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**PALEOENVIRONMENTS AND REGIONAL CORRELATIONS OF
ALBIAN-CENOMANIAN STRATA IN THE FRONTIER LIARD BASIN
OF NORTHWESTERN CANADA**

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ABSTRACT

The frontier Liard Basin is a relatively unexplored basin in northern Canada. A comprehensive outcrop and core study of Albian-Cenomanian strata of the Chinkeh, Garbutt, Scatter, Lepine, Sikanni and Sully formations integrating bio- and sequence stratigraphy, sedimentology, Rock Eval pyrolysis and regional well log correlations details the paleoenvironmental history and response to relative sea level changes. A number of units occur within the Chinkeh and lowermost Garbutt formations and are integrated into a framework of five early Albian sedimentary intervals that provide a high-resolution time control on the paleogeography during Chinkeh deposition. The Chinkeh was deposited by eastwards and westwards prograding shorefaces on opposite margins of a narrow sea and at least one major persistent fluvial/estuarine system situated in the Northwest Territories. Biostratigraphic constraints on deposition of the upper Garbutt and Scatter formations provide ties to events in the Peace River region and Alberta Basin. The Garbutt and Scatter formations were deposited in a high accommodation setting and thin normally eastwards. Unlike correlative strata to the south they do not contain any internal unconformities. The thick Lepine Formation preserves a continuous record of sedimentation although multiple sea level changes produced unconformities elsewhere in the Cretaceous seaway. It is divided into five units in offshore and shelf facies. Events that characterize a low accommodation setting to the south are correlated to the Liard Basin using biostratigraphy and well logs. Analysis of proximal and distal facies from three outcrops of the Upper Albian Sikanni Formation indicates that four sequences can be identified in predominantly wave-dominated deltaic deposits. Fifth-order relative sea level changes are regionally correlative in outcrops and

well logs of the Sikanni Formation and indicate that a previously unrecognized cyclicity is present in the Upper Albian of the WCSB that was likely driven by high frequency changes in flexural loading. The base of the Sully Formation is associated with a prominent transgressive ravinement surface. The Fish-Scales Marker, which marks the Albian/Cenomanian boundary, is present within the Sully Formation. The *Textularia alcesensis* Zone occurs and indicates a continuous record of uppermost Albian and lower Cenomanian sedimentation is present in the Liard Basin.

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Chapter I. INTRODUCTION

For much of late Proterozoic and Paleozoic time, the west coast of Laurentia was a passive margin, and extensive carbonate deposition dominated until the Jurassic (e.g. Monger, 1995). The development of an east-dipping active subduction zone in the middle Paleozoic and a major tectonic reorganization initiated with the break-up of Pangea and the northwestward movement of the North American Plate over the Farallon Plate in the middle Jurassic led to profound changes along the west coast of Laurentia. This large scale, tectonically driven paleogeographic evolution was caused by loading of the continental lithosphere by intrusion of plutons, orthogonal accretion and lateral displacement of pericratonic, and accreted terranes (Monger and Nokleberg, 1995), shortening of the passive margin sedimentary succession by imbricate stacking of thrust sheets, and loading and tilting of the crust by the dynamical effects of mantle convection (Mitrovica et al., 1989; Gurnis, 1992). These static and dynamic loads caused subsidence of a broad area of the craton and formation of a foreland basin, which, combined with a eustatic highstand of sea level, culminated in the Cretaceous Western Interior Seaway in which Boreal and Tethyan waters intermittently flooded southwards and northwards, respectively.

According to Monger and Nokleberg (1995), the period from the Middle Jurassic to the mid-Cretaceous (184-100 Ma) was the interval of the most significant changes in the western Cordillera. By the end of this interval, most major terranes had docked with the cratonic margin and most of the Cordillera had risen above sea level, thus providing a considerable flexural load and sediment source to the foreland basin immediately to the

east. After most terranes had been accreted to the western margin by the mid-Cretaceous, northward translation along dextral transcurrent faults in Late Cretaceous-Tertiary time due to the interaction of the western margin of the North American Plate with the Kula and Farallon plates, which were moving northwards, resulted in radical displacements of some parts of the Cordillera (Umhoefer, 1987); however, paleontological data and paleomagnetic data disagree in the amount and timing of movement (e.g. Kodama and Ward, 2001; Keppie and Dostal, 2001). Because of these uncertainties several different paleogeographic reconstructions are possible and relating sedimentary events in the foreland basin to specific tectonic events in the Cordillera is difficult (Monger, 1993, fig. 5a-c).

Sedimentation and accommodation space

Tectonic events in the Cordillera largely controlled the supply of sediment to the foreland basin and significantly influenced accommodation space. Cant and Stockmal (1989, 1993) outlined the sequence of events likely to have been associated with individual terrane accretion events in the Western Canada Sedimentary Basin (WCSB). Sedimentary sequences in the basin, as well as structural style and geophysical models of loading, reveal a general correlation between unconformity-bounded clastic sedimentary packages and episodes of thrusting in the fold belt. Difficulties arise in separating the effects of tectonic subsidence from eustasy, although transgressions and thrusting events may be generally coincident because they sometimes have the same cause. The uncertain paleogeography of Western Canada during mid-Cretaceous time, notably the amount of dextral strike-slip movement of superterrane along the western margin of the continent,

complicate the picture and hinder higher-resolution models of the relationship between times of individual terrane accretion and sedimentary effects in the foreland basin.

The ultimate link between the tectonics of the hinterland and the Jurassic-Cretaceous deposits of the foreland basin was the cratonic basement, which subsided through the processes of static and dynamic loading. Geophysical modeling of the subducting lithospheric slab (Mitrovica et al., 1989) has shown that pressure variations induced on the base of the continental lithosphere that are produced by mantle convection can explain additional subsidence of the basin in addition to thrust (static) loading. In fact, the wavelength of the deflection increases proportionally with a lessening dip angle of the subducting slab. The developing foreland basin is also understood to have been constantly in a state of flux, such that periods between accretion of terranes (and thus thrusting and loading) involve unloading by erosion and/or extension producing foreland uplift (Heller et al., 1988). Beaumont et al. (1993) suggested that erosion during uplift between terrane docking events resulted in a paleoslope that enabled the emplacement of gravels during the succeeding constructive phase. In summary, the WCSB formed through static and dynamic loading; however, additional accommodation space was created through eustatic sea level change (see below).

Relative Sea Level History of the WCSB

Although local and regional tectonics largely controlled the source and rate of supply of sediments from the hinterland, some of the accommodation space for the deposition of terrigenous clastic sediments was supplied through eustatic sea level change. Separating eustatic effects from those caused by thrust loading is possible in some cases. In the Western Canada foreland basin, Beaumont et al. (1993) noted that

eustatic effects can be separated from tectonically-induced basement subsidence when sedimentation has occurred eastward of that modeled from lithostatic loading alone. Kauffman and Caldwell (1993, and references therein) suggested that most 2nd (6-10 Ma) and 3rd (1-3 Ma) order relative sea level rises in the Cretaceous can be linked to thrusting and/or volcanic events. In the Cretaceous, nine second-order sea level cycles have been documented in the Western Interior Basin of North America (Kauffman and Caldwell 1993). During the Albian, the northern basin was influenced by the Clearwater, Kiowa-Skull Creek, and basal Greenhorn cycles (see Figure V-3). The northern and southern portions of the Western Interior Seaway were connected during the Kiowa-Skull Creek Cycle (late Albian), which reflects high global sea levels in the mid-Cretaceous (2nd order).

Within the third order cyclothems are higher order transgressive-regressive couplets, some of which were documented by Caldwell (1984). These cycles record basin-wide changes in sea level and have sometimes been attributed to mid-Cretaceous increased seafloor spreading rates, but attributing these higher frequency fluctuations to tectonoeustasy is problematic because no known mechanism exists to produce these shorter-term cycles (Kauffman and Caldwell 1993). Others (e.g. Stott, 1993) have stressed that regional tectonics may have also been important in controlling accommodation space; however, these two are not mutually exclusive. Eustatic events and tectonic loading were probably linked by Cretaceous pulses of increased plate spreading rates, and hence are effects of the same cause that may have been relatively simultaneous.

The effects of eustatic rise coupled with high-frequency relative sea level changes are evident in the sedimentary succession in the Liard Basin. The possible causes and effects of relative sea level changes (especially in the Chinkeh, Lepine and Sikanni formations) are discussed in this thesis.

The Liard Basin

Overview

An extensive documentation of the structure and paleogeography of the WCSB, especially the Cretaceous succession, has arisen through detailed study of the seismic, outcrop and voluminous core and well log data that are available from the basin (Wright et al. 1994). For the Cretaceous, this detailed record is especially rich for the Alberta basin, which runs northwards from the Alberta-U.S. border adjacent to the Foreland Fold and Thrust Belt to the Peace River Arch at approximately 56°N latitude. Isopach maps of Phanerozoic strata (Wright et al., 1994, fig. 3.2), clearly show this zone of maximum subsidence forming the Alberta Basin. To the northwest, another distinctively thick sedimentary package in northeastern British Columbia, the southeastern Yukon, and southwestern Northwest Territories to the west of the Bovie Lake Structure fills the Liard Basin (Figure I-1).

Within the Liard Basin, the Phanerozoic succession exceeds 6000 m in thickness and is composed of Cambrian to Cretaceous strata, with the notable exception of Jurassic rocks (Stott, 1982). Most of the Cretaceous succession consists of Albian and lowermost Cenomanian strata, although some more isolated Upper Cretaceous rocks occur in synclinal areas. Leckie et al. (1991) showed how Lower Cretaceous strata lie unconformably on Lower Triassic to Carboniferous rocks from south to north, and Lower

Triassic to Carboniferous rocks from west to northeast (their fig. 6). A map of the principle geologic elements surrounding the Liard Basin reveals that the basin is situated between the Rocky Mountain Fold and Thrust Belt and the Mackenzie Fold Belt and marks a conspicuous change in the orientation of structural elements from north-south in the southern Cordillera to northwest-southeast in the northern Cordillera (Figure I-2).

Although the Liard Basin covers 9500 km² in northeastern British Columbia, Yukon and Northwest Territories it remains relatively unexplored, although significant sweet gas discoveries in the basal Cretaceous at Maxhamish Lake have resulted in increased interest and knowledge of the stratigraphy in that area.

Leckie et al. (1991) constructed a structure contour map on top of the Lower Cretaceous sandstones at Maxhamish that showed a dramatic decrease in structural elevation towards the southwest. The structure contours rise dramatically eastwards over the Bovie structure, but also northwards into the Northwest Territories and Yukon.

The Bovie Structure

The north-south trending Bovie Structure (a.k.a. Bovie Fault Zone, Bovie Anticline, Bovie Trend) extends from south of the Fort Nelson River in northeastern British Columbia to the Muskeg River in the southern Northwest Territories (Figure I-1). It has historically been interpreted as a down-to-the-west normal fault (Taylor and Stott, 1968; Williams, 1978) to the west of a parallel eastward-directed thrust in Northwest Territories (Douglas and Norris, 1976) or south-plunging anticline in British Columbia (Taylor and Stott, 1968). Stratigraphically, it marks the eastward limit of several units, notably the Mississippian Matson Formation, which thins abruptly over it. Leckie et al. (1991) thought there may have been some strike-slip motion along the plane of the fault.

Stott (1993) suggested that the Bovie Lake Fault may be a remnant of the peripheral bulge associated with the formation of the Liard Basin.

The most recent interpretation of this structure is based on seismic lines and well log integration by MacLean (2001, 2002). In his interpretation, west-directed thrusting occurred in post-Mississippian but pre-Cretaceous (possibly Columbian orogenesis) time producing an uplifted hanging-wall block. After this event, erosion thinned the Mattson in the east and later Laramide compression reactivated the fault and eventually produced a shallow eastwards detachment thrust carrying Mississippian strata to the surface where they are now expressed as the Bovie Anticline. Importantly for this study, MacLean (2001) notes that movement on the deep-seated west-directed thrust may have also occurred during the Cretaceous. In MacLean's (2001) interpretation there is thus no normal fault associated with the Bovie Structure. Structural cross-sections of Leckie et al. (1991) show an apparent considerable downthrow of 870 m on top of the Scatter Formation, and if the MacLean (2001) model is correct, then there must have been considerable movement on the west-directed thrust after deposition of the Scatter Formation.

Previous Work

Kindle (1944) and McLearn and Kindle (1950) completed preliminary geological reconnaissance in the Liard Basin. Over a number of field seasons, Stott (1960, 1968, 1982) completed a comprehensive field study of the Cretaceous strata in the basin. Taylor and Stott's (1968) study includes Cretaceous strata in the Maxhamish Lake area and has some foraminiferal identifications. Leckie et al. (1991) formally defined the basal Cretaceous Chinkeh Formation and provided some wireline log cross-sections of

the Liard Basin, whereas Leckie and Potocki (1998) described the Garbutt and Scatter formations and their economic importance. The most recent study of strata in the Liard Basin is the M.Sc. thesis of Frank (2002), who utilized sedimentology, ichnology and some well log correlations in a study of the Chinkeh, Garbutt and Scatter formations in outcrop and core. Dixon (1997, 1999) completed well log correlations from the Peace River area northwards into the Liard Basin and further north. Other regional geology (mainly subsurface) studies include Thompson (1977) and Williams (1977, 1978). Morrow and MacLean (2000), MacLean (2000, 2001, 2002) and MacLean and Morrow (2001) provided structure maps, interpreted seismic lines, and developed a new interpretation of the Bovie structure. Ammonite data from the Cretaceous of the Liard Basin is included in Jeletzky (1968, 1971, 1980, 1981). Foscolos and Stott (1980) completed a geochemical study of Cretaceous shale in northeastern British Columbia with some samples from the Liard Basin. Williams and Stelck (1975) constructed paleogeographic maps of the Cretaceous of North America, including three Albian maps. Other papers that include some discussions on Cretaceous Liard Basin strata are Stott (1975, 1984, 1993), Caldwell (1978, 1984, 1993) and relevant chapters of the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994).

This study is the first comprehensive foraminiferal analysis of Liard Basin strata. Only limited foraminiferal data were included in the section descriptions of Stott (1982). Southwards, however, in the Peace River and Sikanni Chief River areas, a number of foraminiferal studies have resulted in a detailed zonation for the Albian-Cenomanian of northeastern British Columbia, and these are drawn upon heavily in this thesis for systematics and biostratigraphic correlations. These studies include many from the thick

Albian succession in the Peace River area detailed in Wickenden (1951), Stelck et al. (1956, 1958), Sutherland and Stelck (1972), Stelck (1975, 1991, 2000), Stelck and Hedinger (1983), Koke and Stelck (1984, 1985), Stelck and Koke (1987), Stelck and Leckie (1990), and from the Sikanni Chief River area north of Peace River (Schröder-Adams and Pedersen, 2003). Additional faunal comparisons were made with the detailed studies of Tappan (1957, 1960, 1962) from the Alaskan north slope, Chamney (1978) from the northern Yukon Territory (Peel River Plateau) and Sliter (1981) from the Canadian Arctic Islands. These, along with other important studies for comparison with Liard Basin benthic foraminiferal taxa are listed in the synonymy in Chapter VIII.

Objectives

The Liard Basin is a frontier basin with limited biostratigraphic, sedimentological and regional correlations completed to date. The succession covered in this thesis includes the Cretaceous Chinkeh, Garbutt, Scatter, Lepine, Sikanni and Sully formations (Figure I-3). These lithostratigraphic units were deposited during Albian and earliest Cenomanian time (only the middle and upper Sully are Cenomanian), and hence the geochronometric interval ranges from approximately 112-97 Ma (Obradovich, 1993). The age of the Chinkeh Formation remains, however, questionable due to lack of biostratigraphic control. To the south in the Peace River Foothills and plains of northeastern British Columbia and Alberta, a detailed paleogeographic and relative sea level history has been constructed over many years of study by numerous authors; however, the relationship of events in the Peace River region and the remainder of the Alberta Basin to the thick sedimentary succession in the Liard Basin is poorly known. This thesis provides a detailed reconstruction of the Albian and lowermost Cenomanian

succession in the Liard Basin through: a) establishment of a foraminiferal zonation based on outcrop and core samples; b) correlations of subsurface well logs with the aid of the foraminiferal data integrated with the outcrops; c) proposal of a sequence-stratigraphic model for the Liard portion of the Cretaceous Boreal Seaway and the relationship of the sequences in the Liard Basin to those to the south (Figure I-3); and d) paleoenvironmental interpretations of this succession in the Liard Basin.

Study Area and Methods

This study utilizes examination and sampling of core and outcrop sections for micropaleontological, paleoenvironmental, sequence stratigraphic and Rock-Eval geochemical analysis and subsurface cross-sections. The study area includes outcrops along the Alaska Highway west of Fort Nelson in the south to the Franklin Liard, Kotaneelee and La Biche ranges in the Yukon and Northwest Territories. Tables I-1 to I-3 list all localities studied over three field seasons. The mapped locations of the wells and outcrops are figured in the relevant chapters. With a few exceptions, most currently available cores are limited to the Chinkeh, Garbutt and Scatter formations, and these are listed in the relevant tables in chapters II and III.

The field research was conducted under the auspices of the Central Foreland NATMAP Project (under the direction of Dr. Larry Lane) over three field seasons (2000-2002). A total of 41 sections were measured in the Liard basin (Tables I-1 to I-3). The first field season was completed in collaboration with Dr. Per Kent Pederson, who was the major contributor to logging the Chinkeh and Scatter outcrops that season. A total of 17 cores were logged at the Geological Survey of Canada, Calgary, and the Charlie Lake Core Facility in British Columbia. The author and/or Dr. Per Kent Pederson logged a

number of cores, and credit is given to Dr. Pederson for many observations and most of the micropaleontological core samples were obtained by him.

Micropaleontological samples were processed using standard techniques (Then and Doherty, 1983) and picked, identified, counted and photographed under a binocular light microscope. In total, 537 core and outcrop samples were processed for foraminifera, and most of these were picked and identified. In total, 93 species were identified from 13 800 foraminiferal tests. Foraminiferal counts by section are provided in Appendix I. Some field reconnaissance samples collected by Dr. Larry Lane (included in the above totals) were also processed and identified (Appendix II) and provide biostratigraphic constraints for the ages of the problematic strata at those localities. Subsurface correlations were completed using the iDc digital well log database (for correlations in northeastern British Columbia) and IHS AccuX (for correlations in Northwest Territories and northeastern British Columbia). Rock-Eval analyses were run on a DELSI Rock-Eval II/TOC apparatus at the Geological Survey of Canada, Calgary. Rock-Eval geochemical data are provided in Appendix III.

Thesis Layout

This thesis is arranged into five main chapters covering the Lower Cretaceous and lowermost Upper Cretaceous of the Liard basin beginning with the stratigraphically lowest Chinkeh and lowermost Garbutt formations (Chapter II), middle and upper Garbutt and Scatter formations (Chapter III), Lepine (Chapter IV), Sikanni (Chapter V) and Sully formations (Chapter VI). Chapter VII includes all digital well log cross-sections, and Chapter VIII the foraminiferal synonymy and illustrations. Additional data

(foraminiferal counts by section, Rock-Eval data, and results of reconnaissance biostratigraphy samples) are included in the appendices.

Figure I-1. Location of Liard Basin (approximately outlined by outcrop of Dunvegan Formation-coloured) and Bovie Structure in northwest Canada.

Figure I-2. Geological elements of northwest Canada (modified from Morrow and Miles, 2000).

Figure I-3. South to north cross-section of Lower and lowermost Upper Cretaceous lithostratigraphic units in the Liard Basin (Liard River) and their relationships to units to the south (modified from Stott, 1982 and Leckie et al., 1991). Bougie mbr. is informal (Pedersen and Schröder-Adams, 2001). Viking Marker between Peace and Prophet rivers from Schröder-Adams and Pedersen (2003).

	Location/Description	UTM (NAD27)	NTS Map Sheet	Formation	Approximate Thickness	Total Samples
L2000C	Historic Mile 375 Alaska Hwy.	6501867N, 428122E		Chinkeh/Buckinghorse	10 m	5
L2000D	Steamboat Mountain	6504660N, 459717E	94J/12	Sikanni and Buckingham	400 m	93
L2000E	Petitot River-Fort Liard	Across from airstrip	95B/3	Bulwell Mb	7.40 m (40 m)	4
L2000F	Liard/Muskeg river junction	6688308N, 480473E	95B/6	Bulwell Mb	42 m	8
L2000G	Kotanelee River	6676374N, 452583E	95B/4	? Kotanelee Fm ?	70 m	15
L2000H	Muskeg/Arrowhead river junction	6691011N, 496551E	95B/6	Basal Garbutt Shale	54.5 m	12
L2000I	Nearby reference section of Leckie	6743151N, 429726E	95C/16	?Permian?	grab samples	1
L2000J	Directly NW of Locality I	~6743151N, 429726E	95C/16	?Garbutt?	grab samples	2
L2000K	Scatter River	6608703N, 402003E	94N/10	Scatter	344 m	31
L2000L	Tributary to LaBiche river	6739917N, 410978E	95C/15	Chinkeh Fm (shoreface facies)	34.50 m	7
L2000M	Kotanelee River, east of Kotanelee Gap	6718886N, 438333E	95C/9	Chinkeh (fluvial and coal facies)	20 m	9
L2000N	Murky Creek (water slide)	6735626N, 446100E	95B/12	Chinkeh (Lagoonal facies ?)	45 m	15
L2000O	Petitot River	6651906N, 500573E	95B/2	Scatter (Bulwell Mb ?)	76 m	7
L2000P	Unnamed creek north of Murky Creek	6740605N, 444270E	95B/13	Chinkeh (Lagoonal facies ?)	4.5 m	9

Table I-1. Liard Basin localities studied in 2000 field season.

Locality	Location/Description	UTM (NAD27)	NTS Map Sheet	Formation	Approximate thickness	Number of Samples
L2001A	Murky Creek	0445930E; 6734930N	95C/9	Chinkeh (L2000N section)		2
L2001B	Murky Creek	0445275E; 6734055N	95C/9	middle-upper Garbutt	90 m	14
L2001C	south tributary to Murky Creek	0446293E; 6733701N	95B/12	Chinkeh	4-5 m of Chinkeh	1
L2001D	middle headwaters to Sully Creek	4494000E; 6726400N	95B/12	Chinkeh	>10 m of Chinkeh	1
L2001E	Sully Creek; middle tributary	0448134E; 6725500N	95B/12	Lepine? Or Scatter	15 m	4
L2001F	Kootaneelee Rv.	0431700E; 6718325N	95C/9	Chinkeh	>10 m of Chinkeh	3
L2001G	Kootaneelee Rv.	671888N, 438333E	95C/9	Chinkeh		-
L2001H	Kootaneelee Rv.	0441765E; 6717892N	95C/9	Scatter	>47 m	7
L2001I	Kootaneelee Rv.	0445524E; 6708667N	95B/12	Sikanni?	10 m measured	3
L2001J	Toreva Creek	0394283E; 6612085N	94N/10	basal Garbutt Fm.	46 m measured	10
L2001K	Liard, opposite Scatter River	0406207E; 6607691N	94N/10	Sikanni and Sully fms.	130+250 m	43
L2001L	Mt. Martin creek	0435132E; 6667046N	95C/1E	Triassic-Chinkeh-Garbutt	27 m of Chinkeh	6
L2001M	Mt. Martin creek	0434722E; 6667151N	95C/1E	Bulwell-Wildhorn contact	15 m	1
L2001N	Petitot Rv.	0500819E; 6650295N	94O/15W	Bulwell Mbr. Of Scatter?	15 m	2
L2001O	Petitot Rv.	0500121E; 6651456N	95B/2W	Wildhorn Mbr of Scatter?	15 m	1
L2001P	Petitot Rv.	0480373E; 6668779N	95B/3	Dunvegan Fm.	15 m	1
L2001Q	Petitot Rv.	0480759E; 6668595N	95B/3	Sully-Dunvegan contact	12 m	3
L2001R	Petitot Rv.	0476589E; 6673754N	95B/3	Sully Fm?	40 m	5
L2001S	Petitot Rv.	0475778E; 6674083N	95B/3	Sully Fm?	below L2001R	1

Table I-2. Liard Basin localities studied in 2001 field season.

	Location description	UTM (NAD27)	NTS Map Sheet	Formation	Approximate thickness	Number of Samples
L2002A	Muskeg Rv.		95B/6	Lepine?		3
L2002B	East bank Liard opposite Garbutt Creek	~0396300E; 6586700N	94N/7	Upper Scatter - Lepine	170 m	18
L2002C	East bank of Liard Rv.	0397030E; 6589068N	94N/7	near base of Lepine	78 m	10
L2002DA	East bank of Liard north of Garbutt Creek	0396407E; 6587416N	94N/7	Lepine	68 m	6
L2002DB	East bank of Liard between Lepine and Chimney Creeks	0398651E; 6596695N	94N/7	~ middle Lepine Fm.	>500 m	41
L2002E	East bank of Liard between Lepine and Chimney Creeks	0399985E; 6595450N	94N/7	Sikanni Fm.	130 m	6
L2002F	Liard opposite Scatter Rv.	0405516E; 6607513N	94N/10	uppermost Lepine	>250 m	17
L2002G	Liard opposite Scatter Rv.	0406043E; 6607550N	94N/10	Sikanni Fm.	130 m	8
L2002H	Liard opposite Scatter Rv.	~ same as L2001K	94N/10	basal Sully contact	15 m	1
L2002I	Liard opposite Scatter Rv.	~ same as L2001K	94N/10	base of FSMB	15 m	1

Table I-3. Liard Basin localities studies in 2002 field season.

Chapter II. HIGH-RESOLUTION BIOSTRATIGRAPHY, REGIONAL CORRELATION AND PALEOGEOGRAPHY OF THE CHINKEH AND LOWERMOST GARBUTT FORMATIONS IN OUTCROP AND SUBSURFACE IN THE LIARD BASIN

Introduction and Geological Setting

The lowermost Cretaceous strata in the Liard basin are the sandstones of the Chinkeh Formation and shale of the lowermost Garbutt Formation deposited during the early transgression of the Clearwater-Moosebar Sea (see Figure V-3). The Clearwater cycle represents the Aptian?/Early Albian southward marine transgression from the Boreal Sea to approximately latitude 52° in the foothills and plains of Alberta and British Columbia. This flooding was the beginning of the widespread marine invasion that would dominate the Western Interior during much of the remainder of the Cretaceous. In addition to their importance for understanding the paleogeography and relative sea level changes of Early Cretaceous time, these basal Cretaceous deposits are of great interest because of their proven hydrocarbon potential in the Maxhamish field of northeastern British Columbia.

Stratigraphy and Previous Work

Basal Cretaceous beds of the Chinkeh Formation (Figures II-1, II-2) consisting of siltstones, sandstones and conglomerates in the Liard Basin lie on a regional unconformity that truncates successively older beds both northward and eastward. In the Maxhamish area abutting the Bovie Structure, Cretaceous strata lie on Triassic shales of the Liard/Toad formations. At Mount Martin, Cretaceous strata overly the interbedded shale, siltstone and sandstones of the Triassic Toad Formation (MacNaughton and Utting,

2001). In the Liard Plateau they lie on the Carboniferous and Permian Mattson and Fantasque formations, respectively. Previous workers noted the presence of some coarser beds at the base of the Garbutt and Buckinghorse formations (Stott, 1960, 1982; Williams, 1978). Leckie et al., (1991) formally defined the Chinkeh Formation (based on an outcrop study) as a regionally mappable package of strata in the Liard Basin and divided it into four units (see Table II-1). It was concluded that the Chinkeh Formation consists of a lower succession of conglomerates, breccias and non-marine fluvial valley fill overlain by a transgressive lag and prograding coastal sandstones which were finally transgressed by the Moosebar/Clearwater-equivalent deposits of the Garbutt Sea. The sandstone bodies of the Chinkeh were likely formed as a result of reworking of coast-parallel beaches and cliffs along the Bovie Structure during transgression, or as a result of a transgressed barrier island (Leckie et al., 1991). Dixon (1997, 1999) described the Arrowhead B-41 core in the Northwest Territories, and interpreted the Chinkeh Formation there as a fining-upward, channel fill to marine succession overlain by a marine ravinement surface.

In an unpublished M.Sc. thesis, Frank (2002) redefined the Chinkeh Formation based on sedimentological, ichnological and well log correlations as a shoreface complex with point sources, strandplanes, and embayments that prograded westwards and eastwards into a southerly advancing Boreal Sea along either side of the present La Biche and Kotaneelee ranges (from the west and east, respectively). This interpretation equated the subsurface "Chinkeh Formation", best known from the Maxhamish Lake gas pool, with the Bulwell Member of the Scatter Formation, rather than with the Chinkeh Formation described from outcrop to the northwest. Frank (2002) concluded that the

only true Chinkeh Formation lies in a north-south oriented belt far to the west of the Bovie Structure outcropping along the Franklin Liard, Kotaneelee and La Biche ranges. He thus equated the Bulwell Member of the Scatter Formation in outcrop along the western margin of the Liard Basin with the subsurface "Chinkeh Formation" of the Maxhamish field.

Biostratigraphy and other Age Constraints

Biostratigraphic constraints on the age of the Chinkeh Formation have proven difficult to ascertain and have been entirely based on outcrop samples. A Hauterivian to Albian age was suggested from basal Cretaceous sandstone at Jackfish Gap in the northern part of the Liard Plateau based on palynology (Braman and Hills, 1977). Basal Cretaceous shales of the Garbutt Formation overlying Cretaceous sandstones or the pre-Cretaceous unconformity in the Scatter River and Liard Range areas have been dated as Early Albian (with a possibility of Aptian age) based on foraminifera (Wall, in Stott, 1982) and thus place an upper limit on the age of the Chinkeh. Similarly, basal Buckingham Formation beds (approximately equivalent to the basal Garbutt or Chinkeh formations) on the Prophet River were also assigned an Early Albian age (Chamney in Stott, 1973). Palynological data in Leckie et al. (1991, table 1) indicate a Barremian to early Albian age for the Chinkeh Formation in outcrop. Thus, based on previous micropaleontological studies, the age of the Chinkeh can be constrained to Barremian to Early Albian.

Leckie et al. (1991) noted that a burial history curve for a well near Beaver River indicates that the sub-Cretaceous unconformity likely developed during erosion of the underlying Triassic sediments through Jurassic and earliest Cretaceous time.

Purpose and Methods

A number of wells in which the Chinkeh Formation is cored were logged and sampled for micropaleontology and Rock-Eval geochemistry (Figure II-1, Table II-2). Additionally, the Chinkeh Formation also crops out at a number of localities on the flanks of the La Biche, Kotaneelee and Franklin Liard ranges where it overlies the Triassic Toad, Carboniferous Mattson or Permian Fantasque formations. A number of these outcrops were studied and sampled (Figure II-1, Table II-3). Subsurface well log correlations were completed using the iDc digital well log database and Geosection software and IHS AccuX digital correlation software. The evidence presented in this study provides time constraints on the age of the Chinkeh and its development, allows high-resolution, regional stratigraphic correlations of the Chinkeh and lower Garbutt interval, and supports the traditional interpretation of the Bulwell and Chinkeh formations separated by the Garbutt Shale. The evidence comes from well log correlations, biostratigraphy and sedimentology of outcrop and core. One correlation is discussed and figured in the following discussion section; more detailed correlations and discussion are provided in Chapter VII.

Results

In previous studies of the Chinkeh based mainly on outcrop (Leckie et al. 1991) and core and outcrop (Frank, 2002), the Chinkeh was divided into a number of units (each representing a lithofacies assemblage) or facies, respectively (Table II-1). Although the above two studies were generally not based on the same outcrop/core of the Chinkeh Formation, and the latter study concluded that the Chinkeh in outcrop is stratigraphically below the subsurface “Chinkeh”, the present study draws on multiple

lines of evidence to confirm the equivalence of the Chinkeh in core and outcrop. Table II-1 shows the equivalence of Frank's divisions with those proposed here and in previous studies.

Based on core data from the Maxhamish area and detailed subsurface correlations, Pedersen (pers. comm.) showed that the Chinkeh can be subdivided into five units. Table II-1 details these units and their relationship to those in previous studies. In general, the units display an overall fining upward pattern, and are separated by significant surfaces. Facies interpretations in this study are listed in Table II-4.

This study utilizes numerous core and outcrop localities (Figure II-1). The observations are first presented for the Maxhamish Lake area where the Chinkeh and lower Garbutt formations are cored on the eastern margin of the Liard Basin in northeastern British Columbia (including Figures II-1, II-3, II-5, II-6). The expression of the Chinkeh Formation in core and outcrop in the Northwest Territories and Yukon is then presented (including Figures II-1, II-4, II-7, II-8, II-9, II-10 to 17) and integrated with that known from the subsurface at Maxhamish Lake.

Chinkeh Formation in the Subsurface at Maxhamish Lake, British Columbia

The Chinkeh Formation has only been cored in the subsurface on the eastern margin of the basin. Of the studied wells that core the Chinkeh Formation, five are in the region of the Maxhamish gas field and two were drilled in the Northwest Territories, east of the Liard River (Figure II-1, Table II-2). Measured Maxhamish core with micropaleontological data and interpretations are illustrated in Figures II-3a-g. A number of other wells in the Maxhamish area penetrate the Chinkeh Formation or the strata which

directly overlies it. The majority of the wells selected for this study core all or most of the Chinkeh and provide a south-north selection of wells from the field.

In the Maxhamish area, the Chinkeh Formation overlies shale and siltstones of the Triassic Toad Formation. In this area, the Chinkeh consists of approximately 9-16 m of non-bioturbated to heavily bioturbated, glauconitic, thin to thick-bedded, massive, wave-rippled, planar laminated or hummocky cross-stratified very fine-to-fine sandstone with some shale or mudstone strata (Figures II-3a to e). Some intervals are organic rich with abundant coalified woody organic matter on bedding surfaces. In some wells (Figures II-3d, II-3e) several surfaces are characterized by chert pebbles or rare carbonate clasts, and these aid in regional interpretations and the identification of sequence boundaries.

Unit A.

Sedimentology and Well log correlation. Where present, Unit A directly overlies the sub-Cretaceous unconformity, and consists of a planar-laminated to current-rippled siltstone to fine sandstone (F_b) with a conglomerate at its base (F_a) composed of chert and/or angular limestone clasts (Figure II-5a). Unit A is generally less than 1 m in thickness. In well logs, the base of this unit is barely distinguishable from the overlying Unit B, both of which are marked by sharp deflections of the gamma ray and resistivity logs (Figure II-3d).

Micropaleontology. In the c-03-J well (Figure II-3d), a sample from this interval contains a low diversity foraminiferal fauna with specimens of *Ammobaculites* and *Verneuilioides*, indicating a stressed, yet marine environment. A similar fauna occurs in the b-53-G-094-N-014 well to the north (Figure II-3e), along with *Gaudryina nanushukensis*.

Interpretation. Unit A represents initial marine flooding over the sub-Cretaceous unconformity. The foraminiferal fauna represents a restricted, but marine assemblage of the Lower to Middle Albian *Gaudryina nanushukensis* Zone. Subzone resolution is not possible with this low diversity fauna, but overlying strata constrain this interval to the Lower Albian. Carbonate and chert clasts were likely derived locally from the Permian Fantasque Formation and represent a transgressive lag and erosion of coastal cliffs along the Bovie Structure or underlying Paleozoic strata. Sedimentary structures and grain size indicate a middle to upper shoreface environment.

Units B and C.

Sedimentology and Well log correlations. Units B and C are characterized by fine- to medium-grained, clean to muddy, often highly glauconitic, planar-laminated and hummocky cross-stratified sandstone (F_c, Figure II-5a). In some wells, Units B and C are separated by a matrix-supported pebble bed (Figure II-3d, II-3e) or a *Glossifungites* surface (Figure II-3a), while in others it is not possible to distinguish the two units. Some muddy intervals alternate between heavily bioturbated to parallel laminated (laminated and scrambled facies). These units form the main reservoir of the Maxhamish gas field.

Micropaleontology. Foraminiferal yields from fine- to medium-grained sandstones are typically very low, partly because of the difficulty processing coarser-grained sedimentary rocks. Hence this interval was generally not sampled; however, a sample from Unit B in the a-60-B-094-O-11 (Figure II-3a) well was barren.

Interpretation. The abundant hummocky cross-stratification, fine- to medium grain size and bioturbation within Units B and C indicate deposition in a lower to middle shoreface environment. The laminated and scrambled facies are typical of storm-

dominated shoreface to offshore transition zone settings where the upper parts of otherwise non-burrowed tempestites and overlying fair-weather strata are colonized by burrowing organisms (Pemberton et al., 2001). The presence of a pebble bed and/or *Glossifungites* surface between the two units may indicate the presence of a sequence boundary. *Glossifungites* surfaces are formed by erosional exhumation of previously deposited unlithified sediments during a relative sea level fall and subsequent rise followed by heavy burrowing by vertical tracemakers.

Unit D.

Sedimentology and well log correlations. The base of Unit D, especially prominent in the c-03-J well (Figure II-3d), is placed at the chert pebble bed (F_a) in that well (Figure II-5b), above which a distinct fining occurs to heavily bioturbated siltstone (F_d). Abundant bioturbation generally obscures sedimentary structures in this unit. In other wells, the base of the unit is represented by a distinct fining relative to the underlying strata (e.g. b-079-G, Figure II-3c). Unit D is generally 3-5 meters in thickness and a distinct *Glossifungites* surface occurs at the top of it in the a-60-B (Figure II-3a) and c-003-J (Figure II-3d) wells. In the b-079 (Figure II-3c) well, the upper metre of this unit is heavily bioturbated.

Micropaleontology. The lower samples of this unit were generally barren, however samples from the upper part of Unit D yielded a similar but slightly more diverse and abundant fauna from Unit A with the addition of *Ammobaculites* sp., *Trochammina gatesensis*, and *Gaudryina tailleuri*.

Interpretation. The chert pebbles at the base of this unit in the c-03-J well indicate that a combined sequence boundary and transgressive surface of erosion

separates Unit D from the underlying unit; however, no similar evidence is present in the other studied wells that core this interval. This unit is tentatively interpreted to have been deposited in the offshore transition to offshore zone in the c-03-J well, but ranges into the lower shoreface in some of the other wells where it occurs. The barren samples in the lower part of the unit are atypical of an offshore transition to distal lower shoreface type of environment. In a nearby well to b-079-G, Frank (2002) interpreted the equivalent interval as distal lower shoreface (his facies C in Figure II-12).

Unit E.

Sedimentology and Well log correlations. Vertical traces into the top of Unit D are infilled with glauconite (Figure II-5c). These are overlain by the heavily bioturbated, organic rich shale to siltstone (F_e), slight coarsening-upwards interval of Unit E. In many wells, this unit contains abundant coalified terrestrial organic matter (including coalified twigs). A slight coarsening-upwards interval to interbedded siltstone and silty shale at the top of Unit E is seen in wells that core this interval (e.g. b-079-G/094-O-11, c-03-J/094-O-11 wells in Figures II-3c, d).

Micropaleontology. Samples from the base of this unit in most wells studied (e.g. c-03, b-079) preserve a peculiar agglutinated fauna in which most or all foraminifera are composed of bright green glauconitic grains. Residues are extremely rich in glauconitic grains. The foraminiferal species are similar to those in the underlying units and are of low diversity. Additionally, both wells also preserve abundant radiolarians that also appear to be coated with, or secondarily replaced by, glauconite. The upper part of the interval in the b-079-G well was barren, but samples in the c-003-J well preserve a more diverse fauna with the addition of *Ammodiscus rothlis* and *Glomospira* sp.

Interpretation. The *Glossifungites* surface separating Units D and E (in some wells) indicates the presence of a sequence boundary. This surface represents a transgressive surface of erosion (TSE) produced by wave-ravinement during the ensuing transgression. In the c-03-J well, a sample from the base of Unit E contained sand-sized subangular to subrounded chert fragments, providing additional evidence for a subtle TSE and a non-preserved upper shoreface. The distinct faunal assemblage overlying this surface, here referred to as the “Glaucinitic Assemblage”, marks a distinct and peculiar biofacies for the Early Albian of the Liard basin. A second faunal change, best represented by the overlying strata in the c-03-J well (Figure II-3d) within this unit is characterized by what is referred here to as the *Ammodiscus-Glomospira* assemblage within the *Gaudryina nanushukensis* Zone (Figure II-2), also a distinct assemblage of species within the basin suitable for regional correlations.

Although Unit E contains a high amount of organic matter, it is interpreted to represent offshore to offshore transition zone strata. The foraminiferal fauna and the abundant bioturbation (especially in the c-03-J well) indicate a more normal marine assemblage than the underlying units in the Chinkeh Formation. Although Unit E may be superficially mistaken for the Garbutt Formation, it differs from the typical Garbutt facies in the Liard Plateau region; however, the correlations and biostratigraphy presented below indicate that this unit is equivalent to the basal Garbutt mapped lithostratigraphically in the Liard Plateau.

While the uppermost strata in the b-079-G and c-03-J wells are characterized by a slight coarsening-upwards interval, Frank (2002) reported a distinct siltstone bed with a *Glossifungites* surface with subaerial roots at the top in the nearby b-73-G/94-O-11 well

(top of Unit E). He interpreted this as a combined SB/TSE that developed due to forced regression and subsequent transgression. This interval is interpreted here as a normal regression overlain by a transgressive surface of erosion, because it lacks the diagnostic criteria of a forced regression such as sharp-based shoreface deposits overlying gutter casts in offshore mudstone (e.g. Plint and Nummedal, 2000). The fauna of the upper part of unit E persists into the overlying Garbutt Formation, as is shown by its presence in the lower Garbutt Formation (although not lowermost) in the b-053-B well.

Unit F.

Sedimentology and Well log correlations. Unit F consists of black fissile to silty shale that abruptly overlies Unit E (F_r, Figure II-6a, b). Unit F contains numerous 2-10 cm thick bentonite beds. It can be observed at the top of the b-79-G (Figure II-3c) well and is also cored in the b-59-I (Figure II-3f) and b-053-B (Figure II-3g, II-6b) wells.

Micropaleontology. Few wells core Unit F together with the underlying units of the Chinkeh Formation. In the b-79-G well (Figure II-3c), a sample from the base of this unit contains only a single specimen of *Haplophragmoides*. The *Ammodiscus*-*Glomospira* fauna was found at the base of the b-053-B core (Figure II-3g, II-6a) where it is dominated by *Ammobaculites fragmentarius* and *Ammodiscus rotalarius*. In both the b-59-I and b-053-B wells, which do not core the basalmost shales of the Garbutt Formation (Figs. 3f, g), the *Ammodiscus* assemblage is succeeded by barren or poorly yielding samples that are otherwise characterized by fish debris and in some cases abundant radiolarians (Figure II-6b).

Interpretation. Unit F represents shelf deposits of the Garbutt Formation. The fauna at the base of Unit F is similar to the upper part of the underlying Unit E, but a

gradual replacement by a stressed fauna occurs within the unit. Frequent volcanic events combined with the deep shelf conditions appear to have led to dysoxia/anoxia or otherwise toxic conditions for benthic foraminifera. Abundant radiolarians may indicate significant upwelling, and their preservation potential may have been enhanced by increased oceanic silica concentrations due to the silica-rich ash falls. This fauna is assigned to the “Radioactive Radiolarian-Rich Interval” due to its high gamma-ray signature in well logs. The K-32 and B-41 wells in the Northwest Territories also core this interval (see below).

Chinkeh Formation in the Yukon and Northwest Territories

Because the unit divisions of the Chinkeh Formation in the subsurface at Maxhamish Lake are integrated with the sequence stratigraphic interpretation and biostratigraphy, they represent time-correlative packages bounded by unconformities, or stratigraphic sequences. In this section correlation of these units with Chinkeh and lowermost Garbutt Formation strata to the north (on the eastern margin of the basin) and the northwest (on the western margin of the basin) is attempted based on biostratigraphy, sedimentology and well log correlations (see Figures II-4a-c, II-10a-h, II-18).

Subsurface Description. North of 60° latitude, only two wells core the Chinkeh Formation (Table II-2, Figures II-1, II-4a, b, c), and one well cores the overlying shale succession (Figure II-1, II-4d). These wells are located on the northeastern margin of the basin (Figure II-1). The Arrowhead B-41 well (Figure II-4a, b) is notable though, because of its thickness (>23 m of Chinkeh), diversity of physical and biogenic sedimentary structures, and sedimentary environments represented.

In the B-41 well (see Figures II-4a, b for additional sedimentary observations), basal angular limestone and chert clast conglomerates (F_a) are overlain by organic-rich shale (F_g, Figure II-7a, b), thick, planar laminated to cross-bedded medium to fine sandstone (F_h, Figure II-7c) and another interval of organic rich shale with some coarser-grained intervals with mud-drapes on high-angle foresets. The top of the Chinkeh succession is overlain by a burrowed surface with a chert pebble conglomerate (F_a, Figure II-8a, b). Additionally, 15 m of Garbutt Formation is cored above the Chinkeh, providing an important biostratigraphic tie to other localities. In the L-49 well, less than 8 m of the Chinkeh Formation are cored (Figure II-4c), but the core is characterized by planar-laminated to cross-bedded sandstone with abundant organic debris.

Foraminifera were recovered from only the basal part of the lower organic-rich unit, and from some samples within the upper organic-rich unit in the B-41 well (Figure II-4b). The foraminiferal fauna is of lower diversity and abundance, being characterized by *Verneuilinoides cummingensis*, *Saccamina* sp., *Bathysiphon* sp. and *Psamminopelta* sp. No foraminifera were recovered from the L-49 well.

Subsurface Interpretation. Of the two wells studied that core the Chinkeh Formation, both appear to preserve marginal marine deposits. In the B-41 well, the upper and lower organic-rich intervals are interpreted as estuarine deposits (central basin facies). The micropaleontological samples from these intervals were either barren or contained an stressed fauna typical of a brackish estuarine environment. Additionally, some foraminiferal tests recovered were pyritized, and this combined with the high organic matter content of the mudstone may also reflect intermittent oxygen stresses were present. The sharp-based sandstone unit with abundant organic debris and cross-beds is

interpreted as fluvial or tidal channel fill with a basal lag (Figure II-4a, II-7a, b, c). The Arrowhead L-49 (Figure II-4c) is interpreted to be composed of marginal marine, tidally-influenced or tidal channels. The presence of *Verneuilinoides cummingensis* in the B-41 well implies an Early Albian age for this interval, as this foraminifer is typical of the lower part of the *Gaudryina nanushukensis* Zone. The uppermost part of the Chinkeh Formation in the B-41 well is interpreted as a *Glossifungites* surface and TSE (Figure II-8a, b). This indicates the presence of a sequence boundary and TSE at this surface, similar to the Chinkeh-Garbutt transition in the Maxhamish field.

The basal Garbutt Shale in the B-41 well is characterized by the distinctive *Ammodiscus-Glomospira* assemblage observed in Unit E of the Chinkeh at Maxhamish and the basal Garbutt Formation below the radioactive radiolarian-rich interval. As elsewhere, this assemblage occurs below the bentonites (Figure II-4b). Samples from the bentonite interval present in the B-41 and K-32 core (Figures II-4b, d; Figure II-9a, b) are characterized by an absence or low diversity benthic foraminiferal fauna, but preserve abundant radiolarians, fish vertebrae and other fish debris, consistent with this interval in wells in the Maxhamish region of British Columbia. The sedimentary environment is thus interpreted as shelfal with alternating dysoxia and anoxia associated with frequent volcanic events and deep-water conditions. Further correlations of the Northwest Territories wells with those in northeastern British Columbia and the Liard Plateau are provided in the discussion section.

Outcrop Description. Outcrops of the Chinkeh Formation are generally restricted to the Liard Plateau (southern Mackenzie Fold Belt) on the northwestern margin of the basin, although isolated equivalents can be found along some of the tributaries feeding

into the Liard River and in the Steamboat Mountain region of northeastern British Columbia. The outcrops of the Chinkeh Formation in the plateau area are widely varying in thickness, but generally preserve a variety of sedimentary structures indicating a transition from fluvial to marine deposition, and chert and/or carbonate clast conglomerates (F_a) indicative of several cycles of relative sea level fluctuation (Figs. 10b-h). Some of these outcrops have been studied previously by other authors (Leckie et al., 1991; Frank, 2002), although limited biostratigraphic work has been completed to date. The Mount Martin locality (Figure II-10b), newly described here, is the southernmost outcrop of the Chinkeh to be described north of 60° latitude and exceeds 26 m in thickness. A thin Chinkeh Formation was reported by Leckie et al. (1991) from Lepine Creek, northeastern British Columbia, and thicker outcrops occur near Steamboat Mountain (L37 and L9 in Leckie et al., 1991).

All outcrops of the Chinkeh and lowermost Garbutt formations in the Liard Plateau (Figure II-1, II-10a to h) have several features in common, and are here integrated with the unit divisions of Pedersen (pers. commun.) of the Chinkeh Formation established in the subsurface at Maxhamish Lake (Table II-1). The integration of these units is constrained by biostratigraphy and comparison of the stratigraphy of the outcrops with the subsurface data on the eastern margin of the basin. In this section, several outcrops are briefly described and some micropaleontological interpretations are given. The overall interpretations of these outcrops are given in the relevant figures.

The Chinkeh outcrop along the Kotaneelee River (Figure II-10d) at the eastern Kotaneelee Range Gap is most dissimilar to the other outcrops as it contains a thick breccia deposit and several meters of fluvial deposits. This outcrop preserves a basal

fluvial channel below the marine Chinkeh shoreface sandstones (Figure II-16a). Up-river at the west Kotaneelee gap (Figure II-10c, Figure II-16b, c), a thin carbonate breccia and chert pebble conglomerate (F_a) is overlain by a thick succession of coarsening-upwards sandstones (F_c) interpreted by Leckie et al. (1991) as marine shoreface sandstones. In fact, all the other outcrops are generally characterized by a basal chert pebble lag conglomerate overlain by several meters to several tens of meters of often heavily glauconitic (at their base and top), organic rich, slightly to heavily bioturbated hummocky cross-stratified to planar laminated shoreface sandstones. Most outcrops preserve evidence at their base of fluvial or alluvial sedimentation represented by limestone breccia or chert pebble conglomerates. In most areas, these basal non-marine to marginal marine deposits were reworked into lags during the transgression of the Moosebar Sea.

Mount Martin (L2001L)—Lower Sequence. The Chinkeh Formation at Mount Martin is subdivided into a lower and upper sequence. The thick southern expression of the Chinkeh along the west flank of Mount Martin (Figure II-10b; Figures II-11 to II-14) is important for regional correlations. At this locality the strata dip steeply to the west and are exposed along a small creek where they overlie interbedded shale and siltstones and thin fine sandstones of the Triassic Toad-Grayling Formation (Figure II-11a, b). The sub-Cretaceous unconformity is overlain by a clast-supported chert pebble conglomerate with 2-10 cm diameter subrounded pebbles in a medium-grained sand matrix interpreted as a transgressive lag (F_a , Figure II-10b). This is overlain by 0.5 m of medium- to coarse-grained sandstone with abundant organic debris and is overlain by another thin chert pebble bed. The overlying thin-to-thick bedded sandstone succession is parallel to ripple laminated, has moderate amounts of organic material on the bedding surfaces, and is

moderately bioturbated, at least in the uppermost 6 m. Bed thickness and grain size show a slight decrease upwards. This is overlain by a 1.5-m-thick interbedded shale and siltstone interval (Figure II-12a). Foraminifera from this shale interval are characterized by a low to moderate diversity fauna of the *Gaudryina nanushukensis* Zone, including *Ammodiscus* sp. and *G. nanushukensis* (Figure II-10b).

Mount Martin—Upper Sequence. Another chert pebble conglomerate bed (F_a), taken as the base of an upper sequence at this locality, overlies the shale interval (Figure II-12b). Thin- to medium bedded laminated and moderately bioturbated siltstones and fine sandstones with some silty shale interbeds (F_c) characterize the second sequence of the Chinkeh Formation (Figure II-13a). This interval is extremely glauconitic giving a 25 cm silty interval a dark green colour (Figure II-13b). Isolated chert pebbles occur in the lower 10 cm of the Garbutt Shale (Figure II-14), marking the base of the next sequence and the basin-wide flooding event of the Moosebar-Clearwater marine cycle.

A sample from the enriched glauconite strata was barren of foraminifera but contained abundant well-rounded chert fragments. No foraminifera were recovered from the green siltstone interval; however a sample at the base of the Garbutt shale contains glauconitic foraminifera (*Verneuilinoides borealis*) similar to the Glauconitic Assemblage observed in the subsurface Chinkeh Formation. Foraminifera in samples of the overlying Garbutt Formation above this are poorly preserved but contain typical species of the *Gaudryina nanushukensis* Zone.

West Kotaneelee Gap and La Biche River. Northwards from the Mount Martin locality, outcrops in the west Kotaneelee gap (Figure II-10c, II-16b, c) and tributary to La Biche River (Figure II-10h) show coarsening-upwards middle shoreface sandstone

successions underlain by chert pebble lags. At the La Biche River locality, however, there appears to be shale on shale contact with the underlying Permian strata as a low diversity foraminiferal fauna rich in the genus *Ammodiscus* was recovered from below the chert pebble lag. Samples in the lower part of the progradational succession overlying the lag were organic-rich and generally barren of foraminifera (except for the uppermost sample). Leckie (1991a) and Frank (2002) noted the presence of a *Glossifungites* surface at the top of this progradational succession in outcrop to the south of this locality on La Biche River.

At the west Kotaneelee gap locality (Figure II-10c), a low diversity and low abundance fauna along with abundant coalified organic matter was recovered from the lower shale interval overlying the basal lag, and these include uncharacteristically large foraminifera of the *G. nanushukensis* Zone.

Murky and Sully Creeks. North of Murky Creek (L200P, Figure II-10g), a rich foraminiferal fauna was also recovered from a shale interval underlying the Chinkeh sandstone. This fauna is similar to the *Ammodiscus-Glomospira* fauna observed in the upper part or overlying the Chinkeh Formation in the subsurface at Maxhamish. Stratigraphic relationships at this outcrop were obscured by faulting, however, making definitive interpretations difficult.

South of L2000P along the west flank of the Franklin Liard Range, the Murky Creek “Waterslide” outcrop (Figure II-10f; Figure II-10e is 2-3 km south of this) is perhaps most important for regional correlations. At this locality, the 6.5-m-thick progradational sandstone succession overlies a conglomeratic boulder bed and contains abundant glauconite, woody organic matter, and is heavily bioturbated (Figure II-17a to

c). The uppermost part of the Chinkeh here is overlain by a *Glossifungites* surface followed by offshore shales of the Garbutt Formation. The first volcanic ash beds occur approximately 40 m above the base.

Some samples from within the Chinkeh Formation at the Murky Creek “Waterslide” locality contain a low diversity *G. nanushukensis* Zone fauna similar to this equivalent interval elsewhere in the basin, while others are barren (Figure II-10f). A sample in the basal part of the Garbutt is characterized by the peculiar Glauconitic Assemblage fauna, including *Verneuilinoides* sp., *Gaudryina* sp. and radiolarians. Above this, the overlying shale succession below the volcanic ash beds 40 m above the base of the Garbutt Formation contains the *Ammodiscus-Glomospira* Assemblage, but with the addition of calcareous genera (*Globulina lacrima*, *Conorbina* sp., *Saracenaria* sp.) and fish debris.

Interpretation of Outcrops. The Chinkeh Formation in outcrop in the Liard Plateau is usually characterized by a conglomeratic chert pebble transgressive lag (Unit A, sometimes overlying a limestone breccia) overlain by a succession of glauconitic lower to middle shoreface sandstones (Units B and C) that, based on the abundance of organic matter and benthic foraminiferal faunas, were deposited in a stressed marine, lower to middle shoreface environment. The stresses may have been high sedimentation rates and energy associated with frequent storms. Foraminiferal faunas from this interval indicate the *G. nanushukensis* Zone. At some localities, the upper part of the succession (which based on evidence from Mount Martin represents an upper stratigraphic sequence) preserves an extremely glauconite-rich and bioturbated interval of lower to middle shoreface sandstones (i.e. at the Mount Martin and Murky Creek outcrops). This upper

unit is correlative to the sequence of Unit D (Table II-1). The uppermost surface of this succession is characterized by the presence of a sequence boundary (i.e. a *Glossifungites* surface and/or chert pebble lag). The base of the overlying Garbutt shale preserves the Glauconitic Assemblage fauna. This interval is thus correlated with Unit E, providing a strong tie between outcrop on the western margin of the basin, and the Chinkeh Formation in the subsurface on the eastern margin of the basin.

Similarly, the Glauconitic Assemblage and *Ammodiscus-Glomospira* Assemblage faunas that occur in the basal part of the Garbutt Formation below the ash beds at Murky Creek provide a strong tie to Unit E of the Chinkeh Formation and the lower part of the overlying Garbutt Formation in the Maxhamish area.

Although the *Ammodiscus-Glomospira* fauna was not recovered from the Garbutt Formation on Toreva Creek (Figure II-10a, II-15a, b), Wall (in Stott, 1982, section 65-12) did identify a similar fauna in the lowermost Garbutt overlying the Triassic Toad Formation along nearby Scatter River. This fauna is thus widespread throughout the basin.

Several Chinkeh “outliers” exist in outcrop. The *Ammodiscus*-rich shale strata underlying the Chinkeh sandstones at L2000L is difficult to interpret in terms of their depositional environment and correlation to the other outcrops and core. A restricted? marine interval underlies the Chinkeh at this locality and more outcrops need to be studied to better understand this interval. An *Ammodiscus*-bearing (species identification not possible), but more diverse fauna containing *Glomospira* sp., *Verneuulinoides cummingensis*, *Gaudryina stotti* and others was also recovered above the apparent shale-on-shale sub-Cretaceous unconformity contact north of Murky Creek (L2000P). These

localities may preserve an early marine flooding event, which preceded deposition of the thick Chinkeh shoreface succession in this area with a fauna similar to that which occurs in the lower Garbutt Formation. It is possible that this *Ammodiscus*-bearing shale represents a marine and time-equivalent of the thick breccia and fluvial channel deposits preserved at the east Kotaneelee gap locality.

