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LITHOSTRATIGRAPHY, SEQUENCE STRATIGRAPHY AND PALEOENVIRONMENTS OF THE UPPER COLORADO GROUP IN SOUTHERN ALBERTA AND SOUTHWESTERN SASKATCHEWAN: DEFINITION OF THE CARLILE AND NIOBRARA FORMATIONS (UPPER TURONIAN TO UPPER SANTONIAN)

Karsten Schjødt Nielsen

A thesis presented to the Faculty of Graduate studies and Research

In partial fulfillment of the requirements for the degree of

Doctor of Science

Department of Earth Sciences, College of Natural Sciences

Carleton University

Ottawa-Carleton Geosciences Centre

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acceptance of the thesis

Lithostratigraphy, Sequence Stratigraphy and Paleoenvironments of the Upper Colorado Group in Southern Alberta and Southwestern Saskatchewan: Definition of the Carlile and Niobrara Formations (Late Turonian to Santonian Time)

Submitted by

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in partial fulfilment of the requirements

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ABSTRACT

The Upper Turonian to Santonian Upper Colorado Group in southern Alberta and southwestern Saskatchewan, Canada consists of a 120 to 350 m thick shaly interval, which prior to this study lacked a formal stratigraphic definition and subdivision. Using a multidisciplinary approach this thesis resolves the gap in the stratigraphic record and describes in detail the lithostratigraphy, sequence stratigraphy and paleoenvironments of the Upper Colorado Group. The interval, which is defined by the older Carlile Formation overlain by the Niobrara Formation, contains thirteen fourth order sequences with eight facies and four facies associations. These sequences can be correlated across the basin and demonstrate a complex sea-level fluctuations and basin infill history.

The Carlile Formation of Late Turonian age (30 to 160 m thick) is defined as the lower part of the Upper Colorado Group conformably overlying the Second White Specks Formation. The Carlile Formation represents the regressive part of the second order Greenhorn Cycle and is characterized by non-calcareous shale with minor sandstone beds and siderite concretions. The Formation is informally subdivided into a lower, middle and upper members, which correlate with the Haven and Opabin members of the Blackstone Formation and the Cardium Formation, respectively.

Sequences F1 to F7 are correlated within the distal marine Carlile Formation. Low-angle clinoforms strata dominate the internal stratal pattern and sequence boundaries are parallel to sub-parallel to one another. In the lower sequences, strata dip from west to east whereas the upper sequences are dominated by strata that dip from east and west towards the central part of the study area. This indicates a shift in sediment source from

dominantly the west to both from west and east. The upper two sequences are truncated by a major unconformity and indicate the maximum regression of the Greenhorn Cycle creating a narrow seaway located in eastern Alberta and western Saskatchewan.

The Niobrara Formation (80 to 240 m thick) unconformable overlies the Carlile Formation and is characterized as a partly calcareous to calcareous shale with intervals of abundant bentonites and widespread fine-grained sandstones. The Formation represents the transgressive part of the second order Niobrara cycle and is subdivided into the bentonite-rich Verger Member, the sand-rich Medicine Hat Member and the calcareous First White Specks Member. The Niobrara Formation consists of six sequences (F8 – F13) which show a change in mega-scale stratal patterns from high angle in the lower sequences of the Verger Member to low angle in the First White Specks Member.

The overlying Verger Member of Coniacian age represents a major flooding event that created a broad and relative deep interior seaway. The Verger Member is also characterized by a swarm of bentonite layers, which helps to delineate a high angle stratal pattern on densely spaced wire-line logs and marks a distinct boundary with the underlying Carlile Formation. This event is followed by two episodes of significant sea-level falls and subsequent rise are characterized by two regional pebble-layers that form regional onlap surfaces on detailed log cross-sections. These sequence boundaries/flooding surfaces (sequence boundary of F8 and F9) indicate that most of southwestern Alberta and northwestern Montana were subaerially exposed at that time. The lowstand deposits associated with the two sequences are located in west central Alberta in form of the coarse-grained Bad Heart Formation.

The Medicine Hat Member of lower Santonian age consists of sequences F10 and F11, which contain numerous fine-grained sandstones, that outline the moderate to low angular stratal pattern. Sandstones were mainly deposited in a lower shoreface to outer offshore environment on the flanks of the Bow Island Arch, and are widespread with individual sandstones covering more than 3000 km^2. Sandstones are found in all system tracts, but are the thickest and the most widespread in highstand and lowstand deposits. The paleoenvironment during the Medicine Hat time is best described as a shallow sandy shelf.

The Upper Santonian First White Specks Member consists of the two sequences F12 and F13 that have a very low angled stratal pattern dominated by shaly transgressive and highstand system tracts. This member represents the period during the Upper Colorado Group with the deepest water and most open shelf conditions. The sand-rich Sweetgrass Member represents a lowstand system tract within the First White Specks sequences to the northwest of the Bow Island Arch and illustrates that significant sea-level fluctuation took place even during the Santonian deep marine phase.

