Woodbine Age from Texas, Mississippi, Alabama and Georgia. Contributions from the Cushman

- laboratory for foraminiferal research, 22, 3, p. 71-76
- Cushman, J. A. and Jarvis, P. W., 1928. Cretaceous Foraminifera from Trinidad: Contributions of the Cushman Laboratory for Foraminiferal Research, vol. 17, p. 79-100
- Cushman, J. A., 1927a. Some foraminifera from the Cretaceous of Canada. Transactions of the Royal Society of Canada, ser. 3, 21, 4, p. 127-132
- Cushman, J. A., 1927b. An outline of a re-classification of the foraminifera. Contributions from the Cushman Laboratory for Foraminiferal Research, vol 9, p. 32-38
- Cushman, J. A., 1933. Some new foraminiferal genera. Contributions from the Cushman Laboratory for Foraminiferal Research 9. p. 32-38
- Cushman, J. A., 1943. *Gaudryina canadensis*, new name. Contributions from the Cushman Laboratory for Foraminiferal Research, 19, 2, p. 27-28
- Cushman, J.A. and Alexander, C. I., 1932. Some vaginulinas and other Foraminifera from the Lower Cretaceous of Texas. Contributions of the Cushman Laboratory for Foraminiferal Research, 6, p. 1-10
- Defrance, J. L. M., 1824. Dictionaries des Science Naturelles, vol. 32, moll-morf. Strasbourg: F. G. Levrault.
- Ehrenberg, G. G., 1840. Über die Bildung der Kreidefelsen und des Kreidemergels durch unsichtbare Organismen. K. Acad. Wiss. Berlin, Physik. Abh. (1838), p. 59-147
- Eicher, D. L. and Diner, R. 1985. Foraminifera as indicators of watermass in the Cretaceous Greenhorn Sea, Western Interior. In Fine - grained deposits of cyclic sedimentary processes (eds Pratt, L. M., Kauffman, E. G. & Zelt, F. B.), Society of Economic Paleontologists and Mineralogists, 1985 midyear meeting, Golden, CO, Field Trip Guidebook 9, 60 – 71.
- Eicher, D. L. and Worstell, P. 1970. Cenomanian and Turonian foraminifera from the Great Plains, United States Micropaleontology 16, 269 – 324.

- Eicher, D. L., 1965. Foraminifera and biostratigraphy of the Graneros Shale. *Journal of Paleontology*, vol. 39, no. 5, p. 875-909
- Eicher, D. L., 1960. Stratigraphy and micropaleontology of the Thermopolis Shale. *Peabody Museum Natural History, Yale University, Bulletin* 15, 126pp
- Elberdak, 2004 Foraminiferal biostratigraphy and paleoenvironments of the Cretaceous Colorado Group in southeastern and east Central Alberta, Canada. M. Sc. thesis, Carleton University
- Espitalié, J., Laporte, J. L., Madec, M., Marquis, F., Leplat, P., Paulet, J. & Boutefeu, A. 1977. Méthode rapide de caractérisation des roches de mères de leur potentiel pétrolier et de leur degré d'évolution. *Revue de l'Institut Français du Pétrole* 32, 23 – 42.
- Finlay, H. J., 1939. New Zealand Foraminifera: Key species in stratigraphy- No. 3 *Transactions of the Royal Society of New Zealand* 69, p. 309-329
- Gleddie, J. 1954. Upper Cretaceous in western Peace River plains, Alberta. *In* *Western Canada Sedimentary Basin, a symposium* (ed. Clark, L. M.), pp. 486 – 509 (American Association of Petroleum Geologists, Tulsa, Ralph Leslie Rutherford Memorial Volume).
- Gulioy, P., 1966. Two new middle Albian species of Foraminifera from Saskatchewan. *Contributions of Cushman Laboratory for Foraminiferal Research*, vol.17, pt.4, p.142-143
- Haeckel, E., 1894. Systematische Phylogenie. Entwurf eines Natürlichen Systems der Organismen auf Grund ihrer Stammesgeschichte. Theil 1, Systematische Phylogenie der Protisten und Pflanzen. Berlin: Georg Reimer.
- Haq, B.U., Hardenbol, J., and Vail, P.R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science* 235, pp. 1156-1177
- Hay, W. W., Eicher, D. L. and Diner, R. 1993. Physical oceanography and water masses in the Cretaceous Western Interior Seaway. *In* *Evolution of the Western Interior*

- Basin (eds Caldwell, W. G. E. & Kauffman, E. G.), Geological Association of Canada, Special Paper 39, 297 – 318.
- Heron-Allen, E. and Earland, A., 1930. Some foraminifera from the South Atlantic: Pt. III. *Miliammina*, a new siliceous genus. Royal Microbiological Society of London, ser. 3, 50, p.38-45
- Jeletzky, J. A., 1971, Marine Cretaceous biotic provinces and paleogeography of western and Arctic Canada: illustrated by a detailed study of ammonites: Geological Survey of Canada, Paper 70-22, 92 p.
- Jones, R. W. and Charnock, M. A. 1985. 'Morphogroups' of agglutinated foraminifera. Their life positions and feeding habits and potential applicability in (paleo)ecological studies. *Revue de Paleobiologie* 4, 311 – 320.
- Kauffman, E. G. 1975. Dispersal and biostratigraphic potential of Cretaceous benthonic *Bivalvia* in the Western Interior. *In* The Cretaceous System in the Western Interior of North America (ed. Caldwell, W. G. E.), Geological Association of Canada, Special Paper 13, 163 – 194.
- Kauffman, E. G. 1984. Paleogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America. *In* Jurassic - Cretaceous biochronology and paleogeography of North America (ed. Westerman, G. E. G.), Geological Association of Canada, Special Paper 27, 273 – 306.
- Koke, K. R. and Stelck, C. R., 1985, Foraminifera of a Joli Fou Shale equivalent in the Lower Cretaceous (Albian) Hasler Formation, northeastern British Columbia. *Canadian Journal of Earth Sciences*, vol. 22, p. 1299-1313
- Lambeck, K., Cloetingh, S. and McQueen, H. 1987. Intraplate stress and apparent changes in sea level : the basins of northwestern Europe. *In* Sedimentary basins and basin - forming mechanisms (eds Beaumont, C. & Tankard, A. J.). Canadian Society of Petroleum Geologists, Memoir 12, 259 – 268.
- Lamarck, J. B., 1804. Suite des mémoires sur les fossils des environs de Paris. *Annales Musée National d'Histoire Naturelle* 5: 179-188

- Lang, H. R., McGugan, A. 1988. Cretaceous (Albian – Turonian) foraminiferal biostratigraphy and paleogeography of northern Montana and southern Alberta. *Canadian Journal of Earth Sciences* 25, 316 – 342.
- Leckie, D. A., 1986. Tidally influenced, transgressive shelf sediments in the Viking Formation, Caroline, Alberta. *Bulletin of Canadian Petroleum Geology* 34, 111 – 125.
- Leckie, D. A., Schröder-Adams, C. J. and Bloch, J., 2000. The effect of paleotopography on the late Albian and Cenomanian sea-level record of the Canadian Cretaceous interior seaway. *Geological Society of America Bulletin*, vol.112, no.8, pp.1179-1198
- Leckie, D. A. and Smith, D. G. 1992. Regional setting, evolution, and depositional cycles of the Western Canada Foreland Basin. *In* Foreland basins and fold belts (eds Macqueen, R. W. & Leckie, D. A.), American Association of Petroleum Geologists, Memoir 55, 9 – 46.
- Leckie, D. A., Bhattacharya, J., Bloch, J., Gilboy, C. F. & Norris, B. 1994. Cretaceous Colorado / Alberta Group strata of the Western Canada Sedimentary Basin. *In* Geological atlas of the Western Canada Sedimentary Basin (eds Mossop, G. & Shetsen, I.), pp. 335 – 352
- Leckie, D. A., Singh, C., Bloch, J., Wilson, M. & Wall, J., 1992. An anoxic event at the Albian – Cenomanian boundary: the Fish Scale Marker Bed, northern Alberta, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 92, 139 – 166.
- Leckie, R. M., 1987. Paleoecology of mid-Cretaceous planktonic foraminifera: a comparison of open ocean and epicontinental sea assemblages. *Micropaleontology* 33, 164 – 176.
- Leckie, R. M., 1987. Paleoecology of mid-Cretaceous planktonic foraminifera : a comparison of open ocean and epicontinental sea assemblages. *Micropaleontology* 33, 164 – 176.
- Leckie, R. M., Schmidt, M. G., Finkelstein, D. and Yuretich, R. 1991. Paleooceanographic and paleoclimatic interpretations of the Mancos Shale (Upper Cretaceous), Black

Mesa Basin, Arizona. Geological Society of America, Special Paper 260, 139 – 152.

- Leckie, R. M., Yuretich, R. F., West, O. L. O., Finkelstein, D., Schmidt, M., 1998. Paleooceanography of the southwestern Western Interior Sea During the time of the Cenomanian-Turonian boundary (Late Cretaceous). *In* Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA, SEPM Concepts in Sedimentology and Paleontology No. 6, 101-126.
- Loeblich, A. R. Jr. and Tappan, H., 1950. Foraminifera from the type Kiowa Shale, Lower Cretaceous of Kansas. University of Kansas Paleontological Contributions, Protozoa, art. 3, p. 1-15
- Loeblich, A. R. Jr. and Tappan, H., 1961. Cretaceous planktonic Foraminifera: Part I--Cenomanian. *Micropaleontology*, vol. 7, no. 3, p. 257-304
- Lozo, F. E., 1944. Biostratigraphic relations of some north Texas Trinity and Fredricksburg (Comanchean) Foraminifera: *American Midland naturalist*, vol. 31, no. 3, p. 513-582
- Majzon, L., 1943. Adatok Egyes Kárpataljai flis-rétegekhez, tekintettel a Glogotruncanakra: *Évkönyve, Magyar Királyi Földtani Intézet*, 37 (1), p. 1-170
- Mattison, B.W. and Wall, J. H., 1993. Early Cretaceous foraminifera from the Middle and Upper Mannville and Lower Colorado subgroups in the Cold Lake Oil Sands area of east-central Alberta: stratigraphic and paleoenvironmental implications. *Can. J. Earth. Sci.* 30, pp. 94-102
- Mattison, B.W., 1991, Stratigraphic and paleoenvironmental analysis of the upper and middle Mannville sub-groups; Cold Lake Oil Sands area, east-central Alberta, Ph.D. thesis, University of Alberta
- McCrimmon, G. G., 1996, Sedimentology and sequence stratigraphy of the Lower Cretaceous Clearwater Formation, Cold Lake, Alberta. 162pp.
- McCrimmon, G. G.; Arnott, R. W. C., 2002, The Clearwater Formation, Cold Lake, Alberta; a world-class hydrocarbon reservoir hosted in a complex succession of tide-dominated deltaic deposits. *Bulletin of Canadian Petroleum Geology*, vol.50,