In a nearby outcrop to the Murky Creek section, Frank (2002, “Burnt Timber”, fig. III-3) identified a number of transgressive pebble lags and shell hash beds in “lower-middle shoreface” and “intertidal” sandstone that he assigned to the main progradational facies of the Chinkeh Formation. These seem more characteristic of the fluvial-deltaic Mattson Formation, in which benthic macrofossils including brachiopods and bivalves (although not together) were observed in outcrop. Bivalve mollusks are rare in Albian strata in the Liard basin. Identification of the brachiopods and/or bivalves is necessary to confirm or deny whether it is the Mattson Formation. These outcrops north of Murky Creek are structurally complex and caution must be taken in using these to make conclusions about the depositional environment of the Chinkeh Formation.

As to the fluvial deposits, similar strata were also noted at the Chinkeh reference section in the Liard Plateau along the eastern flank of the Kotaneelee Range (L19b), at Tika Creek (L6), and in the river valley south of Steamboat Mountain along Chlotapecta Creek (L9) in northeastern British Columbia by Leckie et al. (1991). Fluvial or and/or tidally influenced strata also dominate portions of the Arrowhead B-41 well in the Northwest Territories.

Discussion

Correlation of Chinkeh and Basal Garbutt Interval (outcrop and subsurface)

Due to the new biostratigraphic and sedimentological data presented here, correlations of the Chinkeh and basal Garbutt formations between outcrop and subsurface are possible. The Chinkeh and basal Garbutt are here divided into several intervals that can be correlated between outcrop and subsurface (Figure II-19):

I. Basal Breccia and/or Conglomeratic Lag (Units A, B)

The base of the Chinkeh is always represented by a chert pebble conglomerate and/or carbonate clast breccia (Unit A). Marine strata usually directly overlie this deposit, except in the few outcrop localities where fluvial deposits overlie (or underlie, depending on the interpretation taken—see Table II-1) this surface.

II. Progradational Chinkeh and Fluvial/Estuarine Valley Fill (Units B, C)

The main Chinkeh reservoir is characterized by fine- to medium-grained, glauconitic, planar-laminated to hummocky cross-stratified sandstones with at least one important genetic surface represented by a *Glossifungites* surface and/or pebble lag (Units B and C). In c-03-J, the finer-grained Unit D has a chert pebble lag at its base and a *Glossifungites* surface at its top (at the base of Unit E). This is very similar to the succession preserved in outcrop at Mount Martin where an extremely glauconitic interval overlies a sequence boundary and provides strong evidence for a regional sequence boundary at the base of Unit D and the upper portion of the Chinkeh at Mount Martin. This also suggests that the two thick progradational cycles at the west Kotaneelee gap and La Biche River localities are

likely separated by a sequence boundary or correlative conformity equivalent to this aforementioned sequence boundary. Foraminiferal faunas recovered from the lower part of the progradational unit of the Chinkeh Formation preserve a low diversity fauna of the Lower Albian *Gaudryina nanushukensis* Zone.

A good correspondence between the Maxhamish and Northwest Territories Chinkeh well log signatures is evident (Figure II-18). Also, Units B and C, which are interpreted to be lower to middle shoreface sandstone at Maxhamish are correlative with the fluvial and/or tidal channel fill facies in the Arrowhead well. Like in the Maxhamish area, a prominent *Glossifungites* surface and TSE overlies the top of the Chinkeh Formation (Unit E) in the Arrowhead B-41 well.

III. Glauconitic Assemblage Interval (Lower Unit E)

The unique Glauconitic Zone was observed both in core (b-079-G, c-03-J) and in outcrop (L2000N, L2001L). This zone directly overlies a prominent *Glossifungites* surface at the base of Unit E. In the B-41 well in the Northwest Territories, the glauconitic assemblage does not occur because Unit E is in estuarine central basin facies (Figure II-4a). This can be seen in the c-03-J to B-41 correlation (Figure II-18). The assumed approximate time-equivalence of this fauna allows correlation of Unit E of the Maxhamish Field with the basal Garbutt shale in outcrop in the Liard Plateau. Correlations also indicate that Unit E, which is interpreted to represent peculiar organic-rich offshore transition zone strata at Maxhamish, is dominated by estuarine facies in the Arrowhead B-41 well.

IV. Ammodiscus-Glomospira Assemblage Interval (Upper Unit E and Unit F in core, basal Garbutt in outcrop)

The *Ammodiscus-Glomospira* Assemblage was observed in the upper part of Unit E in core overlying the Glauconitic Assemblage Zone and in core below the bentonite interval (c-03-J, Arrowhead B-41, b-053-B/94-O-14) and the basal Chinkeh Formation in outcrop (L2000N). In the basal Garbutt Formation overlying Triassic shales along Scatter River in northeastern British Columbia (no Chinkeh is present at that locality, although it could be in offshore facies), Wall (in Stott, 1982, section 65-12) identified a similar fauna. This fauna is thus widespread throughout the Liard Basin. Wall considered this fauna to be Early Albian in age and similar to the assemblage found in the lower part of the Loon River Formation (in Stott, 1982, p. 41). At the “Waterslide” locality at Murky Creek (L2000N) additional calcareous species, such as *Gyroidina nitida* and *Globulina lacrima*, occur in the upper part of this zone.

V. Radioactive Radiolarian-Rich Interval (Basal Garbutt Formation)

An additional time constraint is the bentonite interval preserved in Unit F (or basal Garbutt) in the subsurface, which is here constrained as time equivalent to the bentonites observed in outcrop approximately 40 m above the base of the Chinkeh Formation (b-079-G, c-03-J, b-053-B, b-59-I, b-053-B, Arrowhead B-41, Fort Liard K-32, L2000N). This zone is readily identifiable on well logs as a distinct positive gamma excursion. The well log response is likely due to the abundant potassium-bearing minerals abundant in the bentonite interval. The microfauna of this zone are characterized by a low diversity and abundance or

complete lack of benthic foraminifera, the presence of fish debris and abundant radiolarians. The foraminiferal fauna that underlies this zone (*Ammodiscus-Glomospira* Assemblage), and the radiolarians that characterize the zone, confirm that the bentonites can be used as time-lines across the basin—the bentonites in the basal Garbutt in outcrop are time-equivalent to those in the subsurface overlying the Chinkeh Formation. In other words, the age of the Chinkeh Formation is everywhere older than the bentonites.

Regional Biostratigraphic Correlations

Age constraints and regional faunal correlations of the basal Cretaceous of Western Canada have proven difficult; however, previous work has established a framework and several hypotheses that can be tested with data from the Liard Basin. The ammonite zonation has proven to be the best high-resolution regional correlation tool for shale successions in the basal Cretaceous beds (Jeletzky, 1968, 1971, 1980; Stott, 1982). The main microfaunal biostratigraphic data for correlation to the Liard Basin are foraminiferal studies from the Pine and Athabasca river areas in northeastern British Columbia and northern Alberta (McMurray, Moosebar and Clearwater formations, Stelck et al. 1956; Mellon and Wall, 1956; McLean and Wall, 1981), and the Peace-Tetsa River region (Bullhead Group=Cadomin + Gething formations, and lowermost Buckinghorse Formation, Chamney in Stott, 1973) and the lower Buckinghorse Formation of the Sikanni Chief River area (Schröder-Adams and Pedersen, 2003). Additionally, some foraminiferal data for the lowermost Garbutt Formation have been previously recorded (Wall in Stott, 1982).

Except for a few isolated occurrences of the peculiar *Ammodiscus*-dominated marine shale underlying the main Chinkeh progradational sandstones (not the *Ammodiscus-Glomospira* fauna), the foraminiferal fauna of the Chinkeh and lower Garbutt formations can be assigned to the *Gaudryina nanushukensis* Zone (Figure II-2). The *G. nanushukensis* Zone has been subdivided in the Peace River region into 6 subzones (Caldwell et al., 1978, 1993). A detailed regional comparison between the lowest Albian in the Liard and Alberta basins allows a high resolution zonation of the lowermost Albian.

While the progradational Chinkeh and “Glaconitic Assemblage” units bear similar low diversity foraminiferal faunas, the *Ammodiscus-Glomospira* assemblage below the radioactive radiolarian-rich interval is distinctive and the species present suggest correlation with the lower part of the *Verneulinoides cummingensis*-*Marginulinopsis collinsi* Subzone (Figure II-2). The dominantly calcareous *M. collinsi* fauna has been identified in the shale overlying the basal “glaconitic sand” in the lower parts of the Clearwater and Moosebar formations, including genera such as *Globulina*, *Ammodiscus*, *Gyroidina*, *Haplophragmoides*, *Marginulinopsis*, *Saracenaria*, *Verneulinoides* and *Quadrinorphina*. The Moosebar and Clearwater formations preserve a similar biostratigraphic relationship to the Chinkeh-Garbutt succession in that an arenaceous microfaunal assemblage occurs in the uppermost McMurray Formation and this is overlain by basal Clearwater sediments bearing a calcareous assemblage. Mellon and Wall (1956) and Stelck et al. (1956) considered the upper McMurray Formation to be the southern near-shore facies of the southerly transgressing early Albian Boreal Sea. McLean and Wall (1981) suggested that the southerly transgressing

Moosebar-Clearwater Sea formed extensive estuaries southwards to approximately 52° north latitude in the foothills and the plains regions.

Although missing the zonal marker, the lowermost Garbutt Formation (beneath the radioactive zone) contains a closely similar fauna to that assigned to the lower part of the *Verneulinoides cummingensis*-*Marginulinopsis collinsi* Subzone in the Moosebar and Clearwater formations. Chamney (in Stott, 1973) recovered a similar fauna from the basal Buckinghorse Formation on Prophet River (north of the Sikanni Chief River) although he considered that this fauna may represent a pre-Clearwater Sea (pre-*Subarchthoplites mcconnelli*). In the Liard Basin, the lower part of the *Verneulinoides cummingensis*-*Marginulinopsis collinsi* Subzone is quite distinctive as benthic calcareous foraminifera are only present in this interval of the entire Albian succession in the Liard Basin. Unlike the rich calcareous fauna recovered to the south and southeast (Moosebar Formation in the Peace River area), the fauna in the Liard Basin is less diverse and abundant. This may be due to the location of this basin within the foredeep in close proximity to the uplifting Cordillera and/or a brackish Boreal watermass. A number of cores and outcrops show an especially depauperate fauna especially in the bentonite rich-interval of the lower Garbutt, suggesting that volcanic events and perhaps high sedimentation rates had a deleterious effect on the benthic fauna in this area. Another similarity between the Liard and Alberta Basin faunas is that a shift back to arenaceous faunas also occurs in the middle part of the Clearwater Formation (like in the Garbutt Formation). This may indicate regressive conditions or a drop in salinity in the late Early Albian Sea (Stelck et al. 1956).

The ammonite *Arcthoplites* (= *Lemuroceras*) has been recovered from the basal Buckingham Formation at the type section (Stott, 1982) and it has a widespread distribution elsewhere in the WCSB. Caldwell et al. (1978) equate the upper Lower Albian *Arcthoplites irenensis* and *Subarchthoplites mcconnelli* ammonite zones (Figure II-2) with the *M. collinsi*-*V. cummingensis* microfaunal Subzone. However, the basal Buckingham/Garbutt appears to become older northwards so that in the Liard range the basal Garbutt contains the earliest Albian ammonite *Pachygrycia canadensis* (Jeletzky in Stott, 1982). The ammonites reveal that during *M. collinsi* time, a continuous seaway extended from the Arctic coast to northeastern British Columbia and northern Alberta (check localities), as *Arcthoplites* has been recovered from the Liard, Peace, lower Mackenzie, and Peel River areas and the Torok Formation of Alaska (Stelck et al. 1956, Stott, 1982).

To understand the earliest Cretaceous transgressions and regressions, it is necessary to establish reliable correlations of the Bullhead Group into the Liard Basin. Stott (1968, 1982) and Caldwell (1984) suggested that the lower Buckingham Formation in the Tetsa River valley and the lowermost Garbutt Formation in the Liard River area are correlative with at least the upper portion of the Gething Formation. Previously, Stott (1968, 1973) had suggested that the Bullhead Group was likely at least Barremian-Aptian in age based on palynological analysis. According to Caldwell (1984), the diverse fauna from the Gething outlined by Chamney (in Stott, 1973) does not contain diagnostic pre-Albian foraminifers. Caldwell (1984) also disputed the palynological evidence and thought that at least the entire Gething Formation, and possibly the entire Bullhead Group (Cadomin, Gething and Bluesky formations), could be earliest Albian in age

(*Pachygrycia* ammonite Zone) and suggested that evidence of this lower transgressive-regressive couplet should be sought in the lower Buckinghorse and Garbutt formations. Hence Caldwell (1984, fig.4; 1993, fig. 6), in his south-north simplified stratigraphic cross-sections of northeastern British Columbia indicated stratigraphic equivalence of the Bullhead Group and the lower part of the Garbutt Formation. Leckie et al. (1991), in agreement with these correlations, also suggested that the Cadomin and Chinkeh formations may be stratigraphic equivalents.

As alluded to in Caldwell (1984), the Garbutt Formation at Scatter River (and nearby Toreva Creek) is characterized by a lower and upper coarsening-upward succession (Stott 1982) overlying pre-Cretaceous rocks (Figure II-15a). Caldwell (1984) suggested the lower cycle may be a Gething-equivalent transgressive-regressive couplet. This is because the offshore equivalent to the northerly prograding Gething deltaic succession is justifiably expected to the north as it is believed that the Gething prograded north into a marine embayment. Biostratigraphic recovery from Toreva Creek was relatively poor, but an Early Albian age is assigned to the base of the formation in this area based on the recognition of the *Ammodiscus-Glomospira* Assemblage Zone. This assemblage is correlative with Unit E of the Chinkeh Formation in the subsurface at Maxhamish. Consequently, it seems more likely that this lower interval at Scatter River is correlative with the coarsening-upwards interval present in subsurface-correlations below the radioactive interval in the Maxhamish area (visible in Figure II-18). Hence the problem of the Gething embayment remains largely unresolved, although thin *Ammodiscus*-bearing shale intervals underlying the main Chinkeh sandstones at some localities in the Liard basin may be indicative of the earlier flooding event. An alternative

explanation, which cannot be excluded, is that the *Ammodiscus-Glomospira* fauna is a time-transgressive, paleoenvironmentally-controlled biofacies that is time-equivalent to early or pre-Chinkeh sedimentation on the margins of the basin, and later flooding brought the fauna proximally, within Unit E and the basal part of Unit F.

The glauconite-rich Chinkeh Formation and Glauconitic Assemblage at the base of Unit E (and basal Garbutt in outcrop) is interesting considering the widespread occurrence of glauconite-rich Cretaceous sandstones elsewhere in western Canada (at the top of the Bluesky Formation and in the basal transgressive sandstone overlying the McMurray Formation). The similar glauconite abundance and faunal succession observed in the Liard Basin suggests either time equivalence or a similar succession of biofacies during southwards transgression of the Early Albian Boreal Sea.

Relative Sea level Changes and Paleogeography

The Chinkeh and lowermost Garbutt formations in the Liard basin represent the basal Cretaceous deposits of the southwards transgression of the Boreal Sea via the Mackenzie River basin (e.g. Jeletzky, 1971). Hardenbol et al. (1998) showed a long-term progressive rise in sea level through the Albian and three higher order falls during the Early Albian (and others in the Middle and Late Albian). In the Western Interior Basin, Early Albian relative-sea level fluctuations also punctuate the overall Albian sea level rise. Caldwell (1984) recognized the Clearwater transgressive-regressive couplet (equivalent to the upper Garbutt-Scatter) and possibly an earlier lower Gething couplet (which he equated with the lower Garbutt) and surmised that these couplets likely had a regional tectonic rather than eustatic control. A regional tectonic control is likely considering the combination of conglomerates (Cadomin, lower Chinkeh), bentonites

(lower Garbutt), and the thick Gething and Garbutt successions that indicate thrust-sheet sourcing, active volcanic activity and fast subsidence rates, respectively.

Detailed study of the Chinkeh Formation has revealed evidence of higher-frequency relative sea level fluctuations within the formation although without high-resolution temporal control on the duration of these cycles. In the subsurface, significant relative falls occur at the base of units D, E and F (see Figure II-20). In outcrop, at least one sequence boundary is found at the base of and within the coarsening-upwards sandstones (i.e. at Mount Martin), and another is present at the base of the Garbutt Formation. In general then, the Chinkeh and lower Garbutt interval is characterized by progressive relative deepening from non-marine to marine, nearshore, middle shoreface and offshore conditions and is punctuated by at least three relative falls.

Several theories of the paleogeography during Chinkeh time have been previously proposed. Williams (1978, fig. 4) showed the isolated occurrences of basal Cretaceous sandstones in the southern Northwest Territories. From his diagram, it is tempting to suggest the presence of a valley locally incised into the pre-Cretaceous subcrop. Leckie et al. (1991, fig. 17) considered that the fluvial facies of the Chinkeh exposed in the Liard Plateau was deposited as fluvial valleys incised into sub-Cretaceous rocks were filled and the sea transgressed southwards planing off the sub-Cretaceous topographic highs and leaving the basal TSE deposits. The main coastal Chinkeh reservoir sandstones prograded, were reworked as sea level rose, forming abandoned sandstones (coastal barriers or shelf-shoal deposits) and were finally drowned by the deepening sea during deposition of the Garbutt shale. This process resulted in the deposition of a number of pods of coarsening-upwards shoreface sandstones from a) transgressed beaches and

cliffs; b) transgressed and reworked barrier islands or c) lowstand shorelines and shelf ridges (Leckie et al., 1991).

The Chinkeh does contain a detrital component from the underlying strata. Palynological analysis has shown that the Chinkeh sandstones at Jackfish Gap (north of Murky Creek, Northwest Territories) were derived mainly from the underlying sandstones of the Mattson Formation as they contain reworked Mattson palynomorphs (Braman and Hills, 1977). Based on petrographic analysis, Leckie et al (1991) suggested that the Chinkeh was derived from the underlying Paleozoic carbonate and clastic strata, older quartz sandstones, low-grade quartzose rocks from both east and west, and the Precambrian shield to the east.

Based on the presence or absence of basal Cretaceous sandstones in the subsurface of the Northwest Territories plains, Dixon (1999) suggested the presence of isolated linear isopach thicks of fluvial Chinkeh Formation facies within a west-northwest-trending valley or valleys greater than 100 km in length (Dixon 1999, fig. 33). Foraminifera recovered in this study suggest some marine influence in the finer-grained facies (central basin) above and below the main channel fill sandstone in the Arrowhead B-41 well, thus showing there was significant marine influence; however, poor well-control limits the paleogeographic interpretations for the southern Northwest Territories region. The presence of at least one major valley is confirmed in the cross-sections in Chapter VII. A fluvially-incised valley-to-marine transition relationship is also present at the Kotaneelee Gap and the presence of a widespread fluvial system is further supported by the occurrence of pebble conglomerates at the bases of numerous other outcrops (e.g. Mount Martin).

Frank (2002) hypothesized the presence of a narrow seaway between the areas of the present Franklin Liard and La Biche ranges (i.e. the seaway was 125 km in width). In part, this was based on the interpretation that the Chinkeh Formation in outcrop is stratigraphically below that in the subsurface at Maxhamish Lake. Frank's (fig. II-30) paleogeographic reconstruction envisioned southeastwards and southwestward prograding shorelines fed by point sources (fluvial systems) on both western and eastern margins of the seaway. In his model, reworking of these deposits on a marine shelf resulted in progradation of these shoreface complexes and upward-coarsening parasequences or sequences.

Relationship of the Chinkeh and Scatter Formations. Frank (2002) suggested a correlation between the Bulwell Member of the Scatter Formation and the "Chinkeh" Formation known from the subsurface, leaving the Chinkeh Formation in outcrop along the western margin of the basin as the only "true" Chinkeh Formation. This interpretation was based on a) well log correlations of the Bulwell Member in the western margin of the basin with the "Chinkeh Formation" at Maxhamish; b) the apparent similarity of the facies of the Bulwell Member with the "Chinkeh" at Maxhamish, particularly the lower offshore facies; and c) the absence of glauconite in the "true" Chinkeh Formation where it outcrops on the western margin of the basin.

The results of this study support the traditional interpretation of the Chinkeh Formation and Bulwell Member. Well log correlations (Chapter VII) show that the basal Garbutt radioactive interval, which here has been shown to be a time-line, clearly everywhere overlies the Chinkeh Formation (including in outcrop). The Bulwell Member

progrades and thins eastwards towards Maxhamish and over the Bovie Structure into the 94P map sheet area, and is stratigraphically above the Chinkeh Formation.

Biostratigraphic data show the age-equivalence of the Chinkeh Formation in outcrop with that in the subsurface. This is especially well-constrained by Unit E and the overlying radioactive radiolarian-rich interval in the Garbutt Formation. Biostratigraphic data do not support a late Early Albian or Middle Albian age for the Chinkeh Formation at Maxhamish, which would have to be the case in the Frank (2002) interpretation, but rather an Early Albian age.

Frank (2002) suggested that the absence of glauconite in the outcrops of the Chinkeh in the ranges in the northwest portion of the study area is evidence supporting the correlation of the subsurface Chinkeh with the Bulwell Member (which is glauconitic). This is not sufficient evidence for a stratigraphic correlation across the basin. Additionally, extremely glauconite rich intervals were observed in outcrop of the Chinkeh on the west flank of Mount Martin (L2001L), and glauconite is abundant in samples from other outcrops in the Liard Plateau.

Finally, although the Chinkeh Formation at Maxhamish contains several internal sequence boundaries, no equivalent surfaces have ever been observed in the Bulwell or basal Wildhorn members (Chapter III). The latter only preserve evidence of lower shoreface and shelf deposition. However, sequence boundaries have been recognized in the Chinkeh Formation outcrops on the eastern margin of the basin, and have been correlated here with those at Maxhamish.

Paleogeographic time-slices. The evidence presented here indicates that the units within the Chinkeh Formation preserved in the Liard Plateau, Maxhamish Lake area and

the southern plains of the Northwest Territories are temporally correlative. A series of paleogeographic reconstructions depict the interpretation of the relationships of the various outcrops of the Chinkeh presented here (Figure II-20a to e). In these reconstructions, the Chinkeh Formation is deposited on opposite shores of a southerly and easterly advancing narrow Boreal Sea in the rapidly subsiding Liard Basin.

Distribution of the Chinkeh sandstones was likely controlled by basin topography, proximity to fluvial point sources, composition of the underlying Pre-Cretaceous strata (the Mattson Formation being the main source of sand), and re-working and abandonment of shoreface/barrier sands during transgression.

Table II-1. Simplified outcrop and core unit and facies descriptions of previous studies and their proposed relationship to those described here (in stratigraphic order upwards). The relationship between units 1 and 2 of Leckie et al. (1991) to those here and in other studies is difficult to substantiate, but here it is inferred that these units predate or were syndepositional with Facies B of Frank (2002) and Unit A of this study. Pedersen data from pers. comm.

Leckie et al. (1991) Outcrop Units and Interpretation	Frank (2002) Outcrop Facies	Frank (2002) Subsurface Chinkeh Facies	Pedersen Subsurface (and herein in outcrop)	NWT Subsurface (herein)
Garbutt Formation. Shale and silty shale	I. Distal offshore Garbutt	No well described that penetrates this interval	Units F. Garbutt Formation. offshore marine	Garbutt with basal TSE
		G. Offshore marine Garbutt	Unit E. Organic rich marine?	Unit E. Organic-rich tidally-influenced estuarine
	G. <i>Glossifungites</i> surface with TSE	F. <i>Glossifungites</i> surface, rooted	<i>Glossifungites</i> surface	
Unit 4. Upward-coarsening sandstone: (progradational shoreface)	E. Lower shoreface-offshore transition	E. Offshore marine	Unit D. Restricted marine?	Unit D. Estuarine
	D. Reworked lower-middle shoreface	D. Lower middle shoreface		
	C. Distal lower shoreface flooding surface	C. Distal lower shoreface	Units B & Unit C. Middle and lower shoreface	Units B & C: Organic-rich fluvial-estuarine
Unit 3. Conglomerate lag (ravinement lag)	B. Transgressive lag and lowstand incision events	B. Transgressive lag	Unit A. Transgressive lag and distal lower shoreface?	Unit A. Fluvial-marine transgressive lag
Unit 2. Carbonaceous conglomerate, sandstone, coal, shale (non-marine valley fill)				
Unit 1. Breccia (mass-flow deposit)				

Table II-2. Studied wells of Chinkeh and lowermost Garbutt formations.

Well	Core Interval	Stratigraphic Interval
CAN HUNTER Maxhamish a-60-B/94-O-11	1526-1536 m	Chinkeh
AEC Maxhamish a-13-G/94-O-11	1448.2-1466.2 m	Chinkeh
AEC Maxhamish b-79-G/94-O-11	1617.5-1635.5 m	Chinkeh
AEC Maxhamish c-03-J/94-O-11	1480.5-1498.7; 1498.7-1506.5 m	Chinkeh
AEC Maxhamish b-53-G/94-O-14	1245-1253; 1253-1261 m	Chinkeh
Shell Arrowhead B-41 60-40 122-45	597-615; 615-633 m	Chinkeh-Garbutt
IOE et al. Arrowhead L-49-60-30-122-30	1865-1875'; 1875-1892'	Chinkeh
Cdn Forest Oil fort Liard K-32 60-10 123-15	1322-1339 m	Lower Garbutt
b-053-B/94-O-14	1260-1278	Lower Garbutt
b-059-I/94-O-11	1190.4-1208.4	Lower Garbutt

Table II-3. Studied outcrops of Chinkeh and lowermost Garbutt formations.

Field Designation	Location Description	NTS Coordinates	Stratigraphic Interval
L2001J	Toreva Creek	0394283E; 6612085N	Lower Garbutt
L2000L	West Tributary to La Biche River	6739917N, 410978E	Chinkeh
L2000M	East limb Kootaneelee anticline	6718886N, 438333E	Chinkeh
L2000N	Murky Creek waterslide	6735626N, 446100E	Chinkeh-Garbutt
L2000P	Unnamed creek north of Murky Creek	6740605N, 444270E	Chinkeh
L2001C	South tributary to Murky Creek	0446293E; 733701N	Chinkeh
L2001F	West limb of Kootaneelee anticline	0431700E; 6718325N	Chinkeh
L2001L	West Mount Martin creek	0435132E; 6667046N	Chinkeh-Garbutt

Table II-4. Facies of the Chinkeh and lower Garbutt formations and their interpreted depositional environment.

Facies	Lithology	Physical and biogenic sedimentary structures	Depositional Environment
A	Clast-supported conglomerate; pebble to cobble-sized clasts; angular to rounded clasts composed of chert or limestone		Fluvial to transgressive marine lag
B	Siltstone to fine sandstone	Planar-laminated to current rippled	Transgressive marine sandstone
C	Fine to medium grained sandstone, glauconitic	Planar laminated to hummocky cross-stratified; some heavily bioturbated intervals	Lower to middle shoreface
D	Siltstone to muddy siltstone	Heavily bioturbated	Offshore transition zone?
E	Organic-rich mudstone, coalified plant material	Heavily bioturbated	Offshore?
F	Black shale to silty shale; bentonites		Offshore
G	Organic-rich shale, terrestrial plant debris	Barren or stressed fauna	Estuarine (central basin)
H	Very fine to fine sandstone; abundant organic debris on foresets	planar laminated to high angle cross-bedded; occasional mud drapes	Fluvial or tidal channel fill

Figure II-1. Locations of most of the studied (logged and usually sampled) wells (hollow circles) and outcrops (solid dots) of Chinkeh and lower Garbutt formations superimposed on the NTS grid. Yellow area-approximate limits of Maxhamish gas field.

Stage	Substage	Stratigraphy Moberly Lake NE B.C.	Selected Macrofossil Zones (Warren & Stelck 1969; Caldwell et al. 1978; Jeletzky 1980; Jeletzky and Stelck, 1981; Stott 1982; Caldwell, 1993)	Peace River, British Columbia Foraminiferal Zones (Stelck et al. 1958; Sutherland & Stelck 1972; Koke and Stelck 1984, 1985; Stelck & Koke 1987; Stelck & Hedinger 1983; Stelck 1975, 1991)	Sikanni Chief River, British Columbia Foraminiferal Zones (Schröder-Adams & Pedersen, 2003)	Liard Basin Foraminiferal Zones (Jowett et al. in press and this study)	Liard Basin Stratigraphy (Jowett et al. in press and this study)
Cenomanian	Middle		<i>Acanthoceras althabascense</i>	<i>Verneuilinoides perplexus</i>	Unzoned	Unzoned	Dunvegan
	Early	Upper Cruiser	<i>Beatonoceras beatonense</i> <i>Irenoceras bahani</i> <i>Neogastrolites septimus</i> <i>Neogastrolites maclearni</i>	<i>Textularia alcesensis</i>		<i>Textularia alcesensis</i>	FSU Sully
Albian	Upper	Lower Cruiser	<i>Neogastrolites americanus</i> <i>Neogastrolites muelleri</i> <i>Neogastrolites cornutus</i>	<i>Haplophragmium swareri</i>	Fish-Scale beds <i>Haplophragmium swareri</i> <i>Ammobaculites fragmentarius</i> <i>Trochammina alcesensis</i>	<i>Miliammina manitobensis</i> <i>Haplophragmium swareri</i> subzone B subzone A	Lower Sikanni (upper Lepine)
		Goodrich	<i>Neogastrolites haasi</i>	<i>Haplophragmoides postis goodrichi</i> <i>Verneuilina canadensis</i>		<i>Bathysiphon-A. fragmentarius</i> assemblage <i>Ammomarginulina</i> assemblage	Bougie equivalent Lepine
		Upper Hasler	poorly fossiliferous interval	<i>Reophax troyeri</i> <i>Trochammina umiatensis</i> <i>Trochammina depressa</i> <i>Reophax tundraensis</i> <i>Haplophragmoides gigas phaseolus</i>			
		"Viking"		<i>Haplophragmoides gigas gigas</i> <i>Haplophragmoides uniorbis</i>			
		Lower Hasler	<i>Inoceramus commancheanus</i>	<i>Ammobaculites wenonahae</i> <i>Ammobaculites sp.</i>			
		Basal Hasler	<i>Stelckiceras liardense</i>	<i>Haplophragmoides multiplex</i>			
	Middle	Cadotte	<i>Gastrolites allani</i> <i>Gastrolites kingi</i>	<i>Verneuilinoides cummingensis</i> <i>Marginitellina collinsi</i>	<i>Gaudryina nanushukensis</i> <i>Haplophragmoides multiplex</i> <i>Verneuilinoides cummingensis</i>	<i>Ammobaculites wenonahae</i> <i>Ammobaculites sp.</i> <i>Haplophragmoides nanushukensis</i>	Tussock Wildhorn Bulwell
		Hulcross	<i>Pseudopulchellia pattoni</i>	<i>Reobolovina sp.</i>		<i>Haplophragmoides multiplex</i> <i>Verneuilinoides cummingensis</i> Radioactive Red (Barren) <i>Ammobaculites-Glomospira</i> Glauconitic	Garbutt
	Lower	Gates	<i>Freboldiceras remotum</i>				
		Moosebar	<i>Subarthroplites mcconnelli</i>				
	Lower	Gething	<i>Pachygrycia canadensis</i>				
		Cadomin	<i>Aucellina aptiensis</i>				

Figure II-2. Stratigraphy, ammonite and foraminiferal zonation for Western Canada.

Figure II-3. Studied wells coring Chinkeh and lowermost Garbutt formations in northeastern British Columbia (from south to north) with foraminiferal data and interpretations. Location of micropaleontology samples in left column denoted by foraminifera symbol and number. a) Can Hunter Maxhamish a-60-B/094-O-11. b) AEC Maxhamish a-013-G/094-O-11. c) AEC Maxhamish b-079-G/094-O-11. d) AEC Maxhamish c-003-J/094-O-11. e) AEC Maxhamish b-53-G/094-O-14. f) AEC Maxhamish b-059-I/094-O-11. g) AEC Maxhamish b-053-B/094-O-14.

Well: a-60-B-094-O-11 CAN HUNTER MAXHAMISH

Core #(s): 1

Core Interval: 1526-1536 m

Lithostratigraphy	Samples	Lithology	Sedimentary Observations	Micropaleontology	Foraminiferal Zone	Surfaces	Unit Facies	Sedimentary Environment
Chinkeh Formation	10		non-fissile mudstone glauconitic, gypsum? becomes more muddy glauconitic coalified organic matter and abundant mica coalified organic matter very abundant glauconitic Glossifungites surface alternating heavily bioturbated to parallel laminated with glauconite shale fissile; not bioturbated	7. <i>G. nanushukensis</i> , <i>V. borealis</i> 6. <i>G. nanushukensis</i> , <i>V. borealis</i> , <i>V. tailleurii</i> , <i>Ammodaculites</i> sp., <i>Haplophragmoides</i> sp., 5. Barren 3 Barren, possibly diatoms 1 Barren	<i>G. nanushukensis</i> Zone	Glossifungites Surface TSE	E7 D7 C7 B A	Offshore? Lower Shoreface to Offshore Transition Middle Shoreface? Middle Shoreface
	9							
	8							
	7							
Trask?	6							
	5							
	4							
	3							
Trask?	2							
	1							
	1							
	1							

II-3a.

Well: **a-013-G/094-O-11 AEC MAXHAMISH**

Core #(s): **1**

Core Interval: **1448.20-1466.20 m**

Lithostratigraphy	Samples	Lithology	Sedimentary Observations	Micropaleontology	Surfaces	Facies	Sedimentary Environment
Chinkeh Formation	12		Triassic-looking silty shale	no samples	SB	B	lagoonal?
	11						
Triassic	10						
	9						
	8						
	7						
	6						
	5						
	4						
	3						
	2						
	1						

II-3b.

Well: b-053-B-094-O-14 AEC MAXHAMISH
Core #(s): 1
Core Interval: 1260-1278 m

Samples	Lithology	Sedimentary Observations	Micropaleontology	Foraminiferal Zone	Unit	Sedimentary Environment
17	Dark silty sand					
16						
15						
14	organic matter		P2. Fish debris			Anoxic
13						
12						
11	10 cm thick bentonite					
10						
9						
8			D3. <i>Rogaphax minuta</i> , <i>G. laileuri</i> , <i>H. linki</i> , <i>Ammonoculites</i> sp., <i>Textularia</i> sp., <i>Gaudryna</i> sp., <i>Saccammina latrami</i> , Abundant radiolarians	Radioactive radiolarian-rich interval	N/A	Shelf
7						
6	18 cm thick, mica, framboidal pyrite		P1. Barren			Anoxic
5	36 cm thick					
4						
3	15 cm thick					
2						
1	siltystones bioturbated framboidal pyrite		D1. <i>A. fragmentarius</i> , <i>Ammonoculus rotularius</i> , <i>H. linki</i> , <i>G. laileuri</i> , <i>V. borealis</i> , <i>Milammina</i> sp.	Ammonoculus Assemblage		Shelf

Figure II-4. Wells coring Chinkeh and lowermost Garbutt formations in the Northwest Territories with foraminiferal data and interpretations. a, b) Shell Arrowhead B-41 60-40 122-45. c) IOE et al. Arrowhead L-49 60-30 122-30. d) Canadian Forest Oil et al. Fort Liard K-32 60-10 123-15.

Figure II-4a.

Well: B-41 60-40 122-45 Shell Arrowhead B-41
Core #(s): 1, 2
Core Interval: 597-615 m; 615-633 m (SEE NEXT PAGE FOR UPPER PORTION)

Samples	Lithology	Sedimentary Observations	Micropaleontology	Foraminiferal Zone	Surfaces	Unit	Sedimentary Environment
23	100% sand				SBFSE		Shoreface- Marine Transgression
22	100% sand	wood debris on all bedding surfaces; pyrite abundant	10. <i>Ammobaculoides</i> sp.			Unit E	
21	100% sand		9. <i>Saccammina</i> sp.; <i>Verrillinoides cummingsensis</i>				
20	100% sand	Mud-drapes on foresets	8. Barren	Stressed benthic fauna			
19	100% sand		7. Barren				
18	100% sand		6. <i>Ammobaculoides</i> , <i>Psammimopelta</i> sp.				Highly organic-rich Estuarine Central Basin Facies
17	100% sand	highly bioturbated-mottled				Unit D	
16	100% sand						
15	100% sand						
14	100% sand						
13	100% sand						
12	100% sand						
11	100% sand						
10	100% sand						
9	100% sand						
8	100% sand	organic material on foresets					
7	100% sand	well-sorted quartz sand					
6	100% sand	organic debris common in basal portion					
5	100% sand	coalified wood debris abundant sharp-based					
4	100% sand		5. Barren		Channel Base		
3	100% sand	highly organic rich shale	4. Barren				
2	100% sand		3. Barren	Anoxic or Stressed Fauna		Unit B	Estuarine Central Basin Facies
1	100% sand	angular limestone and chert	2. <i>Saccammina</i> sp.; <i>Psammimopelta</i> sp.				
0	100% sand	chert conglomerate; wood debris abs	1. Barren			Unit A	Debris Flow/Marginal Marine

Well: L-49 60-30 122-30 IOE et al. Arrowhead L-49
 Core #(s): 1, 2
 Core Interval: 568.5-571.5; 571.5-576.7 m (1865-1875'; 1875-1892')

Lithostratigraphy		Samples	Lithology	Sedimentary Observations	Micropaleontology	Surfaces	Units	Sedimentary Environment
Chinkeh Formation		8		<p>limestone clasts</p> <p>syneresis cracks</p> <p>mud interbeds</p> <p>angular chert pebble 4 cm in length</p> <p>wavy bedding</p> <p>microfaults common</p>		<div>Channel Base</div> <div>Channel Base</div>	Unit D?	Marginal Marine Tidally-influenced channels or Tidal Channels
		7						
		6						
		5						
		3			3. Barren			
		2						
		1			2. Barren			
		1			1. Barren		Unit C?	

Figure II-4c.

Figure II-4d.

Figure II-5. Core photographs of c-003-J/094-O-11 well. a) Triassic-Chinkeh contact with large carbonate boulder (c) cored near base of Chinkeh. This is overlain by reservoir sandstone (Unit B). **b)** Chert pebbles up to 3 cm in diameter (TSE) at base of Unit D. **c)** *Glossifungites* surface infilled with glauconitic sand at the base of Unit E.

Figure II-6. Basal Garbutt cored in b-053-B/094-O-14 well. a) (Core boxes 11-13) Laminated and bioturbated shale and silty shale that becomes increasingly interbedded with 3- to 10 cm thick bentonite layers (arrows). The *Ammodiscus* fauna was recovered from this interval. **b)** (Core boxes 9-10) 36-cm-thick bentonite layer (arrow) overlain by intermittently barren shales that are rich in fish debris and radiolarians.

Figure II-7. Shell Arrowhead B-41 photographs. a) basal Chinkeh conglomerate (C) overlain by estuarine shale (E) with a stressed foraminiferal fauna and tidal sandstones (T). b) Main lower highly organic rich estuarine shale barren of microfossils. c) lower estuarine shale (E) overlain by thick fluvial and/or tidally influenced sandstone (F/T).

Figure II-8. Shell Arrowhead B-41 photographs. a) Chinkeh-Garbutt contact (arrow). **b)** Close-up of *Glossifungites* surface and transgressive surface of erosion at base of the Garbutt Formation.

Figure II-9. Canadian Forest Oil et al. Fort Liard K-32 core photographs. a) Typical Lower Garbutt radioactive interval with numerous bentonites (arrows) and fish debris. b) Finely laminated shale with 6-cm-thick bentonite layer.

Figure II-10. Outcrop stratigraphic sections, foraminiferal data and interpretations of the Chinkeh and lowermost Garbutt formations on the flanks of the Franklin Liard, Kotaneelee and La Biche ranges, southeastern Yukon and southwestern Northwest Territories from south to north. a) L2001J. b) 2001L. c) L2001F. d) L2000M. e) L2001C. f) L2000N. g) L2000P. h) L2000L.

Locality: L2001J, Toreva Creek
 NTS Coordinates: 0394283E; 6612085N
 Other Comments: Tributary to Scatter Rv.

Figure II-10a.

Locality: L2001L, Mt. Martin
 NTS Coordinates: 0435132E; 6667046N
 Other Comments:

Lithostratigraphy	Samples	Lithology	Sedimentary Observations	Micropaleontology	Foraminiferal Zone	Surfaces	Units	Sedimentary Environment
Triassic	L6 32	Shale Siltstone Sand Gravel Congl.	isolated chert pebbles up to 10 cm diameter in shale within 10 cm of contact	6. <i>V. tailleur</i> , <i>G. canadensis</i> , <i>V. cummingsensis</i> poor preservation 5. <i>Haplophragmoides</i> sp., <i>V. cummingsensis</i> , <i>V. tailleur</i> , <i>Trochammina</i> sp., very poor preservation 4. Glauconitic <i>Verneuilinoides</i> sp.	Glauconitic Assemblage	SB7/TSE	E	Shelf
	L5 30 L4 28 L3 26 L2 24 L1 22							
Triassic	L18 18 L16 16 L14 14 L12 12 L10 10 L8 8 L6 6 L4 4 L2 2 L0 0	Shale Siltstone Sand Gravel Congl.	siltst. intensely glauconitic; chert grains & increasing glauconite content upwards chert pebbles, 2-5 cm, subrounded in lower 20-50cm thin to medium bedded in upper part parallel to ripple laminated some organic debris and mud lamina medium to upper fine sand, medium to thick-bedded organic debris chert pebbles, subrounded 2-10cm	3. Barren 2. <i>Haplophragmoides</i> sp., <i>Verm.</i> sp., <i>G. nanushukensis</i> sp., <i>Bathysiphon</i> sp., <i>Saccammina</i> sp. 1. <i>Ammodiscus</i> sp., <i>G. nanushukensis</i> , <i>Trochammina</i> sp., <i>Verneuilinoides</i> sp.	G. nanushukensis Zone	SB7/TSE	D	Offshore Transition Upper-Middle Shoreface? Lower Shoreface/Offshore transition
	L1 22							
Triassic	L18 18 L16 16 L14 14 L12 12 L10 10 L8 8 L6 6 L4 4 L2 2 L0 0	Shale Siltstone Sand Gravel Congl.	siltst. intensely glauconitic; chert grains & increasing glauconite content upwards chert pebbles, 2-5 cm, subrounded in lower 20-50cm thin to medium bedded in upper part parallel to ripple laminated some organic debris and mud lamina medium to upper fine sand, medium to thick-bedded organic debris chert pebbles, subrounded 2-10cm	3. Barren 2. <i>Haplophragmoides</i> sp., <i>Verm.</i> sp., <i>G. nanushukensis</i> sp., <i>Bathysiphon</i> sp., <i>Saccammina</i> sp. 1. <i>Ammodiscus</i> sp., <i>G. nanushukensis</i> , <i>Trochammina</i> sp., <i>Verneuilinoides</i> sp.	G. nanushukensis Zone	SB7/TSE	C	Middle Shoreface
	L1 22							
Triassic	L18 18 L16 16 L14 14 L12 12 L10 10 L8 8 L6 6 L4 4 L2 2 L0 0	Shale Siltstone Sand Gravel Congl.	siltst. intensely glauconitic; chert grains & increasing glauconite content upwards chert pebbles, 2-5 cm, subrounded in lower 20-50cm thin to medium bedded in upper part parallel to ripple laminated some organic debris and mud lamina medium to upper fine sand, medium to thick-bedded organic debris chert pebbles, subrounded 2-10cm	3. Barren 2. <i>Haplophragmoides</i> sp., <i>Verm.</i> sp., <i>G. nanushukensis</i> sp., <i>Bathysiphon</i> sp., <i>Saccammina</i> sp. 1. <i>Ammodiscus</i> sp., <i>G. nanushukensis</i> , <i>Trochammina</i> sp., <i>Verneuilinoides</i> sp.	G. nanushukensis Zone	SB7/TSE	B	Alluvial/Upper Shoreface
	L1 22							
Triassic	L18 18 L16 16 L14 14 L12 12 L10 10 L8 8 L6 6 L4 4 L2 2 L0 0	Shale Siltstone Sand Gravel Congl.	siltst. intensely glauconitic; chert grains & increasing glauconite content upwards chert pebbles, 2-5 cm, subrounded in lower 20-50cm thin to medium bedded in upper part parallel to ripple laminated some organic debris and mud lamina medium to upper fine sand, medium to thick-bedded organic debris chert pebbles, subrounded 2-10cm	3. Barren 2. <i>Haplophragmoides</i> sp., <i>Verm.</i> sp., <i>G. nanushukensis</i> sp., <i>Bathysiphon</i> sp., <i>Saccammina</i> sp. 1. <i>Ammodiscus</i> sp., <i>G. nanushukensis</i> , <i>Trochammina</i> sp., <i>Verneuilinoides</i> sp.	G. nanushukensis Zone	SB7/TSE	A	Triassic Offshore
	L1 22							

Figure II-10b.

Locality: L2001F, West Kotaneelee Gap
 NTS Coordinates: 0431700E; 6718325N
 Other Comments: Leckie L12

Figure II-10c.

Locality: L2000M, East Kotaneelee Gap
 NTS Coordinates: 6718886N, 438333E
 Other Comments: Drawn by P. Pedersen

Figure II-10d.

Locality: L2001C, Murky Creek Chinkeh-Garbutt
NTS Coordinates: 0446293E; 6733701N
Other Comments:

Figure II-10e.

Locality: L2000N Waterslide, Tributary to Murky Creek
 NTS Coordinates: 6735626N, 446100E
 Other Comments: "Otterslide" of Frank

Samples	Lithology	Sedimentary Observations	Micropaleontology	Foraminiferal Zone	Surfaces	Units	Sedimentary Environment
Lithostratigraphy Garbutt Formation 50 15 14 30 13 12 11 10 9 8 7 6 5 4 3 2 1 m		fish debris some glauconite very glauconitic glauconite glauconite, woody organic matter abundant bivalve molluscs	15. <i>G. canadensis</i> , <i>V. cummingsensis</i> , <i>Gyrogonia cf. nuda</i> , <i>Globulina lacrima</i> , <i>Glomospira</i> sp., <i>G. stotti</i> , <i>Quinqueloculina</i> sp., <i>Psammimopella</i> sp., <i>Haplophragmoides</i> sp., 14. <i>Glomospira</i> corona, <i>V. cummingsensis</i> , <i>Haplophragmoides</i> sp., <i>Psammimopella</i> sp., 13. <i>G. tailleurii</i> , <i>V. cummingsensis</i> , <i>Glomospira</i> <i>G. stotti</i> , <i>Bathysiphon</i> , <i>Haplophragmoides</i> sp., 12. <i>V. tailleurii</i> , <i>V. cummingsensis</i> , <i>G. stotti</i> , <i>Conorbina</i> sp., <i>Haplophragmoides</i> sp., 11. <i>V. cummingsensis</i> , <i>G. stottianus</i> , <i>Glomospira</i> sp., <i>Ammobaculites</i> sp., <i>Quinqueloculina</i> , <i>Psammimopella</i> , 10. <i>Haplophragmoides</i> sp., <i>Haplophragmoides</i> sp., <i>G. canadensis</i> , <i>G. stotti</i> , <i>Saracenaria</i> sp., <i>Ammobaculites</i> sp., 9. <i>Verneuilinoides</i> <i>tailleurii</i> , <i>Trochammina</i> sp., <i>Haplophragmoides</i> sp., 8. <i>G. canadensis</i> , <i>Glomospira</i> corona, <i>Bathysiphon</i> sp., <i>Verneuilinoides</i> sp., <i>Glauconitic</i> foraminifera: <i>Verneuilinoides</i> , <i>Gaudryina</i> and possibly radiolarians. 5. <i>Verneuilinoides</i> sp., <i>G. nanushukensis</i> . 4. Barren 3. Barren L2001A 1. <i>Miamminia</i> sp., <i>Verneuilinoides</i> sp., <i>Ammobaculites</i> sp.	Calcareous Interval Ammodiscus- Glomospira Assemblage Glauconitic Assemblage	SB/TSE (Glauconitic surface) C? SB/TSE	E C? A	Frequent volcanic events Normal marine shelf Progradational middle shoreface Alluvial/Upper shoreface

Figure II-10f.

Locality: L2000L, Tributary to La Biche River
 NTS Coordinates: 6739917N, 410978E
 Other Comments: Drawn by P. Pedersen

Figure II-10h.

Figure II-11. Outcrop photographs of the Chinkeh at Mount Martin (L2001L). Beds dip almost vertically. **a)** Triassic-Chinkeh contact. **b)** basal sandstone and conglomerate of the Chinkeh Formation.

Figure II-12. Outcrop photographs of the Chinkeh at Mount Martin (L2001L). a) Chinkeh Formation approximately 19-22 m above base. b) Second conglomerate at 21 m above the base of the Chinkeh Formation (sole of bed).

Figure II-13. Outcrop photographs of the Chinkeh and Garbutt formations at Mount Martin (L2001L). a) Uppermost interbedded Chinkeh interval and overlying Garbutt (to left). b) Close-up of intensely glauconitic siltstone interval with well-rounded chert grains (sand fraction).

Figure II-14. Isolated pebbles (arrows) in the basal Garbutt Formation overlying the Chinkeh at Mount Martin (L2001L).

Figure II-15. Photographs of Lower Garbutt Formation exposed along Toreva Creek. a) Aerial view from helicopter of Garbutt and Bulwell Member of Scatter Formation. **b)** Lower Garbutt (creek level is less than 20 m above the Triassic) showing slight coarsening-upwards interval in the lower Garbutt.

Figure II-16. Outcrop photographs of the Chinkeh Formation in the Liard Plateau. a) L2000M Kotaneelee East Gap. Light coloured basal Chinkeh is carbonate clast conglomerate in channel overlain by fluvial deposits. b) Kotaneelee West Gap (L2001F), south side of river showing progradational sandstone units of the Chinkeh Formation overlying Permian strata. c) Kotaneelee West Gap (L2001F), north side of river (view from helicopter) showing progradational sandstone units of the Chinkeh Formation.

Figure II-17. Outcrop photographs of the Chinkeh and lower Garbutt formations in the Liard Plateau. a) Permian-Chinkeh contact at Murky Creek (L200N). Hammer for scale. **b)** (L2000N) basal Garbutt overlying intensely bioturbated Chinkeh siltstone. **c)** Southern tributary to Murky Creek (L2001C) Mattson-Chinkeh (heavily bioturbated) contact.

Figure II-18. Correlation between the lower middle-shoreface-dominated Chinkeh Formation in the Maxhamish Lake area of northeastern British Columbia and the fluviially-dominated Chinkeh in the Northwest Territories.

Chronostratigraphy	Lithostratigraphy	Unit Divisions	Foraminiferal Zonation	Depositional Environment	Sequence Stratigraphy
Lower Albian	Garbutt Formation <i>core</i>	Unit F	Radioactive Radiolarian Interval Calcareous Interval	offshore marine	(core) SB/TSE
		Unit E	<i>Ammodiscus-Glomospira</i> Fauna Glauconitic Assemblage	Organic-rich marine or tidally-influenced estuarine	SB/TSE
	Chinkeh Formation <i>outcrop</i>	Unit D	poor or absent fauna	Restricted marine or estuarine	
		Unit C	poor or absent fauna	Middle and lower shoreface or organic-rich estuarine	SB ?
		Unit B	poor or absent fauna	Middle and lower shoreface or organic-rich estuarine	
		Unit A	poor or absent fauna	transgressive marine	SB/TSE
Pre-K				fluvial valley fill	

Figure II-19. Summary of unit and biostratigraphic divisions, depositional environment and interpreted placement of sequence boundaries in the Chinkeh and lower Garbutt formations. Depositional environment varies for outcrop exposures in the northwest portion of the basin and the Maxhamish field vs. the valley-fill succession present in the Northwest Territories cores.

Figure II-20. Model of the paleogeographic evolution of the Liard Basin during deposition of the Chinkeh and basal Garbutt formations.

Pre-Cretaceous

- Fluvial valleys eroding Fantasque carbonates

Units A and B

- Drowning of river valleys
- Deposition of basal conglomerates
- Southward incursion of Boreal Sea
- Rapid subsidence of Liard Basin

Units C and D

- Time slice during deposition of Unit C
- Shoreface progradation along western and eastern margins of Boreal Sea
- Deposition of fluvial sandstones in B-41 area
- SB/TSE at base of Unit D due to regression and subsequent shoreface ravinement during transgression

Unit E, Time 1

- Glossifungites* surface at base of Unit E (peak lowstand)
- abundant glauconite deposits form along eastern and western margins
- early transgression brings Glauconitic Assemblage

Unit E, Time 2

- Renewed foreland basin subsidence
- Transgression over and reworking of shoreface complexes at Maxhamish
- deposition of highly organic-rich facies along eastern margin of the basin with continued eastwards flooding over Bovie Structure
- Glauconitic Assemblage followed by *Ammodiscus-Glomospira* Assemblage
- Deposition of "Basal Garbutt" in the Liard Plateau area
- highly organic-rich transgressive estuarine deposits in B-41 area

Unit F

- possible lowstand at base followed by major transgression with increased subsidence
- eastwards and southwards transgression of Garbutt Sea
- Bovie Structure completely overstepped
- Ammodiscus-Glomospira* fauna succeeded by Radiolarian-rich Assemblage
- frequent volcanic events deposit numerous ash beds

Chapter III. BIOSTRATIGRAPHIC CONSTRAINTS ON THE DEPOSITIONAL HISTORY OF THE UPPER GARBUTT AND SCATTER FORMATIONS

Introduction

Inundation of the Western Canada Sedimentary Basin in Early Albian time by the Clearwater-Moosebar Sea deposited the lower and middle Garbutt Formation in the Liard Basin. During the middle Albian, relative sea level fall forced the Moosebar shoreline to retreat northwards more than 750 km (Leckie, 1986). In the southern region of northeastern British Columbia and the Peace River plains, the Moosebar/Wilrich Formation is overlain by the numerous lower middle to middle Albian upward-coarsening marine to non-marine cycles of the Gates and Falher/Notikewin sandstones (Leckie and Walker, 1982; Leckie, 1986). These, in turn, are overlain by the mudstones of the Hulcross/Harmon Formation, representing a significant basin-wide flooding event, and then a second relative shallowing is observed in the progradation of the lower Boulder Creek/Cadotte Formation. During Middle Albian time, the wave and tide-dominated shoreline at this southern margin of the seaway was oriented WSW-ENE and the paleoslope was N-NW toward the Liard Basin. In the Liard Basin, progradation of shoreface and shelf sandstones of the Scatter Formation occurred at approximately the same time as the deposition of the Gates and lower Boulder Creek formations towards the south. The shoreline in the Liard basin was situated on the western margin of the basin and was oriented approximately south-north and most sediment was shed eastwards (Leckie and Potocki, 1998).

Stratigraphy

Above the radioactive radiolarian-rich interval (a bentonite-rich interval in the lower Garbutt Formation—see Chapter II), a thick mudstone succession here referred to as the middle and upper Garbutt Formation underlies the shelf and lower shoreface glauconitic sandstones and mudstones of the Scatter Formation (Figure III-2). The Garbutt Formation outcrops in numerous areas along the Liard River and Liard Plateau areas.

The Scatter Formation is divided into the Bulwell, Wildhorn and Tussock members (Figure III-2) and in general is composed of two major sandstone bodies separated by a thick succession of mudstone. Scatter outcrops can be found on the western side of the Franklin-Liard Range (Bulwell Member only), and the flanks of the La Biche and Kotaneelee anticlines (Figure III-1). In the plains of the Northwest Territories, the Bulwell Member outcrops at the junction of Muskeg and Liard rivers and on both western (opposite Fort Liard) and southeastern margins of the broad synclinal area underlying the Petitot River. The strata of the Scatter Formation thin rapidly and undergo a facies change to mudstone southwards from Scatter River. As noted by Stott (1982), opposite Garbutt Creek on the east bank of the Liard River, the Bulwell Member is composed of interbedded mudstone and fine sandstone but the Tussock Member is barely distinguishable from the underlying Wildhorn Member (locality L2002B, Figure III-9). Regionally the Scatter Formation thins to the east and its thickest occurrence is in the southwest. At the type section on the Scatter River, the underlying and overlying contacts and internal contacts between the members within the Scatter Formation are gradational.

Previous Work

The Scatter Formation was originally described on Scatter River by Kindle (1944). At its type section, the formation is thickest and stratigraphically complete and beds dip eastwards along the river near its junction with the Liard River (e.g. Figure III-7). Stott (1960, 1982) measured several Garbutt and Scatter Formation outcrops in the Scatter River area and the Liard Plateau. Leckie and Potocki (1998) described the sedimentology, petrology and regional expression of the Garbutt and Scatter formations in the Liard Basin. Frank (2002) provided facies descriptions (with ichnology) of the Scatter outcrops on Kotaneelee River and Sully Creek, although he equated these with the subsurface “Chinkeh” Formation at Maxhamish Lake (see discussion in previous chapter).

Biozonation

A biostratigraphic correlation chart with the ammonite and foraminiferal zonation and their relationship to strata to the south is provided in Figure III-3. Precise age dates of the Scatter Formation have been difficult to obtain. The basal part of the Garbutt Formation contains ammonites and foraminifera of Early Albian age (see Chapter II). At Scatter River, the basal portion of the overlying Lepine shale (see next chapter) contains foraminifera and ammonites indicative of the *Ammobaculites* sp. and *Gastrolites kingi* (Stott, 1982) zones, respectively. These are followed by the *Ammobaculites wenonahae* foraminiferal (next chapter) and *Stelckiceras liardense* ammonite (Stott, 1982) faunas which are of latest Middle Albian age. Hence the age of the Scatter Formation is bracketed between the Lower Albian lower Garbutt Formation and the uppermost Middle Albian lower part of the Lepine Formation. Stott (1982) reasoned that a portion of the

Wildhorn and Tussock members likely can be assigned to the *Pseudopulchellia pattoni* Zone, and that the Bulwell Member probably is stratigraphically equivalent to the Gates Formation in the Peace River Foothills, and hence can be assigned to the *Archthoplites* Zone (Figure III-3). Wall (in Stott, 1982) reported the presence of *Haplophragmoides multiplum* from shale assigned to the Scatter Formation along Petitot River on the west flank of the Bovie Structure.