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Chapter I

INTRODUCTION

OBJECTIVES OF THE STUDY

The Cretaceous Upper Colorado Group of southern Alberta and southwestern Saskatchewan consists of thick marine shales and numerous fine-grained sandstones. Prior to this Ph.D.-project, this interval was informally named the "unnamed Upper Colorado shale" including the Medicine Hat sandstones and the first white speckled shale (Hankel et al., 1989; Glass, 1990; Schröder-Adams et al., 1997; Nielsen and Schröder-Adams, 1999). One of the objectives of this study was better define this stratigraphic interval and formally subdivide the Upper Colorado Group, which herein has been subdivided into two formations: the older Carlile Formation and younger Niobrara Formation. Previously the detailed stratigraphy and paleoenvironments of these formations was poorly understood, as earlier studies focused mainly on reservoir characteristics of the sandstone intervals (Martin, 1965; Simpson, 1984; Hankel et al., 1989). This study, therefore, is a multidisciplinary sequence stratigraphic and paleoenvironmental analysis of the interval, which reveals stratal patterns, infill history and relative sea-level fluctuations during Late Turonian to Santonian time.

ECONOMIC INTERESTS

Sandstones of the Medicine Hat Member are major biogenic shallow gas producers in southeastern Alberta and southwestern Saskatchewan and have produced gas since 1904. Gas in place reserves are estimated at 8,425 Bcf initial, with 1,629 Bcf gas reserves remaining (The Canadian Gas Potential Committee, 2001). Because of declining

gas reserves the importance of a detailed stratigraphic framework, stratal patterns and mapping of the Upper Colorado Group becomes more urgent. Also detailed sedimentological observations of bioturbation of the shaly sandstones could have major influences on the exploration strategy. The shaly Bowdoin sandstones in the upper unit of the Carlile Formation in southern Saskatchewan and northern North Dakota are also major gas producers, and an understanding and mapping of this sandstone may lead to new opportunities.

DISCIPLINES

The disciplines in this study include sedimentology, petrophysics (wire-line logs), micropaleontology and geochemistry. Sedimentology includes detailed core and outcrop descriptions of lithology, sedimentary structures, concretions, bioturbation, ichnofossils, macrofossils, white specks and bedding contacts. Petrophysical studies of 2800 wire-line logs comprise detailed correlations and are the main data for structural and isopach maps. Micropaleontology includes processing of core and outcrop samples by using the standard method of Then and Dougherty (1983). Foraminifera were picked from 540 samples by using the > 63 μm residue. In this study foraminiferal assemblages were mainly used to establish the biostratigraphic framework, and to enhance the sequence stratigraphic and paleoenvironmental interpretations. The material still awaits detailed taxonomic study. Geochemistry includes interpretation of Rock-eval data, which is used in the lithostratigraphic subdivision, to interpret paleoenvironmental changes and to define key surfaces in the sequence stratigraphic analysis.

FRAMEWORK OF THE THESIS

The structure of the thesis is arranged in a series of three manuscripts, which are ready for submission for publication. Each paper covers a specific topic related to the study of the Upper Colorado Group. Although some overlap regarding study area, data, geological background, etc. is inevitable, each paper is in itself a complete research study and presents results not included in any other paper. A logical succession of the three papers lead the reader from the lithostratigraphic subdivision (chapter II) to a sequence stratigraphic interpretation (chapter III) and finally a paleoenvironmental interpretation (chapter IV) of the Carlile and Niobrara formations. Tables, appendices, references and figures are presented at the end of each paper. Appendices, which include geochemical-data and core descriptions, are at the end of the thesis.

All work of this thesis, excluding what is outlined in this paragraph, was performed by K. S. Nielsen with supervision from Dr. Claudia J. Schröder-Adams, Carleton University and Dr. Dale A. Leckie, Nexen Inc., Calgary. Rock-eval data was prepared by Lloyd Snowden at the Geological Survey in Calgary. Petrographic thin-sections were prepared and analyzed by S. Seif El-Dein, Contrex Consulting, Calgary. Two bentonites were dated using K-Ar geochronology (per. comm. J. Obradovich, Denver, 2000). Macrofossils from outcrops were identified by Jim Haggart, Geological Survey of Canada, Vancouver. The presence of nannofossils in key cores and outcrops were studied by Jim Craig, Bragg Creek.

Digital representation of logs and cross-section software was donated from iDc, Calgary, that provided a working platform for detail and regional correlations. The cores were examined at the AEUB core facility in Calgary or at the SEM in Regina. The plains

of the subsurface study area provided no outcrops of the Upper Colorado Group, but in the vicinity of the Alberta Foothills and northern Montana, five sections were measured and correlated to the subsurface data.

All papers were written and revised by K. S. Nielsen and submitted to co-authors for critical review and discussion. Authorship and current status of the papers contained in this thesis are as follows:

Chapter II

Nielsen, K. S., Schröder-Adams, C. J. and Leckie, A. D., *in prep.*: A new stratigraphic framework for the Upper Colorado Group in southern Alberta and southwestern Saskatchewan, Canada.

The lithostratigraphic subdivision of the Upper Colorado Group in chapter II follows the North American Code of Stratigraphic Nomenclature (NACSN 1983) and represents an objective division of the interval, mainly based on lithology and geochemistry. The new formation names are based on correlations with laterally equivalent established units in Manitoba and southern Saskatchewan (McNeil and Caldwell, 1981; Gilboy, 1989), central and northern Montana (Cobban et al., 1976) and a composite reference section of the Cretaceous Interior Seaway (McGookey et al., 1972).