no.3, pp.370-392

- McNeil, D. H. and Caldwell, W. G. E. 1981. Cretaceous rocks and their foraminifera in the Manitoba Escarpment. Geological Association of Canada, Special Paper 21, 439 pp.
- Mellon, G. B. and Wall, J. H., 1956. Geology of the McMurray Formation. Part 1. Foraminifera of the upper McMurray and basal Clearwater Formations. Alberta Research Council, Report 72, 29pp
- Montfort, P. Denys de, 1808. Conchyliologie Systématique et Classification Méthodique des Coquilles, vol. 1. Paris: F. Schoell.
- Murray, J. W., 1973, Distribution and ecology of living benthic foraminiferids. Crane, Russak Co
- Nauss, A. W., 1947. Cretaceous microfossils fo the Vermilion area, Alberta. Journal of Paleontology, vol. 21, no. 4, p. 329-343
- Nielsen, K. S., 2002, Lithostratigraphy, sequence stratigraphy and paleoenvironments of the Upper Colorado Group in southern Alberta and Southwestern Saskatchewan: definition of the Carlile and Niobrara formations (Upper Turonian to Upper Santonian). Ph. D. thesis, Carleton University
- Nielsen, K. S., Schröder-Adams, C. J., Leckie, D. A., 2003, A new stratigraphic framework for the Upper Colorado Group (Cretaceous) in southern Alberta and southern Saskatchewan, Canada. Bulletin of Canadian Petroleum Geology, Vol. 51, No.3, 304-346
- North, B. R. and Caldwell, W. G. E. 1975a. Foraminiferal faunas in the Cretaceous System of Saskatchewan. *In* The Cretaceous System in the Western Interior of North America (ed. Caldwell, W. G. E.), Geological Association Canada, Special Paper 13, 303 – 331.
- North, B. R. and Caldwell, W. G. E. 1975b. Illustrations of Canadian fossils : Cretaceous Foraminifera from Saskatchewan and Manitoba. Geological Survey Canada, Paper 74 – 38, 35 pp.

- Obradovich, J. D., 1993, A Cretaceous time scale. in W. G. E. Caldwell and E.G. Kauffman, eds., *Evolution of the Western Interior Basin: Geological Survey of Canada, Special Paper 39*, p. 379-396
- Orbigny, A. d', 1839. *Voyage dans l'Amérique méridionale-Foraminifères*, 5(5). p.1-86
- Parker, W. K. and Jones, T. R., 1859. On the nomenclature of the foraminifera. I. On the species enumerated by Linnaeus and Gmelin. *Annals and Magazine of Natural History*, ser. 3, no. 3, p. 474-482
- Plummer, H. J., 1936. [Review of] *Geology of the Tampico region*, by John Malcolm. *Journal of Paleontology*, vol.10, no.4, pp.324
- Price, R.A. 1994, Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin. *In: Geological Atlas of the Western Canada Sedimentary Basin*, (eds Mossop, G. & Shetsen, I), pp. 13-24
- Reinson, G.E., Warters, W.J., Cox, J., and Price, P.R., 1994, Cretaceous Viking Formation of the Western Canada Sedimentary Basin. *In: Geological Atlas of the Western Canada Sedimentary Basin* (eds Mossop, G. & Shetsen, I.), pp. 353-364
- Reuss, A. E., 1862. Entwurf einer Systematischen Zusammenstellung der Foraminiferen. *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften in Wien, Mathematisch-Naturwissenschaftliche Classe* (1861) 44(1). p. 355-396
- Ridgley, J. L., McNeil, D. H., Gilboy, C. F., 2001, Structural and stratigraphic controls on sites of shallow biogenic gas accumulations in the Upper Cretaceous Belle Fourche and Second White Specks—Greenhorn formations of southern Alberta, Saskatchewan and northern Montana. *In D. Anderson et al., eds. Gas in the Rocks*, p241-270
- Rudkin, R.A. 1964. Lower Cretaceous. *In: Geological History of Western Canada*. R.G. McCrossan and R.P. Glaister (eds.). Calgary, Alberta Society of Petroleum Geologists, p. 56-158
- Raehak, A., 1885. Bemerkungen über einige Foraminiferen der Oligocän Formation.

- Verhandlungen des Naturforschenden Vereins in Brünn (1884) 23. p. 123-129
- Sanderson, J. O. G., 1946, Progress of petroleum geology in Western Canada to 1945. Transactions of the Canadian Institute of Mining and Metallurgy, vol. 49, p. 256-266
- Sars, G. O., 1872. Undersøgelser over Hardangerfjordens Fauna. Forhandlinger i Videnskasselskabet i Kristiania, 1871. p. 246-255
- Schröder-Adams, C. J., Adams, P. J., Haggart, J., Leckie, D. A., Bloch, J., Craig, J., McIntyre, D. J., 1998, An integrated paleontological approach to reservoir problems: Upper Cretaceous Medicine Hat Formation and First White Speckled Shale in southern Alberta, Canada. *Palaios*, 1998, Vol. 3, p. 361-375
- Schröder-Adams, C. J., Cumbaa, S. L., Bloch, J., Leckie, D. A., Craig, J., El-Dein, S. A. S., Simons, D. H. A. E., Kenig, F., 2001. Late Cretaceous (Cenomanian to Campanian) paleoenvironmental history of the Eastern Canadian margin of the Western Interior Seaway: bonebeds and anoxic events. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 170, p. 261-289
- Schröder-Adams, C.J., Leckie, D.A., Bloch, J., Craig, J., McIntyre, D.J., and Adams, P.J. 1996. Paleoenvironmental changes in the Cretaceous (Albian to Turonian) Colorado Group of western Canada: microfossil, sedimentological and geochemical evidence. *Cretaceous Research* 17, pp.311-365
- Schwager, C., 1877. Quadro del proposto sistema di classificazione dei forminiferi con guscio. *Bolletín R. Comitato Geologica d'Italia* 9, p. 511-514, 519-529
- Simpson, F., 1982. Sedimentology, paleoecology and economic geology of Lower Colorado (Cretaceous) strata of west-central Saskatchewan. Saskatchewan Energy and Mines, Saskatchewan Geological Survey, Report 150, 182 pp
- Stancliffe, R. P. W. and McIntyre, D. J., 2003, Stratigraphy and palynology of the Cretaceous Colorado Group and Lea Park Formation at Cold Lake, Alberta, Canada. *Bulletin of Canadian Petroleum Geology*, Vol. 51, No. 2, p. 91-98
- Stelck, C. R. 1975. The Upper Albian *Miliammina manitobensis* Zone in northeastern

- British Columbia. *In* The Cretaceous System in the Western Interior of North America (ed. Caldwell, W. G. E.), Geological Association of Canada, Special Paper 13, 253 – 275
- Stelck, C. R. and Wall, J. H. 1954. Kaskapau Foraminifera from Peace River Area of Western Canada. Research Council of Alberta, Report 68, 38 pp
- Stelck, C. R., Wall, J. H. & Wetter, R. E. 1958. Lower Cenomanian Foraminifera from Peace River Area, Western Canada. Research Council of Alberta, Geological Division, Bulletin 2 (1), 4 – 35
- Stelck, C R and Hedinger, A S. 1983. Foraminifera of the lower part of the Sully Formation (upper Albian), northeastern British Columbia. Canadian Journal of Earth Sciences, vol.20, no.8, pp.1248-1259
- Stelck, C. R. and Leckie, D. A., 1990, Biostratigraphy of the Albian Paddy Member (Lower Cretaceous Peace River Formation), Goodfare, Alberta. Canadian Journal of Earth Sciences, vol.27, no.9, pp.1159-1169
- Stelck, C. R. and Wall J. H., 1955. Foraminifera of the Cenomanian *Dunveganoceras* Zone from Peace River area of western Canada. Research Council of Alberta, Report 70, pp.81
- Stelck, C. R., 1991, Foraminifera of the middle to upper Albian transition (Lower Cretaceous), northeastern British Columbia. Canadian Journal of Earth Sciences, vol. 28, pp.561-580
- Stelck, C.R. and Armstrong, J. 1981. Neogastropylites from southern Alberta. Bulletin of Canadian Petroleum Geology 29, p. 399-407. Stelck and Koke, 1987
- Stelck, C.R. and Koke, K.R. 1987. Foraminiferal zonation of the Viking interval in the Hasler Shale (Albian), northeastern British Columbia. Canadian Journal of Earth Sciences 24, pp. 2254-2278
- Stelck, C.R., Wall, J.H., Bahan, W. G., and Martin, L. J., 1956, Middle Albian foraminifera from Athabasca and Peace River drainage areas of western Canada. Alberta Research Council, Report 75.

- Stott, D. F. 1963. The Cretaceous Alberta Group and equivalent rocks, Rocky Mountain Foothills, Alberta. Geological Survey of Canada, Memoir 317, 306 pp.
- Stott, D. F. 1982. Lower Cretaceous Fort St. John Group and Upper Cretaceous Dunvegan Formation of the Foothills and Plains of Alberta, British Columbia, District of Mackenzie and Yukon Territory. Geological Survey of Canada, Bulletin 328, 124 pp.
- Stott, D. F. 1984. Cretaceous sequences of the foothills of the Canadian Rocky Mountains. *In* The Mesozoic of North America (eds Stott, D. F. & Glass, D. J.), Canadian Society of Petroleum Geologists, Memoir 9, 85 – 108
- Stritch, R.A. and Schröder-Adams, C.J. 1999. Foraminiferal response to Albian relative sea-level changes in northwestern and central Alberta, Canada. *Can. Jour. Earth Sci.* 36 pp.1617-1643
- Sutherland, G. G. and Stelck, C. R., 1972. Foraminifera from the Cretaceous Neogastropiles Zone, Moberly Lake, British Columbia. *Bulletin of Canadian Petroleum Geology*, vol. 20, no. 3, p. 549-582
- Tappan, H., 1940, Foraminifera from the Grayson Formation of northern Texas. *Journal of Paleontology*, vol. 14, p. 93-26
- Tappan, H., 1957. New Cretaceous index Foraminifera from northern Alaska. *U.S. natural Museum Bulletin* 215, p. 201-222
- Tappan, H., 1960. Cretaceous biostratigraphy of northern Alaska. *Bulletin of American Association of Petroleum Geologists*, vol. 44, no. 3, p. 273-297
- Tappan, H., 1962. Foraminifera from the Arctic Slope of Alaska, Part 3, Cretaceous Foraminifera. *U.S. Geological Survey, Professional Paper* 236-C, p. 91-209
- Then, D. R. and Dougherty, B. J., 1983. A new procedure for extracting foraminifera from indurated organic shale. *Geological Survey of Canada, Paper*, vol.83-1B, pp.413-414