Methods

Numerous core (Table III-1) and outcrop (Table III-2) sections were logged and sampled for micropaleontology. Outcrop and core locations are provided on Figure III-1. Of the outcrops, three main sections form the bulk of this study because of their completeness. These are the Garbutt-Bulwell strata exposed on Murky Creek (Figures III-4, III-5), the Scatter type section (Figures III-6 to III-8), and the finer-grained facies of the Wildhorn and Tussock members exposed on the east bank of the Liard River opposite Garbutt Creek (Figures III-9, III-10) south of Scatter River. The sedimentology and regional outcrop distribution of the Scatter Formation has already been well-documented (Stott, 1982; Leckie and Potocki, 1998; Frank, 2002). The purpose of this short chapter is to document the foraminiferal fauna, establish a biostratigraphic framework, and provide paleoenvironmental interpretations of the depositional environment. Further regional correlations of the Scatter Formation are included in Chapter VII.

Results

Logged sections of relevant core and outcrops with petrophysical curves (gamma ray and/or resistivity), foraminiferal data and paleoenvironmental interpretations are

provided in Figures III-4 to III-17. A complete list of foraminiferal distribution in all outcrops and cores is provided in Appendix I.

Middle and Upper Garbutt Formation

Lithology. In outcrop, the middle and upper Garbutt is characterized by mudstone with concretionary sideritic bands throughout. The uppermost part of the Garbutt Formation is characterized by a number of coarsening-upwards cycles of mudstone to siltstone and fine sandstone. These are observed along Toreva Creek and Scatter River (Figure III-6a) and on the west flank of the Franklin Liard Range at Murky and Sully creeks (Figures III-4, III-5). Leckie and Potocki (1998) noted the presence of several lenses of contorted sandstone deposits within the Garbutt exposed in the Scatter River area. These were interpreted as slumps on the shelf margin linked to the high-sedimentation rate depocenter of the Scatter Formation in that area. At Murky Creek glauconite becomes abundant in the coarsening-upwards cycles below the amalgamated hummocky cross stratified sandstones of the Bulwell Member.

Numerous cores penetrate the middle and upper Garbutt interval in northeastern British Columbia and the Northwest Territories (Table III-1, Figures III-17a to d, f). Most of these cores preserve typical Garbutt mudstones with thin silt and very fine-grained sandstone interbeds that generally show moderate bioturbation and are hummocky cross-stratified. This interval lacks the bentonites that characterize the basal part of the Garbutt Formation in core and outcrop. Several small coarsening-upwards intervals can be observed in well logs, and one is cored in the b-055-E/94-O-13 well (Core 9, Figure III-17c).

Micropaleontology. Samples from the middle Garbutt interval in core are dominated by *Verneuilinoides tailleuri*, *Verneuilinoides borealis*, *Gaudryina nanushukensis*, *Haplophragmoides linki*, *Haplophragmoides* sp., and more isolated occurrences of *Ammobaculites fragmentarius*. In some wells, parts of the middle Garbutt interval yielded only isolated diminutive foraminifera (a-26-B/94-O-11, Figure III-17; Imperial I-G50, Figure III-17f). Some samples were rich in framboidal pyrite (Imperial G50).

Samples towards the upper part of the Garbutt Formation, taken as within approximately 50 m of the base of the Scatter Formation, generally contain a more abundant and diverse foraminiferal fauna (b-005-E, Core#7, b-66-D/094-O-15, a-77-D/094-O-11). This interval is characterized by a fauna similar to that below with the addition of *Bathysiphon brosgiei*, *Saccammina alexanderi*, *Miliammina* spp., *Reophax vasiformis* and *Trochammina umiatensis*, among others.

At Murky Creek (Figures III-4, III-5), a similar increase in species richness and abundance occurs in the middle to upper Garbutt transition. The fauna is dominated by *Haplophragmoides linki*, *Haplophragmoides sluzari*, *Gaudryina canadensis*, *Uvigerinammina athabascensis*, *Verneuilinoides cummingensis*, *Gaudryina nanushukensis*, *Haplophragmoides multiplum*, *Trochammina* spp, *Ammodiscus* sp. and *Psamminopelta bowsheri*. The succession becomes increasingly silty upwards, making foraminiferal recovery difficult, but a sample from mudstone (#13) immediately below the thick Bulwell Member yielded an abundant and diverse fauna similar to the underlying strata.

Interpretation. The strata of the Garbutt Formation were deposited in an offshore environment and change to the offshore transition zone in the uppermost part of the formation. The foraminiferal fauna in the middle and upper Garbutt Formation is typical of the upper part of the *Marginulinopsis collinsi-Verneuilinoides cummingensis* Subzone of the *Gaudryina nanushukensis* Zone (Stelck et al., 1956; Mellon et al., 1956; Caldwell et al., 1978). *Haplophragmoides multiplum*, which in the past has been used to indicate a Middle Albian (Hulcross/Harmon-equivalent) age, also occurs in the Falher-equivalent interval of the Buckinghorse Formation (Schröder-Adams and Pedersen, 2003), and thus further corroborates their assertion that this species appeared earlier in the northern portion of the WCSB. Commencing approximately with the bentonite-rich interval in the lower Garbutt Formation, the basin appears to have been intermittently stagnant, and bottom water anoxia developed often during the late Early Albian, as indicated by the presence of pyrite and sparse or absent benthic foraminiferal fauna in some samples from northeastern British Columbia and the Northwest Territories plains (see Chapter II).

The diverse and abundant fauna in the upper Garbutt shows that the bottom water conditions became well-oxygenated. This occurs with increased evidence of storms impinging on the floor of the seaway due to the relative lowering of sea level that characterizes the latest early Albian-middle Albian transition throughout the WCSB. The upper Garbutt represents the prograding toe of the prograding Scatter Formation clinoforms.

Scatter Formation-Bulwell Member

Lithology. At its type section, the Bulwell Member of the Scatter Formation consists of sharp-based, fine-grained sandstone beds interbedded with mudstone and

thick intervals of amalgamated hummocky cross-stratified fine sandstone. The base of the Bulwell Member is placed above the Garbutt Formation at the first occurrence of thick-bedded, amalgamated hummocky cross-stratified sandstones. The sandstones also preserve wave rippled, combined flow and parallel laminae/crosslaminae to a lesser degree. In all outcrops, the Bulwell Member is rich in glauconite and heavily bioturbated.

Several cores (Table III-2) and outcrop sections (Table III-1) of the Bulwell Member were studied and sampled for foraminifera. Distinguishing between the members of the Scatter Formation is difficult, especially east and northeast of the isopach thicks along the western margin of the basin. The Bulwell interval was studied in the d-75-E/94-N-08 (Figure III-17e, Core#3) and Imperial Sun Aurora M-47 (Figure III-17g, Core#1) wells and is found in outcrop at Scatter River (Figures III-6 to III-8), Kotaneelee River east of the Kotaneelee Range (Figures III-15, 16), along the Petitot River (Figures III-11 to III-13 and at the Muskeg River-Liard River junction (Figure III-14). In these cores and outcrops, the Bulwell is typically hummocky-cross stratified to planar-laminated, moderately to heavily bioturbated, glauconitic, amalgamated fine-sandstone with some mudstone interbeds.

Micropaleontology. Foraminiferal recovery in many samples was hindered by the dominant coarser-grained lithology of the member. The fauna recovered from the Bulwell Member is similar to the underlying Garbutt Formation. The dominant foraminifera are *Verneuilinoides tailleuri*, *Verneuilinoides borealis*, *Verneuilinoides cummingensis*, *Haplophragmoides multiplum*, *Trochammina gatesensis*, *Trochammina umiatensis*, *Ammobaculites fragmentarius*, *Miliammina ischnia*, *Miliammina sproulei*,

Bathysiphon brosgiei and *Saccamina* sp. *Gaudryina nanushukensis* was recovered from only a few samples at the Petitot (Fort Liard) and Scatter River localities. Generally species diversity and abundance decreased in the coarser intervals of the Bulwell Member at all outcrops.

Interpretation. The Bulwell Member is composed of wave-dominated lower to middle shoreface sandstones deposited during the relative sea level fall of the Moosebar transgressive-regressive cycle. Foraminifera indicate a late Early Albian to Middle Albian age and represent the transition from the *Marginulinopsis collinsi-Verneuilinoides cummingensis* Subzone to the *Haplophragmoides multiplum* Subzone of the *Gaudryina nanushukensis* Zone. Although frequent intense storms may have perturbed the benthic community, the foraminiferal fauna is interpreted to represent well-oxygenated conditions. Lower-yielding samples may be due to difficulties in breaking down sandstone samples for analysis; however, frequent storms may have not provided a stable substrate and sufficient nutrient supply for benthic foraminifera. Additionally, high sedimentation rates may have diluted the concentration of foraminifera.

Scatter Formation-Wildhorn Member

Lithology. The Wildhorn Member, best exposed along the Liard and Scatter rivers, consists of an approximately 150-m-thick succession of mudstone with numerous siderite concretionary bands. At Scatter River the basal contact is somewhat gradational, but southwards opposite Garbutt Creek the contact is sharp (Figure III-9). The gradational contact between the Wildhorn and overlying Tussock Member is characterized by the increased occurrence of siltstone and fine sandstone interbeds at Scatter River (Figure III-7). Unlike in the lower part of the overlying Lepine Formation,

the numerous large concretions within the Wildhorn Member do not contain ammonites. Although the members of the Scatter Formation are difficult to distinguish in well logs, the Imperial Sun Aurora M-47 (Figure III-17g) and Imperial Sun Netla Raven F-73 (Figure III-17h) wells core the middle to upper parts of the Scatter Formation. These cores preserve hummocky cross-stratified, heavily bioturbated fine sandstones with interbedded siltstones and mudstones, with some intervals rich in terrestrial organic matter.

Micropaleontology. The foraminiferal fauna of the Wildhorn Member is dominated by *Gaudryina canadensis*, *Haplophragmoides linki*, *Verneulinoides tailleuri*, *Haplophragmoides multiplum*, *Verneulinoides cummingensis*, *Trochammina* spp., *Ammobaculites* spp., and minor occurrences of *Gaudryina nanushukensis* and several other species. Samples from distinct flooding surfaces within the Wildhorn (e.g. K21 and K26 at Scatter River) yielded the most diverse and abundant faunas. The M-47 well preserves a fauna dominated by *Verneulinoides tailleuri*, *Verneulinoides borealis*, and *Haplophragmoides multiplum*, along with several other species. Additionally, some strata preserve abundant organic matter (plant debris). In the F-73, a similar fauna, but with less diversity, was recovered along with abundant glauconite, mica and woody organic matter.

Interpretation. The Wildhorn Member contains a foraminiferal fauna that can be correlated with the *Haplophragmoides multiplum* Subzone of the *Gaudryina nanushukensis* Zone. Except for the more frequent occurrence of *H. multiplum*, the fauna is not significantly different than that in the underlying upper part of the Garbutt Formation. Despite the lack of ammonites, and unlike the middle Garbutt Formation, the

benthic fauna indicates a relatively favourable benthic environment. Although a distinct flooding surface overlies the Bulwell Member at the base of the Wildhorn Member, no pebbles that may indicate the presence of a transgressive surface of erosion were observed. Thus no sequence boundary is directly observable at this surface, although the equivalent interval to the south in the Peace River area (i.e. base of Harmon/Hulcross Formation overlying the Notikewin Member/Gates Formation) does (Webb et al., 2004). In the Northwest Territories wells that core the middle and upper portion of the Scatter Formation, the presence of a significant amount of organic material may indicate a terrestrial input from the northeastern margin of the Liard Basin.

Scatter Formation-Tussock Member

Lithology. In outcrop, the Tussock is best exposed along Scatter River, where it differs from the Bulwell Member in that it contains a higher proportion of thicker mudstone interbeds and lower concentrations of glauconite. Southwards from Scatter River, only the upper 20 m of the Tussock is silty with some thin-to-medium beds of fine sandstone, and the underlying succession is entirely mudstone, and hence is difficult to distinguish from the underlying Wildhorn Member (Figures III-9, 10).

Micropaleontology. In the mudstone facies opposite Garbutt Creek the Tussock Member contains many of the foraminifera that also characterize the Wildhorn Member. These include *Haplophragmoides linki*, *Gaudryina canadensis*, and *Verneuilinoides cummingensis*, but with the addition of the infrequent occurrence of *Gravellina chamneyi* and several other rare species such as *Spiroplectammina* sp. A. At Scatter River, the samples were too coarse to process properly for foraminifera. Specimens of *Ammobaculites* are noticeably absent from this fauna. Indeterminate gastroplitid

ammonites were reported by Stott (1982) from the Tussock-equivalent beds opposite Lepine Creek on the Liard River.

Interpretation. In part, the Tussock Member represents the regressive phase of the Hulcross/Harmon T-R cycle recorded to the south in deposits of the lower Boulder Creek/Cadotte Formation/Member (Figure III-2). No significant faunal change occurs between the Wildhorn and Tussock Members. This, combined with the lithological changes, indicates a slow relative fall of sea level, from offshore to offshore transition (Garbutt Creek) and lowermost shoreface (Scatter River) occurs in the transition between the two members.

Discussion

In the more southern parts of the Canadian Western Interior Seaway, the deposits of the Moosebar/Clearwater Sea preserve a diverse foraminiferal fauna with a significant calcareous component (*Verneuilioides cummingensis*/*Marginulinopsis collinsi* Subzone of the *Gaudryina nanushukensis* Zone, Figure III-3). No calcareous foraminifera occur above the lower Garbutt interval in the Liard Basin. The change to an agglutinated suite is also observed elsewhere in the basin (although not so low in the succession) with the appearance of the *V. cummingensis* suite (Caldwell et al., 1993). Although there remained a connection to the Boreal Sea during this time, the Liard Basin, unlike in the Moosebar deposits to the south, became intermittently inhospitable to benthic foraminifera. Similarly, some intervals of the lower Buckinghorse Formation are barren of foraminifera (Schröder-Adams and Pedersen, 2003), suggesting that stressed oceanographic conditions were common along the northwestern margin of the foredeep in northeastern British Columbia.

Although the Scatter Formation is characterized by numerous slight coarsening-upwards cycles from offshore and offshore transition zone mudstone to lower shoreface amalgamated hummocky cross-stratified sandstones, the interval is entirely marine and no sequence boundaries were recognized within it. These observations have significant implications for regional correlations of the Scatter Formation (see Chapter VII). In the Peace River area of northeastern British Columbia, Leckie (1986) showed that the marine to non-marine cycles in the Bulwell-equivalent Gates Formation were due to fourth-order sea level cyclicity superimposed on a third-order sea level fall. These cycles observed to the south of the Liard Basin were either due to localized tectonic effects, or the high-accommodation setting within the Liard Basin suppressed the effects of regional or basin-wide high-frequency relative sea level fluctuations as no sequence boundaries are here identified in the Scatter Formation; however, the Bulwell Member does preserve evidence of the third-order cycle, with a slight shallowing-upwards succession overlain by the offshore mudstone of the Wildhorn Member.

The Wildhorn Member represents deposition during the Hulcross/Harmon-equivalent flooding event in the Liard Basin. In the past, it was believed that the Hulcross Sea only transgressed as far as the Peace River drainage area; however the recent discovery of the *H. multiplum* Zone at Fall Creek, Alberta indicates that this transgression extended at least as far south as south-central Alberta (Leckie et al, 2000). Although ammonites have not been recovered from the Wildhorn Member, the *Haplophragmoides multiplum* fauna that characterizes both the Hulcross Formation and Wildhorn Member provides a biostratigraphic tie between the two regions. The Wildhorn thus is probably equivalent, at least in part, to the *Pseudopulchellia pattoni*

Zone (Figure III-3) which occurs in the Hulcross Formation (e.g. Caldwell, 1984). In the Liard Basin, no bentonites were recognized in equivalent strata of the Wildhorn or Tussock members of the Scatter Formation, although some samples in the lower Wildhorn and Tussock-equivalent beds opposite Garbutt Creek do contain concentrations of mica, and thus may be bentonitic. Numerous bentonites have been recognized in the lower part of the Hulcross Formation in both subsurface and outcrop exposures and have proven useful for correlation of the Hulcross transgression (Stelck and Leckie, 1988). Schröder-Adams and Pedersen (2003) also recognized the presence of bentonites in the *Haplophragmoides multiplum* Zone of the Buckinghorse Formation in the Sikanni Chief River area of northeastern British Columbia and drew correlations to the Hulcross/Harmon interval. Well log correlations of these bentonites northwards into the Scatter Formation are not possible because they are not recognizable on logs in the Liard Basin.

According to Caldwell (1984), the lowest point in relative sea level of the Hulcross T-R cycle occurred at the top of the *Gastroplites kingi* Subzone, which is likely at least partially equivalent to the Tussock Member of the Scatter Formation. The *Ammobaculites* sp. Zone characterizes this regression in the lower Boulder Creek/Cadotte Formation; however, this species was not recovered from the Tussock Member, but from the overlying Lepine Formation. This relationship supports the interpretation that the Tussock is at least in part slightly older than the lower Boulder Creek at Peace River, and that the *Ammobaculites* sp. Zone is present in the basal Lepine Formation (see next chapter).

Frank (2002) proposed that the Bulwell Member of the Scatter Formation is equivalent to the gas-producing sandstones of the “Chinkeh” Formation at Maxhamish Lake (see discussion section in previous section). In addition to the reasons already presented, the biostratigraphic data here clearly demonstrate that such a correlation is not possible. If Frank’s hypothesis were true, the mudstone overlying the subsurface Chinkeh should yield a *Haplophragmoides multiplum* fauna, which it does not. Furthermore, no sequence boundaries occur within any part of the Scatter Formation, as they do below, within, and above the Chinkeh Formation in subsurface. If the two stratigraphic units were equivalent, significant subaerial surfaces of erosion would be expected in the more proximal Bulwell Member.

Table III-1. Studied outcrops of Middle-Upper Garbutt and Scatter formations.

Field Designation	Location Description	NTS Coordinates	Stratigraphic Interval
L2000E	Petitot/Liard junction	Opposite Fort Liard airstrip	Bulwell Member
L2000F	Liard/Muskeg junction	6688308N; 0480473E	Bulwell Member
L2000K	Scatter River (Type Section)	6608703N; 0402003E	Entire Scatter Fm
L2001B	Murky Creek	6734055N; 0445275E	middle-upper Garbutt and Bulwell Member
L2001H	Kotaneelee River	6717892N; 0441765E	Bulwell Member
L2001N	Petitot River	6650295N; 0500819E	Bulwell Member?
L2002B	Liard River opposite Lepine Creek	6586700N; 0396300E	Wildhorn and Tussock-equivalent

Table III-2. Studied wells of Middle-Upper Garbutt and Scatter formations.

Well	Stratigraphic Interval
a-077-D/094-O-11	Upper Garbutt
a-026-B/094-O-11	Middle/Upper Garbutt
b-055-E/094-O-13	Middle and Upper Garbutt
b-066-D/094-O-15	Upper Garbutt
d-075-E/094-N-08	Scatter
Imperial Island River G-50 60 10 121 00	Middle Garbutt
Imperial Sun Aurora M-47 60 40 122 30	Scatter
Imperial Sun Netla Raven F-73 60 50 122 30	Scatter

Figure III-1. Location of studied wells (open circles) and outcrops (solid circles) of middle-upper Garbutt and Scatter formations in the Liard Basin.

Subsystem	U. Cr.	Stage					
			Liard Basin	Sikanni Chief River, B.C.	Peace River Foothills Moberly Lake	Northwestern Alberta Plains	Central Plains
			Dunvegan Fm	Dunvegan Fm	Dunvegan Fm	Dunvegan Fm	Belle Fourche Fm.
Lower Cretaceous	Cen.	Upper	FSMB			Shafesbury Fm.	Fish Scales Fm.
			Sully Fm	Sully Fm	Cruiser Fm		Westgate Fm.
			Sikanni Fm	Sikanni Fm	Goodrich Fm		Viking Fm.
			Bougie mbr	Bougie mbr	upper Hasler Fm		Joli Fou Fm.
			Lepine Fm	"Viking" marker bed	"Viking" marker bed		
					lower Hasler Fm		
					Lower Boulder Creek		
					Hulcross Fm		
					Gates Fm		
					Moosebar Fm		
Lower Cretaceous	Cen.	Middle	Fort St. John Group			Fort St. John Group	Colorado Group
			Scatter Fm	Scatter Fm	Scatter Fm		
			Tussock Mbr				
			Wildhorn Mbr				
			Bulwell Mbr				
Lower Cretaceous	Cen.	Lower	Fort St. John Group			Fort St. John Group	Colorado Group
			Garbutt Fm				
Lower Cretaceous	Cen.	Lower	Fort St. John Group			Fort St. John Group	Colorado Group

Figure III-2. Lithostratigraphic correlation chart for the northern Alberta Basin and Liard Basin areas.

Stage	Substage	Stratigraphy Moberly Lake NE B.C.	Selected Macrofossil Zones (Warren & Stoick 1969; Caldwell et al. 1978; Jeleitzy 1980; Jeleitzy and Stoick, 1981; Stoick 1982; Caldwell, 1993)	Peace River, British Columbia Foraminiferal Zones (Stoick et al. 1958; Sutherland & Stoick 1972; Koke and Stoick 1984, 1985; Stoick & Koke 1987; Stoick & Hedinger 1983; Stoick 1975, 1991)	Sikanni Chief River, British Columbia Foraminiferal Zones (Schroder-Adams & Pedersen, 2003)	Liard Basin Foraminiferal Zones (Jowett et al. in press and this study)	Liard Basin Stratigraphy (Jowett et al. in press and this study)
Cenomanian	Middle		<i>Acanthoceras athabascense</i>	<i>Verneuilinoides perplexus</i>	Unzoned	Unzoned	Dunvegan
	Early	Upper Cruiser	<i>Beattonoceras beattonense</i> <i>Irenoceras bahani</i> <i>Neogastrolites septimus</i> <i>Neogastrolites maclearni</i>	<i>Textularia alcesensis</i>		<i>Textularia alcesensis</i>	FSU BFS Sully
Albian	Upper	Lower Cruiser	<i>Neogastrolites americanus</i> <i>Neogastrolites muelleri</i>	<i>Haplophragmium swarēni</i>	Fish-Scale beds	<i>Haplophragmium swarēni</i>	Lower
			<i>Neogastrolites cornutus</i>				
		Goodrich	<i>Neogastrolites haasi</i>	<i>Haplophragmoides postis goodrichi</i>		subzone B	Sikanni
				<i>Verneuilina canadensis</i>		subzone A	(Upper Lapine)
		Upper Hasler	poorly fossiliferous interval	<i>Reophax troyeri</i>		<i>Bathysiphon-A. fragmentarius</i> assemblage	Bougie equivalent
		"Viking"		<i>Trochammina umiatensis</i>		<i>Ammomarginulina</i> assemblage	Lepine
				<i>Trochammina depressa</i>			
				<i>Reophax tundraensis</i>			
				<i>Haplophragmoides gigas phaseolus</i>			
		Lower Hasler	<i>Inoceramus commancheanus</i>	<i>Haplophragmoides gigas gigas</i>			
				<i>Haplophragmoides uniofbis</i>			
		Basal Hasler	<i>Stelckiceras liardense</i>	<i>Ammobaculites wenonahae</i>		<i>Ammobaculites wenonahae</i>	
Lower	Middle	Cadotte	<i>Gastrolites allani</i>	<i>Ammobaculites</i> sp.	<i>Gaudryina nanushukensis</i>	<i>Ammobaculites</i> sp. 1	
			<i>Gastrolites kingi</i>			<i>Haplophragmoides topagorukensis</i>	
		Hulcross	<i>Pseudopulchellia pattoni</i>	<i>Haplophragmoides multiplum</i>		<i>Haplophragmoides multiplum</i>	
	Lower	Gates	<i>Freboldiceras remotum</i>	<i>Verneuilinoides cummingensis</i> / <i>Margulinopsis collinsi</i>		<i>Verneuilinoides cummingensis</i>	
		Moosebar	<i>Subarchthopliites mcconnelli</i>				
		Gething	<i>Pachygyrcia canadensis</i>	<i>Trochammina mcMurrayensis</i>			
	Cadomin		<i>Aucellina aptiensis</i>	<i>Rectobolovina</i> sp.		<i>Gaudryina nanushukensis</i>	
						<i>Haplophragmoides multiplum</i> <i>Verneuilinoides cummingensis</i> Radioactive Rad (Barren) Calcareous Interval <i>Ammobaculites</i> - <i>Glaucospira</i> <i>Glaucospira</i>	Tussock Wildhorn Bulwell Garbutt Chinkeh

Figure III-3. Biostratigraphic correlation chart for Peace River, Sikanni Chief and Liard Basin regions.

Figure III-4. Upper Garbutt Formation and Bulwell Member exposed on Murky Creek (L2001B).

Locality: L2001B, Murky Creek Garbutt-Scatter
 NTS Coordinates: 0445275E; 6734055N
 Other Comments:

Figure III-5. Measured stratigraphic section of L2001B section on Murky Creek.

Figure III-6. Outcrop photographs of Garbutt Fm. and Bulwell Member of the Scatter Fm. in Scatter River area. a) Spectacular outcrop exposures of Garbutt Formation and Bulwell Member along Toreva Creek, a tributary of Scatter River. b) Upper part of Bulwell Member at the type section along Scatter River.

Figure III-7. Outcrop photographs of type section of the Scatter Formation. a) Wildhorn and Tussock members (person for scale in middle of Wildhorn Member). Several coarsening-upwards intervals can be seen at the gradational contact between the two members. b) Gradational contact between Tussock Member of the Scatter Formation and overlying Lepine Formation.

Figure III-8. Stratigraphic section of the Scatter Formation at the type section (L2000D) with location of foraminiferal samples (next two pages).

26. *Gravellina charnevi*, *Trochammina ruthfordi*, *Haplophragmoides* sp.,
Gaudryina canadensis, *Bathysiphon* sp., *Haplophragmoides multipilum*,
Miliammina sproulei, *Glomospirella gaultina*.

24. *Verneuilinoides cummingensis*, *Verneuilinoides* sp., *Trochammina* sp.,
Psammospira sp., *Miliammina* sp.

23. Barren

Locality: L2000K, Scatter River Type Section
 NTS Coordinates: 6608703N, 402003E
 Other Comments: Section Drawn by P. Pedersen

Trace Fossils

Terebellina	
Skolithos	
Zoophycos	
Teichichnus	
Planolites	
Chondrites	
Gordia	
Escape structure	
Siphonites	
Ophiomorpha	
Diplocraterion	
Rosselia	
Rhizocorallium	
Arenicolites	

26. *Gravellina chamneyi*, *Trochammia rutherfordi*, *Haplophragmoides* sp.,
Gaudryina canadensis, *Bathysiphon* sp., *Haplophragmoides multipilum*,

Locality: L2000K, Scatter River Type Section
NTS Coordinates: 6608703N, 402003E
Other Comments: Section Drawn by P. Pedersen

Trace Fossils

Terebellina	
Skolithos	
Zoophycos	
Teichichnus	
Planolites	
Chondrites	
Gordia	
Escape structure	
Siphonites	
Ophiomorpha	
Diplocraterion	
Roscelia	
Rhizocorallium	
Arenicolites

22

22. *Verneuilinoides* cf. *Y. talleur*, *Verneuilinoides borealis*,
Haplophragmoides linki, *Miliammina sproulei*, *Gaudryina*
nanushukensis, *Ammobaculites* sp.

21

21. *Trochammina rutherfordi*, *Ammobaculites lyrelli*, *Verneuilinoides*
cummingsensis, *Verneuilinoides borealis*, *Haplophragmoides*
linki, *Gaudryina canadensis*, *Baltysiphon* sp., *Miliammina*
sproulei, *Glomospira* sp.

20. *Verneuilinoides cummingsensis*, *Gaudryina canadensis*,
Trochammina sp., *Ammobaculites* sp., *Psammimopelia*
dowsheni

20

16

16. Barren

13

13. *Verneuilinoides* sp., *Gaudryina nanushukensis*

Covered section
Probably mainly shale

2-3-m thick
upward-tapering cycles

Legend

Parallel lamination

Hummocky cross-stratification

Planar cross-bedding

Trough cross-bedding

Mud-layer couplets

Ripples symmetrical

Ripples asymmetrical

Lenticular bedding

Lenticular bedding with mud draps

Biurbation

slight
intensive

Fault

Slump

Synaeresis crack

Dewatering

Normal graded lamination

Normal graded bedding

Legend

Parallel lamination	≡
Hummocky cross-stratification	≡
Planar cross-bedding	≡
Trough cross-bedding	≡
Mud-layer couplets	≡
Ripples symmetrical	≡
Ripples asymmetrical	≡
Lenticular bedding	≡
Lenticular bedding with mud draps	≡
Bioturbation	≡
Fault	≡

Figure III-9. Outcrop photographs of Bulwell and Wildhorn members opposite Garbutt Creek. a) View south (upriver) along Liard River of finer-grained expression of Bulwell Member. b) Sharp base of Wildhorn Member overlying Bulwell Member. More silty beds at the top of this section are the Tussock-equivalent.

Locality: **L2002B, Liard River opposite Garbutt Creek**
 NTS Coordinates: **~0396300E; 6586700N**
 Other Comments: **Wildhorn and Tussock Mbr. equivalents**

Figure III-10. Stratigraphic section of Wildhorn and Tussock members opposite Garbutt Creek with location of micropaleontology samples.

Figure III-11. Bulwell Member on the Petitot River (L2001N). a) Outcrop view. b, c) Bioturbated amalgamated hummocky-cross-stratified fine sandstones are overlain by wave-rippled sandstones (arrows).

Figure III-12. Outcrop photographs of the Bulwell Member in the Northwest Territories plains. a) Petitot River near its termination at Liard River (L2000E). b) Muskeg-Liard River junction.

Figure III-13. Stratigraphic section of L2000E section with locations of micropaleontology samples.

Locality: Muskey-Liard River Junction (L2000F)
NTS Coordinates: 6688308N; 0480473E
Other Comments: Section drawn by P. Pedersen

Figure III-14. Stratigraphic section of L2000F section with location of micropaleontology samples.

Figure III-15. Outcrop photographs of Bulwell Member along Kotaneelee River (L0001H). a) Upper Garbutt overlain by hummocky cross-stratified and intensely bioturbated Bulwell Member. **b)** Large *Planolites* burrows.

Figure III-16. Stratigraphic section of L2001H outcrop with locations of micropaleontology samples.

Figure III-17. Stratigraphic sections, location of micropaleontology samples and paleoenvironmental interpretations of studied core of midde-upper Garbutt and Scatter formations. The placement of the core on their respective well log curves is shown to left. Wells are figured in approximate order from south to north. a) a-077-D/094-O-11. b) a-026-B/094-O-11. c) b-055-E/094-O-13. d) b-066-D/094-O-15. e) d-075-E/094-N-08. f) Imperial Island River G-50 60 10 121 00. g) Imperial Sun Aurora M-47 60 40 122 30. h) Imperial Sun Netla Raven F-73 60 50 122 30.

Figure III-17a.

Figure III-17b.

Well: **b-66-D/094-O-15 Tex Ex Tatoo**
 Core #(s): **1**
 Core Interval: **527.6-545.9 m**
 (measured and sampled by P. Pedersen)

Samples	Lithology	Sedimentary Observations	Micropaleontology	Foraminiferal Zone	Surfaces	Unit Facies	Sedimentary Environment
4 17							
16							
15							
14							
13							
12							
11							
10							
9							
8							
7							
6							
5							
4							
3							
2							
1							
1							

Figure III-17d.

Well: IOE Dunedin d-75-E/94-N-08
 Core #(s): 1, 2, 3
 Core Interval: #1. 1594.1-1596.5 m; #2. 1791.3-1796.5 m; #3. 1796.5-1809.0 m
 Sampled by P. Pedersen

Figure III-17e.

Figure III-17f.

Figure III-17g.

Figure III-17h

Chapter IV. PALEOENVIRONMENTS AND REGIONAL STRATIGRAPHIC FRAMEWORK OF THE MIDDLE-UPPER ALBIAN LEPINE FORMATION IN THE LIARD BASIN, NORTHERN CANADA

Introduction

The Liard Basin, a sub-basin of the Alberta Basin straddling the border between British Columbia and the Northwest Territories (Figure IV-1), is generally defined by a thick succession of Phanerozoic sediments to the west of the Bovie structure (e.g. Leckie et al., 1991; Wright et al., 1994). During Albian time, variable depositional environments from non-marine and marginal marine to distal shelf environments occurred within the Western Interior Sea. The Liard Basin represents a dominantly marine, offshore setting throughout the various sea level fluctuations of the interior sea. Sedimentation was punctuated by the wave-dominated shelf sandstones of the Scatter Formation (Leckie and Potocki, 1998) and the wave-dominated shelf and deltaic sandstones of the Sikanni Formation (Figure IV-2), which originated from localized point sources fed from the rising Cordillera into the basin.

The Lepine Formation (Kindle, 1944; Stott, 1982) includes the thick marine shale succession between the Scatter and Sikanni formations (Figure IV-2). Regression of the Interior Sea during middle Albian time produced a widespread unconformity between the Mannville and Colorado groups; however, north-northeastern British Columbia preserves a continuous record of marine sedimentation, which is represented by the Lepine Formation. This succession documents sedimentation during several relative sea level cycles (Webb et al., in press). Foraminiferal assemblages respond to relative sea level changes and allow discrimination between the various marine incursions. Therefore, the

thick, continuous middle and upper Albian outcrop sections of the Lepine Formation provide a unique opportunity to extend the foraminiferal and stratigraphic correlations northwards from the well-documented Peace and Sikanni Chief River areas into the Liard Basin. This study takes the first multidisciplinary approach to understand the paleoenvironments reflected in the thick deposits of the Lepine Formation which otherwise appear monotonous sedimentologically. As noted in Caldwell (1984), the effects of transgressive-regressive cycles in the Western Canada Sedimentary Basin (WCSB) will be more clearly understood when their expression in the Lepine Formation of the Liard Basin is documented, as we seek to do here.

Stratigraphic and Structural Framework

The Bovie Structure is a north–south oriented feature in northeastern British Columbia and the southernmost Northwest Territories (Figure IV-1) over which there is a significant thinning of Cretaceous and underlying strata from west to east. Studies have concluded that the Bovie Structure has a significant normal fault component (e.g., Leckie et al., 1991). With the aid of seismic data (in its northern portion), the Bovie Structure has also been interpreted as a composite of a) a post-Mississippian (post-Mattson Formation) but pre-Cretaceous west-directed reverse fault (although the authors concluded that there was a possibility for some Cretaceous reactivation of the reverse fault) and b) a Laramide east-directed detachment fault within the Banff Formation (MacLean, 2001; Morrow et al., 2002; MacLean, 2002; MacLean and Morrow, 2004, this issue). Although the interpretation of the Bovie structure itself remains controversial, Cretaceous strata thicken markedly westwards across it and cross sections (Chapter VII) indicate that it probably formed a structural high that was inundated during the Early

Albian. In areas to the east (eastern 94O and 94P map areas) and north (Cameron Hills, Northwest Territories) of the Liard Basin succession, the Albian section is much thinner, indicating that significantly less syn-depositional accommodation space was present in these areas.

A thick shale succession of the Lepine Formation crops out along the east bank of the Liard River from the junction of Toad and Liard rivers to Scatter River. In the northern part of the Liard Basin in the southeastern Yukon and Northwest Territories, the Lepine Formation is found in isolated outcrops along the western flank of the Liard Range (e.g. Murky and Sully creeks), the Petitot River above its junction with the Liard River (south of Fort Liard), and the Kotaneelee River between the Liard and Kotaneelee ranges (Figure IV-1). Broad synclinal areas of the Liard Basin are underlain by shale of the Lepine Formation. South of Toad River, rocks equivalent to the Lepine Formation and underlying Scatter Formation are shale and the entire succession is assigned to the Buckinghorse Formation (Figure IV-2). Because of the apparent absence of the Sikanni Formation east of the Liard River in the northern part of the Liard Basin the shale succession overlying the Scatter Formation is not differentiated (Stott, 1982).

At its type section on the Liard River opposite Lepine Creek in northeastern British Columbia (Figure IV-1, inset), the Lepine Formation attains a thickness of 1100 m (Stott, 1982). However, that section includes 200 m of shale and siltstone that is laterally equivalent to the Wildhorn and Tussock members of the underlying Scatter Formation. This succession results from the rapid facies change to shale within the Scatter Formation from its type section at Scatter River southwards to this locality.

Biostratigraphic Framework

Albian

The Albian foraminiferal zonal scheme for the WCSB has been constructed from detailed studies of thick shale successions, especially those of the Fort St. John Group in northeastern British Columbia (Figs. 2, 3). In some areas, the foraminiferal zonation is correlated with the ammonite zonation.

The *Gaudryina nanushukensis* Zone spans the Lower and Middle Albian and is divided into six subzones, which are, in some cases, facies related. The Middle Albian subzones of the *G. nanushukensis* Zone are the *Haplophragmoides multiplum*, *Ammobaculites* sp. and *Ammobaculites wenonahae* subzones. The *H. multiplum* Subzone has been recognized in the Hulcross Formation and Harmon Member (Wickenden, 1951; Stelck, et al. 1956; Stritch and Schröder-Adams, 1999; Leckie et al., 2000), and the middle part of the Buckinghorse Formation (Schröder-Adams and Pedersen, 2003). The *Ammobaculites* sp. Subzone was originally recognized in the Peace River area in the lower Boulder Creek Formation and Cadotte Member of the Peace River Formation (Wickenden, 1951; Stelck et al., 1956; Caldwell et al., 1978), but has recently been found in the Buckinghorse Formation in the Sikanni Chief River area (Schröder-Adams and Pedersen, 2003). The *Ammobaculites wenonahae* Subzone characterizes the lower 65 m of the Hasler Formation in the Hudson Hope (upper Peace River) and Moberly Lake areas of northeastern British Columbia (Koke and Stelck, 1984; Stelck, 1991) and the middle part of the Buckinghorse Formation (Schröder-Adams and Pedersen, 2003). This subzone represents pre-Joli Fou Sea deposition during the interval elsewhere represented by the Mannville-Colorado unconformity. The ammonite *Stelckiceras liardense*, which

is the zonal marker for the uppermost Middle Albian (Jeletzky, 1980), is found from 61–244 m above the base of the Lepine Formation in the Liard Basin (Stott, 1982), and also occurs in the basal shale of the Hasler Formation in the upper Peace River area (Koke and Stelck, 1984), providing a biostratigraphic tie between the two regions.

The *Haplophragmoides gigas* Zone, which marks the base of the upper Albian and is widespread in the WCSB (Caldwell, 1978; Caldwell et al. 1993), has been subdivided into seven subzones in the upper Peace River area of northeastern British Columbia (Koke and Stelck, 1985; Stelck and Koke, 1987; Stelck, 1991). This area is stratigraphically complex because of two unconformities that coalesce southwards into a hiatus spanning the uppermost Middle Albian and the entire *H. gigas* Zone (Stelck and Leckie, 1990a–b; see below discussion). Most of these subzones have not been recognized outside of the Peace River Foothills.

Deposits of the Joli Fou Sea in the lower Upper Albian are widespread (Koke and Stelck, 1984) and represent the flooding over the Mannville-Colorado unconformity and its equivalents in the WCSB. During Joli Fou time, a north–south seaway connecting Boreal and Tethyan waters is thought to have existed, based on the presence of the southerly derived *Inoceramus* fauna and the foraminifer *Ammodiscus kiowensis* in Joli Fou strata of Alberta. The northern seaway was evidently somewhat restricted due to the Transcontinental Arch that formed a barrier to calcareous foraminifera and ammonites at this time (Koke and Stelck, 1985). The Joli Fou shale and the overlying Viking Formation and its equivalents represent the deposits of the third order Skull Creek transgressive-regressive couplet of the Kiowa-Skull Creek Marine Cycle (Kauffman and Caldwell, 1993, and refs. therein).

Three major regressive phases followed by transgression characterize Middle and Late Albian time (Leckie and Reinson, 1993). The following events can be distinguished: 1. valley cutting (Mannville unconformity) into the Cadotte and its equivalents and subsequent flooding of the Joli Fou Sea (lower Hasler Formation); 2. the middle Viking lowstand followed by deposition of the upper Hasler Formation and equivalents; 3. deposition of the “Viking grits” as a result of the third relative sea level fall and transgression of the Mowry Sea (uppermost Hasler Formation, Shaftesbury Formation).

While the Mannville-Colorado unconformity formed over much of central and southern Alberta, high subsidence rates in the Peace River Foothills (Keg River Low) and the Liard Basin enabled the development of a more continuous sedimentary succession than elsewhere along the western margin of the seaway. In the Peace River Plains, the Mannville-Colorado unconformity is represented in the Peace River Formation by valleys cut into the Cadotte Member that were infilled by estuarine deposits of the Paddy Member (e.g. Leckie et al., 1990; Leckie and Singh, 1991; Leckie and Reinson, 1993).

Foraminiferal studies have shown that the major Mannville-Colorado hiatus occurs between the Cadotte and Paddy members because of the presence of two unconformities associated with regressions 1 and 2 above (Stelck and Leckie, 1990a–b). Northwestwards, however, progressively more strata fill in this gap, and at the Moberly Lake Road the entire succession overlying the Cadotte equivalent (lower Boulder Creek Formation) is conformable. The overlying basal Hasler Formation (containing *Stelckiceras liardense* and *Ammobaculites wenonahae*) represents an early flooding event that is not recorded elsewhere due to the unconformity overlying the Mannville. The

“Viking marker bed” and the “Viking grits” that occur in the middle and upper parts of the Hasler Formation, respectively, however, indicate the expression of later relative sea level fluctuations.

The “Viking marker bed” in northeastern British Columbia (Stelck and Koke, 1987) was deposited as part of the eustatic fall that produced the intra-Viking unconformity elsewhere in the basin (Leckie and Reinson, 1993, #2 above). In the Moberly Lake area, the “Viking marker bed” is characterized by the *Reophax tundraensis* Subzone, which separates the basal Hasler shale from the upper Hasler shale. The “Viking marker bed”, because of its stratigraphic position within the *Haplophragmoides gigas* Zone, represents the transgressively-reworked regressive deposits of the Joli Fou Sea, and is thus correlative with the Viking sandstone below the intra-Viking unconformity that is ubiquitous in the WCSB (e.g. Reinson et al., 1994). The Viking interval elsewhere contains more than one sequence boundary that is regionally recognizable; however, these are muted in the higher accommodation Keg River low where they occur as correlative conformities.

The overlying strata containing the *Trochammina depressa*, *Trochammina umiatensis* and *Reophax troyeri* subzones represent the initial flooding of the Mowry Sea. Preservation of these basal strata south of the Peace River Arch greatly varies along the western margin of the seaway. These are overlain by strata containing foraminifera of the *Miliammina manitobensis* Zone, the base of which is placed at a series of thin pebble conglomerate beds (the “Viking grits”) in the upper Hasler and Buckinghorse formations (Stelck and Koke, 1987; Stelck, 1975; Stelck and Leckie, 1990a). This zone also overlies the Viking “grit” beds in the western plains including the Viking “A” grits in the Caroline

area (Hein et al., 1986; Leckie, 1986), the Paddy/Shaftesbury transition in wells near Goodfare (Stelck and Leckie, 1990a), and in outcrop the basal Shaftesbury Formation near Peace River town (Leckie et al., 1990; Leckie and Singh, 1991). This paper attempts to establish the relationship of these events to strata of the conformable succession of the Lepine Formation in the Liard Basin.

Lepine Formation

In previous studies of the Lepine Formation, only molluscan biostratigraphy has been utilized in attempts to correlate these strata with those in the southern part of northeastern British Columbia (the upper Peace River area, Figure IV-3). No ammonites have been recovered from the type section of the underlying Scatter Formation on Scatter River. Stott (1982) and Jeletzky (1980) thought that the Wildhorn and Tussock members of the Scatter Formation may occupy the Middle Albian *Pseudopulchellia pattoni* Zone based on ammonite collections from the Wildhorn Member on Crow River (Figure IV-3). At the Lepine type locality, however, Tussock-equivalent beds have yielded indeterminate gastrolitid ammonites (Stott, 1982).

Unlike the Scatter Formation, the lower part of the Lepine Formation preserves a large abundance of ammonites enclosed in concretions. The basal 60 m of the Lepine Formation are divisible into the *Gastrolites kingi* and *Gastrolites allani* subzones of the *Gastrolites* sensu stricto Zone (Jeletzky, 1980; Stott, 1982). These zones are succeeded by the appearance of *Stelckiceras liardense* from approximately 61 to 244 m above the base of the formation. *S. liardense* forms its own zone marking the top of the Middle Albian, and also has been recovered from the Peace (Koke and Stelck, 1984), Sikanni

Chief, and Buckinghorse River (Stott, 1982) areas. Through the majority of its range it is the sole ammonite species found.

Because the *Gastrolites* and *Stelckiceras* zones are recognized throughout northeastern British Columbia, correlation between the Peace River, Buckinghorse and Scatter-Lepine formations is possible (Figure IV-3) (e.g. Stelck, 1991; Stelck and Koke, 1987; Koke and Stelck, 1984). *Stelckiceras liardense* occurs in the basal Hasler Formation in the Moberly Lake and upper Peace River areas overlying the *Gastrolites*-bearing Lower Boulder Creek/Cadotte sandstone. In the Lepine Formation, *Gastrolites* occurs in the basal 60 m of the Lepine Formation implying that the basal Lepine Formation is equivalent to at least the uppermost part of the Cadotte Formation.

Ammonites have not been recovered from Joli Fou strata, although the bivalve *Inoceramus comancheanus* occurs. Ammonites reappear in the Goodrich/Sikanni Formation, where the first representatives of *Neogastrolites* occur providing a further biostratigraphic tie (Figure IV-3).

Location and Methods

In the Liard Basin, continuous outcrops of the Lepine Formation are limited to those along the Liard River in northeastern British Columbia where the formation attains its greatest thickness. A number of sections were studied northwards from Garbutt Creek to Scatter River (many of these were originally measured by Stott, 1982) resulting in a continuous stratigraphic section of the Wildhorn and Tussock member-equivalents of the Scatter Formation (opposite Garbutt Creek) and the entire Lepine Formation (Figure IV-1). In addition, cores from two wells, Imperial Pan Am Tattoo No. 26 a-26-b/94-O-11

and Imperial Pan Am La Biche b-55-e/94-O-13 penetrate the Lepine Formation and were studied and sampled for micropaleontological analysis.

This study utilizes micropaleontology, stratigraphy, Rock Eval pyrolysis and well log correlations, the latter of which were completed using the iDc digital well log database and Geosection software. A reference well, IOE Dunedin d-75-e/94-N-8, drilled through the thick Lower Cretaceous succession in the western portion of the Liard Basin, was chosen for the well log correlations of this study (Figs. 1, 7). Samples for micropaleontology and Rock-Eval analysis were collected at regular intervals from 3 to 15 m. Foraminiferal samples were processed using standard techniques (Then and Doherty, 1983). Digital light microscope photographs of selected foraminiferal specimens are illustrated in Figure IV-6. Rock-Eval analyses were run on a DELSI Rock-Eval II/TOC apparatus at the Geological Survey of Canada, Calgary.

This paper uses the upper offshore, lower offshore and shelf terminology (e.g. MacEachern et al., 1999). In the sense it is used here, the upper offshore depositional environment lies below fairweather wave base but grades basinward from the lower shoreface and continues to receive significant amounts of sand and silt with clay during non-storm conditions. Hummocky cross-stratified fine sand is deposited in this environment as wave base is lowered during storm conditions. The lower offshore lies basinward of the upper offshore and is characterized by deposition of a higher proportion of clay and silt and a lower proportion of sand during non-storm conditions. Following MacEachern et al. (1999), the upper and lower offshore depositional environments represent what others regard as proximal shelf (e.g. Walker and Plint, 1992). As used

here, the shelf lies basinward of the lower offshore and is dominated by suspension deposition of clay.

Results

Based on the combined evidence of this study, the Lepine Formation can be divided into five units. A composite stratigraphic section of the Lepine formation is shown in Figure IV-4 and a composite range chart of foraminiferal taxa in Figure IV-10. A table of facies that characterize each of the units is provided in Table 1.

Unit 1. Basal Lepine Silty Shale Facies

Opposite Garbutt Creek on the east bank of the Liard River, 60–90 m of rubbly, sideritic and silty shale lies above the Tussock equivalent of the Scatter Formation and is assigned to Unit 1. The basal contact is placed above the last interbeds of very fine sandstone and the appearance of ammonites. Unit 1 is abundantly fossiliferous, with numerous gastroploid ammonites enclosed in concretions (see Figure IV-3 for ammonite zonation) (Stott, 1982).

Micropaleontological samples are characterized by poorly preserved, coarsely agglutinated foraminifera. The lower 45 m contains *Verneuilioides borealis*, *Gaudryina canadensis*, *Trochammina gatesensis*, *Gaudryina nanushukensis*, *Haplophragmoides linki*, and *Ammobaculites humei*. Isolated specimens resembling *Ammobaculites wenonahae* occur 40 m above the base of the Lepine Formation.

Core from Imperial Pan Am La Biche b-55-e/94-O-13 (Core 4, 1136–1142 m) to the northeast of the outcrop penetrates this interval and is characterized by moderately bioturbated silty shale. The microfauna is dominated by *Ammobaculites humei*, *Haplophragmoides* sp. and *Verneuilioides borealis*, and lacks *A. wenonahae*.

In well logs, this unit is difficult to differentiate from the underlying Tussock Member. A distinct and sometimes thick interval of high gamma ray levels characterizes the “Scatter Marker” (Williams, 1978; Dixon, 1997, 1999; Radioactive Marker 3 in Thompson, 1977) within the basal Lepine Formation, and generally directly overlies the Scatter Formation. In the western Liard Basin wells (Figure IV-7, for example), however, a fining upwards interval underlies this gamma kick. In the reference well (Figure IV-7), this interval represents approximately 60 m of strata, and likely corresponds to Unit 1 of the Lepine Formation.

Interpretation. The silty shale facies forms the transition from the Tussock Member of the Scatter Formation, which at Scatter River is characterized by lower shoreface to upper offshore, hummocky cross-stratified, medium-bedded, glauconitic and pervasively bioturbated sandstones interbedded with silty shale (Leckie and Potocki, 1998). Unit 1 thus likely represents an upper offshore environment which was deposited during slow relative sea level rise. Transgressive conditions result in the appearance of abundant ammonites. Foraminifera are indicative of the later part of the *Gaudryina nanushukensis* Zone, and at least for the lower 40 m are pre- *Ammobaculites wenonahae* Subzone. The common presence of *Ammobaculites humei* along with various other indistinct species of *Ammobaculites* in a low diversity assemblage is characteristic of the *Ammobaculites* sp. Subzone. The zonal ammonites, *Gastrolites kingi* and *G. allani* (Stott, 1982) and foraminiferal subzone both indicate a Middle to late Middle Albian age. These fossil occurrences indicate the age equivalence of Unit 1 with the upper Cadotte Member forming a biostratigraphic tie between the Liard Basin and Peace River region.

Unit 2. Flaky Shale Facies

Unit 2 consists of approximately 100 m of black, fissile shale that breaks into flakes (Figure IV-5a, b). The contact between units 1 and 2 is gradational over an interval of 10 m (this can be seen at locality L2002DA). The unit contains abundant ammonites enclosed in concretions that have been assigned to *Stelckiceras liardense* (Stott, 1982). Selenite crystals, bands of sulfur, and some thin bentonites were observed in the lower 60 m. At locality L2002DB, large permineralized fragments of tree trunks occur with ammonites (Figure IV-5b). Fish vertebrae are common, and an almost complete articulated fish vertebral column was recovered 20 m above the wood fragments. The shale becomes progressively more rubbly and rusty weathering upwards. Concretions and ammonites become less frequent and the last *Stelckiceras* ammonite was observed 280 m above the base of the formation, which is taken as the top of the unit.

Foraminiferal assemblages are characterized by increased abundance and improved preservation. The dominant species is *Verneuilinoides borealis*, accompanied by infrequent occurrences of *Ammobaculites wenonahae*, *Ammobaculites humei*, *Saccamina alexanderi* and *Gaudryina canadensis* (Figure IV-10). *Ammomarginulina* and *Ammotium* sp. occur in the upper part of Unit 2. Near the base of the unit, two samples contain the diminutive species *Spiroplectammia* sp. A and *Scherochorella minuta*. Bivalve fragments and abundant ostracods are preserved at 135 m. Algal cysts occur with other woody and non-woody organic matter (Figure IV-4).

Core from Imperial Pan Am Tattoo No. 26 a-26-b/94-O-11 (Core 2, 1014.3–1020.4 m) and Imperial Pan Am La Biche b-55-e/094-O-13 (Core 3, 1073.5–1079.5 m) penetrate this interval. The a-26 well is characterized by bioturbated dark platy shale with some fine sand laminae. The benthic foraminiferal fauna includes *Ammobaculites*

wenonahae and *Verneuilinoides borealis* along with *Ammobaculites petilus* and *Haplophragmoides* sp. and some algal cysts. The b-55 core consists of moderately bioturbated black platy shale with some very fine sand laminae and is dominated by *Ammobaculites tyrelli*, *Verneuilinoides tailleuri* and *V. borealis* but lacks *Ammobaculites wenonahae*. It also contains some algal cysts. In well logs, the base of Unit 2 is placed at the “Scatter marker” (Figs. 7, 8B–C) (see above discussion).

Interpretation. This unit is distinct in the Albian succession of the Liard Basin due to its lithology and geochemistry (see below). No pebble beds were found at its base that would indicate the presence of a sequence boundary (Posamentier and Allen, 1999); however, conditions changed relatively abruptly in this high accommodation setting. As noted by Koke and Stelck (1984), there is also no evidence of a sequence boundary between the *Gastrolites* and *Stelckiceras* zones in upper Peace River Formation strata. The benthic foraminiferal assemblage, in agreement with the ammonites, places this unit within the *Ammobaculites wenonahae* Subzone, and hence marks the uppermost portion of the Middle Albian succession in the basin. Stelck (1991) noted that *A. wenonahae* indicates stressed, possibly brackish marine conditions.

The abundance of organic matter and algal cysts in the lower portion of the unit is typical of major flooding surfaces in the Albian (e.g. lowermost Shaftesbury overlying the Paddy Formation, Leckie et al., 1990; the Fish Scale Marker, Leckie et al., 1992; and base of the Sully Formation, unpublished data), and are likely responsible for the gamma-ray kicks that form the “Scatter Marker” in well logs. Although numerous large wood fragments occur in the lower part of the unit, their co-occurrence with abundant ammonites, fish remains and benthic foraminifera indicates a fully marine environment

and hence they must have been rafted out into the basin. This interval was deposited during relative sea level rise when much of western Canada was subjected to subaerial erosion at the Mannville-Colorado break. Evidently, early flooding in proximal areas allowed the rafting of trees out into the basin.

In the basal Hasler Formation, equivalent to Unit 2, Stelck (1991) noted that the *A. wenonahae* Zone was deposited at mid-neritic depths. The correlative interval in the Liard Basin probably represents lower offshore to shelf deposition. A small thin coal bed was noted in the uppermost part of the *A. wenonahae* Subzone on the upper Peace River (Koke and Stelck, 1987; Stelck, 1991), and was thought to be indicative of a shallowing event. Its relationship to the tree-bearing interval here is difficult to substantiate, but this evidence at least indicates intermittent bottom water anoxia, corroborated by benthic faunal decrease, and abundant terrestrial organic matter supply into the Liard basin and its preservation during *A. wenonahae* time.

Unit 3. Shale and Silty Shale Facies

Unit 3 is characterized by 300 m of rubbly and rusty weathering shale and silty shale from 280 to 600 m above the base of the Lepine Formation. The base is chosen above the last appearance of ammonites. Concretions are present, but less common than in the underlying units.

The foraminiferal assemblage is similar to Unit 2 with a slight increase in species diversity. The dominant benthic foraminifera are *Verneulinoides borealis*, *Ammobaculites wenonahae*, *Ammomarginulina* sp. and *Ammotium* sp., with minor occurrences of *Trochammina* sp. and *Uvigerinammina manitobensis* (Figure IV-10).

In well logs, a persistent marker within Unit 3 overlies the top of a slight coarsening upwards interval (especially apparent in gamma ray logs (Viking marker in Figure IV-7). This marker is distinctive in b-37-i/94-N-9 (Figure IV-8C) and is also labeled in the cross-section of Figure IV-8b.

Interpretation. Unit 3, although more silty, contains a low diversity foraminiferal fauna similar to the underlying unit. The facies represents a depositional environment below storm wave base, probably lower offshore to shelf. Despite the offshore conditions low faunal diversities point towards ecological stresses such as high sedimentation rates and brackish water conditions. Stressed conditions are also supported by the presence of *Ammobaculites wenonahae*, interpreted by Stelck and Koke (1987) as being an aberrant taxon.

Biostratigraphic placement of this interval is based on a) the absence of ammonites in the entire Joli Fou Sea; b) the presence of *Ammomarginulina* as found in the basal Joli Fou elsewhere and c) well log correlations. Stelck and Koke (1987) recorded *Ammomarginulina cragini* in the Joli Fou equivalent shale of the Hasler Formation along with the zonal marker *H. gigas*. In Saskatchewan, *Ammomarginulina asperata* is limited to the lowermost few meters of the equivalent Skull Creek shale, and occurs with *H. gigas* (Guliov, 1967; McNeil and Caldwell, 1981).

