**FORAMINIFERAL BIOSTRATIGRAPHY AND
PALEOENVIRONMENTS OF THE CRETACEOUS COLORADO
GROUP IN SOUTHEASTERN AND EAST CENTRAL ALBERTA,
CANADA**

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

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ABSTRACT

The Colorado Group in the Western Canada Sedimentary Basin is a shale-dominated interval that documents a complex history of the Cretaceous Western Interior Sea. Foraminiferal assemblages play a crucial role in interpreting paleoenvironments closely linked to sea-level changes and anoxic events. This study is based on three reference cores that document deposition and biotic changes from the Latest Albian Westgate Formation to the Santonian Niobrara Formation in southeastern and east central Alberta. The interval covers the Greenhorn and Niobrara sea-level cycles that have resulted in major paleogeographic changes of North America.

The study area falls within the central part of the basin; however, it is influenced at times by the topographic relief of the Sweetgrass Arch providing low accommodation space. During latest Albian time the area was flooded by the Mowry Sea, a well oxygenated, but slightly brackish environment dominated by agglutinated foraminiferal assemblages. Oxygen depleted benthic environments resulting in organic-rich strata, but barren of foraminifera, characterized the Cenomanian. Sea level peaks during the Turonian brought warm Tethyan water masses into Canada that stratify with Boreally derived colder waters, resulting in deposition of the organic-rich Second White Specks Formation. These strata are characterized by planktic foraminifera only. The regression of the Greenhorn cycle and severe constriction of the seaway is documented in the Upper Turonian Carlile Formation with the return to agglutinated assemblages. Renewed transgression deposited the Niobrara Formation with mixed agglutinated/calcareous benthic and planktic faunas. Subtle faunal changes resulted in a refined subzonation.

Morphogroups of benthic and planktic foraminifera and their vertical and lateral compositional changes deliver important information on paleoecological change.

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INTRODUCTION

This study addresses foraminiferal assemblages and paleoenvironmental changes in the Cretaceous Western Interior Sea (**WIS**) as observed in subsurface core in southeastern and east-central Alberta (Figure 1). The Colorado Group was deposited in the Western Canada Sedimentary Basin (**WCSB**) during Albian to Santonian time. The deposition of the Colorado Group was coincident with a regional tectonic downflexing of the North American craton (Lambeck et al., 1987). The asymmetric basin of the Western Canada foreland basin is a series of stacked westward-thickening clastic wedges that extend for more than 1300 km from the Rocky Mountains to the Manitoba Escarpment.

The Colorado Group is dominated by shale and mudstone interrupted by several sandstone and conglomerate units, some of which are hydrocarbon horizons. These include the Viking/Bow Island formations and Medicine Hat Member. Within the Colorado Group, the Fish Scales Formation, Second White Specks Formation and First White Specks Member have high total organic carbon content, and might act as source rock (Bloch et al., 1999). An interval such as the Second White Specks Formation is potentially both a source and a reservoir rock for hydrocarbons (Leckie et al., 1994).

The Lower Colorado Group consists of three shale formations that have been recognized in the subsurface across western Canada, which are, in ascending order the Late Albian Westgate Formation, Early Cenomanian Fish Scales Formation and Middle to Late Cenomanian Belle Fourche Formation (Figure 2; Bloch et al., 1993).

Excluding the Second White Specks Formation, the Upper Colorado Group had not until recently been formally subdivided in much of the subsurface of the WCSB. Nielsen et al. (2003) have identified two regionally mappable stratigraphic units in the

Upper Colorado Group, which are the Carlile Formation and Niobrara Formation (Figure 2). The Late Turonian Carlile Formation is a non-calcareous shale, whereas the Santonian Niobrara Formation is partially a calcareous shale with intervals of abundant sandstone. The latter is subdivided into the Verger, Medicine Hat and First White Specks members. These have been described in the vicinity of the Sweetgrass Arch in southeastern Alberta and southern Saskatchewan (Figures 2 and 3).

Nielsen (2002) and Nielsen et al. (2003) proposed a new stratigraphy, a sequence stratigraphic framework and interpreted paleoenvironmental changes. Interpretations were mainly based on sedimentological analysis of a large core base complemented by outcrop observations and detailed correlations of densely spaced log cross-sections. Previous studies of the Upper Colorado Group in southeastern Alberta and southeastern Saskatchewan focused mainly on reservoir characteristics of the sandstone intervals and stratigraphy (Hankel et al., 1989; Schröder-Adams et al., 1997; Nielsen and Schröder-Adams, 1998). In these studies foraminiferal assemblages were not studied in detail and therefore are chosen here in order to complete the multidisciplinary approach.

Utilizing three selected cores in southeastern Alberta (Figures 1 and 3), this study proposes a biostratigraphic framework for the Late Albian to Santonian interval, refining the existing foraminiferal zonation from Caldwell et al. (1978). Foraminiferal assemblage changes further define existing paleoenvironmental models and add to our understanding of the basin complexity and basin response to Cretaceous sea-level change.

Figure 1. Location map showing wells used in the study area.

Figure 1

Figure 2. Stratigraphic nomenclature for the Colorado Group and equivalent strata in the Western Canada Basin. This study is based on a composite section of the Lower and Upper Cretaceous Colorado Group from Southeastern and East Central Alberta. Nomenclature for columns 1 to 5 after Stott (1963, 1982, 1984); columns 4 and 5 after Bloch et al. (1993) and Strich and Schröder-Adams (1999); column 6 after Simpson (1982); column 7 after McNeil and Caldwell (1981) and column 8 this study and after Nielsen et al. (2003).

Figure 2

Figure 3. Structure contour map of the top of the Colorado Group showing major structural features in the study area. The three main structural features are: broad arches, north-plunging folds and local domes (modified after Nielsen, 2002). Contours are elevations in meters above sea level on top of Colorado Group. Contours interval is 500 m.

Figure 3

GEOLOGICAL SETTING

The elongate trough that extends from the eastern flanks of the Rocky Mountains to the stable interior platform (North American craton), and from the Arctic Ocean to the southern international border with the United States is known as the WCSB. The tectonic and stratigraphic history of this asymmetrical foreland basin is related to the origin and evolution of the Canadian Cordillera. It is a wedge of supracrustal rocks, which overlie the Precambrian crystalline rocks and diminish towards the Northeast (Price, 1994). During Cretaceous time, North America was subjected to extensive flooding as a result of global sea-level rise to form the WIS that connects, at the time of sea-level highstand, the Tethyan and the Boreal seas (Figure 4; Hay et al. 1993).

Sea-Level History

Deposition in the foreland basin was influenced by global changes in sea level (Haq et al., 1987, 1988) and by local tectonics (Kauffman and Caldwell, 1993). Leckie and Smith (1992) have divided the depositional history of the foreland basin into five cycles, each representing strata bounded by major unconformities and change in lithology. The Colorado Group was deposited in Cycle 3 during early late Albian to Santonian time (Figure 2). The Greenhorn and Niobrara transgressive/regressive marine cycles are the expression of two major second order sea-level changes (Figure 5, Kauffman, 1984; Haq et al., 1988).

The Joli Fou Formation was deposited during the early Late Albian as a result of a sea-level rise that produced a narrow seaway connecting the Tethyan and Boreal seas (Leckie and Smith, 1992). This was succeeded by a sea-level lowstand depositing the Viking Formation that consists of marine sandstone and conglomerate throughout much

of central Alberta and Saskatchewan. Along the western margin incised valleys were cut and subsequently infilled with estuarine sediments during sea-level rise (Hein et al., 1986; Leckie and Smith, 1992).

Subsequent transgression is associated with the Mowry Sea bringing low-salinity, cool, Boreal watermasses and depositing the Latest Albian Westgate Formation (Bloch et al., 1993; Schröder-Adams et al, 1996). This transgression represents the beginning of the eustatic Greenhorn marine cycle (Figure 5; Caldwell, 1984). The Greenhorn transgressive Cycle is interrupted by several sea-level falls. A bioclastic conglomerate at the base of the Fish Scales Formation indicates marine erosion close to the Albian/Cenomanian boundary (Leckie et al., 1992; Bloch et al., 1993).

A Middle Cenomanian lowstand is associated with progradation of the Dunvegan Delta as seen in northwestern Alberta and northeastern British Columbia (Bhattacharya and Walker, 1991a). This is followed by rapid transgression indicated by planktic foraminiferal occurrences in the uppermost Belle Fourche Formation giving evidence for the first presence of Tethyan-sourced waters in the Canadian part of the **WIS** (Schröder-Adams et al, 1996).

During the latest Cenomanian to the early Turonian, warm Tethyan waters of normal salinity entered the northern parts of the basin as a result of maximum transgression of the Greenhorn Sea (Figure 5; Kauffman, 1977, 1984; McNeil and Caldwell, 1981; Haq et al., 1988; Leckie and Smith, 1992; Caldwell et al., 1993; Schröder-Adams et al, 1996). This resulted in the deposition of the Second White Specks Formation and equivalents across the basin (Figure 2).

Figure 4. Western Interior Seaway during Lower Turonian sea-level highstand (modified after Hay et al., 1993).

Figure 4

Figure 5. Transgressive-regressive cycles of the Western Canada Basin (modified after Schröder-Adams et al., 1996 and Nielsen, 2002) during the Cretaceous (Albian to Santonian) and transgressive-regressive cycles of the Western Interior of the United States, compared against radiometric scale developed for the Western Interior of North America (Million Years Before Present =MYBP) (modified after Kaufman, 1977).

Figure 5

The upper Turonian is marked by a regressive event documented in the Jumping Pound sandstone in southwestern Alberta at the boundary between the Second White Specks Formation and the Carlile Formation (Figure 2; Nielsen et al., 2003). The sea-level fall resulted in a narrow seaway at Late Turonian time associated with the deposition of the Cardium Formation in western Alberta (Figure 2; Wall and Singh, 1975; Wright and Walker, 1981; Leckie et al., 1994), the Frontier sandstone in southern Montana and northern Wyoming (Krystinik and Desjarnett, 1995), and the Bowdoin sandstone in south-central Saskatchewan and southern Alberta (Figure 2; Nielsen et al., 2003). In central Saskatchewan, the regression at the end of the Greenhorn cycle combined with a tectonic uplift resulted in a widespread disconformity spanning from the middle Turonian to the lower Santonian (North and Caldwell, 1975; Caldwell et al., 1978; Schröder-Adams et al., 1996, 2001; Nielsen et al., 2003).

After the final lowstand terminating the Greenhorn Cycle, renewed marine inundation is related to the Niobrara transgressive Cycle (Figure 5; Kauffman, 1977, 1984). The Niobrara Cycle has been divided into small higher-order transgressive pulses separated by minor regressive pulses (Figure 5; Kauffman, 1984). The transgressive phase of the Niobrara Cycle encompasses the Verger, Medicine Hat and First White Specks members of the Niobrara Formation (Figure 2; Nielsen et al., 2003). In southeastern Alberta and southwestern Saskatchewan, the transgressive phase of the Niobrara Cycle was interrupted by two major relative sea-level falls (Nielsen, 2002). The first major relative sea-level lowstand is most likely expressed in the upper part of the Bad Heart Formation in the Northwest Plains of Alberta (Nielsen, 2002). The second major relatively sea-level lowstand is expressed in the sandstones of the Sweetgrass

Member of the Niobrara Formation (Schröder-Adams et al., 1997; Nielsen, 2002). The final regressive phase of the Niobrara Cycle is related to the siltstone and sandstone facies of the Milk River/Lea Park formations overlying the Colorado Group (Figure 2).

Stratigraphic Framework

Adoption of the term Colorado Group into the Canadian literature was after correlation of the Colorado Group of the northwestern part of Montana with the Alberta Shale of the southern plains of Alberta. (Cobban, 1951; Cobban, 1959). The Colorado Group was subject to numerous studies that evaluated various aspects of stratigraphy and biostratigraphy (i.e. Dowling, 1917, 1919; Spratt, 1931; Wickenden and Shaw, 1943; McLearn, 1944; Wickenden, 1945; Gleddie, 1949; Stott, 1963, 1967, 1984; Wall, 1967; North and Caldwell, 1975; Caldwell et al., 1978; Stelck and Armstrong, 1981; Simpson, 1982; Lang and McGugan, 1988; Bloch et al., 1993; Schröder-Adams et al., 1996, 1997, 1998). As a result, a number of frameworks have been proposed (Figure 2). Some of the biostratigraphic frameworks have been integrated with Cretaceous biostratigraphy worldwide, without synthesizing them regionally (Cobban and Reeside, 1952; Jeletzky, 1968).

In the subsurface of central and southern Alberta and Saskatchewan, the Colorado Group describes strata overlying the Mannville Group and underlying the Milk River Formation (Figure 2, Schröder-Adams et al, 1997, 1998). Rudkin (1964) informally subdivided the Colorado Group into two subgroups separated by the base of the Fish Scales Formation. However, Simpson (1982) provided another subdivision where he separated the group at the base of the Second White Specks Formation. The Lower Colorado Group is known as the interval from the base of the basal Colorado sand to the

top of the Belle Fourche Formation. The Upper Colorado Group on the other hand, is the interval from the base of the Second White Specks Formation to the top of the First White Specks Member of the Niobrara Formation.

The lowermost formal lithostratigraphic unit of the Colorado Group is represented by the Spinney Hill Sandstone in eastern and central Saskatchewan, the Basal Colorado Sandstone in southeastern Alberta and shale of the Joli Fou Formation in most other areas (Figure 2). Bloch et al. (1993) revised the stratigraphy of strata above the Viking Formation in south and central Alberta and Saskatchewan and distinguished four regionally mappable lithostratigraphic units. These are, in ascending order, the Westgate, Fish Scales, Belle Fourche and Second White Specks formations. The lower Colorado Group is about 700 m thick in southwestern Alberta and thins to about 200 m eastwards toward the Manitoba Escarpment (Bloch et al., 1993; Schröder-Adams et al., 1996). In northeastern Alberta, in comparison, the thickness of the lower Colorado Group exceeds 1500 m where it overlies the Peace River Arch (Leckie et al., 1994).

Leckie et al. (1994) described the general architecture of the Colorado Group succession. The sandy Medicine Hat unit within the Upper Colorado Group was named informally after the city of Medicine Hat (Hancock and Glass, 1968). The calcareous First White Specks shale of the Upper Colorado Group was recognized early as the first calcareous dark shale below the Milk River Formation (Stott, 1963). Schröder-Adams et al. (1997) described sedimentology and reservoir features of the Medicine Hat sandstones and the overlying First White Specks shale in southeastern Alberta. Finally, Nielsen et al. (2003) formally described the Upper Colorado Group and identified two regionally mappable stratigraphic units, which are the Carlile Formation overlain by the Niobrara

Formation (Figure 2). Based on the variations in lithology, petrophysical character and geochemistry, the two defined formations were further subdivided. The Late Turonian Carlile Formation is informally subdivided into lower, middle and upper units; whereas, the overlying Niobrara Formation is formally subdivided into the Verger, Medicine Hat and First White Specks members (Figure 2; Nielsen et al., 2003).

Lithostratigraphy

The Joli Fou Formation is a dark gray, non-calcareous marine shale interbedded with fine to medium grained sandstone. Roughly equivalent strata in the Manitoba Escarpment are the Skull Creek Member, Skull Creek Formation of the Dakota Group in Montana and Thermopolis Formation in Wyoming (McGookey et al., 1972; Weimer, 1984). The Joli Fou Formation disconformably overlies the Mannville Group where the Basal Colorado/Spinney Hill sandstones are missing (Koke and Stelck, 1985). Fossil assemblages suggest that the Tethyan and Boreal watermasses were connected through a narrow marine seaway (Williams and Stelck, 1975; Leckie et al., 1994).

Describing the gas-producing sandstones in east-central Alberta, Slipper (1918) was first to define the Viking Formation (Leckie et al., 2000). The formation was deposited as a result of a sea-level lowstand terminating the Joli Fou Seaway. It consists of interbedded units of mudstone, interbedded sandstone-shaly siltstone, clean sandstone and conglomeratic sandstone (Leckie et al. 1994). In east-central Alberta, the thickness of the Viking Formation is 15 to 30 m; in southern Alberta, it thickens to about 65 m, and in both southward and westward directions, the thickness of the formation increases (Reinson et al., 1994).

The Viking Formation is equivalent to part of the Paddy Member of the Peace River Formation (Leckie and Singh 1991), the upper part of the Bow Island Formation in southern Alberta (Raychaudhuri and Pemberton, 1992; Pedersen et al., 2002), the Muddy Sandstone in Montana, Newcastle Formation in Wyoming and J-sandstone in Colorado (Beaumont, 1984; Weimer, 1984). The interval is a major hydrocarbon producer and contains an estimated 406 million barrels of oil and 6073.2 bcf of natural gas (Leckie et al., 2000).

The Albian Westgate Formation is a wedge of non-calcareous mudstone to siltstone (Bloch et al., 1993). The thickness of the interval ranges from approximately 20 m on the Saskatchewan-Manitoba border to 120 m in northwestern Alberta. Bioturbation within the interval increases upwards from minimal at the base to intense at the top (Bloch et al., 1993; Schröder-Adams et al., 1996). The basal contact with the underlying Viking Formation is characterized by the disappearance of sandstone and /or a noticeable decrease in siltstone content (Bloch et al., 1993).

The equivalent stratum in the Manitoba Escarpment is the Westgate Member of the Ashville Formation. The formation is partially correlative to the Shaftesbury Formation in the Northwest Plains (Stelck and Leckie, 1990; Bloch et al., 1993), and Hasler Formation in northeastern British Columbia (Stelck and Koke, 1987; Stelck and Leckie, 1990). In southwestern Alberta, west of the 5th Meridian, the Westgate Formation is not present (Bloch et al., 1993; Leckie et al., 2000). In the United States, strata equivalent to the Westgate Formation are large parts of the Shell Creek and Mowry formations (McNeil and Caldwell, 1981). The boundary between the Westgate Formation

and the overlying Fish Scales Formation is a sharp lithological contact (Schröder-Adams et al, 1996).

The Fish Scales Formation is a non-calcareous claystone to mudstone with a basal coarse sandstone or pebble layer containing bioclastic debris composed of phosphatic skeletal remains or intraclasts (Bloch et al., 1993). In southwestern Alberta, the Barons sandstone unconformably overlies the Fish Scales Formation and locally may remove Fish Scales Formation shales westward towards outcrops in the Rocky Mountain Foothills (Leckie et al., 2000). The Fish Scales Formation and upper Mowry Formation in Montana may be correlative (Bloch et al. 1993).

The overlying Belle Fourche Formation is non-calcareous to slightly calcareous mudstone and siltstone (Bloch et al., 1993). Westward thickening of the Belle Fourche Formation is associated with the progradation of the Dunvegan Delta as result of a sea-level lowstand (Bhattacharya and Walker, 1991a, b). In the western Plains, two coarsening-up cycles are present at the middle and top of the Belle Fourche Formation (Bloch et al., 1993). The Belle Fourche Formation is correlative with the Belle Fourche Member of the Ashville Formation in the Manitoba Escarpment (McNeil and Caldwell, 1981; Bloch et al., 1993). The interval is partially correlative to the upper Shaftesbury, Dunvegan and lower Kaskapau formations in northwestern Alberta, and the Sunkay Member of the Blackstone Formation in the Southern Rocky Mountain Foothills. In Montana, the Belle Fourche Shale forms equivalent strata. The contact between the Fish Scales and the Belle Fourche formations is conformable and is discerned by the first presence of *Inoceramids* or a noticeable increase in bioturbation (Bloch et al., 1993).

The Second White Specks Formation is a non-bioturbated, calcareous claystone to siltstone in eastern and southern Alberta and grading to a calcareous siltstone in northwest Alberta (Bloch et al., 1993). A conspicuous bentonite bed, usually associated with calcite concretions, is commonly present at or near the basal contact (Bloch et al., 1993). In the Alberta Foothills, the Vimy Member of the Blackstone Formation is stratigraphically equivalent to the Second White Specks Formation whereas in the Manitoba Escarpment, the equivalent interval is the Favel Formation (McNeil and Caldwell, 1981). In the United States equivalent strata are represented by the Greenhorn Formation. The upper boundary with the overlying Carlile Formation is marked by distinct biostratigraphic and lithological changes as described by Bloch et al. (1993). In southwestern Alberta, the Jumping Pound sandstone straddles the boundary between the Second White Specks Formation and the Carlile Formation (Nielsen et al., 2003).

The Late Turonian Carlile Formation that spans the regressive phase of the Greenhorn Cycle is a non-calcareous shale with minor occurrences of sandstone partings and a middle interval with an abundance of siderite concretions (Nielsen et al., 2003). Lithological changes allow a subdivision into a lower, middle and upper unit (Nielsen et al., 2003). The upper unit is fine-grained sandstone, informally named the Bowdoin sandstone beds (Nielsen et al., 2003).

In the southern Alberta Foothills, the stratigraphic equivalent of the Carlile Formation is the upper Blackstone and Cardium formations (Wall and Rosene, 1977). Rice (1981) and Gilboy (1996) suggested the term 'Carlile' for the strata in southwestern Saskatchewan equivalent to the Carlile Formation. In central and north-central Montana, the Carlile Formation is equivalent to the Carlile Shale and the Ferdig Member of the

Marias River Formation (Cobban et al., 1976). A distinctive zone of numerous bentonites distinguishes the boundary between the Carlile Formation and the overlying Verger Member of the Niobrara Formation (Nielsen et al., 2003).

The Niobrara Formation is composed of marine shales, siltstones, very fine-grained sandstones, and few layers of chert pebbles. Based on lithological, geochemical and petrophysical variations, the interval is subdivided into three mappable members, which are in ascending order; the Verger, Medicine Hat and the First White Specks members (Nielsen et al., 2003).

Detailed lithological facies of the three members of the Niobrara formation are described by Nielsen et al. (2003). The Verger Member is a slightly to moderately bioturbated, silty shale recognized by its abundance of bentonites, mica and concretions; the middle Medicine Hat Member is composed of two mainly coarsening-up cycles of moderately to intensively bioturbated, interlaminated sandstones, siltstones and shales; and the First White Specks Member is dominated by calcareous mudstone and siltstone, with minor amounts of sandstone. The upper boundary of the Niobrara Formation and the Colorado Group is a sharp lithological change from dark calcareous shale to a sandy, bioturbated siltstone of the Milk River/Lea Park formations.

The name of the Niobrara Formation was adopted in southern Alberta and southwestern Saskatchewan from the equivalent Niobrara strata in southern Manitoba, Saskatchewan and the United States (Nielsen et al., 2003). In the southern Foothills of Alberta, the Wapiabi Formation is stratigraphic equivalent to the Niobrara Formation and to the Kevin Member of the Marias River Formation in the area of the Sweetgrass Hills of Montana (Cobban, 1959; 1976; Lopez, 1995).

Biostratigraphy

The presence of foraminifera in Cretaceous rocks in the WCSB is well known (Caldwell et al., 1978). Excluding the endemic species that developed within the Western Interior basin, the foraminiferal faunas of the Cretaceous in the Interior Plains have generally more species in common with assemblages of strata at the Arctic slope of Alaska than with those of the Gulf Coast (Schröder-Adams et al., 1996).