- Wall, J. H. 1967a. Cretaceous foraminifera of the Rocky Mountain Foothills, Alberta. Research Council of Alberta, Bulletin 20, 185 pp
- Wall, J. H., 1967b. Paleocology of Cretaceous marine microfaunas in the Rocky Mountain foothill of Alberta and British Columbia. *In* Paleoenvironments of the Cretaceous Seaway in the western Interior: Golden, Colorado School of Mines, p. 173-196
- Wall, J. H., 1967c. Microfauna of the Cretaceous Alberta Shale on Deer Creek, international boundary, Great Plains region. Geological Association of Canada, Proc., v. 18, p. 93-108
- Weisner, H., 1931. Die Foraminiferen der deutschen Südpolar-Expedition 1901-1903. Deutsche Südpolar-Expedition, vol. 20, Zoologie 12. p. 53-165
- West, O. L. O., Leckie, R. M., Schmidt, M., 1998, Foraminiferal paleocology and paleoceanography of the Greenhorn cycle along the southwestern margin of the Western Interior Sea. *In* Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA (eds. W. E. Dean and M. A. Arthur), SEPM Concepts in Sedimentology and Paleontology No. 6, 79-99.
- Wickenden, R. T. D., Shaw, G., 1943. Stratigraphy and structure in Mount Hucross-Commotion Creek map area, British Columbia (summary account). Paper - Geological Survey of Canada, vol.17, no.8, pt.14, pp., 1943
- Wickenden, R. T., 1932. A useful foraminiferal horizon in the Alberta Shale of southern Alberta. Journal of Paleontology, vol. 6, no. 2, p. 203-207
- Williams, G. K., 1958, Influence of the Peace River arch on Mesozoic strata. Journal of Alberta Society of Petroleum Geologists, vol. 6, p. 74-81
- Williams, G.D. and Stelck, C.R. 1975. Speculations on the Cretaceous palaeogeography of North America. *In* The Cretaceous system in the Western Interior of North America. Edited by Caldwell W.G.E. Geological Association of Canada, Special Paper 13, p.1-20
- Williams-Mitchell, E. 1948. The zonal value of Foraminifera in the Chalk of England.

Proc. Geol. Assoc., v. 59, pt. 2, p. 91-112

PLATES

Plate I Foraminifera from the Joli Fou Formation (1)

Scale at the right bottom corner of the plate applies to every figure.

Figure:

- 1 *Saccammina* cf. *alexanderi* Loeblich and Tappan. ROB 5, sample 65, 307.45m
- 2 *Saccammina lathrami* Tappan. DDOB 5, sample 112, 317.5m
- 3 *Glomospira corona* Cushman and Jarvis. DDOB 5, sample 116, 310.1m
- 4 *Ammodiscus kiowensis* Loeblich and Tappan. DDOB 5, sample 112, 315m
- 5 *Miliammina awunensis* Tappan. DDOB 5, sample 120, 305.2m
- 6 *Miliammina sproulei* Nauss. DDOB 5, sample 126, 298.3m
- 7 *Miliammina manitobensis* Wickenden. DDOB 5, sample 120, 305.2m
- 8 *Miliammina manitobensis* Wickenden. ROB 5, sample 65, 307.45m
- 9 *Miliammina awunensis* Tappan. DDOB 5, sample 51, 297.6m
- 10-12 *Haplophragmoides linki* Nauss. ROB 5, sample 60, 320.7m
- 13 *Haplophragmoides topagorukensis* Tappan. DDOB 5, sample 124
- 14 *Haplophragmoides* sp. ROB 5, sample 65, 307.45m
- 15 *Haplophragmoides* cf. *kirki* Wickenden. ROB 5, sample 62, 315.05m
- 16a, b *Haplophragmoides* cf. *kirki* Wickenden. DDOB 5, sample 114, 312.2m
- 17a, b *Haplophragmoides rota* Nauss. ROB 5, sample 60, 320.7m
- 18a, b *Haplophragmoides topagorukensis* Tappan, ROB 5, sample 60, 320.7m
- 19a, b, c *Haplophragmoides spiritense* Stelck and Wall. ROB 5, sample 65, 307.45m
- 20a, b *Haplophragmoides gigas* Cushman. DDOB 5, sample 112, 317.5m
- 21a, b, c *Haplophragmoides topagorukensis* Tappan, ROB 5, sample 60, 307.45m

Plate II Foraminifera from the Joli Fou Formation (2)

Scale at the right bottom corner of the plate applies to every figure, otherwise specified.

Figure:

- 1a, b *Haplophragmoides postis* Stelck and Wall. ROB 5, sample 61, 317.5m
- 2a, b *Haplophragmoides postis* Stelck and Wall. ROB 5, sample 62, 315.05m
- 3a, b *Haplophragmoides hendersonense* Stelck and Wall. DDOB 5, sample 124, 300.4m
- 4 *Haplophragmoides* sp. B ROB 5, sample 61, 317.5m, scale bar 400µm
- 5 *Haplophragmoides postis* Stelck and Wall. ROB 5, sample 61, 317.5m
- 6 *Haplophragmoides postis* Stelck and Wall. DDOB 5, sample 124, 300.4m
- 7a, b *Haplophragmoides* cf. *yukonensis* Tappan. ROB 5, sample 60, 320.7m, scale bar
400µm
- 8 *Haplophragmoides collyra* Nauss. ROB 5, sample 65, 307.4m
- 9a, b *Haplophragmoides hendersonense* Stelck and Wall. DDOB 5, sample 124, 300.4m
- 10a, b *Haplophragmoides collyra* Nauss. DDOB 5, sample 124, 300.4m
- 11a, b *Ammobaculites tyrrelli* Nauss. ROB 5, sample 61, sample 317.5m
- 12a, b *Haplophragmoides postis* Stelck and Wall. DDOB 5, sample 113A, 313m
- 13a, b *Haplophragmoides postis* Stelck and Wall. ROB 5, sample 65, 307.45m
- 14a, b *Haplophragmoides collyra* Nauss. DDOB 5, sample 112, 317.5m
- 15a, b *Ammobaculites humei* Nauss. ROB 5, sample 60, 320.7m
- 16 *Ammobaculites petilus* Eicher. DDOB 5, sample 112, 317.5m

Plate III Foraminifera from the Joli Fou Formation (3)

Scale at the right bottom corner of the plate applies to every figure.

Figure:

- 1, 2 *Ammobaculites fragmentarius* Cushman. DDOB 5 sample 112, 317.5m
- 3a, b, 4 *Ammobaculites fragmentarius* Cushman. ROB 5 sample 61, 317.5m
- 5 *Ammobaculites petilus* Eicher. DDOB 5, sample 108, 322.35m
- 6 *Reophax* sp. ROB 5, sample 63, 312m
- 7 *Ammomarginulina asperata* Guliov. DDOB 5, sample 112, 317.5m
- 8 *Ammomarginulina asperata* Guliov. ROB 5, sample 61, 317.5m
- 9 *Ammobaculoides whitneyi* (Cushman and Alexander). ROB 5, sample 60, 320.7m
- 10 *Textulariopsis minuta* (Berthelin). ROB 5, sample 60, 320.7m
- 11 *Ammobaculites tyrrelli* Nauss. ROB 5, sample 63, 312m
- 12, 13, 18, 21 *Gaudryina irenensis* Stelck and Wall. ROB 5, sample 61, 317.5m
- 14 *Gaudryina irenensis* Stelck and Wall. ROB 5, sample 61, 317.5m
- 15, 17, 19, 20, 22 *Gaudryina canadensis* Cushman. ROB 5, sample 61, 317.5m
- 16 *Verneuilioides* sp. DDOB 5, sample 113A, 313m
- 23 *Gravellina chamneyi* Stelck. DDOB 5, sample 108, 322.35m
- 24a, b, 25 *Gravellina chamneyi* Stelck. DDOB 5, sample 122, 302.8m
- 26, 27 *Pseudobolivina variana* (Eicher). ROB 5, sample 60, 320.7m

Plate IV Foraminifera from the Viking Formation

Scale at the right bottom corner of the plate applies to every figure.

Figure:

- 1 *Bathysiphon* sp. ROB 5, sample 76, 288.3m
- 2 *Bathysiphon vitta* Nauss. DDOB 5, sample 63, 287.3m
- 3 *Glomospira corona* Cushman and Jarvis. DDOB 5, sample 51, 297.6m
- 4 *Glomospira corona* Cushman and Jarvis. ROB 5, sample 75, 288.6m
- 5 *Glomospira reata* Eicher. DDOB 5, sample 61, 290m
- 6a, b *Glomospira* sp. ROB 5, sample 73, 290m
- 7a, b *Thalmannammina* (?) sp. DDOB 5, sample 61, 290m
- 8 *Miliammina sproulei* Nauss. DDOB 5, sample 60, 291.1m
- 9 *Miliammina inflata* Eicher. DDOB 5, sample 58, 293.3m
- 10a, b *Miliammina ischnia* Tappan. ROB 5, sample 74, 289.5m
- 11 *Miliammina* (?) sp. DDOB 5, sample 51, 297.6m
- 12a, b, 13 *Haplophragmoides cushmani* Loeblich and Tappan. DDOB 5, sample 58, 293.3m
- 14 *Haplophragmoides* sp. DDOB 5, sample 51, 297.6m
- 15a, b *Trochammina rutherfordi* Stelck and Wall. ROB 5, sample 76, 288.3m
- 16, 17 *Haplophragmoides cushmani* Loeblich and Tappan . ROB 5, sample 73, 290m
- 18a, b *Trochammina depressa* Lozo. DDOB 5, sample 59, 292.2m
- 19a, b *Trochammina umiatensis* Tappan. DDOB 5, sample 59, 292.2m
- 20 *Haplophragmoides hendersonensis* Stelck and Wall. DDOB 5, sample 124, 300.4m

- 21 *Gaudryina* cf. *irenensis* Stelck and Wall. ROB 5, sample 70, 292.85m
- 22 *Textularia* sp. ROB 5, sample 77, 287.9m
- 23 *Textularia* (?) sp. ROB 5, sample 74, 289.5m
- 24 *Gaudryina* cf. *canadensis* Cushman. ROB 5, sample 70, 292.85m
- 25 *Pseudobolivina variana* (Eicher). ROB 5, sample 71, 291.55m
- 26, 27 *Gaudryina* cf. *irenensis* Stelck and Wall. ROB 5, sample 77, 287.9m
- 28 *Arenobulimina* sp. ROB 5, sample 75, 288.6m
- 29 *Verneulinoides* (?) sp. DDOB 5, sample 59, 292.2m
- 30 *Verneulinoides* (?) sp. ROB 5, sample 78, 287.3m
- 31 *Uvigerinammina manitobensis* (Wickenden). ROB 5, sample 70, 292.85m
- 32 *Pseudobolivina variana* (Eicher). ROB 5, sample 70, 292.85m

Plate V Foraminifera from the Westgate Formation

Scale at the right bottom corner of the plate applies to every figure.