The Viking marker bed marks the end of Joli Fou deposition. It was originally described as a 15-m-thick coarsening upwards interval in the Hudson Hope-Moberly Lake area (Stelck and Koke, 1987). In the Buckinghorse Formation along the Sikanni Chief River in northeastern British Columbia, Schröder-Adams and Pedersen (2003) found the *H. gigas* Zone based on the presence of *Trochammina alcanensis*. There, the

Joli Fou deposits are overlain by a coarser grained interval interpreted as the Viking marker bed that in turn is overlain by strata containing the *Miliammia manitobensis* Zone. In well logs, the Viking Marker, identified by a major flooding surface overlying a coarsening upwards interval, was correlated between the Sikanni Chief River region and the Peace River Foothills (Schröder-Adams and Pedersen, 2003).

In order to define the Viking marker in the Lepine Formation we traced this surface in logs northwards to the top of a distinct coarsening-upwards interval in the 94G15 map area (Figure IV-8b). Farther north into the Liard Basin this log marker becomes more subtle, but tentatively places the Viking marker in the middle part of the Lepine Formation (Figure IV-8b, c), about 300 m above the base in the reference well (Figure IV-7). In the a-39-b/94-N-8 well (Figure IV-8b), this surface is clearly overlain by strata with high gamma-ray signatures characteristic of a significant transgression.

In outcrop along the Liard River the Viking marker cannot be identified (Figure IV-4). Assuming a constant thickening of the succession from the reference well (Figure IV-7) to the outcrop sections along the Liard River, the Viking marker equivalent should fall approximately 400–450 m above the base of the Lepine Formation at the outcrop location (Figs. 1, 4). This position is 150 m above the last occurrence of ammonites and the base of Unit 3. No distinct lithological or foraminiferal change occurs at this point in the succession suggesting that the basin here remained relatively deep and no faunal changeover was triggered.

Unit 4. Interbedded Siltstone and Silty Mudstone Facies

Unit 4 is gradational with the underlying unit and is characterized by interbedded thin siltstone and very fine sandstone, silty mudstone, and shale (Table 1). The base of

the unit is placed at approximately 600 m above the base of the Lepine Formation and the unit is 380 m thick. Unit 4 differs from the underlying unit in its foraminiferal fauna and the presence of coarser grained interbeds. The unit forms a massive cliff section on the east bank of the Liard River north of Lepine Creek (Figure IV-1, IV-5c, L2002DB section). A prominent bed of cone-in-cone structure, 16 cm in thickness, is present near the top of the unit (Figure IV-5d, e) and allows correlation downriver between L2002DB and L2002F sections. No macrofossils were recovered from this unit. Rhythmic 5 to 10 m thick coarsening-upward intervals from mud to silt are evident throughout the unit (Figure IV-5d).

Beginning near the base of Unit 4 in siltstone interbeds at ~640 m above the base of the Lepine Formation, a notable increase in abundance and diversity of benthic foraminifera occurs. *Bathysiphon brosgiei* appears in great abundance along with *Verneuilinoides borealis*, *Ammobaculites fragmentarius*, *Miliammina sproulei*, *Trochammina gatesensis*, *Trochammina rutherfordi* and others in lower abundances. At the top of this unit (the lower part of L2002F section), *Haplophragmium swareni* and *Trochammina umiatensis* also appear and *Ammobaculites fragmentarius* dominates the fauna. *Miliammina manitobensis* appears in L2002F7, 860 m above the base of the Lepine Formation. Also notable is the absence of *Ammomarginulina* and *Ammobaculites wenonahae* in this unit.

In well logs Unit 4 contains numerous muted coarsening-upwards cycles (Figure IV-7, IV-8b, c), the last of which is overlain by a distinct regional flooding surface marking the base of the overlying unit.

Interpretation. The great increase in abundance and diversity of benthic foraminifera and the absence of the stressed taxon *A. wenonahae* indicates a return to more normal, probably better oxygenated, marine bottom water conditions. Schröder-Adams and Pedersen (2003) noted also an abundance and diversity increase above the Viking interval with the dominant appearance of *Haplophragmium swareni* in the Sikanni Chief River region. *Bathysiphon* has often been considered a bathyal form, and can be a dominant benthic foraminifer in turbidite successions (Brouwer, 1965).

Faunal composition of the incoming diverse assemblage, in particular the dominance of *Ammobaculites fragmentarius*, is typical for the Joli Fou/Mowry transition (Schröder-Adams and Pedersen, 2003). In the upper part of Unit 4, incoming species such as *Miliammina manitobensis* and *Haplophragmium swareni* are indicative of the *M. manitobensis* Zone associated with the Mowry Sea. The transition between the two major marine inundations occurs in a thick, conformable succession in this northern basin.

As discussed under the previous unit, log correlations and their projection to the outcrop places the Viking marker below Unit 4 in an interval without faunal changes. This would suggest that the major faunal change occurs more than 200 m above this Viking marker. The faunal change appears near the base of an interval that can be confidently correlated in well logs southwards to the Sikanni Chief River area where it is expressed in coarser facies of the Bougie member (Figure IV-7, IV-8b; Pedersen and Schröder-Adams, 2001).

Unit 5. Soft Shale Facies

At approximately 1000 m above the base of the Lepine Formation along the Liard River, a 100 to 120-m-thick monotonous recessive interval of soft black mudstone overlies Unit 4 (Figure IV-5d). This unit is visible in the cliffs opposite Scatter River and further upriver (south). Unit 5 is overlain by the Sikanni Formation. The mudstone is generally devoid of siltstone interbeds and some concretionary horizons are present. No macrofossils were recovered from this unit.

Unit 5 contains an abundant and diverse benthic foraminiferal fauna transitional from the uppermost portion of Unit 4. *Miliammina manitobensis* appears more frequently, along with *Ammobaculites fragmentarius*, *Verneulinoides borealis*, *Trochammina umiatensis*, *Haplophragmoides postis*, *Gravellina chamneyi* and *Haplophragmium swareni*.

The base of Unit 5 is a prominent fining on gamma and resistivity logs marking the base of a distinct flooding interval (Figure IV-7, IV-8b, c) overlying the northern equivalent of the Bougie member. The top of Unit 5 is placed at the first coarsening-upwards cycle that marks the base of the Sikanni Formation.

Interpretation. Because of its stratigraphic position and foraminiferal content, the base of Unit 5 is likely equivalent to the “Viking grit” transgressive lag deposits (not equivalent to the “Viking Marker”) 80 m below the Sikanni and correlative Goodrich formations at Sikanni Chief River and the Peace River Foothills, respectively (Stelck, 1975; Stelck and Koke, 1987). No pebbles were observed at this surface in the Lepine Formation. Eastwards into the 94P map sheet area, the Bougie member can still be seen as a prominent coarsening-upwards interval (Figure IV-8b).

The rich foraminiferal assemblage is characteristic of the Upper Albian *Miliammina manitobensis* Zone, and continues into the overlying Sikanni Formation (Schröder-Adams and Pedersen, 2003; Jowett and Schröder-Adams, in press). The unit likely represents deposition in normal marine, oxygenated shelf conditions below storm wave base.

Rock-Eval Geochemistry

Rock-Eval analysis was run on splits from most micropaleontology samples. Total organic carbon (TOC) ranges from 0.60% to 3.58%, with the highest values in the lower part of Unit 2 (average 1.7 %). TOC decreases steadily upwards from the middle part of Unit 2 to the top of Unit 4, the latter of which averages 1 %. In Unit 5, TOC values are again higher at 1.6 % (Figure IV-9b).

Units 2 and 3 are generally characterized by relatively high hydrogen index (HI) values with an average >140 mgHC/gTOC, and maximum values of 230 mgHC/gTOC in the middle part of Unit 2 (Figure IV-9a). HI decreases upwards into Units 4 and 5, averaging 52 mgHC/gTOC.

HI ranges between 100–200 mgHC/gTOC make interpretation of organic matter type difficult (Espitalé et al. 1985). An S_2 (mg pyrolysate/g rock vs. %TOC) curve (Langford and Blanc-Valleron, 1990; Cornford, et al. 1998) indicates that the kerogen is mainly of Type III (terrestrial) origin (Figure IV-9b); however, the samples from Unit 2 contain a mixture of Type III and some Type II kerogen.

The trends described above indicate that the units of the Lepine Formation can be differentiated by their Rock-Eval geochemical signatures (Figs. 9a–b). Unit 2, while not fully marine, appears to have been the closest to normal marine in the succession. This

reflects deposition in the Joli Fou Seaway, when connections existed to the Tethys and Boreal Sea. A similar trend was recognized in the Buckinghorse Formation (Schröder-Adams and Pedersen, 2003). TOC and S₂ values decrease steadily in Units 3 and 4 with no obvious break.

Discussion

Paleoenvironment

The Lepine Formation preserves a continuous record of sedimentation documenting late Middle to Late Albian marine inundation of Western North America. Fossil occurrences (ammonites and foraminifera) in this shale succession are an important tool to subdivide the formation stratigraphically. Paleoecological conditions were influenced at times by a) relative sea level changes; b) the interaction of Boreal and Tethyan watermasses; c) the possible intermittent presence of barriers restricting communication of the interior sea with the northern Boreal Sea; and d) freshwater and sediment input from rivers draining the rising Cordillera. This study correlates a complete succession to more proximal parts of this basin that record pronounced transgressive/regressive cycles, but where unconformities obscure the sedimentary record and basin history.

The distribution of ammonites during Middle and Late Albian time gives some indication of the paleoecological conditions within the seaway. Within the Western Interior Sea and Arctic, occurrences of *Stelckiceras liardense* are restricted to the lower Lepine Formation, middle Buckinghorse Formation and basal Hasler Formation making the species endemic to northeastern British Columbia. It may have had a wider distribution in the interior sea, but equivalent strata are not preserved elsewhere due to

the Manville unconformity. Jeletzky (1971, 1980) attributed this distribution to the complete or near complete isolation of the interior sea from the Arctic basin during latest Middle Albian time due to widespread uplift in the northern Northwest Territories and Yukon. Furthermore, Jeletzky (1980) considered *Stelckiceras* to be the ancestor of the *Neogastrolites* lineage, also endemic to the Canadian Western Interior Basin, and neither appears to have had northward migrations into the Arctic region. This led Jeletzky (1980) to conclude that the Canadian Western Interior Sea had poor or intermittently no connection with the Arctic region during the Middle to Late Albian, perhaps only being fully connected during times of widespread subsidence. Long periods of restriction might have influenced bottom water oxygen availability in the interior basin.

Although the Sverdrup Basin appears to have been a radiative center for ammonites through much of the Albian (Jeletzky, 1980), during deposition of units 2 and 3 the ammonite fauna is either completely endemic to the Western Interior or the strata are barren of ammonites, respectively. The latter is the case during deposition in the Joli Fou Sea. Benthic foraminifera of the Joli Fou Sea corroborate this pattern, as they are considerably reduced in both diversity and abundance in the Liard Basin (*A. wenonahae* Zone and *Ammomarginulina* assemblage Zone) and Sikanni Chief River region. These observations indicate greatly stressed oceanic and benthic environments in the northern Joli Fou Seaway. In addition, the thick sedimentary succession suggests that significant localized thrust loading adjacent to the Liard Basin and Sikanni Chief River areas produced high sedimentation rates in pace with significant subsidence. Localized or widespread brackish conditions and turbidity could have been caused by riverine input

from the rising Cordillera, as Rock-Eval indicates a transition to dominantly Type III terrestrial organic matter. Wave-dominated deltaic conditions did develop in the area in the overlying Sikanni Formation, but direct evidence for fluvial input in the Lepine is not preserved in the foothills. These, in combination with the restricted Boreal connection, led to a reduced benthic and nektonic fauna. Faunal comparisons between the Liard and Peel River areas (Chamney, 1978) indicate considerable differences suggesting two separate paleoenvironments with restricted communication.

Unlike the Liard and Sikanni Chief River areas, the Peace River Foothills preserves a much more diverse *A. wenonahae* and *H. gigas* fauna, although the latter also lacks ammonites (Stelck and Koke, 1987). We propose that ecological conditions of the *Stelckiceras/wenonahae* interval and Joli Fou Sea in northern northeastern British Columbia were strongly influenced by these tectonic, sedimentary and oceanographic processes, whereas southern localities in the seaway were controlled by paleoceanographic circulation of more normal marine oxygenated waters.

Stratigraphic correlations

Based on mineralogy and inorganic geochemistry Foscolos and Stott (1975) divided the Lepine Formation into four units (their fig. 36; Figure IV-10 here). These correspond to our five units except that our units 3 and 4 were not differentiated. By comparing both studies, our units 2 and 5 have similar mineralogy and these are both interpreted as transgressive successions as the former represents the Joli Fou Sea-equivalent, and the latter represents the Mowry Sea flooding over the Bougie member-equivalent strata within the Lepine Formation. Differentiation between units 3 and 4

based on faunal changes indicates oxygenation of the basin, but does not correspond to a mineralogical change.

Our regional subsurface correlations between the Liard Basin and the Sikanni Chief River and Peace River regions show a gradual thinning of the succession southwards. However, problems were encountered with previous thickness calculations. The Lepine Formation in the Liard Basin reaches a thickness of 1100 m. Correlative strata in the Sikanni Chief River region are approximately 545 m thick (Schröder-Adams and Pedersen, 2003). The correlative Hasler Formation according to Stelck and Koke (1987) is 530 m thick in the Amoco Moberly 16-20-79-25-W6 well immediately east of the Hudson Hope Moberly Lake road (Stelck, 1991). Subsurface cross-sections northwards and eastwards from the Moberly Lake area indicate that this thickness of the Hasler Formation is incorrect. The base of the Hasler was placed at a depth of 860 m in the Amoco Moberly 16-20-079-25-W6 well. Our subsurface correlations indicate that this is actually the Notikewin top, and the actual depth is at 725–750 m (Figure IV-11). The thickness of the Hasler Formation is thus between 250 m and 340 m depending on the placement of the base of the Hasler and overlying Goodrich Formation. The thickness of the Hasler between the basal Hasler and the Viking marker is approximately 125 m, which is less than half that Stelck and Koke (1987) calculated for the same interval, and a third of the same interval in Stelck et al. (2000, fig. 3). Our correlations of distinct surfaces thus indicate a much thinner package in the south than was measured in outcrops. Unless a drastic thickness change occurs between outcrop along the Hudson-Hope-Moberly Lake Road and the nearby well, the *A. wenonahae* and lower *H. gigas* zones are much thinner than previously reported.

In a regional subsurface study of Lower Cretaceous strata north of Peace River in northeastern British Columbia, Webb et al. (2004) show the thickening of Joli Fou strata westward into the foredeep as the Cadotte Member increases in shale content and the post-Cadotte, pre-Viking interval increases in thickness between townships 84 and 87 (their Sequence 3). Their transgressive surface TS11, which overlies Sequence 3, is the Viking Marker bed, and is correlative to that in Schröder-Adams and Pedersen (2003). This shows how the *A. wenonahae* and lower *H. gigas* zones (which occur between the Cadotte and Viking marker) thicken northwestwards as is confirmed here in the Liard Basin.

In the Buckinghorse Formation, the Viking marker occurs (labeled as “top of Paddy eq.”) at a depth of approximately 700 m in the c-54-b/94-G-7 well (Schröder-Adams and Pedersen, 2003, fig. 7), which is 250 m below the top of the Bougie member and 210 m above the Boulder Creek/Cadotte equivalent. Between the Liard Basin and the Keg River Basin a structural high in the area of Fort Nelson, B.C. (Wright et al., 1994, fig. 3.2) makes long-distance subsurface well log correlations of Cretaceous strata difficult. However, we identify the Viking equivalent marker 370 m above the base of the Lepine Formation and 320 m below the top of the Bougie member in the reference well (Figure IV-7) suggesting a northward thickening.

Schröder-Adams and Pedersen (2003) recognized the transition from the Joli Fou to the Mowry depositional cycle based on a faunal change associated with a coarsening upwards interval within the Buckinghorse Formation. This transition was linked to the Viking Marker based on biostratigraphy. This outcrop interval was then projected to the distinct Viking marker in a nearby reference well. No faunal change is observed in the

Lepine Formation where this marker is projected in outcrop. If these correlations are correct then the Viking lowstand event had no effect on the fauna in the Liard Basin. A distinct faunal change marked by the *Bathysiphon/Ammobaculites fragmentarius* assemblage does occur stratigraphically higher at a level that falls close to the base of the Bougie member (Unit 4).

A detailed subzonation of the Joli Fou/Mowry transition (Viking interval) resulted from rich foraminiferal assemblages in the Peace River Foothills (Koke and Stelck, 1985; Stelck and Koke 1987; Stelck 1991). These have not been recognized in the more northern regions. Stelck et al. (2000) show increased diversity of benthic foraminifera, as noted by the appearance of calcareous benthic foraminifera, within the middle part of the “Viking succession” in core from the Giroux Lake field in central Alberta. They correlate this interval that preserves a number of parasequences with the *Trochammina umiatensis* Zone in the Hudson-Hope region where a similar fauna was recovered (Stelck and Koke, 1987; Harrison, 1988). In addition, Stelck et al. (2000) imply that all upper (“upper gigas” in Figure IV-11a) subzones of the Hudson-Hope foraminiferal zonation can be included within an extended Viking Formation interval (not just those beds included in the “Viking marker” that are equivalent to the *Reophax tundraensis* Subzone of the *H. gigas* Zone). This supports the interpretation of a more normal marine interior sea in the interval between the middle Viking lowstand and the Viking grits (Harrison, 1988). Although the benthic fauna in the Liard region was not nearly as diverse as that in the Keg River subbasin and West Alberta Basin, this post middle-Viking but pre-Viking grit interval appears to be homotaxially equivalent to the thick Bougie-equivalent member (Unit 4) in the Liard Basin. We propose here that renewed inundation associated

with the early Mowry Sea and possibly the opening of Boreal connections triggered these faunal changes basin-wide.

The Viking Grits are another transgressive lag (distinct from, and stratigraphically above the Viking Marker) overlying a sequence boundary that represents reworked shoreface gravels within the lower Mowry Sea. In the Peace River Foothills, a 1–2 m thick pebble conglomerate bed in a sandstone matrix occurs in the upper Hasler Formation 80 m below the Goodrich Formation and based on faunal analysis forms the base of the *Miliammina manitobensis* Zone (Stelck and Koke, 1987). Farther northwest in the Buckinghorse Formation, Stelck (1991) equated the base of the *M. manitobensis* Zone to a thin pebble bed 83 m below the base of the Sikanni Formation, although he noted that this placement was somewhat arbitrary. Schröder-Adams and Pedersen (2003) moved the base of the *M. manitobensis* Zone stratigraphically lower in the section, which would indicate that Stelck's grit bed documents a lowstand during Mowry Sea time.

Based on subsurface correlation and biostratigraphy, it is suggested here that these grits are correlative with the flooding surface overlying Unit 4 (the Bougie member) in the Lepine Formation. Alternatively, the grit beds may be transgressive lags associated with the development of the first Sikanni sandstone (Harrison, 1988), although in the Liard Basin, transgressive lags within the Sikanni Formation are interpreted to occur above the Bougie-equivalent interval (unpublished data).

Stelck and Koke (1987) and Stott (1961) indicate that a major lithological change occurs within or at the top of the upper *H. gigas* Zone within the Hasler shale where silty shale with sandy beds are overlain by shale. This surface is likely equivalent to the top of the Bougie member (Figure IV-11).

The Bougie member is most strongly developed in the Sikanni Chief River area where it consists of numerous stacked progradational and retrogradational/aggradational parasequence sets of bioturbated shelf sandstones that fine to shale towards the east (Pedersen and Schröder-Adams, 2001). In core from this area, foraminiferal yields have been poor, but the member can be confidently traced on logs northwards in the subsurface to Unit 4 of this study. A regional south–north cross section from the Peace River to north of the Sikanni Chief River region shows the fining and thinning of the Bougie southwards (Schröder-Adams and Pedersen, 2003). In the Peace River Foothills region, its position consists of a single sharp deflection on the resistivity curve approximately 130 m above their Viking marker and 100 m below the Sikanni Formation, supporting the equating of the Bougie with the “Viking grit beds” in the foothills. It is possible that the Bougie merges onto the top of the Viking marker in the east towards the Alberta/British Columbia border (as it appears to do in a regional cross-section of Schröder-Adams and Pedersen, 2003, fig. 9). This would explain the presence of the younger *M. manitobensis* Zone within the upper Paddy Member in the Peace River Plains (Stelck and Leckie, 1990a). In this interpretation, the multiple sea level fluctuations that produced the Paddy, Viking and “Viking grit beds” in Alberta are expressed in a much thicker and relatively conformable succession in the Buckinghorse and Lepine formations, where only correlative conformities exist.

In both W–E and SE–NW cross sections, no unconformities are apparent in the Lepine Formation. Subtle markers in the shale and siltstone succession, representing subtle coarsening-upwards cycles overlain by flooding surfaces, can be traced for long distances. In Figure IV-8b, the Bougie, Sikanni and Base Fish Scales markers can be

identified in a condensed interval to the east in the 94P map sheet area. This indicates that no significant break occurs in the Lepine succession even to the east of the Bovie structure, although significantly less accommodation was present in that area.

These stratigraphic relationships highlight the role subsidence plays in creating accommodation space. During an interval punctuated by multiple relative-sea level falls that appear to be basin-wide (Leckie and Reinson, 1993), the Liard sub-basin, even though receiving very high sediment supply, preserved a continuous record of marine sedimentation in a non-condensed succession without any major stratigraphic breaks.

Units	Lithology	Foraminiferal Abundance	Foraminiferal Diversity	Miscellaneous Observations	Depositional Environment
5	soft mudstone	high	high	silty beds uncommon; prominent flooding surface at base; overlain by Sikanni Formation	shelf; normal marine
4	interbedded mudstone, silty shale and hummocky cross-stratified fine sandstone	high	high	cone-in-cone beds; small coarsening-upwards cycles	upper offshore; normal marine; Bougie-equivalent
3	shale and silty shale	low	low	no ammonites; less frequent concretions	restricted marine? lower offshore
2	flaky shale; abundant concretions	low to medium	low to medium	abundant ammonites enclosed in concretions; wood fragments, fish vertebrae, bentonites, algal cysts	marine shelf
1	Silty shale; abundant concretions	low	low	fining upwards from top of Scatter Formation; forams coarsely agglutinated; abundant ammonites enclosed in concretions	lower offshore

Table IV-1. Units of the Lepine Formation and their environmental interpretation.

Figure IV-1. Liard Basin localities. UTM coordinates (NAD27) for sections in inset are *L2002B*: 0396300E, 6586700N; *L2002C*: 0397030E, 6589068N (and downstream to 0397095E, 6589543N); *L2002DA*: 0396407E, 6587416N; *L2002DB*: 0398651E, 6596695N; *L2002F*: 0405516E, 6607513N.

Subsystem	Stage					
		Liard Basin	Sikanni Chief River, B.C.	Peace River Foothills Moberly Lake	Northwestern Alberta Plains	Central Plains
	U. Cr.	Dunvegan Fm	Dunvegan Fm	Dunvegan Fm	Dunvegan Fm	Belle Fourche Fm.
Lower Cretaceous	Cen.	FSMB			Colorado Group	Fish Scales Fm.
		Sully Fm	Sully Fm	Cruiser Fm		Westgate Fm.
		Sikanni Fm	Sikanni Fm	Goodrich Fm		Viking Fm.
		Bougie mbr	Bougie mbr	upper Hasler Fm		Joli Fou Fm.
		Lepine Fm	"Viking" marker bed	"Viking" marker bed		
				lower Hasler Fm		
				Lower Boulder Creek		
				Hulcross Fm		
				Gates Fm		
				Moosebar Fm		
Lower Cretaceous	Albian	Fort St. John Group			Fort St. John Group	
		Scatter Fm	Buckinghorse Fm			
		Tussock Mbr				
		Wildhorn Mbr				
		Bulwell Mbr				
Lower Cretaceous	Middle	Fort St. John Group			Fort St. John Group	
		Scatter Fm	Buckinghorse Fm			
		Tussock Mbr				
		Wildhorn Mbr				
		Bulwell Mbr				
Lower Cretaceous	Lower	Fort St. John Group			Fort St. John Group	
		Scatter Fm	Buckinghorse Fm			
		Tussock Mbr				
		Wildhorn Mbr				
		Bulwell Mbr				
Lower Cretaceous	Upper	Fort St. John Group			Fort St. John Group	
		Scatter Fm	Buckinghorse Fm			
		Tussock Mbr				
		Wildhorn Mbr				
		Bulwell Mbr				
Lower Cretaceous	Lower	Fort St. John Group			Fort St. John Group	
		Scatter Fm	Buckinghorse Fm			
		Tussock Mbr				
		Wildhorn Mbr				
		Bulwell Mbr				

Figure IV-2. Relationships of strata in the Liard Basin to other areas of northeastern British Columbia and Alberta. Scatter/Lepine-Cadotte correlations mainly from molluscan biostratigraphic data of Jeletzky (1980), Stott (1982) and interpretations here.

Stage	Substage	Stratigraphy Moberly Lake NE B.C.	Selected Macrofossil Zones (Warren & Stelck 1969; Caldwell et al. 1978; Jelezky 1980; Jelezky and Stelck, 1981; Stott 1982; Caldwell, 1993)	Peace River, British Columbia Foraminiferal Zones (Stelck et al. 1958; Sutherland & Stelck 1972; Koke and Stelck 1984, 1985; Stelck & Koke 1987; Stelck & Hedinger 1983; Stelck 1975, 1991)	Sikanni Chief River, British Columbia Foraminiferal Zones (Schröder-Adams & Pedersen, 2003)	Liard Basin Foraminiferal Zones (Jowett et al. in press and this study)	Liard Basin Stratigraphy (Jowett et al. in press and this study)		
Cenomanian	Middle		<i>Acanthoceras athabascense</i>	<i>Verneuilinoides perplexus</i>		Unzoned	Dunvegan		
	Early	Upper Cruiser	<i>Beatonoceras beatonense</i> <i>Irenoceras bahani</i> <i>Neogastrolites septimus</i> <i>Neogastrolites maclearni</i>	<i>Textularia alcesensis</i>	Unzoned	<i>Textularia alcesensis</i>	FSU		
Albian	Upper	Lower Cruiser	<i>Neogastrolites americanus</i> <i>Neogastrolites muelleri</i>	<i>Haplophragmium swareri</i>	Fish-Scale beds	<i>Haplophragmium swareri</i>	BFS		
			<i>Neogastrolites cornutus</i>				Lower		
		Goodrich		<i>Haplophragmoides postis goodrichi</i>		subzone B	Sikanni		
			<i>Neogastrolites haasi</i>	<i>Verneuilina canadensis</i>		subzone A		(upper Lepine)	
		Upper Hasler	poorly fossiliferous interval	<i>Reophax troyeri</i>		<i>Haplophragmium swareri</i> <i>Ammobaculites fragmentarius</i>	<i>Bathysiphon-A. fragmentarius</i> assemblage		
		"Viking"		<i>Trochammina umiatensis</i>					
		Lower Hasler		<i>Trochammina depressa</i>				<i>Trochammina alcesensis</i>	<i>Ammomarginulina</i> assemblage
				<i>Reophax tundraensis</i>					
				<i>Haplophragmoides gigas phaseolus</i>					
				<i>Haplophragmoides gigas gigas</i>					
			<i>Inoceramus commancheanus</i>	<i>Haplophragmoides uniobis</i>		Lepine			
Middle	Basal Hasler	<i>Stelckiceras liardense</i>	<i>Ammobaculites wenonahae</i>	<i>Ammobaculites wenonahae</i>	<i>Ammobaculites wenonahae</i>				
	Cadotte	<i>Gastrolites allani</i>	<i>Ammobaculites</i> sp.	<i>Ammobaculites</i> sp. 1	<i>Ammobaculites</i> sp.				
		<i>Gastrolites kingi</i>							
	Hulcross	<i>Pseudopulchellia pattoni</i>	<i>Haplophragmoides multiplum</i>	<i>Haplophragmoides topogorukensis</i>	<i>Haplophragmoides multiplum</i> <i>Verneuilinoides cummingsensis</i> <i>Verneuilinoides cummingsensis</i>				
Lower	Gates	<i>Freboldiceras remotum</i>	<i>Verneuilinoides cummingsensis</i> / <i>Margulinopsis collinsi</i>	<i>Gaudryina nanushukensis</i>	<i>Gaudryina nanushukensis</i> <i>Haplophragmoides multiplum</i> <i>Verneuilinoides cummingsensis</i> <i>Verneuilinoides cummingsensis</i> Radioactive Rad (Barron) Calcareous Interval <i>Ammobaculites</i> <i>Glaucospira</i> <i>Glaucospira</i>	Scatter Fm.	Tussock		
	Moosebar	<i>Subarthroplites mcconnelli</i>	<i>Trochammina mcmurrayensis</i> <i>Rectobolivina</i> sp.	Wildhorn					
	Gething	<i>Pachygyrcia canadensis</i>		Bulwell					
	Cadomin	<i>Aucellina aptiensis</i>		Garbutt					
							Chinkeh		

Figure IV-3. Foraminiferal and molluscan biostratigraphic correlations in northeastern British Columbia. Unit divisions for the Lepine Formation are not to scale.

Figure IV-4. Composite stratigraphic section for the Lepine Formation with foraminiferal and algal cyst abundances.

Figure IV-5 Outcrop photographs of the Lepine Formation. a) Outcrop of flaky shale facies of Lepine Formation along east bank of Liard River with numerous ammonites contained in concretions (L2002C section, see Figure 1 caption for coordinates). b) *Stelckiceras liardense* and permineralized wood debris found weathering out of flaky shale facies (underlying). c) Middle to upper part of Lepine Formation showing silty shale facies with increasing number of interbedded platy siltstone beds (L2002DB). Prominent marker in middle of cliff is cone-in-cone marker bed. d) Upper Lepine Formation, east bank of Liard River opposite Scatter River. Cone-in-cone marker bed occurs near base of section and ties this one with that in c (locality L2002DB). Slight rhythmic coarsening-upward intervals to silty shale and siltstone are visible, and a prominent coarsening upwards interval near the top of section in photograph is overlain by softer shale. Base of Sikanni Formation is approximately 100–150 m above this surface. e) Close-up of indurated siltstone overlain by cone-in-cone marker bed in Lepine Formation.

Figure IV–6. Selected foraminifera from the Lepine Formation (followed by sample number that specimen was recovered from).

- 6.1 *Ammobaculites humei* Nauss (DA3), X50.
- 6.2 *Haplophragmoides linki* Nauss (C2), X80.
- 6.3 *Ammobaculites humei* Nauss (C7), X100.
- 6.4 *Spiroplectammina* sp. A (C5), X185.
- 6.5 *Ammobaculites wenonahae* Tappan (C2), X80.
- 6.6 *Ammobaculoides* sp. diminutive (C5), X190.
- 6.7 *Verneuilinoides borealis* Tappan (DB6), X50.
- 6.8 *Verneuilinoides tailleuri* Tappan (DB6), X70.
- 6.9 smooth spherical object (DB6), X50.
- 6.10 *Ammomarginulina* sp. (DB6), X80.
- 6.11 *Ammomarginulina* sp. (DB15), X70.
- 6.12 *Ammomarginulina* sp. (DB15), X70.
- 6.13 *Ammomarginulina* sp. (DB18), X50.
- 6.14 *Ammotium* sp. (DB21), X100.
- 6.15 flat object (DB26), X50.
- 6.16 *Gaudryina canadensis* (Cushman) (DB30), X70.
- 6.17 *Trochammina gatesensis* Stelck and Wall (DB33), X100.
- 6.18 *Miliammina sproulei* Nauss (DB33), X65.
- 6.19 *Ammobaculites petilus* Eicher (DB35), X80.
- 6.20 *Ammobaculites fragmentarius* (Cushman) (DB36), X70.
- 6.21 *Bathysiphon brosgei* Tappan (DB36), X50.
- 6.22 *Verneuilina canadensis* Cushman (DB38), X55.
- 6.23 *Uvigerinammina manitobensis* (Wickenden) (DB41), X100.
- 6.24 *Trochammina rutherfordi* Stelck and Wall (DB41), X115.
- 6.25 *Haplophragmoides postis* Stelck and Wall (F2), X150.
- 6.26 *Verneuilinoides borealis* Tappan (F2), X100.
- 6.27 *Trochammina alcesensis* Stelck (F9), X100.
- 6.28 *Miliammina manitobensis* Wickenden (F12), X65.
- 6.29 *Trochammina umiatensis* Tappan (F14), X60.
- 6.30 *Haplophragmium swareni* Stelck and Hedinger (F16), X70.
- 6.31 *Gravellina chamneyi* Stelck (F17), X110.
- 6.32 *Pseudobolivina variana* (Eicher) (F17), X60.

Figure IV-7. Reference well log d-075-e/094-N-08 (see Figure 1 for location).

Figure IV-8. Subsurface cross-sections. a) (above) Location of well log cross-sections in b and c. (foldouts following pages). b) SE-NW subsurface cross-section into the Liard Basin. c) W-E subsurface cross-section in northern portion of Liard Basin.

Southeast A

Figure IV-8b.

Lepine Formation

Northwest
A'

Figure IV-8c.

Lepine Formation

a-079-b/094-O-11

b-085-h/094-O-11

a-045-e/094-O-10

a-078-l/094-O-10

d-077-k/094-O-10

d-013-l/094-O-09

d-017-g/094-P-12

East
B'

b-085-h/094-O-11

a-045-e/094-O-10

a-078-l/094-O-10

d-077-k/094-O-10

d-013-l/094-O-09

d-017-g/094-P-12

a-025-i/094-P-10

Figure IV-9. Rock Eval geochemistry plots for Lepine Formation samples. a) HI-OI plot of all geochemical samples. b) S₂/TOC plot for all geochemical samples.

Figure IV-10. Composite micro- and macrofossil range chart for the Lepine Formation. Left: Units of this study and those of Foscolos and Stott (1975).

Figure IV–11. (next two pages). **a)** West-east subsurface cross-section from the Amoco Moberly 16-20-79-25W6 well showing the relationships of the Hasler Formation and Viking marker within it. **b)** Location of cross-section in **a**.

Figure IV-11a.

Figure IV-11b.

Chapter V. SEQUENCES AND PALEOENVIRONMENTAL CHANGES IN THE ALBIAN SIKANNI FORMATION IN THE FRONTIER LIARD BASIN OF NORTHWESTERN CANADA

Introduction

The Liard Basin is a relatively unexplored frontier foreland basin covering approximately 9500 km² in the foothills and plains of northeastern British Columbia, Yukon, and southwestern Northwest Territories of Canada (Figure V-1). It is bounded to the east by the northerly-trending Bovie structure. Most recently, this structure has been considered to have formed by post-Mississippian but pre-Cretaceous (possibly Columbian orogenesis) west-verging thrusting that was later decapitated by a shallow Laramide detachment fault (MacLean, 2001).

The Liard Basin is bounded to the southwest by the Rocky Mountain Foothills, and to the west and northwest by the Liard Plateau. The Cretaceous sedimentary package thickens markedly west of the Bovie Structure, and is preserved as the dominantly marine sandstone and shale deposits of the Fort St. John Group. The group is represented by the Albian and earliest Cenomanian age Chinkeh, Garbutt, Scatter, Lepine, Sikanni, and Sully formations and is overlain by the alluvial-deltaic, middle Cenomanian Dunvegan Formation (Figure V-2), and some isolated younger strata (Stott, 1982). The Liard Basin is centered in the northernmost northeastern corner of British Columbia west of the Bovie Structure, but the stratigraphy is carried northwards into the Yukon and Northwest Territories. The Albian succession thins considerably in the southern plains of the Northwest Territories (Dixon, 1999).

The petroleum-rich nature of the Western Canada Sedimentary Basin (WCSB) has resulted in a detailed knowledge of its paleoenvironmental history and sequence stratigraphy (Mossop and Shetson, 1994). The global third order Clearwater Cycle (Kaufman 1977; Haq et al., 1987, 1988; Kaufmann and Caldwell, 1993) marks the beginning of the Albian Stage and the first major inundation of the Cretaceous Canadian basin and is followed by the late Albian Kiowa-Skull Creek Cycle (Figure V-3). During the peak of the Kiowa-Skull Creek cycle, in early Late Albian time, a marine connection was established between the Boreal and Tethyan seas, forming the Joli Fou Seaway in the WCSB (Williams and Stelck, 1975). The regression that followed Joli Fou time is reflected in deposition of the Viking Formation and its regional equivalents. The following transgression of the Mowry Sea, which brought the transgressive estuarine valley-fill sediments of the upper Paddy Member of the Peace River Formation and the overlying Shaftesbury Formation in the Peace River Plains, is also reflected in northern British Columbia in sediments above the regional Viking Marker Bed in the upper Buckinghorse Formation and the middle part of the Lepine Formation (Schröder-Adams and Pedersen, 2003; Jowett and Schröder-Adams, in press). This transgression represents the initiation of the Greenhorn marine cycle.

Within the third order Kiowa-Skull Creek and early Greenhorn cycles, several transgressive-regressive couplets, which were apparently controlled by non-eustatic sea level changes, are recognized regionally within the Western Interior Basin (Figure V-3; Stott, 1975, 1984; Caldwell, 1984; Kauffman and Caldwell, 1993). The relationships of the Liard Basin strata to these transgressive-regressive couplets that have been studied in more detail to the south are not well understood. The Greenhorn Marine Cycle is a

eustatic sea level cycle that reached its acme during the early Turonian, and resulted in sea levels up to 300 m above present (Haq et al., 1987; McDonough and Cross, 1991). Caldwell (1984) noted that the initiation of the Greenhorn Marine Cycle, while recording fine-grained deposition elsewhere (“the Mowry Sea”), contains higher frequency transgressive-regressive couplets in northeastern British Columbia and the Northwest Territories that correspond to the Lepine/Buckinghorse-Sikanni and Sully- Dunvegan T-R couplets (Figures V-2, V-3). He also recognized that the alternating regressive/transgressive facies of the Sikanni Formation implied even higher frequency relative sea level fluctuations—that have not been recognized elsewhere in the Western Interior Basin. These higher frequency cycles are detailed here by the identification of four sequence boundaries within the Sikanni Formation and overlying basal Sully succession.

The expression of Albian-Cenomanian relative sea level history with respect to paleoenvironmental changes and faunal evolution in the Cretaceous strata of the Liard Basin has yet to be fully documented. This paper builds on the work of previous Cretaceous stratigraphers who originally mapped this remote region and proposed a stratigraphic framework (Hage, 1944; Kindle, 1944; Thompson, 1977; Stott, 1960, 1968, 1982; Taylor and Stott, 1968; Williams, 1978; Leckie et al., 1991; Leckie and Potocki, 1998; Dixon, 1997, 1999). By integrating sedimentology, foraminiferal micropaleontology, and organic geochemistry (Rock-Eval pyrolysis) in three outcrops we address the uppermost Albian Sikanni Formation in its proximal and distal expression. High order relative sea level cyclicity is recognized and is regionally correlated. The

outcrop representing proximal sedimentation is easily accessible along the Alaska Highway at Steamboat Mountain.

Regional Stratigraphic Framework

The Sikanni Formation (Figure V-2) is characterized by an alternating succession of sandstones and shales that ranges from approximately 100-400 m in thickness. North of the Peace River Arch, and in the southern portion of the Liard Basin in northeastern British Columbia along the western margin of the WCSB, the Sikanni Formation gradationally overlies the thick shale and silty shale package of the Albian Buckinghorse Formation. In the northern part of the Liard Basin, at approximately the latitude of Lepine Creek (Figure V-1), the Sikanni gradationally overlies the shales and siltstones of the Lepine Formation, which is equivalent to the upper Buckinghorse Formation (Figure V-2).

The recessive shales of the Sully Formation overlie the Sikanni Formation, although in the area of the Muskwa and Tetsa rivers (the Steamboat Mountain section discussed in this paper), the contact is covered. The type section of the Sikanni Formation, on Sikanni Chief River in northeastern British Columbia, preserves 115 m of strata in four 10-22 m thick sandstone successions separated by shale and silty shale (Hage, 1944; Stott, 1960, 1968; Stelck, 1975). South of the type section, the Sikanni Formation has been recognized in outcrop in the Halfway River area where it contains three sandstone units (Irish, 1970). South of the Peace River Arch, the Goodrich sandstone is a correlative lithostratigraphic unit to the Sikanni Formation. North of the type section the formation thickens markedly. In the region of Muskwa and Tetsa rivers,

the formation reaches its greatest thickness of 300 m as measured by Stott (1982) and contains more than four cycles of sandstone and shale. Stott (1982) considered that this northwesterly increase in thickness from the type section to the Muskwa-Tetsa region was due to the uppermost mapped sandstone becoming progressively younger northwards. Hence he thought that the overlying Sully Formation at the type section is equivalent to the uppermost Sikanni in the Muskwa-Tetsa region. Northwards from this region in northeastern British Columbia, southern Yukon Territory and Northwest Territories, the Sikanni Formation thins to 130 m in thickness. South of Scatter River (Section 65-15 of Stott, 1982, northeast of Lepine Creek here) the section contains four prominent sandstone units, which become predominantly shale and silty shale further north at the junction of the Scatter and Liard rivers (Figure V-1). The Sikanni Formation is mapped in isolated, incomplete outcrops along the Kotaneelee River and the west flank of the Liard Range, where it attains a thickness of 107 m and consists predominantly of shale and silty shale, with one low-angle cross-bedded 6-m-thick sandstone unit showing low-angle cross-bedding (Stott, 1960, sections 1, 2). Eastwards, the Sikanni Formation grades into siltstone and shale.

Foraminiferal Zonal Scheme

No foraminiferal zonal scheme exists for the Liard Basin. Previous work and stratigraphically correlative biostratigraphic studies south of the study area along the Sikanni Chief River indicate that the Upper Albian *Miliammina manitobensis* Zone straddles the uppermost Buckinghorse, Sikanni and lowermost Sully formations (Stelck 1975; Stelck and Hedinger, 1983) (Figure V-4). This zone is subdivided into three

subzones, which are in ascending order, *Verneuilina canadensis*, *Haplophragmoides postis goodrichi* and *Haplophragmium swareni*. The *V. canadensis* Subzone, which is the most widespread in the WCSB, was originally described from the Sikanni Chief River area and characterizes the uppermost part of the Buckinghorse Formation and the lower part of the Sikanni Formation in northeastern British Columbia (Stelck, 1975). The *V. canadensis* Subzone is correlative to the interval above the *Gastroplites* ammonite Zone at the base of the *Neogastroplites haasi* Zone (Figure V-4) (Warren and Stelck, 1969; Stelck, 1975). The latter ammonite appears in the third Sikanni sandstone succession at Sikanni Chief River, although *N. cf. N. haasi* occurs lower in the section (Stelck, 1975).

The fauna of the *Haplophragmoides postis goodrichi* Subzone was described from the distal portion of the Goodrich sandstone south of Moberly Lake from the lower *Neogastroplites* Zone including the ammonite subzones, *N. haasi* and *N. cornutus*, in ascending order (Sutherland and Stelck, 1972). In central Alberta, Stritch and Schröder-Adams, (1999) found the *Haplophragmoides postis goodrichi* Subzone in strata underlying the *Verneuilina canadensis* Subzone. This may indicate that this species is facies controlled. Although not reported to date, ammonite correlations indicate that the *H. postis goodrichi* Subzone fauna should occur within the upper part of the Sikanni sandstone succession, within the shales above the second or third sandstone.

Location and Methods

This project was completed in collaboration with the Geological Survey of Canada's Central Foreland NATMAP Project, which has been recently concentrating on 1:50 000-scale mapping in the Liard Basin area. Although numerous outcrops were

examined, the sections presented here represent the most complete that were accessible (Figure V-1). Three outcrops of the Sikanni Formation are detailed here: a) along the Alaska Highway on Steamboat Mountain west of Fort Nelson; b) along the escarpment on the east bank of the Liard River between Lepine and Chimney creeks; and c) in the cliffs on the east bank of the Liard River opposite Scatter River. The latter two sections were first measured by Stott (1982, sections 65-15 and 65-10a, respectively).

In addition to measuring and describing outcrops, samples were taken for micropaleontology and Rock-Eval pyrolysis (Espitalié et al., 1977). Sample intervals ranged from 0.2 m to approximately 12 m based on changes in lithology, sedimentological structures, and the presence of important surfaces that were considered to have sequence stratigraphic importance. Micropaleontological samples were processed after the method of Then and Doherty (1983) and picked for foraminifera.

Facies, facies successions and depositional environments. In this study, strata characterized by a particular combination of lithology, physical and biological sedimentary structures and foraminiferal content, abundance and diversity, are grouped into facies. These are grouped into facies successions permitting interpretations of the depositional environment in which the sediments were deposited (Walker, 1992). In the Sikanni Formation, although terrestrial to marginal marine strata occur, most deposits represent fully marine depositional environments and are divided into upper, middle and lower shoreface, offshore transition and shelf according to the wave and storm-dominated classification of Walker and Plint (1992).

Biofacies. The variable depositional environments in time and space represented in the three outcrops presented in this study necessitate the definition of biofacies. As

used here, biofacies represent distinctive groupings of benthic foraminiferal taxa and their relative abundances and diversities whose distribution is controlled by the depositional environment and the age of the strata they are associated with. In this study, four biofacies are recognized (Table V-3), and their distribution is controlled by the stratigraphic sequence that the strata are assigned to (S_1 - S_4), which represents the time component, and the interpreted depositional environment.

Sequence stratigraphic methodology. Sequence stratigraphy (Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1988, 1990) has been increasingly utilized in finer scale core, outcrop and densely spaced regional well log correlation studies. With enough data, third and even fourth order cycles are resolvable in successions with high sediment input relative to subsidence (Mitchum and Van Wagoner, 1991). Embry (2002) has called attention to the problems applying traditional sequence stratigraphic techniques. These include the diachroneity of a number of the sequence stratigraphic surfaces, such as the regressive surface of marine erosion (RSME) and the transgressive surface of marine erosion (TSE) when not combined with a sequence boundary (SB). He proposed that the subaerial unconformity, combined SB /TSE (his “shoreface ravinement-unconformable” surface), maximum flooding surface (MFS) and his proposed “maximum regressive surface” have the greatest utility and scientific objectivity in applying sequence stratigraphic concepts. In a frontier basin such as the Liard with relatively sparse outcrop, core and well log data, sequence stratigraphic interpretation is limited to interpolating from the available data. In this predominantly outcrop and well log-based study, subaerial unconformities, transgressive surfaces of erosion (both combined and non-combined with the sequence boundaries), and regressive

surfaces of marine erosion have been utilized in order to reconstruct the relative sea level history and the paleogeography of the Upper Albian Sikanni Formation.

The recognition of systems tracts, the subdivisions of sequences that are driven by changes in depositional trend, is problematic in frontier areas because of the diachroneity of some surfaces. For example, a RSME develops during the entire interval of base level fall, and the sandstone that overlies it hence becomes progressively younger downdip. Embry (2002) proposed that only the transgressive systems tract (TST) and his regressive systems tract (RST) be utilized as systems tracts divisions. The RST includes strata between the MFS and SB and corresponds to the HST, FSST and LST of traditional sequence stratigraphy. Despite these problems, we identify RSME surfaces and the falling stage systems tract (FSST) that overlies it here because they provide information about relative sea level changes (forced regression), and allow prediction of the architecture and paleogeographic evolution of the basin. Sequence stratigraphic interpretations based mainly on limited outcrop data are also difficult because some of the features that define important surfaces or systems tracts are only visible in detailed well log correlations or downdip correlation of successive outcrops. The FSST, for example, is characterized by offlap of stratal terminations (i.e. visible with high-resolution subsurface correlations), and lies stratigraphically above highstand and below lowstand systems tracts (Plint and Nummedal, 2000), none of which can usually be observed at a single outcrop. Here we identify (Table V-2, Figures V-4, V-8, V-11) the lowstand (LST), transgressive (TST), highstand (HST) and falling stage systems tracts (FSST). Similar to Plint (1996), systems tracts are identified based on key surfaces

(RSME, SB, TSE), but cannot be identified based upon the stratigraphic architecture (which is not directly observable in this study).

In the Cretaceous western interior, the basin was characterized by a ramp rather than strongly developed shelf and slope physiography. Forced regressive wedges, basin floor fans, and lowstand sands that characterize relative sea level fall on passive margins are thus not typical of the Cretaceous foreland basin. Instead, many studies have shown the presence of numerous sharp-based shoreface sandbodies overlain by pebble beds (TSE) (Plint and Norris, 1991). Much debate has focused on the placement of the sequence boundary in successions linked to forced regression defined as sediments deposited during relative sea level fall but prior to the lowest point of sea level (Posamentier, 1992; Hunt and Tucker, 1992, 1995; Kolla et al., 1995; Plint and Nummedal, 2000; Posamentier and Morris, 2000; Embry, 2002). Sediments deposited during this interval have been termed the Falling Stage Systems Tract (FSST) (Plint and Nummedal, 2000) or the Forced Regressive Wedge Systems Tract (FRWST) (Hunt and Tucker, 1992). The sequence boundary has either been placed coincident with the RSME at the base of the forced-regressive sandbody (Posamentier and Morris, 2000), or the subaerial erosion surface overlying it and potentially separating it from a lowstand sand (Plint and Nummedal, 2000) which may be encased in marine shales further downdip (Walker and Plint, 1992). However, a lowstand systems tract may not always be present, and sharp-based, forced-regressive sandbodies may just pinch out downdip into more basinal facies (Plint and Nummedal, 2000). Because we can recognize some evidence of sequence boundaries above regressive surfaces of marine erosion, we chose to differentiate these surfaces in the sense of Plint and Nummedal (2000).

Sikanni Formation

The three outcrops detailed here provide a proximal to distal (orogenward to cratonward in the sense of Cant and Stockmal, 1993) expression of the Sikanni Formation in the southern and middle parts of the Liard Basin. A new segment of the Alaska Highway, west of Fort Nelson, uncovered an excellent relatively continuous section of the Sikanni Formation that attains a thickness of approximately 400 m, and includes some facies interpreted as the most proximal depositional environment in the Sikanni Formation (Figures V-1, V-4). A prominent exposure of the formation can also be found high on the escarpment on the east bank of the Liard River between Lepine and Chimney creeks, here termed the Lepine Creek locality (Figure V-1), where the formation attains a thickness of 130-140 m and contains four thin to thick-bedded fine sandstone units interbedded with shale, silty shale and fine sandstone (Figure V-9). The upper portion of the formation at this locality was inaccessible. Lastly, the Sikanni Formation outcropping further north on the Liard River opposite Scatter River (Figure V-1) preserves predominantly shelf facies and is 130 m in thickness (Figure V-11). The base of the Sikanni Formation is defined lithostratigraphically by the first occurrence of a prominent, often hummocky cross-stratified fine-grained sandstone bed above the mudstone dominated Buckinghorse Formation. The top of the Sikanni Formation is placed at the last prominent sandstone or conglomerate overlain by mudstones of the Sully Formation.

Our purpose here is to show that detailed stratigraphic, sedimentological and micropaleontological analyses reveal that the Sikanni Formation contains four sequences (S₁-S₄) bounded by unconformities or correlative conformities developed in shelf to delta plain and distributary channel facies (Figure V-5). The entire section contains up to five

thick sandstone successions (A-E) underlain by thick shale packages. The strata have been grouped into facies (A-K) (Table V-1), and facies successions (I-IV) (Table V-2), that enable identification of sedimentary environments and placement of the entire succession into a sequence stratigraphic framework.

Sequence 1

Sedimentology and facies. At Steamboat Mountain the lowermost Sequence 1 (S₁) is developed as a coarsening-upward cycle from the underlying shales (F_A) of the Buckinghorse Formation (Figure V-5). The base of this sequence is not exposed. Thick sandstone units represent the upper part of the sequence (Figure V-5; Figure V-6a, d). There, fissile shale and mudstone (Facies A) pass upwards into interbedded mudstone and thin, fine, sharp- to diffuse-based, rippled, hummocky-cross stratified and planar-laminated sandstone beds with convoluted beds (Facies B) and into a 13-m-thick, amalgamated hummocky cross-stratified fine-grained sandstone interval (Facies C) (Sikanni Sandstone A, Figure V-6a, d).

At Lepine Creek, Sandstone A is similarly represented by a coarsening-upwards interval where Facies A and B of the underlying Lepine Formation are overlain by 8 m of Facies C (Figure V-9). Although HCS dominates the coarsening-upward interval from the Lepine Formation and the lower portion of Sandstone A, the sandstone beds become planar-laminated and fine- to medium-grained with abundant organic material on the bedding surfaces (Facies D).

Opposite Scatter River, the base of the Sikanni Formation is defined lithostratigraphically at the base of a 0.4 m-thick, planar laminated to hummocky cross-stratified sandstone bed that occurs above a small coarsening-upwards cycle in the

uppermost Lepine Formation (Stott, 1982) (Figure V-11; Figure V-12a). Although a distinct flooding surface overlies this sandstone unit, no pebble bed was observed. A 15 m-thick interval of shale (Facies A) overlies this sandstone bed and becomes more interbedded with heavily bioturbated thin silty and sideritized interbeds (Facies B). More proximal Facies C and D are not present.

Micropaleontology and geochemistry. Benthic foraminiferal analysis within the upper Buckinghorse and Lepine formations indicate a diverse and abundant fauna that is here assigned to the informal subzone B of the *Miliammina manitobensis* Zone. A sample from the coarsening-upward succession into Sandstone A₁ at Lepine Creek yielded a moderately diverse and low abundance fauna dominated by *Miliammina manitobensis* Wickenden and *Verneuilina canadensis* Cushman, a combination that is typical of the basal subzone of the *M. manitobensis* Zone (Caldwell et al., 1978) and here referred to as Biofacies A (Table V-3). At Steamboat, abundance and diversity fluctuate throughout the upper Buckinghorse Formation. Above the base of the Sikanni Formation, faunal abundance and diversity increases (Figure V-5). Below Sandstone A₂, foraminifera are sparser and coarsely agglutinated, and coalified wood fragments and other organic matter are present. The fauna is dominated by *Haplophragmoides postis* Stelck and Wall, *Ammobaculites fragmentarius* Cushman, *Verneuilinoides borealis* Tappan, and several species of the genus *Miliammina* (Biofacies A). Total organic carbon (TOC) data within S₁ are relatively constant at 1.5 wt.% throughout the lower part of the sequence, but increase to approximately 2 wt.% at the base of Sandstone A at Steamboat.

Interpretation. Sequence 1 preserves Facies Succession 1 corresponding to the normal regressive progradation from shelf and offshore transition zone to a wave-dominated shoreface or delta at the Steamboat and Lepine Creek localities. Foraminiferal and TOC data indicate a well-oxygenated shelf changing progressively into a shoreface environment, where coalified wood fragments indicate the influence of a fluvial source. Convolute beds at Steamboat indicate rapid rates of deposition, supporting a possible deltaic interpretation.

The succession at Scatter River is more difficult to interpret because of its apparent distal nature where paleoecological changes were too subtle to trigger a foraminiferal assemblage change.

Sequence 2

Sedimentology and facies. At Steamboat the sequence boundary that represents the base of Sequence 2 overlies the top of Sandstone A (Figure V-5; Figure V-6a, b, c). A distinct flooding surface (which overlies the sequence boundary) followed by 2.7 m of shale and thin, rippled siltstone and fine sandstone beds (Facies I) overlies Sandstone A (Figure V-6a, b). A chert pebble bed (pebbles up to 10 cm in diameter) (Facies H) follows (Figure V-6b, c) that is overlain by a thick mudstone package of Facies A. Sandstone B is composed of a complex set of facies and occurs approximately 88 m above the base of Sequence 2 (Figures V-4, V-6). The base of B is marked by a channelized thick-bedded sandstone with some coal fragments at its base (Figure V-7d, f). The main channel that is visible in outcrop is approximately 9 m in width. In ascending order, the succession grades upwards into: a) thick-bedded to massive, hummocky cross-stratified, fine-grained sandstone with some clay clasts and organic

material (Facies C); b) herringbone cross-stratified fine sandstone (Figure V-7c) and sandstone containing the trace fossil *Macaronichnus* (Facies E); c) a coal bed (Facies F); d) symmetrically rippled sandstone; and e) medium-grained low angle cross-stratified organic-rich sandstones with basal conglomerates (Facies G, Figure V-7e).

At Lepine Creek, the base of Sequence 2 is placed at the top of Sandstone A where a 5-cm-thick, thin layer of disseminated chert pebbles and sideritized clay clasts occurs at the base of a fine- to medium-grained sandstone (Facies H or G) (Figure V-9; Figure V-10a). The sandstone is overlain by 20 m of mudstone that becomes increasingly silty upwards (Facies B). Sandstone B is characterized by 14 m of thin-bedded fine sandstone interbedded with some silt and shale interbeds (Facies B-C). At its base, B is characterized by hummocky cross stratification (HCS), changing upwards to planar and low angle cross-lamination (Facies D). Some organic debris was observed in the uppermost portion of B, including a 3-cm-long coal fragment 10 cm below the top of the succession. The top of B is characterized by a wave-rippled surface with abundant *Skolithos* burrows in its uppermost bedding surface.

Opposite Scatter River, a 5-cm-thick chert pebble conglomerate (Facies H), (pebbles 0.5-2 cm in diameter), occurs encased in mudstone (Figure V-11, V-12b) 20 m above the base of the Sikanni Formation and marks the base of Sequence 2 at this locality. A 10-12 m thick silt and fine sandstone interval of Facies B overlies this conglomerate. Pervasive bioturbation included *Chondrites* and *Diplocraterion* (Figure V-11; Figure V-12c).