Chapter III

Nielsen, K. S., Leckie, D. A., and Schröder-Adams, C. J. *in prep.*: Basin-wide stratal patterns and sediment infill history: Cretaceous Colorado Group in Western Canada. An applied sequence stratigraphic study.

A new developed method of densely spaced resistivity logs for correlation is described in chapter III. This technique helps recognizing stratal patterns and allows for a detailed sequence stratigraphic subdivision, which illustrates a complex basin infill history and sea-level fluctuation. The sequence stratigraphic subdivision uses the first major flooding surface as a sequence boundary (Embry, 1995), as this is the easiest recognizable surface on the densely spaced wire-line logs in the distal settings of the Carlile and Niobrara formations. Sedimentology, geochemistry and micropaleontology are used to enhance the sequence stratigraphic interpretation. Key surfaces and deposits are correlated to adjacent regions to enhance the understanding of the basin evolution. A composite sea-level history is interpreted, which explains the stratal pattern and sediment infill history.

Chapter IV

Nielsen, K. S., Schröder-Adams, C. J., and Leckie, D. A., *in prep.*: Paleoenvironment of the Carlile and Niobrara formations in southern Alberta and southwestern Saskatchewan, Canada.

Chapter IV addresses the paleoenvironmental changes in nine paloegeographic maps representing various Late Turonian to Santonian time-slices, illustrating the dynamic evolution of the basin. These maps are mainly based on sedimentological and geochemical data with additional use of stratal patterns, key sequence stratigraphic surfaces and micropaleontologically information. The maps are expanded from the study area by using other published data to include most of the Western Interior Seaway of Canada and the northern part of the U.S.A and illustrate new outlines of the interior seaway during Late Turonian to Santonian time.

Chapter II

A NEW STRATIGRAPHIC FRAMEWORK FOR THE UPPER COLORADO GROUP IN SOUTHERN ALBERTA AND SOUTHWESTERN SASKATCHEWAN, CANADA

ABSTRACT

Extensive marine shales and shallow-marine sandstones of the Cretaceous Upper Colorado Group are one of the last thick informally-named strata units in the southern part of the Western Canada Sedimentary Basin. Two regionally-mappable formations in southern Alberta and southwestern Saskatchewan are introduced: The older Carlile Formation overlying the Second White Specks Formation and the younger Niobrara Formation underlying the Milk River Formation. Both names are taken from lithologically similar and laterally equivalent strata in adjacent parts of the Interior Seaway in Canada and the United States. The boundary between the formations is recognized at a distinct zone of bentonites. The age of the formations, determined by foraminiferal zones and bentonite dating, ranges from Late Turonian to Santonian.

Variations in lithology, petrophysics and geochemistry of the sediments make it possible to further subdivide these two new formations. The Late Turonian Carlile Formation is subdivided into lower, middle and upper units. The latest Turonian to Santonian Niobrara Formation is formally subdivided into three mappable members: the shaly, non-calcareous Verger Member, the sandstone-rich Medicine Hat Member and the calcareous First White Specks Member.

Biogenic gas from the Medicine Hat Member was discovered in 1884 and has been produced since 1904 with an estimated 8.425 Bcf initial gas in place, and remaining

1,629 Bcf gas. The upper part of the Carlile Formation also has potential for gas reserves within shaly Bowdoin sandstones, which are major gas producers in northern Montana.

An outcrop reference section of the Carlile Formation is designated at Deer Creek east of West Butte in the Sweetgrass Hills of north-central Montana. The only core cut from the Carlile Formation in southern Alberta and southwestern Saskatchewan is located at 13-20-17-7W4 and includes twelve meters of the upper part of the formation. It is used as a reference boundary section between the Carlile and Niobrara formations. A reference core of the Niobrara Formation is located at 4-16-22-15W4, which also is designated as the type section of the Verger, Medicine Hat and First White Specks members. An outcrop section at the Ghost River Spillway, west of Calgary, serves as the outcrop reference section for the Medicine Hat Member and is correlated directly to the subsurface using wire-line logs and biostratigraphy.

INTRODUCTION

Extensive shale intervals of the Upper Cretaceous Colorado Group were until recently one of the last informally-named strata in the Western Canada Sedimentary Basin (WCSB). The underlying Lower Colorado Group was subdivided into four formations by Bloch et al. (1993). This paper addresses the Upper Colorado Group in southern Alberta and southwestern Saskatchewan in a multidisciplinary study and proposes a new stratigraphic framework for the interval from the top of the Second White Specks Formation to the top of the Colorado Group.

A detailed stratigraphic framework is in the interest of the petroleum industry and government since extensive exploration in this interval is ongoing. Biogenic gas from the Medicine Hat Member was discovered in 1884 and has produced since 1904 with an estimated 8,425 Bcf initial gas in place, and remaining 1,629 Bcf gas reserves (The Canadian Gas Potential Committee, 2001).

The Carlile Formation and the Niobrara Formation are newly defined in this paper. Both names are taken from lithologically similar and laterally equivalent strata in adjacent parts of the Interior Seaway in Canada and the US. The Niobrara Formation is subdivided into three members; the shaly Verger, the sand-rich Medicine Hat and the shaly and calcareous First White Specks members. The Carlile Formation is subdivided into three informal units; a lower, middle and upper unit.