Benthic foraminiferal assemblages are sensitive to bottom water conditions and substrate variations, allowing interpretation of basin paleoenvironments (Schröder-Adams and McNeil, 1994; Sageman, 1989). Planktic species are depending on water masses and require generally stable marine conditions with low sediment input, and can also be used as indicators of paleoclimates and paleoceanographic circulation pattern (Leckie et al., 1998; Schröder-Adams et al., 1996). Calcareous benthic foraminifera, on the other hand, live in a variety of environments, but their preservation is dependent on marine chemical conditions saturated with respect to calcium carbonate. Moreover, benthic foraminifera can be used to indicate the degree of oxygenation within sediments and at the sediment-water interface (West et al., 1998).

Foraminiferal zones of the Cretaceous of the Western Interior of North America are mainly constructed from data that have been derived from shaly intervals (Jeletzky, 1968; Wall, 1967; Caldwell et al., 1978). Nauss (1974) was the first to attempt an examination of foraminifera through a complete section of the eastern Alberta Cretaceous system (Caldwell, 1978). In southeastern Saskatchewan and southwestern Alberta, foraminiferal assemblages for the Lower Colorado Group correspond with the regionally proposed zonation of Caldwell et al. (1978, 1993) (Figure 6).

In western Canada, the agglutinated species composition of the Latest Albian Westgate Formation shows an affinity to Arctic agglutinated assemblages of the equivalent strata of northern Alaska described by Tappan (1962). The foraminiferal assemblages of the Westgate Formation are typical for the *Miliammina manitobensis* Zone of latest Albian time (Figure 6; Bloch et al. 1993; Schröder-Adams et al., 1996). The *Miliammina manitobensis* Zone is best developed in the foredeep of the Western Interior Basin in northeastern British Columbia (Caldwell et al., 1978, 1993) where the zonal microfauna has been subdivided into three subzones: *Verneuilina canadensis*; *Haplophragmoides postis goodrichi* and *Haplophragmium swareni* (Figure 6; Caldwell et al., 1978). The lower *Verneuilina canadensis* Subzone is often the only subzone of the *Miliammina manitobensis* Zone that is found in the plains area of western Canada (Caldwell et al., 1978; Schröder-Adams et al., 1996), although Stritch and Schröder-Adams (1999) found *Haplophragmoides postis goodrichi* in central Alberta. In the Manitoba Escarpment, the *Miliammina manitobensis* Zone occurs within the Westgate Member of the Ashville Formation (McNeil and Caldwell, 1981). Some of the *Miliammina manitobensis* Zone elements have been recorded from the Arctic Red River Formation of Northern Yukon Territory, and from the Shell Creek Formation of Wyoming (Caldwell et al., 1978).

Stelck et al. (1958) described the *Textularia alcesensis* Zone from the upper Shaftesbury Shale in the Peace River area (Caldwell et al., 1978). In the Rocky Mountain Foothills, the *Textularia alcesensis* Zone spans the interval from the base of the Fish Scale Marker to the base of the Dunvegan Formation (Figure 6; Caldwell et al., 1978), straddling the Albian/Cenomanian boundary.

Figure 6. Comparison of the foraminiferal zones and subzones of the Western Interior of North America proposed by Caldwell et al. (1978) with the zones and subzones in this study covering the time interval from Late Albian to Santonian

This Study			The foraminiferal zonation scheme proposed by Caldwell et al. (1978).		
Foraminiferal Zonation		Foraminiferal Zonation		Stage	
Zones	Subzones	Subzones	Zones		
<i>Trochammina ribstonensis</i>			<i>Trochammina ribstonensis</i>	Campanian	
<i>Globigerinelloides</i> sp.	<i>Heterohelix</i> cf. <i>reussi</i> <i>Gavelinella herbesti</i>	<i>Heterohelix</i> cf. <i>reussi</i> <i>Gavelinella herbesti</i>	<i>Globigerinelloides</i> sp.	Santonian	
<i>Bullopore laevis</i>	<i>Neobulimina canadensis</i> <i>Haplophragmoides bonanzaense</i> <i>Marssonella oxycona</i>		<i>Bullopore laevis</i>	Coniacian	
<i>Pseudoclavulina</i> sp.- <i>Trochammina</i> sp.			<i>Trochammina</i> sp.		
			<i>Pseudoclavulina</i> sp.		
<i>Hedbergella loetterlei</i>	<i>Whitella aprica</i> <i>Mixed foraminiferal assemblage</i>	<i>Whitella aprica</i> <i>Clavibergella simplex</i>	<i>Hedbergella loetterlei</i>	Turonian	
		<i>Haplophragmoides spiritense</i> <i>Ammobaculites pacalis</i>	<i>Flabellammina gleddei</i>		
		<i>Gaudryina trenensis</i> <i>Ammobaculites gravenori</i>	<i>Verneuilinoides perplexus</i>	Cenomanian	
			<i>Textularia alcesensis</i>		
<i>Miliammina manibensis</i>		<i>Haplophragmium swareri</i> <i>Haplophragmoides postis goodrichi</i> <i>Verneulina canadensis</i>	<i>Miliammina manibensis</i>	Albian	

Figure 6

In the Interior Plains of Canada, the *Textularia alcesensis* Zone is missing and the Fish Scales Formation is barren of foraminifera (North and Caldwell, 1975a, Caldwell et al., 1978, Bloch et al., 1993, Schröder-Adams et al., 1996). A latest Albian to early Cenomanian age has been assigned to the *Textularia alcesensis* Zone (Figure 6; Caldwell et al., 1978).

The Middle Cenomanian Belle Fourche Formation is marked by a low species richness and strongly fluctuating numbers of agglutinated foraminiferal specimens that indicate a slight and gradual improvement of ecological conditions for benthic organisms (Schröder-Adams et al, 1996). The foraminiferal assemblages form the *Verneuilioides perplexus* Zone that has been recognized in most of the WCSB (Stelck and Wall, 1955; Wall, 1967; North and Caldwell, 1975a; North and Caldwell, 1975b, McNeil and Caldwell, 1981; Leckie et al, 1992; Bloch et al 1993; Schröder-Adams et al., 1996). In the plains of northeastern British Columbia and northwestern Alberta, the *Verneuilioides perplexus* Zone is divided into two subzones, *Ammobaculites gravenori* and *Gaudryina irenensis* (Figure 6; Caldwell et al., 1978).

Foraminifera from the Upper Colorado Group in the WCSB have been described by Wickenden (1932a, b), Nauss (1947), Wall (1960, 1967a, b), Wall and Singh (1975), McNeil and Caldwell (1981), Schröder-Adams et al. (1997, 1998), Nielsen (2002) and Nielsen et al. (2003). At Late Cenomanian to early middle Turonian time sea level within the WIS had reached a maximum allowing warm water planktic taxa to migrate to the northern parts of the basin. These planktic foraminifera form the principal components of the *Hedbergella loetterlei* Zone that has been recognized within the Second White Specks

Formation and equivalent strata in the WCSB (Figure 7; Wall, 1967a, b; Caldwell, 1978; McNeil and Caldwell, 1981; Bloch et al., 1993; Schröder-Adams et al., 1996). In Manitoba and eastern Saskatchewan, the *Hedbergella loetterlei* Zone is divided into two subzones: the older *Clavihedbergella simplex* Subzone and the younger *Whiteinella aprica* Subzone (Figure 7; Caldwell et al., 1978).

The *Hedbergella loetterlei* Zone is one of the most widespread zones occupying the basin when it was at its broadest dimension (Figure 4). Its elements are found from the Rocky Mountain Foothills in the west to the Manitoba Escarpment in the east to the Arctic Slope of Alaska in the north and throughout southern Montana, Dakota, Wyoming, Colorado and Kansas in the south (Caldwell et al., 1978). In central Saskatchewan, a widespread unconformity is indicated by the occurrence of the *Globigerinelloides* sp. Zone of Santonian age directly overlying a thin remnant of the *Hedbergella loetterlei* Zone of early Turonian age (Figure 7; North and Caldwell, 1975a; Caldwell et al., 1978; Schröder-Adams et al., 1996).

Paleoecological conditions during peak transgression of the Greenhorn Sea differ from south to north. Whereas the southern seaway in the US also allowed calcareous benthic assemblages to develop, the northern regions contain dominantly planktic taxa. The mid-Cretaceous deepest-dwelling planktic keeled foraminifera are restricted in the WCSB to southernmost Alberta (Lang and McGugan, 1988), but are common in the US (Caldwell et al., 1993; Leckie et al., 1998).

The final regressive phase of the Greenhorn Cycle is expressed in the Upper Blackstone and Cardium formations of the Rocky Mountain Foothills and adjacent plains (Caldwell, 1978). These intervals carry the exclusively agglutinated *Pseudoclavulina*,

Figure 7. Comparison of the biostratigraphic zonation chart of the Upper Colorado Group in this study with the biostratigraphic zonations of the nearby regions (modified after Schröder-Adams et al., 1997).

Upper Colorado Group Biostratigraphic Zonation

Stage	Rocky Mountain Foothills Wall, 1967a	Southern Plains Alberta Schröder-Adams et al, 1997	This Study Central & Southeastern Alberta				Central Saskatchewan Caldwell and North, 1964 Caldwell et al., 1978	Manitoba McNeil and Caldwell, 1981	
	Microfauna	Zone	Zone	Subzone	Formation	Zone	Zone	Subzone	
Campanian	<i>Trochammina ribstonensis</i>	<i>Haplophragmoides kirki</i> <i>Trochammina ribstonensis</i>	<i>Trochammina ribstonensis</i>		MILK RIVER	<i>Haplophragmoides kirki</i>	<i>Trochammina ribstonensis</i>		
Santonian	Upper Pelagic	Agglutinated assemblages with rare planktics ----- <i>Trochammina</i> spp. <i>Haplophragmoides</i> spp.	<i>Globigerinelloides</i> sp.	<i>Heterohelix</i> cf. <i>reussi</i>	FIRST WHITE SPECKS	<i>Globigerinelloides</i> sp.	<i>Globigerinelloides</i> sp.	<i>Globigerinelloides</i> sp.	
	<i>Gavelinella henbesti</i>			MEDICINE HAT					
	<i>Neobulimina canadensis</i>								
<i>Brachyocythere-Bullopore</i>	Agglutinated assemblages	<i>Bullopore laevis</i>	<i>Haplo-phragmoides bonanzaense</i>	VERGER					
			<i>Marssonella oxycona</i>						
Coniacian	<i>Trochammina</i> sp. 1	Not Studied	<i>Trochammina</i> sp.	CARLILE					
Cardium Formation	<i>Pseudoclavulina</i> sp.								
Turonian	<i>Pseudoclavulina</i> sp.	Not Studied	<i>Hedbergella loetterlei</i>	<i>Whiteinella aprica</i> mixed foraminiferal assemblage	SECOND WHITE SPECKS	<i>Hedbergella loetterlei</i>	<i>Hedbergella loetterlei</i>	<i>Whiteinella aprica</i> <i>Clavithedbergella simplex</i>	
Lower Pelagic									

Figure 7

Cardium and *Trochammina* faunas (Wall, 1967a; Caldwell, 1978). In Manitoba, the equivalent to these intervals is the Morden Formation, which carries either the *Pseudoclavulina* fauna or a mixed assemblage of the *Pseudoclavulina* and *Trochammina* faunas (Caldwell, 1978; McNeil and Caldwell, 1981). This is a result of a significant eastward reduction in thickness of the interval and zones between the *Hedbergella loetterlei* Zone and *Globigerinelloides* sp. Zone (Figure 7; Caldwell et al., 1978).

The *Pseudoclavulina* sp. microfauna is present in the strata straddling the contact between the Haven and Opabin members of the Blackstone Formation in the southern and central Foothills (Wall, 1967a; Caldwell et al., 1978). A trace of the *Pseudoclavulina* microfauna was found within the upper part of the Kaskapau Formation in the northern Foothills (Wall, 1967a). Wall and Germundson (1963) reported the presence of the *Pseudoclavulina* sp. Zone above a thin band of chert and quartzite pebbles, which may be the same as the one at the base of Wapiabi Formation in the Foothills (Wall, 1967a). As a result, Wall (1967a) suggested that the stratigraphic position of the *Pseudoclavulina* sp. Zone in the plains might be above the Cardium Formation. An early late Turonian age has been assigned to the *Pseudoclavulina* sp. Zone (Figure 6; Caldwell et al., 1978; Wall, 1967a).

The *Trochammina* sp. microfauna has a wide distribution in the central and southern Rocky Mountain Foothills of Alberta where the designated species has been found in the Muskiki Member of the Wapiabi Formation, immediately above the Cardium Formation (Wall, 1967a; Caldwell et al., 1978). In the Kevin- Sunburst oil field of northern Montana, the zonal marker species was found below the MacGowan concretionary bed in the lower part of the middle unit of the Kevin Shale Member of the

Marias River Formation (Wall, 1967a). A Latest Turonian and/or Early Coniacian age has been assigned to the *Trochammina* sp. Zone (Figure 6; Caldwell et al., 1978).

The *Bullopore laevis* microfauna consists of agglutinated and calcareous foraminifera indicating deepening of the basin following the entirely agglutinated *Trochammina* sp. microfauna (Wall, 1967a). The zonal marker species has been found within the upper Alberta Group of the Plains of southern Alberta (Caldwell et al., 1978). The *Bullopore laevis* Zone can be traced throughout the Rocky Mountain Foothills of Alberta from the Wapiti River Valley in the north to the Crowsnest Pass area in the South (Wall, 1967a). The *Bullopore laevis* microfauna has been collected from the Dowling Member and lower Thistle Member of the Wapiabi Formation in the southern and central Foothills and from the Muskiki Formation in the northern Foothills (Wall, 1967a). In central Saskatchewan, the *Bullopore laevis* Zone is missing due to a widespread unconformity marking a position where the Santonian *Globigerinelloides* sp. Zone directly overlies a thin remnant of the Early Turonian *Hedbergella loetterlei* Zone (North and Caldwell, 1964; Caldwell et al., 1978; Schröder-Adams et al., 1996). In northern Montana, some of the elements of the *Bullopore laevis* microfauna have been collected from the middle unit of the Kevin Shale Member of the Marias River Formation (Wall, 1967a). The relative age of this microfauna to the megafaunal succession ranges from Coniacian to middle Santonian (Wall, 1967a). However, Caldwell et al. (1978) assigned a Late Coniacian to Early Santonian age to this zone based on Cobban's (1975) zonal classification (Figure 6).

The *Globigerinelloides* sp. Zone is associated with the First White Specks Member of the Niobrara Formation (Caldwell et al., 1978; Schröder-Adams et al., 1997;

Nielsen et al., 2003), which was deposited at the time of maximum transgression of the Niobrara Sea (Nielsen, 2002). The zone is represented by a mixed benthic agglutinated and calcareous and planktic assemblage (Wall, 1967a, Caldwell, et al, 1978; McNeil and Caldwell, 1981; Schröder-Adams et al., 1997, 2001). The base of the *Globigerinelloides* sp. Zone is diachronous from east to west across the Interior Plains and north to south in the Rocky Mountain Foothills when compared to the molluscan faunal zones (Figure 7; Caldwell et al., 1978; Schröder-Adams et al., 1997). In the southern Rocky Mountain Foothills, Saskatchewan and Manitoba Escarpment, the *Globigerinelloides* sp. Zone is divided into a lower *Gavelinella henbesti* Subzone and an upper *Heterohelix* cf. *reussi* Subzone (Figure 7; Caldwell et al., 1978; McNeil and Caldwell, 1981). In southeastern Alberta over the Sweetgrass Arch, the First White Specks Member contains agglutinated foraminifera with rare planktic specimens (Figure 7; Schröder-Adams et al., 1997, 1998).

MATERIALS AND METHODS

This study is based on three reference cores from wells in southeastern and central Alberta including Anderson et al Paradise 10-22-47-3W4, 13-20-17-7W4 which is the reference core of the contact between the Carlile and Niobrara formations and PCP Verger 16-4-22-15W4 which is the type core for the three members of the Niobrara Formation (Figure 1). The last two cores are located in the vicinity of the Sweetgrass Arch, whereas the first core is located north of the Sweetgrass Arch (Figure 3). The cores form a composite section covering the interval from the latest Albian Westgate Formation to the Campanian Milk River Formation (Figure 2). Cores were sampled for micropaleontological analysis. Samples were taken in 30 cm to 1 m intervals and

sampling frequency increased at the lithological boundaries and critical intervals. Measurements are either in feet or meters, facilitating comparisons to the original core measurements. The core at 10-22-47-3W4 covers the interval from the late Albian Westgate Formation to the Coniacian Verger Member of the Niobrara Formation; the core at 13-20-17-7W4 covers the interval from the Late Turonian Carlile Formation to the Coniacian Verger Member of the Niobrara Formation and the third core at 16-4-22-15W4 covers the interval from the Coniacian Verger Member to the Campanian Milk River Formation. Interpretations are based on a combination of micropaleontology, sedimentology and Rock Eval data. The two southern cores are integral parts of the detailed study by Nielsen (2002); his sedimentological descriptions and Rock-Eval data are used here.

A total of 248 samples for foraminifera analysis were prepared according to standard methods of Then and Dougherty (1983) and washed over a 63 μm sieve. Total numbers of foraminiferal specimens per species counted in each sample are listed in Appendix B. Relative foraminiferal abundance is expressed in three categories: rare for samples that have less than 15 specimens, common for samples that have from 15 to 30 specimens and abundant for samples that have over 30 specimen (Figures 9, 13 and 16). Preservation of foraminifera was generally moderate to poor allowing in many cases generic identification only. Moreover, different species concepts among previously published studies impede regional correlations and somewhat distort paleontological, and consequently, paleogeographic reconstructions. Approximate abundances of fish remains and bivalve shell prisms (*Inoceramus* prisms) in the sand-sized fractions are estimated for

environmental interpretations, and are listed under 'Miscellaneous Components' (Figures 9, 13 and 16).

Jim Craig examined nannofossils from the Second White Specks Formation in core 10-22-47-3W4. Categories for relative abundances are expressed as follows: rare-less than 500 specimens, common-500-1000 specimens and abundant-more than 1000 specimens per sample (Figure 9).

Sedimentological analysis is based on lithological description of the core, which includes visual characteristics of sediments in terms of composition, grain size, sedimentary structure, degree of bioturbation and fossil content. Detailed facies analysis of 13-20-17-7W4 and 16-4-22-15W4 are provided in Nielsen (2002).

Rock-Eval pyrolysis was performed in duplicates on pulverized shale samples using standard procedures on a DELSI Rock-Eval II/TOC apparatus (Espitalie et al., 1977). The information obtained includes the type of organic matter (oxygen (OI) and hydrogen (HI) indices), and the amount of total organic carbon (TOC) (Appendix B). Tmax is the temperature at which maximum hydrocarbon generation occurs during pyrolysis and is an indication of maturity of the organic matter contained in the sample. Rock-Eval analysis was performed at the Geological Survey of Canada, Calgary.

Figure 8. Legend for sedimentological, lithological, micropaleontological and miscellaneous components data abundance and seaway maps symbols.

Legend

Figure 8

RESULTS

Data presented herein are from three cores that represent a composite section of the uppermost Lower and entire Upper Colorado Group in central and southeastern Alberta (Figure 1), covering the interval from the latest Albian Westgate Formation to the Campanian lower Milk River Formation (Figure 2). These are the first detailed foraminiferal data from the area over and north of the Sweetgrass Arch.

The non-calcareous **Westgate Formation** is cored at 10-22-47-3W4 and consists of a 1.5 ft thick coarsening-upwards cycle of very fine sandstone overlain by two major fining-upwards cycles (Figure 9). The interval is moderately to intensely bioturbated and contains some burrows of *Terebellina* filled with green marine clays mainly at the base of the first fining-upwards cycle at 1565 feet. Sedimentary structures are obscured by the degree of bioturbation. The upper boundary is a sharp lithological contact with the overlying Fish Scales Formation.

The total organic carbon (TOC) content averages 1.2 wt% and is mainly terrestrially derived type III organic matter (Figures 9 and 11). In general, The HI values show a similar trend to the TOC content, but at 1550-1553 ft (the middle part of the second fining-upwards cycle) the HI values drop slightly from 76 mgHC/gOC to about 40 mgHC/gOC (Figure 9). This coincides with a peak in agglutinated foraminiferal abundance and richness (Figures 10).

Agglutinated foraminifera of high richness and abundance dominate the interval (Figures 9 and 12). The basal sandstone is dominated by *Ammobaculites fragmentarius*, *Miliammina manitobensis* and *Ammobaculites petilus* with relatively coarse-grained agglutinated tests. Agglutinated fragments are common to abundant in this cycle.

Figure 9. Core 10-22-47-3W4 representing the interval from the Late Albian Westgate Formation to the Early Coniacian Verger Member of the Niobrara Formation in east-central Alberta showing an estimated abundance of the micropaleontological assemblages including foraminifera, planktic and benthic (calcareous and agglutinated) and nannofossils; miscellaneous components including fish remains and *Inoceramus* prisms; biostratigraphic zonation and geochemistry including TOC, HI and organic matter type. For sedimentological legend see figure 8. Core location on figures 1 and 3.

Paradise Well: 10-22-47-3W4

Figure 9

Figure 10. Characteristic features and interpretation of core 10-22-47-3W4 related to sea-level changes and micropaleontological assemblage response to these changes. First Appearance Datum (FAD).

Paradise Well: 10-22-47-3W4

Figure 10

The lower fining-upwards cycle (1578.5-1559ft.) resulted in increasing richness as relative sea-level rises creating suitable bottom water conditions for benthic foraminifera to inhabit the sea floor. At 1556 ft, abundance and richness of benthic foraminifera reach a peak with more than 30 different species (Figures 10 and 12). Specimens have relatively fine-grained tests. *Ammobaculites* sp., *Saccammina alexanderi* and *Miliammina manitobensis* are the dominant taxa (Figure 12).

At the base of the second fining-upwards cycle, the richness and abundance are significantly reduced; however they recover throughout the second cycle. A total of 42 species have been recognized in this interval and the assemblage is associated with the *Miliammina manitobensis* Zone (Figures 9 and 12). Abundances of phosphatic debris vary, but are generally high and increase towards the top (Figure 9). No remains of *Inoceramid* bivalves were found (Figure 9).

The base of the **Fish Scale Formation** at 10-22-47-3W4 consists of a 2 inch-thick (1529-1528.8 ft), non-calcareous, coarse-grained sandstone rich in bioclastic debris; wave rippled with sole marks at the base (Figure 10). This layer is overlain by non-calcareous, non-bioturbated black shale and wisps of discontinuous coarse siltstone. Two 1 cm-thick bentonites have been recognized at 1528.2 and 1526 ft. A 10 cm-thick fine-grained sandstone bed at 1525 ft contains mud drapes and fish remains (Figure 10). The total thickness of the formation is about 4 meters with a conformable contact to the overlying Belle Fourche Formation. The upper contact has been discerned by the appearance of *Inoceramus* prisms and increasing bioturbation (Figure 10). The bioclastic layer at the base of the formation is characterized by low TOC and HI values increasing significantly above, but fluctuating throughout the formation (Figure 9)

The Fish Scales Formation is barren of foraminifera at this location (Figures 9 and 12). The fish and vertebrate remains including shark teeth are abundant throughout the interval and decrease gradually towards the top of the formation at the contact with the overlying Belle Fourche Formation (Figure 9).