Micropaleontology and geochemistry. Sequence 2 contains the *Miliammina manitobensis* Zone fauna. At Steamboat, the basal 2.7 m of Sequence 2 below the pebble

bed (Figure V-6b) contains a unique benthic fauna dominated by successively increasing numbers of specimens of *Verneuilina canadensis* Cushman and *Ammotium* sp. TOC values decline from greater than 3 wt.% to 1.5 wt. % directly underneath the pebble bed. The foraminiferal fauna above the pebble bed is characterized by *Haplophragmium swareni* Stelck and Hedinger, *Reophax vasiformis* Chamney, *Glomospirella* sp., *Miliammina manitobensis*, and some isolated specimens of *Textularia* sp., but does not include specimens of *V. canadensis* or *Ammotium*. This fauna is assigned to Biofaces C. Foraminifera 2.5 m below Sandstone B become diminutive in size and occur with coalified wood fragments and other abundant organic matter. Sandstone B is a 32-m-thick interval that yielded a low abundance and diversity of foraminifera only at its base. TOC values range between 0.5-1.5 wt.% for most of S₂, reaching a maximum within the coal bed (Figure V-5).

At Lepine Creek, an abundant and relatively diverse benthic foraminiferal fauna was recovered from the lower and middle portion of S₂. Biofacies B was not encountered at this locality. The fauna is dominated by *Ammobaculites fragmentarius* (Cushman), *Miliammina manitobensis* and *Verneuilinoides borealis* Tappan. A few specimens of *Textularia* sp. were recovered, indicating a correlation to Biofacies C at Steamboat Mountain.

Opposite Scatter River, a sample immediately below a second pebble bed (see below), at the top of S₂ is the most diverse and abundant of all samples, and is dominated by *Ammobaculites fragmentarius*, *Miliammina manitobensis*, *Haplophragmoides* sp., *Saccammina alexanderi* Loeblich Tappan, *Verneuilinoides tailleuri* Tappan, and

Verneuilinoides borealis, all characteristic of Biofacies A (Table V-3). No biofacies change is observed from S₁ to S₂.

Interpretation. *Ammotium* sp. occurs in the estuarine fill of the Paddy Member of the Peace River Formation (Stelck and Leckie, 1990) and is diagnostic of estuaries and brackish lagoons (Leckie and Olson, 2003). The successively increasing abundance of *Ammotium* and *V. canadensis*, to the exclusion of other species characteristic of upper Albian strata below the pebble bed at Steamboat, indicates that this interval may represent estuarine valley fill. Thus the sequence boundary is placed at the base of this unit (Figure V-6a). The pebble bed overlying the estuarine shale at Steamboat near the base of S₂ is interpreted to represent a lag deposit from transgressive ravinement. The estuarine succession, transgressive lag and overlying shelf strata represent the deposits of Facies Succession II and the transgressive systems tract (TST) (Table V-2). Only a few meters of early transgressive estuarine shale is preserved and the only remains of the overlying shoreface is the pebble lag.

The complex facies of Sandstone B at Steamboat, along with the disappearance of foraminifera above its base, are interpreted to represent progradation of a wave-dominated delta with middle and upper shoreface (distal delta front), coastal plain and distributary channel facies (Facies Succession I). Distinguishing between forced regressive deposits and autocyclic (delta-lobe switching) processes in a deltaic system is difficult in more distal environments because of the similar facies expected for both processes. The sharp, concave-upwards base of Sandstone B at Steamboat, which is followed by a shoaling-upwards succession to non-marine or marginal marine facies (coal), is not considered a candidate for a forced regression. No gutter casts occur at its

base and there is no evidence for a RSME at the base of the equivalent sandstone at Lepine Creek. At Steamboat, we interpret the interval as a submarine distributary channel deposit (ie. coal fragments at its base). This interpretation should be tested with detailed well log cross-sections (not currently available) that would reveal normal clinoform progradation rather than offlap and downstepping expected for forced regressive sandbodies (see discussion in Plint and Nummedal, 2000). The basal interval of Sandstone B is thus interpreted to have resulted from autocyclic processes and normal regressive progradation of a wave-dominated deltaic system (with minor tidal influence) into the basin. The former brought channelized flow onto the shelf (as seen at the base of Sandstone B) and the latter brought coastal plain with distributary channel facies into the basin.

At Lepine Creek (Figure V-9; Figure V-10a), the pebbles at the base of Sequence 2 were deposited on an erosional surface with at least 10 cm of relief. This either represents a pebble lag deposit from a distributary channel or some reworking that occurred during transgressive erosion, supporting its correlation with the transgressive estuarine interval at Steamboat (overlying Sandstone A). Based on the foraminiferal fauna and stratigraphic correlations, the second sandstone preserved at Lepine Creek is correlative with the second sandstone at Steamboat Mountain. The succession is interpreted to represent the transition from lower shoreface to middle shoreface/delta front (Facies Succession I). The presence of coal fragments in the upper part of Sandstone B at this locality probably relates to the occurrence of a coal near the top of S₂ at Steamboat Mountain.

At Scatter River, the foraminiferal fauna is also assigned to the basal subzone of the *M. manitobensis* Zone, but it contains a deeper water biofacies dominated by *Ammobaculites* and *Verneuilinoides* (Biofacies A). The chert pebble bed forming the base of the unit is also interpreted as a lag from transgressive ravinement during relative sea level rise at the beginning of S₂; however, no shoreface strata remain and the lag is encased in shelf mudstone. Above this the succession is dominated by shelf deposition.

Sequence 3

Sedimentology and facies. At Steamboat, the base of Sequence 3 is placed at the base of the interbedded shale and fine sandstone interval below the top of Sandstone B (Figure V-5; Figure V-7a, b). The uppermost portion of the distributary channel sandstone of B contains a lag deposit of chert and concretionized clay clasts (Figure V-7e). This lag is overlain by an interbedded interval with 3 m of planar-bedded, lenticular sandstone and shale, followed by an 8-m-thick very fine-to-fine sandstone that contains abundant organic debris (Facies I). A distinct 30-cm-thick pebble bed overlies B (Facies H, Figure V-5; “TSE” on Figure V-7a, b). This is overlain by approximately 30 m of shale and interbedded siltstone that coarsens into Sandstone C, an 8-m-thick, hummocky cross-stratified fine sandstone unit with a few shaly interbeds (Figure V-8a) (Facies C). A thick mudstone section, which lacks pebbles at its base, overlies Sandstone C, and fine-grained sandstone interbeds up to 0.5 m in thickness that contain abundant HCS and bioturbation increase up section (Facies B). This interbedded unit is overlain by Sandstone D (Figure V-5). D is a sharp and erosionally-based, 19 m thick, hummocky cross-stratified, relatively mud-free fine sandstone (Facies J, Figure V-8b). Underlying and at the base of D, 1-2 m wide starved hummocks occur frequently within the

mudstone, and hummocky cross-stratified sandstone fills gutter casts up to 1 m in width at the base of Sandstone D (Figure V-8b, c). Only isolated shale pockets occur within the sandstone. Approximately 3 m below the top of Sandstone D, isolated concentrations of rounded, sideritized clay clasts up to 5 cm in length occur on the hummocks (Figure V-8d). A distinct flooding surface overlies D, but no pebble bed was identified in the strata overlying it.

At Lepine Creek, the base of Sequence 3 is placed at the top of Sandstone B at the base of a 10-cm-thick, clast supported chert pebble bed that is overlain by shale (Facies H) (Figure V-9). This is overlain by 10 m of silty shale and thin beds of siltstone and fine sandstone (Facies B) that coarsen upwards into the thin-to-thick and massive bedded, approximately 27-m-thick Sandstone C (Figure V-10b, c). The base of C is characterized by well preserved planar laminated and hummocky cross-stratified fine sandstone capped by combined-flow ripples (Figure V-10b). Several cycles of planar lamination, HCS, and wave ripples occur in this lower unit passing upwards to sandstones that are thick-bedded or amalgamated into massive beds, highly bioturbated, and characterized by very large-scale HCS (Facies C). The middle portion of C is dominated by medium- to thick-bedded fine sandstone. The upper 10 m of C is characterized by medium- to thick-bedded and planar laminated fine sandstone (Facies D).

Opposite Scatter River, a second prominent clast-supported, conglomeratic 10-cm-thick chert pebble bed (similar to the first) (Facies H) occurs 12 m above the base of the first conglomeratic bed (Figure V-11). Slickensides were observed on the surface of one sandstone bed between the two pebble beds, but no other evidence for faulting was found that could have caused duplication of strata. A thick interval of concretionary

shale, muddy siltstone, and thin siltstone beds overlies the second conglomerate (Facies A, B). Approximately 70 m above the base of the formation thin to medium bedded siltstone and fine sandstone beds occur frequently in a 10 m interval. This interval again passes upwards into mudstone and is overlain by a relatively sharp-based, 3-m-thick interval of interbedded silty mudstone and muddy siltstone (Facies A-B) (Figure V-11; Figure V-12d).

Micropaleontology and geochemistry. At Steamboat, tests of *Miliammina manitobensis* are rare in a sample from the middle of the interbedded interval at the top of Sandstone B, whereas a sample from the base of this interval is barren. TOC values are relatively high at 2.3 wt. %. A moderately abundant and diverse benthic foraminiferal fauna overlies the pebble bed on top of B, and contains some distinctive taxa not found in the underlying sequences. The fauna is dominated by *Haplophragmium swareni* Stelck and Hedinger, *Verneuilioides borealis*, *Trochammina umiatensis* Tappan, and *Haplophragmoides postis*. Additionally, *Textularia gravenori* Stelck and Wall and *Textularia rioensis* Carsey are also common, although they are not found in the underlying sequences. This fauna is assigned to Biofacies D (Table V-3). A sample within a laminated shale pocket in C yielded only isolated foraminifera and a flood of diatoms. This shale has an unusually high TOC content of 3.5 wt. %. One of the shale pockets within D yielded a very low abundance and diversity fauna of similar species composition to the underlying strata (Biofacies D) along with abundant coalified organic matter and mica.

At Lepine Creek, the foraminiferal fauna from Sequence 3 remains moderately diverse and abundant and is assigned to Biofacies D of the *Miliammina manitobensis*

Zone. A sample in the lower part of the sequence contained abundant coalified plant organic matter and relatively abundant foraminifera. A sample immediately below C contained only a few specimens of *M. manitobensis*.

At Scatter River, the foraminiferal fauna becomes more diverse above the second pebble bed. *Haplophragmium swareni* and *Trochammina umiatensis* appear along with more isolated specimens of *Textularia* sp. and *Textularia rioensis*. The strata above the second pebble bed are thus characteristic of Biofacies D (Table V-3). No significant faunal changes occur in the uppermost portion of the Sikanni Formation at this locality. The entire section shows little variation in TOC values, which range between 1.0 and 1.5 wt. %.

Interpretation. At Steamboat, the sequence boundary marking the base of Sequence 3 is placed at the base of the interbedded unit of Sandstone B (Figure V-7a, b), below the reappearance of foraminifera. Since sparse foraminifera do occur above the S₃ boundary, this interval is interpreted to represent the early transgression of the proximal portion of a wave-dominated delta (Facies Succession II, Table V-2). The uppermost unit within Sandstone B is interpreted to be of nearshore origin, perhaps a barrier that was subsequently transgressed. The pebble bed overlying the uppermost sandstone of B is interpreted to represent a lag deposit overlying a transgressive surface of erosion (TSE). The shelf facies of Sequence 3 differs from the shelf facies of Sequence 1 and 2. This interval is interpreted to represent deposition in the offshore transition zone; however, the abundance and diversity of foraminifera are not as large as in the underlying zone, and their diminutive size indicates some kind of environmental stress was present, which could have been a high sedimentation rate. The coarsening-upward cycle into Sandstone

C, a lower to middle shoreface sandstone, represents a parasequence within Sequence 3 overlain by a flooding surface. The peculiar high-TOC diatom-rich facies within a distinctive fissile shale interbed in the uppermost portion of the parasequence represents a preserved remnant of quiet water deposition in between major storm events. Evidence of this parasequence is also present in Sandstone C at Lepine Creek, which is also characterized by storm-dominated middle shoreface deposition above the base of Sequence 3.

At Steamboat, Sandstone D is characterized by a sharp, erosive base, mud-free upper fine sandstone overlying shelf and offshore transition facies. The sedimentary and micropaleontological features of Sandstone D indicate that it is a lower to middle shoreface deposit. The isolated sideritized clay clasts near the top of Sandstone D in hummocky cross-stratified to planar laminated fine sandstone indicate a middle to upper shoreface depositional environment. These observations suggest that the base of Sandstone D represents a RSME (Plint, 1988) overlying shelf and offshore transition facies and that Sandstone D represents a forced regressive deposit. Sandstone D can thus be assigned to the falling stage systems tract (FSST) and Facies Succession III (Table V-3). Plint and Nummedal (2000) have formally defined the FSST as being characterized by a sharp-based, hummocky cross-stratified sandstone overlying a RSME. The FSST is overlain by a subaerial surface of erosion and sequence boundary or correlative conformity. A RSME forms during the initiation of base-level fall (forced regression) as wave base is lowered into previously deeper water environments and is overlain by shallowing-upward shelf and shoreface strata (Plint, 1991; Hunt and Tucker, 1991; Posamentier et al., 1992; Plint and Nummedal, 2000).

At Lepine Creek, the abundant terrestrial organic material in the lower part of Sequence 3 and the abundant silty and very fine-grained sandstone interbeds indicate that the succession here represents offshore transition deposition. The base of Sandstone C is gradational with the underlying offshore transition deposits and the sedimentary structures suggest deposition above fair weather wave base. The cycles of planar-lamination overlain by combined-flow ripples represent waning deposition during major storm events. Sandstone C at this locality is very similar to the thick Sandstone C at Steamboat Mountain, and both are likely normal progradational sandstones overlain by marine flooding surfaces and are hence interpreted as parasequences.

Opposite Scatter River, the second pebble lag indicates the presence of a combined sequence boundary and TSE. The shoreface prograded out at least as far as this outcrop during relative sea level fall and was subsequently reworked during the ensuing transgression that once again deposited shelf mud at this locality. Paleontological data, notably the appearance of *Textularia* and *Haplophragmium* above the base of Sequence 2 opposite Scatter River, indicate that this sequence boundary is equivalent to the one overlying Sandstone B at Steamboat and Lepine Creek. A significant facies change occurs from fine-grained shelf facies opposite Scatter River to offshore transition zone and lower-middle shoreface facies in sandstones B and C at Lepine Creek. The subtle coarsening upwards interval 75 m above the base of the formation opposite Scatter River is likely a distal expression of the parasequence Sandstone C that is prominent at both other localities and is interpreted to represent the distal toe of the Sandstone C clinoform. The Scatter River outcrop is located approximately 15 km northeast of the Lepine Creek locality. A SE-NW oriented

shoreline (based on the facies distribution in Sikanni Formation outcrops), and a deltaic lobe likely centered in the Steamboat area, suggests that the Scatter River locality was probably more than 10 km from the early highstand shoreline allowing for this significant facies change. The two pebble beds in the lower part and another overlying the Sikanni Formation opposite Scatter River, however, indicate that the shoreface did migrate at least this distance during relative sea level falls. The sharp-based siltstone interval 120 m above the base of the formation at Scatter River (Figure V-11; Figure V-12d) may be a distal expression of the FSST preserved at Steamboat Mountain (see Sequence 4 section).

Sequence 4

Sedimentology and facies. The base of the Sequence 4 within the Sikanni Formation at Steamboat Mountain is placed near the top of the Sandstone D (Figure V-5). Approximately 3 m below the top of D, isolated concentrations of rounded, sideritized clay clasts up to 5 cm in length occur on the hummocks (Figure V-8d). A distinct flooding surface overlies D, but no pebble bed was identified in the overlying strata. A relatively thick mudstone package of Facies A separates Sandstone D from E. A 3-m-thick mudstone divides the massive and fine-grained Sandstone E₁ from E₂ (7.5 m and 20 m, Figure V-5, V-8e). The lower contact of E₁ is gradational, and the sandstone is massive and fine-grained. A distinct lithological change within the upper part of E₂ separates the lower well-sorted fine-grained, hummocky cross-stratified sandstone from the upper 10 m of organic-rich, fine- to medium-grained, lithic, thin to thick-bedded sandstone and pebble conglomerate. Disseminated pebbles can be found throughout this uppermost sandstone, and are concentrated on some bedding planes. The pebbles are up to 2 cm in length and include chert and igneous clasts. The uppermost part of the E₂ is

covered, although the recessive nature of the overlying beds suggests that the shale of the Sully Formation directly overlies E₂.

At Lepine Creek, a 2 to 4-m-thick, sharp-based sandstone bed (Sandstone D) can be observed approximately 20 m above Sandstone C at this locality (Figure V-9; Figure V-10c). This upper portion of the outcrop was partially inaccessible and observations from Stott (1982) are utilized. Sandstone E (inaccessible) (Figure V-9; Figure V-10c) is 15 m in thickness and the upper part is a distinct prominent buff pink colour.

Two prominent coarser units mark the top of the Sikanni Formation opposite Scatter River (Figure V-11; Figure V-12d to f): a 3-m-thick interval of interbedded silty mudstone and muddy siltstone (Facies A-B), and a 4-m-thick interval of thin to medium-bedded very fine sandstone and siltstone interbedded with muddy siltstone that becomes muddy siltstone towards the top. A matrix-supported pebble lag occurs at the base of a fine-grained, 20 cm thick sandstone bed 0.5 m below the overlying Sully mudstone (Figure V-12e). The lag is composed of sideritized clay clasts and chert pebbles up to 2.5 cm in diameter in a matrix of fine- to medium-grained sandstone. The base of the lag shows some erosional relief into the underlying strata.

Micropaleontology and geochemistry. The shale above the flooding surface overlying Sandstone D (FSST) at Steamboat contains abundant phosphatic material and a low diversity foraminiferal fauna dominated by *Reophax vasiformis* Chamney and *Uvigerinamina manitobensis* (Wickenden) that becomes more diverse upwards and is assigned to Biofacies D. TOC values within Sequence 4 range between 1.0 and 2.0 wt. % and show a slight increasing trend upwards. Opposite Scatter River, the mudstone below and between the two coarser intervals at the top of the Sikanni Formation contain a

diverse and abundant assemblage of benthic foraminifera dominated by *M. manitobensis*, *Trochammina umiatensis*, *Bathysiphon brosgiei* Tappan, *Saccammina alexanderi* and *Haplophragmoides* spp., all typical of Biofacies D of the *M. manitobensis* Zone.

Interpretation. At Steamboat hummocky cross-stratified Sandstone D is interpreted to have been deposited in a middle shoreface environment. Clay clasts at the base of the hummocks (Figure V-8d) must have originated from an exposed muddy surface, which formed after the deposition of the falling stage sandstone and during the development of a sequence boundary. This follows the FSST model of Plint and Nummedal (2000), where during relative sea level fall, a sequence boundary develops atop the shoaling-upwards FSST sandstone as it progrades and offlaps into the basin. In theory, subaerial deposits should overlie the sequence boundary; however, during ensuing relative sea level rise, transgressive reworking of these deposits may result in only a thin sheet sandstone indistinguishable from the FSST sandbody (Plint, 1996). At Lepine Creek, the sharp-based Sandstone D below the uppermost E sandstone may be a distal expression of this forced regression.

Opposite Scatter River, the sharp-based interbedded siltstone interval 120 m above the base of the Sikanni Formation is interpreted to represent the distal expression of the FSST of Sandstone D that is more conspicuous at the Steamboat and Lepine Creek localities. The only expression of forced regressions in offshore environments may be an abrupt coarsening without a regressive surface of erosion (with gutter casts, etc) (Plint and Nummedal, 2000) like is seen here.

Deposits of the lowstand systems tract can overlie the FSST downdip (e.g. in the I-1 sandstone in Plint, 1996) if the rate of relative sea level fall exceeds the creation of

accommodation space so that a zone of subaerial bypass develops downdip of the FSST (Plint, 1996, fig. 25E). Hence, lowstand deposits may lie further basinwards, but no evidence of a detached lowstand sandstone is present at the distal Scatter River outcrop (Plint and Nummedal, 2000), although such a deposit could exist further basin-ward where there is poor well control. A distinct flooding surface (to shelf facies) overlies this interval at all localities, and is especially evident by the abundant phosphatic debris in the shale overlying the sandstone at Steamboat.

At Steamboat and northeast Lepine Creek, Sandstone E is interpreted as a normal progradational lower to middle shoreface sandstone succession (HST) overlain in its uppermost part by an alluvial (fluvial) sandstone. A sequence boundary underlies these alluvial strata and marks the base of a lowstand systems tract (Facies Succession IV, Table V-2) that underlies the Sully Formation. Opposite Scatter River, the Sikanni-Sully transition preserves evidence of a channel lag (Figure V-12e) followed by a transgressive ravinement lag (Figure V-12f). The channel lag is the remnant deposit of a relative sea level lowstand that is preserved as non-marine conglomeratic sandstone deposits in the uppermost Sikanni Formation at Steamboat Mountain and the northeast Lepine Creek locality. In the Dunedin River area north of Steamboat Mountain, Stott (1982) recorded the presence of up to 12 m of chert pebble conglomerate in the uppermost portion of the Sikanni Formation, which supports this interpretation. This conglomerate lies on a regional sequence boundary that separates the Sikanni and Sully formations.

Discussion

Foraminiferal faunas and zones

All foraminifera recovered from the Sikanni and Sully formations are benthic, agglutinated taxa, typical of most Albian strata in the Canadian Western Interior Basin. Subzones A (characterized by Biofacies A) and B (characterized by Biofacies C and D), which are similar to the *Verneuilina canadensis* and *Haplophragmoides postis goodrichi* subzones of the *Miliammina manitobensis* Zone established in the Peace River region, are here recognized in the Sikanni Formation (Figure V-4). The faunal transition between the two zones occurs at the base of S₂ and continues into S₃, where the fauna is most like that previously assigned to the *H. postis goodrichi* Subzone (Sutherland and Stelck, 1972; Caldwell et al., 1978). Except in the most proximal environments, benthic foraminifera appear to have been surprisingly resilient to paleoecological changes that must have accompanied the late Albian relative sea level changes. Consequently, the subzones of the *Miliammina manitobensis* Zone are more difficult to differentiate in deep sublittoral (outer shelf) environments such as those present in the strata of the Sikanni Formation preserved along the Liard River. The most profound changes were associated with the second and third sequences. Watermass changes also affected the ammonites during this interval, as the transition from the *Neogastrolites haasi* to the *N. cornutus* ammonite subzone occurs in the same strata (e.g. Stelck, 1975).

Other evidence suggests that paleoenvironmental changes associated with sequence boundaries had often little influence on biostratigraphic ranges of marine faunas. *Neogastrolites cornutus* (Whiteaves), for example, continues from the

uppermost Sikanni Formation along the Sikanni Chief River into the lower Sully shale (Stelck and Hedinger, 1983). Palynological analysis has also shown that no significant changes occur in the spore and pollen record between the uppermost Buckinghorse and Sully formations, although there is a decline in abundance of phytoplankton and spores and pollen in the Sully Formation at Sikanni Chief River (Anan-York and Stelck, 1978). It is probable that much greater faunal changes occurred in the more proximal facies, but these have been removed through transgressive ravinement (represented by the pebble beds) and hence only a limited record of proximal facies and biofacies is preserved.

Paleogeography

Our interpreted data indicate that the Sikanni Formation preserves wave-dominated deltaic and shoreface strata in which sedimentation was punctuated by four relative sea level changes. These fluctuations produced sequence boundaries associated with each of the four major sandstones preserved in the succession (in addition to a single parasequence sandstone preserved at the Steamboat Mountain locality). The thickness and facies of the Sikanni Formation preserved in the Muskwa-Tetsa region suggest that the Sikanni delta was probably centered in that area (Figure V-13). An HI/OI plot indicates (Figure V-14) that the Sikanni Formation is characterized by terrestrial (Type III) organic matter, which is typical of Albian strata in the northern portion of the WCSB.

Previously, Stott (1982, 1984) considered that the Sikanni Formation consists of progradational shoreface deposits because of the lack of associated delta-plain facies and its relatively constant thickness over long distances. The new outcrops at Steamboat Mountain, however, show a 400-m-thick succession with preserved delta plain and distributary channel deposits. Distinguishing wave-dominated deltaic deposits from that

of a wave-dominated shoreline can be difficult. By definition, a prominent lobe should be identified in order to define the formation as representing wave-dominated deltaic deposits, such as those identified in the subsurface Dunvegan Formation (Bhattacharya and Walker, 1991a-b). The present outcrop and well control for the Liard Basin does not allow us to clearly identify the presence of a deltaic lobe of the Sikanni Formation, although the thickness and facies present in the Muskwa-Tetsa rivers region strongly suggests that this area was the depocenter. The Steamboat outcrop is also situated further east than the more distal deposits preserved along the Sikanni Chief River and in the northern portion of the Liard Basin. According to Stott (1984), the Sikanni-Goodrich shoreline was at least sinuous, and extended from Kakwa River, south of Grande Prairie in the south to the present day Mackenzie River in the Northwest Territories (fig. 21 of Stott, 1984).

Relative sea level fluctuations likely had varied effects along the margins of the Sikanni shoreline. During the Mesozoic, ramp-type margins developed in the western foreland basin. Posamentier and Allen (1999) note that in ramp-type basins characterized by deltaic-lobes and non-deltaic shorelines, the latter migrate significantly further during relative sea level falls because they are characterized by a lower gradient than the adjacent deltaic lobe. It is thus not surprising that pebble beds are observed in distal shelf facies opposite Scatter River which is far from the deltaic lobe of the Sikanni depocenter at Steamboat Mountain.

Regional correlations

Well logs containing upper Albian and Cenomanian strata in the Liard Basin are sparse. Based on well log correlations, Dixon (1997, 1999) proposed that an

unconformity is present near (below) the base of the FSM interval. Dixon considered that the pre-Fish Scales unconformity truncates increasingly older strata eastwards, such that the Sikanni Formation is not preserved in the Great Slave Plain area. Eastwards across the Bovie Fault and into the Plains, Dixon (1999) proposed that pre-Fish Scales erosion removed the entire Sikanni and upper Lepine formations. Unpublished cross sections and others from the Sikanni Chief River area (Schröder-Adams and Pedersen, 2003) indicate that four sequences can be recognized and traced from the Sikanni Chief River area into the Liard Basin. In the Cameron Hills and Great Slave Plain areas of the southeastern Northwest Territories, however, it is more difficult to distinguish the sequences of the Sikanni Formation. This may be due to reactivation of the Tathlina High (an Early Devonian feature) in the Late Albian (Dixon 1999), or change to finer-grained facies northwards and eastwards (basinward) distant from the Sikanni delta depocenter.

Regional well log correlations of the Sikanni Formation are figured in Chapter VII. An excellent reference well that preserves most of the interval of this study is IOE Dunedin D-075-E/094-N-08, in northeastern British Columbia approximately 25 km south of the junction of the Scatter and Liard rivers (Figure V-15). The base of the Sikanni Formation occurs approximately 100 m above a regional flooding surface in the Lepine Formation. This flooding surface overlies the informal Bougie member, a regionally correlative sandstone unit within the upper Buckinghorse and Lepine Formations in the Sikanni Chief and Liard River areas (Pedersen and Schröder-Adams, 2001). All four of the Sikanni sequences can be differentiated in D-075-E. The base of the Fish-Scales interval in both the gamma-ray and resistivity curves can be identified as

two small coarsening-upwards intervals approximately 10 m apart, similar to its expression in outcrop opposite Scatter River.

It is not clear how much eastwards truncation of the Sikanni Formation, if any, has occurred. Some truncation is evident because of the presence of transgressive surfaces of erosion. The presence of sequence boundaries amalgamated with transgressive surfaces of erosion with pebble lags implies that lowstand shorelines must have been present seaward of these locations (Plint, 1988), but as of yet, lowstand shorelines have been difficult to locate in the Sikanni Formation. The Sandstone D at Steamboat Mountain is here deemed equivalent to Sandstone D preserved along the Liard River northeast of Lepine Creek and both do show evidence of being formed above a regressive surface of erosion and thus are considered to be lowstand shorelines. The apparent absence of other lowstand sand bodies eastwards may be due, in part, to poor well control and the lack of outcrops in the eastern portion of the basin. Alternatively, these shorelines may have been eroded during subsequent transgression. The thin chert pebble beds present in the Sikanni Formation opposite Scatter River that are completely incased in offshore and offshore transition zone mudstone facies indicate that a considerable amount of reworking and winnowing must have accompanied the relative sea level changes in the area. It is not clear how far eastwards and southeastwards (basinward) evidence of relative sea level lowstands may be preserved. No pebble beds have been reported from time-equivalent Shaftesbury Formation in northern Alberta or the Fort St. John Plains.

Stott (1982, fig. 12) considered that the lower and part of the middle member of the Sully Formation in the Liard Basin and in the Sikanni Chief River area is equivalent

to the uppermost sandstone of the Sikanni Formation in the Steamboat Mountain region. Hence in the Muskwa-Tetsa region, the top of the Sikanni Formation was thought by Stott (1982) to correspond approximately to the Fish Scales marker bed, which would suggest that the base of the Sully Formation in that region is only of earliest Cenomanian age. This conclusion was based on some macrofossil and stratigraphic evidence.

Neogastrolites cornutus is found only below the basal Sully Formation in the Sikanni Chief River and Sully Creek areas, to the south and north of the Muskwa-Tetsa rivers region, respectively (Stott, 1982). Hence the *N. cornutus* Subzone lies below the Sully Formation in these areas. However, no ammonites were obtained from the uppermost Sikanni or Sully formations in the Muskwa-Tetsa region west of Fort Nelson. The paucity of macrofossil data from the Muskwa-Tetsa River region makes this hypothesis difficult to substantiate. The foraminiferal evidence, however, does not support this conclusion, as S₄ at Steamboat lies within subzone B of the *Miliammina manitobensis* Zone. Subsurface correlations do not support this conclusion either. The Sikanni Formation increases in thickness northwest from the Sikanni Chief River area to the Muskwa-Tetsa region as well as southwards from the northern portion of the Liard Basin towards the Muskwa-Tetsa region, but this most likely is due to increased sediment supply and accommodation at the Sikanni delta depocenter in the Steamboat region.

Stott (1982) considered that uppermost Sikanni strata are approximately at the same stratigraphic horizon in the Muskwa-Tetsa region, but eastwards the Sikanni-Sully contact is placed at the top of successively older sandstones. The sequence stratigraphic approach of this paper stresses that four sequences can be recognized in most outcrops of the Sikanni Formation and hence the basal Sully Formation, although time-transgressive,

is approximately equivalent and records a flooding event across the Liard Basin and southwards in the Sikanni Chief River area and in the equivalent Cruiser and Shaftesbury formations. It is possible, however, that significant amounts of strata were removed during formation of the basal Sully unconformity (SB) and subsequent transgressive ravinement. Dixon's (1999) "pre-Sully" unconformity may represent erosion in the Great Slave Plain associated with the formation of this sequence boundary.

Relative Sea level Changes- Mechanisms and Regional Extent

Previously recognized cyclicity. The sequences described here occur within the third order tectono-eustatic Greenhorn Marine Cycle of Kaufmann (1969; 1977; 1993). Its base is represented by the flooding of the Mowry Sea above the Viking Formation and its equivalents in the Canadian Western Interior Basin (Jowett and Schröder-Adams, in press). Caldwell (1984) detailed the evidence for higher-order "transgressive-regressive couplets" in Lower Cretaceous deposits of the western interior. He noted five T-R couplets throughout the Albian-Cenomanian, the last two of which he termed the Hasler (=Lepine-Sikanni) and Sully (=Sully-Dunvegan). The Lepine-Sikanni couplets appear localized in the interior basin where influx of coarser sediment must have been related to tectonic events adjacent to the basin in northeastern British Columbia (Caldwell, 1984). The cyclicity present within the Sikanni Formation, which is characterized by four distinct sandstones overlain by shale, "point(s) to repeated short-term transgressive-regressive fluctuations of the sea and to variation in the grade and rate of deposition of sediment being supplied (Caldwell, 1984, p. 197)". We have shown here that this cyclicity observed by Caldwell was due to relative sea level fluctuations that produced surfaces above which significant basinward shifts in facies occurred.

Constraints on frequency. Ammonite and foraminiferal data combined with the geochronologic time-scale can be used to estimate the duration and frequency of the sequences identified here. Strata of the Sikanni Formation span most of the *Neogastrolites hassi* and *N. cornutus* ammonite zones (Warren and Stelck, 1969, Stott, 1982, Stelck, 1975), although the latter zone persists into the lower Sully Formation (Warren and Stelck, 1969; Stelck and Hedinger, 1983). Obradovich (1993) gives $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 98.74 ± 0.59 Ma for bentonites from probable *Neogastrolites hassi* Zone strata from the Thermopolis Shale, Wyoming, and 98.52 ± 0.41 Ma for *N. cornutus*-bearing beds of the Arrow Creek Member of the Colorado Shale in Montana. The lowest occurrence of the *Neogastrolites* lineage is *N. cf. hassi* from the correlative to the lower part of S₂ of this paper at Sikanni Chief River (Stelck, 1975). *N. hassi* is found in the “Third Sikanni Sand Member” in the Sikanni Chief River area (Stelck, 1975), which is probably equivalent to the top of S₂ or the base of S₃ here. *N. hassi* has also been recovered from 140 ft above the base of the Goodrich sandstone (Warren and Stelck, 1969). Below the lowest regional occurrences of *Neogastrolites*, there is a significant gap down to the last occurrence of *Stelckiceras liardense*, which is approximately 280 m above the base of the Lepine Formation along the Liard River (Stott, 1982; Jowett and Schröder-Adams, in press); however, Skull Creek shale (Joli Fou Sea equivalent; correlative to the middle part of the Lepine Formation, Jowett and Schröder-Adams, in press) strata containing the bivalve *Inoceramus comancheanus* have been dated by conventional K-Ar methods to 104.4 ± 2.1 Ma (Odin 1982). Hence isotope dating techniques suggest there is a 5-6 Ma time interval between deposition of the Joli Fou Sea

and its equivalents and the lower to middle parts of the Sikanni Formation. On the Liard River, this represents about 600 m of strata.

Although the lowermost sequence within the Sikanni Formation falls slightly lower than the base of the *Neogastrolites hassi* Zone, the upper two sequences appear to span as little as 200 kyr based on the radiometric dates above. Assuming a constant deposition rate for S₁-S₄ (the strata from the flooding surface overlying the Bougie Member to the top of the Sikanni Formation) the entire succession likely spans no more than 700-1000 kyr. These crude calculations indicate a period of between 100 and 250 kyr for each of the sequences in the Sikanni Formation.

Causal mechanism(s). It is problematic to propose a causal mechanism for these higher-frequency cycles within the Sikanni Formation. Because of the deltaic nature of the Sikanni Formation, autocyclicity may be expected to have played a role in the development of the sandstones. The widespread occurrence of sequence boundaries along strike, regional well log and outcrop correlations, and benthic foraminiferal and macrofossil changes associated with their boundaries, however, argue that they are synchronous and represent basin-wide relative sea level changes. This is true at least for the more proximal (orogenward) environments that are generally exposed in outcrop in the western portion of the Liard Basin.

Normally, the mechanism thought to be responsible for cycles with a periodicity of 10⁵-10⁶ yrs is orbital forcing (by buildup of continental glaciers, changes in volume of groundwater storage and/or changes in the volume of ocean water) (Haq et al., 1987; Mitchum and Van Wagoner, 1991; Vail et al. 1991; Jacobs and Sahagian, 1995), although it is contentious whether significant continental ice sheets existed during the

Mesozoic (Francis, 1986; Frakes and Francis, 1988; Vail et al., 1991; Plint, 1991; Dewey and Pitman, 1988; Markwick and Rowley; Stoll and Schrag, 1996; Price 1999; Alley and Frakes, 2003). Sequences in foreland basins may also be driven by regional tectonics, autocyclic changes (such as delta-lobe switching), sediment supply cycles possibly controlled by Milankovitch cycles (Elder et al., 1994; Plint, 2003), changes in intraplate stress regimes (Cloetingh et al., 1985), and basement control (Quinlan, 1987; Peper et al., 1992; Hart and Plint, 1993). In the Canadian Western Interior, cycles with 10^4 - 10^5 year periodicities have been identified in the Falher/Gates (Leckie, 1986, Carmichael, 1988, Casas and Walker, 1997), Cardium (Plint, et al. 1986; Bergman and Walker, 1987; Walker and Eyles, 1988), Viking (Power, 1988; Leckie and Reinson, 1993), Muskiki and Marshybank (Plint, 1991a, b), and Dunvegan (Bhattacharya 1988; Bhattacharya and Walker, 1991a,b; Plint, 1996, 2000, 2003) formations, and hence their presence is well-established.

Evidence for Cretaceous glacio-eustasy has been mounting. Like the Sikanni, the Dunvegan Formation is also characterized by prograding wave-dominated deltaic and shoreline sandstones overlain by transgressive surfaces of erosion that were considered to have been driven by tectonically induced subsidence (Bhattacharya 1988; Bhattacharya and Walker 1991a). It was concluded that although the overall progradation of the Dunvegan depositional systems may have been related to a third-order global sea level drop, the allomember bounding surfaces were probably driven by local tectonics producing a 200 kyr relative sea level cyclicity (Bhattacharya, 1988). Plint (2003) indicated that Milankovitch cyclicity may have exerted at least a climatic control on the region affecting sequence development.

Plint (1991) reasoned that high-frequency eustasy, attributable to <10 m sea level fluctuations due to waxing and waning of continental ice sheets, could best explain the parasequence deposition in the Coniacian-Santonian Marshybank Formation in Western Canada with an apparent 100 kyr periodicity. Similarly, Gale et al. (2002) showed global synchronicity in Cenomanian sequences that they attributed to the 400 kyr Milankovitch long eccentricity cycle and Miller et al. (2003) showed that rapid sea-level changes in the Late Cretaceous are linked to ^{18}O excursions implying a glacioeustatic control.

Although similar cycles have been observed in the Cenomanian Dunvegan Formation, correlative high-frequency relative sea level fluctuations to those described here from the Sikanni Formation of northeastern British Columbia have yet to be identified in the Western Interior Basin. The correlative Goodrich Formation south of Peace River likely preserves similar evidence of relative sea level changes, but the remainder of the Canadian Western Interior Basin is characterized by significant flooding during the latest Albian. Worldwide, however, Late Albian sea level fluctuations appear to have fluctuated rapidly with amplitudes from 30-50 m (Immenhauser and Scott, 1999, 2002), but inter-basin correlation, especially into the Western Interior Basin, has yet to be completed.

If the observed relative sea level fluctuations were not driven by orbital forcing, regional tectonic events (flexural loading and subsidence followed by uplift), changes in in-plate stress (Cloetingh, 1986) and/or reactivation of basement features would have to be invoked to explain them. In the past, it was generally believed that tectonic events did not operate at a rate fast enough to drive such high-frequency cycles, and thus many invoked glacio-eustasy whenever such cycles were observed in the stratigraphic record

(Goldhammer et al. 1987; Plint, 1991; Plint et al. 1992; Devlin et al., 1993). There is no direct evidence of basement control, or control of accommodation space by Cretaceous reactivation along the Bovie structure. Within-plate lithospheric stress changes, however, have been invoked to explain high-frequency relative sea level changes of at least up to 1 cm/1000 yrs (Cloetingh, 1986; Peper et al., 1992; Yoshida, 1996; Yoshida et al., 1998; Willis, 2000), and hence in-plate stress changes may have had significant effects on the topography of the Liard Basin bounded on its eastern margin by the Bovie structure. This is a possible mechanism for driving the cyclicity seen in the Sikanni Formation.

Some evidence regarding the origin of the cyclicity within the Sikanni Formation may be observed from the overall character of the basin. The transition from the Late Albian to the Cenomanian in the Western Canada Sedimentary Basin represents a profound change in paleogeography. Most of Albian time was characterized by north to northeastern or northwestern progradation of shoreface environments (ie. the Spirit River and Peace River formations); however, in the Late Albian, flooding of the Mowry Sea was widespread and eastwards progradation of the Bougie member and Sikanni Formation in the Late Albian and then southeastwards progradation of the Dunvegan Formations occurred in the Cenomanian. In a sense, the alluvial-deltaic Dunvegan Formation marks the culmination of this pattern and shows that the region of maximum Cordilleran disturbance migrated northwards during the Late Albian-Cenomanian, probably as a result of right-lateral movement of accreted terranes (Stott, 1982; Poulton et al., 1994). The earliest expressions of these northerly sediment sources are the Bougie member (Pedersen and Schröder-Adams, 2001) and Sikanni Formation in northeastern British Columbia. It thus seems likely that a lower-order (10^6 - 10^7 yr) control on

deposition of the Sikanni Formation was this northerly migrating zone of tectonic disturbance that influenced accommodation space through flexural subsidence (and possibly changes in in-plane stresses) and provided abundant clastic sediment supply to fill that accommodation space.

Cant and Stockmal (1989) imply the opposite, however, and suggest that this change to southeastwards transport implies that greater thrust-loading occurred in the southern Canadian Cordillera during the Late Albian or that loads in the north were displaced even further northwards into the Yukon or Alaska creating a tectonically-induced southwards slope to the basin. We think that greatest thrusting must have been in the north because this is where the greatest subsidence occurred, as clearly revealed by sediment thicknesses and facies distributions combined with regional southeast to northwest cross-sections. Flexural models show that subsidence decreases exponentially away from the load (Beaumont, 1981).

How could tectonic events be related to the relative sea level falls that brought pebbles out into the basin during deposition of the Sikanni Formation? The relationship between tectonism and clastic sedimentation is complex and many factors such as sediment supply and available accommodation space must be accounted for. The conventional view has been that wedges of coarse clastic sediment are syntectonic, but in many cases, thrusting initiates rapid tectonic subsidence in the proximal foreland that is followed later in the distal foreland by thrust-derived sediment being transported out into the basin when the load in the proximal foreland is removed by erosion or some other mechanism (lateral fault migration of terranes, for example, could be a possibility) and the thrust belt rebounds isostatically (Heller et al., 1988; Heller et al., 1989; Leithold,

1994; Kamola and Huntoon, 1995). Repeated flooding events to shelf facies overlying sequence boundaries followed by shallowing-upwards successions or forced regressive sandbodies in the Sikanni Formation combined with the lack of evidence elsewhere in the basin for equivalent time-equivalent eustatic changes, and a significant 10^7 Ma frequency change in basin sediment transport imply that high-frequency changes in flexural load (Peper et al., 1992) in the region of northeastern British Columbia during the latest Albian may account for the observed cyclicity. In this sense, we suggest that model of Heller et al. (1988) applies to the observed stratigraphic cyclicity, where thrusting and associated crustal shortening causes rapid subsidence and traps coarser sediment in the proximal foreland and then migrates basinward (cratonward, away from the orogen) upon cessation of thrusting due to isostatic rebound. In addition, intra-plate stress changes associated with thrusting may have played a major role in generation of the cyclicity by vertical structural movement within the Liard Basin.

Table V-1. Description of facies A-K. FWWB-Fair weather wave base.

Facies	Lithology	Foraminiferal Abundance	Foraminiferal Diversity	Physical and biogenic sedimentary structures and other observations	Depositional Environment
A	fissile shale and mudstone, few rippled thin-bedded fine sandstone and siltstone interbeds	high	high	no grading in sand or silt beds; heavily bioturbated	shelf, mostly suspension deposition
B	interbedded mudstone and fine sandstone; HCS	high	high	heavily bioturbated, planar and current ripple lamination, no grading; some HCS	offshore transition, below FWWB; occasional storms generating wave and current activity; occasional convoluted bedding
C	medium to thick-bedded, very fine to fine sandstone	low	low	HCS; coalified organic matter often present	wave/storm-dominated lower to middle shoreface or delta
D	fine- to medium-grained sandstone	N/A	N/A	planar-laminated; abundant organic debris on bedding planes	upper shoreface to foreshore
E	fine sandstone	barren	barren	herringbone cross-stratification; <i>Macaronichnus</i>	tide-dominated delta, distal distributary channel
F	coal	barren	barren		coastal/delta plain
G	fine- to medium-grained channelized massive sandstone; sideritized clay clast at base	barren	barren	low-angle cross-stratification; organic-rich	distal distributary channel with basal conglomerates
H	well-sorted, clast- to matrix-supported chert pebble conglomerate, 10-30 cm in thickness	N/A	N/A		lag deposit from transgressive ravinement
I	fissile shale interbedded with thin rippled siltstone and fine sandstone beds	moderately high	very low	abundant <i>Ammotium</i> ; organic rich	estuarine
J	sharp and erosionally based, thick-bedded, , fine sandstone	low	low	amalgamated hummocky cross-stratification; sideritized clay clasts on bases of some hummocks	lower to middle shoreface; base is regressive surface of marine erosion (RSME)
K	organic-rich, fine to medium-grained, thin to thick bedded sandstone and pebble conglomerate	barren	barren	disseminated pebbles throughout, and concentrated on some bedding planes; pebbles chert and igneous	fluvial

Table V-2. Facies successions and their sequence stratigraphic interpretation.

Facies Succession	Facies	Sequence stratigraphic, systems tract interpretation
I. Coarsening-upward shelf and shoreface/delta succession	A, B, C, D, E, F, G, K	Normal progradation of shoreface or wave-dominated delta; highstand systems tract (HST)
II. Estuarine, transgressive lag, and shelf deposits	I, H, A (Facies I often not present)	Estuarine (rare) and marine transgressive succession; Transgressive surface of erosion (TSE) combined with, or overlying SB; Transgressive systems tract (TST)
III. Sharp-based shoreface	A and/or B overlain by J	Forced regressive shoreface or wave-dominated delta; Falling stage systems tract (FSST) overlain by SB
IV. Non-marine or marginal marine	(FSII overlain by) K	Abrupt basinward shift in facies to fluvial deposits; Lowstand systems tract (LST)

Table V-3. Benthic foraminiferal biofacies present within the Sikanni Formation.

Biofacies	Main Species	Diversity	Paleoecological Interpretation	Distribution
A	<i>Ammobaculites fragmentarius</i> , <i>Miliammina manitobensis</i> , <i>Verneuulinoides borealis</i> , <i>Verneuilina canadensis</i> , <i>Haplophragmoides postis</i> , <i>Saccammina alexanderi</i>	moderate to diverse	Well-oxygenated shelf	S ₁ at all localities S ₂ at Scatter River
B	<i>Verneuilina canadensis</i> , <i>Ammotium</i> sp.	low	Estuarine (stressed)	Base of S ₂ at Steamboat
C	<i>Haplophragmium swareni</i> , <i>Reophax vasiformis</i> , <i>Miliammina manitobensis</i> , <i>Glomspirella</i> sp., <i>Textularia</i> sp.	moderate	Offshore transition	S ₂ at all localities (except base of S ₂ at Steamboat)
D	<i>Haplophragmium swareni</i> , <i>Verneuulinoides borealis</i> , <i>Trochammina umiatensis</i> , <i>Haplophragmoides postis</i> , <i>Textularia gravenori</i> , <i>Textularia rioensis</i>	Low to moderate	Offshore transition to lower shoreface; stressed by frequent storms and high silty sediment input	S ₃ at all localities S ₄ at Scatter River and Steamboat (inaccessible at Lepine Creek)

Figure V-1. Location map of main portion of study area indicating outcrop localities at Steamboat Mountain, Lepine Creek and Scatter River. Shaded area represents limits of Upper Cretaceous Dunvegan Formation (after Leckie et al. 1991) and approximate limits of the Liard Basin. UTM coordinates (NAD27) are: Scatter-0406043E, 6607550; NE Lepine Creek-0399985E, 6595450N; Steamboat Mountain-0459717E, 6504660N. a) Scatter River. b) Chimney Creek c) Lepine Creek d) Garbutt Creek e) Graybank Creek.

Figure V-3. Sea level curve for Albian strata of the Western Canada Sedimentary Basin. Global transgressive-regressive (T-R) cycles after Kauffman and Caldwell (1993). Higher frequency Early Cretaceous T-R couplets after Caldwell (1984). Time scale after Obradovich (1993). Transgression is to the right.

Stage	Substage	Selected Macrofossil Zones (Warren & Steick 1969; Caldwell et al. 1978; Jelezky 1980)	Peace River, British Columbia (Steick et al. 1958; Sutherland & Steick 1972; Steick & Koka 1987; Steick & Hedinger 1983; Steick 1975, 1991)	Sikanni Chief River, British Columbia (Schröder-Adams & Pederson, 2003)	Liard Basin	Liard Basin Stratigraphy
Cenomanian	Middle	<i>Acanthoceras athabascense</i>	<i>Verneullinoides perplexus</i>	Unzoned	Unzoned	Dunvegan Formation
	Early	<i>Beatonoceras beatonense</i> <i>Irenoceras bahani</i> <i>Neogastrolites septimus</i> <i>Neogastrolites maclearni</i>	<i>Textularia alcesensis</i>		<i>Textularia alcesensis</i>	FSU Sully Formation
Albian	Late	<i>Neogastrolites americanus</i> <i>Neogastrolites muelleri</i> <i>Neogastrolites cornutus</i>	<i>Haplophragmium swareni</i>	Unzoned	<i>Millammina manitobensis</i> <i>Haplophragmium swareni</i>	Lower
		<i>Neogastrolites haasi</i>	<i>Haplophragmoides postis goodrichi</i>		subzone B	Sikanni Formation
			<i>Verneullina canadensis</i>		subzone A	
		poorly fossiliferous interval	<i>Reophax troyeri</i> <i>Trochammina umiatensis</i> <i>Trochammina depressa</i> <i>Reophax tundraensis</i> <i>Haplophragmoides gigas phaseolus</i> <i>Haplophragmoides gigas gigas</i> <i>Haplophragmoides uniorbis</i>		<i>Haplophragmium swareni</i> <i>Ammobaculites fragmentarius</i>	Bathysiphon-A. fragmentarius assemblage
	Middle	<i>Inoceramus commancheanus</i>	<i>Haplophragmoides gigas</i>	<i>Trochammina alcesensis</i>	<i>Ammomarginulina assemblage</i>	Bougie Equivalent
						Buckinghorse/ Lepine Formation
		<i>Stelckiceras liardensis</i>	<i>Ammobaculites wenonahae</i>	<i>Ammobaculites wenonahae</i>	<i>Ammobaculites wenonahae</i>	

Figure V-4. Upper Albian-Cenomanian foraminiferal zonation and subzonation of northeastern British Columbia.

Figure V-5. TOC data, foraminiferal biostratigraphy, lithostratigraphy, and composite stratigraphic section including Sikanni sandstones (A-E), foraminiferal abundances, sequence stratigraphic framework and depositional environment interpretations of Sikanni Formation strata at Steamboat Mountain, NE British Columbia. See Figure 1 for location. Micropaleontological sampling was approximately twice as dense as the TOC data points. EST- estuarine foraminiferal fauna. FS- Flooding surface. SB-Sequence boundary. TSE-Transgressive surface of erosion. SB-TSE-Combined sequence boundary and transgressive surface of erosion. RSME-Regressive surface of marine erosion. LST-lowstand systems tract. TST-Transgressive systems tract. HST-Highstand systems tract. FSST-Falling stage systems tract. For symbols see legend Figure 6.

Figure V-6. Sikanni Formation at Steamboat Mountain roadcut. a) TOC data and stratigraphy of sandstone A2 and S₁-S₂ boundary (see Figure 5 for overview). b) Estuarine shale and pebble bed overlying S₂ at Steamboat Mountain. The estuarine shale overlies the top of Sandstone A₂. (Person for scale). c) close-up showing thin layer of dispersed pebbles up to 7 cm in length. d) base of 20-m-thick, amalgamated hummocky cross-stratified Sandstone A underlain by offshore transition facies.

a

b

c

d

Legend

Parallel lamination	==
Hummocky cross-stratification	~
Planar cross-bedding	///
Ripples symmetrical	~
Lenticular bedding	~
Bioturbation	slight moderate intensive
Dewatering	~
Pebbles	•
Clay clast	~
Concretion	~
Coal fragment	~
Roots	~
Bentonite	~

Figure V-7. Sikanni Formation at Steamboat Mountain roadcut S₂ photographs. a) TOC data and detailed stratigraphy of Sandstone C and S₂-S₃ transition (see Figure 5 for overview). Coal bed at 254 m has 71 wt.% TOC (not plotted on TOC curve). b) Outcrop photograph of complex succession of B at Steamboat Mountain. c) Herringbone cross-stratified sandstone within the B sandstone at Steamboat. d, f) Channelized base of hummocky cross-stratified fine sandstone of B at Steamboat Mountain, interpreted as the basal deposits of a delta lobe of the Sikanni delta. e) Channel lag with sideritized clay clasts and chert pebbles in medium-grained sandstone above the coal bed.

Figure V–8. Sikanni Formation at Steamboat Mountain roadcut S₃ and S₄ photographs. a) Hummocky cross-stratified, very fine-to-fine sandstone of parasequence (C) within S₃ at Steamboat Mountain. The entire sandstone is interpreted as lower shoreface and no sequence boundary could be recognized through sedimentological or paleontological analyses. b, c) Sharp, erosional base of hummocky cross-stratified fine sandstones of D at Steamboat Mountain. The base of D is interpreted as a regressive surface of erosion (S₄). d) Large-scale hummocky cross-stratified fine sandstone 3 m below the top of D. Sideritized clay clasts occur along hummocks below the top of D. e) Uppermost coarsening-upward succession (E) in the Sikanni Formation at Steamboat Mountain. Shale interbedded with hummocky cross-stratified fine sandstone grades upward into hummocky cross-stratified fine sandstone, which in turn is overlain by a lithic sandstone and conglomerate. The top of S₄ lies at this change to alluvial sandstone and conglomerate. This uppermost conglomerate is recognized throughout the Muskwa-Tetsa River area and elsewhere in the Liard Basin where the basal Sully Formation is exposed.

Figure V-9. Foraminiferal zones, stratigraphy and relative foraminiferal abundance of the uppermost Lepine and Sikanni formations in the cliffs northeast of Lepine Creek, east bank of Liard River (see Figure 1).

Figure V-10. Sikanni Formation northeast of Lepine Creek in cliffs on east bank of Liard River. (C, D and E sandstones are labeled). a) Chert pebbles in fine to medium sand at top of Sandstone A. These mark the base of S_2 within the Sikanni Formation at this locality. b) The base of C at the Lepine Creek locality preserves large-scale HCS topped by wave ripples in several cycles at its base. c) View of C, D and E sandstones at the Lepine Creek locality of the Sikanni Formation along the Liard River. These thick sandstones differ markedly from the predominately shelf facies succession preserved nearby opposite Scatter River.

Figure V-11. TOC data, foraminiferal biostratigraphy, stratigraphy, sequence stratigraphy and paleoenvironmental interpretations of the Sikanni Formation opposite Scatter River (see Figure 1). TOC data points also correspond to frequency of micropaleontological samples.

Figure V-12. Outcrop photographs of Sikanni Formation opposite Scatter River. a) Base of the Sikanni Formation (white line) opposite Scatter River. b) 5-10-cm-thick chert pebble conglomerate interpreted as the base of S_2 , 20 m above the base of the Sikanni Formation opposite Scatter River. This conglomerate is encased in shale and is not associated with a coarsening-upwards succession. c) *Diplocraterion* trace in fine-grained sandstone interbed within S_2 . d) Uppermost Sikanni Formation and basal Sully Formation (white line) opposite Scatter River. Approximately 25 m uppermost Sikanni strata can be seen. Mudstone overlying upper siltstones is Sully Formation. e) Chert pebble conglomeratic channel fill at the base of a fine sandstone bed underlying mudstone of the Sully Formation, interpreted as the base of the Sully Formation. f) Structureless fine sandstone bed (above conglomerate in f) is overlain by siltstone and then mudstone with 0.1 m of clast-supported chert pebble conglomerate with rounded pebbles up to 8 cm in length. This surface is interpreted to represent the TSE associated with the relative sea level rise that resulted in deposition of the Sully Formation in the Liard Basin.

Figure V-13. Interpreted Late Albian paleogeography during deposition of the Sikanni Formation. Arrow indicates interpreted location of depocenter of the Sikanni wave-dominated delta. Yellow-predominantly shoreface/delta front sandstone; green-predominantly offshore mudstone facies.

Figure V-14. HI-OI plot for all samples from the Sikanni Formation.

d-075-e/094-N-08

Figure V-15. Representative well log (IOE Dunedin D-075-E/094-N-08) from the central portion of the Liard Basin showing tops of the Scatter, Lepine and Sikanni formations as well as sequences within the Sikanni and the Base of Fish Scales (BSF) marker. For location of well see Figure 1.

Chapter VI. THE ALBIAN-CENOMANIAN SULLY FORMATION IN THE LIARD BASIN AND NORTHERN EXPRESSION OF THE FISH-SCALES MARKER

Introduction and Regional Stratigraphic Framework

In the Liard Basin (Figure VI-1), the Sully Formation overlies the Sikanni Formation, and is correlative with a number of other shale-dominated lithostratigraphic units in the WCSB including the upper Shaftesbury and Cruiser formations (Figure VI-2). The Sully is predominantly shale with minor silty shale, but coarsens-upwards into the overlying shoreface and alluvial-deltaic sandstones of the Cenomanian Dunvegan Formation. Stott (1960, 1982) measured a number of sections of the Sully Formation in the Sikanni Chief River region northwards into the Liard Range. Thicknesses range from 213 m in the Sikanni Chief River area to approximately 122 m in the Muskwa-Tetsa region (Figure VI-1). Eastwards, its thickness increases to 200 m due to a lateral change in facies Stott (1982). Stott (1982) thought that shales marking the base of the Sully Formation are diachronous, becoming progressively older from west to east. The Sully Formation is generally poorly exposed north of the Sikanni Chief River and in the southern part of the Liard Basin (Muskwa-Tetsa region). The base of the formation is covered in the sections measured by Stott (1982). However, Stott (1982) proposed that the Fish Scales Marker Bed, an important basin-wide radioactive marker, could be placed approximately at the top of the Sikanni Formation in the Muskwa-Tetsa region.