The Carlile Formation spans the regressive phase of the Greenhorn Cycle, whereas the Niobrara Formation represents the transgressive and highstand periods of the

Niobrara Cycle (McNeil and Caldwell, 1981). The allocyclic events (eustasy, major continent plate tectonics) responsible for these second order cycles in most of the Interior Seaway are poorly described and understood in southern Alberta and southwestern Saskatchewan. Furthermore, the paleogeography of the area, formed by the interaction of these allocyclic events, regional basement tectonics and autocyclic sedimentary processes, is only grossly known. The first step in solving these problems is to establish a lithostratigraphic and biostratigraphic framework, upon which sequence stratigraphic and paleoenvironmental aspects can be addressed.

Isopach maps of the new stratigraphic units described herein are based on correlations from a dense grid of 2800 wireline-logs that are linked to 81 cores and 5 outcrops (appendix I). From this data set a composite type section including several cores and outcrops is chosen to represent the two new formations. Paleontology, sedimentology and organic geochemistry of the type section have been studied in detail. A number of reference cores illustrate the lateral facies variability of the formations, and the Medicine Hat Member is also described from an outcrop reference section. Since the Carlile Formation is only partly represented in one core, a composite outcrop reference section at the edge of the study area demonstrates the lithology of the formation. A 147 m long core at location 16-4-22-15W4 in Alberta is chosen as the main reference core for most of the Niobrara Formation.

GENERAL STRATIGRAPHY AND REGIONAL CORRELATIONS OF THE NEW FORMATIONS

The Greenhorn and Niobrara second order sea-level cycles are described from the Late Cretaceous Interior Seaway in the US and Canada (Kaufmann, 1967; McNeil and

Caldwell, 1981). The Middle Cenomanian to Late Turonian Greenhorn Cycle was followed by the Coniacian to Santonian Niobrara Cycle (figure 2-1). In southern Alberta and southwestern Saskatchewan (figures 2-1 and 2-2), the Niobrara Cycle includes the previously unnamed upper Colorado shale, the Medicine Hat sandstones and the first white speckled shale. All these units are informal, but are well known and used by government geologists and the petroleum industry.

Our new stratigraphic framework proposes the Carlile Formation, subdivided into three informal units represents the regressive phase of the upper Greenhorn Cycle. The transgressive part of Niobrara Cycle encompasses the Niobrara Formation, subdivided into the Verger, Medicine Hat and First White Specks members. The formation names are chosen based on correlations with laterally equivalent units in Manitoba and southern Saskatchewan (McNeil and Caldwell, 1981; Gilboy, 1989), central and northern Montana (Cobban et al., 1959; 1976) and a composite reference section of the Cretaceous Interior Seaway (McGookey et al., 1972).

The northwards extension of the shaly Carlile Formation, from the US interior seaway into Canada, is based on a lithostratigraphic and biostratigraphic analysis of a composite reference section from the Sweetgrass Hills in northern Montana. The outcrop is situated on the West Butte of the Sweetgrass Hills in Montana, close to the Canada-USA border (figures 2-2 and 2-3). Locally, in the Sweetgrass Hills outcrop area, the shales are named the Ferdig Member of the Marias River Formation (Lopez, 1995; Cobban et al., 1976). The Ferdig Member is correlated to the Carlile Shale in central and southern Montana (figure 2-1; Cobban 1951; Cobban et al., 1959 and 1976). The outcrop section, which represents what we define to be the Carlile Formation in southern Alberta

and southwestern Saskatchewan, was correlated to the study area using wire-line logs (figures 2-4 and 2-5). In much of the Cretaceous Interior Seaway of the northern United States, the name Carlile Formation or Carlile Shale is used for the Middle to Upper Turonian marine non-calcareous shale between the Greenhorn and Niobrara formations (McGookey et al., 1972). The Haven and Opabin members of the Blackstone Formation and the Cardium Formation, in the southern Alberta Rocky Mountain Foothills, correlate with the Carlile Formation. In southern Manitoba, the Morden Shale correlates with the Carlile Formation (figure 2-1).

The Niobrara Formation includes shales and fine-grained sandstones above the Carlile Formation and its equivalent strata in outcrops and is overlain by the Milk River, Lea Park or Alderson formations (Leckie et al., 1994; Simpson, 1984). The Niobrara Formation is extended northwards from the US interior seaway and is illustrated on the general reference section of McGookey et al. (1972) (figure 2-1). Presently the name is used in Manitoba and southern Saskatchewan to describe Coniacian to Santonian strata (McNeil and Caldwell, 1981; Gilboy, 1989).

The Verger Member of the Niobrara Formation is correlated with the Muskiki Formation/Member of the southern Alberta Foothills and west-central plains (Wall, 1967b; Wall and Rosene, 1977; Plint, 1991). In Montana, it is correlative with the lower unit and the lower part of the middle unit of the Kevin Member (figure 2-1; Cobban et al, 1976). The Medicine Hat Member is correlated with the Marshybank and Dowling members (Wall and Rosene, 1977) of the southern Foothills of Alberta (figure 2-1). In the west-central Foothills and plains of Alberta, the Medicine Hat Member correlates with the Marshybank, Bad Heart and Puskwaskau formations (Plint, 1991). The First White

Specks Member is correlative to the Thistle and the lower part of Hanson members in the Alberta Foothills (Wall and Rosene, 1977).