At 10-22-47-3W4, the contact between the **Belle Fourche Formation** and the underlying Fish Scales Formation is gradational, and recognized by an increase in bioturbation and a decrease in HI values towards Type III (Figures 9 and 11). Sediments of the lower part of the formation are black to gray, non-calcareous shale. Bioturbation is moderate to intensive throughout the formation. Non-bioturbated shales intervals occur above the second siderite concretion bed at 1463.6 ft. and at 1460 to 1452.5ft (Figure 10). The upper part of the formation consists of non-bioturbated non-calcareous black shale interbedded with wisps and lenticels of very fine sandstone, that is wave rippled and contains abundant mud drapes forming a minor coarsening-upwards cycle (Figure 10). The upper boundary is a sharp lithological contact between the silty shale below and a conglomeratic layer above. The formation has a high content of pyrite and siderite (Figure 10).

The total organic carbon (TOC) content averages 1.7 wt% and is mainly terrestrially derived type III organic matter (Figures 9 and 11). Low TOC values are remarkably uniform, whereas, the HI values decrease gradually towards the top of the formation (Figure 9). The strong increase of the HI and TOC values coincides with the deposition of the coarsening-upwards cycle at the top of the formation and peaks in the bonebed, considered the base of the overlying Second White Specks Formation (Figure 9).

Figure 11. Geochemistry of the core 10-22-47-3W4 represents the Westgate, Fish Scales, Belle Fourche, Second White Specks, Carlile formations and Verger Member of the Niobrara Formation illustrated in HI/OI plots.

Figure 11

Figure 12. Distribution chart representing most common foraminiferal species from core 10-22-47-3W4 including biostratigraphic zonations and their relation to different stages. (See Appendix A for complete reference to all recognized foraminiferal species).

Paradise Well: 10-22-47-3W4

Despite the degree of bioturbation that ranges from moderate to intensive, the formation is barren of benthic foraminifera (Figures 9 and 12). In general, fish remains are rare throughout the interval and increase gradually at the top of the formation (Figure 9). Rare *Inoceramus* prisms appear at the formation base, but disappear throughout the remaining interval (Figure 9).

The **Second White Specks Formation** cored at 10-22-47-3W4 is a black to gray, calcareous, non-bioturbated, fissile and finely laminated shale containing abundant pyrite in the form of small balls and rods. At 1419-1400 ft, the shale is interbedded with fecal pellets rich in coccoliths up to 1 cm thick giving the interval a whitish appearance (Figure 10). Calcite concretions occur at 1403.5 ft. A very thin conglomeratic layer rich in bioclastic debris forms the base and contact to the underlying Belle Fourche Formation (Figures 9 and 10).

The TOC values within the interval are high, ranging from 6 to 9.19 % of dominantly marine derived Type II organic matter (Figures 9 and 11). HI values are generally greater than 320 mgHC/gOC. At the top of the formation, a significant decrease in HI and TOC values coincides with the calcite concretions (Figure 9).

Agglutinated and planktic foraminifera are present in this interval (Figures 9 and 12). Agglutinated specimens of *Trochammina* first occur at 1439 ft together with a few planktic specimens of *Heterohelix globulosa* and *Hedbergella loetterlei* (Figure 12). Abundance and richness of the pelagic assemblage gradually increase towards the top of the formation (Figure 12). A total of 10 species have been identified including *Trochammina* spp, *Uvigerammina manitobensis*, *Haplophragmoides howardense*, *Heterohelix globulosa*, *Hedbergella* spp., *Hedbergella loetterlei*, *Hedbergella delrioensis*,

Whiteinella aprica, *Hedbergella portdownensis*, and *Hedbergella amabilis*. This species composition is typical for the *Hedbergella loetterlei* Zone (Figure 12).

Nannofossils have been examined from 15 samples within the interval and more than 30 species were identified. The abundance of nannofossils shows an opposite trend compared to that of planktic foraminifera, where the richness and abundance of species gradually decrease towards the top of the formation (Figures 9 and 10). Dominant nannofossil species are *Ahmuellerella octoradiata*, *Arkhangelskiella cymbiformis*, *Biscutum melaniae*, *Eiffellithus turriseiffeli*, *Predicosphaera cretacea*, *Zygodiscus diplogrammus*, *Zygodiscus acanthus*, and *Watznaueria barnesae*. Fish remains are present throughout the interval and decrease gradually towards the top of the formation (Figure 9). *Inoceramus* prisms are very abundant throughout the formation and reach maximum abundance at the top of the formation (Figure 9).

In the plains of southern Alberta and southwestern Saskatchewan, the Late Cretaceous unnamed Colorado Shale has recently been formally subdivided into the Late Turonian Carlile Formation and the Coniacian to Santonian Niobrara Formation (Figure 2; Nielsen et al., 2003). The boundary between the Carlile Formation and the underlying Second White Specks Formation is distinguished by a change from a calcareous shale with high organic matter content usually > 3% to non-calcareous shale with usually < 2% TOC (Figure 9; Nielsen, 2002). In the wireline well logs, the boundary between the two formations is defined as the point on the resistivity log of maximum decline from the high resistivity values of the Second White Specks Formation (Nielsen, 2002). The upper boundary is a sharp lithological contact between the gray, non-calcareous, silty and sandy shale of the upper Carlile Formation below and a dark gray, occasionally calcareous shale

with abundant bentonites of the Verger Member of the Niobrara Formation above (Figures 9 and 13; Nielsen et al., 2003).

Nielsen et al. (2003) informally subdivided the Carlile Formation into lower, middle and upper units (Figure 2). The lower unit of the Carlile Formation is homogenous gray shale with few non-bioturbated sand partings, no macrofossils and microfossils and an average TOC value of 2.2%. The middle unit is dark gray, slightly bioturbated, silty shale with bands of siderite concretions, no fossils and an average TOC value of 1.4%. The upper unit contains more sands with some macrofossils and bioturbation and TOC values vary between 0.5 and 2.5%.

In this study, the Carlile Formation has been studied at two locations. The first core is located in the vicinity of the Sweetgrass Arch area at 13-20-17-7W4 (Figure 3) and includes twelve meters of the upper part of the formation (Figure 13). The second core is located north of the Sweetgrass Arch area at 10-22-47-3W4 (Figure 3) and represents the entire formation (Figure 9).

The basal contact of the **Carlile Formation** at 10-22-47-3W4 is discerned by a distinct lithological change from a black to gray calcareous shale below to a non-calcareous black finely laminated fissile shale with wisps of siliciclastic detritus above and the disappearance of foraminifera (Figure 9). At this location north of the Sweetgrass Arch the Carlile Formation contains only two thin bentonite beds at 1380 and 1363 ft. Based on degree of bioturbation and HI values the formation is divided here into a lower and upper unit (Figure 9). The lower unit is non-bioturbated with HI values exceeding 300 mgHC/gOC, whereas the upper unit of the Carlile Formation is bioturbated and HI values are below 300 mgHC/gOC (Figure 9). In general, HI values of the lower unit are

relatively uniform and range from 303 to 360 mgHC/gOC. The TOC values within this unit vary from 4 to 6 % with a sharp drop to 2.8% at 1379.5 ft that corresponds to a bentonite bed (Figure 9). In contrast, the TOC and HI values of the upper unit gradually decrease upwards, and range from 0.04 to 2.04 % and from 100 to 262 mgHC/gOC respectively. The organic matter is overall of marine origin type II (Figures 9 and 11).

The core of the Carlile Formation at 13-20-17-7W4 on the northern flank of the Sweetgrass Arch is an upward coarsening cycle from finely laminated shale with two sandstone beds to a silty fine-grained sandstone, dominated by wave rippled, lenticular bedding with some thin discontinuous hummocky beds (Figure 13). Bioturbation ranges from light to intense increasing upwards (Figure 13). The interval contains a single bentonite at 544 m. TOC and HI values within this interval are relatively low (Figures 12 and 14). The average TOC is 1.38 wt%, ranging from 0.91 to 1.85 % and HI values range from 107 to 189 mgHC/gOC. The organic matter is mainly of type II, but a slight change towards type III terrestrial-derived organic matter is observed in the upper Carlile Formation (Figure 9) associated with the Bowdoin sandstone at the top of the interval (Figure 13).

At 10-22-47-3W4, the lowermost portion of the lower unit of the Carlile Formation is barren of foraminifera (Figure 10). From 1388.6 ft to 1370.6 ft. agglutinated species occur with the appearance of some poorly preserved specimens of *Haplophragmoides* spp., *Trochammina* spp., *Haplophragmoides howardense*, *Gaudryina canadensis*, *Trochammina rainwateri* and *Dorothia* cf. *smokyensis* (Figure 12).

Figure 13. Core 13-20-17-7W4. Reference core of the boundary between the Carlile and Niobrara formations in southeastern Alberta showing an estimated abundance of the foraminiferal assemblages including foraminifera, planktic and benthic (calcareous and agglutinated); miscellaneous components including fish remains and *Inoceramus* prisms; geochemistry including TOC and HI and sea-level fluctuations. For sedimentological legend see figure 8. Core location on figures 1 and 3.

Well: 13-20-17-7W4

Figure 13

Figure 14. Geochemistry of the reference core 13-20-17-7W4 represents the upper Carlile Formation and lower Verger Member of the Niobrara Formation illustrated in HI/OI plots.

Well: 13-20-17-7W4 **Figure 14**

The bioturbated upper unit of the Carlile Formation is barren of foraminifera (Figures 9 and 12). Fish remains occur throughout the Carlile Formation, but are particularly abundant at the base and in the upper unit (Figure 9). *Inoceramus* prisms are very abundant in the lower middle portions of the lower unit and decrease towards the top to become common in the upper unit (Figure 9).

The Carlile Formation at 13-20-17-7W4 contains a mixed foraminiferal assemblage of abundant agglutinated and rare planktic and calcareous foraminifera (Figures 12 and 15). Planktic and calcareous benthic foraminifera occurrences are rare and sporadic with the exception of *Neobulimina albertensis*. Agglutinated taxa are represented by *Trochammina rainwateri*, *Trochammina wetteri*, *Haplophragmoides* sp. 2, *Haplophragmoides collyra*, *Verneuilinoides bearpawensis*, *Verneuilinoides* spp., and *Pseudobolivina rollaensis* (Figure 15). Fish remains are abundant throughout the interval. *Inoceramus* prisms gradually increase upwards from rare at the base to abundant at the top of the interval (Figure 13).

The **Verger Member** of the Niobrara Formation has been cored at the three studied localities; 10-22-47-3W4, 13-20-17-7W4 and 16-4-22-15W4 (Figures 1 and 3). The first two cores represent the lower part of the member, whereas the upper part is represented in the third core. At 10-22-47-3W4 the basal contact of the Verger Member with the underlying Carlile Formation is unconformable and is expressed in lithology and microfossil content (Figures 9 and 12). The boundary separates non-calcareous, black, finely laminated, fissile shale with wisps of siliciclastic detritus barren of foraminifera of the upper Carlile Formation from black to gray, calcareous shale, rich in calcareous wisps of coccoliths containing a mixed foraminiferal assemblage of benthic (agglutinated and

calcareous) and planktic foraminifera of the Verger Member. The 15 feet of the Verger Member at this location contains a 6 inch-thick bentonite bed at 1344 ft (Figure 10). The member is light to moderately bioturbated with abundant pyrite in forms of small balls and rods. In general, the average value of TOC within this interval is 1.8% and the HI values range from 141 to 273 mgHC/gOC. The TOC is marine derived type II organic matter (Figures 9 and 11).

At 13-20-17-7W4, the boundary between the Verger Member and the underlying Carlile Formation is drawn at the change from thin, intensively bioturbated, lithic graywacke at the top of the Carlile Formation to a thin, dark shale showing an abrupt decrease in degree of bioturbation (Figure 13). The Verger Member at this location contains dark calcareous shale with abundant white specks (fecal pellets) inter-laminated with non-calcareous shale. A swarm of seventeen bentonites occurs one meter above the lower boundary of the member condensed in only three meters of silty shale (Figure 13). The thickness of individual bentonites ranges from 0.5 to 16 centimetres. The TOC and HI values in the Verger Member are higher than those of the underlying Carlile Formation (Figure 13). The average TOC is 1.71 % and the HI values range from 95 to 431 mgHC/gOC. The organic matter is a mixture of marine-derived type II and III (Figure 14).

At 16-4-22-15W4, the cored portion of the Verger Member consists of homogenous dark gray silty shale with few sandstone beds and a pebble layer at the top (Figure 16). The interval is slightly to moderately bioturbated with pyrite and calcite concretions. The calcareous shale within this interval is inter-laminated with non-calcareous shale.

Figure 15. Distribution chart representing foraminiferal species from core 13-20-17-7W4 and biostratigraphic zonations and their relation to different stages.

Figure 16. Core 16-4-22-15W4. Reference and type core of the three members of the Niobrara Formation, Verger, Medicine Hat and First White Specks members in southeastern Alberta showing relative abundance of the foraminiferal assemblages including foraminifera, planktic and benthic (calcareous and agglutinated); miscellaneous components including fish remains and *Inoceramus* prisms and geochemistry including TOC, HI and organic matter type. For sedimentological legend see figure 8. Core location on figures 1 and 3.

Figure 16

The interval contains several bentonite beds ranging in thickness from 1 to 5 cm (Figure 17). The upper boundary with the overlying Medicine Hat Member is placed just below a lag of well-rounded pebbles (Figure 17). The average TOC value within this interval is 1.4 wt% and the HI values range from 164 to 35 mgHC/gOC (Figure 16).

In the three cores the Verger Member of the Niobrara Formation contains a mixed foraminiferal assemblage of benthic (agglutinated and calcareous) and planktic foraminifera (Figures 11, 15 and 19). At 10-22-47-3W4, planktic and calcareous benthic foraminifera appear at the bottom and the top of the cored interval and disappear at the central part where agglutinated species dominate (Figures 9 and 12). At the bottom of the interval, the planktic species *Heterohelix globulosa* and the calcareous benthic species *Neobulimina albertensis* are present, whereas, at the top the planktic *Hedbergella delrioensis* replaces *Heterohelix globulosa* (Figure 12). The middle portion of the interval is dominated by agglutinated species that include *Pseudoclavulina* sp., *Trochammina* spp., *Saccammina alexanderi*, *Haplophragmoides* spp., *Haplophragmoides howardense*, *Dorothia* cf. *smokyensis*, and *Marssonella oxycona* (Figure 12).

At 13-20-17-7W4, planktic foraminiferal species occur within the lower shaly portion of the interval below the bentonite beds together with a few calcareous benthic species. The planktic foraminifera include *Hedbergella delrioensis*, *Hedbergella* spp., *Hedbergella planispira* and *Hedbergella portsdownensis*. Above the bentonite swarm agglutinated species dominate the upper portion of the interval (Figure 15). The agglutinated taxon *Marssonella oxycona* is the most abundant species. Within the bentonite interval foraminifera disappear (Figure 15).

Figure 17. Characteristic features and interpretation of the reference core 16-4-22-15W4 related to sea-level changes and the response of micropaleontological assemblages to these changes. First Appearance Datum (FAD).

REMARKS

At 16-4-22-15W4, agglutinated foraminifera are present throughout the interval with high abundance and species richness (Figures 15 and 18). First appearances of planktic and calcareous benthic foraminifera are recorded at 560 m (Figure 17). At this depth a single planktic species of *Heterohelix globulosa* has been found along with a few calcareous benthic taxa that include *Gavelinella talaria*, *Gavelinella henbesti*, *Valvulineria* sp. and *Bullopore laevis* (Figure 18). The planktic species *Hedbergella delrioensis* occurs at 555 m along with abundant agglutinated species (Figure 18). Benthic calcareous foraminifera reappear at the top of the interval in reduced numbers and richness. The Verger Member within the three cores contains moderate to abundant fish and vertebrate remains throughout the interval, whereas *Inoceramus* prisms are restricted to the basal part of the interval (Figures 9, 13 and 15).

The base of the overlying **Medicine Hat Member** of the Niobrara Formation at 16-4-22-15W4 is a lag of well-rounded pebbles (Figure 17). The sandy Medicine Hat Member at this location consists of three alternating, dark gray, silty to sandy shale intervals with three sandstone intervals. The sandstone intervals have been named in ascending order “D”, “C” and “A” sandstone (Figure 17; Nielsen et al., 2003). The slightly to moderately bioturbated lower Medicine Hat shale overlies the Verger Member (Figure 17). The D-Sandstone interval consists of two intensely bioturbated, silty sandstones and is in turn overlain by dark gray, silty shale that is similar in lithological features to the lower Medicine Hat shale (Figure 17). The C-Sandstone zone overlies the middle shale and consists of several individual fine-grained, heavily bioturbated sandstones and one pebble bed. The third thin shale is similar to the other two shales with relatively frequent fine white speckled laminae. The A-Sandstone zone is the coarsest

sandstone within the interval and consists of very fine to fine-grained chert-rich litharenite with few small chert and siderite pebbles (Figure 17). The top of the A-Sandstone zone forms the boundary with the overlying First White Specks Member of the Niobrara Formation (Figure 17).

Generally, the TOC values within the Medicine Hat Member are low and average 1.5 wt% and the HI values range from 20 to 304 mgHC/gOC (Figures 15 and 19). The TOC values from the Lower Medicine Hat shale average 1.57 wt%, the D-sandstone 1.12 wt%, the middle shale 1.22 wt%, C-sandstones 1.19 wt%, the upper sandy shale averages 1.66 wt% and the A-Sandstone zone averages 1.07 wt%. The HI-index shows a similar trend to the TOC trend (Figure 16). Type II organic matter is most dominant in the lowest shale unit of the Medicine Hat Member.

Similar to the underlying Verger Member, this interval contains mixed foraminiferal assemblages of benthic (agglutinated and calcareous) and planktic taxa (Figures 16 and 18). Due to the sandy nature of this interval the foraminiferal assemblages are poorly preserved. Agglutinated species have their highest abundance and richness in the lower and middle shale intervals (Figure 16). Calcareous benthic foraminifera are mostly found within the lower and middle shales and few within the C-Sandstone zone (Figures 15 and 18). Planktic species, in contrast, are only found within the lower Medicine Hat shale (Figures 15 and 18). Fish remains are present throughout the interval with highest abundances within the lower portion of the C-Sandstone zone that coincides with a pebble layer (Figure 16). Generally, sandstone zones have higher fish remain abundances than the shaly intervals. *Inoceramus* prisms show the opposite trend to fish remains, being most abundant within the shaly intervals (Figure 16).

Figure 18. A distribution chart represents the most common foraminiferal species from core 16-4-22-15W4 and biostratigraphic zonations and their relation to different stages. (See appendix A for complete reference for all recognized foraminiferal species).

Figure 18

Figure 19. Geochemistry of the reference core 16-4-22-15W4 represents the Verger, Medicine Hat and First White Specks members of the Niobrara Formation and the lower part of the Milk River Formation illustrated in HI/OI plots.

Well - 16-04-22-15W4

Figuer 19

The **First White Specks Member** of the Niobrara Formation at 16-4-22-15W4 is a calcareous, dark gray, fissile to platy, slightly to non-bioturbated shale with abundant fecal pellets observed as white specks in the core. Lags of shell and sandstone are common and are often associated with sharp-based thin, fine-grained sandstone beds. Two pebble layers are present at the middle of the Member (Figure 17). Across the boundary between the older Medicine Hat Member and the younger First White Specks Member, organic geochemistry changes significantly (Figure 16). The TOC values sharply increase from 0.9 wt% at top of the Medicine Hat to about 2 wt% at base of the First White Specks Member (Figure 16). The TOC values within the interval initially increase upwards to a maximum in the middle, followed by a steady decrease towards the top of the member (Figure 16). The average value of TOC within the interval is 2.38 wt% (Figure 19). The HI-index shows a similar trend to the TOC and the values range from 114 to 318 mgHC/gOC (Figure 16).

Similar to the underlying Medicine Hat Member, the foraminiferal assemblages within the First White Specks Member are poorly preserved and contain a fauna of mixed of benthic (agglutinated and calcareous) and planktic taxa (Figure 17). Agglutinated foraminifera are rarely present throughout the interval becoming barren at the middle of the member just above the second pebble layer (Figures 15 and 18). This gap coincides with the first appearance and only presence of the planktic foraminifera within the interval (Figures 15 and 18). Calcareous benthic foraminifera are found just above the fine-grained sandstone bed at the top of the interval (Figure 16). The species composition of the member is typical of the *Globigerinelloides* sp. Zone (Figure 16). In general, fish remains are present throughout the interval ranging from moderate to high in abundance

(Figure 16). Unlike the underlying Medicine Hat the highest abundances coincide with shaly parts of the interval. *Inoceramus* prisms are present throughout with high abundance at the base of the interval (Figure 16). The upper boundary of the member is also the upper boundary of the formation and is a sharp lithological contact with the overlying Milk River Formation (Figure 17).

Foraminiferal Zonation

Paleontology has played an important role in establishing the paleogeography, paleoecology and sea-level history of the WCSB and WIS. Macrofossils such as ammonites and mollusks are used as biostratigraphic markers in regional correlations and zonations, correlated with absolute time scales (Caldwell et al., 1978, 1993; Obradovich, 1993). However, limited Cretaceous rock exposures have yielded limited macrofossils for basin-wide correlations (McNeil and Caldwell, 1981). Alternatively, microfossils have proven to be useful in biostratigraphy and subsurface correlations, being present in most of the Cretaceous rocks of the Interior Plains of Canada (Caldwell et al, 1978, 1993). Caldwell et al. (1978) proposed a foraminiferal zonal scheme comprising seventeen formally established zones widely traceable through the Cretaceous system of the WCSB. The present biostratigraphic analysis of the Late Albian to Campanian strata in southeastern and central Alberta is based on the distribution of foraminiferal assemblage zones. Foraminifera occur with varying degrees of abundance and richness in most of the stratigraphic units from the base of the Westgate Formation to the basal Milk River Formation. Whereas biostratigraphic ranges of most agglutinated foraminifera appear relatively long, foraminiferal assemblages show pronounced compositional changes, which may be correlated with changes in lithology and sequences (Figures 11, 15 and 18).

For the latest Albian to Early Campanian time interval, the zonal scheme of Caldwell et al., (1978) is represented by ten zones that include in ascending order the *Miliammina manitobensis*, *Textularia alcesensis*, *Verneuilioides perplexus*, *Flabellamina gleddiei*, *Hedbergella loetterlei*, *Pseudoclavulina* sp., *Trochammina* sp., *Bullopore laevis*, *Globigerinelloides* sp. and *Trochammina ribstonensis* zones (Figure 6).