Although the type section is located at Sully Creek, on the west flank of the Liard Range (Stott, 1960), the best exposures of the Sully Formation (and those studied here) occur along the east bank of the Liard River opposite Scatter River (Figure VI-1) in

northeastern British Columbia (Stott, 1982, section 65-10). There the Sully strata are continuous with both the underlying Sikanni and overlying Dunvegan formations and attain a thickness of almost 300 m. At this locality, Stott (1982) informally divided the formation into an 85-m-thick lower concretionary member, a 122-m-thick middle flaky shale member and an upper 91-m-thick concretionary member that grades into the overlying Dunvegan Formation. Based on his stratigraphic correlations, Stott (1982) suggested that the lower and part of the middle member of the Sully Formation in this region is equivalent to the upper part of the Sikanni Formation in the Muskwa-Tetsa River region.

The Fish Scales Marker (FSM) interval is ubiquitous in the WCSB. The base of the FSM interval is a regional stratigraphic marker characterized in outcrop in the Peace River Plains by a relatively thin but complex unit containing abundant fish remains, high TOC values, and impoverished benthic microfauna (see Leckie et al., 1992 for a detailed study). The base of the FSM interval corresponds to the Albian-Cenomanian boundary. The basal conglomerate is the result of basin winnowing during a sea level lowstand (Leckie et al., 2000). In southern Alberta and Saskatchewan the base of the FSM interval forms the base of the Fish Scales Formation, barren of foraminifera (Bloch et al., 1993; Schröder-Adams et al., 1996). Although the FSM is easily identified in well log curves to the southeast of the Liard Basin and Sikanni Chief River areas, it is more difficult to identify in the northwest and is rarely found in outcrop. It was tentatively identified in an interval of argillaceous siltstone with fish debris approximately 15 m thick beginning 61 m above the top of the Sikanni Formation on Sikanni Chief River (Stott, 1982, section 62-21; Stelck and Hedinger, 1983). Reexamination of that outcrop, however, places a

distinct transgressive surface of erosion at approximately 90 m above the Sikanni Formation (Schröder-Adams, unpublished data). This study gives the first account of the FSM interval in the Liard Basin area and places this interval clearly above the Sikanni Formation within the Sully shale.

Foraminiferal Zonation

The *Haplophragmium swareni* Subzone (Figure VI-3) of the *Miliammina manitobensis* Zone was described from the lower part of the Sully Formation below the FSM on the Sikanni Chief River (Stelck and Hedinger, 1983). The *H. swareni* Subzone has been recognized only in the Sikanni Chief River area of northeastern British Columbia and in the Nordegg area of the foothills of Alberta (Stelck and Hedinger 1983). Schröder-Adams and Pedersen (2003) reported that the first occurrence of *H. swareni* is within the Upper Buckinghorse Formation along the Sikanni Chief River.

The *Textularia alcesensis* Zone, which overlies the *M. manitobensis* Zone, is known from the Peace River area (Stelck et al., 1958; Caldwell et al., 1978) and adjacent parts of the plains of northwestern Alberta (Leckie et al., 2000). In the Peace River region, the *Textularia alcesensis* Zone (Stelck et al., 1958; Caldwell et al., 1978) was described from the Shaftesbury Formation as straddling the Albian-Cenomanian boundary and continuing to the uppermost Shaftesbury. The base of the *Textularia alcesensis* Zone coincides with the base of the Cenomanian stage, and it includes the *Neogastrolites maclearni*, *N. septimus*, *Irenicoceras bahani* and *Beatonoceras beattonense* zones (Caldwell et al., 1978). The base of the *Textularia alcesensis* Zone also approximately coincides with the FSM, but only where no paraconformity exists. The fauna represents the recovery fauna that appears above the generally barren beds of

the FSM interval (Caldwell et al., 1978). In the southern prairies a paraconformity exists, where the *T. alcesensis* Zone, *H. swareni*, and *Haplophragmoides postis goodrichi* subzones are missing and the *Verneuulinoides perplexus* Zone overlies the barren beds of the Fish Scales Formation, which in turn overlies strata with the *Verneuulina canadensis* Subzone fauna (Schröder-Adams et al., 1996).

Results

The Sully Formation in the cliffs opposite Scatter River along the Liard River (Figure VI-1) is 265 m thick (Figures VI-4, VI-6), is well exposed and directly overlies the Sikanni outcrop described in Section 6.3. Stott (1982) divided the Sully Formation into three zones: lower and upper concretionary members separated by a middle flaky shale member (see Section 2) without identifying the Fish Scales marker. In this study, Stott's (1982) original subdivision is supported and elaborated upon with foraminiferal, well log, and sedimentological evidence. In keeping with more recent nomenclature and regional correlation purposes, however, these are distinguished as the Lower Sully Formation, Fish Scales Marker interval (FSM), and Upper Sully Formation.

Lower Sully Formation

Stratigraphy and micropaleontology. Opposite Scatter River, the base of the Sully Formation is well exposed, unlike most other outcrops of the Sully in northeastern British Columbia, and is placed at a 20-cm-thick upper fine- to medium-grained sandstone bed containing chert and clay clast pebbles at its base (Figures VI-4, VI-5a). The base of the sandstone cuts erosively into the underlying siltstone and fine-grained sandstone beds. The lag is overlain by 15 cm of silty shale and siltstone up to 12 cm thick and is in turn overlain by the soft, black and concretionary mudstone that represents

the typical facies of the Sully Formation. At the base of the mudstone succession, however, well-rounded chert pebbles up to 8 cm in length (Figure VI-5b) occur within the mudstone. Approximately 60 m of soft, black, concretionary shale overlies this TSE and is here referred to as the Lower Sully Formation (Figure VI-6a). The top of the lower Sully is constrained by the base of the FSM interval, as established below.

The basal shales of the Sully Formation yielded a relatively diverse and abundant benthic foraminiferal fauna dominated by *Ammobaculites fragmentarius*, *Saccammina alexanderi*, and *Verneuilinoides borealis*, although all foraminifera are diminutive in size. This assemblage is present directly above the chert pebble horizon in the basal Sully mudstone. Some of the samples in the lowermost strata of the Sully did not yield a high abundance of foraminifera. The fauna displays some differences from the underlying Sikanni Formation in lacking *Miliammina manitobensis*, although other *Miliammina* species are present in very low abundances (Appendix I). The samples from the basal 25 m of the Sully Formation also contain abundant coalified woody organic material. Samples from the Lower Sully interval are characterized by Type III organic matter (Figure VI-7), which on the S_2 (mg hydrocarbon/g rock) vs. TOC (total organic carbon) graph, plot between the FSM and Upper Sully intervals. The TOC values range from approximately 1.0 to 1.4 wt. % (Figures VI-4, VI-7).

Interpretation. The uppermost Sikanni sandstone, where exposed, is typically characterized by fine- to medium-grained lithic sandstone and conglomerate interpreted as foreshore and alluvial deposits. These deposits represent maximum regression of the uppermost Sikanni sandstone (Chapter V) and overly a regional sequence boundary. The chert and clay clast horizon at the base of the medium-grained sandstone opposite Scatter

River is interpreted as a channel lag overlying a sequence boundary associated with base-level fall that characterized the top of the Sikanni Formation throughout northeastern British Columbia (Chapter V). Hence, at this locality the uppermost Sikanni Formation appears to have been erosively scoured by channeling related to the end Sikanni regression, and represents the more distal expression of the uppermost Sikanni regression. The prominent chert pebble concentration overlying this channeled unit within the basal Sully mudstone is interpreted to represent a transgressive lag deposit overlying a TSE. The benthic foraminiferal faunas apparently were re-established quickly although their diminutive size and lesser abundance compared to the underlying Sikanni Formation indicates that certain environmental stresses were present such as brackish water and/or high turbidity.

Fish Scales Marker Interval (FSM)

Stratigraphy and micropaleontology. An unconsolidated, light gray weathering, silty, 0.25-m-thick mudstone bed occurs 63 m above the base of the Sully Formation (Figures VI-4, VI-6a, b). Above this bed, 0.05-m-thick sideritized beds occur commonly over an interval of about 7 m and are followed by another 0.25-m-thick, gray-weathering, silty mudstone bed. Above the second silty bed the overlying strata consist of a 80-m-thick shale succession. The FSM interval comprises approximately 80 m of strata (Figure VI-4; see below). In outcrop, shales within the FSM interval are distinguished from the overlying and underlying members in that they weather slightly lighter in colour, are finer grained containing very few concretions, have numerous sulfur-rich bands and are generally coated in weathering sulfur.

A sample 1 m above the first silty mudstone bed yielded abundant sulfur and gypsum, some woody organic material, and a few foraminifera represented by *Ammobaculites fragmentarius*, *Verneuilina* sp., *Miliammina* sp. and *Uvigerinammina manitobensis*. Another sample, 3 m above the last, yielded a more diverse fauna than the preceding sample, with the addition of *Haplophragmium swareni*, *Trochammina umiatensis*, *Haplophragmoides* sp., *Ammobaculites obliquus*, and *Textularia riowensis*. This sample also contains abundant organic matter, common algal cysts, and abundant diatoms. A sample above the second grey silty mudstone, contains algal cysts and flaky organic matter along with gypsum, coalified organic material and abundant biotite, but is barren of foraminifera. All samples between 62 and approximately 134 m are barren or contain very few foraminifera assigned to *Saccammina*, *Uvigerinammina manitobensis* and *Verneuilina* sp. and commonly contain abundant algal cysts, gypsum, organic matter flakes and coalified organic matter. Above 134 m, the benthic fauna becomes progressively more abundant and diverse. Foraminifera in this interval include *Textularia alcesensis* Stelck and Wall and *Ammobaculites* sp. Stelck and Wall. A distinct increase in TOC values, from approximately 1.4 to 2.8 wt. % occurs in the first 20 m of the FSM interval followed by a consistent decrease throughout the remainder of the Sully Formation (Figures VI-4, 7).

Interpretation. Several lines of evidence suggest that the middle part of the Sully Formation, beginning 63 m above the top of the Sikanni Formation can be assigned to the FSM interval: the absence of benthic foraminifera at the base of the interval; abundant algal cysts, sulfur, gypsum and organic matter; increased TOC values relative to underlying strata; and the presence of a recovery fauna in the upper part of the FSM

interval, which is assigned to the *Textularia alcesensis* Zone due to the presence of the zonal species and others first described from this zone in the Peace River area (Stelck et al., 1958).

The FSM, described in an interdisciplinary study from the Shaftesbury Formation outcropping on the Smoky River south of the town of Peace River in Alberta, consists of only 1.5 m of strata and is divided into three units with high TOC values: a lower, rippled sandstone, a middle fish hash conglomerate, and an upper anoxic, black, platy shale with abundant fish debris (Leckie et al. 1992). The abundant gypsum observed along various horizons in this portion of the Sully Formation is likely from the weathering of pyrite. This, along with the increased TOC values, corroborates with the evidence presented in Leckie et al. (1992), and suggests that anoxic conditions resulting in the production of pyrite by sulphate-reducing bacteria were present in this much more northern portion of the WCSB. In the Cold Lake Region, the overlying Belle Fourche Formation above the Fish Scales Formation is also barren of foraminifera, suggesting that at least in northeastern Alberta anoxia continued for some time.

Opposite Scatter River, the strata containing abundant flaky organic matter, gypsum, sulfur, algal cysts and a stressed or barren foraminiferal fauna encompass approximately 80 m (Figure VI-4). Although this is seemingly an extreme difference in thickness between the Peace River and Liard Basin localities, it is not inconceivable given the cross section of Bhattacharya and Walker (1992), which shows that the FSM interval becomes extremely condensed southwards (see discussion section). The FSM interval is also distinctive from the underlying and overlying units based on Rock-Eval

data. This is shown on the S_2 vs. TOC graph (Figure VI-7a) where the elevated S_2 and TOC values plot away from the other samples.

Upper Sully Formation

Stratigraphy and micropaleontology. The base of the Upper Sully is difficult to place because of its transitional nature from the underlying FSM interval. If placed above the FSU bentonite marker (see below), the thickness of the Upper Sully is approximately 75 m; however, it is probably better placed at 134 m above the base of the Sully Formation where more abundant foraminifera assigned to the *Textularia alcesensis* Zone occur and there is an increase in silt content. At 130 m above the base of the Sully, the shale becomes slightly silty and the proportion of silt generally increases upwards while the amount of gypsum, sulfur and flaky organic matter decreases (Figure VI-4). A few sideritized and silty beds form prominent ledges that form an impermeable barrier to groundwater seepage. The first of these occurs 153 m above the base of the Sully and consists of silty shale and argillaceous siltstone containing *Planolites* traces. At 180 m, another impermeable silty, and sideritized bed, with abundant gypsum crystals occurs and is overlain by shale that becomes increasingly interbedded with thin siltstone and very fine sandstone beds. Two thin bentonite beds, 10 cm and 5 cm in thickness, occur 186 and 192 m above the base of the Sully Formation. In this silty interval, at 245 m above the base of the Sully Formation, thin to thick, planar to low angle cross-laminated fine sandstone beds become common and grade upwards into medium to thick bedded fine- to medium-grained lithic sandstones of the Dunvegan Formation. The base of the Dunvegan Formation is placed at the first medium-bedded lithic sandstone overlying the Sully Formation opposite Scatter River.

A sample below the silty bed at 153 m yielded a foraminiferal fauna of low diversity and abundance. A sample immediately overlying the bed was barren of foraminifera, however one approximately 10 m above this yielded a more diverse and abundant foraminiferal fauna, including *Textularia alcesensis*, and *Ammobaculites* sp. of Stelck et al., (1958). The aforementioned species, along with *Tritaxia* sp., *Gaudryina* sp., and very small specimens of the genus *Trochammina* are present sporadically throughout the upper Sully Formation. Foraminiferal yields in this interval vary considerably, with some samples being barren and others yielding low to high abundance faunas of medium diversity. A sample overlying the bentonite beds contains only single specimens of very small *Haplophramoides* and *Trochammina* but contained abundant phosphatic debris. Foraminifera were recovered below the first medium-grained lithic sandstones of the Dunvegan Formation. In this upper coarsening upward interval, the samples become increasingly mica and silt rich, as well as with coalified organic matter and phosphatic material. Samples from the Upper Sully interval are geochemically distinctive as they have very low HI/OI ratios and low S₂ and TOC values (Figure VI-7).

Interpretation. The increasing silt content, fluctuating abundance and diversity of foraminifera, increasing number of silt and fine sandstone beds, and increasing amount of detrital mica and coalified organic material are interpreted to indicate the advancing influence of the initial downlapping clinoforms of the middle Cenomanian Dunvegan Formation as shown by Bhattacharya and Walker (1991a). Foraminiferal data indicate that the strata below the Dunvegan Formation and above the base of the FSM at this locality can be assigned to the *Textularia alcesensis* Zone of early Cenomanian age. No evidence was found that would indicate the presence of the late Cenomanian

Verneuilioides perplexus Zone, suggesting that the base of the Dunvegan Formation at this locality is older than towards the southeast, as is suggested by well log cross-sections. The Upper Sully represents the distal progradational deposits of the Dunvegan delta (see discussion).

Discussion

Foraminiferal Faunas and Zones

The lower part of the Sully Formation in the Sikanni Chief River, below the base of the FSM, was assigned to the *Haplophragmium swareni* Subzone of the *Miliammina manitobensis* Zone by Stelck and Hedinger (1983). In the lower Sully opposite Scatter River, *Ammobaculites fragmentarius*, a long-ranging form, occurs in greater abundance, except in the uppermost part of the lower Sully. Both Sully sections are characterized by an entirely agglutinated assemblage with common occurrences of *Saccamina*, *Reophax* and *Trochammina* towards the top of the lower Sully. *Haplophragmoides* is rare in both regions (Stelck and Hedinger, 1983; this study). Overall, the assemblage is moderately diverse, with low to common abundances and small tests indicating environmental stress. Generally, species occurring in the mudstone dominated facies of the Sikanni Formation range into the lower Sully Formation, however, with lower numbers and smaller tests.

In well log cross-sections, clinoforms of the basal Dunvegan Formation downlap onto the FSU (Fish Scales Upper) marker (above the FSM) ("FSU" in Bhattacharya and Walker, 1991a). Bhattacharya and Walker (1991a) showed that the shales of the upper Shaftesbury Formation (equivalent to the upper Sully Formation) above the FSU in the Fort. St. John area of northeastern British Columbia can be seen in cross section to downlap and pinch out to the southeast. Similarly, the FSU and BFS become

indistinguishable towards the southeast. They thus were able to explain the loss of the *T. alcesensis* Zone in the Plains and Foothills outside of northeastern British Columbia. The *T. alcesensis* zone disappears because the FSU and BFS become indistinguishable and Dunvegan becomes younger as it downlaps towards the southeast. The data presented here support this conclusion. The *Textularia alcesensis* Zone is present in the Liard Basin strata within the FSM interval and persists as far up-section as directly below the base of the Dunvegan Formation opposite Scatter River. The presence of the *T. alcesensis* Zone in the Liard Basin demonstrates that lowermost Cenomanian strata are preserved in this area and that the base of the Dunvegan Formation is older in the Liard Basin than it is towards the southeast.

Regional Stratigraphic Correlations

As discussed in Chapter V, Stott (1982) considered that the uppermost Sikanni strata are approximately at the same stratigraphic horizon in the Muskwa-Tetsa region, but eastwards the Sikanni-Sully contact is placed at the top of successively older sandstones. The sequence stratigraphic approach of this paper stresses that four sequences can be recognized in most outcrops of the Sikanni Formation and hence the basal Sully Formation, although time-transgressive, is approximately equivalent and records a flooding event across the Liard Basin and southwards in the Sikanni Chief River. It is possible, however, that a significant thickness of strata was removed during formation of the basal Sully unconformity (SB) and subsequent transgressive ravinement. Dixon (1999) thought that his “pre-Sully” unconformity represented erosion in the Great Slave Plain associated with the formation of this sequence boundary, but this is disputed in this study (see Chapter VII). In all outcrops studied of the Sully here, the uppermost Sikanni-

Sully transition is characterized by significant conglomeratic facies indicating a profound relative sea level fall followed by extensive flooding in the Lower Sully interval.

Detailed study of the FSM interval and its equivalents in the southern Rocky Mountain Foothills (Barons sandstone) indicates that the basal sandstone and overlying bioclastic conglomerate that generally mark the base of the FSM interval were formed through regression and subsequent transgressive ravinement (Leckie et al., 2000). South of the Peace River Arch, where the shelf-equivalent Barons sandstone was deposited, the sedimentological evidence suggests that multiple high-frequency sea level falls punctuated this interval (Leckie et al., 2000). In the WCSB, the FSM has been identified at least as far north the Peace River Plains, where it lies within the Shaftesbury Formation (Warren and Stelck 1969; see Leckie et al., 1992), in the Sikanni Chief River area (Stott, 1982), and in northeastern Alberta associated with the Fish Scales Formation within the Colorado Group (Leckie et al., 2000).

An argillaceous siltstone with concretionary sandy and bentonitic horizons and some fish fragments was identified approximately 62 m above the base of the Sully Formation along the Sikanni Chief River (Stott 1982, Section 62-21). In the Shaftesbury Formation on Peace River, the lowermost unit (rippled sandstone-Unit 2A) overlain by a fish-scale conglomerate (Unit 2B) marking the base of the FSM interval has been interpreted to have resulted from upwards shallowing and the development of a marine disconformity (Leckie et al., 1992; Leckie et al., 2000). The structureless, somewhat unconsolidated silty mudstone marking the base of the FSM interval in the Sully Formation opposite Scatter River and the absence of a recognizable bioclastic layer is not typical of the FSM; however its presence is identified by the occurrence of a coarser

interval within a thick interval of mudstone/claystone, an increase in TOC, a lack of benthic foraminifera, and the presence of abundant organic matter, algal cysts and gypsum. Unit 2C of Leckie et al. (1992) was interpreted to represent a condensed interval and anoxic phase, and, like in the FSM interval reported here, contains abundant amorphous organic matter, an absence of benthic foraminifera, and a large number of pelagic marine algal cysts indicative of reduced surface salinity. Although few fish scales were recovered from this interval, it is clear that the FSM interval in the Sully Formation opposite Scatter River represents a much thicker and probably more continuous record of sedimentation, similar to that observed by Bhattacharya and Walker (1991a-b) in the Shaftesbury Formation of northwestern Alberta. The thick zone of sediments dominated by amorphous organic matter and algal cysts indicates that this anoxic unit is much more expanded in the Liard Basin than in the Shaftesbury Formation. Unlike in the Shaftesbury Formation, however, there is no indication of a concentration of marine (Type II) organic matter within the FSM interval. The absence of a bioclastic conglomerate layer at this locality and the presence of the *Textularia alcesensis* Zone may indicate that the sequence boundary associated with the base of the FSM interval is present in this portion of the Liard Basin as a correlative conformity. The most comparable expression of the Barons Sandstone in the southern region might be the outcrop at Cadomin, where the *Textularia alcesensis* Zone is also preserved in a series of four coarsening-upward cycles from mudstone to sandstone (Leckie et al., 2000).

The Upper Sully Formation in the Liard Basin records the progressive influx of coarser siliciclastics from the southwards progradation of the Dunvegan Formation over the area. A shallowing-upwards cycle is present beginning in the Upper Sully and the

succession appears to be continuous into the lower Dunvegan Formation. The Upper Sully shows a progressive decrease in TOC and HI values upwards from the FSM interval (Figures VI-4, 7). The low HI/OI ratio is similar to that recorded in the Belle Fourche Formation, and is typical of proximal prodeltaic depositional environments (de Caritat et al., 1994, and refs. therein; Bloch et al., 1999).

The presence of bentonites in the Sully Formation is interesting considering that bentonites are also present in the Sully Formation near Fort St. John (Warren and Stelck, 1969) and in unit 2C of the FSM in the Shaftesbury Formation (Leckie et al. 1992). In their study of *Neogastrolites*-bearing strata in the Fort St. John area of northeastern British Columbia, Warren and Stelck (1969) identified “First” and “Second” volcanic tuff marker beds at 91 m and 116 m, respectively, below the base of the Dunvegan Formation, and the base of the Fish Scale marker bed 207 m below the base of the Dunvegan Formation. They also placed the top of the fourth Sikanni sand 244 m below the base of the Dunvegan Formation. Warren and Stelck (1969) recorded the presence of *Neogastrolites septimus* Warren and Stelck (refer to Figure VI-3 for regional ammonite zonation) “well above” the Fish Scales marker bed and below the Second Tuff marker bed and *Beatonoceras beatonense* Warren and Stelck 30 ft below the First Tuff marker bed.

In the Shaftesbury Formation near the Peace River, Unit 2C consists of 1.17 m of black platy shale with abundant fish debris and a prominent 0.20 m thick bentonite bed 0.76 m above its base (Leckie et al. 1992). Bhattacharya and Walker (1991a), however, showed that the FSM interval in the Shaftesbury Formation is extremely condensed, and that a gamma-ray marker 50 m below of the base of the Dunvegan Formation in the

northwestern-most portion of their study area, which they termed the Fish Scales Upper Marker (FSU), becomes coincident with the FSM of Leckie et al. (1992) towards the southeast. Hence, the thickness of strata between the Base of Fish Scales (BSF) and FSU increases northwestwards. Their cross-section shows that the FSU is a regional downlap surface onto which the distal toes of the Dunvegan clinoforms prograded.

The only bentonites identified in the Sully Formation opposite Scatter River occur 186 and 192 m above the base of the Sully Formation in an interval of thin-bedded silt and fine sandstones interbedded with shale. High-resolution biostratigraphic correlations are not possible for the upper Sully Formation as no macrofossils have been found in this interval opposite Scatter River. It is suggested here that the interval of bentonites between 186 and 192 m above the base of the Sully Formation and approximately 120 m above the base of the FSM in the cliffs opposite Scatter River may correspond to the FSU of Bhattacharya and Walker (1991a). In wells logs in the Liard region this horizon forms a distinct marker ("Upper Sully Marker", Chapter VII).

Figure VI-1. Location map of main portion of study area indicating outcrop localities at Steamboat Mountain, NE Lepine Creek and Scatter River. Shaded area represents limits of Upper Cretaceous Dunvegan Formation (after Leckie et al. 1991) and approximate limits of the Liard Basin. UTM coordinates (NAD27) are: Scatter-0406043E, 6607550; NE Lepine Creek-0399985E, 6595450N; Steamboat Mountain-0459717E, 6504660N.

Stage	Substage	Selected Macrofossil Zones (Warren & Steick 1969; Caldwell et al. 1978; Jelezky 1980)	Peace River, British Columbia (Steick et al. 1958; Sutherland & Steick 1972; Steick & Koke 1987; Steick & Hedinger 1976)	Sikanni Chief River, British Columbia (Schröder-Adams & Pederson in, 2003)	Liard Basin	Liard Basin Stratigraphy
Cenomanian	Middle	<i>Acanthoceras athabascense</i>	<i>Verneullinoides perplexus</i>	Unzoned	Unzoned	Dunvegan Formation
	Early	<i>Beatonoceras beatonense</i> <i>Irenoceras bahani</i> <i>Neogastrolites septimus</i> <i>Neogastrolites maclearni</i>	<i>Textularia alcesensis</i>		<i>Textularia alcesensis</i>	FSU Sully Formation
Albian	Late	<i>Neogastrolites americanus</i> <i>Neogastrolites muelleri</i> <i>Neogastrolites cornutus</i>	<i>Haplophragmium swarēni</i>	<i>Haplophragmium swarēni</i> <i>Ammobaculites fragmentarius</i>	<i>Haplophragmium swarēni</i>	BFS Lower Sully Formation
			<i>Haplophragmoides postis goodrichi</i>		subzone B	Sikanni Formation
		<i>Neogastrolites haasi</i>	<i>Verneullina canadensis</i>		subzone A	
		poorly fossiliferous interval	<i>Reophax troyeri</i> <i>Trochammina umiatensis</i> <i>Trochammina depressa</i> <i>Reophax tundraensis</i> <i>Haplophragmoides gigas phaseolus</i> <i>Haplophragmoides gigas gigas</i> <i>Haplophragmoides uniorbis</i>	<i>Trochammina alcesensis</i>	<i>Bathysiphon-A. fragmentarius</i> assemblage <i>Ammomarginulina</i> assemblage	Bougie Equivalent Buckinghorse/ Lepine Formation
	Middle	<i>Inoceramus commancheanus</i>				
		<i>Stelckiceras liardensis</i>	<i>Ammobaculites wenonahae</i>	<i>Ammobaculites wenonahae</i>	<i>Ammobaculites wenonahae</i>	

Figure VI-3. Upper Albian-Cenomanian foraminiferal zonation and subzonation of northeastern British Columbia. Foraminiferal zones are bolded.

Figure VI-4. TOC data, foraminiferal biostratigraphy and stratigraphy of the Sully Formation opposite Scatter River. TOC data points also correspond to frequency of micropaleontological samples. Widths of shaded bars represent relative abundances of algal cysts and benthic foraminifera. BSF—Base of Fish Scales; FSU—Fish Scales Marker Bed; FSM—Fish Scales Marker interval

Figure VI-5. Outcrop photographs of the Sully Formation opposite Scatter River. a) Chert pebble conglomeratic channel fill at the base of a fine sandstone bed underlying mudstone of the Sully Formation, interpreted as the base of the Sully Formation. b) Structureless fine sandstone bed (25 cm above conglomeratic sandstone in Figure 5a) is overlain by siltstone and then mudstone with 0.1 m of clast-supported chert pebble conglomerate with rounded pebbles up to 8 cm in length. This surface is interpreted to represent the TSE associated with the relative sea level rise that resulted in deposition of the Sully Formation in the Liard Basin.

Figure VI-6. Outcrop photographs of the Sikanni and Sully formations opposite Scatter River. a) Outcrop view of uppermost Sikanni, Sully and Dunvegan formations preserved in the cliffs opposite Scatter River. View is eastwards from mouth of Scatter River. BSF-Base of Fish Scales; FSU-Fish Scales Upper marker. Photograph courtesy Per Kent Pedersen. **b)** A light-grey weathering, structureless and poorly lithified silty mudstone 62 m above the base of the Sully Formation (base marked by white line in foreground and background) opposite Scatter River marks the base of the FSMB. The FSMB is overlain by 3 m of mudstone and numerous sideritized siltstone beds. Distinct sulfur-rich shale occurs above this bed and a number of horizons at which large gypsum crystals have precipitated form an impervious barrier to groundwater.

a.

b.

Figure VI-7. Rock Eval geochemistry plots for samples from the Lower, FSM and Upper units of the Sully Formation. a) HI vs. OI. b) S₂ vs. TOC.

Chapter VII. REGIONAL WELL LOG CORRELATIONS

Introduction and Previous Work

Although the density of wells is low and the preservation of Albian strata is rare, a number of important markers have been recognized in the Cretaceous succession of the Liard Basin and some correlations have been previously attempted (Thompson, 1977; Williams, 1978; Stott, 1982; Dixon, 1997, 1999; Leckie et al., 1991; Leckie and Potocki, 1998; Frank, 2002). In well logs, the Fort St. John Group in the subsurface of northeastern British Columbia can usually be subdivided into its component formations, and a few markers have been recognized. These include markers within the basal Garbutt (Marker 1, basal Cretaceous—here referred to as the basal Garbutt radioactive marker, and “Hot Rad” in the cross sections), basal Lepine/Buckinghorse (Scatter Marker or Marker 3), basal Sully (Sikanni Marker), FSMB or BFSC (Fish-Scale Marker=Base of Fish Scales, Marker 4) and, rarely, an upper Sully marker. Williams (1978) thought Marker 4 marked the top of the Sikanni Formation and hence the base of the Sully, whereas Dixon (1999) proposed that this marker is correlative to the top of a coarsening-upwards unit in the lower part of the Lepine Formation. The markers that are used here are outlined below (in Results).

In the Cameron Hills area (west of approximately 119°W) and westwards to the front ranges in Northwest Territories and adjacent areas of southeastern Yukon, the Fort St. John Group nomenclature and correlations continue from the Liard basin proper. Correlations in the plains of the Northwest Territories become increasingly difficult due to the thinning, lateral facies change to shale, the possible presence of a number of

unconformities in the succession (Dixon 1997, 1999), and the sparse distribution of wells with logs of the Lower Cretaceous succession.

Methods

Well log correlations were performed using two separate software packages—iDC Geosection software and IHS AxxuX. Geosection was used for most subsurface correlations in northeastern British Columbia. AxxuX was acquired part way through this research by donation from IHS for this thesis (with a thesis-specific project map). It was needed to correlate wells in the Northwest Territories and from northeastern British Columbia into the Northwest Territories, because of the lack iDC well data north of 60° latitude. In northeastern British Columbia, additional digital well logs became available (.las files) during the project for importation into AxxuX, particularly some in the Maxhamish Lake area and enabled densely spaced correlations of the Chinkeh Formation and overlying strata. In both Geosection and AccuX, all available wells were utilized to construct a database of formation tops and other markers and this was cross-referenced by multiple cross-section lines through the Liard Basin in order to maintain the highest accuracy of the marker picks. The cross-sections presented here are only a subset of the total number constructed as part of this project. For identification of log curves see caption of Figure VII-2.

The datums that are used in the cross-sections are the Hot Rad marker, Scatter top, Lepine top or Sikanni sandstone 2 marker. The choice of datum for each cross-section is given in the relevant figure caption. In the Chinkeh correlations, it was found that the choice of the Hot Rad marker or Scatter top produced significantly different paleogeographic interpretations (see below). In most large-scale correlations of the

Lower and lowermost Upper Cretaceous succession, it was found that the use of the Scatter top as a datum produced the best fit of eastwards prograding clinoforms, in addition to being the easiest surface to pick in the basin. Since the succession thins normally eastwards away from the foredeep without any major erosive unconformities or syn-sedimentary faulting, the choice of datums (excluding the Chinkeh Formation) has little effect on the resulting interpretation. In general, using a datum surface that was stratigraphically closer (i.e. Lepine or Sikanni 2 top for the Sikanni correlations) to the interval being presented produced a more comprehensible cross-section because of differential subsidence rates through time and space.

Results

Subsurface correlations are presented in Figures VII-1 to VII-14. The use of two software packages, and the aerial scale of correlations necessitated the use of two location maps (Figures VII-1, VII-10). Some cross-section lines are reproduced twice, with one showing a comprehensive correlation of all the formations, and the other with a detailed view of a smaller stratigraphic interval. The first set of cross-sections focuses on the Chinkeh and Garbutt interval (Figures VII-2 to VII-6). Large-scale correlations of the entire studied interval are presented in Figures VII-7 to VII-9. Finally, cross-sections detailing the upper Lepine, Sikanni and Sully succession are detailed in Figures VII-11 to VII-14

There are a number of important markers that were used in the subsurface correlations. From oldest to youngest, these are the Unit A-E markers (Chinkeh Formation), Hot Rad (basal Garbutt), Garbutt Marker (Garbutt top), Scatter (Scatter top), Scatter Marker (basal Lepine radioactive marker, combined with the Scatter marker in the

east and north), Bougie (Bougie top), Lepine (Lepine top), Sikanni (Sikanni top), BFSC (Base of Fish-Scales), and the Upper Sully Marker. In the Sikanni Formation, five coarsening-upwards cycles are interpreted to represent the five Sikanni sandstones identified in outcrop (Chapter V) and represent good markers in the western part of the Liard Basin in northeastern British Columbia. Additionally, several more minor unnamed markers were correlated within Garbutt, Scatter, Lepine and Sully formations (see Figure VII-7 for most of these markers), and were used in the database for high-resolution correlations.

Chinkeh and Garbutt formations

The base and top of the Chinkeh Formation are defined by the sub-Cretaceous top (Paleozoic or Triassic) and the Unit E top, respectively. The majority of the wells with well logs that penetrate the Chinkeh Formation are in the Maxhamish area of northeastern British Columbia where gas is currently being produced from the Chinkeh. At this locality, a densely spaced drilling grid enables a high-resolution view of the Chinkeh, although over a limited lateral extent. In the plains of the Northwest Territories, numerous wells penetrate the basal Cretaceous interval, but few have more than a thin silty basal Cretaceous interval overlain by Garbutt shale (Dixon, 1997). Several strike and parallel-oriented sections (presuming the Chinkeh shoreline was oriented approximately north-south on the eastern margin of the basin) of the Chinkeh and overlying Cretaceous beds were constructed using IHS AccuX software (Figures VII-2 to VII-6) and the locations of the sections are shown in Figure VII-1.

Dip-oriented cross sections A-A' and B-B' (Figures VII-2, VII-3) show the Chinkeh and overlying Garbutt formations. The strata are divided into five units,

designated A-E, based on integrated well log correlations, biostratigraphy and sedimentology of core (see Chapter II). In well logs, most of the units are clearly expressed as coarsening-upwards cycles. The subdivision into units and the interpretation of several relative sea level changes based on outcrop and core is clearly reflected in the subsurface. Major flooding surfaces, reflected by sharp deflections in the gamma-ray and resistivity logs, are especially apparent at the bases of units C and E and the base of the overlying Garbutt Formation. A south-north section of the basal Cretaceous interval from south of Maxhamish into the Northwest Territories Plains (Figure VII-4) shows the along-strike distribution of the Chinkeh in the Maxhamish area and its infrequent occurrence in the Northwest Territories. Little, if any, south to north variation in the distribution of the various units (A-E) is visible in these cross-sections in the Maxhamish area, although there is some indication that the sharp surface overlying Unit E disappears northwards (Figure VII-4). When flattened on the basal Garbutt radioactive marker, the Chinkeh Formation appears to only occur in topographic lows below the marker (e.g. in the B41 and M056020212245 wells). This assumes that the radioactive marker represents a topographic surface of equal elevation at the time of the deposition of the Chinkeh and lowermost Garbutt formations. The abrupt northwards thinning of the Cretaceous succession is also evident.

In the plains of the Northwest Territories the Chinkeh Formation is dominated by fluvial and central basin facies (Chapter II). Williams (1978) first mapped the distribution of basal Cretaceous sandstones and showed that they occurred on the eroded surface of the Mississippian Flett Formation. The distribution of Chinkeh deposits in this area, combined with their facies interpretation and subsurface correlation indicates the

probable presence of an easterly-narrowing valley cut into Paleozoic strata (Figure VII-5), beginning in the area of the H13 well and continuing southeastwards for some distance (C60 well?). This valley is especially evident in a south-north cross-section over the region of interest (Figure VII-6). When hung on the basal Garbutt radioactive marker, the Chinkeh occupies “low positions” below the marker, and elsewhere is not present.

All or most of the units of the Chinkeh Formation appear to terminate abruptly eastwards at the Bovie Structure, although it is possible that Unit E persists on the western fringe of the structure. The choice of datums (Radioactive marker, Figure VII-1; Scatter Top, Figure VII-2) shows two extremes of the possible paleotopography at the time of deposition of the Chinkeh Formation. Leckie et al. (1991) showed the significant structural relief that is currently present over the Bovie Structure, as the Cretaceous strata on the western side are downthrown by greater than 800 m. The abrupt disappearance of the Chinkeh eastwards appears to indicate that the earliest Albian shoreline abutted coastal cliffs of the Bovie Structure at this locality, but this does not account for the apparent eastern continuation of the basal Garbutt radioactive marker over the structure. The Hot Rad marker and its distinctive positive kick in the gamma-ray log is interpreted to be due to abundance of volcanic ashes in this interval, with some thick (>20 cm) bentonites at this depth in the well logs. Hence this marker represents a time-synchronous surface for correlation, but may represent a surface of widely varying paleotopography.

In the basal Garbutt, at least one slight coarsening-upwards interval underlies the basin-wide basal Garbutt radioactive marker (Figures VII-2, VII-3). Westwards from the

Maxhamish field, the Garbutt Formation thickens dramatically (F-F', Figure VII-7). The basal Garbutt marker can be traced westwards into most wells, but it is not possible to trace the units of the Chinkeh Formation from the Maxhamish field. The Chinkeh Formation appears to thicken and undergo a facies change to mudstone westwards from Maxhamish towards the Liard River. Thick Chinkeh shoreface sandstones can be found on the northwestern margin of the basin—hence the depositional model of Chapter II which proposes a narrow basin with the Chinkeh on the eastern and western margins. In outcrop and subsurface along the western margin of the basin, the Chinkeh Formation appears to be limited to the north, although it does occur in outcrop as far south as the Mount Martin locality (see Chapter II) in the southern Yukon Territory. A possible Chinkeh or Chinkeh-equivalent sandstone was examined in outcrop at Historic Mile 375 on the Alaska Highway (also in Stott, 1982), and this could be one of the most southerly outcrops of the formation. It is thus possible that undiscovered Chinkeh occurs in the subsurface along the western and southwestern margins of the basin.

Scatter Formation

The base and top of the Scatter Formation is defined in the subsurface correlations by the Garbutt and Scatter markers, respectively. In northeastern British Columbia, the thick Scatter Formation can be traced eastwards where it thins steadily up to and over the Bovie Structure into the 94P map sheet area. Several coarsening upwards cycles can be traced with some difficulty over the entire basin (F-F', Figure VII-7). Scatter correlations in the Maxhamish field are visible in section A-A', B-B', C-C' (Figures VII-2, 3, 4, 8, 9). The top of the Garbutt Formation is chosen at the top of the first coarsening-upwards cycle. The top of the Scatter Formation is taken at the Scatter Top marker below the

radioactive Scatter Marker (Thompson, 1977; Williams, 1978), which Dixon (1997) interpreted as a maximum flooding surface. In Chapter IV it is suggested that this level may represent the top of the *Ammobaculites wenonahae* Subzone. In the subsurface, the Scatter Formation is not easily divisible into its three members, and therefore is not attempted here.

A regional southeast-northwest correlation of the top of the Scatter Formation from the Sikanni Chief River area to the Liard Basin is figured in cross-section A-A' in Chapter IV, Figure VII-8b. The correlations here indicate that the Scatter Formation thins normally eastwards (offshore) and northeastwards (Figure VII-4) over a broad shallow marine shelf which subsided rapidly syn-depositionally along the western foredeep, although correlations into the Northwest Territories are difficult because of the sparse well coverage and relatively thin Albian succession. These two interpretations differ substantially from an exploration perspective as Dixon's model suggests the possible presence of significant shoreface sandstones at the hingeline of his hypothesized broad uplifted area, whereas the model presented here suggests that Scatter Formation becomes more distal eastwards.

Lepine Formation

Subsurface correlations of the Lepine Formation are discussed and figured in Chapter IV. The Scatter and Lepine tops define the base and top of the Lepine Formation, respectively. Discussion here is limited to a few extra points concerning the cross sections figured in this chapter. Like the Scatter Formation, the Lepine Formation thins steadily eastwards and northeastwards from the western margin of the foredeep of the Liard Basin (Figure IV-8c and cross-sections F-F', Figure VII-7 and A-A', Figure

VII-8) where it is 1000 m in thickness to the Maxhamish area where it is 380 m thick (see also). The Lepine Formation can be traced further eastwards into the 94P map sheet area where it is only 200 m thick. Although few digital curves are available from strata above the Scatter Formation, the Bougie Member can be traced with some difficulty eastwards into the 94P area (cross section B-B', Figure IV-8c). In the few wells that have digital data for the upper part of the Albian succession in the Northwest Territories, the Bougie Member is present as a prominent coarsening-upwards interval (cross-section D-D', Figure VII-5).

Sikanni Formation

The Lepine and Sikanni tops define the base and top of the Sikanni Formation, respectively. Some discussion of regional correlations of the Sikanni Formation was presented in Chapter V, which is expanded upon here. The five Sikanni sandstones studied in outcrop in the Steamboat Mountain area (Chapter V) are recognized in the cross-sections here (i.e. Figure VII-12). Outcrop and cross-section correlations indicate that the four sequences that are present in the Sikanni Formation in the Liard Basin area can be correlated to the Sikanni Chief River area. The four sequences comprising the Sikanni Formation can be traced in cross-section northwards from the Sikanni Chief River to southwest of Fort Nelson (H-H', Figure VII-11). The flooding surface on top of the second Sikanni sandstone forms the datum in cross-section H-H' (Figure VII-11). The sandstone below this is much more subtle in well logs and is difficult to correlate southwards to the Sikanni Chief River area because west and northwest of Fort Nelson few well logs contain data from the upper part of the Buckinghorse/Lepine, Sikanni and Sully formations.

East-west sections (F-F', Figure VII-12 and I-I', Figure VII-13) indicate that the Sikanni Formation undergoes a rapid facies change from sandstone to mudstone eastwards towards the Bovie Structure. The lowermost sandstone is difficult to pick, and several subtle deflections in the resistivity log occur in the succession below the second sandstone. It is not clear how far eastwards the pebble conglomerates that are associated with sandstones 1, 2 and 5 (Chapter V) occur in the Liard Basin. Sharp deflections in the resistivity and gamma-ray logs are indicative of coarser intervals. These indicate that the relative sea level lows that are expressed in the Sikanni sandstones in outcrop on the western margin of the basin did have effects in the subsurface to the east (Figures VII-12, VII-13).

Few wells preserve the upper part of the Albian succession in the Northwest Territories. Several, wells, however, show a strong expression of the Sikanni Formation (J-J', Figure VII-14; also see D-D', Figure VII-5). In the L49 and F73 wells (Figure VII-14), three distinct coarsening-upwards cycles are visible in the Sikanni Formation above the Bougie marker and below the FSMB.

Sully Formation

The lowermost Sully Formation is generally easy to identify as it lies above the last Sikanni sandstone cycle throughout the basin and is placed above the Sikanni top. The top of the Sully Formation is more difficult to pick, and is not labeled on the cross-sections, although a good marker may be a prominent gamma-ray excursion above the Upper Sully Marker (i.e. visible in the b-037 well in Figure VII-12). In most wells, at least one small coarsening-upwards cycle can be correlated below the FSMB. Subsurface correlations of the Sully Formation are visible in A-A' (Figure VII-8), C-C' (Figure VII-

9), H-H' (Figure VII-11), F-F' (Figure VII-12), and I-I' (Figure VII-13). The base of the FSMB is placed at the base of the second of two distinctive closely spaced coarsening-upwards cycles overlain by a distinct flooding surface (high gamma kick). Two coarsening-upwards cycles from shale to siltstone were also found associated with the FSMB in outcrop opposite Scatter River (see Chapter VI). In the easternmost wells in the Northwest Territories and easternmost northeastern British Columbia, the FSMB is more subtle but usually can be identified by a gamma-ray kick (e.g., D-D', Figure VII-5).

A slight coarsening-upwards interval overlain by a distinct flooding surface, which is sometimes associated with high gamma-ray levels, is present above the FSMB and below the Dunvegan Formation in all wells that preserve this lowermost Cenomanian interval. This is correlated as the Upper Sully Marker in the cross sections (e.g., F-F', I-I'). In outcrop opposite Scatter River, this interval is associated with a number of thin bentonite beds (Chapter VI). This surface is interpreted as the regional downlap surface of the Cenomanian Dunvegan Formation (Chapter VI).

Discussion

The Liard Basin is characterized by a very thick Albian-Cenomanian succession to the west of the Bovie Structure in northeastern British Columbia and its northern extension into the southern plains of the Northwest Territories. The thick package of sediments in the west is due to high subsidence rates along the foredeep of the Liard Basin that characterized all of Albian time.

Dixon's (1997, 1999) northward correlation of the uppermost Spirit River Formation (Notikwein Member) and Cadotte-Paddy unconformities northwards, so that a significant thickness of strata in northeastern British Columbia and the Northwest

Territories plains are truncated by these unconformities is not supported here. Dixon proposed the presence of three “major unconformities”. The first two are within the Scatter Formation—possibly within the upper Bulwell Member (Notikewin equivalent), and a second within the Tussock Member (Paddy/Cadotte equivalent). The third was interpreted to be present near the base of the FSMB (“pre-Fish Scales”). Dixon considered that the pre-Fish Scales unconformity truncates increasingly older strata eastwards, such that the Sikanni Formation is not preserved in the Great Slave Plain area.

Eastwards across the Bovie Fault and into the Plains, Dixon (1999) thought that the erosional events represented by the unconformities removed a significant thickness of strata, such that Pre-Fish Scales erosion removed the entire Sikanni and upper Lepine formations. Dixon’s (1997, 1999) methodology involved hypothesizing the presence of unconformities where major thickness variations are present. These unconformities were correlated to the major known erosional events that are well-documented at the top of the Notikewin Member and Cadotte Formation. He invoked the presence of a broad uplifted area in the Albian in the Great Slave Plains and northeasternmost British Columbia (to the east of the Bovie Structure). Invoking unconformities to explain significant thickness variations is not necessary because of the widely varying subsidence and sediment supply rates that affected the western versus the eastern margins of the basin. In addition, no sequence boundary was found at the top of the Bulwell Member or anywhere else within the Scatter Formation. Furthermore, biostratigraphy combined with subsurface correlations and outcrop sedimentology indicates that the Viking Marker equivalent (i.e. the Cadotte-Paddy unconformity) occurs in the middle part of the Buckinghorse and Lepine formations (not at the top of or within the Tussock Member of the Scatter

Formation) as a correlative conformity and thus did not remove any strata (Chapter IV; Schröder-Adams and Pedersen, 2003). The correlations presented here also indicate that the Sikanni Formation is present in the Northwest Territories plains and eastwards across the Bovie Structure. This contradicts the assertion of Dixon (1997, 1999) that a pre-Fish Scales unconformity truncates strata eastwards in the Great Slave Plain and easternmost northeastern British Columbia areas (94P). The cross-sections indicate that the Sikanni thins and fines eastwards. It is likely that some strata were removed at intra-Sikanni unconformities, but the paucity of available well logs does not allow high-resolution correlation to the easternmost wells. Thus, well log correlations presented here, as well as the findings in the other relevant chapters, indicate that there are no intra-Scatter unconformities nor a major erosive basal Sully unconformity (removing the Sikanni and upper Lepine formations) in the Liard Basin.

As discussed in Chapter II, Frank (2002) correlated the Bulwell Member of the Scatter Formation exposed in outcrop on the western margin of the basin with the “Chinkeh Formation” in the subsurface at Maxhamish. He provided some cross-sections to support his claim, which, based on data presented in chapters II, III and here, is not supported by the evidence of this study.

The rapid thinning of Cretaceous sediments across the Bovie Structure led Dixon (1997, 1999) to conclude that there may have been repeated reactivations of an eastern platform (possibly related to the Tathlina high) during the Albian removing significant thickness of strata and resulting in the thin succession to the east of an arcuate hinge-line stretching into the Northwest Territories. The cross-sections presented here, combined with the sedimentological and biostratigraphic data of this study indicate that significant

erosional events are not necessary to account for the thin succession to the east of the Bovie Structure. In agreement with Williams (1978), the facies and subsurface correlations indicate that the easternmost northeastern British Columbia and the Great Slave Plain areas of the Northwest Territories preserve a relatively uninterrupted Albian and lowermost Cenomanian stratigraphic succession. The shoreline is interpreted to have been oriented north-northwest and sloped cratonward. One possible exception to this paleogeography is that which existed during earliest Albian time prior to and during deposition of the Chinkeh Formation, as facies analysis and well log correlations in the Northwest Territories indicate the presence of a tidally-influenced fluvial system in the area of the B-41 and L-49 wells. This seems to indicate that the earliest Albian transgression moved eastwards up over existing pre-Cretaceous topography (Chapter II). In the Maxhamish area and in the Liard Plateau, it is difficult to determine with certainty whether shoreface sandstones of the Chinkeh abutted against pre-existing topography, or are re-worked, abandoned barriers of the southerly transgressing Early Albian Boreal Sea.

Figure VII-1. Locations of cross-sections A-E and J. Maxhamish Field outlined in yellow.

Figure VII-2. Cross section A-A'. West-east cross section of Chinkeh and Garbutt interval in 94O11 map sheet area (Maxhamish pool) northeastern British Columbia. Datum is Hot Rad marker. See Figure 1 for location of cross-section. For AccuX correlations (Figures 2-6, 8, 9), gamma-ray logs are brown and are always on the left track (scale 0-150 API units); resistivity logs are green or black and are always on the right track (log scale is 0.2 –2000 ohmm²/m). For Geosection correlations (Figures 7, 11-14), left track is gamma-ray log (scale 0-150 API units), and right track is resistivity log (log scale is 0.2 –2000 ohmm).

A

West

A'

East

Figure VII-3. Cross section B-B'. West-east cross section of Chinkeh and Garbutt interval in 94O14 map sheet area (Maxhamish pool) northeastern British Columbia. Datum is Scatter top. See Figure 1 for location of cross-section.

B
West

200B028B094O1400

COMPLETED

200D037B094O1400

GAS

200B024B09401400
GAS

200B033B09401400
GAS

200C012B09401400
GAS

01400

200B031B09401400

200C020A09401400

200A028D09401

GAS

GAS

ABAND

200B031B09401400

GAS

200C020A09401400

GAS

200A028D09401500

ABAND

B'
East

Figure VII-4. Cross section C-C'. South-north cross section of Chinkeh and Garbutt interval from south of the Maxhamish gas field northwards into the Northwest Territories plains. Datum is Hot Rad marker. See Figure 1 for location of cross-section.

C South

200A079B09401100
ABAND

200B053G09401100
CMP-GAS

200B073G09401100
GAS

200C003J09401100
GAS

200C051J09401100
GAS

200C051J09401100
GAS

200D072J09401100
GAS

200C012B09401400
GAS

200B033B09401400
GAS

200B053B09401400
GAS

01400

200C072B09401400
GAS

200B009H09401400
GAS

200B049H09401400
CMP-GAS

300M056020122450
ABAND

300M056
AB

C'
North

300M058030123000
ABAND

300B768030122450
ABAND

300D508030122450
ABAND

300B416040122450
SUS-UNDES

300M478040122300
ABAND

Figure VII-5. Cross section D-D'. NW-SE cross-section of Cretaceous strata at location of fluvial Chinkeh Formation in the Northwest Territories plains. Datum is Hot Rad marker. See Figure 1 for location of cross-section.

D
NW

300H136040123150
ABAND

300D506030122450
ABAND

30

2450

300B416040122450
SUS-UNDES

300L496030122300
ABAND

300B256030122301
ABAND

256030122300
ABAND

300D666030122150
ABAND

300K016030122150
ABAND

300C606
AB

300C606010121150
ABAND

300G506010121000
ABAND

300D296010121000
SUS

30

506010121000
ABAND

300D296010121000
SUS

300N456010120450
ABAND

SE
D'

BFSC

SIKANNI

BOUGIE

SCATTER

HOT RAD
CHINKEH?

Figure VII-6. Cross section E-E'. South-north cross section showing valley filled with Chinkeh Formation sediments in the Northwest Territories plains. Datum is Hot Rad marker. See Figure 1 for location of cross-section.

E South

300N336100122300
ABAND

North

Figure VII-7. Cross section F-F'. West-east cross section showing detailed correlations of the Scatter Formation. Datum is Scatter top. See Figure 10 for location of cross-section.

West F

A-077-D-094-O-11

C-020-F-094-O-11

B-004-K-094-O-11

B-052-K-094-O-11

A-079-B-094-O-11

B-059-I-094-O-11

B-085-H-094-O-11

B-085-H-094-O-11

D-067-A-094-O-11

A-045-E-094-O-10

B-096-E-094-O-10

A-027-L-094-O-10

A-078-L-094-O-10

A-002-D-094-O-15

A-002-D-094-O-15

D-077-K-094-O-10

D-013-L-094-O-09

D-017-G-094-P-12

D-014-I-094-P-12

D-055-L-094-P-11

B-006-A-094-P-14

D-077-K-094-O-10

D-013-L-094-O-09

D-017-G-094-P-12

D-014-I-094-P-12

D-055-L-094-P-11

B-006-A-094-P-14

A-025-I-094-P-10 East
F'

Figure VII-8. Cross section A-A'. West-east cross-section of entire Albian-Cenomanian interval in Maxhamish area. Datum is sea level. See Figure 1 for location of cross-section.

A
West

200B052K09401100
COMPLETED

200B049J05
COMPLE

Scatter
Garbutt
Chinken
Pre-K

Unit E
Unit D
Unit C
Units A+B

200B049J094O1100
COMPLETED

200D036J094O1100
GAS

200C0

200C055J094O1100
GAS

200A053J094O1100
GAS

200C0

200C051J094O1100
GAS

200B059I094O1100
ABAND

200A07

200A078L094O1000

GAS

200D077K094O1000

ABAND

A'

East

Figure VII-9. South-north cross-section C-C' of entire Albian Cenomanian interval in Maxhamish area. Datum is Hot Rad marker. See Figure 1 for location of cross-section.

200C032F09400600 ABD-GAS	200A079B09401100 ABAND	200B073G09401100 GAS	200C051J09401100 GAS	200C012B09401400 GAS	200B053B09401400 GAS
200A093C09400600 ABAND	200D052K09400600 CMP-GAS	200B053G09401100 CMP-GAS	200C003J09401100 GAS	200D072J09401100 GAS	200B033B09401400 GAS
					200C072B09401400 GAS

C South

200C051J09401100 GAS	200C012B09401400 GAS	200B053B09401400 GAS	200B009H09401400 GAS	300M056020122450 ABAND	300B766030122450 ABAND	300B416040122450 SUS-UNDES
9401100	200D072J09401100 GAS	200B033B09401400 GAS	200C072B09401400 GAS	200B048H09401400 CMP-GAS	300M056030123000 ABAND	300D506030122450 ABAND
						300M476040122300 ABAND

C'
North

Figure VII-10. Locations of cross sections F, H and I. Maxhamish field area shaded yellow.

Figure VII-11. Cross section H-H'. SE-NW cross-section showing detail of Sikanni Formation correlations. Datum is Sikanni 2 marker. See Figure 10 for location of cross-section.

H SE

00/B-050-C-094-H-04-0

00/D-077-D-094-H-04-0

00/A-025-H-094-G-01-0

00/B-099-H-094-G-01-0

00/B-044-J-094-G-01-0

0044-J-094-G-01-0 00/B-010-B-094-G-08-0 00/D-042-C-094-G-08-0 00/B-028-F-094-G-08-0 00/D-073-E-094-G-08-0 00/B-045-H-094-G-07-0 00/A-049-L-094-G-08-0 00/

49-L-094-G-08-0 00/C-055-I-094-G-07-0 00/D-085-I-094-G-07-0 00/D-075-C-094-G-09-0 00/B-088-B-094-G-09-0 00/B-026-G-094-G-10-0 00/C-078-G-094-G-10-0 00/

078-G-094-G-10-0 00/C-046-K-094-G-09-0 00/D-076-L-094-G-09-0 00/D-037-B-094-G-15-0 00/D-031-A-094-G-15-0 00/A-085-A-094-G-15-0 00/D-021-B-094-J-03-0 00/A

H'
SE

00/D-021-B-094-J-03-0

00/A-075-K-094-J-03-0

00/D-035-G-094-O-04-0

00/A-075-E-094-O-04-0

00/A-039-B-094-N-08-0

00/D-075-E-094-N-08-0

Figure VII-12. Cross section F-F'. W-E cross-section showing detail of Sikanni correlations in the middle part of Liard basin in northeastern British Columbia. Datum is Sikanni 2 marker. See Figure 10 for location of cross-section.

F West

D-075-E-094-N-08-0 00/B-037-I-094-N-09-0 0

00/A-059-L-094-0-11-0 00/A-091-A-094-0-12-0 00/A-077-D-094-0-11-0

094-0-11-0 00/C-020-F-094-0-11-0 00/B-004-K-094-0-11-0 00/B-052-K-094-0-

052-K-094-0-11-0 00/A-079-B-094-0-11-0 00/B-059-I-094-0-11-0 00/B-085-H-0

A-079-B-094-0-11-0 00/B-059-I-094-0-11-0 00/B-085-H-094-0-11-0 00/D-C

F'
East

Figure VII-13. Cross section I-I'. W-E cross section showing detail of Sikanni correlations in the northern part of Liard basin in northeastern British Columbia. Datum is Lepine top. See Figure 10 for location of cross-section.