HISTORICAL OVERVIEW AND PREVIOUS WORK

An overview of the subsurface geology of south and central Alberta was first published by Dowling (1917; 1919). He described the shaly Colorado Group and included the calcareous Niobrara Formation and the Medicine Hat gas horizon in southern Alberta in this interval. He also outlined the Bow Island Anticline (later named the Bow Island Arch) and described it as a broad, low anticline plunging north into the central plains (Dowling, 1919, p. 13).

The Colorado shale, described in northern Montana by Collier (1929), was correlated to the Alberta plains by Spratt (1931). The Colorado shale was subdivided in a lower sand-rich unit of 750 feet and an upper shaly unit of about 1000 feet, now known as the Lower and Upper Colorado Group, respectively.

In the Foothills of southern Alberta, the Alberta Formation was defined as the Alberta Shale, properly equivalent to the Colorado Shale and the lower part of the Milk River Formation (Russell and Landes, 1940). Exclusive use of macrofossils did not allow distinction between the lower Milk River Formation and the upper part of the Alberta shale (Russell and Landes, 1940).

The Colorado Group; as defined in the northwestern part of Montana, was correlated to the Alberta shale of the southern plains of Alberta (Cobban, 1951; Cobban et al., 1959). The term Colorado Group was thereafter slowly adopted into the Canadian literature to describe strata overlying the Mannville Group and underlying the Milk River

Formation/Lea Park Formation in the plains of southern Alberta and southern Saskatchewan (Stott, 1963, 1984; Caldwell et al. 1978; Simpson 1982, 1984; Schröder-Adams et al., 1997, 1998). The Upper Colorado Group is known as the interval from the base of the Second White Specks Formation to the top of the first white speckled shale (Caldwell et al., 1978).

Little is published in recent literature on the upper Colorado shale in the plains of southern Alberta and Saskatchewan. Only one small outcrop exists in the plains of Alberta and southwestern Saskatchewan (Russell and Landes, 1940; Wall, 1967a). The outcrop straddles the border between Alberta and Montana in the coulees of Deer Creek (not to be confused with the outcrop at Deer Creek on East Butte in Montana), just north of the West Butte of Sweetgrass Hills (figure 2-2).

Wireline-log signatures of the Upper Colorado Group in southern Alberta were demonstrated in Leckie et al. (1994), Schröder-Adams et al. (1997), Simpson (1984) and Gilboy (1993). North of the study area in the Foothills of west-central Alberta and northwestern British Columbia, the Muskiki and Marshybank formations (Coniacian-Santonian) were correlated into the subsurface of western central Alberta (Plint et al., 1990; Plint, 1991).

The sandstones in the upper part of the Colorado shale are known as the Medicine Hat sandstones. They were named "the Medicine Hat Gas Horizon" and are stratigraphically located about 35 m below the top of the Colorado shale (Spratt, 1931; Russell and Landes, 1940). In the Medicine Hat gas field area, "the Medicine Hat sand-rich unit" was documented and partly mapped by Martin (1965). Hancock and Glass (1968) described the sandstones in the area of the city of Medicine Hat and named them

the Medicine Hat sandstones. Kendall and Simpson (1974) recorded calcite layers (cone-on-cone structures) within the sandstones and placed the sandstones within the first white speckled shale. Simpson (1981; 1984), describing the reservoir characteristics of the sandstones, also places them within the first white speckled shale. The Medicine Hat sandstones are correlative to the Martin Sand-rich Zone defined in Saskatchewan (Simpson, 1979a, 1979b). The zone is a general term which includes all silty to fine-grained sandstones in the upper part of the Colorado Group in northern Montana and southwestern Saskatchewan (Glass, 1990).

Hankel et al. (1989) described sedimentology and reservoir features of the Medicine Hat sandstones, which they named the Medicine Hat Formation. Schröder-Adams et al. (1997, 1998) and Nielsen and Schröder-Adams (1999) also use the formal name Medicine Hat Formation in their description of the sandstones. These authors all placed the sandstones between the unnamed Colorado shale and the first white-speckled shale. Studies from western Saskatchewan by Simpson (1981; 1984) and Gilboy (1989; 1993) indicate that the Medicine Hat sandstones are placed within the first white speckled shale. In the description of the Medicine Hat sandstones by Glass (1990), the sandstones are also placed in the first white-speckled shale in southeastern Alberta. To date no formal description of the Medicine Hat sandstones has been published. One of the purposes of this chapter is to establish a formal definition for the sandstones applicable across southern Alberta and southwestern Saskatchewan.

The calcareous first white-speckled shale was recognized early in the subsurface as the first calcareous dark shale below the Milk River Formation. The calcareous Thistle Member of the Wapiabi Formation in the Canadian Rocky Mountain Foothills is

correlated with the first white speckled shale in the plains (Stott, 1963). Schröder-Adams et al. (1997) defined the sand-rich Sweetgrass Member within the first white speckled shale on the northwestern flank of the Bow Island Arch.