Missing Zones

In the study area only five zones were recognized (Figure 6) representing the interval from the Westgate Formation to the First White Specks Member of the Niobrara Formation. At 10-22-47-3W4, the interval from the base of the Fish Scales Formation to the top of the Belle Fourche Formation is barren of foraminifera (Figure 10). Consequently the *Textularia alcesensis*, *Verneuilioides perplexus*, and *Flabellamina gleddiei* zones were not recognized. Lack of these zones is either caused by an erosional hiatus or due to unfavorable environmental conditions for foraminifera.

The *Textularia alcesensis* Zone of latest Albian to Early Cenomanian time is known only from northeastern British Columbia and parts of the plains of northwestern Alberta (Caldwell et al., 1978; Leckie et al., 2000). The zonal microfauna has been found within the strata from the base of the Fish Scale Marker to the base of the Dunvegan Formation, which is time equivalent to the Fish Scales Formation in the study area (Figure 12). The presence of the bioclastic layer that forms the base of the Fish Scales Formation might indicate a period of erosion linked to the absence of the zonal microfauna (Schröder-Adams et al., 1996).

The Early Late Cenomanian *Verneuilioides perplexus* Zone, on the other hand, is relatively widespread (Figure 6; Caldwell, et al., 1978; 1993). The zonal microfauna is

well established in the plains of northwestern Alberta and northeastern British Columbia where the zone is divided into *Ammobaculites gravenori* and *Gaudryina irenensis* subzones. In the southern Rocky Mountain Foothills of Alberta and across the plains of southern Alberta, Saskatchewan, and Manitoba, however, the richness of this zone is noticeably reduced, disallowing subzonation (Caldwell et al., 1978).

Schröder-Adams et al. (1996) found the zone well established within the Belle Fourche Formation at 11-12-6-16W4, 6-34-30-8W4 and further north at 6-18-45-1W4. However, species abundance and richness is markedly reduced within the Belle Fourche Formation at 10-35-45-2W4 where only four specimens of *Trochammina rutherfordi mellariolum* were found at the top of the formation (Schröder-Adams et al., 1996). In this study, the Belle Fourche Formation at 10-22-47-3W4 and further north at the Cold Lake area (Tu, pers. comm., 2004) is barren of foraminifera. The foraminiferal assemblages within the Belle Fourche Formation show a noticeable decrease in species abundance and richness in the central basin from south to north suggesting restricted bottom water oxygen conditions in the more northern parts.

The *Flabellammina gleddiei* Zone of Late Cenomanian to Early Turonian time is known only in the Peace River district of northwestern Alberta and adjacent northeastern British Columbia (Figure 6; Caldwell et al., 1978). The zone is divided into *Ammobaculites pacalis* and *Haplophragmoides spiritense* subzones, which contain a diverse fauna. The zone is missing in the Rocky Mountain Foothills and the southern plains of Canada including the study area (Caldwell, et al., 1978).

Recognized Zones

The recognized zones in this study are the *Miliammina manitobensis*, *Hedbergella loetterlei*, *Pseudoclavulina* sp.- *Trochammina* sp., *Bullopore laevis*, *Globigerinelloides* sp. and *Trochammina ribstonensis* zones (Figure 6). The *Pseudoclavulina* sp.- *Trochammina* sp. Zone of McNeil and Caldwell (1981) represents the interval from the Carlile Formation to lowermost Verger Member of the Niobrara Formation at 10-22-47-3W4 and 13-20-17-7W4 (Figures 11 and 15).

The *Miliammina manitobensis* Zone is the most widespread of the Albian zones across the Interior Plains of Canada (Wall, 1967a; Caldwell et al, 1978; McNeil and Caldwell, 1981) and contains exclusively agglutinated foraminifera (Caldwell, 1981; McNeil and Caldwell, 1981; Bloch et al., 1993; Schröder-Adams et al, 1996). Across the plains the *Miliammina manitobensis* microfauna is much less diverse than in the Rocky Mountain Foothills of British Columbia, where the *Verneuilina canadensis*, *Haplophragmoides postis goodrichi* and *Haplophragmium swareni* subzones can be recognized (Sutherland and Stelck, 1972; Caldwell et al, 1978, 1993). The *Verneuilina canadensis* Subzone has the greatest lateral extent. In the plains of western Canada, Bloch et al. (1993), however, found elements of the lower *Verneuilina canadensis* and middle *Haplophragmoides postis goodrichi* subzones including both subzonal marker species. In northwestern and central Alberta, moreover, the two lower subzonal marker species were found, but in a reversed order (Stritch and Schröder-Adams, 1999). In the Manitoba Escarpment, elements of the *Miliammina manitobensis* Zone occur within the Westgate Member of the Ashville Formation and the lowermost of the Belle Fourche

Member; however, none of the subzonal marker species have been found (McNeil and Caldwell, 1981).

At 10-22-47-3W4, the Westgate Formation consists of agglutinated taxa (Figures 9 and 12). Total abundance of specimens and species richness vary significantly throughout the formation. A total of 38 agglutinated species has been identified within the Westgate Formation (Figure 12). The zonal marker species *Miliammina manitobensis* is the most abundant throughout the formation. The subzonal marker species *Verneuulina canadensis* is absent; however, the later two subzonal marker species have been found and occur within the lower fining-upwards cycle (Figure 12). However, no distinct faunal change is observed in the studied section of the Westgate Formation to imply a useful subzonation (Figure 6).

The widespread *Hedbergella loetterlei* Zone corresponds to the beds containing the “Lower Pelagic Microfauna” of Wall and Germundson (1963) and Wall (1967a) and to zone V of North and Caldwell (1975a, b) (Figure 7). In the plains, the zone straddles the boundary between the Lower and Upper Colorado Group (Caldwell et al., 1978). The *Hedbergella loetterlei* Zone occurs in the Second White Specks Formation and its stratigraphic equivalent strata (Figure 7). In Manitoba and eastern Saskatchewan, the *Hedbergella loetterlei* Zone is divided into the lower *Clavihedbergella simplex* and upper *Whiteinella aprica* subzones (Figure 7; Caldwell et al., 1978).

At 10-22-47-3W4, the Second White Specks Formation is characterized by a two-fold subdivision of the foraminiferal fauna. The lower 1.6 ft of the Second White Specks Formation, including the conglomeratic phosphatic layer that forms the basal boundary is barren of foraminifera. From 1442 ft to 1433 ft, the interval contains a mixed assemblage

of few agglutinated and abundant planktic taxa and forms a transition to a fully pelagic assemblage (Figures 7 and 12). A single specimen of the calcareous benthic species *Neobulimina albertensis* has been found within the lower interval at 1439 ft. Agglutinated specimens are poorly preserved and are related to *Trochammina* spp. and *Uvigerammina manitobensis*. The planktic *Heterohelix globulosa* is the dominant species of the lower interval. Subzonal marker species such as *Clavihedbergella simplex*, typical of Second White Specks cores and outcrops in Saskatchewan (Figure 7; North and Caldwell, 1975a) and Manitoba (McNeil and Caldwell, 1981), or *Haplophragmoides spiritense*, typical of the Peace River District (Stelck and Wall, 1954), do not occur. However, the mixed nature of the assemblage and occurrence of *Neobulimina albertensis*, suggest equivalent interval in Central Alberta of late Cenomanian/early Turonian time (McNeil and Caldwell, 1981; Schröder-Adams et al., 1996). The pebble layer at the base of the Second White Specks Formation suggests erosion, although the extent of missing section is difficult to discern due to the barren Belle Fourche Formation (Figure 12).

The upper pelagic fauna includes *Hedbergella loetterlei*, *Hedbergella planispira*, *Whiteinella aprica*, *Hedbergella delrioensis*, *Hedbergella portsdownensis* and *Hedbergella amabilis*. This species composition is typical of the *Whiteinella aprica* Subzone, which forms the upper part of the *Hedbergella loetterlei* Zone (Figures 6 and 7). McNeil and Caldwell (1981) have assigned an early to middle Turonian age to the *Whiteinella aprica* Subzone, whereas Caldwell et al. (1978) limited the age to Early Turonian.

The boundary between the Second White Specks Formation and the overlying Carlile Formation is placed where the calcareous shale changes to non-calcareous shale

and where the pelagic fauna and flora disappears (Figures 9 and 10). At 10-22-47-3W4 the Carlile Formation is divided into a lower and upper unit (Figure 9). The base of the lower unit (1400-1391.6 ft) is barren of foraminifera (Figure 10). Similar observations were recorded in the Manitoba Escarpment where the lowermost Morden Shale (time equivalent to the Carlile Formation) is also barren of foraminifera (McNeil and Caldwell, 1981).

In the Rocky Mountain Foothills of Alberta, the *Pseudoclavulina* sp. and the *Trochammina* sp. microfauna are separated by the Cardium Formation microfauna (Figure 7; Wall, 1967a). In the Manitoba Escarpment the Morden Shale shares faunal components with the two zones, but neither of the zonal markers are found resulting in the *Pseudoclavulina* sp.- *Trochammina* sp. Zone (McNeil and Caldwell, 1981). Agglutinated foraminifera dominate the two zones, but also include sparse calcareous benthic and planktic specimens (North and Caldwell, 1975 a, b; McNeil and Caldwell, 1981).

North of the Sweetgrass Arch, at 10-22-47-3W4, elements of the *Pseudoclavulina* sp.- *Trochammina* sp. Zone occur in the Carlile Formation and lowermost portion of the Verger Member of the Niobrara Formation (Figure 12). Part of these include poorly preserved specimens of *Trochammina* spp, *Haplophragmoides* spp, *Trochammina rainwateri*, *Haplophragmoides howardense*, *Reophax incompta* and *Dorothia* cf. *smokyensis* are found within the lower unit of the Carlile Formation (Figure 12). Unlike in the Manitoba Escarpment, the key species *Pseudoclavulina* sp. occurs only within the lowermost portion of the Verger Member of the Niobrara Formation together with *Neobulimina canadensis*, *Ammobaculites fragmentarius*, *Pseudobolivina rollaensis*,

Gaudryina canadensis, *Heterohelix globulosa*, *Hedbergella delrioensis* and *Reophax* sp. (Figure 12).

The presence of the marker species *Pseudoclavulina* sp. in the Verger Member confirms the hypothesis of Wall, (1967a, p. 19), who suggested that the occurrence of *Pseudoclavulina* sp. is stratigraphically higher in the plains above the Cardium Formation. This hypothesis was based on the finding of the zonal marker in approximately 50 feet below the Bad Heart sandstone and 50 feet above a thin band of chert and quartzite pebbles, which may be the same as the one at the base of the Wapiabi Formation in the Foothills (Wall, 1967). This position is correlative to the Verger Member (Figure 2).

The presence of planktic and calcareous species within this zone at 10-22-47-3W4 is comparable to the assemblage of the Morden Shale in Manitoba and eastern Saskatchewan (North and Caldwell, 1975a, b), Manitoba Escarpment (McNeil and Caldwell, 1981) and Blue Hill Shale Member at Pueblo, Colorado (Eicher, 1966). Therefore, the *Pseudoclavulina* sp.- *Trochammina* sp. Zone at 10-22-47-3W4 spans the Carlile Formation and the lowermost Verger Member.

Close to the Sweetgrass Arch at 13-20-17-7W4, the *Pseudoclavulina* sp.- *Trochammina* sp. Zone also spans the interval from the upper portion of the Carlile Formation and lowermost portion of the Verger Member of the Niobrara Formation (Figure 15). At this location, the microfauna is more abundant and diverse than at 10-22-47-3W4. Also, the key species *Trochammina* sp.1 (= *Trochammina* sp.) has been found in the lower portion of the upper Carlile Formation (Figure 15). The middle part of the interval is dominated by the calcareous benthic species *Neobulimina albertensis*. In both

core localities the boundary between the Carlile Formation and Verger Member is marked by an increase in planktic species.

Wall's separation of three microfaunas in the Rocky Mountain Foothills correlated to the Haven/Opabin members, Cardium Formation and lower Wabiabi Formation (Figure 2) is based on very little faunal difference. In the central part of the basin only an amalgamated foraminiferal zone can be recognized in a much-condensed section. Wall (1967a) placed the *Pseudoclavulina* sp., Cardium Formation and *Trochammina* sp. microfauna into the Late Turonian to Early Coniacian (Figure 7). Dating of two bentonites from the lower part of the Verger Member provides an age of 88.19 and 89.40 Ma or Late Turonian to Early Coniacian (Nielsen et al., 2003). McNeil and Caldwell (1981) suggested that the *Pseudoclavulina* sp.- *Trochammina* sp. Zone in the Manitoba Escarpment is not older than the late Middle Turonian (Figure 7).

The *Bullopore laevis* Zone can be traced throughout the Rocky Mountain Foothills of Alberta (Wall, 1967a), southern Plains of Alberta (Wickenden, 1932c; Wall, 1967a) at least as far as the southwest corner of Saskatchewan and into northern Montana (Wall, 1967a). In central Saskatchewan, the zonal position is marked by a prominent disconformity at the base of the *Globigerinelloides* sp. Zone (Figures 6 and 7; North and Caldwell, 1975; Caldwell et al., 1978; Bloch et al., 1993; Schröder-Adams et al, 1996, 1997, 2001). In the Manitoba Escarpment, the Santonian *Globigerinelloides* sp. Zone overlies directly the late Middle Turonian *Pseudoclavulina* sp.- *Trochammina* sp. Zone (Figure 7; McNeil and Caldwell, 1981). On the crest of the Sweetgrass Arch, Wall (1967c) found diagnostic elements of the zonal assemblage 183 to 216 m below the top

of the undivided Alberta Shale (Colorado Group). The zonal microfauna consists of abundant agglutinated and calcareous benthic foraminifera and few planktic species.

In this study, the *Bullopore laevis* Zone is well established and most of the diagnostic elements of Wall (1967a) and Caldwell et al. (1978), including the zonal marker species, have been recognized. The *Bullopore laevis* Zone is recognized throughout the interval from the Verger Member to the lower shaly interval of the Medicine Hat Member of the Niobrara Formation (Figure 18). Characteristic faunal changes within the zone related to sea-level fluctuations allowed a threefold subzonation (Figure 18). The zone is divided into a lower *Marssonella oxycona*, middle *Haplophragmoides bonanzaense*, and upper *Neobulimina canadensis* Subzone (Figure 18). The lower *Marssonella oxycona* Subzone has been recognized in three cores, whereas the other two are only recognized in the core at 16-4-22-15W4 (Figures 11, 15 and 18).

***Marssonella oxycona* Subzone:**

An exclusively agglutinated assemblage distinguishes the *Marssonella oxycona* Subzone. The principal elements are *Marssonella oxycona* (Reuss), *Haplophragmoides howardense* Stelck and Wall, *Haplophragmoides collyra* (Nauss), *Ammobaculites fragmentarius* (Cushman), *Trochammina rainwateri* (Cushman), *Trochammina ribstonensis* (Wickenden), *Pleurostomella watersi* (Cushman), *Spiroplectammina semicomplanata* (Carsey), *Reophax* sp.1 (Wall), *Gaudryina canadensis* (Cushman), together with unidentified species of *Haplophragmoides* and *Trochammina*. As shown in the foraminiferal distribution charts (Figures 11, 15 and 18), numerous species of this subzone range into younger or older zones in central and southeastern Alberta. In

Southeastern Alberta close to the Sweetgrass Arch at 16-4-22-15W4 and 13-20-17-7W4, the subzonal microfauna is more abundant and diverse than at 10-22-47-3W4 (Figure 12).

***Haplophragmoides bonanzaense* Subzone:**

The *Haplophragmoides bonanzaense* Subzone is distinguished by a mixed assemblage of agglutinated and calcareous-walled benthic species as well as a few planktic species (Figure 18). In southeastern Alberta, the subzonal principal elements are *Haplophragmoides* sp. 2 (Wall), *Haplophragmoides howardense* Stelck and Wall, *Haplophragmoides collyra* (Nauss), *Ammobaculites fragmentarius* (Cushman), *Ammobaculites tyrrelli* (Nauss), *Ammobaculites* sp. 1 (Wall), *Gavelinella henbesti* (Plummer), *Gavelinella talaria* (Nauss), *Trochammina wetteri* Stelck and Wall, *Haplophragmoides bonanzaense* Stelck and Wall, *Dorothia* sp., *Bullopore laevis* (Sollas), *Hedbergella delrioensis* (Carsey), *Heterohelix globulosa* (Ehrenberg), *Dentalina* sp. 1 (Wall), together with unidentified species of *Haplophragmoides*, *Dorothia*, *Ammobaculites*, *Anomalinoidea*, and *Trochammina*. The *Haplophragmoides bonanzaense* Subzone is represented in the upper portion of the Verger Member of the Niobrara Formation at 16-4-22-15W4 (Figure 18).

***Neobulimina canadensis* Subzone:**

The *Neobulimina canadensis* Subzone represents the lower shaly interval of the Medicine Hat Member of the Niobrara Formation at 15-4-22-15W4 (Figures 15 and 18). This shaly interval of Medicine Hat Member may be correlate to the shaly Puskwaskau Formation in west central Alberta (Plint, 1990), to the shaly part of the Dowling Member in the southern Alberta Foothills (Wall, 1967a) and to the shaly middle unit of the Kevin Member in northwestern Montana (Nielsen, 2002). The subzone carries abundant

calcareous and agglutinated benthic species as well as few planktic species. Many of the *Marssonella oxycona* and *Haplophragmoides bonanzaense* subzones microfauna elements continue to occur in the *Neobulimina canadensis* Subzone (Figure 18). The subzonal principal elements are *Neobulimina canadensis* Cushman and Wickenden, *Hedbergella delrioensis* (Carsey), *Hedbergella planispira* Tappan, *Ammobaculites fragmentarius* (Cushman), *Trochammina ribstonensis* Wickenden, *Gavelinella talaria* (Nauss), *Gavelinella henbesti* (Plummer), *Haplophragmoides* sp. 2 (Wall), *Ammobaculites* sp. 1 (Wall), *Haplophragmoides howardense* Stelck and Wall, *Gavelinella kansasensis* (Morrow), *Nodosarella* sp., *Archaeoglobigerina cretacea* (d'Orbigny), together with unidentified species of *Haplophragmoides*, *Dorothia*, *Anomalinoidea*, *Cibicides*, *Ammobaculites* and *Trochammina*.

The *Globigerinelloides* sp. Zone is coincident with the First White Specks Member of the Niobrara Formation and forms the top of the Upper Colorado Group in southern and southwestern Alberta and equivalent strata across the basin (Caldwell et al., 1978). The zone extends across the Interior Plains of Western Canada from the Manitoba Escarpment to the Rocky Mountain Foothills (Caldwell et al, 1978; McNeil and Caldwell 1981). In the southern Rocky Mountain Foothills and southernmost Manitoba, the *Globigerinelloides* sp. Zone is divided into a lower *Gavelinella henbesti* and upper *Heterohelix* cf. *reussi* Subzone (Figures 6 and 7; Wall, 1967a; Caldwell et al, 1978; McNeil and Caldwell, 1981). In the remaining Interior Plains of Western Canada, only a single *Globigerinelloides* sp. Zone can be distinguished (Figure 7; Caldwell et al., 1978). In southern Alberta, in the vicinity of the Sweetgrass Arch, the First White Specks

Member of the Niobrara Formation is unusual in carrying dominantly agglutinated species (Figure 7; Schröder-Adams et al, 1997).

At 16-4-22-15W4, the *Globigerinelloides* sp. Zone is well established and spans the interval from the Medicine Hat Member to the First White Specks Member (Figure 18). The interval carries two-fold subdivision of foraminiferal assemblages allowing subzonation. The lower *Gavelinella henbesti* Subzone carries a mixed assemblage of agglutinated and calcareous benthic foraminifera (Figure 18), whereas planktic species mainly of *Globigerinelloides* distinguishes the upper *Heterohelix* cf. *reussi* Subzone (Figure 18).

In close vicinity to the Sweetgrass Arch at 16-4-22-15W4 the *Gavelinella henbesti* Subzone spans the interval from the lower shaly unit in the Medicine Hat Member to the lower portion of the First White Specks Member (Figure 18). With the exclusion of planktic species, most of the “*Planulina* microfauna” of Wall and Germundson (1963) are found in this interval. The subzonal principal elements are *Haplophragmoides* sp. 2, *Ammobaculites fragmentarius*, *Pseudobolivina rollaensis*, *Trochammina ribstonensis*, *Dorothia glabrata*, *Gavelinella henbesti*, *Trochammina rainwateri*, *Pseudobolivina variana*, and *Ammobaculites* sp. 1, together with unidentified species of *Haplophragmoides*, *Dorothia*, *Ammobaculites* and *Trochammina* (Figure 18). The absence of planktic species at this locality might indicate the influence of the Sweetgrass Arch as a topographic high providing near-shore environment conditions, prohibited planktic species to thrive. The upper boundary of the *Gavelinella henbesti* Subzone with the overlying *Heterohelix* cf. *reussi* Subzone is transitional and discerned at the earliest appearance of the planktic foraminifera (Wall, 1967a). In this study

therefore, the boundary between the two subzones was drawn at the first appearance of planktic foraminifera in the upper First White Specks Formation above the conglomeratic layer at 470 m (Figure 18). Caldwell et al., (1978) assigned an Early to Middle Santonian age to the *Gavelinella henbesti* Subzone, in correspondence to the Zone I in the ammonite zonal scheme of Jeletzky (1968).

The *Heterohelix* cf. *reussi* Subzone is distinguished by mixed agglutinated and calcareous-walled benthic foraminifera as well as by several planktic species (Figure 18). The subzonal microfauna represents the upper part of the First White Specks Member. Many of the principal elements including the subzonal marker species of the underlying *Gavelinella henbesti* Subzone continue to occur in the *Heterohelix* cf. *reussi* Subzone. The presence of some planktic species such as the planispiral morphotype *Globigerinelloides* distinguishes this subzone. The *Heterohelix* cf. *reussi* Subzone represents the peak transgression of the Niobrara Cycle (Figure 16). In southeastern Alberta, in close vicinity to the Sweetgrass Arch, the subzonal principal elements are *Globigerinelloides bentonensis*, *Globigerinelloides prairiehillensis*, *Globigerinelloides messinae*, *Hedbergella amabilis*, *Hedbergella planispira*, *Hedbergella delrioensis*, *Heterohelix globulosa*, *Trochammina ribstonensis*, *Haplophragmoides* sp. 2, *Ammobaculites fragmentarius*, *Haplophragmoides collyra*, *Bolivina* cf. *elkensis*, *Neobulimina canadensis*, *Nodosarella* sp., *Gavelinella henbesti*, *Saccammina* sp. cf. *S. alexanderi* and *Heterohelix* cf. *reussi* (Figure 18).

In general, the *Globigerinelloides* sp. Zone is Early to Late Santonian in age (Figure 7; Caldwell et al., 1978; Wall, 1967a). In the Rocky Mountain Foothills, however, Wall (1967a) suggests that the beds containing the zonal microfauna may be diachronous

from north to south. In the Interior Plains of Western Canada, moreover, the zonal base is also diachronous from east to west when compared to molluscan faunal zones (Figure 7; Caldwell et al., 1978; Schröder-Adams et al, 1997).