I West

00/B-037-I-094-N-09-0

0

00/A-067-D-094-0-13-0

00/A-098-D-

098-D-094-O-13-0

00/B-055-E-094-O-13-0

I'
East

55-E-094-0-13-0

00/B-021-K-094-0-14-0

Figure VII-14. Cross section J-J'. Correlation of Upper Albian succession in the southern Northwest Territories. Datum is Scatter top. See Figure 1 for location of cross-section.

J

300N026040123000
ABAND

300B416040122450
SUS-UNDES

300F736050122300
ABAND

001246050122000
ABAND

300A456030121450
ABAND

300M736040121150
ABAND

300E566020121000
ABAND

300G5060101
ABAND

300E566020121000
ABAND

300G506010121000
ABAND

300M416010121000
SUS

300K306010121000
ABAND

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Chapter VIII. FORAMINIFERAL FAUNA AND SYNONYMY

Foraminiferal Fauna

Figures 1-15 represent separately the dominant faunas present in the Chinkeh, lower Garbutt, middle and upper Garbutt, Scatter, Lepine, Sikanni and Sully formations. Discussion of the nature and importance of the faunas in each interval can be found in the relevant chapters.

Figure VIII–1. Benthic foraminifera from the Chinkeh Formation (outcrop and subsurface).

- a, b)** *Ammodiscus rotalarius* Loeblich and Tappan, x98, x85 (2000L1, c-003-J#10).
- c)** *Verneulinoides borealis* Tappan, x65 (2000L5).
- d)** *Gaudryina nanushukensis* Tappan, x30 (2000N12).
- e, f, g)** glauconitic *Verneulinoides borealis* Tappan, x90, x100, x110 (b-079-G/94-O-11#4, b-079-G#4, c-003-J/094-O-11#8).
- h)** glauconitic *Glomospira* sp., x130 (c-003-J#8).
- i)** *Psamminopelta* sp., x50 (Arrowhead B-41#2).
- j)** *Saccamina* sp., x50 (Arrowhead B-41#2).

Figure VIII-2. Benthic foraminifera from the lower Garbutt interval in core and outcrop (I).

- a, b)** *Ammobaculites* sp., x100, x70 (b-53-B/94-O-14#3).
- c, d)** *Gaudryina canadensis* (Cushman), x45 (L2000N8, 00N10).
- e)** *Gaudryina stotti* Chamney, x120 (L2000N11).
- f-i)** *Verneulinoides borealis* Tappan, x50, x50, x70, x80 (00N8, 8; K-32#6; b-053-B/094-O-14#1).
- j-l)** *Verneulinoides tailleuri* Tappan, x85, x65, x70 (b-053-B/094-O-14#8, b-053-B/094-O-14#3, 00N13).
- m, n)** *Verneulinoides cummingensis* (Nauss), x90, x75 (L2000N9, 11).
- o)** *Textularia topagorukensis* Tappan, x105 (K-32#1).
- p)** *Trochammina mcmurrayensis* Mellon and Wall, x140 (K-32#1).

Figure VIII-3. Benthic foraminifera and other microfossils from the lower Garbutt interval in core and outcrop (II).

- a) *Haplophragmoides* sp., x90 (L2000N10).
- b) *Haplophragmoides sluzari* Mellon and Wall, x120 (L2000N11).
- c) *Glomospira* sp., x105 (L000N11).
- d, e, f) *Ammodiscus* sp., x100, x85, x95 (L2000N8, N11, b-053-B#1).
- g) *Ammobaculites* sp., x100 (b-053-B/094-O-14#3).
- h) *Bathysiphon brosegi* Tappan, x55 (b-066-D/094-O-15#4).
- i) *Saccamina alexanderi* (Loeblich and Tappan), x75 (b-066-D/094-O-15#2).
- j) fish tooth, x100 (L2000N9).
- k) *Conorbina* sp., 125 (L2000N12).
- l) *Gyroidina* cf. *nitida* (Reuss), x120 (L2000N15).
- m) *Saracenaria* sp., x75 (L2000N10).
- n) *Quinqueloculina* sp., x90 (L2000N11).
- o, p) radiolarians, x105, x120 (b-053-B/094-O-14#3).
- q) *Trochammina* sp., x125 (b-053-B#2).
- r) *Textularia* sp., x90 (B-53-B#2).

Figure VIII–4. Characteristic foraminifera of the Middle and Upper Garbutt interval.

- a)** *Haplophragmoides* sp., x105 (01B1).
- b, c)** *Haplophragmoides linki* Nauss, x90, x120 (01B1, b-66-D/94-O-15#2).
- d-f)** *Haplophragmoides multiplum* Stelck and Wall, x60, x85, x90 (01B1, 01B2, 01B3).
- g)** *Ammodiscus* sp., x100 (01B2).
- h, i)** *Saccamina* sp., x60 (01B2).
- j)** *Miliammina ischnia* Tappan, x60 (d-75-E#7).
- k)** *Miliammina sproulei* Nauss, x90 (01B13).
- l)** *Ammobaculites fragmentarius* (Cushman), x60 (01B13).
- m)** *Verneuilinoides cummingensis* Nauss, x75 (01B2).
- n-p)** *Gaudryina nanushukensis* Tappan, x60, x60, x90 (b-66-D/94-O-15#4, #3, 01B13).
- q)** *Gaudryina canadensis* (Cushman), x75 (01B1).
- r)** *Uvigerinamina manitobensis* Wickenden, x80 (01B1).
- s)** *Psamminopelta bowsheri* Tappan, x70 (01B13).
- t)** *Miliammina* sp. X70 (b-66-D/94-O-15#4, #2).

Figure VIII–5. Characteristic foraminifera of the Scatter Formation (I).

- a)** *Psamminopelta bowsheri* Tappan, x70 (L2000K20).
- b)** *Saccamina lathrami* Tappan, x75 (L2002B1).
- c)** *Glomospirella gaultina* Berthelin, x105 (L2000K26).
- d)** *Ammodiscus* sp., x150 (L2000K21).
- e₁)** *Trochammina rutherfordi* (spiral view) Stelck and Wall, x90 (L2000K21).
- e₂)** *Trochammina rutherfordi* (umbilical view) Stelck and Wall, x90 (L2000K21).
- f, g)** *Haplophragmoides multiplum* Stelck and Wall, x100, x145 (L2000K26, L2002B1).
- h, i)** *Haplophragmoides linki* Nauss, x155, x190 (L2002B17, L2000K21).
- j)** *Spiroplectammina* sp., x133 (L2002B17).
- k, l, m)** *Ammobaculites tyrelli* Nauss, x75, x90, x80 (L2002B17, L2000K21, L2002B13).
- n)** *Ammobaculites fragmentarius*, x60 (d-75-E/94-N-08#7).
- o)** *Bathysiphon brosegi* Tappan, x70 (L2002B17).
- p)** *Gaudryina canadensis* (Cushman), x70 (d-75-E/94-N-08#7).

Figure VIII-6. Characteristic foraminifera of the Scatter Formation (II).

- a, b)** *Gaudryina canadensis* (Cushman), x95, x75 (L2002B1, L2000K20).
c, d, e) *Gaudryina nanushukensis* Tappan, x75, x105, x85 (d-75-E/94-N-08#8, #8, L2000K22).
f) *Verneuilinoides tailleuri* Tappan, x70 (L2002B13).
g) *Verneuilinoides cummingensis* (Nauss), x80 (L2000K24).
h) *Miliammina sproulei* Nauss, x70 (L2000K26).
i-l) *Verneuilinoides borealis* Tappan, x90, x90, x115, x85 (L20002B17, L2000K21, K21, K20).

Figure VIII–7. Characteristic foraminifera of the Lepine Formation (I) (All L2002).

a, b, e, f, g, h, i) *Ammobaculites wenonahae* Tappan, x70, x75, x80, x75, x85, x85, x80, x85, x80 (DB6, DB8, DB18, DB15, DB15, DB24, DB21, DB8, C2).

c, d, j) *Ammomarginulina* sp., x80 (DB6).

k-p) *Ammotium* sp., x80, x40, x100, x100, x60, x45 (C10, DB21, DB21, DB6, DB21, DB1).

Figure VIII–8. Characteristic foraminifera of the Lepine Formation (II) (All L2002).

- a, b)** *Trochammina gatesensis* Stelck and Wall, (spiral and umbilical view) x105 (DB33).
- c)** *Trochammina gatesensis* Stelck and Wall, x75 (DB35).
- d, e)** *Trochammina alcesensis* Stelck, (spiral and umbilical view) x100 (F9).
- f, g)** *Haplophragmoides postis* Stelck and Wall, x110, x150 (F12, F2).
- h)** *Haplophragmoides linki* Nauss, x80 (C2).
- i, j)** *Trochammina rutherfordi* Stelck and Wall, (umbilical and spiral view) x115 (DB41).
- k, l)** *Trochammina rutherfordi* Stelck and Wall, (spiral and umbilical view) x100 (F16).
- m-p)** *Verneuilinoides borealis* Tappan, x50, x100, x70, x55 (DB6, F2, DB25, DB25).
- q)** *Verneuilina canadensis* Cushman, x55 (DB38).

Figure VIII-9. Characteristic foraminifera of the Lepine Formation (III) (all L2002).

- a)** *Verneuilinoides tailleuri* Tappan, x70 (DB6).
- b)** *Pseudobolivina variana* (Eicher), x60 (F17).
- c)** *Uvigerinammia* sp., x90 (DB41).
- d, e)** *Uvigerinammia manitobensis* (Wickenden), x85, x100 (F12, DB41).
- f)** *Haplophragmium swareni*., x70, (F16)
- g)** *Haplophragmium* sp., x30 (DA3).
- h)** *Gravellina chamneyi* Stelck, x110 (F17).
- i)** *Ammobaculites petilus* Eicher, x70 (DB35).
- j, k)** *Ammobaculites humei* Nauss, x115, x40 (C7, D10).
- l)** *Ammobaculites fragmentarius* (Cushman), x70 (D27).
- m-p)** *Gaudryina canadensis* (Cushman), x140, x60, x70, x70 (C6, F17, DB30, DB34).

Figure VIII–10. Characteristic foraminifera of the Lepine Formation (IV) (All L2002).

- a)** *Miliammina awunensis* Tappan, x95 (F14).
- b)** *Miliammina sproulei* Nauss, x65 (DB33).
- c)** *Ammobaculites petilus* Eicher, x80 (DB33).
- d, e)** *Bathysiphon brosgei* Tappan, x40, x50 (DB35, DB36).
- f-j)** *Spiroplectammina* sp. A, x165, x200, x185, x185, x123 (C5, C5, C5, C5, F9).
- k)** *Saccammina alexanderi* (Loeblich and Tappan), x65(B13).
- l)** *Ammodiscus mangusi* (Tappan), x140 (C5).
- m, n)** unknown flattened spheres, x130, x150 (DB26).
- o, p)** unknown spheres, x130, x140 (DB26, DB6).

Figure VIII–11. Characteristic foraminifera of the Sikanni Formation (I) (all L2000D).

- a) *Psamminopelta bowsheri* Tappan, x105 (D2).
- b) *Miliammina awunensis* Tappan, x70 (D4).
- c, d) *Miliammina manitobensis* Wickenden, x65, x75 (D31, L2001KA5).
- e) *Glomospirella* sp., x65 (D48).
- f, g) *Thuramminoides* sp., x125, x140 (D20, D20).
- h) *Glomospira* sp., x70 (D46).
- i) *Reophax vasiformis* Chamney, x65 (D21).
- j) *Saccamina lathrami* Tappan, x90 (D20).
- k) *Saccamina alexanderi* (Loeblich and Tappan), x85 (D18).
- l) *Ammobaculoides* sp., x40 (D24).
- m) *Ammobaculites fragmentarius* (Cushman), x60 (D27).
- n) *Haplophragmium swareni* Stelck and Hedinger, x60 (D48).
- o) *Verneuilinoides tailleuri* Tappan, x90 (D4).
- p) *Verneuilinoides borealis* Tappan, x95 (D21).

Figure VIII-12. Characteristic foraminifera of the Sikanni Formation (II).

- a, b)** *Verneuilina canadensis* Cushman, x60, x60 (00D47, 00D47).
- c, d)** *Uvigerinammina manitobensis* (Wickenden), x105, x50 (00D71, L2001KA1).
- e, f)** *Textularia rioensis* Carsey, x50, x75 (KA2, KA2, 00D68).
- g, h)** *Textularia gravenori* Stelck and Wall, x90, x90 (00D69).
- i)** *Textularia* sp. Sutherland and Stelck, x120 (00D51).
- j, k)** *Ammotium* sp., x50, x100 (00D47, 00D47).
- l, m, n)** *Haplophragmoides postis* Stelck and Wall, x135, x45, x50 (00D4, D49, D48).
- o, p)** *Trochammina alcesensis* Stelck, x95 (spiral and umbilical views) (00D4).

Figure VIII–13. Characteristic foraminifera of the Sully Formation (I) (All L2001).

- a)** *Haplophragmium swareni* Stelck and Hedinger, x60 (KC6).
- b)** *Ammobaculites fragmentarius* (Cushman), x60 (KC4).
- c, d, e)** *Ammobaculites* sp. Stelck, Wall and Weter, x60, x60, x80 (KB10, KB8, KB8).
- f, g)** *Trochammina umiatensis* Tappan, (spiral view and umbilical views) x100 (KC6).
- h)** *Haplophragmoides postis* Stelck and Wall, x140 (KC6).
- i-k)** *Textularia alcesensis* Stelck and Wall, x105, x75, x90 (KB8, KB5, KB8).
- l)** *Verneulinoides borealis?* Tappan, x200 (KC3).

Figure VIII–14. Characteristic foraminifera of the Sully Formation (II) (All L2001).

- a)** *Verneuilinoides borealis?* Tappan, x100 (KC3).
- b)** *Verneuilinoides tailleuri* Tappan, x50 (KB10).
- c, d)** *Tritaxia* sp. Stelck and Wall, x65, x70 (KB10, KB10).
- e)** *Textulariopsis minuta* Tappan, x70 (KC4).
- f)** *Gaudryina canadensis* (Cushman), x45 (KB17).
- g, h)** algal cysts, x70, x60 (KC10, KC10).
- i, j)** diatoms, x130, x170 (KC6).
- k)** twinned gypsum crystal, x35 (KC8).

Synonymy List

The synonymy list below includes all species identified on the foraminiferal distribution charts (Appendix I). Although not exhaustive, the synonymy list includes the original reference followed by most additional publications used for identification of taxa and for comparison with the Liard Basin fauna.

Ammobaculites fragmentarius (Cushman)=*Ammobaculites fragmentaria* Cushman, 1927, p. 130, pl. 1, fig. 8; Stelck and Wall, 1956, p. 21, pl. 5, fig. 18, 19; Tappan, 1962, p. 136, pl. 32, figs. 8-11; Stelck, 1975, pl. II, figs. 21-23, 25-27; Wall, 1967, p. 55, pl. 1, figs. 7-9; North and Caldwell, 1975, pl. II, figs. 2-5; Chamney, 1978, p. 14, pl. 3, figs. 9a-b, 10; McLean and Wall, 1981, pl. 8, figs. 9, 10; Stelck and Hedinger, 1983, pl. 1, figs. 33, 34, 36; Koke and Stelck, 1985, pl. 3, figs. 3, 6, 12; Stelck and Koke, 1987, pl. 3, figs. 18, 21, 31, 32.

Ammobaculites humei Nauss, 1947, p. 333, pl. 48, fig. 1; Mellon and Wall, 1956, p. 15, pl. 1, fig. 18; Stelck and Wall, 1956, p. 22, pl. 2, figs. 25, 26; Stelck, 1991, pl. 5, figs. 12-16.

Ammobaculites obliquus Loeblich and Tappan, 1949, p. 90-91; Loeblich and Tappan, 1950, p. 7, pl. 1, figs. 14a-17; Eicher, 1960, p. 62, 63; pl. 4, figs. 2, 6; Stelck and Leckie, 1990, pl. 1, 11, 17-21, 34; figs. 24, 25.

Ammobaculites petilus Eicher, 1960, p. 62, pl. 4, figs. 2, 6; Guliov, 1967, p. 28, pl. 5, fig. 2; North and Caldwell, 1975, pl. II, figs. 6, 7; McNeil and Caldwell, 1981, p. 159, pl. 12, fig. 8.

Ammobaculites tyrelli Nauss, 1947, p. 333, pl. 48, fig. 2; Guliov, 1967, p. 28, pl. 5, figs. 3a-b; Stelck, 1975, pl. II, figs. 28, 29, pl. III, figs. 1, 2, 15; North and Caldwell, 1975, pl. II, figs. 8, 9; McNeil and Caldwell, 1981, p. 159, 160, pl. 12, figs. 9, 10; Koke and Stelck, 1984, pl. 1, figs. 38, 39, 45, 46.

Ammobaculites wenonahae Tappan, 1960, p. 291, pl. 1, figs. 3-6; Tappan, 1962, p. 138, pl. 32, figs. 1-7; Koke and Stelck, 1984, pl. 1, figs. 33-35; Stelck, 1991, pl. 5, figs. 17-34, pl. 6, figs. 1-6, 7, 8, 13-15.

Ammobaculites sp. Stelck and Wall, 1958, p. 26, pl. III, figs. 1-3.

Ammobaculites sp. Stelck and Wall, 1956, p. 24, 25, pl. 5, fig. 22.

Ammobaculites sp. B Sutherland and Stelck, 1972, p. 572, pl. 4, figs. 6, 7.

Ammobaculites sp.

Ammobaculoides athabascensis Stelck and Wall, 1956, p. 25, pl. 5, fig. 21; Stelck and Koke, 1987, pl. 4, fig. 19; Stelck, 1991, pl. 3, figs. 6-7.

Ammobaculoides sp.

Ammodiscus mangusi (Tappan) = *Involutina mangusi* Tappan, 1957, p. 203, pl. 65, figs. 13, 14; Tappan, 1962, p. 10, pl. 1, figs. 19a-b, 20 a- b; Chamney, 1978, p. 10, pl. 1, figs. 19a-b, 20a-b; Koke and Stelck, 1984, pl. 1, fig. 20, 21.

Ammodiscus rotalarius Loeblich and Tappan, 1949, p. 247, pl. 46, fig. 1; Tappan, 1962, pl. 1, figs. 15a-c, 16a-c; Chamney, 1978, p. 10, pl. 1, figs. 15a-c, 16a-c; Sliter, 1981, p. 53, pl. 9, figs. 12, 14; McNeil and Caldwell, 1981, 136, 137, pl. 9, fig. 15; Stelck and Koke, 1987, pl. 2, figs. 16, 17.

Ammodiscus sp.

Ammomarginulina sp. cf. Guliov, 1967, p. 32, pl. 6, fig. 3; cf. McLean and Wall, 1981, pl. 7, figs. 14, 15; Stelck and Leckie, 1990, pl. 1, figs. 29-31.

Ammomarginulina cragini Loeblich and Tappan, 1950, p. 6, pl. 1, figs. 4-6; Eicher, 1960, p. 60, 61, pl. 3, fig. 20; Koke and Stelck, 1985, pl. 3, figs. 18-22; Stelck and Koke, 1987, pl. 3, fig. 15.

Ammomarginulina sp.

Ammotium sp. cf. North and Caldwell, 1975, pl. II, figs. 14-16; cf. McLean and Wall, 1981, pl. 7, figs. 16, 17; cf. Stelck and Hedinger, 1983, pl. 2, fig. 32; cf. Stelck and Leckie, 1990, pl. 1, figs. 22, 23.

Bathysiphon brosegi Tappan, 1957, p. 202, pl. 65, figs. 1-5; Tappan, 1962, p. 128, pl. 29, figs. 5.

Conorbina sp. cf. Stelck and Wall, 1956, p. 27, pl. 1, figs. 22-24; Chamney, 1978, p. 33, pl. 11, fig. 1a-g; cf. McLean and Wall, 1981, pl. 8, fig. 9-11.

Gaudryina canadensis (Cushman) = *Bigenerina angulata* Cushman, 1927, p. 131, pl. 1, fig. 10; Cushman, 1943, p. 28, pl. 6, figs. 7, 8; Tappan, 1962, p. 148, pl. 34, figs. 11-15; North and Caldwell, 1975, pl. III, figs. 9a-b, 10a-b, 11a-b; Chamney, 1978, p. 20, pl. 4, figs. 9-11; Koke and Stelck, 1985, pl. 3, figs. 23, 24; Stelck and Koke, 1987, pl. 4, fig. 28.

Gaudryina nanushukensis Tappan, 1951, p. 2, pl. 1, figs. 8a-11; Tappan, 1962, p. 148, pl. 34, figs. 11-15; Chamney, 1978, p. 18, pl. 4, figs. 3a-c, 5; Sliter, 1981, p. 57, pl. 11, 13-15, 17; McLean and Wall, 1981, pl. 8, figs. 13-15.

Gaudryina stotti Chamney, 1978, p. 20, pl. 4, figs. 6a-c, 8.

Globulina lacrima Reuss var. *canadensis* Mellon and Wall, 1956, p. 15, pl. 2, fig. 6; Tappan, 1962, p. 183, 184, pl. 47, figs. 18, 19.

Glomospira corona [= *Glomospira charoides* (Jones and Parker) Cushman var. *corona*] Cushman and Jarvis, 1928, p. 89, pl. 12, figs. 9-11; McLean and Wall, 1981, pl. 8, figs. 4, 5.

Glomospira reata Eicher, 1960, p. 56, 57, pl. 3, figs. 4, 5; Stelck and Koke, 1987, pl. 2, figs. 13, 14; Stelck and Leckie, 1990, pl. 1, figs. 5-8.

Glomospira sp.

Glomospirella gaultina (Berthelin)=*Ammodiscus gaultinus* Berthelin, 1880, p. 19, pl. 1 (24), figs. 3a, b; Tappan, 1962, p. 130, pl. 29, figs. 17-20.

Glomospirella sp.

Gravellina chamneyi Stelck, 1975, p. 267, 268; pl. III, figs. 27, 28, 37-44; McNeil and Caldwell, 1981, p. 185, 186, pl. 14, figs. 22a-b; Koke and Stelck, 1985, pl. 4, figs. 29, 32, 33; 30, 31, 34-36; Stelck and Hedinger, 1983, pl. 2, figs. 24, 28, 29, 35, 36; Stelck and Koke, 1987, pl. 4, figs. 33, 34; Stelck, 1991, pl. 3, figs. 36-38.

Gyroidina cf. *nitida* (Reuss)= cf. *Rotalina nitida* Reuss, 1844, p. 214; Stelck and Wall, 1956, p. 33, 34, pl. 1, figs. 11-13; pl. 2, figs. 7-9.

Haplophragmium swareni Stelck and Hedinger, 1983, p. 140, pl. 1, figs. 1-5; Koke and Stelck, 1985, pl. 3, figs. 8, 9, 14-16; Stelck and Koke, 1987, pl. 3, figs. 33, 34, 37, pl. 4, fig. 1.

Haplophragmium sp.

Haplophragmoides collyra Nauss, 1947, p. 337, 338, pl. 49, figs. 2a-b, 5; Koke and Stelck, 1985, pl. 2, figs. 34-36; Stelck, 1991, pl. 5, figs. 1-2.

Haplophragmoides kirki? Wickenden, 1932, p. 85, pl. 1, figs. 1a-c; Gulio, 1967, p. 24, pl. 4, figs. 2a-b; Stelck, 1991, pl. 2, figs. 25-26.

Haplophragmoides linki Nauss, 1947, p. 339, pl. 49, fig. 7; Stelck and Wall, 1956, p. 36, pl. 4, figs. 17, 18, pl. 5, figs. 5, 6; North and Caldwell, 1975, pl. 1, fig. 17; Chamney, 1978, p. 13, pl. 3, figs. 6a-b, 7; McLean and Wall, 1981, pl. 8, figs. 6-8; Stelck and Koke, 1987, pl. 2, figs. 40-43.

Haplophragmoides multiplum Stelck and Wall, 1956, p. 37, pl. 4, figs. 14-16; (Haplophragmoides sp. E. Wickenden, 1951, pl. IB, fig. 2); Stelck, 1991, pl. 4, figs. 23-24.

Haplophragmoides postis Stelck and Wall, 1956, p. 38, pl. 4, figs. 23, 24; Stelck and Koke, 1986, pl. 2, figs. 29-34, pl. 3, figs. 3, 7, 4, 9; Stelck, 1991, pl. 4, figs. 28-40.

Haplophragmoides sluzari Mellon and Wall, 1956, p. 17, pl. 1, fig. 15; Stelck and Wall, 1956, pl. 2, figs. 23, 24.

Haplophragmoides topagorukensis Tappan, 1957, p. 203, pl. 65, figs. 15-25; Tappan, 1962, pl. 31, figs. 1-15; Chamney, 1978, p. 11, pl. 3, figs. 1, 2a-b, 3.

Haplophragmoides sp.

Hippocrepina sp. cf. McNeil and Caldwell, 1981, p. 130, 131, pl. 9, figs. 3, 4.

Hyperamminoides sp. cf. Stelck and Wall, 1958, p. 29, pl. IV, figs. 12, 13.

Miliammina awunensis Tappan, 1957, p. 210, pl. 67, figs. 19-21; Tappan, 1962, pl. 36, figs. 20-24; Stelck and Koke, 1985, pl. 1, 30-31; Stelck and Koke, 1987, pl. 2, figs. 23, 24.

Miliammina ischnia Tappan, 1957, p. 211, pl. 67, figs. 25, 26; Tappan, 1962, p. 160, pl. 37, figs. 1-5.

Miliammina manitobensis Wickenden, 1932, p. 90, pl. 1, figs. 11a-c; Tappan, 1962, p. 160, pl. 36, figs. 12-18; North and Caldwell, 1975, pl. 1, figs. 12-14; McLean and Wall, 1981, pl. 7, figs. 2, 3; McNeil and Caldwell, 1981, p. 143, 144, pl. 10, fig. 9-14; Stelck and Hedinger, 1983, pl. 1, figs. 13-15; Koke and Stelck, 1985, pl. 1, figs. 32-35; Stelck, 1991, pl. 2, figs. 11-12; Stelck and Leckie, 1990, pl. 1, figs. 12, 13, 15, 16.

Miliammina subelegantica Mellon and Wall, 1956, p. 22, pl. 1, fig. 6; Stelck and Koke, 1987, pl. 2, figs. 25, 26.

Miliammina sproulei Nauss, 1947, p. 339, pl. 48, figs. 13a-b; Gulioy, p. 22, pl. 3, figs. 6a-c; McLean and Wall, 1981, pl. 7, figs. 4-7.

Psamminopelta bowsheri Tappan, 1957, p. 211, pl. 67, figs. 11-18, 22-24; Tappan, 1962, p. 157, pl. 37, figs. 11, 12; Sutherland and Stelck, 1972, p. 566, 567, pl. 2, figs. 14-17; pl. 3, figs. 1-3; North and Caldwell, 1975, pl. I, figs. 10, 11; Chamney, 1978, p. 21, pl. 4, figs. 12a-b, 13a-b; Koke and Stelck, 1984, pl. 1, figs. 22, 23; Koke and Stelck, 1985, pl. 2, fig. 6.

Psamminopelta sp.

Psammospheara sp. cf. Koke and Stelck, 1985, pl. 1, figs. 11, 12.

Pseudobolivina variana (Eicher)=*Bimonilina variana* Eicher, 1960, p. 67, pl. 4, figs. 15-19; North and Caldwell, 1975, pl. II, figs. 19, 20; Koke and Stelck, 1985, pl. 4, fig. 10; Stelck and Koke, 1987, pl. 4, figs. 25, 31, 32.

Quinqueloculina sp.

Reophax deckeri Tappan, 1940, p. 94, pl. 14, fig. 3; Stelck, 1991, pl. 1, figs. 16, 17, 18-22.

Reophax minuta Tappan, 1940, p. 94, pl. 14, figs. 4a-b; Tappan, 1962, p. 132, pl. 30, fig. 10; Stelck and Hedinger, 1983, pl. 1, figs. 17, 18; Stelck and Koke, 1985, pl. 1, 25, 26.

Reophax sikaniensis Stelck, 1975, p. 266, pl. I, figs. 16-18.

Reophax vasiformis Chamney, 1978, p. 10, pl. 1, figs. 12-14; Koke and Stelck, 1985, pl. 1, figs. 17-19; Stelck and Koke, 1987, pl. 1, figs. 38, 39; Stelck, 1991, pl. 4, figs. 3, 6, 7, 15.

Saccamina alexanderi (Loeblich and Tappan)=*Protonina alexanderi* Loeblich and Tappan 1950, p. 5, pl. 1, figs. 1, 2; Sutherland and Stelck, 1972, p. 558, 559, pl. 1, figs. 3, 4; Stelck, 1975, pl. 1, figs. 21, 22; Koke and Stelck, 1985, pl. 1, figs. 14-15; Stelck and Koke, 1987, pl. 1, figs. 32, 33.

Saccamina lathrami Tappan, 1960, p. 289, pl. 1, figs. 1, 2; Koke and Stelck, 1985, pl. figs. 13, 16.

Saccamina sp.

Saraceneria projectura Stelck and Wall, 1956, p. 50, pl. 3, figs. 22-25; (= *Saracenaria* sp. Mellon and Wall, 1956, p. 26, pl. 2, figs. 18, 19).

Saracenaria sp.

Scherochorella minuta Loeblich and Tappan; Stelck, 1991, pl. 1, figs. 9-10; Stelck and Leckie, 1990, pl. 1, fig. 14.

Spiroplectamina sp. cf. *Spiroplectamina* sp. Tappan, 1962, p. 139, pl. 33, fig. 5.

Textularia alcesensis Stelck and Wall, 1958, pl. IV, figs. 19-21.

Textularia gravenori Stelck and Wall, 1955, p. 55, pl. 2, fig. 36; Tappan, 1962, p. 141, pl. 33, figs. 16, 17; Sutherland and Stelck, 1972, p. 572, 574, pl. 4, figs. 15, 16.

Textularia rioensis Carsey, 1926, p. 24, pl. 7, fig. 2; Eicher, 1965, p. 897, pl. 104, fig. 6; Sutherland and Stelck, 1972, p. 574, pl. 4, figs. 11, 12.

Textularia sp. 1 cf. Sutherland and Stelck, 1972, p. 574, pl. 4, figs. 13, 14.

Textularia sp.

Textulariopsis minuta Tappan, Stelck and Hedinger, 1983, pl. 2, figs. 9, 10; Koke and Stelck, 1985, pl. 4, figs. 27, 28; Stelck and Koke, 1987, pl. 4, figs. 26, 27; Stelck, 1991, pl. 3, figs. 23, 24, 30-32.

Textulariopsis topagorukensis Tappan, 1957, p. 205, pl. 66, figs. 8-9; Tappan, 1962, p. 141, figs. 7-11; Stelck, 1975, pl. III, figs. 22, 23; Stelck and Hedinger, 1983, pl. 2, figs. 22, 23.

Thuramminoides sp.

Tritaxia sp. Stelck and Wall, 1958, p. 32, pl. IV, figs. 14-17.

Trochammina alcanensis Stelck, 1975, p. 266, 267, pl. III, figs. 16, 17, 20, 21; Stelck and Koke, 1987, pl. 4, figs. 14-16.

Trochammina gatesensis Stelck and Wall, p. 53, pl. 4, figs. 9-11; Koke and Stelck, 1984, pl. 1, figs. 52, 53; Koke and Stelck, 1985, pl. 4, figs. 11, 12, 17, 18; Stelck, 1991, pl. 3, figs. 13, 14.

Trochammina mcmurrayensis Mellon and Wall, 1956, p. 28, pl. 1, figs. 2-5.

Trochammina umiatensis Tappan, 1957, p. 214, pl. 67, figs. 27-29; Tappan, 1962, p. 156, pl. 38, figs. 5-8; Sutherland and Stelck, 1972, p. 575, pl. 5, figs. 1-4; Stelck, 1975, pl. III, figs. 9, 10, 18, 19; Stelck and Hedinger, 1983, pl. 2, figs. 25, 26; Stelck and Koke, 1987, pl. 4, figs. 5-11, 17, 18; Stelck and Leckie, 1990, pl. 1, figs. 26-28.

Trochammina rainwateri Cushman and Applin, 1946, p. 75, pl. 13, fig. 9; Tappan, 1962, p. 152, pl. 39, figs. 7-12; North and Caldwell, 1975, pl. II, figs. 21a-b, 22, 23a-b, pl. III, fig. 1a-c; Chamney, 1978, p. 22, pl. 4, figs. 18, 19.

Trochammina rutherfordi Stelck and Wall, 1955, p. 56, pl. 1, figs. 11, 12, 14, 16, pl. 3, figs. 20, 21, (?36), 37; Eicher, 1965, p. 89, pl. 105, fig. 1.

Trochammina wetteri Stelck and Wall, 1954, p. 10, 11, 13; Sutherland and Stelck, 1972, p. 575, 576; pl. 5, figs. 5, 6; Stelck and Hedinger, 1983, pl. 2, figs. 19, 20, 33, 34.

Trochammina wetteri Stelck and Wall, 1955, p. 59, pl. 2, figs. 1-3, 6; Eicher, 1967, p. 184, pl. 18, figs. 7, 9.

Trochammina sp.

Quinqueloculina cf. *Quinqueloculina sphaera* Nauss, 1947, p. 340, pl. 37, fig. 6; cf. Tappan, 1962, p. 157, pl. 37, fig. 6.

Uvigerinammina athabascensis (Mellon and Wall)=*Tritaxia athabascensis* Mellon and Wall, 1956, p. 27, pl. 1, figs. 16, 17; McLean and Wall, 1981, pl. 8, fig. 17); Tapan, 1962, pl. 33, fig. 12; Stelck and Koke, 1987, pl. 4, figs. 22, 23.

Uvigerinammina manitobensis (Wickenden)=?*Tritaxia manitobensis* Wickenden, 1932, p. 87, pl. 1, fig. 10; "*Tritaxia*" sp. cf. *T. manitobensis* Wickenden, Sutherland and Stelck, 1972, p. 579, pl. 5, figs. 11-13; Tappan, 1962, p. 145, pl. 33, figs. 18-23; North and Caldwell, 1975, pl. III, figs. 18a-b; Koke and Stelck, 1985, pl. 4, figs. 2-5; Stelck and Koke, 1987, pl. 4, figs. 38-41.

Uvigerinammina sp.

Verneuilina alameda Eicher, 1965, p. 900, pl. 104, figs. 10, 11; Sutherland and Stelck, 1972, p. 578, pl. 5, figs. 15, 16.

Verneuilinoides borealis Tappan, 1957, p. 206, pl. 66, figs. 10-18; Tappan, 1962, p. 142, pl. 34, figs. 1-9; Stelck, 1975, pl. III, figs. 35-36.

Verneuilina canadensis Cushman, 1927, p. 131, 132, pl. 1, fig. 11; Eicher, 1965, p. 901, pl. 105, fig. 5; North and Caldwell, 1975, pl. III, figs. 6a, b; McNeil and Caldwell, 1981, p. 176, 177, pl. 14, fig. 3; Stelck and Koke, 1985, pl. 4, fig. 1; Stelck and Koke, 1987, pl. 4, figs. 36, 37.

Verneuilinoides cummingensis (Nauss)= "*Verneuilina*" *cummingensis*, Nauss, 1947, p. 341, pl. 49, fig. 4); North and Caldwell, 1975, pl. III, figs. 4, 5a, b; McLean and Wall, 1981, pl. 7, figs. 20-22.

Verneuilinoides tailleuri Tappan, 1957, p. 208, pl. 66, figs. 19-22; (= *Gaudryina tailleuri*, Tappan, 1962, p. 149, pl. 35, figs. 8-16; Stelck, 1975, pl. III, figs. 29-34; McLean and Wall, 1981, pl. 8, fig. 16); Chamney, 1978, p. 15, pl. 3, figs. 17, 18; Stelck and Koke, 1987, pl. 4, fig. 24.

Chapter IX. CONCLUSIONS

Basal Cretaceous deposits of the early Albian transgression in the Liard Basin, represented by the Chinkeh Formation and overlying lowermost Garbutt Formation, can be correlated using biostratigraphy, sedimentology and well logs. Well log correlations of the Chinkeh Formation are possible between the Maxhamish Lake and Northwest Territories on the eastern margin of the basin where the units can be traced with some difficulty; however, the interpretation can differ significantly depending of whether the bentonite interval in the Garbutt Formation is chosen as a datum. Westwards the strata appear to undergo a facies change to shale, although the western margin of the basin preserves thick Chinkeh sandstone in outcrop.

Six units can be recognized in the subsurface at Maxhamish Lake and the Northwest Territories which are here correlated to outcrop on the western margin of the basin. Integrated analysis demonstrates that the units and their associated faunas can be divided into five main events: 1. deposition of basal breccias and conglomerate lags reworked during the initial transgression of the Moosebar Sea; 2. progradation of shoreface sandstones on the western and eastern margins of the Liard Basin (and fluvial/estuarine valley fill on the eastern margin of the basin in the Northwest Territories) with at least one internal sequence boundary; 3. Appearance of the Glauconitic Assemblage after a major relative sea level fall; 4. Appearance of the *Ammodiscus-Glomospira* fauna at the top of the Chinkeh Formation (which is correlative with the basal Garbutt Formation in outcrop in the Liard Plateau); 5. Appearance of the radioactive radiolarian-rich interval near the base of the Garbutt Formation.

The Chinkeh Formation is assigned to the *Gaudryina nanushukensis* foraminiferal Zone. The distinctive *Ammodiscus-Glomospira* fauna provides additional time constraints on the age of the lowermost Garbutt Formation as it is correlative with the lower part of the early Albian *Verneuilinoides cummingensis-Marginulinopsis collinsi* Subzone of the *Gaudryina nanushukensis* Zone.

The Chinkeh Formation is interpreted to have been characterized by eastwards and westwards prograding shorefaces on opposite margins of a narrow sea and at least one major persistent fluvial/estuarine system situated in the Northwest Territories. The southerly advancing, narrow Boreal Sea underwent a number of relative sea level changes during deposition of the Chinkeh Formation which reworked shoreface sandbodies and left pebble lags and *Glossifungites* surfaces but eventually flooded the entire region for the remainder early Albian time.

The middle to upper Garbutt and Scatter formations record the varying environments during the late early Albian and most of middle Albian time. Strata from the middle Garbutt are characterized by a stressed benthic fauna at some localities. The upper Garbutt Formation, in contrast, contains an abundant and diverse fauna of the upper part of the *Verneuilinoides cummingensis-Marginulinopsis collinsi* Subzone of the *Gaudryina nanushukensis* Zone. Unlike the stratigraphic equivalents in the southernmost deposits of the Moosebar-Clearwater Sea, no calcareous foraminifera are found above the strata of the lower part of the Garbutt Formation.

The Wildhorn Member of the Scatter Formation contains a foraminiferal fauna assigned to the *Haplophragmoides multiplum* Subzone of the *Gaudryina nanushukensis* Zone. No significant faunal change is observed in the transition from the Wildhorn to the

overlying Tussock Member, supporting the correlation of the uppermost Tussock and basal Lepine Formation with the lower Boulder Creek/Cadotte Formation in the Peace River plains as they are characterized by *Ammobaculites* sp. Subzone fauna.

In well logs, the base and top of the Scatter Formation can be traced clearly across the basin where it thins eastwards; however, it is difficult to trace the numerous internal coarsening-upwards cycles or the individual members with confidence across the basin with the existing well control. Although numerous slight coarsening-upwards cycles overlain by flooding surfaces occur in the Scatter Formation, no sequence boundaries occur below, within, or at the base of the overlying Lepine Formation. This likely indicates that deposition of the middle Albian strata in the Liard Basin occurred in a high accommodation setting despite the high sedimentation rates that resulted in deposition of the thick Garbutt and Scatter formations.

The extraordinarily thick and lithologically monotonous Lepine Formation in the Liard Basin reflects deposition during Middle to Late Albian time and can be divided into five units based upon lithology, micropaleontology, well log correlations and geochemistry. Lepine strata document the sea level history of the interior sea encompassing a continuous record of the Joli Fou Sea and its complex transition to the Mowry Sea. In ascending order, foraminiferal assemblages responded with the *A. wenonahae* Zone, *Ammomarginulina* assemblage, and the *Bathysiphon-A. fragmentarius* assemblage. Faunal assemblages differ considerably from those described from equivalent strata in the Peace River Foothills and from the Sikanni Chief River area.

Regional well log correlations show a pronounced thickening of the Middle to Late Albian succession northwards into the Liard Basin where the Lepine Formation

reaches a thickness of 1000 m on the western margin of the basin and several important log markers reflecting major transgressive surfaces can be traced. These include the Scatter, Viking and Bougie markers, the last of which was here correlated with the “Viking grit” beds of the Peace River Foothills. The Lepine Formation thins steadily eastwards to some 200 m in the 94P map sheet area in northeastern B.C., and no major unconformities have been recognized within it (although the Viking Marker-equivalent is present as a correlative conformity).

In outcrop, the Scatter marker near the base of the Lepine Formation is associated with the base of the *A. wenonahae* Zone. No lithological or faunal change is associated with the interval that is projected to the Viking marker in the outcrop section along the Liard River. The Bougie interval represents a distinct change in faunal abundance and diversity and is represented lithologically by small coarsening-upwards cycles to siltstone overlain by shale.

The thick succession of the Lepine Formation, dominated by lower and upper offshore and shelf paleoenvironments, represents deposition in a high accommodation and sediment supply setting that produced a continuous and uncondensed sedimentary record during a portion of middle and latest Albian time. Despite offshore and shelf conditions, biota are relatively poor throughout a thick portion of the Lepine. This is attributed to oceanographic restrictions in the northern portion of the interior sea due to periods of uplift. The paucity of ammonites and foraminifera is diagnostic in the Joli Fou-equivalent strata and the lower part of the Viking interval.

In the Liard Basin, the Sikanni Formation contains four sequences developed in shelf, lower through upper shoreface and prodeltaic through delta-plain facies. The upper

Buckinghorse/Lepine Formation and lower Sikanni Formation (S_1) are assigned to the informal subzone A, and the upper Sikanni Formation, beginning at the base of Sequence 2, is assigned to the informal subzone B. These zones have common elements of the *Verneuilina canadensis* and *Haplophragmoides postis goodrichi* subzones, respectively, established from correlative strata to the south in the Peace River region. The facies within the Sikanni Formation indicate that deposition occurred in wave-dominated shoreface and deltaic environments. The thickest deposits of the Sikanni Formation occur in the Muskwa-Tetsa River region, west of Fort Nelson, which appears to have been the depocenter of the Sikanni delta. The four stratigraphic sequences present within the Sikanni Formation can be traced over long distances from the Sikanni Chief River area northwards into the Liard Basin. Lack of well control hinders high-resolution correlation, but the Sikanni Formation appears to undergo facies change to shale rapidly eastwards from the western margin of the basin. The internal Sikanni sequences also appear to be present in the Northwest Territories, although very few wells preserve this interval.

Chert pebble lag deposits from transgressive ravinement are present even in thick distal mudstone sections, indicating that the shoreline/delta front migrated basinward considerably during relative sea level falls with a 10^5 year cyclicity. The recognition of four sequences that are widely correlative within the Sikanni Formation in the Liard Basin and elsewhere along the western margin of the foredeep indicates that relative sea level fluctuated more rapidly in the late Albian than has been previously recognized. These high-frequency cycles occur within an overall 10^6 - 10^7 year northward migration of maximum Cordilleran deformation as revealed by subsidence rates and the development

of the Bougie member shoreface, Sikanni and Dunvegan deltas. The repeated flooding events overlying sequence boundaries in the Sikanni Formation, and the lack of evidence elsewhere in the basin for eustatic sea level fluctuations in correlative Upper Albian strata (although similar cycles may be present in the Goodrich Formation) suggest that high-frequency changes in flexural loading due to crustal shortening and later isostatic rebound drove the observed cyclicity. Alternatively, the cyclicity in the Late Albian may have been driven by high-frequency glacio-eustasy and similar, yet unrecognized evidence (in the form of sequence boundaries or correlative conformities) may be present in the Cruiser, Shaftesbury and other equivalent formations in the WCSB.

The Sully Formation, which preserves the Albian-Cenomanian boundary interval, reaches almost 300 m in thickness in the Liard Basin and was deposited over a sequence boundary after a significant basin-wide lowstand in the uppermost Sikanni Formation. The basin-wide flooding surface at the base of the Sully Formation is easy to recognize on well logs throughout the basin. At least one coarsening-upwards cycle occurs below the Fish Scale Interval on the western margin of the basin. The FSM (Fish Scale Marker) interval is expressed as two coarsening-upwards cycles overlain by distinct flooding surfaces, similar to that observed in outcrop along the Liard River. In well logs, the Dunvegan Formation is underlain by the Upper Sully Marker, interpreted as the regional downlap surface onto which the Dunvegan delta prograded.

The lower Sully preserves the *Haplophragmium swareni* Subzone fauna of the latest Albian *Miliammina manitobensis* Zone. The FSM interval occurs 62 m above the base of the Sully Formation in outcrop on the Liard River. It differs from other occurrences in the WCSB in that it is very thick and lacks bioclastic conglomerate, but

otherwise preserves abundant evidence of bottom-water anoxia. In this northern sub-basin of western Canada, high subsidence rates combined with abundant fine-grained sediment supply that characterized Albian-Cenomanian time in the Liard Basin resulted in the muted expression of relative sea level changes in the thick succession in which the Fish Scales Marker interval occurs. In this area, the Fish Scales Marker thus exists as a correlative conformity. Despite the sedimentological differences, similar oceanographic conditions existed in the Liard Basin, with persistent anoxia demonstrated by the elevated TOC levels, absence of foraminifera and preservation of algal cysts. Above the base of the FSM interval, a fauna assigned to the lowermost Cenomanian *Textularia alcesensis* Zone shows the slow recovery of the seaway to more normal marine conditions. The zone is also present in the upper Sully Formation and corroborates earlier studies which demonstrated that the uppermost Sully (and equivalents) and basal Dunvegan Formation are older in the northwest portion of the WCSB because of the southwards progradation of clinoforms associated with the Dunvegan delta.

Chapter X. REFERENCES CITED

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APPENDIX I. FORAMINIFERA COUNTS

Chinkeh, Garbutt and Scatter Outcrops

L2000E (Bulwell Mbr. Opposite Airstrip)

Sample	2	3
Foraminiferal species		
<i>Verneuilinoides tailleuri</i>	10	1
<i>Gaudryina nanushukensis</i>	2	
<i>Saccamina</i> sp.		1
<i>Trochamina</i> sp.		1

L2000L (Chinkeh Fm. along Tributary to La Biche River)

Sample	1	2	3	4	5
Height above base (m)	1.5	2.5	3.9	4.8	5.9
Foraminiferal species		B	B		
<i>Ammodiscus crenulatus</i>	29				
<i>Bathysiphon</i> sp.	2				
<i>Verneuilinoides</i> sp.	1				7
glauconite				p	p
red mineral				a	

L2000N (Chinkeh along "waterslide" tributary to Murky Creek)

Sample	1	3	4	5	8	9	10	11	12	13	14	15
Foraminiferal species	pre-K	B	B									
<i>Ammodiscus</i> sp.								4				
<i>Ammobaculoides</i> sp.							3					
<i>Bathysiphon</i> sp.					1					1		1
<i>Conorbina</i> sp.									4			
<i>Gaudryina canadensis</i>					1		5			12		13
<i>Gaudryina nanushukensis</i>												
<i>Gaudryina stotti</i>				3			4	10	14	1		8
<i>Globulina lacrima</i> Reuss var. <i>canadensis</i>												1
<i>Glomospira corona</i>					2						9	
<i>Glomospira</i> sp.								7		3		11
<i>Gyrodina</i> cf. <i>nitida</i> Stelck et al. 1956												2
<i>Haplophragmoides</i> sp.						1	17		20	36		
<i>Haplophragmoides</i> sp. (small)								45			4	9
<i>Psammionopelta</i> sp.								5				3
<i>Psammospheara</i> sp.											4	
<i>Saccamina</i> sp.								4				
<i>Saracenaria projectora</i>							1					
<i>Trochammina</i> sp.						4					6	
<i>Quinqueloculina</i> cf. <i>sphaera</i> Nauss								9				
<i>Verneuilinoides cummingensis</i>								38	29	36	2	1
<i>Verneuilinoides tailleuri</i>						4			15			
<i>Verneuilinoides</i> sp.				8	(GLAUC)							
glauconite		p	p	a	p				p			
radiolarians				p?								
fish bits					p							

2000P (Chinkeh north of Murky Creek)

Sample	2	4	5	6	7	9
Foraminiferal species	B	pre-K				B
<i>Ammobaculoides</i> sp.			3			
<i>Ammodiscus</i> sp.			1			
<i>Haplophragmoides</i> sp.			10			
<i>Gaudryina stotti</i>			1		7	
<i>Glomospira corona</i>			9			
<i>Saccamina</i> sp.					2	
<i>Textularia</i> sp.				6		
<i>Verneuilinoides</i> sp.					11	
<i>Verneuilinoides cummingensis</i>			11	6		
<i>Verneuilinoides tailleuri</i>				7	8	
molluscs		p				
Conodonts		p				

L2001A (Chinkeh along Murky Creek)

Sample	1	2
Foraminiferal species		
<i>Bathysiphon</i> sp.	1	
<i>Miliammina sproulei</i>	1	
<i>Haplophragmoides</i> sp.	2	
organic matter	a	
glauconite	p	

L2001B (Garbutt-lower Scatter fms. along Murky Creek)

Sample	0	1	2	3	5	7	8	13	14
Height above base (m)	20	0	4.5	10	18	30	36	75	
Foraminiferal species									
<i>Ammobaculites fragmentarius</i>								31	
<i>Ammobaculites wenonahae</i>		2							
<i>Ammobaculites</i> sp.	5	4		3			1		
<i>Ammobaculoides</i> sp.			4						
<i>Ammodiscus</i> sp.			7						
<i>Bathysiphon brosgei</i>			2					2	3
<i>Haplophragmoides linki</i>		18						19	
<i>Haplophragmoides multiplum</i>		2		15				5	
<i>Haplophragmoides sluzari</i>			11	25				14	
<i>Haplophragmoides</i> sp.	5				3				
<i>Gaudryina canadensis</i>		10	7						
<i>Gaudryina nanushukensis</i>	2	2				10		6	5
<i>Miliammina sproulei</i>	8							5	9
<i>Psamminopelta bowsheri</i>				8				2	3
<i>Psamminopelta</i> sp.	7	10							
<i>Psammospheara</i> sp.	4								
<i>Reophax</i> sp.			2	2				11	
<i>Saccamina lathrami</i>	4								
<i>Saccamina</i> sp.			3						
<i>Trochamina</i> sp.		20	2	3				2	
<i>Trochamina</i> sp. high spire									
<i>Uvigerinamina athabascensis</i>		9	3	1				3	
<i>Uvigerinamina manitobensis</i>					1				
<i>Verneuilinoides</i> sp.	10						2		
<i>Verneuilinoides cummingensis</i>		3	12	2	3				5
<i>Verneuilinoides tailleuri</i>						5			

L2001H (Bulwell along Kootaneelee Rv.)

Sample	1	7
Height above base (m)	0	47
Foraminiferal species		
<i>Bathysiphon</i> sp.		1
<i>Verneuilinoides borealis</i>	19	11
<i>Verneuilinoides tailleuri</i>	2	19
<i>Trochammina gatesensis</i>	3	4

L2001J (Garbutt along Toreva Creek)

Sample	1	2	3	6	9
Height above base (m)	0	3	7.5	21	36
Foraminiferal species					
<i>Ammobaculites</i> sp.		2			
<i>Gaudryina nanushukensis</i>		1	3	9	9
<i>Haplophragmoides</i> sp.	6	7			
<i>Psamminopelta</i> sp.		3		1	
<i>Saccammina</i> sp.			1		
<i>Trochammina</i> sp. (tiny)			1		
<i>Verneuilinoides</i> sp.	6	24	3	6	8
<i>Verneuilinoides tailleuri</i>			3	4	

L2001L (Chinkeh and lower Garbutt at Mt. Martin)

Sample	1	2	3	4	5	6
Height above base (m)	19.5	20.8	22.3	26	28.5	31
Foraminiferal species						
glauconitic foraminifera				a		
<i>Ammodiscus</i> sp.	1					
<i>Bathysiphon</i> sp.		4				
<i>Gaudryina canadensis</i>						1
<i>Gaudryina nanushukensis</i>	1	2				
<i>Gaudryina</i> sp.		2				
<i>Haplophragmoides</i> sp. (tiny)		8			13	
<i>Saccamina</i> sp.		1				
<i>Trochammina</i> sp.	12				8	
<i>Verneuilinoides cummingensis</i>					7	2
<i>Verneuilinoides</i> sp.	1	4				
<i>Verneuilinoides tailleuri</i>					2	24
tiny chert pebbles			p			
Glauconite	p	p	a	a		
coalified organic matter	a					
rounded chert grains			a			

L2001N (Bulwell along Petitot Rv.)