Figure:

1. *Bathysiphon brosgei* Tappan. DDOB 5, sample 8, 235.9m
2. *Glomospira tortusa* Eicher. ROB 5, sample 80, 286.15m
3. *Glomospira* sp. ROB 5, sample 93, 256.5m
4. *Miliammina* (?) sp. ROB 5, sample 82, 283.5m
5. *Miliammina awunensis* Tappan. ROB 5, sample 92, 258.6m
6. *Miliammina ischnia* Tappan. DDOB 5, sample 70, 259.75m
- 7a, b *Miliammina manitobensis* Wickenden. ROB 5, sample 83, 280.9m
- 8a, b *Miliammina* cf. *ischnia* Tappan. DDOB 5, sample 4, 237.8m
- 9a, b *Miliammina manitobensis* Wickenden. ROb 5, sample 80, 286.15m
- 10, 15 *Pseudobolivina variana* (Eicher) . ROB 5, sample 88, 267.2m
- 11 *Gaudryina irenensis* Stelck and Wall. ROB 5, sample 93, 256.5m
- 12 *Gaudryina canadensis* Cushman . ROB 5, sample 93, 256.5m
- 13 *Reophax troyeri* Tappan. DDOB 5, sample 6, 236.2m
- 14 *Verneuilinoides* sp. DDOB 5, sample 8, 235.9m
- 16 *Gaudryina tailleuri* (Tappan). ROB 5, sample 92, 258.6m
- 17 *Verneuilina canadensis* Cushman. ROB 5, sample 82, 283.5m
- 18 *Verneuilina canadensis* Cushman. ROB 5, sample 92, 258.6m
- 19 *Verneuilina* cf. *canadensis* Cushman. ROB 5, sample 82, 283.5m
- 20 *Verneuilina canadensis* Cushman. ROB 5, sample 88, 267.2m

- 21 *Verneuilina* cf. *canadensis* Cushman. ROB 5, sample 88, 267.2m
- 22 *Verneuilinoidea* sp. DDOB 5, sample 8, 235.9m
- 23 *Ammobaculites* cf. *fragmentarius* . ROB 5, sample 92, 258.6m
- 24 *Verneuilina canadensis* Cushman. ROB 5, sample 83, 280.9m
- 25 *Ammobaculites pacalis* Stelck and Wall. ROB 5, sample 90, 264.75m
- 26 *Verneuilinoidea* sp. ROB 5, sample 82, 283.5m
- 27 *Trochammina rainwateri* Cushman and Applin. ROB 5, sample 90, 264.75m
- 28 *Haplophragmoides* cf. *gilberti* Eicher. ROB 5, sample 89, 266.18m
- 29a, b *Haplophragmoides gilberti* Eicher. ROB 5, sample 92, 258.6m
- 30a, b *Haplophragmoides* cf. *kirki* Wickenden . ROB 5, sample 93, 256.5m
- 31 *Trochammina* sp. ROB 5, sample 80, 286.15m
- 32 *Discorbis norrisi* (?) Mellon and Wall. DDOB 5, sample 6, 236.2m
- 33 *Haplophragmoides* (?) sp. DDOB 5, sample 8, 235.6m
- 34a, b *Trochammina* sp. ROB 5, sample 92, 258.6m
- 35a, b *Quadriformina albertensis* (?) Mellon and Wall. DDOB 5, sample 5, 236.5m
- 36 *Arenobulimina paynei* Tappan. ROB 5, sample 92, 258.6m
- 37 *Haplophragmoides kirki* Wickenden . DDOB 5, sample 3, 238.8m

Plate VI Foraminifera from the Second White Specks Formation

Scale at the right bottom corner of the plate applies to every figure.

Figure:

- 1, 2 *Hedbergella amabilis* Loeblich and Tappan. DDOB 5, sample 36, 196.7m
- 3 *Hedbergella* (?) sp. ROB 5, sample 31A, 198.45m
- 4-8 *Hedbergella amabilis* Loeblich and Tappan. ROB 5, sample 31A, 198.45m
- 9, 10 *Hedbergella amabilis* Loeblich and Tappan. ROB 5, sample 29, 200.85m
- 11a, b *Hedbergella loetterlei* (Nauss). DDOB 5, sample 36, 196.7m
- 12a, b, 13, 20 *Hedbergella delrioensis* (Carsey). ROB 5, sample 32, 197.4m
- 14a, b, 15a, b *Hedbergella delrioensis* (Carsey). DDOB 5, sample 36, 196.7m
- 16a, b *Hedbergella planispira* (Tappan). ROB 5, sample 29
- 17a, b, 24 *Hedbergella planispira* (Tappan). ROB 5, sample 32, 197.4m
- 18a, b, c *Hedbergella planispira* (Tappan). ROB 5, sample 33, 194.71m
- 19a, b, c *Hedbergella delrioensis* (Carsey). ROB 5, sample 33, 194.71m
- 21, 22, 23a, b *Hedbergella loetterlei* (Nauss). ROB 5, sample 32, 197.4m
- 25a, b, c *Hedbergella portsdownensis* (Williams-Mitchell). ROB 5, sample 32, 197.4m
- 26-31 *Heterohelix globulosa* (Ehrenberg). ROB 5, sample 32, 197.4m
- 32-39 *Neobulimina albertensis* (Stelck and Wall). ROB 5, sample 29, 200.85m

Plate VII Foraminifera from the Verger Member and lower Medicine Hat equivalent

Scale at the right bottom corner of the plate applies to every figure.

Figure:

- 1 *Reophax* cf. *troyeri* Tappan. DDOB 5, sample 37, 194.4m
- 2 *Haplophragmoides* cf. *crickmayi* Stelck and Wall. DDOB 5, sample 38, 193.65m
- 3a, b *Trochammina rutherfordi* Stelck and Wall. ROB 5, sample 40, 187.6m
- 4a, b, 7a, b *Haplophragmoides* cf. *crickmayi* Stelck and Wall. DDOB 5, sample 37, 194.4m
- 5 *Haplophragmoides howardense* Stelck and Wall. DDOB 5, sample 37, 194.4m
- 6a, b *Haplophragmoides collyra* Nauss. ROB 5, sample 38A, 191.2m
- 8a, b *Haplophragmoides howardensis* Stelck and Wall. ROB 5, sample 42, 184.35m
- 9a, b, c, 10a, b *Archaeoglobigerina* sp. ROB 5, sample 39, 189.2m
- 11a, b, 12a, b *Gavelinella henbesti* (Plummer). ROB 5, sample 41, 185.75m
- 13a, b, 14a, b *Gavelinella* cf. *talaria* (Nauss). ROB 5, sample 41, 185.75m
- 15 *Dorothia* sp. ROB 5, sample 40, 187.6m
- 16 *Spiroplectammina semicomplanta* (Carsey). ROB 5, sample 41, 185.75m
- 17-20 *Praebulimina reussi* (Morrow). ROB 5, sample 39, 189.2m
- 21-23 *Neobulimina albertensis* (Stelck and Wall). ROB 5, sample 41, 185.75m

Plate VII

Plate VIII Foraminifera from the middle and upper Medicine Hat equivalent

Scale at the right bottom corner of the plate applies to every figure.

Figure:

- 1a, b *Haplophragmoides* sp. DDOB 5, sample 80, 176.3m
- 2, 12 *Haplophragmoides howardense* Stelck and Wall. DDOB 5, sample 83, 174.4m
- 3a, b *Haplophragmoides howardense* Stelck and Wall. DDOB 5, sample 80, 176.3m
- 4 *Haplophragmoides collyra* Nauss. DDOB 5, sample 83, 174.4m
- 5a, b *Haplophragmoides* cf. *crickmayi* Stelck and Wall. DDOB 5, sample 83, 174.4m
- 6a, b *Trochammina rutherfordi* Stelck and Wall. DDOB 5, sample 81, 175.7m
- 7a, b *Haplophragmoides* sp. DDOB 5, sample 80, 176.3m
- 8a, b *Trochammina* sp. ROB 5, sample 45, 180m
- 9 *Haplophragmoides bonanzaense* Stelck and Wall. ROB 5, sample 48, 174.4m
- 10a, b *Haplophragmoides howardense* Stelck and Wall. DDOB 5, sample 82, 175.1m
- 11a, b *Trochammina* cf. *rutherfordi* Stelck and Wall. DDOB 5, sample 82, 175.1m
- 13a, b *Trochammina rutherfordi* Stelck and Wall. DDOB 5, sample 83, 174.4m
- 14a, b *Trochammina rutherfordi mellariolum* Eicher. ROB 5, sample 43, 183m
- 15a, b *Haplophragmoides* sp. DDOB 5, sample 82, 184.35m
- 16 *Haplophragmoides* sp. DDOB 5, sample 78, 177.7m
- 17a, b *Haplophragmoides howardense* Stelck and Wall. ROB 5, sample 45, 180m
- 18a, b *Haplophragmoides howardense* Stelck and Wall. ROB 5, sample 44, 181m
- 19a, b, c *Haplophragmoides postis* Stelck and Wall. ROB 5, sample 46, 178.5m

- 20 *Dorothia smokyensis* Wall. DDOB 5, sample 80, 176.3m
- 21 *Dorothia smokyensis* Wall. DDOB 5, sample 77, 178.2m
- 22, 24 *Dorothia smokyensis* Wall. ROB 5, sample 44, 181m
- 23 *Dorothia smokyensis* Wall. DDOB 5, sample 83, 174.4m
- 25 *Spiroplectammina* cf. *mordenensis* Wickenden. DDOB 5, sample 83, 174.4m
- 26 *Pseudobolivina rollaensis* (Stelck and Wall). ROB 5, sample 48, 174.4m
- 27 *Dorothia smokyensis* Wall. DDOB 5, sample 82, 175.1m
- 28 *Ammobaculites* sp. DDOB 5, sample 89, 169.9m
- 29, 30 *Pseudobolivina* sp. ROB 5, sample 49, 171.15m
- 31 *Spiroplectammina* cf. *mordenensis* Wickenden. ROB 5, sample 44, 181m
- 32 *Pseudobolivina rollaensis* (Stelck and Wall). ROB 5, sample 44m 181m
- 33 *Pseudobolivina rollaensis* (Stelck and Wall). DDOB 5, sample 83, 174.4m
- 34 *Pseudobolivina* sp. ROB 5, sample 48, 174.4m
- 35 *Hippocrepina* sp. DDOB 5, sample 83, 174.4m
- 36 *Pseudobolivina* sp. ROB 5, sample 44, 181m
- 37 *Neobulimina albertensis* (Stelck and Wall). ROB 5, sample 49, 171.15m

Plate VIII

Plate IX Foraminifera from the First White Specks Member

Scale at the right bottom corner of the plate applies to every figure.