PHYSIOGRAPHY AND TECTONIC SETTING

Deposition of the Late Cretaceous upper Colorado Group took place in the asymmetrical foreland basin of Western Canada. The combined effect of maximum subsidence rates in the basin foredeep and a high sediment flux from the rising Cordillera in the west resulted in an westward thickening wedge of the Colorado Group (McNeil and Caldwell, 1981; Bloch et al., 1993; Leckie et al., 1994). In southern Alberta, this general tectonic setting is complicated by the Bow Island Arch, which plunges northwards, dividing the Western Canada Basin into the Alberta Basin to the west and the Williston Basin to the east (figure 2-3).

During Precambrian to Jurassic time, prior to the onset of Cordilleran orogenesis, the arch was positioned as a flexural hinge on the shelf of the western continental margin (Lorenz, 1982). Beaumont (1981) implies that the arch originated in the pre-Cambrian, and was the result of Paleozoic lithospheric upwarp between the Williston Basin in the east and an ancestral basin in the west. The Sweetgrass Arch comprises several subarches, domes and faults (Podruski, 1988). The southern part of the arch in the United States, - South Arch and Kevin-Sunburst Dome were active and periodically formed a structural high throughout the Phanerozoic. In contrast, it is argued that the Canadian side of the arch, the Bow Island Arch, did not develop prior to the Late Cretaceous Laramide phase (Podruski, 1988).

In Canada, the tectonic movement of the Bow Island Arch during the Cretaceous has been documented by Hankel et al. (1989), Schröder-Adams et al. (1997; 1998) and Myhr and Meijer-Drees (1976). Using paleontological evidence the Bow Island Arch was interpreted as a subtle positive topographic feature creating a shallower marine environment during Santonian time in comparison to more distal settings north and east of the arch (Schröder-Adams et al., 1998). The depositional environment and gas pools of the overlying Campanian Milk River Formation also appear to be controlled by the Sweetgrass Arch (Myhr and Meijer-Drees, 1976; Payenberg, 2002). In northern Montana, a slight uplift of the Sweetgrass Arch during late Cretaceous time was sufficient to disrupt the east-west drainage system in the nonmarine deposits of the Two Medicine Formation equivalent to the Belly River Formation in Alberta (Lorenz and Gavin, 1984).

METHODS

Wire-line logs from 2800 wells and 86 measured sections (81 cores and five outcrops) are used in this integrated study of the Upper Colorado Group (Appendix I). Regional correlations of 12 wire-line cross-sections, each consisting of 50-120 wells provided a reference grid. An additional 52 detailed cross-sections were used for local correlations. Two cross-sections, cores from eight wells and two outcrops are chosen to illustrate the new formations and members. The Deer Creek outcrop from the Sweetgrass Hills exposing part of the Second White Specks Formation, the entire Carlile Formation and part of the Niobrara Formation is chosen as a reference section for the Carlile Formation. An outcrop near the Ghost River Spillway, west of Calgary, is chosen as a reference section for the Medicine Hat Member (figure 2-2).

As part of a larger ongoing multidisciplinary project on the Upper Colorado Group in the western Interior Seaway of Canada, this chapter describes new formations and members using sedimentology, paleontology, geochemistry and petrophysical wire-line correlations. The formal description and naming of the new units follows the North American Code of Stratigraphic Nomenclature (NACSN 1983).

Samples collected at one meter intervals from outcrops and cores are analyzed for micropaleontology, geochemistry and in some cases examined petrographically. Sample spacing was reduced in intervals of specific interest, such as lithological and sequence stratigraphic boundaries.

Lithologies were classified after Folk (1974). Primary and secondary features of the shales follow the nomenclature of Potter et al. (1980). Observations of trace-fossils, degree of bioturbation, abundances of macrofossils and fecal pellets containing nannofossils (white specks) were noted. Detailed petrographic analysis of 40 sandstone samples within the Medicine Hat Member was performed by Contrex Consulting (Calgary).

A total of 540 samples for foraminiferal analysis were prepared using the standard method of Then and Dougherty (1983). Processed samples were washed over a 0.063 mm sieve and foraminifera were picked from the dried residues. The existing general foraminiferal zonation of Caldwell et al. (1978) in the Western Interior Seaway has been used to establish a biostratigraphic subdivision of the interval (figure 2-1).

Selected core samples were examined by J. Craig (Calgary) for their nannofossil content, and are incorporated in the biostratigraphic framework. Nannofossil smear slides

were prepared using techniques modified from Edwards (1963) and Stover (1966). Macrofossils were identified by J. Haggart (GSC, Vancouver) and C. Collom (Calgary).

Rock-Eval pyrolysis is used for characterizing the maturity and type of organic matter present in the rocks. Using the technique and methods of Espitalié et al. (1977; 1984); Peters (1986) and Tissot et al. (1987) 810 samples were processed and analyzed for their total organic carbon content (TOC), Hydrogen Index (HI) and level of thermal maturity (T_{max}, S1, S2, S3). Effects of weathering on the organic geochemistry of outcrop samples were corrected based on the methods outlined by Espitalié et al. (1984) and Leythaeuser (1973). For example, weathering will oxidize organic material and accordingly lower the HI and increase the Oxygen Index (OI) up to 25% and 50%, respectively.