Sample	1
Foraminiferal species	
<i>Ammobaculites fragmentarius</i>	13
<i>Saccamina alexanderi</i>	1
<i>Trochammina gatesensis</i>	19
<i>Haplophragmoides linki</i>	4
<i>Verneulinoides borealis</i>	18
<i>Miliammina</i> sp.	3
<i>Gaudryina nanushukensis</i>	3
mica	a

L2002DA (Upper Scatter and lower Lepine opposite Garbutt creek and north of L2002B)

Sample	2	3	4	5	6
Height above base (m)	15	28	38	46	68
Foraminiferal species					
<i>Ammobaculites petilus</i>	2				
<i>Ammobaculites humei</i>		12			
<i>Ammobaculites wenonahae</i>		2	3		
<i>Ammobaculites humei</i>	2				
<i>Ammobaculoides</i> sp.	3				
<i>Bathysiphon</i>	9				
<i>Haplophragmium</i> sp.		?			
<i>Haplophragmoides linki</i>	15				
<i>Haplophragmoides topagorukensis</i>	2	10			
<i>Gaudryina canadensis</i>					1
<i>Gaudryina nanushukensis</i>	1				
<i>Gravellina chamneyi</i>		7			
<i>Miliammina</i> sp.					3
<i>Saccamina</i> sp.					6
<i>Trochammina gatesensis</i>	17	1			
<i>Trochammina</i> sp.		21			
<i>Verneuilinoides borealis</i>	11	28			6
<i>Verneuilinoides</i> sp.			7		12
diatoms	1?			flood	
sulfur	a				

L2002DB (Lepine Formation opposite Lepine Creek)

Sample	1	4	6	7	8	11	12	13	15	16	18	
Height above base (m)	0	42	75	90	111	145	170	199	220	241	271	2
Foraminiferal species												
<i>Ammobaculites fragmentarius</i>												
<i>Ammobaculites obliquus</i>	5											
<i>Ammobaculites petilus</i>												
<i>Ammobaculites tyrelli</i>												
<i>Ammobaculites wenonahae</i>		3	13				1	1	27		14	
<i>Ammobaculites</i> sp.					1							
<i>Ammobaculites</i> sp. Stelck et al 1956												
<i>Ammodiscus mangusi</i>												
<i>Ammomarginulina</i> sp./ <i>Ammotium</i>			11	2	6	13		2			10	
<i>Ammomarginulina cragini</i>												
<i>Ammotium</i> sp.	1											
<i>Bathysiphon brosgel</i>												
<i>Bigennerina</i> sp.			1								3	
<i>Haplophragmoides gigas</i>												
<i>Haplophragmoides collyra</i>												
<i>Haplophragmoides kirki</i>												
<i>Haplophragmoides linki</i>												
<i>Haplophragmoides postis</i>												
<i>Haplophragmoides</i> sp.			7					1				
<i>Hippocrepina</i> sp.			1									
<i>Gaudryina canadensis</i>				1								
<i>Gaudryina nanushukensis</i>												
<i>Gaudryina</i> sp.	10										10	
<i>Glomospirella</i> sp.												
<i>Miliammina sproulei</i>												
<i>Miliammina manitobensis</i>												
<i>Psamminopelta bowsheri</i>											2	
<i>Psamminopelta</i> sp.				1								
<i>Psammospheara</i> sp.												
<i>Pseudobolivina variana</i>												
<i>Pseudobolivina</i> sp.											1	
<i>Reophax</i> sp.			1									
<i>Reophax vasiformis</i>						6						

[illegible]

<i>Saccammina alexanderi</i>												1
<i>Saccammina lathrami</i>												
<i>Saccammina</i> sp.												
<i>Textularia riowensis</i>												
<i>Textularia</i> sp.	1											
<i>Trochammina gatesensis</i>								3				
<i>Trochammina rutherfordi</i>												
<i>Trochammina umiatensis</i>												
<i>Trochammina</i> sp.												9
<i>Uvigerinammina manitobensis</i>					1							
<i>Uvigerinammina</i> sp.												
<i>Verneulina canadensis</i>												
<i>Verneulinoides borealis</i>	16	6	36	7	10	45	20	9	38	5	22	
<i>Verneulinoides tailleuri</i>	10		9									
<i>Verneulinoides</i> sp.						4						
polished spherical things			6	6								
rust-stained spheres				52								y
polished flattened objects												
diatoms												
algal cysts			y	y								

[illegible]

<i>Uvigerinammina manitobensis</i>	2		2		8	2		2	4
<i>Verneuilinoides borealis</i>	40		8	22	7	12	6	26	23
<i>Verneuilinoides tailleuri</i>	9		1		1	1			
polished flattened objects								p	

Sikanni Formation

L000D (Sikanni at Steamboat Mountain)

(next two pages)

Steamboat Mountain L2000 Locality D

Locality designation															
Sample	1	2	3	4	5	6	8	10	13	15	17	18	20	21	24
Height above base	0.0	5.0	14.0	18.0	24.0	29.0	45.0	50.0	65.0	80.0	90.0	95.0	103.0	104.0	116.5
Foramiferal Species											B				
<i>Ammobaculites fragmentarius</i>	10	16	27	71	6	20		2					26	26	12
<i>Haplophragmium swareri</i>	9	3	9	7	13	6								8	3
<i>Gravellina chamneyi</i>	4			5		3								3	
<i>Verneulinoides borealis</i>		8			6	7						3	22	37	
<i>Trochammina umlatensis</i>				1		5							3	1	
<i>Trochammina alcanensis</i>		1	14	6	5	5							21	16	
<i>Psammimopelta howsheri</i>		6			1								9	12	1
<i>Reophax vasiformis/sikaniensis</i>				6								2	19	9	4
<i>Verneuilina canadensis</i>		3													
<i>Verneulinoides</i> sp.															
<i>Saccammina alexanderi/lathrami</i>		1	4	1	3	3	2	1	1					25	5
<i>Miliammina spruillei</i>			2	1	3								16	3	2
<i>Miliammina subepletica</i>			3			3				1					
<i>Miliammina manitobensis</i>															11
<i>Verneulinoides tailleurii</i>				15	6	4							6	4	3
<i>Miliammina awunensis</i>			8										7		
<i>Miliammina</i> sp.															
<i>Haplophragmoides postis</i>				23	9	3			2					1	48
<i>Uvigerinammina manitobensis</i>					1										
<i>Saccammina lathrami</i>												3	7		
<i>Bathysiphon brosgel</i>													2	5	2
<i>Hippocrepina</i> sp.													2		
<i>Glomospirella</i>														3	
<i>Gaudryina canadensis</i>														4	
<i>Eggerella</i> sp.														1	
<i>Textularia minuta</i>															
<i>Verneuilina alameda</i>															
<i>Reophax minuta</i>															
<i>Textularia</i> sp. Sutherland and Stelek															
<i>Textularia gravenori</i>															
<i>Pseudobolivina</i> sp.															
<i>Glomospira reata</i>															
<i>Glomospirella elongata</i>															
<i>Textularia riowensis</i>															
<i>Ammobaculites</i> sp. B Sutherland and Stelek															
<i>Ammodiscus</i> sp.															
<i>Trochammina wetteri</i>															
<i>Trochammina rainwateri</i>															
<i>Ammotium</i> sp.															
<i>Gaudryina</i> sp.															
<i>Ammobaculoides</i> sp.													6	1	19
cf. <i>Quinqueloculina sphaera</i>					2	2									7
<i>Trochammina high spire</i>				2									5	2	
<i>Reophax</i> sp.				1											
<i>Haplophragmoides</i> sp.		2	8										48	14	13
<i>Ammobaculites</i> fragments	12		31	42	30	44							30	59	32
<i>Miliammina</i> sp.												3			11
<i>Psammospaera</i> sp.												3	20	12	
fragments													66	60	
fish bits															
diatoms															
radiolarians															

[illegible]

[illegible]

67	68	69	71	72	73	75	76	77	79	81	84	85	86	87	90	91	93	92
0	274.3	274.6	280.6	291.3	292.8	293.3	296.8	334.0	341.1	351.4	358.9	376.4	377.0	334.0	347.0	354.5	360.4	360.7
																B		
		2	5	8					7	2			1	11				
22	8		10					1										
									1									
9		6		4			2	7	4									
9	7	38	34	15					2			4		2				
2									2						1			
9	6			7		2		18	4	9								
												2		3				
																	4	
		30	13	5					4				5					
2								4			7	2	46	9				
3	5		6					5										
5	1	10	27															
1			4	2			1			1	2	3	8	4	1			
						1							2					
		2																
	4																	
		27	6	1						8								
	6	12							1	4								
		3								2								
		2																
															1			
																8		
																	6	
			13									1				2		
												1				1		
									6	7		1						
			8															
													1					
							flood											
												p						

L2002G, L2001K(A) (Sikanni Formation opposite Scatter River)

Locality designation	L2002G						L2001K(A)													
Sample	1	2	3	4	5	6	1	2	4	5	6	7	8	10	11	12	13	14		
Height above base (m)	10	0.5	19	21	27	32	45	51	65	76	79	84	94	108	116	120	126	136		
Foraminiferal Species																				
<i>Ammobaculites fragmentarius</i>	23	8	50	20	52	15	31		33											
<i>Haplophragmium</i> sp.							8	1												
<i>Uvigerinammina manitobensis</i>							4	5	3	5			1		1					
<i>Verneuilinoides borealis</i>	6	2	9	9	4	4	1	9	1		6	9	5							
<i>Saccamina alexanderi</i>					9		16				2	15		46	11	1	70			
<i>Reophax sikanniensis</i>					2															
<i>Saccamina lathrami</i>								6												
<i>Reophax vasiformis</i>							1	5		1	2	2	16				1	1		
<i>Gaudryina</i> sp.							1								1					
<i>Psammosphaera</i> sp.							6	2					6		1		8	1		
<i>Haplophragmoides linki</i>	9		13	14	13	9														
<i>Haplophragmoides postis</i>							18	22	38	2	22	13	13	12	5		11			
<i>Miliammina awunensis</i>						3	4		7		6	33		43		13				
<i>Miliammina sproulei</i>							24	2	101											
<i>Psamminopelta bowsheri</i>							1		2								1			
<i>Miliammina manitobensis</i>	3	12		19	16	23		17	25		20	38	22	31	21		20			
<i>Glomospira</i> sp.									5		2									
<i>Trochammina umiatensis</i>					5				5	7	5	11		35		4	20			
<i>Verneuilinoides tailleuri</i>					6				4	30		8	2	2		3				
<i>Bathysiphon brosgei</i>		4		2	2	4		2	5	1	2	28	5	18			28			
<i>Gravellina chamneyi</i>					1				3											
<i>Ammobaculoides</i> sp.									8											
<i>Haplophragmium swareni</i>					2			69	1	1	10		7		1		7			
<i>Gaudryina canadensis</i>									1											
<i>Quinqueloculia</i> sp.								12				16		25		2				
<i>Glomospirella</i>								3												
<i>Verneuilina canadensis</i>								1												
<i>Miliammina</i> sp.										8										
<i>Haplophragmoides</i> sp.								5	11	3		3		9		3	3			
<i>Ammobaculites</i> fragments							72	28	59		10	2								
<i>Textularia riowensis</i>											2	10	4							
<i>Pseudobolivina variana</i>	1		5								4									
<i>Textularia</i> sp.											2					3				
foram fragments												30		50			18			
<i>Trochammina</i> high spire													1							

	13	14
	126	136
	70	
	1	1
	8	1
	11	
	1	
	20	
	20	
	28	
	7	
	3	
	18	

L2002E (Sikanni Formation NE of Lepine Creek (Stott Section 65-15))

Locality designation	L2002E					
Sample	1	2	3	4	5	6
Height above base (m)	- 4	8.4	17	26	44	55
Foraminiferal species						
<i>Verneuilina canadensis</i>	5					
<i>Ammobaculites fragmentarius</i>	1	37	11	2	15	
<i>Miliammina manitobensis</i>	9	5	15	4	20	4
<i>Haplophragmoides</i> sp.	4	14	4		7	
<i>Trochammina umiatensis</i>		6	1		1	
<i>Bathysiphon brosgiei</i>	1	9	11		1	
<i>Saccammina</i> sp.		1				
<i>Psamminopelta bowsheri</i>		2				
<i>Miliammina awunensis</i>		4				
<i>Verneuilinoides borealis</i>		5	2	15	19	
<i>Reophax vasiformis</i>		7			2	
<i>Pseudobolivina variana</i>		8	10		3	
<i>Uvigerinammina manitobensis</i>		4				
<i>Miliammina sproulei</i>			12			
<i>Textularia</i> sp.			3			
<i>Gaudryina canadensis</i>	1			4	1	
<i>Saccammina alexanderi</i>					7	

Sully Formation

(next page)

L2002H, L2001K(C), L2002I, L2001K(B) (Sully Formation opposite Scatter River)

[illegible]

• River)

21	L2001K(C)					L2001K(B)																		
1	7	8	9	10	11	1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
68	72	83	91	103	110	111	116	128	134	142	149	154	159	166	174	184	193	207	222	244	248	262	274	281
	B							B					B		B					B	B			B
																6								
			2		1						5													
			1																					
6																								
1																								
														13		26	1							
1				1		1	1			2	9													
5			1	1			1					2												
			1														12	1	2	1				2
							1			5														
											1		15					2				15	11	
									8		1													
									4															
										2				19		40		1						
											4			6		7			2			3		
												7		11		16		7					19	
																1						1		
3												5				3						2	11	
	C	R	V	V	V	C	V						R	R	S	R							S	
									x															
	A	A	A					C		C	C				C	R			C					
	A	V	V	C	C			R	R	R	R				R									
		A	C	C		C		C	R	R			C	R	C	R			C					
	C	C	C		C	C		C						R	A			V	C	V	C		C	C
	A																		C		A	V	V	V
																	A		A			V		V
																				V				

British Columbia Core**A-26-B/94-O-11**

Sample	2	3	4	5	6	7	9
Foraminiferal species							
<i>Ammobaculites</i> sp.	2	1					
<i>Ammobaculites fragmentarius</i>			3			7	21
<i>Haplophragmoides</i> sp. (small)		1	18	4	3		9
<i>Trochammina</i> sp. (small)			5			8	
<i>Verneuilinoides borealis</i>			4	3	1		3
<i>Gaudryina nanushukensis</i>			2				
<i>Reophax</i> sp.			4			2	
<i>Saccammina</i> sp.			1	1			
<i>Ammobaculites wenonahae</i>			9	1	7		
<i>Ammobaculites petilus</i>				2	6		
<i>Gaudryina canadensis</i>							1
<i>Verneuilinoides tailleuri</i>					1		
<i>Verneuilina canadensis</i>						3	
<i>Textularia riowensis</i>						9	
<i>Miliammina manitobensis</i>						1	1
algal cysts			p	p	p		
mica			a		a		
pyrite						a	

A-60-B/94-O-11

Sample	1	3	5	6	7
Foraminiferal species	B		B		
<i>Ammobaculites</i> sp.				3	
<i>Gaudryina nanushukensis</i>				9	7
<i>Haplophragmoides</i> sp.				3	
<i>Verneuilinoides borealis</i>				11	4
<i>Verneuilinoides tailleuri</i>				5	2
rust-stained spheres		a		1	
woody organic matter		a	a		
glauconite		p		a	a
gypsum		p			p

A-77-D/94-O-11

Sample	2	3
Foraminiferal species		
<i>Ammobaculoides</i> sp.	8	
<i>Gaudryina nanushukensis</i>	5	5
<i>Haplophragmoides</i> sp.	17	7
<i>Psamminopelta</i> sp.	4	
<i>Verneuilinoides borealis</i>	11	6
<i>Verneuilinoides tailleuri</i>	5	
framboidal pyrite	p	p
mica	P	p
glauconite		p

B-53-B/94-O-14

Sample	1	3	Per 1	Per 2
Foraminiferal species			B	B
<i>Ammobaculites fragmentarius</i>	1	13		
<i>Ammodiscus rotarius</i>	4			
<i>Haplophragmoides linki</i>	4	11		
<i>Gaudryina tailleuri</i>	9	13		
<i>Verneuilinoides borealis</i>	10			
<i>Miliammina</i> sp.	1			
<i>Reophax minuta</i>		19		
<i>Textularia</i> sp.		4		
<i>Gaudryina</i> sp.		3		
<i>Saccammina lathrami</i>		1		
radiolarians		a		
bentonite			p	
fish debris				p
framboidal pyrite			p	

B-53-G/94-O-11

Sample	1
Foraminiferal species	
<i>Verneuilinoides</i> sp.	10
<i>Trochammina</i> sp.	2
<i>Gaudryina nanushukensis</i>	3

B-55-E/94-O-13

Sample	6	7	8	10	13A	20	22	24	27
Foraminiferal species									
<i>Ammobaculites fragmentarius</i>	6				5	12			
<i>Ammobaculites tyrelli</i>			14	14					
<i>Ammobaculites wenonahae</i>		1							
<i>Ammobaculites</i> sp.								2	
<i>Ammotium</i> sp.								1	4
<i>Gaudryina nanushukensis</i>							3	2	1
<i>Haplophragmoides</i> sp. (small, involute)			10	10	12	35	5		2
<i>Miliammina manitobensis</i>		4							
<i>Psammospheara</i> sp.			2	4					
<i>Pseudobolivina</i> sp.				4	5	2			
<i>Reophax vasiformis</i>	2	2			7	14			
<i>Trochammina umiatensis</i>						10			
<i>Trochammina</i> sp.					13				
<i>Uvigerinammina manitobensis</i>	1		1?	4?			2		
<i>Verneuilinoides borealis</i>	14	1	7	9	14	2		4	5
<i>Verneuilinoides tailleuri</i>	2	1		9	4	9		2	3
rust-stained spheres	p			p	6				
shiny spheres		1							
algal cysts				p					

B-59-I/94-O-11

Sample	1	3	5	8
Foraminiferal species	B	B	B	
<i>Gaudryina nanushukensis</i>				2
flaky organic matter	a	a	a	
fish debris			p	
gypsum	p	p		
mica	p			
woody organic matter	p			

B-66-D/94-O-15

Sample	2	4
Foraminiferal species		
<i>Ammobaculites fragmentarius</i>	13	4
<i>Bathysiphon brosgel</i>		7
<i>Gaudryina nanushukensis</i>	8	19
<i>Haplophragmoides linki</i>	2	6
<i>Miliammina</i> sp.		2
<i>Reophax</i> sp.		4
<i>Saccammina alexanderi</i>	21	7
<i>Ammobaculoides</i> sp.	13	
<i>Verneuilinoides tailleuri</i>	1	
<i>Haplophragmoides sluzari</i>	9	
<i>Gaudryina tailleuri</i>	1	
mica		a

D-75-E/94-N-08

Sample	7	8
Foraminiferal species		
<i>Ammobaculites fragmentarius</i>	17	1
<i>Gaudryina tailleuri</i>	9	1
<i>Bathysiphon</i> sp.	2	
<i>Saccammina alexanderi</i>	8	
<i>Miliammina ischnia</i>	2	
<i>Ammobaculites wenonahae</i>	1	
<i>Trochammina</i> sp.	41	7
<i>Gaudryina nanushukensis</i>		9
<i>Verneuilinoides borealis</i>	1	
pyritized		y

Northwest Territories Core***Imperial Sun Aurora M-47***

Sample	3	4	6
Foraminiferal species			
<i>Verneuilinoides tailleuri</i>	9		12
<i>Verneuilinoides borealis</i>	7		10
<i>Haplophragmoides multiplum</i>	1		
<i>Trochammina gatesensis</i>	5		
<i>Ammobaculites minuta</i>	2		
<i>Miliammina</i> sp.			1
<i>Trochammina</i> sp.			4

Fort Liard K-32

Sample	1	2	4	7	6
Foraminiferal species		B	B	B	
<i>Ammobaculites humei</i>	65				
<i>Ammobaculoides</i> sp.	5				
<i>Haplophragmoides</i> sp.					3
<i>Miliammina</i> sp.					2
<i>Textularia topagorukensis</i>	27				
<i>Trochammina mcmurrayensis</i>	11				
<i>Verneuilinoides cummingensis</i>					11
diminutive foraminifera	y				y

Imperial Sun Netla Raven F-73

Sample	3
Foraminiferal species	
<i>Verneuilinoides tailleuri</i>	3
<i>Verneuilinoides borealis</i>	3
glauconite	p
woody organic matter	p
mica	p

Imperial Island River No. 1 (I-G50)

Sample	1	2
Foraminiferal species		B
<i>Verneuilinoides borealis?</i>	1	
framboidal pyrite	p	p
shiny spherical things	p	p
rust stained disc and spherical things	p	p

IOE Arrowhead L-49

Sample	1	2	3
Foraminiferal species	B	B	B

Shell Arrowhead B-41

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Foraminiferal species	B		B	B	B		B	B					
<i>Ammobaculoides</i> sp.						3				1			
<i>Ammodiscus</i> sp.											3		
<i>Bathysiphon</i> sp.		2											
<i>Gaudryina tailleuri</i>											3		3
<i>Haplophragmoides sluzari</i>											3		
<i>Haplophragmoides</i> sp.													6
<i>Psamminopelta</i> sp.		6				2							
<i>Pseudobolivina</i> sp.													
<i>Saccamina</i> sp.		4							3	1			
<i>Trochammina</i> sp.													3
<i>Verneuilinoides cummingensis</i>									3				
<i>Glomospira</i> sp.											1		
glauconite													
fish bits/phosphatic debris											a		a
radiolarians												a	a
organic material				a		p	p	p			a		
pyrite										a	a		
abraded foraminifera									y				

APPENDIX II.

GSC Reconnaissance Samples (from Larry Lane, GSC-Calgary, NATMAP)

Sample	2000L HA27-2	2002L HA14-1	2002L HA14-5	2002L HA15-2	2002L HA16-6	2002L HA17-3A	2002L HA17-3B	HA17-3C
C-Number	C-417628	C-417877	C-417880	C-417885	C-417887	C-417890	C-417889	
Map Sheet	95B/4	95B/12	95B/12	95B/1	95B/12	95B/12	95B/12	
NTS Easting	447133	450813	449037	550306	451388	464950	464950	
NTS Northing	6678832	6712299	6710478	6674456	6712381	6714161	6714161	6674456
Foraminiferal species								
<i>Ammobaculites fragmentarius</i>					38	6		
<i>Ammobaculites petilus</i>					9			
<i>Ammobaculites wenonahae</i>	2							
<i>Ammobaculites</i> sp.	27						3	
<i>Ammotium</i> sp.						3?		
<i>Bathysiphon brosgel</i>						7		
<i>Gaudryina canadensis</i>	6			4	2	3		
<i>Gaudryina nanushukensis</i>							7	
<i>Gaudryina</i> sp.								
<i>Glomospira</i> sp.								
<i>Haplophragmium swareri</i>					2			
<i>Haplophragmoides</i> sp.	4						1	
<i>Haplophragmoides postis</i>		5						
<i>Haplophragmoides</i> sp. (tiny)			3	36	8	30		
<i>Haplophragmoides</i> sp. inflated								
<i>Miliammina manitobensis</i>					2	1?		
<i>Miliammina sproulei</i>								
<i>Psamminopelta bowsheri</i>								
<i>Psamminopelta</i> sp.								
<i>Saccammina</i> sp.						1		
<i>Textularia</i> sp.			2					
<i>Trochammina</i> sp. (small)					9			
<i>Uvigerinammina manitobensis</i>								
<i>Verneuilinoides borealis</i>	22				1	9	3	
<i>Verneuilinoides tailleuri</i>	2				1	6		
<i>Verneuilinoides</i> sp.			3				7	
algal cysts			FLOOD					
rust-stained spheres								
conical rads								
spherical rads								
discoid rads								
pyritized forams								
woody organic debris	p							
glauconite	p							
gypsum/selenite		p						p
sulfur								

[illegible]

GSC SAMPLES

202L -1A	2002L HA21-1B	2002L HA21-2	2002L HA30-2	2002L HA32-2	2002F NA13-3	2002F NA20-4	2002F NA26-4A	2002F NA26-5	2002GF H26-3	2002LCP 95-1-1	2002L CP97-1-1
C- 899	C- 417900	C- 417901	C- 417915	C-417922	C- 416646	C- 416664	C- 416673	C- 416675	C- 417831	C- 432005	C- 432006
B/6	95B/6	95B/6	95C/8	95B/13	95C/15	95B/5	95C/6	95C/3	95C/6	95C/15	95C/15
630	496630	496838	444589	447353	402356	470186	363679	388010	371407	409873	410437
900	6689900	6690193	6693710	6739959	6752425	6695352	6702504	6673352	6695525	6738422	6751745
	37	44						14			
		1									
						3					
						1					
	2				2		1		7		
2					5						6
6					8	19 large					5
	3			3							
1								1			
7		18								8	
	18						2	4	7		
				Abundant	74						28
	2							6			
						3					
	3				2						
	6					2			2	1	
3	15							6			
											2?
2	7	9				9			5		
5	1				2				4		
			slender	1	2		1?	12			
	1										
			a								
			a								
			a								
			a								
											p
	p				a				r		
								p			
								r			

Biostratigraphy of GSC Reconnaissance Samples

Locations of samples collected by GSC geologists are given in table on preceding page. The interpreted biostratigraphic range of each sample is provided in this section.

C-417628

- 2 (=Box number on slide). *V. tailleuri*-2
- 2. *Ammobaculites* -27
- 3. *G. canadensis*?-6 (poor preservation)
- 4. *Ammobaculites wenonahae*?-2
- 5. *Haplophragmoides* sp. (small)-4
- 6. *V. borealis* (small)-22

Biostratigraphic range: Lower to middle Lepine based on presence of *A. wenonahae*; fauna does not contain typical elements of lower or upper Sully, and definitely not middle Sully (which is the FSMB)

C-417801

Not processed

C-417877

- 1. (large and small) evolute *Haplophragmoides*-5

Biostratigraphic range: atypical of Lepine or Sully Fm.; possibly stressed fauna within Lepine

C-417879

Not processed

C-417880

- 1. flood of algal cysts
- 2. diminutive *Haplophragmoides* sp.-3
- 3. *Verneuilinoides* sp.-3
- 4. *Textularia* sp.? -2

Assignment: floods of algal cysts rare in the Liard basin- have only been found in the FSMB; foraminiferal fauna is diminutive and of very low abundance and diversity. Could be FSMB within middle Sully (although no gypsum is present) or another major flooding surface overlying a sequence boundary

C-417885

1. extremely diminutive and flat *Haplophragmoides* sp. -36
2. extremely diminutive *Gaudryina canadensis*?-4

This sample contains a highly stressed and diminutive fauna of only two or three genera with a high abundance of *Haplophragmoides* sp. and is extremely organic-rich. It is probably associated with a major flooding surface like that of the basal Lepine or FSMB.

C-417887

- 1-A. *fragmentarius*-38
25. *A. petilus*-9
38. *Haplophragmium swareni*-2
2. *Haplophragmoides* small-8
3. *Trochammina* sp. (small)-9
4. *Miliammina manitobensis*-2
5. *V. borealis*-1
6. *V. tailleuri*-1
7. *G. canadensis*-2

This fauna is most typical of the upper Lepine formation, possibly *M. manitobensis* Zone.

C-417890

1. *A. fragmentarius*-6
2. *Haplophragmoides* small-30
4. *Bathysiphon* sp.-7
5. *M. manitobensis*?-1
6. *G. canadensis*-3
7. *V. borealis*-9
9. *V. tailleuri*-6
10. *Saccammina* sp. -1
15. *Ammotium* sp.? (very diminutive)-3

C-417889

1. *Ammobaculites* sp.?-3
2. *Haplophragmoides* sp.-1
4. *Verneuilinoides* sp.-7
- 3,5. *G. nanushukensis*-7
7. *V. borealis*-3

Clearly *G. nanushukensis* Zone

C-417899

1. *G. nanushukensis*-6
2. *Haplophragmoides* sp (small)-7
3. *G. canadensis*-2
5. *V. tailleuri*-5
6. *Glomospira* sp. -1
7. *V. borealis*-2
12. *Trochammina* sp.-3

Age: Presence of *G. nanushukensis* would indicate this is probably the Garbutt Formation., although *G. nanushukensis* may occur within the Lepine. Agglutination coarser and slightly darker than 41700 and 41701 and prominent absence of *Ammobaculites* (which is more typical of Garbutt).

C-417900

1. *A. fragmentarius*-37
2. *Haplophragmoides* sp. (small)-18
3. *Trochammina* sp. (small)-15
4. *V. borealis*-7
5. *Psamminopelta* sp.? -3
6. orange spherical thing-1
7. *Gaudryina* sp.-3
8. *Miliammina sproulei*-2
9. *Saccammina* sp. -6
10. (minute) *V. tailleuri*?-1
12. *Bathysiphon* sp. -2

Age: fauna is not completely diagnostic but typical of upper-middle and upper parts the Lepine formation.

C-417901

1. *A. fragmentarius*-44
2. *Haplophragmoides* sp. (small)-18
31. *A. petilus*-1
3. *V. borealis*-9

Age: this fauna can be assigned tentatively to the Lepine formation (middle to upper part like in 417900) although it is not diagnostic. It does not appear to be from the Garbutt Formation.

C-417915

1. conical rads
2. spherical rads
3. discoid rads, diatoms or foraminifera?—some of these probably *Haplophragmoides*
4. isolated pyritized specimens of *Verneuilinoides* sp, *Reophax* sp, and *V. tailleuri*? (slender elements typical of other samples from lower Garbutt formation in core)

This sample is unique as it contains abundant pyritized? radiolarians of conical and spherical morphology. This is typical of a limited stratigraphic interval in the lower Garbutt formation (elsewhere this the radiolarian biofacies has been found as primary silica within bentonites and as glauconite).

C-417922

- 1,2. large number of discoid to spherical *Haplophragmoides* looking things---ask Claudia
4. *Gaudryina* sp. -3
4. *Verneuilinoides* sp. -1

C-416646

- 1-7. Inflated *Haplos*?- large number of dark ones--~74 (compare to C-417922)
9. *Psamminopelta* sp. -2
10. *Verneuilinoides* sp.-2
18. *G. nanushukensis*-8
19. *G. canadensis* (diminutive)-5
20. *Bathysiphon* sp.-2
28. *V. tailleuri*-2

Garbutt fauna.

C-416664

All tests large and bleached in colour

- 1-3. *G. nanushukensis* (robust forms)-19
4. *Ammobaculites* -1 (large)
6. *Ammobaculites wenonahae*?-3
7. *Saccamina* sp.-2
8. *Psamminopelta bowsleri*-3
9. *V. borealis*?-9 (very large)

This is an unusually diverse and robust fauna not found in any other Chinkeh strata with distinctive *G. nanushukensis*. The forams are relatively coarsely agglutinated and large.

C-416673

2. tiny *Haplophragmoides*-2
3. tiny *Bathysiphon*-1
4. questionable *Verneulinoides*-1

This is a stressed fauna and hence little biostratigraphic info present.

C-416675

2. *Ammobaculites fragmentarius* (*slender)-14
3. *Haplophragmoides* sp. (small)-4
4. *Verneulinoides* sp (small). -12
5. *Miliammina sproulei* (almost manitobensis)-6
6. *Glomopsira* sp.? -1
13. *Trochammina* (mostly tiny)-6

Age: fauna not particularly diagnostic

C-417831

1. *V. tailleuri*? -4 (long and slender, diminutive)
2. *Haplophragmoides*-7
4. *Bathysiphon*-7
5. *Saccammina*-2
6. *V. borealis*?-5

Age: fauna not particularly diagnostic, but slender *V. tailleuri* may indicate lower Garbutt

C-432005

1. *Saccammina* sp.-1
2. *Haplophragmoides* sp. (small and flattened) -8

Age: stressed fauna, age not clear

C-432006

1. large and smaller inflated *Haplophragmoides*-28
4. *G. nanushukensis*-5
5. slender *G. canadensis*-6
6. *Uvigerinammina manitobensis*??-2

Age: this sample is definitely Garbutt, probably in the lower to middle part of the formation.

APPENDIX III. ROCK-EVAL DATA

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
9107	100.0	441	0.86	12.75	0.48	0.06	26.56	1.14	4.90	262	10
1 D1	100.2	444	0.10	1.42	0.21	0.06	6.76	0.13	1.62	89	13
2 D3	100.2	434	0.04	0.73	0.65	0.05	1.12	0.08	1.52	49	43
3 D5	100.8	438	0.06	1.33	0.06	0.04	22.17	0.12	1.45	93	4
4 D7	100.2	439	0.07	1.48	0.25	0.04	5.92	0.14	1.54	97	16
5 D8	100.2	439	0.12	1.27	0.00	0.09	0.00	0.12	1.34	96	0
6 D10	100.4	435	0.11	0.86	0.01	0.12	86.00	0.08	1.39	63	1
7 D12	100.5	440	0.05	0.72	0.00	0.07	0.00	0.07	0.65	112	0
8 D14	100.2	438	0.12	1.83	0.08	0.06	22.88	0.17	1.50	123	5
9 D16	99.9	438	0.20	2.62	0.06	0.07	43.67	0.24	1.60	165	4
10 D20	100.9	438	0.04	1.06	2.03	0.04	0.52	0.10	1.64	65	124
11 D21	100.0	436	0.04	0.83	1.29	0.04	0.64	0.08	1.54	55	84
12 D24	100.6	443	0.03	0.39	0.86	0.08	0.45	0.04	0.89	45	97
9107	100.2	438	1.05	12.93	0.47	0.07	27.51	1.17	4.95	262	9
13 D25	99.7	439	0.07	0.84	1.61	0.07	0.52	0.08	1.22	70	132
14 D27	100.5	439	0.04	0.62	1.67	0.06	0.37	0.06	1.16	54	144
15 D29	100.5	441	0.01	0.35	1.40	0.04	0.25	0.04	0.95	38	147
16 D31	100.8	439	0.03	0.81	0.71	0.04	1.14	0.08	1.24	66	57
17 D34	100.6	440	0.09	0.82	0.02	0.10	41.00	0.08	0.72	115	3
18 D38	99.7	439	0.03	0.63	0.27	0.04	2.33	0.06	0.95	67	28
19 D39	100.2	439	0.04	0.44	0.10	0.09	4.40	0.04	0.49	92	20
20 D40	99.8	439	0.44	4.43	0.03	0.09	147.67	0.41	2.34	191	1
21 D41	100.0	441	0.13	1.46	1.92	0.08	0.76	0.14	1.45	102	132
22 D42	99.7	440	0.07	0.89	1.09	0.07	0.82	0.08	0.94	96	116
23 D44	100.2	438	0.13	4.85	0.75	0.03	6.47	0.44	3.02	162	25
24 D45	100.2	437	0.10	2.79	0.01	0.04	279.00	0.25	1.91	148	1
25 D46	100.5	439	0.06	0.95	1.36	0.06	0.70	0.09	1.45	67	94
26 D47	99.9	439	0.03	1.16	0.51	0.03	2.27	0.11	1.70	69	30
9107	99.8	438	1.06	13.13	0.48	0.07	27.35	1.19	4.93	268	10
27 D48	100.3	434	0.05	1.71	0.39	0.03	4.38	0.15	1.50	115	26
28 D51	100.7	436	0.05	1.04	0.71	0.05	1.46	0.10	1.24	85	57
29 D52	99.8	436	0.05	0.82	0.69	0.06	1.19	0.08	1.04	80	66
30 D53	100.0	440	0.02	0.73	0.61	0.03	1.20	0.07	1.21	61	50
31 D54	100.9	439	0.01	0.11	0.56	0.05	0.20	0.01	0.42	26	133
32 D55	100.7	438	0.05	1.14	0.04	0.04	28.50	0.10	0.94	122	4
33 D57	100.1	437	0.08	1.32	0.31	0.06	4.26	0.12	1.11	121	28
34 D59	10.2	438	21.97	135.39	0.76	0.14	178.14	13.32	71.44	191	1
9107	100.2	440	0.99	12.14	0.46	0.07	26.39	1.11	4.97	246	9
35 D60	100.3	435	0.03	0.67	1.28	0.04	0.52	0.07	1.19	57	108
36 D62	100.3	439	0.23	3.28	0.23	0.06	14.26	0.30	2.29	145	10
37 D63	100.4	444	0.07	1.70	0.19	0.04	8.95	0.15	1.60	108	12
38 D65	100.3	432	0.05	0.92	0.94	0.05	0.98	0.09	1.38	67	68
39 D67	100.4	439	0.02	0.54	0.83	0.03	0.65	0.05	1.13	49	73
40 D69	100.6	439	0.03	0.97	0.52	0.03	1.87	0.09	1.31	76	40
41 D70	100.2	437	0.03	1.08	0.22	0.02	4.91	0.10	1.31	83	17

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
42 D73	100.4	438	0.03	1.05	0.26	0.03	4.04	0.09	1.14	93	23
43 D75	100.7	438	0.04	2.60	2.00	0.02	1.30	0.24	3.43	77	58
44 D76	100.6	441	0.01	0.47	0.65	0.02	0.72	0.04	0.93	52	70
45 D78	99.9	444	0.04	0.75	3.11	0.05	0.24	0.07	1.53	50	203
46 D80	100.0	440	0.02	0.75	0.15	0.03	5.00	0.07	0.72	106	21
47 D81	100.3	441	0.03	0.61	0.22	0.04	2.77	0.05	0.62	100	35
48 D84	99.9	439	0.06	0.83	0.53	0.06	1.57	0.07	0.92	91	58
9107	99.9	441	0.99	12.36	0.42	0.07	29.43	1.12	4.96	251	8
49 D85	100.6	441	0.01	0.33	0.86	0.04	0.38	0.03	0.81	42	106
50 D86	100.4	444	0.01	0.15	0.53	0.04	0.28	0.02	0.48	31	110
51 D88	100.3	441	0.02	0.74	0.00	0.03	0.00	0.07	0.77	97	0
52 D93	100.4	438	0.06	1.52	1.26	0.04	1.21	0.15	1.74	89	72
53 L2002G1	100.4	429	0.03	1.00	0.78	0.02	1.28	0.09	1.45	70	54
54 L2002G2	100.8	436	0.05	0.78	0.24	0.06	3.25	0.07	0.93	85	26
55 L2002G3	100.6	432	0.04	1.32	0.90	0.03	1.47	0.12	1.39	96	65
56 L2002G4	100.0	429	0.02	0.95	0.21	0.02	4.52	0.09	1.08	89	19
57 L2002G5	101.0	428	0.09	1.73	0.45	0.05	3.84	0.16	1.36	128	33
58 L2002G6	100.0	428	0.05	1.24	0.83	0.04	1.49	0.12	1.51	83	55
59 L2001KA1	100.3	433	0.04	0.89	0.64	0.04	1.39	0.08	1.07	84	60
60 L2001KA2	100.9	428	0.05	1.66	0.86	0.03	1.93	0.15	1.61	104	53
61 L2001KA3	100.0	427	0.32	1.90	0.29	0.14	6.55	0.19	1.40	136	21
62 L2001KA4	100.3	429	0.05	1.43	0.66	0.03	2.17	0.13	1.49	97	44
9107	100.4	440	0.99	12.30	0.52	0.07	23.65	1.12	4.97	249	10
63 L2001KA5	100.0	428	0.03	1.02	1.27	0.03	0.80	0.09	1.32	78	96
64 L2001KA6	100.0	435	0.02	0.72	1.30	0.02	0.55	0.07	1.26	58	103
65 L2001KA8	100.4	432	0.02	0.87	0.44	0.02	1.98	0.08	1.25	70	35
66 L2001KA9	100.0	432	0.02	0.96	0.58	0.02	1.66	0.09	1.25	78	46
67 L2001KA10	100.3	432	0.02	0.80	0.40	0.02	2.00	0.07	1.28	63	31
68 L2001KA11	100.1	432	0.03	1.21	0.71	0.02	1.70	0.11	1.60	77	44
69 L2001KA12	100.6	439	0.02	0.74	0.96	0.03	0.77	0.07	1.35	56	71
9107	100.3	438	1.04	13.00	0.63	0.07	20.63	1.18	4.98	262	13
70 L2001KA13	100.0	434	0.02	0.74	1.26	0.02	0.59	0.07	1.45	52	87
71 L2001KA14	100.3	435	0.03	1.51	0.51	0.02	2.96	0.14	1.63	94	31
72 L2001KA15	100.5	433	0.03	1.73	0.18	0.02	9.61	0.15	1.78	98	10
73 L2001KC1	100.9	438	0.03	1.35	0.38	0.02	3.55	0.12	1.24	110	31
74 L2001KC2	100.8	432	0.04	1.27	0.99	0.03	1.28	0.11	1.35	95	73
75 L2001KC3	100.8	439	0.01	0.90	0.31	0.01	2.90	0.08	1.30	70	24
76 L2001KC4	100.1	441	0.01	0.64	0.33	0.02	1.94	0.06	1.13	58	29
77 L2001KC5	100.4	438	0.03	1.10	0.60	0.02	1.83	0.10	1.58	71	38
78 L2001KC6	100.3	426	0.02	2.12	0.76	0.01	2.79	0.19	2.24	96	34
79 L2001KC7	100.0	427	0.02	1.89	0.38	0.01	4.97	0.17	1.96	97	19
80 L2001KC8	100.0	418	0.06	4.93	0.58	0.01	8.50	0.44	2.85	174	20
81 L2001KC9	100.4	420	0.04	2.53	0.58	0.02	4.36	0.23	2.32	110	25
82 L2001KC10	100.7	420	0.04	2.20	0.61	0.02	3.61	0.21	2.23	100	27
83 L2001KC11	100.7	422	0.04	3.47	0.36	0.01	9.64	0.31	1.96	178	18
84 L2001KB1	100.0	416	0.04	1.63	1.27	0.03	1.28	0.17	2.21	74	57
9107	99.7	441	0.98	12.49	0.54	0.07	23.13	1.13	5.00	251	11

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
85 L2001KB2	100.3	421	0.05	3.35	0.88	0.01	3.81	0.30	2.36	143	37
86 L2001KB3	100.5	420	0.03	2.77	0.71	0.01	3.90	0.25	1.96	142	36
87 L2001KB4	100.0	421	0.04	1.53	0.76	0.02	2.01	0.15	1.84	84	41
88 L2001KB5	100.6	422	0.02	1.28	0.33	0.02	3.88	0.12	1.30	99	25
89 L2001KB6	100.6	422	0.03	1.64	0.50	0.02	3.28	0.15	1.62	102	31
90 L2001KB7	100.2	425	0.03	2.68	0.74	0.01	3.62	0.24	2.04	132	36
91 L2001KB8	100.3	425	0.02	1.23	0.58	0.02	2.12	0.12	1.48	84	39
92 L2001KB9	100.9	421	0.02	0.58	0.29	0.03	2.00	0.06	0.98	60	30
93 L2001KB10	100.3	426	0.03	1.27	0.82	0.02	1.55	0.12	1.63	79	50
94 L2001KB11	100.0	432	0.01	0.52	0.62	0.02	0.84	0.06	1.33	40	47
95 L2001KB12	100.9	440	0.01	0.64	0.76	0.02	0.84	0.07	1.43	46	53
96 L2001KB13	100.3	428	0.02	0.44	0.70	0.04	0.63	0.05	1.32	34	53
97 L2001KB14	99.8	436	0.03	0.86	0.90	0.03	0.96	0.08	1.62	54	56
9107	100.5	438	1.03	11.82	0.51	0.08	23.18	1.08	4.94	240	10
98 L2001KB15	99.7	435	0.01	0.54	0.55	0.03	0.98	0.05	0.95	58	58
99 L2001KB16	99.9	434	0.01	0.42	0.14	0.02	3.00	0.04	0.78	55	18
100 KB17	100.3	431	0.01	0.60	0.44	0.02	1.36	0.06	1.01	60	44
101 KB18	100.8	441	0.01	0.13	0.16	0.04	0.81	0.01	0.27	48	59
102 L2002E1	99.9	432	0.03	0.97	0.73	0.03	1.33	0.09	1.30	75	56
103 L2002E2	100.4	431	0.02	0.77	0.53	0.03	1.45	0.07	1.17	67	45
104 L2002E3	100.5	431	0.02	0.67	1.08	0.03	0.62	0.06	1.27	54	85
105 L2002E4	100.9	434	0.02	0.43	0.40	0.04	1.08	0.04	0.75	59	53
106 L2002E5	99.8	432	0.02	0.89	0.87	0.02	1.02	0.09	1.63	55	53
107 L2002E6	100.3	436	0.01	0.77	0.27	0.01	2.85	0.07	1.49	53	18
108 L2002H1	100.1	429	0.08	2.11	0.28	0.04	7.54	0.19	1.60	133	18
109 L2002I1	100.8	434	0.01	0.41	0.35	0.02	1.17	0.04	1.36	31	26
110 L2002J1	100.6	462	0.21	0.73	0.20	0.22	3.65	0.09	1.24	60	16
9107	100.1	438	0.99	9.90	0.52	0.09	19.04	0.92	4.92	202	11
111 L2002J3	99.6	459	0.21	0.42	0.25	0.33	1.68	0.06	1.06	41	24
112 L2002J5	99.5	461	0.15	0.40	0.36	0.27	1.11	0.05	1.00	41	36
113 L2002J6	100.5	461	0.18	0.88	0.26	0.16	3.38	0.10	1.57	57	17
114 L2002J7	100.5	453	0.16	0.27	0.11	0.37	2.45	0.04	0.74	38	15
115 L2002J8	100.5	464	0.11	0.48	0.32	0.18	1.50	0.05	1.21	40	26
116 L2002J9	100.1	465	0.12	0.44	0.24	0.21	1.83	0.05	0.97	46	25
117 L2002J10	100.8	462	0.16	0.56	0.15	0.22	3.73	0.07	1.11	51	14
118 L2000N3	100.3	441	0.03	0.21	0.03	0.11	7.00	0.02	0.45	47	7
119 L2000N4	100.6	439	0.06	0.47	0.05	0.12	9.40	0.05	0.63	76	8
120 L2000N5	99.9	441	0.06	0.45	0.05	0.11	9.00	0.04	0.66	70	8
121 L2000N8	100.0	441	0.14	1.60	0.00	0.08	0.00	0.15	0.97	166	0
122 L2000N9	100.6	443	0.06	0.86	0.02	0.07	43.00	0.08	1.13	77	2
123 L2000N10	100.6	440	0.02	0.39	0.00	0.05	0.00	0.04	1.02	39	0
124 L2000N11	100.1	436	0.02	0.46	0.37	0.04	1.24	0.05	0.89	53	42
125 L2000N12	100.0	440	0.02	0.52	0.27	0.04	1.93	0.05	0.85	62	32
126 L2000N13	100.5	438	0.02	0.36	0.16	0.04	2.25	0.03	0.80	46	20
127 L2000N14	100.3	436	0.02	0.30	0.15	0.05	2.00	0.03	0.74	42	20
128 L2000N15	99.8	437	0.01	0.28	0.12	0.05	2.33	0.03	0.68	43	18
129 L2001B0	100.6	436	0.02	0.45	0.51	0.05	0.88	0.04	0.75	61	68

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
130 L2001B1	100.6	439	0.01	0.40	0.55	0.02	0.73	0.04	0.90	46	61
131 L2001B3	100.2	444	0.01	0.36	0.70	0.03	0.51	0.04	0.93	40	75
132 L2001B5	100.5	438	0.02	0.52	0.59	0.03	0.88	0.05	0.87	61	68
133 L2001B7	99.8	438	0.02	0.41	0.54	0.05	0.76	0.04	0.72	58	75
134 L2001B8	100.5	434	0.03	0.63	0.66	0.04	0.95	0.06	0.95	67	69
135 L2001B9	99.9	436	0.04	0.45	0.21	0.09	2.14	0.04	0.48	94	44
136 L2001B10	100.3	436	0.14	0.92	0.27	0.13	3.41	0.09	0.68	137	40
137 L2001B11	100.6	428	0.22	1.48	0.33	0.13	4.48	0.14	0.75	199	44
138 L2001B12	101.0	438	0.05	0.64	0.53	0.07	1.21	0.07	0.90	72	59
9107	100.3	439	0.93	11.37	0.77	0.08	14.77	1.04	4.88	234	16
139 L2001B13	99.9	441	0.01	0.48	0.67	0.03	0.72	0.05	1.03	48	65
140 L2001B14	100.5	441	0.01	0.40	0.76	0.02	0.53	0.04	0.90	46	84
141 L2000K1	100.5	441	0.34	0.38	0.37	0.47	1.03	0.07	0.76	50	49
142 L2000K5	100.3	443	0.07	0.53	0.21	0.11	2.52	0.05	0.58	93	36
143 L2000K10	100.1	455	0.02	0.30	0.43	0.06	0.70	0.04	0.65	48	66
144 L2000K13	100.7	454	0.01	0.15	0.37	0.04	0.41	0.02	0.30	50	123
145 L2000K15	100.6	449	0.02	0.34	0.12	0.06	2.83	0.03	0.71	49	17
146 L2000K18	100.2	454	0.02	0.35	0.37	0.06	0.95	0.04	0.72	50	51
147 L2000K20	99.9	450	0.01	0.18	0.25	0.05	0.72	0.02	0.41	44	61
148 L2000K21	100.0	443	0.05	0.56	0.08	0.08	7.00	0.05	0.91	63	9
9107	100.2	440	1.01	12.42	0.67	0.07	18.54	1.13	4.89	255	14
9107	100.5	440	0.97	12.64	0.89	0.07	14.20	1.14	4.91	259	18
99986	100.0	413	0.07	8.56	0.80	0.01	10.70	0.73	3.07	279	26
149 L2000K22	100.8	445	0.05	0.54	0.62	0.08	0.87	0.05	0.87	63	71
150 L2000K23	100.1	445	0.03	0.58	0.52	0.05	1.12	0.06	1.09	54	48
151 L2000K24	100.0	447	0.02	0.43	0.43	0.04	1.00	0.04	0.81	54	53
152 L2000K26	100.5	452	0.01	0.27	0.49	0.05	0.55	0.03	0.72	38	68
153 L2000K28	100.7	444	0.01	0.21	0.20	0.06	1.05	0.02	0.45	47	44
154 L2000K30	100.3	440	0.01	0.20	0.49	0.06	0.41	0.02	0.38	53	129
155 L2000K31	100.2	443	0.01	0.16	0.34	0.06	0.47	0.01	0.29	55	117
156 L2002DA2	99.7	446	0.03	0.18	0.40	0.14	0.45	0.03	0.57	32	70
157 L2002DA4	100.6	435	0.15	5.16	0.26	0.03	19.85	0.46	3.58	145	7
158 L2002DA5	100.4	435	0.32	6.11	0.12	0.05	50.92	0.54	3.31	186	4
159 L2002DA6	100.5	438	0.10	1.22	0.25	0.08	4.88	0.12	1.70	72	15
160 L2002C1	100.5	454	0.01	0.12	0.74	0.09	0.16	0.01	0.59	20	125
161 L2002C2	100.5	443	0.01	0.18	0.63	0.05	0.29	0.02	0.73	25	86
162 L2002C4	99.8	440	0.13	2.64	0.11	0.05	24.00	0.24	1.93	138	6
163 L2002C5	100.7	443	0.12	2.26	0.15	0.05	15.07	0.20	1.66	137	9
9107	100.0	440	0.97	12.03	0.75	0.07	16.04	1.09	4.88	248	15
164 L2002C7	100.4	436	0.21	2.41	0.17	0.08	14.18	0.23	1.73	140	10
165 L2002C9	100.1	436	0.17	1.89	0.23	0.08	8.22	0.18	1.98	96	12
166 L2002C10	100.5	431	0.07	0.90	0.15	0.07	6.00	0.09	1.45	63	10
167 L2002DB1	100.4	436	0.29	4.59	0.18	0.06	25.50	0.42	2.81	164	6
168 L2002DB2	100.5	443	0.23	4.76	0.30	0.04	15.87	0.42	2.11	227	14
169 L2002DB3	100.5	443	0.39	2.77	0.25	0.12	11.08	0.27	1.55	180	16
170 L2002DB5	100.8	441	0.95	4.42	0.06	0.18	73.67	0.45	1.91	232	3
171 L2002DB7	100.0	441	0.34	3.03	0.11	0.10	27.55	0.29	1.52	200	7

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
172 L2002DB8	100.5	440	0.17	3.08	0.25	0.05	12.32	0.28	1.85	168	14
173L2002DB11	100.5	439	0.09	2.14	0.34	0.04	6.29	0.20	1.75	123	19
174L2002DB12	100.8	439	0.07	1.69	0.42	0.04	4.02	0.15	1.53	111	27
175L2002DB13	100.3	440	0.20	2.17	0.54	0.08	4.02	0.20	1.71	127	32
176L2002DB16	100.2	438	0.06	1.10	0.60	0.05	1.83	0.11	1.51	74	40
177L2002DB18	100.1	435	0.12	1.42	0.21	0.08	6.76	0.13	1.47	97	14
9107	100.1	440	0.94	11.62	0.74	0.07	15.70	1.06	4.90	239	15
178L2002DB20	100.7	436	0.16	2.10	0.27	0.07	7.78	0.19	1.30	162	21
179L2002DB21	100.6	439	0.09	1.45	0.84	0.06	1.73	0.14	1.56	94	54
180L2002DB23	99.7	436	0.32	3.77	0.17	0.08	22.18	0.35	1.69	224	10
181L2002DB25	100.6	435	0.07	1.53	0.32	0.04	4.78	0.14	1.49	103	21
182L2002DB27	100.8	436	0.04	0.68	0.55	0.06	1.24	0.07	1.16	59	47
183L2002DB29	100.4	436	0.06	1.56	0.22	0.04	7.09	0.14	1.34	117	16
9107	100.0	436	0.92	11.22	0.78	0.08	14.38	1.03	4.86	232	16
184L2002DB31	100.3	433	0.06	1.28	0.29	0.04	4.41	0.12	1.29	100	22
185L2002DB33	100.7	437	0.03	0.42	0.36	0.06	1.17	0.04	0.84	51	43
186L2002DB35	100.9	436	0.07	1.26	0.20	0.05	6.30	0.12	1.19	107	17
187L2002DB37	100.3	436	0.20	0.84	0.29	0.19	2.90	0.09	1.16	73	25
188L2002DB40	100.5	435	0.07	1.89	0.32	0.04	5.91	0.17	1.54	123	21
189L2002DB41	100.6	431	0.05	0.56	0.54	0.08	1.04	0.06	1.06	54	51
190 L2002F2	100.7	428	0.01	0.18	0.97	0.03	0.19	0.03	0.93	19	104
191 L2002F3	100.4	431	0.01	0.26	0.78	0.03	0.33	0.04	0.97	27	80
192 L2002F5	100.9	431	0.03	0.45	0.64	0.07	0.70	0.05	0.99	46	65
193 L2002F7	100.1	425	0.01	0.33	1.01	0.04	0.33	0.04	1.13	29	89
194 L2002F8B	100.6	430	0.11	0.54	0.61	0.17	0.89	0.07	1.20	46	51
9107	100.3	439	0.94	11.62	0.73	0.07	15.92	1.06	4.89	239	15
195 L2002F11	100.2	431	0.01	0.15	2.14	0.03	0.07	0.03	0.74	20	289
196 L2002F12	100.0	430	0.02	0.42	1.12	0.05	0.38	0.05	0.94	45	119
197 L2002F13	100.6	427	0.02	0.53	2.25	0.03	0.24	0.07	1.80	30	125
198 L2002F16	100.9	428	0.01	0.43	1.32	0.02	0.33	0.06	1.47	30	90
199 L2002F17	100.2	431	0.02	1.29	0.26	0.02	4.96	0.12	1.74	75	15
200 L2000G1	100.6	435	0.00	0.11	0.86	0.03	0.13	0.02	0.80	14	108
201 L2000G2	99.9	441	0.00	0.10	0.61	0.02	0.16	0.01	0.58	17	105
202 L2000G3	100.6	441	0.05	0.33	0.49	0.13	0.67	0.04	0.98	35	50
203 L2000G4	100.3	443	0.00	0.19	0.59	0.01	0.32	0.03	1.04	18	57
204 L2000G5	99.9	435	0.00	0.10	0.57	0.02	0.18	0.01	0.78	13	73
205 L2000G6	100.3	431	0.00	0.16	0.74	0.02	0.22	0.02	0.98	16	76
206 L2000G7	101.0	438	0.00	0.21	0.69	0.01	0.30	0.03	1.10	20	63
207 L2000G8	100.6	443	0.00	0.06	4.88	0.06	0.01	0.01	0.40	15	1220
9107	100.5	441	0.91	11.30	0.68	0.07	16.62	1.03	4.87	233	14
208 L2000G9	100.3	439	0.00	0.13	0.68	0.03	0.19	0.02	0.80	16	85
209 L2000G10	100.4	425	0.00	0.17	0.90	0.03	0.19	0.03	1.15	15	78
210 L2000G12	100.3	431	0.00	0.07	0.64	0.04	0.11	0.01	0.59	12	108
211 L2000G13	100.1	435	0.00	0.04	0.80	0.05	0.05	0.01	0.24	17	333
212 L2000G14	100.8	435	0.00	0.08	0.50	0.03	0.16	0.01	0.62	13	81
213 L2000G15	100.7	427	0.00	0.16	0.53	0.03	0.30	0.02	0.94	17	56
214 L2001A1	99.8	440	0.12	1.88	0.78	0.06	2.41	0.17	2.16	88	36

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
215 L2001F1	100.8	427	0.08	1.70	0.40	0.05	4.25	0.16	1.06	161	38
216 L2001F2	100.3	426	1.27	18.71	0.39	0.06	47.97	1.68	4.48	419	9
217 L2001L1	100.2	432	0.05	1.32	2.73	0.04	0.48	0.14	2.55	52	107
218 L2001L2	100.5	436	0.04	0.90	1.34	0.04	0.67	0.09	1.45	63	92
9107	99.9	439	0.93	11.78	0.86	0.07	13.70	1.07	4.95	239	17
219 L2000L3	100.1	435	0.00	0.09	0.35	0.04	0.26	0.01	0.25	36	140
220 L2000L4	100.3	435	0.02	0.55	0.40	0.04	1.38	0.05	0.85	65	47
221 L2000L5	100.0	434	0.03	1.09	0.78	0.02	1.40	0.10	1.55	71	50
222 C-03-J2	99.7	440	0.14	0.98	0.12	0.12	8.17	0.10	0.79	125	15
223 C-03-J4	100.2	438	0.98	3.10	0.19	0.24	16.32	0.34	1.81	172	10
224 C-03-J5	100.2	438	0.33	1.27	0.21	0.21	6.05	0.14	0.85	149	25
225 C-03-J6	100.4	444	0.34	2.01	0.19	0.14	10.58	0.20	1.15	176	17
226 C-03-J7	100.1	442	0.26	1.76	0.18	0.13	9.78	0.17	1.00	177	18
227 C-03-J8	100.1	443	0.25	1.76	0.18	0.12	9.78	0.17	1.08	164	17
228 C-03-J9	100.0	439	0.32	2.17	0.13	0.13	16.69	0.21	1.27	172	10
229 C-03-J10	100.2	443	0.09	1.03	0.18	0.08	5.72	0.10	0.63	165	29
230 C-03-J11	100.5	445	0.37	2.19	0.25	0.14	8.76	0.22	1.35	164	19
9107	100.3	440	0.97	12.02	0.76	0.07	15.82	1.09	4.87	248	16
231 B-41-1	101.0	428	0.30	0.68	0.27	0.31	2.52	0.09	0.95	72	28
232 B-41-2	100.1	430	0.34	1.59	0.40	0.18	3.98	0.17	1.42	113	28
233 B-41-3	99.7	435	0.27	2.27	0.93	0.11	2.44	0.23	2.01	114	46
234 B-41-4	100.1	436	0.37	2.24	0.49	0.14	4.57	0.23	1.86	122	26
235 B-41-5	100.3	430	0.61	3.30	0.31	0.16	10.65	0.34	2.06	162	15
9107	100.1	439	0.98	12.22	0.75	0.07	16.29	1.11	4.90	251	15
236 B-41-6	100.4	435	0.32	0.89	0.29	0.26	3.07	0.11	1.12	80	26
237 B-41-8	100.5	435	0.41	2.42	0.38	0.14	6.37	0.25	2.14	114	18
238 B-41-9	100.5	429	0.64	3.19	0.51	0.17	6.25	0.33	2.54	127	20
239 B-41-11	100.1	433	0.20	2.21	0.36	0.08	6.14	0.21	1.57	141	23
240 B-41-13	100.2	414	0.44	5.05	1.04	0.08	4.86	0.48	2.88	175	36
241 K-32-1	99.8	435	0.84	7.80	0.25	0.10	31.20	0.73	2.38	329	11
242 K-32-2	99.8	433	1.00	9.10	0.33	0.10	27.58	0.84	2.64	345	13
243 K-32-4	100.5	438	0.55	5.79	0.36	0.09	16.08	0.53	1.96	296	18
244 K-32-6	100.4	440	0.38	4.31	0.28	0.08	15.39	0.40	1.75	247	16
245 K-32-7	100.1	436	0.67	5.14	0.17	0.12	30.24	0.49	1.98	261	9
246 B-53-B1	100.3	441	0.06	0.37	0.32	0.15	1.16	0.04	1.04	36	31
247 B-53B2	100.7	435	0.01	0.05	0.19	0.20	0.26	0.01	0.04	125	475
248 B-53B3	99.8	438	0.83	6.56	0.13	0.11	50.46	0.62	2.37	277	5
249 B-53-B4	100.6	443	0.28	2.04	0.45	0.12	4.53	0.20	1.44	142	31
9107	100.4	440	0.96	12.27	0.86	0.07	14.27	1.11	4.91	251	18
250 B-53-B5	100.5	435	1.51	11.41	0.28	0.12	40.75	1.08	3.44	332	8
251 B-66-D1	100.9	436	0.07	1.42	0.36	0.05	3.94	0.13	1.02	139	35
252 B-66-D4	100.0	437	0.07	1.92	0.42	0.04	4.57	0.17	1.27	152	33
253 A-60-B1	100.8	455	0.02	0.12	0.26	0.15	0.46	0.02	0.19	63	137
254 A-60-B3	100.3	447	0.48	2.92	0.29	0.14	10.07	0.29	2.28	129	13
255 A-60-B5	100.2	444	0.68	9.19	0.25	0.07	36.76	0.83	4.14	223	6
256 A-60-B6	100.5	444	0.88	4.06	0.50	0.18	8.12	0.42	2.91	141	17
257 A-60-B7	100.7	448	0.32	1.33	0.32	0.19	4.16	0.14	1.16	116	28

Sample	Qty	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
9107	100.1	441	0.95	12.11	0.89	0.07	13.61	1.10	4.94	247	18