Figure:

1a, b, 5a, b, 6a, b *Globigerinelloides messinae* (Broenniman). DDOB 5, sample 91, 166.4m

2a, b *Globigerinelloides messinae* (Broenniman). ROB 5, sample 56, 158.72m

3a, b, 8 *Globigerinelloides messinae* (Broenniman). DDOB 5, sample 99, 158.9m

4a, b *Globigerinelloides bentonensis* (Morrow). DDOB 5, sample 91, 166.4m

7a, b, 11 *Globigerinelloides messinae* (Broenniman). ROB 5, sample 97, 155.5m

9 *Globigerinelloides messinae* (Broenniman). DDOB 5, sample 97, 160.5m

10 *Globigerinelloides messinae* (Broenniman). DDOB 5, sample 100, 157.5m

12a, b *Globigerinelloides bentonensis* (Morrow). ROB 5, sample 104, 150.8m

13a, b *Hedbergella delrioensis* (Carsey). ROB 5, sample 55, 160.65m

14 *Neobulimina albertensis* (Stelck and Wall). DDOB 5, sample 91, 166.4m

15-18 *Heterohelix globulosa* (Ehrenberg). DDOB 5, sample 91, 166.4m

19 *Heterohelix globulosa* (Ehrenberg). ROB 5, sample 55, 160.65m

20 *Heterohelix* cf. *reussi* (Cushman). DDOB 5, sample 99, 158.9m

21 *Heterohelix* cf. *reussi* . ROB 5, sample 56, 158.72m

22 *Heterohelix moremani* . DDOB 5, sample 91, 166.4m

Plate IX

APPENDICES

Appendix 1 Foraminiferal Data

[illegible]

[illegible]

ROB 5	Belle Fourche					Second White Specks Formation								Verger Member								
SAMPLE NUMBER	23	24	25	27	28	28A	29	30	31	31A	32	32A	33	34	35	36	37	38	38A	38B		
DEPTH (m)	206.75	205.2	203.3	202.25	201.45	201	200.85	200.25	199.75	198.45	197.4	195.9	194.71	194.55	194.1	194.09	192.8	192.7	191.2	190.2		
BARREN	X	X	X	X	X	X		X	X					X	X	X	X	X		X		
<i>Gaudryina irregularia</i>																						
<i>Gaudryina</i> sp.																						
<i>Haplophragmoides kirki</i>																						
<i>Hedbergella amabilis</i>							1			1												
<i>Hedbergella delrioensis</i>							2				>100	5	17									
<i>Heterohelix globulosa</i>							7			2	3	>100	>100									
<i>Heterohelix moremani</i>							2															
<i>Neobulimina albertensis</i>							8															
<i>Neobulimina canadensis</i>																						
<i>Hedbergella loetterlei</i>										1	>100	10	32									
<i>Hedbergella planispira</i>										20	46		11									
<i>Hedbergella portsdownensis</i>											2											
<i>Whiteinella aprica</i>											2											
<i>Dorothia</i> sp.																						
<i>Pseudobolivina rollaensis</i>																						
<i>Gavelinella henbesti</i>																						
<i>Gavelinella</i> cf. <i>talaria</i>																						
<i>Spiroplectammina semicomplanata</i>																						
<i>Haplophragmoides</i> cf. <i>howardense</i>																						
<i>Trochammina rutherfordi mellariolum</i>																						
<i>Ammobaculites</i> sp.																						
<i>Dorothia smokyensis</i>																						
<i>Textularia</i> sp.																						
<i>Haplophragmoides rota</i>																						
<i>Haplophragmoides bonanzaense</i>																						
<i>Trochammina wetteri</i>																						
<i>Globigerinelloides messinae</i>																						
<i>Miliammina</i> sp.																						
<i>Heterohelix</i> cf. <i>reussi</i>																						
<i>Globigerinelloides bentonensis</i>																						
foram debris																				C		
fish remains			R	A	C	A	C	A														
shell prims									A	A										A		
quartz grains				A	A	A		A						R						R		
mica		R																		R		
Radiolaria																						

ROB 5	Medicine Hat equivalent														First White Specks Mbr.					
SAMPLE NUMBER	39	40	41	42	43	44	45	46	46A	47	48	48A	49	49A	50	50A	51	52	53	53A
DEPTH (m)	189.2	187.6	185.75	184.35	183	181	180	178.5	177	175.6	174.4	172.5	171.15	170	169	168	167.35	166.4	164.72	163.5
BARREN															X	X	X	X	X	X
<i>Gaudryina irregularia</i>																				
<i>Gaudryina</i> sp.																				
<i>Haplophragmoides kirki</i>																				
<i>Hedbergella amabilis</i>																				
<i>Hedbergella delrioensis</i>	25																			
<i>Heterohelix globulosa</i>	3		1																	
<i>Heterohelix moremani</i>																				
<i>Neobulimina albertensis</i>			34										21							
<i>Neobulimina canadensis</i>			33																	
<i>Hedbergella loetterlei</i>																				
<i>Hedbergella planispira</i>																				
<i>Hedbergella portsdownensis</i>																				
<i>Whiteinella aprica</i>																				
<i>Dorothia</i> sp.		2		11		10					17									
<i>Pseudobolivina rollaensis</i>		1		4	21	22	11	18			21		3							
<i>Gavelinella henbesti</i>			5																	
<i>Gavelinella</i> cf. <i>talaria</i>			5																	
<i>Spiroplectamina semicomplanata</i>			3																	
<i>Haplophragmoides</i> cf. <i>howardense</i>				4		3								3						
<i>Trochammina rutherfordi mellariolum</i>						2														
<i>Ammobaculites</i> sp.						2														
<i>Dorothia smokyensis</i>						18	5	5		3										
<i>Textularia</i> sp.						5														
<i>Haplophragmoides rota</i>								1												
<i>Haplophragmoides bonanzaense</i>											4									
<i>Trochammina wetteri</i>											1									
<i>Globigerinelloides messinae</i>																				
<i>Miliammina</i> sp.																				
<i>Heterohelix</i> cf. <i>reussi</i>																				
<i>Globigerinelloides bentonensis</i>																				
foram debris				C		C														
fish remains	C		R												A	C	R	R	A	C
shell prims																				
quartz grains			C								A		C	A	R				R	R
mica														A		C	A	R		
Radiolaria				C		A	C	A									R	A		

[illegible]

[illegible]

DDOB 5	Belle Fourche Fm.							Second White Specks Formation								Verger Member				
SAMPLE NUMBER	24	25	25A	26	27	28	29	30	31	32	33	34	35	36	36A	37	38	39	40	41
DEPTH (m)	209.9	209.2	208.8	207.7	207.2	206.1	202.4	200.7	200	199.4	198.4	197.4	197.2	196.7	195.5	194.4	193.65	192.25	191.75	190.9
BARREN	X	X	X	X	X	X	X	X	X	X					X				X	
<i>Reophax troyeri</i>																				
<i>Hedbergella amabilis</i>											3			1						
<i>Hedbergella delrioensis</i>											8	14	1	15						
<i>Heterohelix globulosa</i>											13	17								
<i>Hedbergella planispira</i>											2	18		22						
<i>Hedbergella loetterlei</i>											10	27	1	15						
<i>Dorothia</i> sp.																21				5
<i>Haplophragmoides</i> cf. <i>crickmayi</i>																7	1			
<i>Haplophragmoides</i> <i>howardense</i>																7		1		
<i>Haplophragmoides</i> cf. <i>eocacula</i>																4				
<i>Reophax</i> cf. <i>troyeri</i>																1				
<i>Haplophragmoides</i> cf. <i>kirki</i>																				
<i>Spiroplectammina</i> cf. <i>mordenensis</i>																				
<i>Verneuilinoides</i> sp.																				
<i>Dorothia smokyensis</i>																				
<i>Haplophragmoides bonanzaense</i>																				
<i>Trochammina</i> sp.																				
<i>Haplophragmoides collyra</i>																				
<i>Haplophragmoides</i> <i>howardense</i>																				
<i>manifestum</i>																				
<i>Trochammina rutherfordi</i>																				
<i>Trochammina rutherfordi mellariolum</i>																				
<i>Pseudobolivina rollaensis</i>																				
<i>Spiroplectammina mordenensis</i>																				
<i>Globigerinelloides messinae</i>																				
<i>Heterohelix moremani</i>																				
<i>Neobulimina albertensis</i>																				
foram debris																				
fish remains							A				R	R	R			A				
shell prims									C					R						
quartz grains							A									A	R			R
mica																				
Radiolaria																	C			

[illegible]

Appendix 2 Nannofossil Data

Number of specimens represented by abundance codes:

R = 1-5 specimens

RF = 6-15 specimens

F = 16-35 specimens

FC = 36-75 specimens

C = 76-150 specimens

CA = 151-300 specimens

A = 301-600 specimens

VA = 600-1000 specimens

ROB 5 07-08-065-03W4

ROB#16 - 201.00m	R	Rf	F	FC	C	CA	A	VA
Ahmuellerella octoradiata								
Arkhangelskiella cymbiformis								
Biantholithus sp.								
Bidiscus dentata								
Bidiscus monocavus								
Biscutum blackii / constans								
Braarudosphaera africana								
Braarudosphaera bigelowii								
Braarudosphaera discula								
Broinsonia bevieri								
Broinsonia furtiva lacuna								
Broinsonia parca								
Calculites obscurus								
Calculites ovalis								
Chiastozygus amphipons								
Chiastozygus plicatus								
Corollithion completum								
Corollithion exiguum								
Corollithion rhombicum								
Corollithion signum								
Cretarhabdus conicus								
Cretarhabdus cren.hansmanii								
Cretarhabdus decorus								
Cretarhabdus surirellus								
Cribrospira ehrenbergi								
Cricolithus multiradiatus								
Cyclolithella armilla								
Cylindralithus asymmetricus								
Cylindralithus coronatus								
Cylindralithus gallicus								
Discorhabdus ignotus								
Eiffellithus eximius								
Eiffellithus trabeculatus								
Eiffellithus turrisseffeli								
Gartnerago costatum								
Gartnerago segmentatum								
Gartnerago zipperum								
Hexalithus sp.								
Kamptnerius magnificus								
Kamptnerius punctatus								
Lithastrinus floralis								
Lithastrinus grilli								
Lithraphidites carniolensis								
Lucianorhabdus cayeuxi								
Lucianorhabdus maleformis								
Manivitella pemmatoidea								
Manivitella solida								
Markalius circumradiatus								
Marthasterites furcatus								
Marthasterites inconspicuus								
Marthasterites simplex								
Microrhabdulus belgicus								
Microrhabdulus decoratus								
Micula decussata								
Micula staurophora								
Parahabdolithus angustus								

[illegible]

[illegible]

ROB5#46 - 188.60m	R	RF	F	FC	C	CA	A	VA
<i>Ahmuelerella octoradiata</i>								
<i>Arkhangelskiella cymbiformis</i>								
<i>Biantholithus</i> sp.								
<i>Bidiscus dentata</i>								
<i>Bidiscus monocavus</i>								
<i>Biscutum blackii</i> / <i>constans</i>								
<i>Braarudosphaera africana</i>								
<i>Braarudosphaera bigelowii</i>								
<i>Braarudosphaera discula</i>								
<i>Broinsonia bevieri</i>								
<i>Broinsonia furtiva lacuna</i>								
<i>Broinsonia parca</i>								
<i>Calculites obscurus</i>								
<i>Calculites ovalis</i>								
<i>Chiastozygus amphipons</i>								
<i>Chiastozygus plicatus</i>								
<i>Corollithion completum</i>								
<i>Corollithion exiguum</i>								
<i>Corollithion rhombicum</i>								
<i>Corollithion signum</i>								
<i>Cretarhabdus conicus</i>								
<i>Cretarhabdus cren.hansmanii</i>								
<i>Cretarhabdus decorus</i>								
<i>Cretarhabdus surirellus</i>								
<i>Cribrospaerella ehrenbergi</i>								
<i>Cricolithus multiradiatus</i>								
<i>Cyclolithella armilla</i>								
<i>Cylindralithus asymmetricus</i>								
<i>Cylindralithus coronatus</i>								
<i>Cylindralithus gallicus</i>								
<i>Discorhabdus ignotus</i>								
<i>Eiffellithus eximius</i>								
<i>Eiffellithus trabeculatus</i>								
<i>Eiffellithus turriseiffeli</i>								
<i>Gartnerago costatum</i>								
<i>Gartnerago segmentatum</i>								
<i>Gartnerago zipperum</i>								
<i>Hexalithus</i> sp.								
<i>Kamptnerius magnificus</i>								
<i>Kamptnerius punctatus</i>								
<i>Lithastrinus floralis</i>								
<i>Lithastrinus grilli</i>								
<i>Lithraphidites carniolensis</i>								
<i>Lucianorhabdus cayeuxi</i>								
<i>Lucianorhabdus maleformis</i>								
<i>Manivitella pemmatoidea</i>								
<i>Manivitella solida</i>								
<i>Markalius circumradiatus</i>								
<i>Marthasterites furcatus</i>								
<i>Marthasterites inconspicuus</i>								
<i>Marthasterites simplex</i>								
<i>Microrhabdulus belgicus</i>								
<i>Microrhabdulus decoratus</i>								
<i>Micula decussata</i>								
<i>Micula staurophora</i>								
<i>Parhabdololithus angustus</i>								

ROB5#46 - 188.60m	R	RF	F	FC	C	CA	A	VA
<i>Parhabdololithus embergeri</i>								
<i>Predicosphaera cretacea</i>								
<i>Predicosphaera spinosa</i>								
<i>Quadrum gartneri</i>								
<i>Rhabdolithina splendens</i>								
<i>Rucinolithus hayi</i>								
<i>Scapholithus</i> sp.								
<i>Sollasites horticus</i>								
<i>Stephanolithion laffittei</i>								
<i>Tetralithus aculeus</i>								
<i>Vagalapilla matalosa</i>								
<i>Vekshinella dibrachiata</i>								
<i>Vekshinella elliptica</i>								
<i>Vekshinella imbricata</i>								
<i>Watznaueria barnesae</i>								
<i>Watznaueria fossacincta</i>								
<i>Zygodiscus acanthus</i>								
<i>Zygodiscus compactus</i>								
<i>Zygodiscus deflandrei</i>								
<i>Zygodiscus diplogrammus</i>								
<i>Zygodiscus elegans</i>								
<i>Zygodiscus erectus</i>								
<i>Zygodiscus fibuliformis</i>								
<i>Zygodiscus orionatus</i>								
<i>Zygodiscus theta</i>								
<i>Prinsiosphaera</i> sp.								
<i>Thoracosphaera</i> sp.								

ROB5#74 - 168.00m	R	RF	F	FC	CA	AVA
<i>Ahmuellerella octoradiata</i>						
<i>Arkhangelskiella cymbiformis</i>						
<i>Biantholithus</i> sp.						
<i>Bidiscus dentata</i>						
<i>Bidiscus monocavus</i>						
<i>Biscutum blackii</i> / <i>constans</i>						
<i>Braarudosphaera africana</i>						
<i>Braarudosphaera bigelowii</i>						
<i>Braarudosphaera discula</i>						
<i>Broinsonia bevieri</i>						
<i>Broinsonia furtiva lacuna</i>						
<i>Broinsonia parca</i>						
<i>Calculites obscurus</i>						
<i>Calculites ovalis</i>						
<i>Chiastozygus amphipons</i>						
<i>Chiastozygus plicatus</i>						
<i>Corollithion completum</i>						
<i>Corollithion exiguum</i>						
<i>Corollithion rhombicum</i>						
<i>Corollithion signum</i>						
<i>Cretarhabdus conicus</i>						
<i>Cretarhabdus cren. hansmanii</i>						
<i>Cretarhabdus decorus</i>						
<i>Cretarhabdus surirellus</i>						
<i>Cribrospira ehrenbergi</i>						
<i>Cricolithus multiradiatus</i>						
<i>Cyclolithella armilla</i>						
<i>Cylindralithus asymmetricus</i>						
<i>Cylindralithus coronatus</i>						
<i>Cylindralithus gallicus</i>						
<i>Discorhabdus ignotus</i>						
<i>Eiffellithus eximius</i>						
<i>Eiffellithus trabeculatus</i>						
<i>Eiffellithus turriseiffeli</i>						
<i>Gartnerago costatum</i>						
<i>Gartnerago segmentatum</i>						
<i>Gartnerago zipperum</i>						
<i>Hexalithus</i> sp.						
<i>Kamptnerius magnificus</i>						
<i>Kamptnerius punctatus</i>						
<i>Lithastrinus floralis</i>						
<i>Lithastrinus grilli</i>						
<i>Lithraphidites carniolensis</i>						
<i>Lucianorhabdus cayuxi</i>						
<i>Lucianorhabdus maleformis</i>						
<i>Manivitella pemmatoidea</i>						
<i>Manivitella solida</i>						
<i>Markalius circumradiatus</i>						
<i>Marthasterites furcatus</i>						
<i>Marthasterites inconspicuus</i>						
<i>Marthasterites simplex</i>						
<i>Microrhabdulus belgicus</i>						
<i>Microrhabdulus decoratus</i>						
<i>Micula decussata</i>						
<i>Micula staurophora</i>						
<i>Parhabdololithus angustus</i>						

ROB5#74 - 168.00m	R	RF	F	FC	CA	AVA
<i>Parhabdololithus embergeri</i>						
<i>Predicosphaera cretacea</i>						
<i>Predicosphaera spinosa</i>						
<i>Quadrum gartneri</i>						
<i>Rhabdolithina splendens</i>						
<i>Rucinolithus hayi</i>						
<i>Scapholithus</i> sp.						
<i>Sollasites horticus</i>						
<i>Stephanolithion laffittei</i>						
<i>Tetralithus aculeus</i>						
<i>Vagalapilla matalosa</i>						
<i>Vekshinella dibrachiata</i>						
<i>Vekshinella elliptica</i>						
<i>Vekshinella imbricata</i>						
<i>Watznaueria barnesae</i>						
<i>Watznaueria fossacincta</i>						
<i>Zygodiscus acanthus</i>						
<i>Zygodiscus compactus</i>						
<i>Zygodiscus deflandrei</i>						
<i>Zygodiscus diplogrammus</i>						
<i>Zygodiscus elegans</i>						
<i>Zygodiscus erectus</i>						
<i>Zygodiscus fibuliformis</i>						
<i>Zygodiscus orionatus</i>						
<i>Zygodiscus theta</i>						
<i>Prinsiosphaera</i> sp.						
<i>Thoracosphaera</i> sp.						