Resistivity wire-line logs proved to be the best tool for correlating in the marine Upper Colorado Group. The gamma-ray, sonic and density logs are useful in lithological interpretations, but are affected by caving in the bore-hole, which is common problem in these strata. We therefore recommend the use of resistivity logs for correlations in this interval and use of the gamma-ray only with caution. Standard terminology for log trends and patterns (Cant, 1992) are used in this study. To illustrate the regional changes of the wireline log response, two cross-sections, including gamma-ray, resistivity and sonic logs, are shown in figures 2-5 and 2-6. Detailed correlations of the Carlile and Niobrara formations using densely spaced resistivity logs are illustrated in chapter III.

STRATIGRAPHIC SECTIONS

CARLILE FORMATION

General Description

The Carlile Formation is a non-calcareous shale with minor fine sandstone partings and a middle interval with a abundant siderite concretions. The Formation is subdivided into three informal units. The lower boundary is the top of the calcareous Second White Specks Formation marked by a distinct biostratigraphic and lithological change as described by Bloch et al. (1993). The upper boundary is sharply demarcated by the bentonite zone of the overlying Verger Member of the Niobrara Formation, and is characterized by a faunal change in foraminifera. The formation ranges between 40 and 160 m thick, thinning eastwards (figure 2-7A). The gamma-ray and resisitivity logs response to the formation is a general upward-coarsening trend composed of three or four funnel shaped log patterns. Shale is slightly harder than in the overlying Niobrara shale, and as a result bore holes generally show little caving, which is reflected by an even caliper log.

Type and reference sections of the Carlile Formation

The only core cut from the Carlile Formation in the southern Alberta and southwestern Saskatchewan area is located at 13-20-17-7W4 (figure 2-8) and includes twelve meters of the upper part of the formation. It is used as a reference boundary section between the Carlile and Niobrara formations.

The outcrop reference section of the Carlile Formation is located at Deer Creek east of West Butte in the Sweetgrass Hills of Montana (figure 2-4). Previously it has been mapped to include the Cone and Ferdig members of the Marias River Formation (Lopez, 1995). As the Ferdig Member is equivalent to the Carlile Shale of central Montana (Cobban et al., 1951; 1976), the Deer Creek section is used in this paper to demonstrate the lithology of the Carlile Formation in the study area. The type section of the Ferdig Member (Cobban et al., 1976) is located ca. 60 km east of Deer Creek and its correlation to the Deer Creek outcrop is shown in figure 2-4.

The outcrop section at Deer Creek exposes 85 m of the Carlile Formation and is correlated with wire-line logs from well 10-7-1-8W4 in Alberta, 14 km north of the outcrop (figures 2-4 and 2-9). The section is composed of 11 separate outcrops. The general strike direction of strata is 70°-90°, with a dip of 12°-22° degree. Details of the outcrop are listed in appendix II.

Description of the Carlile Formation

Lower Unit

Lithology

Based on observations from the Deer Creek outcrop, the lower unit (35-40 m thick) of the Carlile Formation is a homogenous platy to flaggy, non-calcareous, gray to bluish-gray, non-bioturbated shale changing gradually upwards to a slightly harder gray flaggy to slabby shale. Two intervals of fine laminated to thin bedded, lenticular, very fine sand partings are observed (30-35 m and 47-49 m), which form isolated trains of rippled sand lenses with a maximum thickness of 3 cm and 30 cm in length. The sand

lenses are mainly external symmetrical, but shows cross-lamination in one preferred direction.

The lower boundary of the unit (also lower formation boundary) is not exposed at Deer Creek, but is recognized regionally (Cobban et al., 1976; Lopez, 1995; Bloch et al., 1993) to be marked by a sharp change from the platy, calcareous Second White Specks Formation to a platy to flaggy, non-calcareous shale. The upper boundary of the lower unit is formed by the appearance of brownish to orange colored siderite concretions of the middle unit. No macrofossils where collected from this unit; only a few small fish scales were observed.

Geochemistry

The average TOC and HI values for the lower unit are 2.2 % and 74 mg HC/g OC respectively (figure 2-4; appendix III). These values are notably lower than those of the underlying Second White Specks Formation with TOC values of 5.1%, and HI values over 200 mg HC/g OC (Bloch et al., 1993). The upper unit boundary is marked by a sharp increase in TOC and HI values. Despite the effects of recent weathering of the shale, it is believed that the organic matter is of terrestrial origin (type III) (figure 2-10). The three units of the Carlile Formation all plot similar on a Van Krevelen Diagram, and are difficult to differentiate. The T_{max} values (av. 446°C) of the Carlile Formation at Deer Creek are relatively high (appendix III) and indicate a high maturity in the upper part of the oil window, close to the peak for generation of wet gas (Teichmuller and Durand, 1983). Igneous intrusions of Eocene age are believed to have caused this abnormal maturity in the area of the Sweetgrass Hills (Lopez, 1995), and is expected to be considerably lower throughout the rest of the study area.