The almost entirely agglutinated fauna of the *Trochammina ribstonensis* Zone marking the strata of the Milk River Formation above the First White Specks Member and above the top of the Colorado Group in the Plains region (Wall, 1967a). The basal boundary of the *Trochammina ribstonensis* Zone with the underlying *Globigerinelloides* sp. is taken at the level where the pelagic microfauna disappears and is replaced by a dominantly agglutinated microfauna (Wall, 1967a).

The zonal marker species was first described by Wickenden (1932a) from the lower Milk River/Lea Park Formation in east-central Alberta, who described a species range to the base of the Milk River Formation. However, *Trochammina ribstonensis* also occurs in the First White Specks Formation in the southern Interior Plains (North and Caldwell, 1975a; Caldwell et al, 1978) and equivalent strata in the Rocky Mountain Foothills (Wall and Germundson, 1963; Wall, 1967a). In the Manitoba Escarpment, some of the principal elements have been found in the Pembina Member of the Pierre Formation and lowermost part of the Millwood Member, but the zonal marker has not been found (McNeil and Caldwell, 1978). In central Saskatchewan, the *Trochammina ribstonensis* Zone corresponds to the lower beds of the Milk River /Lea Park Formation that carries the *Haplophragmoides kirki* microfauna (Figure 7; North and Caldwell, 1964; Caldwell et al., 1978).

In the southern part of the study area, the cored part of Milk River Formation at 16-4-22-15W4 carries an almost entirely agglutinated assemblage with only a single

specimen of the calcareous species *Gavelinella henbesti* found in the lowermost portion. The principal components of the zone in southern Alberta are *Trochammina ribstonensis*, *Ammobaculites* sp. 1, *Haplophragmoides* sp. 2, *Haplophragmoides collyra*, *Trochammina ribstonensis*, *Ammobaculites fragmentarius*, *Haplophragmoides rota*, *Pleurostomella watersi*, *Trochammina wetteri*, *Reophax* sp.1, and *Gavelinella henbesti*. As shown in the foraminiferal distribution chart (Figure 18), all of these components range into older zones.

Based on the molluscan zonal scheme, the relative age of the *Trochammina ribstonensis* Zone may be diachronous, becoming younger from west to east in western Canada (Caldwell et al., 1978). In the northern Foothills, the *Trochammina ribstonensis* Zone ranges in age from middle Santonian to Early Campanian (Wall, 1967a). Across the southern Interior Plains of Canada, the age of the *Trochammina ribstonensis* Zone is restricted to the Early Campanian (Wall, 1967a; Caldwell et al., 1978). In the Manitoba Escarpment, however, McNeil and Caldwell (1981) indicated that the *Trochammina ribstonensis* Zone straddles the boundary between the early and late Campanian (Figure 7).

DISCUSSION

Paleoenvironments

The study and interpretation of paleoenvironments of the Cretaceous Colorado Group in western Canada has led to the establishment of assorted models reflecting the basin complexity. The large sedimentary wedge tapering eastward translates to lateral and vertical variability in depositional and environmental conditions. Broad paleoenvironmental and depositional changes through time resulted in different formations of the Colorado Group, whereas lateral changes are linked to intraformational facies and biofacies changes across the basin (Schröder-Adams et al, 1996). Four structural sedimentary zones characterize the foreland basin, each of which is influenced by a variable but different sedimentation rate and sediment source (Kauffman, 1977, 1984; McNeil, 1984; Schröder-Adams et al, 1996). Maximum sedimentation and subsidence rates in relatively shallow water characterize the western foredeep; high subsidence and sedimentation rates in deep water occur in the west-median trough, moderate subsidence and sedimentation rates in shallower water occur in the hinge zone and the lowest of both occurs in the eastern platform (Kauffman, 1984; Leckie and Smith, 1992; Schröder-Adams et al, 1996)

Integration of sedimentological, geochemical and micropaleontological data reveals a complex paleoenvironmental history during the deposition of the Cretaceous Colorado Group in the WIS of Canada. Schröder-Adams et al. (1996) addressed the vertical and lateral paleoenvironmental changes of the lower Colorado Group from the Late Albian Westgate Formation to the Middle Turonian Second White Specks Formation. Nielsen (2002) studied the paleoenvironments of the entire Upper Colorado

Group, from the Turonian Second White Specks Formation to Santonian First White Specks Member of the Niobrara Formation, and produced several paleogeographic maps representing seaway paleogeography at various time intervals (Figure 20).

This study adds micropaleontological data including occurrences of foraminifera, nannofossils, and other biogenic components such as fish remains and mollusks to paleoenvironmental interpretations. Planktic and benthic (agglutinated and calcareous) foraminifera are present in this study. Planktic foraminifera are a useful tool to interpret the nature of the upper portion of the water column such as productivity, stratification, temperature and salinity (Leckie et al., 1998). Benthic foraminifera, on the other hand, have been used to provide useful information about benthic oxygenation, salinity and water depth (Culver, 1988; Murray, 1991). Nannofossils are phytoplankton and add to interpretations of the nature of the uppermost water column.

Westgate Formation

Following the sea-level lowstand, which resulted in the deposition of the Viking Formation and equivalents, a major transgressive phase marking the base of the latest Albian Westgate Formation initiated the Mowry Sea (Figure 21). This transgression represents the beginning of the eustatic Greenhorn marine cycle (Figure 21; Caldwell, 1984; Schröder-Adams et al, 1996; Stritch and Schröder-Adams, 1999). The Mowry Sea carried the cool-temperate Boreal water mass as far south as Colorado in the U.S. portion of the basin (Wall, 1967 b; Caldwell et al., 1993).

The Westgate Formation at 10-22-47-3W4 consists of two major fining-upward cycles indicating sea-level fluctuations or changes in sediment source and/or supply (Figure 10). Agglutinated foraminifera respond in test grain size to their substrate.

Species with relatively large and coarse-grained tests are associated with sandstone beds at the bottom of both cycles, changing to relatively small and fine-grained tests upwards. The intensity of bioturbation throughout the interval and presence of horizontal trace fossils such as *Terebellina* indicates well-oxygenated bottom-waters (Figure 21). The high abundance and richness of the exclusively agglutinated assemblage present within the interval is another indicator of well-oxygenated benthic environment (Figures 11 and 21). Most of the agglutinated species found within the interval are of Boreal origin. The microfauna represents the *Miliammina manitobensis* Zone, which relates to a shallow, cool and brackish marine environment (Wall, 1967b; Stelck and Leckie, 1990; Schröder-Adams et al, 1996). Freshwater influx bringing terrestrial sediments is indicated by dominantly type III organic matter that is diluted by detritus to less than 2 wt% (Figures 9 and 11).

By comparison with modern analogues (Murray, 1991) the zone microfauna represents three different benthic foraminiferal feeding strategies. Infaunal species dominate a large part of the fauna (26 out of 38 taxa), 11 epifaunal species and only one erect species. The dominance of infaunal taxa indicates the presence of abundant food without complete oxygen depletion in pore waters (Corliss and Emerson, 1990; Leckie et al., 1998). Infaunal species such as *Miliammina manitobensis*, *Ammobaculites fragmentarius*, *Ammobaculites tyrrelli* and *Ammobaculites petilus* are the dominant species throughout the formation. Epifaunal species include *Saccamina alexanderi*, *Saccamina lathrami*, *Haplophragmoides hendersonense*, *Haplophragmoides collyra* and *Trochammina alcanensis*. Most of these taxa are considered to be fairly tolerant to brackish conditions (Chamney, 1976).

Peak richness and abundance of agglutinated foraminifera at 1556 ft indicate deepening of the water column and a tendency to more normal marine conditions. This coincides with the increase in abundance of the only erect species *Bathysiphon brosgiei* towards the top of the upper fining-upward cycle (Figure 12). This agglutinated species prefers deeper and quieter water environments (Chamney, 1976)

Fish Scales Formation

At 10-22-47-3W4, a thin bioclastic coarse-grained sandstone bed rich in bioclastic debris of fish and other vertebrate remains forms a sharp lithological contact with the underlying Westgate Formation (Figure 10). Over a broad area of the WCSB, the interval is associated with a basal bioclastic conglomerate overlain by black anoxic shale barren of foraminifera (Caldwell et al., 1978; Bloch et al., 1993; Schröder-Adams et al, 1996; this study). In the Peace River area, however, Stelck et al., (1958) described the *Textularia alcesensis* microfauna of latest Late Albian to Early Cenomanian time straddling the Fish Scales marker bed (Caldwell et al., 1978; Schröder-Adams et al, 1996). Work on the Fish Scales Formation and Barons Sandstone in outcrops along the Rocky Mountain Foothills has clearly showed that the bioclastic layer indicates a marine ravinement surface caused by transgression after sea-level lowstand (Figure 21; Leckie et al., 2000). In the Plains of Alberta it represents an unconformable boundary. Where the *Textularia alcesensis* Zone is preserved, the boundary might be more conformable.

The Fish Scales Formation is interpreted as a condensed section (Figure 10; Leckie et al., 1992; Leckie and Smith, 1992; Schröder-Adams et al, 1996), its base being associated with the Albian/Cenomanian boundary (Figure 21, Singh, 1983).

Figure 20. Western Interior Seaway maps during: A- Highstand Second White Specks Formation, B- Upper Carlile Formation, C- Verger Member of the Niobrara Formation and D- Highstand First White Specks Member of the Niobrara Formation (modified after Nielsen, 2002). For sedimentological legend see figure 8).

Figure 20

This interval may coincide with an unconformity associated with seafloor spreading in the Amerasia Basin in Arctic Canada (Dixon, 1993) and an episode of kimberlite emplacement (103- 94 Ma) in central Saskatchewan (Heaman et al., 2003).

The absence of foraminifera and sparse to nonexistent bioturbation in the Fish Scales Formation over a broad area of the Plains indicate widespread inhospitable conditions for benthic organisms. Bottom-water anoxia related to density stratification in the water column as result of two different watermasses was discussed by Bloch et al. (1993) and Schröder-Adams et al. (1996). However, the absence of Tethyan derived nanofossils and some tolerant planktic foraminifera in the northern region of the seaway do not support the entrance of the Tethyan waters hypothesis (Schröder-Adams et al, 1996). Climatic change might have caused an increase of runoff and periods of heavy precipitation introduced low density, brackish surface water masses resulting in density stratification, which in turn resulted in severe oxygen depletion (Figure 21; Cadrin, 1992; Schröder-Adams et al, 1996).

In anoxic bottom-water conditions, anaerobic organisms take over the degradation of organic matter, which results in release of more nutrients from sediments in the form of increasing nitrogen and phosphorus concentrations in the water column, supporting algal blooms (Paerl, 1988). Schröder-Adams et al. (1996) indicated that the Fish Scales Formation is rich in algal cysts. Oxygen depletion also causes the production of toxic compounds such as hydrogen sulfide and ammonia gas, which can be harmful to fish and benthic organisms (Paerl, 1988). The basin wide disappearance of benthic foraminifera at the end of the Albian indicates a profound paleoecological change in the WIS.

Belle Fourche Formation

The contact between the Belle Fourche and the underlying Fish Scales Formation is transitional and discerned by an increase in bioturbation; change in organic matter type from Type II to dominantly Type III and the presence of *Inoceramus* (Figure 9; Bloch et al., 1993; Schröder-Adams et al., 1996). The WIS was much influenced by the cold and low-salinity waters of the Boreal Sea at the time of the Belle Fourche Formation deposition (Eicher and Diner, 1985; Cadrin, 1992; Caldwell et al., 1978, 1993; Schröder-Adams et al., 1996). However, the presence of a few species of agglutinated foraminifera and increase in bioturbation within the Belle Fourche Formation indicates only a slight improvement in the benthic environment (Schröder-Adams et al., 1996). Unstable environmental conditions are reflected in abrupt fluctuations in the total number of foraminiferal species (McNeil and Caldwell, 1981; Schröder-Adams et al., 1996). During the middle Cenomanian the progradation of the extensive Dunvegan Delta associated with a sea-level fall may have affected circulation patterns within the WIS adding to stagnant basin conditions for the more southern regions (Schröder-Adams et al., 1996).

The Belle Fourche Formation at 10-22-47-3W4 differs from other cores in being entirely barren of foraminifera, which indicates unfavorable environments for agglutinated foraminifera at this location (Figure 21). However, the presence of bioturbation throughout much of the interval indicates that other organisms were able to colonize the seafloor (Figure 10). Foraminifera might have been fragile and therefore not preserved due to taphonomic processes. Near the top of the formation absence of bioturbation and abundance of fish scales indicates bottom-water anoxia similar to that of the underlying Fish Scales Formation (Figure 10). This coincides with a sudden decrease in HI values and slight increase in OI values, which may indicate fresh-water influx that

caused a stratified water column and bottom-water anoxia (Figure 10). TOC values in the Belle Fourche Formation are relatively uniform ranging from 1.1 to 2.7 (Figure 9). At the top of the formation a sudden increase in TOC values to 6.6 coincides with a rippled, minor coarsening-upward cycle with wisps and lenticular beds of very fine, slightly calcareous sandstone with mud drapes (Figures 9 and 10). The mud drapes indicate deposition in a shallow marine environment with tidal influence but little wave influence (Dalrymple, 1992). The mud is most likely deposited in the form of fecal pellets rather than individual clay flakes (Dalrymple, 1992).

The presence of nannofossils and planktic foraminifera in the uppermost Belle Fourche Formation in Southern Alberta at 11-12-6-16W4 and 11-36-22-1W2 (Schröder-Adams et al., 1996) indicates entrance of Tethyan-sourced waters to this part of the basin. The lack of planktic species further north indicates that paleoecological conditions differed along a north/south transect. The development of fully marine conditions took place diachronously within the basin. In the Cold Lake area north of township 45 in Alberta similar restricted marine conditions are observed (Tu, 2004).

Second White Specks Formation

During the early to middle Turonian, the interior seaway had reached maximum width related to the peak transgression of the Greenhorn Cycle (Figure 20a; Kauffman, 1977, 1984; Haq et al., 1988; Kauffman and Caldwell, 1993). As a consequence of rising sea level, the warm Tethyan waters of normal salinity spread widely into the southern Interior Plains of Canada (Figure 20a; North and Caldwell, 1975a, b; Caldwell et al., 1978; Kauffman, 1984; Eicher and Diner, 1985; Schröder-Adams et al., 1996). Dominantly calcareous shale of the Second White Specks Formation was deposited in the

northern regions (including the study area), whereas chalky shales were found in the south and southeast regions (Kauffman, 1984). In Canada, highest planktic and nannofossils abundances and diversities are found on the eastern platform (McNeil and Caldwell, 1981; Schröder-Adams et al, 2001), where clastic input is reduced. Ocean circulation models also suggest that during the Greenhorn transgression the Tethyan water mass moved northward along the eastern side of the seaway spilling slowly westwards and creating a diachronous appearance of Tethyan indicators (Eicher and Diner, 1985; Caldwell et al, 1993; Schröder-Adams et al, 1996, 2001).

At 10-22-47-3W4 a bioclastic conglomerate layer marks the contact between the Second White Specks and Belle Fourche formations (Figure 10). Bloch et al. (1993) indicated that over much of Alberta, a bentonite bed and concretionary layer are commonly associated with the bioclastic conglomeratic bed at the base of the Second White Specks Formation. At this location, the bentonite marker bed is not present, but was possibly not preserved. The basal conglomeratic bed indicates a marine erosion surface associated with the early transgressive phase of the Greenhorn cycle (Figure 21). A concretionary layer occurs at the top of the formation (Figure 10). The interval is characterized by high TOC values (up to 9.19 wt%) of dominantly Type II organic matter (Figure 9). However, a significant decrease in TOC and HI values coincides with the calcite concretion bed at the top of the formation, which may indicate a short-lived break in stratification bringing oxygen to the seafloor enhancing organic matter degradation. On the Bainbridge River in the Pasquia Hills, Manitoba Escarpment, a significant decrease in the TOC values also coincides with the Marco Calcarene marker bed at the top of the equivalent Favel Formation (Schröder-Adams et al., 2001).

Figure 21. Interpretation of paleoenvironmental changes throughout the studied interval of the Colorado Group from the Late Albian Westgate Formation to the Santonian First White Specks Member of the Niobrara Formation in central and southeastern Alberta and foraminiferal assemblage response to relative sea-level fluctuations and paleoenvironmental changes.

Colorado Group paleoenvironments: Central-Southeastern and Southeastern Alberta

Figure 21

The non-bioturbated, calcareous, black, fissile, finely laminated shale of the Second White Specks Formation contains mixed foraminiferal assemblages of rare benthic and abundant planktic foraminifera and nannofossils (Figure 12). The presence of planktic foraminifera and nannofossils indicates the influence of the Tethyan derived warm, saline water masses. This transition is gradual, indicated by the mixed fauna at the base (Figure 10). The epifaunal genus *Trochammina* and the infaunal taxon *Uvigerammina manitobensis* and only a single specimen of the infaunal calcareous species *Neobulimina albertensis* represent benthic foraminifera. This assemblage is considered to be an equivalent to the *Clavhedbergella simplex* Subzone of late Cenomanian to Early Turonian time (Bloch et al., 1993; Schröder-Adams et al, 1996).

The low benthic species richness and abundance and presence of the calcareous benthic species *Neobulimina albertensis* are an indication of low oxygen conditions. As this mixed assemblage dies out *Heterohelix globulosa* and *Hedbergella loetterlei* dominate the assemblage, both species regarded as the Epicontinental Sea Fauna by Leckie (1987), which tolerates eutrophic environments, lower salinities and temperatures. Caldwell et al. (1993) indicated that the dominance of the surface-dwelling *Heterohelix* might be linked to salinity reduction in the upper water column. In contrast, Leckie et al., (1991, 1998) related *Heterohelix* dominance to expansion or incursion of an oxygen minimum zone into the seaway.

The first appearance of planktic foraminifera coincides with the first appearance of nannofossils at 1442 ft (Figures 9 and 10). Whereas foraminifera appear with ecologically tolerant, shallow-dwelling species such as *Heterohelix globulosa* and *Hedbergella loetterlei*, nannofossils, on the other hand, are represented by a high species

richness and abundance (Figure 9). Similar observations have been recorded in the stratigraphic equivalent lower Favel Formation in the Pasquia Hills in the Manitoba Escarpment (Schröder-Adams et al, 2001). In Manitoba and Saskatchewan, species of the widespread planktic genera *Heterohelix* and *Hedbergella* first appear in, and increase in number throughout, the upper part of Belle Fourche Member of the Ashville Formation (North and Caldwell, 1975a, b; McNeil and Caldwell, 1981) signaling a slow establishment of Tethyan water masses in the Canadian portion of the WIS. Where a bioclastic conglomerate is found at the base of the Second White Specks Formation, this intermediate zone might be missing due to erosion.

Towards the top of the formation, planktic foraminifera became more diverse and the number of specimens per species increased significantly (Figure 9). In contrast, nannofossil abundance and richness decreased upwards (Figure 9). Thunell and Sautter (1992) suggested that during peaks of primary productivity nannofossil populations decline whereas the proportion of foraminifera in the sediment increases. Watkins (1989) found that nannofossils assemblages showed a reverse relationship with productivity. Therefore, an enhanced productivity at this time interval might be the cause of the nannofossil abundance and richness decrease and planktic foraminifera increase.

The upper section of the Second White Specks Formation is characterized by thin rippled nannofossil-bearing sand laminations that become coarser upwards (Figure 10). These are inferred to be the result of bottom-flowing, unidirectional currents in the seaway concentrating the nannofossils (Schröder-Adams et al., 1996). The foraminiferal assemblage of the upper section is entirely of planktic nature (Figure 12). The subzonal microfauna is indicative of open-marine conditions. Species of *Hedbergella* and

Whiteinella belong to trochospiral morphotypes, which probably lived in the uppermost water column close to the surface where nutrients are concentrated (Leckie, 1987; Leckie et al., 1998). These taxa represent the “Shallow Water Fauna” (Leckie et al., 1998).

Complete absence of benthic foraminifera in the upper section suggests inhospitable bottom conditions. However, *Inoceramus* prisms in the sand-sized fraction are abundant throughout most of the Second White Specks Formation (Figure 9). These prisms belong to several bivalve species primarily of the genus *Inoceramus* (Schröder-Adams et al., 1996). These epifaunal suspension feeders lived above the sediment-water interface without burrowing activity (Hattin, 1982). The abundance of *Inoceramus* throughout most of the Second White Specks Formation is evidence of their ability to survive oxygen depleted benthic environments (Kauffman, 1988; Sageman, 1989).

Carlile Formation

During the regressive phase of the Greenhorn cycle a widespread lithological and paleontological change occurred in the interior seaway reflected in the Carlile Formation or Morden Shale (Schröder-Adams et al., 2001; Nielsen, 2002; Nielsen et al., 2003; this study). In southwestern Alberta, significant evidence of the regressive phase of the Greenhorn cycle is found in the Jumping Pound sandstone above the Second White Specks Formation (Figure 2; Nielsen, 2002).

Paleoecological change at the end of the Second White Specks Formation is reflected in the disappearance of planktic foraminifera and nannofossils, and a decrease in TOC values in southeastern Saskatchewan. However, in areas distant to the Sweetgrass Arch, as also observed in the Morden Formation in the Manitoba Escarpment, TOC values remain relatively high throughout the regressive phase of the Greenhorn Cycle

(see Figure 3 in Schröder-Adams et al., 2001). This indicates the persistence of bottom water anoxia in these areas. The topographic high (forebulge) present in Central Saskatchewan (see Figure 4-3 in Nielsen, 2002) may have caused stratification break down, resulting in degradation of organic matter. A sea-level fall created a wide area of hinterland and possible higher fresh water input, bringing suspended clay from turbid river plumes into the surface water layer, creating unfavorable conditions for planktic foraminifera and most nannofossils (Nielsen, 2002).

In the Southern Foothills, Wall, (1967a) suggested that a sea-level fall after the Greenhorn maximum transgression created a near-shore, shallow-water, somewhat turbid environment, linked with deposition of the Haven and Opabin members of the Blackstone Formation, and brackish, probably lagoonal type, environments linked with deposition of the Cardium Formation. Nielsen (2002) indicated that the Haven and Opabin members of the Blackstone Formation are time-equivalent to the Lower Carlile Formation in southern Alberta and southeastern Saskatchewan. At 10-22-47-3W4, the lower Carlile Formation was deposited in a deeper marine environment in the central part of a narrow seaway, reflected in the formation lithology and geochemistry (Figure 9 and 20b).

The upper unit of the Carlile Formation at 10-22-47-3W4 is characterized by a sharp decrease in TOC and HI values and disappearance of benthic foraminifera, which indicates fresh-water input, and formation of unfavorable conditions for benthic foraminifera (Figure 9). However, the presence of bioturbation and abundant *Inoceramus* prisms indicates some availability of oxygen (Figure 21). In contrast, the upper Carlile Formation at 13-20-17-7W4 carries a mixed foraminiferal assemblage of few agglutinated, abundant benthic calcareous and few planktic species (Figures 12 and 15).