[illegible][illegible]

Appendix 3 Geochemical Data

Rock-Eval Pyrolysis ROB 5 07-08-065-03W4																										
Depth (m)	Sample No.	Qty	S1	S2	S2	PI	S3CO ₂	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO	OICO ₂	OIRE6	MINC %	S4CO	S4CO ₂	RCCO(%)	S4CO ₂	S5aCO ₂	S5bCO ₂	KFID	RCCO ₂ (%)
158.72	56	100.2	0.36	28.99	0.04	0.01	4.46	403	442	1.11	2.49	6.47	3.98	449	17	69	60	0.6	16.6	119.7	0.711	119.7	0	11.9	1335.8	3.26
160.65	55	99.8	0.33	29.62	0.05	0.01	4.52	403	442	1.31	2.55	6.64	4.09	447	20	68	61	0.7	17.4	122.5	0.746	122.5	0	13.3	1335.8	3.34
162.84	54	99.8	0.42	35.33	0.05	0.01	4.51	401	440	1.21	3.02	7.12	4.1	497	17	63	56	0.7	16.1	125.2	0.69	125.2	0	12.7	1335.8	3.41
164.72	53	100.1	0.26	26.56	0.04	0.01	4.67	403	442	1.37	2.29	6.39	4.1	416	21	73	65	0.7	16.5	124.4	0.707	124.4	0	12.1	1335.8	3.39
166.4	52	99.9	0.25	26.14	0.04	0.01	4.93	406	445	1.31	2.25	6.62	4.37	395	20	74	65	0.6	17.9	132.2	0.767	132.2	0	10	1335.8	3.61
167.35	51	99.7	0.28	29.39	0.05	0.01	4.84	405	444	1.46	2.53	6.99	4.46	421	21	69	62	0.6	17.8	135.5	0.763	135.5	0	12	1335.8	3.7
169	50	99.9	0.43	28.17	0.04	0.01	4.78	402	441	1.29	2.43	6.92	4.49	408	19	69	61	0.7	17.1	137.7	0.733	137.7	0	12.4	1335.8	3.76
171.15	49	100.2	0.2	23.71	0.04	0.01	4.22	408	447	1.26	2.04	5.77	3.73	412	22	73	66	0.5	16.4	111	0.703	111	0	9.4	1335.8	3.03
174.4	48	100.6	0.26	8.87	0.02	0.03	2.6	402	441	0.82	0.79	3.86	3.07	230	21	67	61	0.2	15.5	88.2	0.664	88.2	0	3.9	1335.8	2.41
175.6	47	100.7	0.1	2.47	0.01	0.04	1.52	402	441	0.62	0.24	2.12	1.88	117	29	72	69	0.2	10.7	52	0.459	52	0	3.5	1335.8	1.42
178.5	46	100.6	0.04	2.64	0.01	0.02	1.44	411	450	0.32	0.24	1.76	1.52	151	18	82	70	0.2	8.3	42.8	0.356	42.8	0	3.3	1335.8	1.17
180	45	100.6	0.06	2.36	0	0.02	1.47	407	446	0.49	0.22	1.77	1.55	133	28	83	76	0.2	8.3	43.7	0.356	43.7	0	3.2	1335.8	1.19
181	44	99.8	0.05	3.91	0.01	0.01	1.51	412	451	0.4	0.35	2.04	1.69	192	20	74	65	0.2	9.2	47.3	0.394	47.3	0	3.7	1335.8	1.29
183	43	100.5	0.06	3.64	0.01	0.02	1.97	410	449	0.52	0.33	2.21	1.88	165	24	89	78	0.2	9.6	54	0.411	54	0	3.5	1335.8	1.47
184.35	42	100.2	0.06	1.38	0	0.04	1.19	407	446	0.45	0.14	1.53	1.39	90	29	78	73	0.2	7.6	39	0.326	39	0	3.2	1335.8	1.06
185.75	41	99.8	0.1	8.85	0.02	0.01	1.91	414	453	0.49	0.77	2.79	2.02	318	18	68	60	0.3	10.4	57.7	0.446	57.7	0	5.4	1335.8	1.57
187.6	40	100.4	0.06	1.96	0	0.03	1.26	402	441	0.51	0.19	1.72	1.53	114	30	73	70	0.2	7.7	44.1	0.33	44.1	0	3	1335.8	1.2
189.2	39	100.4	0.17	17.66	0.03	0.01	3.05	409	448	0.85	1.52	4.51	2.99	392	19	68	60	0.5	13.7	88.1	0.587	88.1	0	10	1335.8	2.4
192.7	38	99.8	0.1	9.45	0.02	0.01	2.27	414	453	0.67	0.82	3.06	2.24	309	22	74	66	0.4	11.1	64.8	0.476	64.8	0	6.8	1335.8	1.77
192.8	37	100.9	0.54	9.62	0.01	0.05	3.19	390	429	1.54	0.91	4.32	3.41	223	36	74	74	0.6	16.9	98.6	0.724	98.6	0	4.7	1335.8	2.69
194.1	35	99.9	0.83	21.61	0.01	0.04	4.08	393	432	2.27	1.96	6.91	4.95	313	33	59	62	0.6	17.8	153.5	0.763	153.5	0	5	1335.8	4.19
194.55	34	100.6	0.88	19.34	0.01	0.04	4.65	390	429	2.33	1.78	7.17	5.39	270	32	65	66	0.6	23.5	160.8	1.007	160.8	0	5.2	1335.8	4.39
194.71	33	100.7	0.48	36.3	0.05	0.01	5.8	402	441	1.78	3.13	8.29	5.16	438	21	70	63	0.7	18.9	159.6	0.81	159.6	0	12.2	1335.8	4.35
195.9	32A	99.8	0.33	28.54	0.04	0.01	4.98	402	441	1.36	2.46	6.79	4.33	421	20	73	65	0.7	15.1	135	0.647	135	0.1	13.2	1335.8	3.68

Rock-Eval Pyrolysis ROB 5 07-08-065-03W4																										
Depth (m)	Sample No.	Qty	S1	S2	S2	PI	S3CO ₂	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO	OICO ₂	OIRE6	MINC %	S4CO	S4CO ₂	RCCO(%)	S4CO ₂	S5aCO ₂	S5bCO ₂	KFID	RCCO ₂ (%)
197.4	32	100	0.47	40.18	0.04	0.01	6.76	401	440	1.6	3.45	8.81	5.36	457	18	77	66	1.1	16.1	171.1	0.69	171.1	0.1	18.1	1335.8	4.67
198.45	31A	99.8	0.74	53.06	0.07	0.01	7.33	400	439	2.08	4.56	10.85	6.29	490	19	68	60	0.8	18.7	201.4	0.801	201.4	0	15.1	1335.8	5.49
198.45	31A	50.5	0.56	53.29	0.07	0.01	7.04	402	441	2.02	4.56	11.04	6.48	483	18	64	57	0.9	23.9	200	1.024	200	0	15	1335.8	5.45
199.75	31	100.3	0.59	51.08	0.06	0.01	6.99	402	441	2.05	4.38	10.74	6.36	476	19	65	58	0.8	20.8	200.4	0.891	200.4	0	10.7	1335.8	5.47
199.75	31	50.7	0.53	51.23	0.06	0.01	6.57	403	442	2.15	4.39	10.91	6.52	470	20	60	55	0.8	27.1	196.3	1.161	196.3	0	13.8	1335.8	5.35
200.25	30	100.2	0.16	10.12	0.03	0.02	5.3	401	440	1.57	0.92	5.08	4.16	200	31	104	93	0.8	16.9	125.9	0.724	125.9	0	7.8	1335.8	3.43
200.85	29	100.1	0.45	21.5	0.03	0.02	5.55	411	450	1.13	1.87	5.72	3.85	376	20	97	82	0.9	13.7	119.8	0.587	119.8	0.1	15.1	1335.8	3.27
201	28A	100.5	0.3	10.79	0.02	0.03	3.76	410	449	0.77	0.96	3.75	2.79	288	21	100	85	0.7	11.3	84.6	0.484	84.6	0	11.8	1335.8	2.31
201.45	28	100.6	0.2	9.96	0.02	0.02	2.58	401	440	0.79	0.88	3.79	2.91	263	21	68	61	0.3	13.7	85.2	0.587	85.2	0	4.4	1335.8	2.32
202.25	27	99.7	0.37	9.99	0.01	0.04	3.23	393	432	0.68	0.89	4.19	3.3	239	16	77	65	0.4	14.7	97.9	0.63	97.9	0	5.1	1335.8	2.67
203.3	25	100.4	0.29	13.33	0.02	0.02	2.85	401	440	0.89	1.17	4.49	3.32	297	20	63	57	0.3	13.9	100	0.596	100	0	5.2	1335.8	2.73
205.2	24	100.3	0.12	2.94	0.04	0.04	1.51	402	441	0.56	0.28	2.1	1.82	142	27	72	68	0.2	8.8	53.1	0.377	53.1	0	3.5	1335.8	1.45
206.75	23	100.2	0.12	1.71	0	0.07	1.34	402	441	0.65	0.18	1.91	1.73	90	34	70	70	0.3	9.8	47.9	0.42	47.9	0	4.4	1335.8	1.31
209.28	21	100.3	0.28	4.65	0.01	0.06	1.96	406	445	0.52	0.43	3.11	2.68	150	17	63	56	0.3	14.5	75.6	0.621	75.6	0	4.2	1335.8	2.06
213	20	100.2	0.13	2.65	0	0.05	1.79	409	448	0.73	0.26	2.39	2.13	111	31	75	72	0.3	10.5	61.6	0.45	61.6	0	3.4	1335.8	1.68
214.6	19	100.3	0.61	3.01	0	0.17	1.81	406	445	0.72	0.33	2.35	2.02	128	31	77	74	0.4	10.8	57.1	0.463	57.1	0	4.2	1335.8	1.56
217.16	18	100.5	0.05	1.27	0.02	0.04	0.87	419	458	0.27	0.12	1.46	1.34	88	18	60	54	0.2	7.8	37	0.334	37	0	3.4	1335.8	1.01
220.2	17	100.5	0.03	1.7	0.01	0.02	0.61	433	472	0.29	0.16	1.62	1.46	106	18	38	38	0.2	8.4	40.3	0.36	40.3	0	3.5	1335.8	1.1
222.2	16	100.3	0.05	2.96	0.01	0.02	2.15	430	469	0.38	0.27	1.68	1.41	177	23	128	106	0.4	7.2	40.3	0.309	40.3	0	3.7	1335.8	1.1
224.6	15	100.4	0.05	3.92	0.01	0.01	2.78	431	470	0.36	0.35	1.92	1.57	205	19	145	116	0.4	7.9	45.1	0.339	45.1	0	3.7	1335.8	1.23
227.9	14	100.9	0.07	6.8	0.01	0.01	1.6	431	470	0.46	0.59	2.31	1.72	295	20	69	62	0.3	8.6	49.4	0.369	49.4	0	4.2	1335.8	1.35
231.15	13	100.3	0.09	1.42	0	0.06	1.59	408	447	0.71	0.16	2.28	2.12	62	31	70	69	0.3	11.1	60.3	0.476	60.3	0	3.9	1335.8	1.64
231.8	12	100.1	0.08	1.37	0	0.06	2.26	409	448	0.82	0.16	2.25	2.09	61	36	100	93	0.4	9.6	61.7	0.411	61.7	0	3.8	1335.8	1.68
233.3	11	100	0.36	6.52	0.01	0.05	3.27	407	446	1.55	0.64	4.95	4.31	132	31	66	66	0.4	20.6	125.8	0.883	125.8	0	4.8	1335.8	3.43