The presence of planktic and calcareous benthic foraminifera in the upper Carlile formation in southern Alberta (Nielsen, 2002; this study) and the Morden Shale in Manitoba Escarpment (McNeil and Caldwell, 1981) gives evidence of the presence of Tethyan waters despite sea-level fall at the end of the Greenhorn cycle (Figure 20b). The upper Carlile Formation in northwestern and northern parts of the Canadian basin lack planktic and calcareous benthic foraminifera, indicating a dominant influence of Boreal waters.

At 13-20-17-7W4, agglutinated epifaunal species of *Trochammina* and *Haplophragmoides*, tolerant towards brackish conditions, dominate the lower shaly and upper sandy parts of the upper Carlile Formation. The dominance of epifaunal fauna and absence of infaunal taxa is an indication of oxygen depletion in pore waters due to excess terrestrial organic matter (see Figure 4 in Leckie et al., 1998), which is reflected in low TOC and HI values (Figures 12 and 14). Calcareous benthic and planktic foraminifera occur in the middle portion of the formation indicating deepening of the water column and entrance of southern warm waters (Figures 12 and 15). The calcareous benthic infaunal taxon *Neobulimina albertensis* dominates the middle portion of the interval (Appendix B). The change in species dominance from agglutinated epifaunal in the lower shaly part to calcareous benthic infaunal taxa indicates a significant environmental shift. This was also reflected in lithology and organic matter type changes (Figure 13). Moderate to well-oxygenated bottom-water conditions at the top of the Carlile Formation are reflected in the exclusively agglutinated foraminifera assemblage of mixed epifaunal and infaunal species, degree of bioturbation and relatively low TOC values (Figures 12, 13 and 15).

A paleoenvironmental map at the late Turonian age indicates a narrow seaway with deposition of the marginal marine Cardium Formation in the west of Alberta, the Frontier sandstone in southwestern Montana and northern Wyoming and the Bowdoin sandstone in southeastern Alberta (Figure 20b; Nielsen, 2002). A period of erosion removing the Carlile Formation and lower part of the Niobrara Formation in northern and central Saskatchewan is marked by a thin layer of the Second White Specks Formation directly overlain by the First White Specks Member of the Niobrara Formation (Bloch et al., 1993; Schröder-Adams et al., 1996). At 10-22-47-3W4, in Manitoba and east of central Saskatchewan, the upper boundary of the Carlile Formation (Morden Shale) shows no sign of erosion.

In the Manitoba Escarpment, the Morden Shale contains the *Pseudoclavulina* sp.-*Trochammina* sp. Zone microfauna, which consists of a mixed foraminiferal assemblage of benthic and planktic species (McNeil and Caldwell, 1981). The planktic species either represent remaining species of the late Greenhorn cycle or are brought into the basin by the initial transgressive phase of the Niobrara cycle. In either case more or less continuous influence of Tethyan waters in the eastern part of the basin is linked to planktic occurrences. North and Caldwell (1975) described a few planktic and calcareous-walled benthic species from a small part of their Zone VI associated with the Morden Member of the Vermilion River Formation in eastern Saskatchewan and Manitoba. In this study area, the *Pseudoclavulina* sp.-*Trochammina* sp. microfauna is represented in the Carlile Formation and the lowermost part of the Verger Member of the Niobrara Formation, which was indicated by the presence of the marker species *Pseudoclavulina* sp. along with few planktic and agglutinated specimens in the

lowermost portion of the Verger Member of the Niobrara Formation at 10-22-47-3W4 (Figure 12 and 15).

Niobrara Formation

The Coniacian/Santonian Niobrara transgression left a more heterogeneous mudstone package when compared with the Greenhorn transgression where faunal assemblages change over in vertical succession, but also show major lateral biofacies changes (Nielsen, 2002). The Niobrara transgression encompasses the Verger, Medicine Hat and First With Specks members of the Niobrara Formation (Nielsen et al., 2003).

Verger Member

A similar foraminiferal species composition is found in the lowermost portion of the Verger Member at 10-22-47-3W4 and 13-20-17-7W4, which could be considered a useful bio-event for correlations. The presence of the mixed epifaunal and infaunal benthic assemblage, bioturbation and low TOC values associated with the uppermost portion of the *Pseudoclavulina* sp.-*Trochammina* sp. Zone indicate short-lived oxygenated benthic environment. At 13-20-17-7W4, foraminiferal assemblages disappear just above this bio-event, due to a swarm of bentonites resulting from ashfalls that may have created unfavorable environments for both benthic and planktic foraminifera (Figure 15). However, at 10-22-47-3W4, no bentonites were observed, but planktic and calcareous benthic foraminifera disappear just above the biomarker layer allowing few poorly preserved agglutinated foraminifera (Figure 12). These form the *Marssonella oxycona* Subzone of the *Bullopore laevis* Zone, which can be traced in the three studied cores. The subzone exclusively agglutinated foraminiferal assemblage of high abundance and richness represents different feeding strategies indicating a well-oxygenated benthic

environment (Figure 21). The degree of bioturbation and relatively low TOC values of type II organic matter also indicates the presence of oxygenated bottom waters. Low HI values and coarser sediments of siltstone and very fine sandstone indicate periodic fresh-water influx, which may have created brackish surface water prohibiting planktic foraminifera to thrive.

A maximum flooding surface is characterized by an increase in foraminiferal abundance and richness at 560 m (Figure 17). These distinguish the base of the *Haplophragmoides bonanzaense* Subzone of the *Bullopore laevis* Zone, which represents the highstand system tract of sequence F8, defined by Nielsen et al., (2003). A well-oxygenated benthic environment is indicated by the presence of abundant and diverse benthic foraminifera that represent different feeding strategies, the degree of bioturbation as well as low TOC values (Figure 16 and 18). The dominance of the epifaunal-shallow infaunal taxa “*Gavelinella*” indicates normal marine waters, higher oxygen levels and pulses of organic matter (West et al., 1998). The periodic influence of Tethyan warm waters is indicated by sporadic appearances of planktic foraminifera (Figure 16). Volcanic activity indicated by several bentonites may have resulted in unfavorable environmental conditions for planktic foraminifera (Figure 16). The upper part of the highstand is truncated by the overlying sequence boundary, reflected in a lag of well-rounded pebbles (Figure 17). This pebble-layer is interpreted as a transgressive lag, a product of reworking of the underlying, eroded lowstand deposit. It separates the shaly Verger and sandy Medicine Hat members (Figure 17; Nielsen, 2002). Preserved lowstand deposits are found to be a part of the Bad Heart Formation to the northwest of the study area (Nielsen, 2002).

Medicine Hat Member

The lower marine shales of the Medicine Hat Member above the transgressive lag are deposited as result of continuing sea level rise following the deposition of the Verger Member (Nielsen et al., 2003) and lowstand deposits of the Bad Heart Formation (Plint, 1991; Donaldson et al., 1998). The sandstones of this member were deposited in lowstand, highstand and transgressive system tracts (Nielsen et al., 2003). The source of these sandstones is either from coastal erosion or deltaic input (Nielsen, 2002). Paleoenvironments during the Medicine Hat Member are interpreted as a sandy offshore and shelf environment (Nielsen, 2002). The Medicine Hat sandstones are locally deposited on the flanks of the Sweetgrass Arch (Hankel et al., 1989; Glass, 1990; Nielsen et al., 2003).

High TOC and HI values and the presence of planktic foraminifera in the lower shale indicate deposition under fully marine conditions with influence of the Tethyan waters (Figure 16). The dominant calcareous benthic species is the infaunal and subzonal marker species *Neobulimina canadensis* (Appendix B). Change in dominance from the epifaunal - shallow infaunal taxon "*Gavelinella*", associated with the highstand system tract (upper section of the Verger Member) to infaunal taxa of *Neobulimina* associated with the transgressive system tract (lower Medicine Hat shale) indicates a major ecological shift. Sea-level rise brought warm, oxygen-poor water masses of Tethyan origin, allowing low-oxygen infaunal taxa of *Neobulimina* to thrive (Leckie et al., 1998) (Appendix B). Low oxygen levels are indicated by a significant increase in TOC values (up to 2.5 wt%).

At 16-4-22-15W4, the “D”, “C” and “A” sandstones are characterized by agglutinated assemblages. The fauna of the “D” sandstone is most diverse whereas “C” and “A” are dominated by the epifaunal species of *Trochammina* and *Haplophragmoides* that are considered to be fairly tolerant to brackish water conditions (Chamney, 1976) and indicate stress (Boltovskoy et al., 1991). The intermittent shale-rich intervals are marked by increasing bioturbation and suggest basin deepening and tendency toward normal marine conditions (Figure 17). These are marked by short appearances of benthic calcareous species. The presence of *Gavelinella* and bioturbation suggests oxygenated bottom conditions (West et al., 1998). However, organic matter seems to preserve well in these intervals (Figure 16) suggesting a higher organic matter influx than organic matter degradation taking place in the upper sediments. The Medicine Hat Member demonstrates how system tracts related to relative sea-level are linked to foraminiferal compositions and morphogroups.

First White Specks Member

In southern Alberta and southeastern Saskatchewan, the Sweetgrass Arch influenced the depositional environment of the Medicine Hat and First White Specks Member (Arnott et al., 1995; Hankel et al., 1989; Schröder-Adams et al., 1997, 1998; Nielsen et al., 2003). Micropaleontology indicates that the water-depth probably never got as deep as in the Second White Specks Formation and as in other areas distant from the arch during First White Specks time (Figure 20d; Schröder-Adams et al., 1997).

The First White Specks Member at 16-4-22-15W4 contains a mixed foraminiferal assemblage of benthic calcareous and agglutinated and planktic species, each of which dominates a part of the interval (Figure 16). Compositional changes may

indicate three different short-lived depositional and paleoecological environments as a result of sea-level fluctuations that may be influenced by movement of the Sweetgrass Arch. In the lower portion of the interval below the two conglomeratic layers, an agglutinated fauna dominates and is represented by few epifaunal and infaunal species. This faunal composition may indicate a marine environment that periodically received high influx of fresh-water. As sea level rises as the result of renewed transgression (leaving two transgressive gravel lags, Figure 16) (Nielsen et al., 2003), warm, low-oxygenated southern waters entered this part of the basin, allowing planktic species to become established for a brief period. Benthic environments are anoxic as a result of water column stratification. Presence of the planispiral morphotype *Globigerinelloides* indicates the deepest marine conditions or maximum flooding during the Niobrara cycle where the Sweetgrass Arch had no or limited affect on the depositional environment (Figures 15 and 21). The TOC and HI values indicate variability of the organic matter sources in this unit (Figures 16 and 18).

The top unit of the First White Specks Member (Sequence 13 as defined by Nielsen, 2002) is dominated by shale. Basin shallowing, however, is indicated by the loss of planktic foraminifera and gradually decreasing TOC and HI values (Figure 16). Calcareous and benthic foraminifera are present again and represent epifaunal and infaunal feeding strategies, which indicate moderate to well-oxygenated benthic environments. As oxygen-poor Tethyan-derived intermediate waters retreated, *Gavelinella* occurred briefly (Figure 16). Towards the top of the formation the benthic environment was under increasing influence of cool, moderate to well oxygenated Boreal waters allowing agglutinated foraminifera to dominate the uppermost portion of the

interval (Figure 16). This latest stage of the Niobrara regressive cycle deposited the overlying Milk River/Lea Park Formation associated with the *Trochammina ribstonensis* Zone (Figures 15, 17 and 18).

Major Paleoecological Controls On Foraminiferal Assemblages

The previous discussion has described the biotic and environmental changes associated with sea-level fluctuations through Albian to Santonian time in southeastern and central Alberta (Figure 21). Understanding the major paleoecological controls on foraminiferal assemblages in this part of the basin would provide improved evaluation of paleoenvironmental changes that have been documented in western Canada (e.g. Wall, 1967a; McNeil and Caldwell, 1981; Schröder-Adams et al, 1996; Nielsen, 2002). The distribution of foraminiferal assemblages in the basin is controlled by changes in the environmental parameters such as water depth, oxygen concentrations, temperatures, salinity and food supply, substrate, energy conditions and others. Planktic and benthic foraminifera are present in this study and have proven to be reliable proxies to interpret paleoenvironments. Morphogroups enhance paleoenvironmental interpretation by looking at foraminiferal life positions and feeding strategies.

Some agglutinated species such as *Haplophragmoides howardense* and *Trochammina ribstonensis* do not respond to paleoecological changes and therefore show long biostratigraphic ranges. Calcareous benthic foraminifera tend to be most sensitive to ecological change ultimately related to sea-level changes.

Occurrence of planktic foraminifera in the WIS are associated with warm, Tethyan derived waters. An exclusively planktic foraminiferal assemblage is marking the peak transgression of the Greenhorn and Niobrara cycles. Species richness and

abundances in the WIS vary significantly based on factors such as temperature differences, clastic input, or freshwater influx (e.g. Eicher, 1969; Eicher and Worstell, 1970; Eicher and Diner, 1985; McNeil and Caldwell, 1981; this study). Keeled taxa are the most stenotopic planktic foraminifera (Leckie et al., 1998) and are restricted to the southeastern parts of the WIS that was occupied by warm, normal marine waters (Leckie et al., 1998). Peak transgression of the Niobrara sea-level cycle never reached the same fully marine conditions in Southern Alberta when compared with the Greenhorn cycle.

Volcanic activity resulting in ash falls directly affected planktic foraminiferal assemblage as seen in the Verger Member. Basin topography such as the Sweetgrass Arch or forebulge may affect paleoceanographic circulation patterns that in turn influence planktic foraminifera. Significant differences are observed, for example, between assemblages from the Eastern platform region with low sedimentation rates and the arch with increased sedimentation rates. This study shows that careful analysis of even subtle faunal changes, integrated with sedimentological and geochemical data, uncovers the large complexity of the depositional and paleoceanographic history of the WIS.

Conclusion

Foraminiferal assemblages of the late Albian to Santonian Colorado Group were studied from three selected cores in east-central and southeastern Alberta. Relative sea-level fluctuations resulted in paleoenvironmental changes, variable lithologies and changing foraminiferal assemblages. Whereas agglutinated foraminifera dominate the Lower Colorado Group, mixed foraminiferal assemblages of planktic and benthic calcareous and agglutinated taxa distinguish the Upper Colorado Group. Compositional changes in

foraminiferal assemblages allowed a zonation and subzonation that refines the existing foraminiferal zonation from Caldwell et al. (1978). Foraminiferal morphogroups based on life position and feeding habits added interpretations of paleoenvironments. Benthic foraminifera include infaunal and epifaunal morphogroups and planktic foraminifera include biserial, trochospiral and planispiral morphogroups. The following conclusions resulted from this study:

- 1- The Late Albian Westgate Formation is characterized by fining upward sequences containing abundant agglutinated foraminifera of mixed infaunal and epifaunal morphotypes, indicating a well-oxygenated sea floor of the Mowry Sea. Agglutinated foraminiferal assemblage abundance and richness peak at initial stages of deepening towards normal marine waters.
- 2- The Late Albian *Miliammina manitobensis* Zone is well established within the Westgate Formation in the study area. However, finding the principal elements of the three subzones combined in one-assemblage questions the biostratigraphic importance of these subzones in a broad context.
- 3- In the Lower Colorado Group, lack of foraminiferal zones or subzones, totally or partially, is always associated with a bioclastic coarse-grained and/or conglomeratic layer, indicating erosion of the seafloor. Examples are the bases of the Fish Scales and Second White Specks formations, associated with the missing *Textularia alcesensis* Zone and the lower *Clavihedbergella simplex* Subzone of the *Hedbergella loetterlei* Zone respectively.

- 4- A relative sea-level fall at the Albian/Cenomanian boundary caused a severe paleoecological change. Widespread bottom water anoxia at the time of the Fish Scales Formation prohibited benthic assemblage to develop.
- 5- Increase of fresh water and terrestrial sediment influx at the time of the Belle Fourche Formation deposition associated with the progradation of the Dunvegan Delta during Middle to Late Cenomanian time increased sedimentation rates. Reoccurring bioturbation suggests improved benthic conditions, however foraminifera are scarce, possibly due to oxygen depleted intermediate waters entering the basin from the south.
- 6- By the end of the Belle Fourche Formation parts of east Alberta were within tidal influence and marine erosion, followed by rapid transgression depositing the Second White Specks Formation.
- 7- During transgression of warm, marine waters, coupled with the incursion of oxygen-poor intermediate waters and stratification of Tethyan and Boreal waters, is reflected in exclusively planktic assemblages.
- 8- Enhanced organic matter productivity during the Second White Specks Formation may have resulted in high abundances of foraminifera, but reduced numbers of nannofossils.
- 9- The transition from the Greenhorn to the Niobrara cycle is represented by one foraminiferal zone in Eastern Alberta compared to three zones in the Foothills. Paleoecological changes in this central part of the basin remained moderate resulting in long ranging taxa despite the regression at the end of the Greenhorn cycle.

- 10- The dominance of the Epifaunal-shallow infaunal *Gavelinella* taxa is associated with phases of seafloor oxygenation, whereas epifaunal *Neobulimina* dominance is associated with low oxygen periods.
- 11- Periods of frequent ash falls documented in the occurrence of numerous bentonites created inhospitable environmental conditions for foraminiferal assemblages, especially for planktic species.
- 12- The *Bullopore laevis* Zone, spanning the upper Verger to lower Medicine Hat members, is subdivided into three new subzones. These are, in ascending order, the *Marssonella oxycona*, *Haplophragmoides bonanzaense* and *Neobulimina canadensis* subzones. This subdivision will support expansion of the stratigraphic framework of the Upper Colorado Group into other regions.
- 13- The Sweetgrass Arch influenced the depositional and paleoecological environments during Medicine Hat and First White Specks time keeping planktic foraminifera out of the region most of the time. Epicontinental planktic species were favored during Verger time, when the arch had no positive relief. A brief highstand phase during the First White Specks time inundated the arch to a depth of normal marine conditions allowing trochospiral planktic species to move in.

Plates

Plate I

Figure 1. *Miliammina awunensis* Tappan, X 79, Westgate Formation 10-22-47-3W4, (1559 ft), 1a side view, 1b edge view, 1c opposite side view

Figure 2. *Miliammina ischnia* Tappan, X 72. Westgate Formation 10-22-47-3W4, (1571 ft), side view

Figures 3, 6. *Miliammina manitobensis* Wickenden, 3) X 82, 6) X 78, Westgate Formation 10-22-47-3W4, 3a side view and 3b opposite side view, (1544 ft). 3c edge view. 6a side view, 6b opposite side view, (1571 ft)

Figures 4, 5. *Bathysiphon brosgiei* Tappan, 4) X 80, 5) X 75, Westgate Formation 10-22-47-3W4, (1577 ft), side views

Figures 7, 8. *Reophax troyeri* Tappan, 7) X 57, 8) X 52, Westgate Formation 10-22-47-3W4, (1580, 1571 ft), side views

Figures 9, 10, 15. *Ammobaculites fragmentarius* Cushman, 9 and 10) X 60, 15) X 50, Westgate Formation 10-22-47-3W4, (1566, 1577 & 1571 ft), 9a, 10, 15 side views, 9b edge view

Figure 11. *Ammobaculites petilus* Eicher, X 56, Westgate Formation 10-22-47-3W4, (1574 ft), side view

Figures 12, 13. *Psamminopelta browsheri* Tappan, 12) X 75, 13) X 80, Westgate Formation 10-22-47-3W4, (1574, 1547 ft), side and opposite side views

Figure 14. *Textularia gravenori* Tappan, X 79, Westgate Formation 10-22-47-3W4, (1571 ft), side view

Plate I
Miliammina manitobensis Zone

Plate II

Figures 1-2. *Gravellina chamneyi* Stelck, 1) X 73, 2) X 72, Westgate Formation 10-22-47-3W4, (1541 and 1577 ft), side views

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Figure 5. *Gaudryina canadensis* Cushman, X 73, Westgate Formation 10-22-47-3W4, (1574 ft), side view

Figure 6. *Haplophragmoides rota* Nauss, X 58, Westgate Formation 10-22-47-3W4, (1544 ft), 6a side view, 6b opposite side view, 6c peripheral view

Figure 7. *Haplophragmium swareni* Stelck and Hedinger, X 97, Westgate Formation 10-22-47-3W4, (1568 ft), 7a and 7b side views

Figure 8. *Haplophragmoides collyra* Nauss, X 63, Westgate Formation 10-22-47-3W4, (1556 ft), 8a side view, 8b opposite side view

Figure 9. *Haplophragmoides postis goodrichi* Sutherland and Stelck, X 78, Westgate Formation 10-22-47-3W4, (1559 ft), 9a and 9b side views.

Figure 10. *Reophax incompta* Loeblich and Tappan, X 37, Westgate Formation 10-22-47-3W4, (1577 ft), side view

Figures 11-13. *Saccamina alexanderi* Loeblich and Tappan, X 71, Westgate Formation 10-22-47-3W4, (1556 – 1577 ft), side views

Figures 14-16. *Uvigerinamina manitobensis* Wickenden, 14) X 78, 15) X 62, 16) X 76, Westgate Formation 10-22-47-3W4, (1571- 1559 ft), side views

Figures 17. *Verneuilioides perplexus* Loeblich, X 59, Westgate Formation 10-22-47-3W4, (1974 ft), side view

Plate II
Miliammina manitobensis Zone

Plate III

Figure 1. *Hedbergella amabilis* Loeblich and Tappan, X 80, Second White Specks Formation 10-22-47-3W4, (1412 ft), 1a spiral view, 1b umbilical view, 1c peripheral view

Figures 2-4. *Heterohelix globulosa* Ehrenberg, 2) X 66, 3) X 70, 4) X 60, Second White Specks Formation 10-22-47-3W4, (1424 ft), 1, 2 side views, 3 apertural view

Figures 5,6. *Hedbergella planispira* Tappan, 5) X 70, 6) X 67, Second White Specks Formation 10-22-47-3W4, (1400.2 ft), 5a, 6b umbilical views, 5b, 6a spiral views

Figures 7, 8. *Hedbergella delrioensis* Carsey, 7) X 67, 8) X 73, Second White Specks Formation 10-22-47-3W4, (1400.2 ft), 7a, 8a spiral views, 7b, 8b umbilical views and 7c apertural view

Figure 9. *Hedbergella portsdownensis* Williams-Mitchell, X 65, Second White Specks Formation 10-22-47-3W4, (1403.9 ft), 9a spiral view; 9b and 8b umbilical views

Figure 10. *Hedbergella loetterlei* Nauss, X 76, Second White Specks Formation 10-22-47-3W4, (1403.9 ft), 10a spiral view, 10b umbilical view, and 10c edge view

Figure 11. *Whiteinella aprica* Loeblich and Tappan, X 75, Second White Specks Formation 10-22-47-3W4, (1400.2 ft), 11a umbilical view, and 11b spiral view

Plate III
Hedbergella loetterlei Zone

Plate IV

Figure 1. *Trochammina rainwateri* Cushman & Applin, X 69, Carlile Formation 10-22-47-3W4, (1373.6 ft), 1a umbilical view, 1b spiral view

Figure 2. *Trochammina* sp.1 Wall, X 65, Carlile Formation 13-20-17-7W4, (553 m), 2a spiral view, 2b peripheral view, 2c umbilical view

Figure 3. *Trochammina rutherfordi* Stelck & Wall, X 94, Carlile Formation 13-20-17-7W4, (553 m), 3a spiral view, 3b umbilical view, 3c peripheral view

Figure 4. *Nodosaria* sp., X 90, Carlile Formation, 13-20-17-7W4, (548 m), side view

Figure 5. *Dorothia smokyensis* Wall, X 80, Verger Member 10-22-47-3W4, (1353 ft)

Figures 6, 13. *Dorothia* cf. *D. smokyensis* Wall, 6) X 79, 13) X 75, Verger Member 10-22-47-3W4, (1353 ft), side views

Figures 7, 8. *Pseudoclavulina* sp. Wall, 7) X 76, 8) X74, Verger Member 10-22-47-3W4, (1353 ft), side views

Figure 9, 10. *Neobulimina albertensis* Stelck & Wall, 9) X 74, 10) X 67, 9, Carlile Formation 13-20-17-7W4 (545 m) and 10 Carlile Formation 10-22-47-3W4, (1357 ft)

Figure 11. *Trochammina* sp.2 Wall, X 24, Carlile Formation 13-20-17-7W4, (553 m)

Figure 12. *Gavelinella* sp., X 72, Verger Member 13-20-17-7W4, (542 m), side view

Figure 14. *Pseudobolivina* sp. North and Caldwell, X 30, Verger Member 10-22-47-3W4, (1353 ft), broken species, side view

Figure 15. *Neobulimina canadensis* Cushman and Wickenden, X 108, Verger Member 10-22-47-3W4, (1357 ft), side view

Figure 16, 17. *Heterohelix globulosa* (Ehrenberg), 16) X 72, 17) X 77, Verger Member 10-22-47-3W4, (1357 ft), side views

Plate IV
Pseudoclavulina sp.-*Trochammina* sp. Zone

Plate V

Figures 1; 10; 17. *Haplophragmoides howardense* Stelck and Wall, 1) X 82, 10) X 73, 17) X 69, Verger Member 10-22-47-3W4, 16-4-22-15W4 & 13-22-17-7W4, (542 m, 568 m & 1342 ft), 1a, 10, 17 side views, 1b edge view

Figure 2. *Saccamina lathrami* Tappan, X 77, Verger Member 10-22-47-3W4, (1347 ft), side view

Figures 3 – 7. *Marssonella oxycona* Reuss, 3) X 72, 4) X 62, 5) X 52, 6) X 68, 7) X 44, Verger Member 16-4-22-15W4 & 10-22-47-3W4, (564 m & 1351ft), 3; 5 & 6 side views, 4 & 7 apertural views

Figures 8; 9. *Trochammina ribstonensis* Wickenden, X 93 – X 83. Verger Member 16-4-22-15W4, (565 m), 8a; 9 spiral views and 8 umbilical view.

Figure 11. *Trochammina rainwateri* Cushman and Applin, X 42, Verger Member 16-4-22-15W4, (563 m), umbilical view.

Figure 12. *Ammobaculites* sp. 1 Wall, X 58, Verger Member 16-4-22-15W4, (561 m), 12a side view, 12b edge view.

Figure 13. *Pleurostomella watersi* Cushman, X 49, Verger Member 16-4-22-15W4, (565 m), side view.

Figures 14; 15. *Pesudobolivina rollaensis* Stelck and Wall, 14) X 49, 15) X 46, Verger Member, 16-4-22-15W4, (563; 565 m), side views

Figure 16. *Spiroplectammina semicomplanata* (Carsey), X 67, Verger Member, 15-4-22-15W4, (564 m), side view.

Figure 18. *Haplophragmoides topagorukensis* Tappan, X 89, Verger Member, 16-4-22-15W4, (563 m), 18a side view, 18b apertural view.

Plate V
Bullopore leavis Zone/*Marssonella oxycona* Subzone

Plate VI

Figure 1. *Spiroplectammina semicomplanata* (Carsey), X 72, Verger Member 16-4-22-15W4, (564 m), side view

Figure 2. *Pesudobolivina rollaensis* Stelck and Wall, X 90, Verger Member 16-4-22-15W4, (563 m), side view

Figure 3. *Gavelinella talaria* Nauss, X 93, Verger Member 16-4-22-15W4, (560 m), 3a side view, 3b opposite side view and 3c apertural view

Figure 4. *Haplophragmoides* sp. 2 Wall, X 67, Verger Member 16-4-22-15W4, (563 m), 4a side view, 4b edge view and 4c opposite side view

Figure 5. *Hedbergella delrioensis* Carsey, X 68, Verger Member 10-22-47-3W4, (1342 ft), 5a umbilical view, 5b apertural view and 5c spiral view.

Figures 6, 8. *Haplophragmoides bonanzaense* Stelck and Wall, X 64 – X 80, Verger Member 16-4-22-15W4, (558, 554 m), 6a side view, 6b apertural view and 8 opposite side view

Figure 7. *Haplophragmoides rota* Nauss, X 67, Verger Member 16-4-22-15W4, (551 m), 7a side view, 7b opposite side view

Figures 9-11. *Bullopore laevis* Sollas, 9) X 41, 10) X 68, 11) X 48, Verger and Medicine Hat members 16-4-22-15W4, (560, 541 m), side views

Figure 12. *Dentalina* sp.1 Wall, X 70, Verger Member 16-4-22-15W4, (560 m)

Figure 13. *Haplophragmoides collyra* (Bullocki), X 59. Verger Member 16-4-22-15W4, (564 m), 13a edge view and 13b side view

Figure 14. *Anomalinoides* sp., X 74, Verger Member 16-4-22-15W4, (560 m), 14a side view, 14b apertural view and 14c opposite side view

Plate VI
Bullopore leavis Zone/*Haplophragmoides bonanzaense* Subzone

Plate VII

Figure 1. *Gavelinella* cf. *turbinate* (Martin), X 94, Medicine Hat Member 16-4-22-15W4, (544 m), 1a side view, 1b opposite side view

Figure 2. *Gavelinella henbesti* (Plummer), X 81, Medicine Hat Member 16-4-22-15W4, (542 m), 2a side view, 2b apertural view and 2c opposite side view

Figure 3. *Neobulimina canadensis* Cushman and Wickenden, X 71, Medicine Hat Member 16-4-22-15W4, (540 m), side view

Figure 4. *Anomalinoides* sp., X 102, Medicine Hat Member 16-4-22-15W4, (542 m), 4a side view, 4b apertural view and 4c opposite side view

Figure 5. *Reophax* sp.1 Wall, X 78, Verger Member 16-4-22-15W4, (567 m), side view

Figure 6. *Ammobaculites* sp., X 49, Verger Member 16-4-22-15W4, (567 m), side view

Figure 7. *Cibicides* sp., X 91, Medicine Hat Member 16-4-22-15W4, (540 m), 7a side view, 7b edge view and 7c opposite side view

Figures 8, 9. *Nodosarella* sp., 8) X 67, 9) X 108, Medicine Hat Member 16-4-22-15W4, (544, 540 m), side views

Figure 10. *Archaeoglobigerina cretacea* (d'Orbigny), X 101, Medicine Hat member 16-4-22-15W4, (544 m), 10a spiral view, 10b apertural view and 10c umbilical view

Figure 11. *Gavelinella kansasensis* (Morrow), X 109, Medicine Hat Member 16-4-22-15W4, (512 m), side view

Plate VII
Bullopore leavis Zone/*Neobulimina canadensis* Subzone

Plate VIII

Figures 1, 2. *Gavelinella henbesti* (Plummer), 1) X 85, 2) X 87, Medicine Hat Member 16-4-22-15W4, (536, 512 m), 1a, 2a side views, 1b, 2b opposite side views

Figures 3, 9. *Globigerinelloides prairiehillensis* (Pessagno), 3) X 297, 9) X 200, First White Specks Member 16-4-22-15W4, (567, 569 m), side views

Figure 4. *Gavelinella sandidgei* (Sliter), X 99, Medicine Hat Member 16-4-22-15W4, (512 m), 4a side view, 4b opposite side view

Figures 5, 6. *Globigerinelloides messinae* (Broennimann), 5) X 358, 6) X 304, First White Specks Member 16-4-22-15W4, (467 m), 6a side view, 5, 6b opposite side views

Figure 7. *Globigerinelloides bentonensis* (Morrow), X 258, First White Specks Member 16-4-22-15W4, (569 m), 7a side view, 7b opposite side view

Figure 8. *Globigerinelloides* sp., X 210, First White Specks Member 16-4-22-15W4, (469 m), 8a side view, 8b opposite side view

Figures 10, 11. *Heterohelix* cf. *reussi* Cushman, 10) X 266, 11) X 273, First White Specks Member 16-4-22-15W4, (461 m); side views

Figures 12-14. *Bolivina* cf. *elkensis* (Nauss), 12) X 253, 13) X 160, 14) X 152, First White Specks Member 16-4-22-15W4, (461 m), 12, 14 side views and 13 apertural view

Plate VIII
Globigerinelloides sp. Zone

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Jour. Paleontology, vol. 21, p. 337, pl. 49, figs. 2a, b, 5

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***Haplophragmoides fraseri* (Wickenden); North and Caldwell, 1975.**

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***Trochammina wetteri* Stelck and Wall, 1955.**

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Tritaxia manitobensis Wickenden, 1932.

***Uvigerinammina manitobensis* (Wickenden); Tappan, 1962.**

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***Verneuilioides bearpawensis* Wickenden, 1932.**

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***Verneuiliinodes fischeri* Tappan, 1957.**

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Verneuulinodes kansasensis Loeblich and Tappan, 1950

Verneuulinoides perplexus Loeblich, 1946.

***Verneuulinoides perplexus* (Loeblich); Stelck and Wall, 1955.**

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Ticinella aprica Loeblich and Tappan, 1961

***Whiteinella aprica* (Loeblich and Tappan); Eicher and Worstell, 1970b.**

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Appendix A

Rock-Eval Data

TOC	Total Organic Carbon Content (in weight %)
S1	The amount of free HC's (Gas or oil) that are volatilised For 2 minutes at 300 degree Celsius
S2	The amount of HC's coming from kerogen cracking between 300 and 600 degree C. and from heavy extractable compounds such as resins and asphaltenes
S3	The amount of CO₂ trapped separately during kerogen cracking
HI	Hydrogen Index. $HI = ([100 \times S2]/TOC)$
OI	Oxygen Index. $OI = ([100 \times S3]/TOC)$
PI	Production Index ($S1/S1 + S2$), free hydrocarbons in relation to the Total amount of HC.
Tmax	The average of 20 temperature measurements made on both of the Top of peak S2. Indicator of organic matter maturation

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
1342	1.71	0.11	5.18	428	0.58	4.6	0.58	33	269
1342	1.72	0.11	5.29	426	0.59	4.7	0.61	35	273
1344	2.1	0.04	4.85	427	0.17	4.68	0.73	34	222
1344	2.14	0.03	5.25	425	0.16	5.09	0.74	34	237
1347	1.71	0.03	2.51	420	0.08	2.43	0.46	26	142
1347	1.7	0.04	2.49	420	0.09	2.4	0.47	27	141
1351	2.13	0.03	5.74	422	0.16	5.58	0.81	38	261
1351	2.15	0.03	5.8	424	0.16	5.64	0.76	35	262
1353	1.86	0.04	3.68	426	0.13	3.55	0.58	31	190
1353	1.86	0.03	3.62	426	0.12	3.5	0.59	31	188
1357	1.58	0.04	4.05	427	0.15	3.9	0.56	35	246
1357	1.6	0.04	3.96	429	0.14	3.82	0.5	31	238
1359	0.04	0.2	0.05	373	0.01	0.04	0.01	25	100
1359	0.03	0	0.03	416	0	0.03	0.05	166	100
1360	1.68	0.03	4.36	425	0.12	4.24	0.49	29	252
1360	1.66	0.03	4.48	425	0.13	4.35	0.43	25	262
1363	2.04	0.03	4.69	417	0.15	4.54	0.55	26	222
1363	2.04	0.03	4.69	417	0.16	4.53	0.54	26	222
1365	4.74	0.03	15.34	406	0.53	14.81	1.22	25	312
1365	4.79	0.03	15.29	405	0.51	14.78	1.22	25	308
1368	5.19	0.05	18.39	402	0.86	17.53	1.46	28	337
1368	5.24	0.04	18.12	404	0.78	17.34	1.32	25	330
1370.5	5.42	0.04	17.11	402	0.64	16.47	1.61	29	303
1370.5	5.35	0.04	17.17	400	0.68	16.49	1.54	28	308
1373.5	5.96	0.03	21.49	403	0.72	20.77	1.59	26	348
1373.5	6.13	0.03	21.48	404	0.73	20.75	1.4	22	338
1376.5	4.14	0.03	13.37	408	0.39	12.98	1.16	28	313
1376.5	4.16	0.03	13.79	406	0.42	13.37	1.12	26	321
1379.5	2.77	0.04	8.96	410	0.32	8.64	0.93	33	311
1379.5	2.85	0.03	9.43	410	0.32	9.11	0.93	32	319
1382.5	5.88	0.03	21.56	405	0.65	20.91	1.43	24	355
1382.5	5.91	0.03	20.86	403	0.61	20.25	1.66	28	342
1385.5	4.75	0.03	16.16	405	0.46	15.7	1.23	25	330
1385.5	4.75	0.03	16.25	404	0.49	15.76	1.23	25	331
1388.5	6.12	0.03	21.82	402	0.65	21.17	1.5	24	345
1388.5	6.17	0.03	22.11	402	0.68	21.43	1.56	25	347
1391.5	4.53	0.03	15.32	405	0.44	14.88	1.24	27	328
1391.5	4.58	0.03	15.81	402	0.46	15.35	1.22	26	335
1394.5	4.92	0.03	16.5	403	0.47	16.03	1.28	26	325
1394.5	4.89	0.03	16.3	405	0.45	15.85	1.29	26	324
1397.5	5.38	0.03	17.6	402	0.58	17.02	1.38	25	316
1397.5	5.44	0.03	17.56	402	0.58	16.98	1.35	24	312
1400	5.65	0.03	20.33	405	0.59	19.74	1.41	24	349
1400	5.7	0.03	21.2	404	0.64	20.56	1.42	24	360
1448	6.59	0.02	25.83	404	0.63	25.2	1.72	26	382
1448	6.59	0.03	26.08	403	0.66	25.42	1.71	25	385
1451	1.23	0.05	0.55	417	0.03	0.52	0.59	47	42

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
1451	1.24	0.06	0.64	416	0.04	0.6	0.52	41	48
1454	1.16	0.04	0.49	418	0.02	0.47	0.48	41	40
1454	1.15	0.02	0.47	417	0.01	0.46	0.53	46	40
1457	1.3	0.05	1.06	429	0.05	1.01	0.35	26	77
1457	1.3	0.06	1.06	429	0.06	1	0.48	36	76
1460	1.34	0.05	1.19	427	0.06	1.13	0.38	28	84
1460	1.37	0.05	1.24	428	0.06	1.18	0.37	27	86
1463	1.14	0.03	0.71	423	0.02	0.69	0.3	26	60
1463	1.12	0.03	0.64	424	0.02	0.62	0.35	31	55
1466	1.21	0.05	0.76	423	0.04	0.72	0.32	26	59
1466	1.24	0.05	0.74	421	0.04	0.7	0.32	25	56
1469	1.34	0.05	1.98	432	0.1	1.88	0.32	17	140
1469	1.36	0.05	2	432	0.11	1.89	0.27	19	138
1472	1.42	0.05	2.34	432	0.11	2.23	0.29	20	157
1472	1.41	0.06	2.28	431	0.13	2.15	0.3	21	152
1475	1.5	0.04	2.5	432	0.09	2.41	0.32	21	160
1475	1.51	0.03	2.55	432	0.08	2.47	0.33	21	163
1478	1.36	0.04	2.17	433	0.09	2.08	0.34	25	152
1478	1.37	0.05	2.19	432	0.1	2.09	0.3	21	152
1481	1.44	0.04	2.67	434	0.12	2.55	0.42	29	177
1481	1.44	0.05	2.72	434	0.13	2.59	0.42	29	179
1484	1.37	0.03	2.08	435	0.07	2.01	0.38	27	146
1484	1.36	0.03	2.17	436	0.07	2.1	0.38	27	154
1487	1.19	0.06	1.94	432	0.11	1.83	0.28	23	153
1487	1.18	0.06	1.77	431	0.11	1.66	0.31	26	140
1490	1.26	0.09	2.11	434	0.19	1.92	0.3	23	152
1490	1.25	0.09	1.97	434	0.18	1.79	0.27	21	143
1493	1.65	0.04	3.17	433	0.12	3.05	0.37	22	184
1493	1.65	0.04	3.09	434	0.12	2.97	0.37	22	180
1496	1.51	0.02	2.59	435	0.06	2.53	0.42	27	168
1496	1.53	0.03	2.59	435	0.07	2.52	0.45	29	164
1499	1.84	0.03	4.05	436	0.12	3.93	0.51	27	213
1499	1.83	0.03	3.89	436	0.12	3.77	0.52	28	206
1502	2.13	0.06	5.61	435	0.36	5.25	0.48	22	246
1502	2.16	0.07	5.64	435	0.37	5.27	0.46	21	243
1505	1.79	0.03	4.98	431	0.13	4.85	0.43	24	270
1505	1.78	0.03	5	432	0.13	4.87	0.41	23	273
1507	0.73	0.05	1.67	426	0.08	1.59	0.18	24	217
1507	0.76	0.04	1.94	427	0.08	1.86	0.19	25	244
1508	2.34	0.02	6.67	438	0.15	6.52	0.57	24	278
1508	2.36	0.02	6.7	436	0.16	6.54	0.54	22	277
1511	2.69	0.02	8.47	435	0.18	8.29	0.64	23	308
1511	2.69	0.02	8	436	0.17	7.83	0.62	23	291
1514	2.24	0.03	6.83	436	0.19	6.64	0.84	37	296
1514	2.25	0.03	7.15	437	0.2	6.95	0.88	39	308
1517	3.55	0.04	5.43	414	0.23	5.2	0.95	26	146
1517	3.55	0.04	5.46	414	0.22	5.24	0.91	25	147

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
1520	6.34	0.05	17.83	409	0.81	17.02	1.58	268	24
1520	6.22	0.05	17.34	406	0.82	16.52	1.52	24	265
1523	5.36	0.04	12.27	408	0.51	11.76	1.44	26	219
1523	5.29	0.04	12.05	409	0.51	11.54	1.41	26	218
1526	6.68	0.03	23.33	404	0.79	22.54	1.65	24	337
1526	6.62	0.03	23.57	404	0.82	22.75	1.69	25	343
1528.2	4.19	0.04	9.82	408	0.41	9.41	1.28	30	224
1528.2	4.11	0.04	9.78	408	0.42	9.36	1.17	28	227
1528.7	0.74	0.16	0.64	427	0.1	0.54	1.28	172	72
1528.7	0.75	0.16	0.61	427	0.1	0.51	1.43	190	68
1529	1.51	0.05	1.53	422	0.08	1.45	0.42	27	96
1529	1.51	0.05	1.43	423	0.07	1.36	0.48	31	90
1532	1.53	0.08	1.88	425	0.15	1.73	0.39	25	113
1532	1.53	0.07	1.93	427	0.14	1.79	0.48	27	116
1535	1.72	0.04	1.6	419	0.07	1.53	0.43	25	88
1535	1.71	0.04	1.59	418	0.07	1.52	0.46	26	88
1538	1.68	0.05	1.39	418	0.07	1.32	0.42	25	78
1538	1.71	0.05	1.48	417	0.07	1.41	0.43	25	82
1541	1.2	0.06	0.85	420	0.05	0.8	0.26	21	66
1541	1.19	0.05	0.78	420	0.04	0.74	0.27	22	62
1544	1.29	0.06	1.04	426	0.06	0.98	0.24	18	75
1544	1.32	0.06	1.13	427	0.07	1.06	0.25	18	80
1547	1.45	0.09	1.49	427	0.13	1.36	0.32	22	93
1547	1.45	0.07	1.48	430	0.11	1.37	0.3	20	94
1550	1.02	0.08	0.48	423	0.04	0.44	0.2	19	43
1550	1.02	0.1	0.49	423	0.05	0.44	0.2	19	43
1553	1.14	0.08	0.52	422	0.04	0.48	0.23	20	42
1553	1.14	0.09	0.47	422	0.04	0.43	0.25	21	37
1556	1.43	0.08	1.18	426	0.09	1.09	0.24	16	76
1556	1.43	0.08	1.14	425	0.09	1.05	0.25	17	73
1559	0.95	0.12	0.74	433	0.09	0.65	0.25	26	68
1559	0.94	0.12	0.73	430	0.09	0.64	0.26	27	68
1562	1.21	0.1	1.29	428	0.13	1.16	0.23	19	95
1562	1.21	0.11	1.28	427	0.14	1.14	0.22	18	94
1565	1.1	0.1	0.84	427	0.08	0.76	0.16	14	69
1565	1.11	0.09	0.87	429	0.08	0.79	0.15	13	71
1568	1.17	0.12	0.86	428	0.1	0.76	0.19	16	64
1568	1.16	0.13	0.88	428	0.11	0.77	0.2	17	66
1571	1.23	0.13	0.94	427	0.12	0.82	0.17	13	66
1571	1.25	0.14	1.01	428	0.14	0.87	0.17	13	69
1574	1.18	0.14	1.13	429	0.16	0.97	0.14	11	82
1574	1.19	0.15	1.17	430	0.17	1	0.16	13	84
1577	1.03	0.15	0.99	428	0.15	0.84	0.13	12	81
1577	1.04	0.16	0.95	428	0.15	0.8	0.14	13	76
1580	0.87	0.23	0.78	428	0.18	0.6	0.14	16	68
1580	0.86	0.23	0.79	428	0.18	0.61	0.14	16	70