Rock-Eval Pyrolysis ROB 5 07-08-065-03W4																										
Depth (m)	Sample No.	Qty	S1	S2	S2	PI	S3CO ₂	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	O/CO	O/CO ₂	OIRE6	MINC %	S4CO	S4CO ₂	RCCO(%)	S4CO ₂	S5aCO ₂	S5bCO ₂	KFID	RCCO ₂ (%)
234.9	10	100.2	0.14	2.42	0	0.06	1.83	407	446	0.86	0.25	2.73	2.48	89	32	67	67	0.3	12.7	71	0.544	71	0	4.3	1335.8	1.94
235.2	9	100.1	0.06	1.01	0	0.06	1.52	411	450	0.69	0.12	1.89	1.77	53	37	80	79	0.3	8.9	50.8	0.381	50.8	0	3.6	1335.8	1.39
235.84	8	100.8	0.08	1.44	0	0.05	2.01	410	449	0.95	0.17	2.36	2.19	61	40	85	85	0.3	10.4	64	0.446	64	0	3.7	1335.8	1.75
236.2	7	100.6	0.05	0.85	0	0.06	1.24	411	450	0.54	0.1	1.6	1.5	53	34	78	76	0.2	8	42.3	0.343	42.3	0	3.6	1335.8	1.15
237.9	6	100.1	0.03	0.46	0.01	0.07	1.15	411	450	0.47	0.06	1.21	1.15	39	39	95	91	0.2	5.9	33	0.253	33	0	3.1	1335.8	0.9
241.8	5	99.8	0.05	0.74	0.01	0.06	1.29	409	448	0.64	0.09	1.66	1.57	45	39	78	79	0.2	8.3	44.6	0.356	44.6	0	3.3	1335.8	1.22
244.55	4	100.5	0.04	0.53	0	0.06	0.91	411	450	0.4	0.06	1.37	1.31	39	29	66	65	0.2	6.6	37.5	0.283	37.5	0	3.3	1335.8	1.02
248.8	3	100.4	0.03	0.39	0	0.06	0.86	415	454	0.37	0.05	1.08	1.03	36	34	80	78	0.2	5.3	29.3	0.227	29.3	0	3	1335.8	0.8
251.8	1	100.3	0.02	0.11	0.01	0.13	0.57	413	452	0.34	0.03	0.3	0.27	40	113	190	203	0.3	1.4	7.6	0.06	7.6	0	1.4	1335.8	0.21
252.5	95	100.3	0.01	0.17	0	0.05	0.42	419	458	0.18	0.02	0.6	0.58	28	30	70	68	0.1	2.8	16.9	0.12	16.9	0	2.2	1335.8	0.46
253.2	94	100.4	0.01	0.26	0	0.05	0.5	420	459	0.24	0.03	0.79	0.76	33	30	63	63	0.1	3.9	21.8	0.167	21.8	0	2.3	1335.8	0.59
256.5	93	100.4	0.02	0.38	0	0.05	0.83	419	458	0.33	0.05	1.23	1.18	31	27	67	64	0.2	6.1	33.6	0.261	33.6	0	3.1	1335.8	0.92
258.6	92	100.1	0.01	0.23	0	0.04	0.72	419	458	0.24	0.03	0.94	0.91	24	26	77	71	0.1	4.5	26.4	0.193	26.4	0	2.9	1335.8	0.72
261.5	91	100.8	0.01	0.39	0	0.04	0.87	419	458	0.22	0.04	1.23	1.19	32	18	71	62	0.2	5.8	34.6	0.249	34.6	0	3.3	1335.8	0.94
264.75	90	100.4	0	0.12	0	0.04	0.45	419	458	0.15	0.02	0.56	0.54	21	27	80	74	0.1	2.7	15.6	0.116	15.6	0	2.1	1335.8	0.43
266.18	89	100.6	0.01	0.15	0	0.07	0.58	420	459	0.19	0.02	0.63	0.61	24	30	92	84	0.1	3.1	17.4	0.133	17.4	0	2.3	1335.8	0.47
267.2	88	100.8	0.01	0.16	0	0.04	0.5	419	458	0.15	0.02	0.66	0.64	24	23	76	68	0.1	3.1	18.6	0.133	18.6	0	2.3	1335.8	0.51
268.8	87	100.2	0.01	0.31	0	0.05	0.87	419	458	0.25	0.04	1.16	1.12	27	22	75	67	0.2	5.8	32.1	0.249	32.1	0	3	1335.8	0.88
272.05	86	100.1	0.01	0.41	0	0.03	0.91	420	459	0.21	0.04	1.2	1.16	34	18	76	66	0.1	5.6	33.8	0.24	33.8	0	3	1335.8	0.92
276.15	85	100.2	0.02	0.4	0	0.04	0.83	419	458	0.23	0.04	1.19	1.15	34	19	70	62	0.1	5.7	33.1	0.244	33.1	0	3.1	1335.8	0.9
277.92	84	100.3	0.02	0.58	0	0.03	1.14	422	461	0.36	0.07	1.43	1.36	41	25	80	72	0.2	6.8	39	0.291	39	0	3.6	1335.8	1.06
280.9	83	100.1	0.02	0.37	0	0.04	0.9	419	458	0.25	0.04	1.26	1.22	29	20	71	63	0.2	6.4	34.7	0.274	34.7	0	3.2	1335.8	0.95
283.5	82	100.2	0.02	0.39	0	0.05	0.75	419	458	0.37	0.05	1.11	1.06	35	33	68	68	0.2	5.5	30.2	0.236	30.2	0	3.2	1335.8	0.82
286	81	100.1	0.03	0.67	0	0.05	1.18	416	455	0.47	0.08	1.65	1.57	41	28	72	68	0.2	7.7	45.5	0.33	45.5	0	3.4	1335.8	1.24

Rock-Eval Pyrolysis ROB 5 07-08-065-03W4																										
Depth (m)	Sample No.	Qty	S1	S2	S2	PI	S3CO ₂	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO	OICO ₂	OIRE6	MINC %	S4CO	S4CO ₂	RCCO(%)	S4CO ₂	S5aCO ₂	S5bCO ₂	KFID	RCCO ₂ (%)
286.15	80	100.1	0.02	0.54	0	0.04	1.07	416	455	0.33	0.06	1.34	1.28	40	25	80	72	0.2	5.9	37.5	0.253	37.5	0	3	1335.8	1.02
286.55	79	100.5	0.00	0.14	0.00	0.03	1.82	427	466	0.28	0.02	0.47	0.45	30	60	387	316	1.8	2.2	12.9	0.094	12.9	0.0	2.4	1335.8	0.35
287.3	78	100.4	0.01	0.14	0	0.06	0.57	419	458	0.16	0.02	0.72	0.7	19	22	79	70	0.1	3.5	20.2	0.15	20.2	0	2.3	1335.8	0.55
287.9	77	100.8	0.01	0.08	0	0.08	0.27	419	458	0.01	0.01	0.27	0.26	30	4	100	75	0.1	1.2	7.8	0.051	7.8	0	1.4	1335.8	0.21
288.3	76	100.1	0.01	0.13	0	0.05	0.51	425	464	0.1	0.02	0.71	0.69	18	14	72	60	0.1	3.5	19.8	0.15	19.8	0	2.3	1335.8	0.54
288.6	75	100.5	0.01	0.14	0	0.06	0.44	420	459	0.23	0.02	0.69	0.67	20	33	64	65	0.1	3.4	19.3	0.146	19.3	0	2.2	1335.8	0.53
289.5	74	99.8	0.01	0.13	0	0.05	0.43	419	458	0.11	0.02	0.63	0.61	21	17	68	59	0.1	3.1	17.4	0.133	17.4	0	2.1	1335.8	0.47
290	73	100.6	0.01	0.16	0	0.06	0.55	420	459	0.17	0.02	0.74	0.72	22	23	74	67	0.1	3.6	20.7	0.154	20.7	0	2.3	1335.8	0.56
291.5	72	99.7	0.01	0.26	0.03	0.04	0.71	419	458	0.25	0.04	0.75	0.71	39	33	95	88	0.1	3.5	20.5	0.15	20.5	0	2.2	1335.8	0.56
291.55	71	99.8	0.01	0.19	0	0.07	0.65	420	459	0.17	0.02	0.76	0.74	25	22	86	75	0.1	3.8	21.2	0.163	21.2	0	2.3	1335.8	0.58
292.85	70	100	0.01	0.18	0	0.05	0.61	419	458	0.17	0.02	0.83	0.81	22	20	73	65	0.2	4.2	23.1	0.18	23.1	0	2.6	1335.8	0.63
294.8	69	100.4	0.01	0.2	0	0.06	0.64	419	458	0.18	0.03	0.83	0.8	24	22	77	69	0.2	4	23.2	0.171	23.2	0	2.5	1335.8	0.63
296.85	68	100.9	0.01	0.19	0	0.06	0.66	415	454	0.3	0.03	0.83	0.8	23	36	80	79	0.2	3.9	23.1	0.167	23.1	0	2.8	1335.8	0.63
301.3	67	100.1	0.01	0.13	0	0.07	0.51	419	458	0.26	0.02	0.76	0.74	17	34	67	68	0.1	3.8	21.2	0.163	21.2	0	2.6	1335.8	0.58
304.7	66	100.5	0.01	0.14	0	0.06	0.57	415	454	0.13	0.02	0.77	0.75	18	17	74	64	0.1	3.9	21.5	0.167	21.5	0	2.5	1335.8	0.59
307.45	65	99.9	0.01	0.13	0	0.06	0.51	415	454	0.1	0.02	0.68	0.66	19	15	75	63	0.1	3.1	19.4	0.133	19.4	0	2.4	1335.8	0.53
309.65	64	100	0.01	0.16	0	0.06	0.57	413	452	0.18	0.02	0.73	0.71	22	25	78	71	0.1	3.6	20.3	0.154	20.3	0	2.8	1335.8	0.55
312	63	100.4	0	0.07	0	0.05	0.54	415	454	0.06	0.01	0.4	0.39	18	15	135	107	0.2	2	11.2	0.086	11.2	0	2	1335.8	0.31
315.05	62	100.7	0.01	0.08	0	0.07	0.47	418	457	0.17	0.01	0.48	0.47	17	35	98	91	0.1	2.4	13.6	0.103	13.6	0	2	1335.8	0.37
317.5	61	100.2	0.01	0.09	0	0.07	0.59	415	454	0.16	0.02	0.63	0.61	14	25	94	83	0.1	3	17.8	0.129	17.8	0	2.4	1335.8	0.49
320.7	60	100.8	0.01	0.13	0	0.07	0.72	415	454	0.18	0.02	0.8	0.78	16	23	90	79	0.1	3.9	22.4	0.167	22.4	0	2.7	1335.8	0.61
323.3	59	99.9	0.02	0.22	0	0.08	0.79	412	451	0.24	0.03	1.08	1.05	20	22	73	66	0.2	5.5	29.8	0.236	29.8	0	3.2	1335.8	0.81