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
535	1.17	0.08	1.22	424	0.10	1.12	0.54	46	96
536	1.98	0.07	4.14	422	0.31	3.83	0.81	41	193
536.5	2.09	0.04	7.70	415	0.33	7.37	1.30	62	353
537	3.00	0.04	8.99	419	0.34	8.65	1.16	39	288
537.5	1.52	0.07	2.52	422	0.17	2.35	0.71	47	155
538	2.02	0.07	3.99	425	0.26	3.73	0.87	43	185
539	2.51	0.05	9.96	415	0.45	9.51	1.46	58	379
539.1	0.02	0.00	0.01	0	0.01	0.00	0.18	900	0
539.4	4.29	0.04	19.22	413	0.71	18.51	2.15	50	431
539.5	0.51	0.06	1.24	417	0.07	1.17	0.58	114	229
539.8	0.01	1.00	0.05	0	0.05	0.00	0.42	4200	0
540	2.20	0.05	8.63	416	0.44	8.19	1.04	47	372
540.1	1.56	0.09	4.22	421	0.37	3.85	0.74	47	247
541	0.76	0.07	1.78	418	0.12	1.66	0.56	74	218
541.7	0.00	1.00	0.02	0	0.02	0.00	0.37	0	0
542	0.74	0.12	2.36	416	0.29	2.07	0.58	78	280
543	1.14	0.25	2.40	419	0.60	1.80	0.71	62	158
543.2	1.86	0.08	3.09	409	0.26	2.83	0.88	47	152
543.8	1.52	0.11	2.89	420	0.33	2.56	0.86	57	168
544	0.91	0.27	1.40	418	0.38	1.02	0.55	60	112
545	1.07	0.19	1.55	422	0.29	1.26	0.62	58	118
546	1.29	0.14	1.62	421	0.23	1.39	0.41	32	108
547	1.47	0.19	2.53	420	0.49	2.04	0.72	49	139
548	1.36	0.17	2.42	421	0.42	2.00	0.78	57	147
549	1.12	0.14	2.19	420	0.30	1.89	0.60	54	169
550	1.13	0.18	1.56	420	0.28	1.28	0.38	34	113
551	1.34	0.19	2.14	422	0.41	1.73	0.66	49	129
552	1.85	0.12	3.56	420	0.41	3.15	0.78	42	170
553	1.74	0.16	3.93	420	0.64	3.29	0.67	39	189
554	1.76	0.12	3.77	417	0.46	3.31	0.85	48	188

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
426	0.68	0.22	0.18	443	0.04	0.14	0.47	69	21
430	0.89	0.22	0.41	425	0.09	0.32	1.55	174	36
439	0.82	0.19	0.54	425	0.10	0.44	0.82	100	54
440	1.02	0.20	0.71	424	0.14	0.57	0.48	47	56
441	0.98	0.21	0.61	425	0.13	0.48	0.49	50	49
442	0.99	0.20	0.46	424	0.09	0.37	0.48	48	37
443	1.04	0.24	1.07	422	0.26	0.81	0.47	45	78
444	0.97	0.41	1.22	423	0.50	0.72	0.39	40	74
445	1.07	0.30	0.88	420	0.26	0.62	0.51	48	58
446	1.39	0.15	1.37	416	0.21	1.16	0.67	48	83
447	1.02	0.18	0.93	416	0.17	0.76	0.60	59	75
448	1.05	0.13	0.70	419	0.09	0.61	0.86	82	58
449	1.30	0.11	1.15	419	0.13	1.02	0.86	66	78
450	1.34	0.10	1.25	423	0.12	1.13	0.93	69	84
451	1.36	0.10	1.57	423	0.16	1.41	1.03	76	104
452	1.29	0.18	1.60	423	0.28	1.32	0.62	48	102
453	1.42	0.09	2.29	415	0.20	2.09	0.63	44	147
454	1.18	0.13	1.48	420	0.19	1.29	0.67	57	109
455	1.87	0.05	4.00	414	0.21	3.79	0.89	48	203
456	1.74	0.09	3.05	412	0.28	2.77	0.78	45	159
457	2.00	0.04	2.53	407	0.11	2.42	1.49	75	121
458	2.39	0.05	5.05	414	0.25	4.80	1.21	51	201
459	2.37	0.05	5.57	413	0.30	5.27	1.43	60	222
460	1.29	0.06	3.14	418	0.18	2.96	0.76	59	229
461	2.74	0.06	7.01	417	0.39	6.62	1.82	66	242
462	2.35	0.03	3.81	405	0.13	3.68	1.48	63	157
463	2.38	0.05	5.55	414	0.25	5.30	1.60	67	223
464	2.48	0.07	5.17	408	0.35	4.82	1.23	50	194
465	2.34	0.05	4.61	414	0.25	4.36	1.53	65	186
466	2.69	0.06	6.63	410	0.38	6.25	1.48	55	232
467	3.04	0.09	9.40	410	0.81	8.59	1.77	58	283
468	3.11	0.05	8.93	410	0.48	8.45	1.74	56	272
469	3.24	0.07	10.54	411	0.69	9.85	1.78	55	304
470	2.70	0.03	6.56	411	0.21	6.35	1.54	57	235
471	2.90	0.04	7.34	409	0.26	7.08	1.87	64	244
472	2.87	0.03	5.90	403	0.16	5.74	1.70	59	200
473	2.20	0.03	3.39	402	0.11	3.28	1.68	76	149
474	3.36	0.06	10.31	409	0.60	9.71	2.16	64	289
475	2.07	0.06	3.37	411	0.21	3.16	1.36	66	153
476	2.37	0.04	4.34	412	0.19	4.15	1.39	59	175
477	2.10	0.08	4.39	412	0.35	4.04	1.21	58	192
478	2.43	0.03	7.98	412	0.24	7.74	1.72	71	319
479	2.45	0.03	4.98	403	0.14	4.84	1.77	72	198
480	2.28	0.04	4.37	410	0.16	4.21	1.55	68	185
481	2.26	0.03	3.79	408	0.11	3.68	1.23	54	163
482	3.25	0.02	6.54	402	0.15	6.39	2.01	62	197
483	2.27	0.06	2.77	407	0.17	2.60	1.62	71	115

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
484	2.58	0.04	3.95	409	0.14	3.81	1.88	73	148
485	1.86	0.05	3.58	417	0.17	3.41	1.26	68	183
486	0.90	0.03	0.64	419	0.02	0.62	0.61	68	69
487	1.07	0.04	0.93	421	0.04	0.89	0.84	79	83
488	0.94	0.04	0.89	420	0.04	0.85	0.63	67	90
489	1.31	0.05	1.28	418	0.06	1.22	0.81	62	93
490	1.15	0.05	1.23	419	0.06	1.17	0.79	69	102
491	2.25	0.04	3.83	420	0.16	3.67	1.66	74	163
492	1.76	0.08	2.36	418	0.19	2.17	0.92	52	123
493	1.38	0.09	1.69	418	0.15	1.54	0.84	61	112
494	1.26	0.10	0.86	421	0.09	0.77	0.72	57	61
495	1.28	0.13	0.94	418	0.12	0.82	0.77	60	64
496	1.18	0.07	0.75	422	0.05	0.70	0.70	59	59
497	1.22	0.12	0.93	423	0.11	0.82	0.76	62	67
498	1.34	0.11	1.07	419	0.12	0.95	0.83	62	71
499	1.20	0.11	1.12	421	0.12	1.00	0.69	58	83
500	1.19	0.03	1.15	418	0.04	1.11	0.67	56	93
501	1.75	0.07	1.86	419	0.13	1.73	0.89	51	99
502	1.30	0.14	1.23	420	0.17	1.06	0.70	54	82
503	1.13	0.12	1.34	421	0.16	1.18	0.53	47	104
504	1.29	0.09	1.46	418	0.13	1.33	0.62	48	103
505	0.74	0.09	0.64	420	0.06	0.58	0.40	54	78
506	0.71	0.08	0.73	418	0.06	0.67	0.45	63	94
507	1.79	0.05	1.96	415	0.09	1.87	0.71	40	104
508	1.60	0.09	2.61	416	0.23	2.38	0.74	46	149
509	1.47	0.04	2.11	418	0.09	2.02	0.71	48	137
510	1.19	0.05	1.48	418	0.07	1.41	0.54	45	118
511	1.85	0.06	3.18	413	0.20	2.98	1.03	56	161
512	1.30	0.11	1.52	424	0.17	1.35	0.79	61	104
513	1.22	0.12	1.39	422	0.17	1.22	0.70	57	100
514	0.91	0.16	0.64	417	0.10	0.54	0.68	75	59
515	0.80	0.08	0.37	421	0.03	0.34	0.47	59	43
516	1.01	0.12	0.74	422	0.09	0.65	0.47	47	64
517	0.92	0.08	0.50	421	0.04	0.46	0.50	54	50
518	0.94	0.11	0.56	424	0.06	0.50	0.71	76	53
519	0.98	0.08	0.71	424	0.06	0.65	0.54	55	66
520	0.93	0.07	0.41	419	0.03	0.38	0.49	53	41
521	1.35	0.24	1.95	419	0.46	1.49	1.27	94	110
522	1.02	0.17	0.90	421	0.15	0.75	0.92	90	74
523	1.01	0.17	0.88	422	0.15	0.73	0.68	67	72
524	0.90	0.06	0.66	421	0.04	0.62	0.49	54	69
525	1.01	0.08	0.61	418	0.05	0.56	1.00	99	55
526	1.27	0.11	1.16	422	0.13	1.03	0.86	68	81
527	1.07	0.10	0.39	416	0.04	0.35	1.11	104	33
528	1.17	0.14	1.11	422	0.15	0.96	0.91	78	82
529	1.16	0.12	0.93	422	0.11	0.82	0.60	52	71
531.25	1.01	0.27	1.39	417	0.38	1.01	0.63	62	100

Depth	TOC	PI	S1+S2	TMAX	S1	S2	S3	OI	HI
532	1.34	0.46	2.32	419	1.06	1.26	0.60	45	94
533	1.21	0.39	1.78	421	0.69	1.09	0.55	45	90
534	1.21	0.39	1.76	421	0.69	1.07	0.63	52	88
535	0.98	0.32	1.00	424	0.32	0.68	0.46	47	69
536	1.17	0.25	1.05	422	0.26	0.79	0.45	38	68
537	1.22	0.25	1.01	419	0.25	0.76	0.49	40	62
538	0.96	0.59	1.42	414	0.84	0.58	0.48	50	60
539	1.30	0.13	1.12	420	0.14	0.98	0.50	38	75
540	2.36	0.09	3.72	409	0.32	3.40	1.18	50	144
541	2.03	0.12	4.35	418	0.52	3.83	0.98	48	189
542	1.96	0.10	3.07	418	0.32	2.75	0.86	44	140
543	2.52	0.05	3.52	412	0.17	3.35	1.34	53	133
544	1.52	0.19	1.94	423	0.37	1.57	0.81	53	103
545	1.36	0.13	1.46	422	0.19	1.27	0.78	57	93
545.30	0.08	1.00	0.07	0	0.07	0.00	0.26	325	0
546	1.68	0.09	1.34	409	0.12	1.22	0.94	56	73
547	0.80	0.15	0.33	415	0.05	0.28	0.87	109	35
548	1.27	0.14	0.64	413	0.09	0.55	0.98	77	43
549	1.09	0.18	1.93	426	0.35	1.58	0.73	67	145
550	1.36	0.24	1.20	420	0.29	0.91	0.77	1	67
551	1.37	0.14	0.84	416	0.12	0.72	0.79	58	53
552	1.31	0.12	0.69	421	0.08	0.61	0.64	49	47
553	0.91	0.06	0.50	421	0.03	0.47	0.45	49	52
554	1.13	0.12	0.65	421	0.08	0.57	0.53	47	50
555	1.91	0.05	1.80	418	0.09	1.71	0.84	44	90
556	1.50	0.10	1.99	424	0.19	1.80	0.62	41	120
557	1.58	0.08	1.32	418	0.11	1.21	0.69	44	77
558	1.54	0.14	1.89	423	0.26	1.63	0.60	39	106
559	1.65	0.09	1.46	421	0.13	1.33	0.70	42	81
560	1.19	0.25	1.33	425	0.33	1.00	0.54	45	84
561	1.53	0.13	1.98	522	0.25	1.73	0.56	37	113
562	1.37	0.06	1.39	420	0.09	1.30	0.62	45	95
563	1.75	0.07	1.53	417	0.11	1.42	0.77	44	81
564	1.44	0.10	1.85	424	0.18	1.67	0.56	39	116
565	1.35	0.06	0.88	416	0.05	0.83	0.74	55	61
566	1.82	0.05	3.16	421	0.17	2.99	0.77	42	164
567	0.89	0.15	1.06	422	0.16	0.90	0.46	52	101
568	1.22	0.12	1.73	420	0.21	1.52	0.46	38	125

Appendix B

Foraminifera Data

	Westgate Formation																	Fish Scales Formation							
Depth (ft)	1580	1577	1574	1571	1568	1565	1562	1559	1556	1553	1550	1547	1544	1541	1538	1535	1532	1529	1528.8	1528.2	1526	1523	1520	1517	
Barren																			x		x		x		x
Foraminiferal species																									
Miliammina awlneris	5	1		3	1	1		1	3		1														
Miliammina ischia	2	3	5	6	2	1			1	1		2	4			5		6							
Bathysiphon brosel	2				2							2						6							
Ammobaculites pellicus	7	4	3	7	1	1			5			2	6				1								
Reophax troyeri	3		5	3		4			1																
Ammobaculites fragmentarius	10	9	6				3		5	8	6	3	1	2											
Ammobaculites sp.	1			2			6		11	5	2	4	3												
Textularia topogorkensis	2	1							1	1		4				2	1								
Ambulimina paynei	2						1																		
Miliammina maritimaensis	6	8	10	5	1	4			16	10	6	12	4	7	3	3	6	2							
Psammimopella bowsheri	1			3		1			2	5		5	1	7	2	1		2							
Trochammina spp.	4					2			2																
Textularia graveoroi	2	1				2					2														
Vermiculitoides perplexus	1		3	3		4			3	4		1													
Vermiculitoides lyrelli	6	7	6						9	4	5	2	1												
Gaudryna canadensis		6	2				2		2	3	4	3		3											
Reophax incompta		5				1					2														
Haplophragmoides hendersonense		4				1			1			3													
Saccammina alexanderi		2	1	1		6	2		1	1	3				3	1									
Haplophragmoides collyra		6				8			4																
Haplophragmoides gilberti			1						4			1	2												
Uvigerammina maritimaensis			3																						
Haplophragmoides postis goodrichi					2	1	3	2	1	2	6	2	1	2	3	3	1	1							
Vermiculitoides sp.					3		17	2	5	1			4	1	3	5	2								
Trochammina alcarasis					2				3																
Haplophragmium swaneri					1				3																
Trochammina weileri					2	3		1	3				1	1											
Saccammina alexanderi					2		1		15	5	6							2							
Vermiculitoides fischeri					1				1																
Reophax sikamensis									3			1													
Trifarina alhabascensis						2			2	1	1	1													
Haplophragmoides spp.						3			2																
Saccammina latirami									3	4	3	3		5			2	5							
Haplophragmoides rola									1	1	2		1	3		1		1							
Pseudobulimina variata									1																
Pseudobulimina sp.									2				1												
Reophax tundrensis																									
Heteroleix globulosa																									
Hedbergella loeblii																									
Neobulimina albertensis																									
Hedbergella planispira																									
Wittalinella apfca																									
Hedbergella deltoensis																									
Hedbergella portsmouthensis																									
Hedbergella amabilis																									
Haplophragmoides howardense																									
Trochammina rainwateri																									
Dorthis cf. Smokyensis																									
Pseudobulimina rollaensis																									
Reophax sp. 1																									
Neobulimina canadensis																									
Pseudobulimina sp.																									
Marsomella oxycona																									

10-22-47-3W4

10-22-47-3W4

Carile Formation

[illegible]

[illegible]

[illegible]

Well: 16-04-22-15W4

Medicine Hat Member[illegible]

[illegible]

Well: 16-04-22-15W4

	Medicine Hat Member														First White Specks Member													
Depth (m)	499	498	497	496	495	494	493	492	491	490	489	488	487	486	485	484	483	482	481	480	479	478	477					
								x					x					x										
Barren																												
Foraminiferal species																												
Haplophragmoides howardense															1	1	2		12									
Haplophragmoides collyra																												
Ammobaculites fragmentarius																												
Ammobaculites tyrrelli																												
Trochammina rainwateri																												
Spiroplectammina semicomplanata																												
Reophax sp.1									1											1								
Saccammina lathrami																	1											
Marssonella oxycona																												
Verneuilinoides sp.																												
Haplophragmoides topagorukensis																												
Trochammina rutherfordi																												
Trochammina ribstonensis																												
Haplophragmoides rota																												
Haplophragmoides sp. 2		1		2	2		2		6						4	3	2		6									
Pseudobolivina rollaensis			12																									
Ammobaculites sp. 1	28			3	2	5	10		1					2					10									
Reophax toryeri																												
Pleurostomella watersi																												
Pseudobolivina variana																												
Gaudryina canadensis																												
Trochammina sp.																												
Gaudryina sp.																												
Bullopore laevis																												
Gavelinella talaria																												
Gavelinella henbesti		1																										
Trochammina spp.		6		7	8		16		16	12	6	3		5	7	2	3		3				8					
Dentalina sp.1																												
Valvulineria sp.																												
Heterohelix globulosa																												
Anomalinoidea sp.																												
Bathysiphon broegei																												
Trochammina wetteri																												
Haplophragmoides bonanzaense																												
Dorothia glabrata	12		5	8	9	6	3					3																
Uvigerinammina manitobensis																												
Saccammina complanata																												
Hedbergella delrioensis																												
Gavelinella cf. turbinata																												
Gavelinella sandidgei																												
Archaeoglobigerina cretacea																												
Neobulimina canadensis																												
Nodosarella sp.																												
Hedbergella planispira																												
Cibicides sp.																												
Spiroplectammina sp.																												
Textularia topagorukensis																												
Trochammina diagonis																												
Globigerinelloides prairiehillensis																												
Globigerinelloides messinae																												
Globigerinelloides bentonensis																												
Hedbergella amabilis																												
Bolivina elkensis																												
Heterohelix cf. reussi																												
Miliammina awunensis																												
Saccammina sp. cf. S. alexanderi																												
Dorothia smokyensis																												

Well: 16-04-22-15W4

First White Specks Member

Depth (m)	476	475	474	473	472	471	470	469	468	467	466	465	464	463	462	461	460	459	458	457	456	455	454
Barren							x				x	x	x	x									
Foraminiferal species																							
<i>Haplophragmoides howardense</i>			3	4																			
<i>Haplophragmoides collyra</i>																		2		1	5		
<i>Ammobaculites fragmentarius</i>			1	3														2	2	5	6	3	
<i>Ammobaculites tyrrelli</i>																							
<i>Trochammina rainwateri</i>															4						5	1	
<i>Spiroplectammina semicomplanata</i>																							
<i>Reophax</i> sp.1			1	3													2		1	1	2		
<i>Saccammina lathrami</i>																							
<i>Marssonella oxycona</i>																							
<i>Verneulinoides</i> sp.																							
<i>Haplophragmoides topagorukensis</i>																							
<i>Trochammina rutherfordi</i>																					2		
<i>Trochammina ribstonensis</i>																				3	25	2	
<i>Haplophragmoides rota</i>																							
<i>Haplophragmoides</i> sp. 2																	2		8	12	6	4	
<i>Pseudobolivina rollaensis</i>																							
<i>Ammobaculites</i> sp. 1			4	3	3	1											1			2		2	
<i>Reophax toryeri</i>																							
<i>Pleurostomella watersi</i>																							
<i>Pseudobolivina variana</i>																							
<i>Gaudryina canadensis</i>																							
<i>Trochammina</i> sp.																							
<i>Gaudryina</i> sp.																							
<i>Bullopore laevis</i>																							
<i>Gavelinella talaria</i>																	3						
<i>Gavelinella henbesti</i>																	12						
<i>Trochammina</i> spp.	7	7		8	2																		
<i>Dentalina</i> sp.1																							
<i>Valvulineria</i> sp.																							
<i>Heterohelix globulosa</i>								1	1														
<i>Anomalinoidea</i> sp.																							
<i>Bathysiphon broegei</i>																							
<i>Trochammina wetteri</i>																							
<i>Haplophragmoides bonanzaense</i>																							
<i>Dorothyia glabrata</i>																							
<i>Uvigerinammina manitobensis</i>																					3		
<i>Saccammina complanata</i>																							
<i>Hedbergella delrioensis</i>										3													
<i>Gavelinella</i> cf. <i>turbinata</i>																	2						
<i>Gavelinella sandidgei</i>																							
<i>Archaeoglobigerina cretacea</i>																							
<i>Neobulimina canadensis</i>																	3	3					
<i>Nodosarella</i> sp.																	3	1					
<i>Hedbergella planispira</i>								1															
<i>Cibicides</i> sp.																							
<i>Spiroplectammina</i> sp.																							
<i>Textularia topagorukensis</i>																							
<i>Trochammina diagonis</i>																							
<i>Globigerinelloides prairiehillensis</i>								1	2														
<i>Globigerinelloides messinae</i>								2	3														
<i>Globigerinelloides bentonensis</i>								2	4														
<i>Hedbergella amabilis</i>								1	2														
<i>Bolivina elkensis</i>																							
<i>Heterohelix</i> cf. <i>reussi</i>																	3						
<i>Miliammina awunensis</i>																	2						
<i>Saccammina</i> sp. cf. <i>S. alexanderi</i>																			6	3			
<i>Dorothyia smokyensis</i>																			4	2		5	3

Well: 16-04-22-15W4

Milk River Formation																	
Depth (m)	453	452	451	450	449	448	447	446	445	444	443	442	441	440	439	430	426
Barren																x	
Foraminiferal species																	
Haplophragmoides howardense							1	2									3
Haplophragmoides collyra			1	3			3	4		4					2		2
Ammobaculites fragmentarius				5		1		3		2		5	3	1	7		5
Ammobaculites tyrrelli							3			2		1					
Trochammina rainwateri								2									
Spiroplectammina semicomplanata																	
Reophax sp.1				1			2	2		1		4	2		1		2
Saccammina lathrami																	
Marssonella oxycona																	
Verneuilinoides sp.																	
Haplophragmoides topagorukensis																	
Trochammina rutherfordi																	
Trochammina ribstonensis				2	7	4	2	5	10				1				
Haplophragmoides rota								3					2				
Haplophragmoides sp. 2				3			2					3	2				
Pseudobolivina rollaensis						1	2		4	1					1	1	1
Ammobaculites sp. 1	1	2	3	1			3	1		1	2	3	1		9		1
Reophax torreyi							1										
Pleurostomella watersi				4			1										
Pseudobolivina variana																	
Gaudryina canadensis																	
Trochammina sp.																	
Gaudryina sp.																	
Bullopore laevis																	
Gavelinella talara																	
Gavelinella henbesti							1										
Trochammina spp.																	
Dentalina sp.1																	
Valvulinera sp.																	
Heterohelix globulosa																	
Anomalinoides sp.																	
Bathysiphon brosgel																	
Trochammina wetteri															1		
Haplophragmoides bonanzaense																	
Dorothia glabrata																	
Uvigerinammina manitobensis																	
Saccammina complanata																	
Hedbergella delrioensis																	
Gavelinella cf. turbinata																	
Gavelinella sandidgei																	
Archaeoglobigerina cretacea																	
Neobulimina canadensis																	
Nodosarella sp.																	
Hedbergella planispira																	
Cibicides sp.																	
Spiroplectammina sp.																	
Textularia topagorukensis																	
Trochammina diagonis																	
Globigerinelloides prairiehillensis																	
Globigerinelloides messinae																	
Globigerinelloides bentonensis																	
Hedbergella amabilis																	
Bolivina elkensis																	
Heterohelix cf. reussi																	
Miliammina awunensis																	
Saccammina sp. cf. S. alexanderi																	
Dorothia smokyensis																	