Wire-line log correlations

The thickness of the lower unit is uniform (35-40 m) throughout most of the area (figures 2-5 and 2-6), decreasing to 15 m at the eastern edge and increasing to 50 m at the western margin (figures 2-5 and 2-6). The lower boundary between the Second White Specks Formation and the Carlile Formation is easily recognized on most wireline-logs (figures 2-5, 2-6, 2-8 and 2-11; see also Bloch et al., 1993). The resistivity log pattern changes from being irregular and with multiple peaks to a more evenly curved log pattern (figures 2-5, 2-6 and 2-8). The boundary is defined on the resistivity log at the point of maximum decline, which corresponds with a major decrease in gamma-ray values. Only in the eastern most part of the study area the gamma-ray remains high in the lower unit of the Carlile Formation. In general, the unit is recognized by a narrow funnel shaped log pattern that can be seen on the gamma-ray and resistivity logs (figures 2-5 and 2-6).

Middle Unit

Lithology

The non-calcareous middle unit (30 m thick) is characterized as a slightly bioturbated, silty gray shale with abundant 5-15 cm-thick, isolated siderite concretions (figure 2-4). The unit is platy and soft in the lower part changing upwards to flaggy and more resistant shale.

Few laminar and thin bedded sandstones are concentrated in a silty zone in the middle part of the unit. Orange-brownish siderite concretions distinguish this unit from the lower and upper units. Within the middle unit, the siderite concretions change from being continuous beds in the lower part to individual concretions in the upper part. The

upper boundary is marked by a gradual change from the siderite concretion-rich silty shale to a dark gray shale with no concretions. A five cm thick bentonite is present at the top of the unit.

A low degree of bioturbation is observed in the upper part of the unit, in which the horizontal traces are identified as *Planolites, Gordia* or *Plioichnus* (pers. comm., A. Uchman 2000; Uchman, 1999). Well-preserved traces of *Chondrites* are present within siderite concretions, which indicates early diagenesis of the concretions. A poorly preserved elongated ammonite (*Baculites* spp.) was found in the lower part of outcrop 6.

Geochemistry

The average TOC and HI values for the middle unit are 1.4% and 42.4 mg HC/gOC respectively generally decreasing upwards (figure 2-4, appendix 2-III). These values are lower than those of the lower unit. The lower and upper boundaries are marked by a sharp change in TOC and HI (figure 2-4). Based on the Van Krevelen diagram (figure 2-10) the organic matter is of terrestrial origin (type III). The T_{max} average (454 ^{o}C) is slightly higher than that of the lower unit (446 ^{o}C).

Wire-line correlation

The gamma-ray response of the middle unit has an even to jagged log pattern (figures 2-5, 2-6, 2-8 and 2-11) and its values are generally slightly lower than in the lower unit. In the northeastern part of the study area, the gamma-ray count is still relatively high comparable to values of the lower unit (figures 2-5 and 2-6). The resistivity log shows similar trends as the gamma-ray log, and has an almost even log pattern through most of the interval.

Upper Unit

Lithology (Deer Creek Outcrop, figure 2-4)

The upper unit is represented by 30 m of sediment in the Deer Creek outcrop (figure 2-4) and partly (11 m) in a core located at 13-20-17-7W4 (figures 2-6 and 2-8). The well is situated in the distal part of the basin whereas the Deer Creek outcrop is assumed to represent more proximal marine sediments.

At Deer Creek, the unit is characterized by two intensively bioturbated, upward-coarsening intervals from silt to fine sand (92 to 100 m and 107 to 109 m, figure 2-4), each overlain by silty shale. The shaly part of the unit is gray, flaggy to slabby, slightly to intensively bioturbated, and is dominated by small horizontal burrows of *Gordia* and *Pilichnus dichotomus*. The two upward-coarsening intervals show remnants of lenticular bedding, fine lamination and a few isolated small hummocky beds. A 1-cm-thick bentonite was observed in the lower part of the unit (at 93 m) and a three cm thick bentonite at the top (at 109 m).

Concretions are not as common as in the middle unit, and are gray and mainly calcareous. An exception is at the very top of the formation where flattened, large yellow to orange concretions (0.5 m thick) form a discontinuous bed. Well preserved bivalves of *Cremnoceramus* sp. (Haggart, 2002) are abundant on the upper surface of the concretions.

Lithology (core 13-20-17-7W4, figure 2-8)

The lithology of the upper unit in the core at 13-20-17-7W4 is an upward coarsening interval from a thin (1.5 m), dark gray, finely-laminated, moderately bioturbated shale to an intensively bioturbated, 8 m thick, sand-rich and gray siltstone, overlain by a 1 m thick fine-grained sandstone. Broken macrofossils are abundant. Trace

fossils are dominated by *Gordia*, *Pilichnus dichotomus* and *Chondrites*. The upper thin sandstone is a lithic wacke dominated by very fine subrounded to angular quartz and lithofragments of chert and volcanic fragments. A shell-layer occurs in the lower part of the sandstone. The sharp upper boundary of the unit (also formation boundary) is described in the section on the Verger Member of the Niobrara Formation.

Geochemistry

In the Deer Creek outcrop and the core at 13-20-17-7W4, the TOC and HI values are relatively low, but higher than the underlying units (figure 2-4, appendix 2-III). The average TOC is 1.5 %, ranging from 0.5 to 2.5 %. HI values range from an average of 58 mg HC/gOC of the Deer Creek section to an average of 144 mg HC/gOC in the core.

The organic material is mainly of type III (terrestrial) (figure 2-10A). A slight increase in marine-derived organic matter is observed in the core located at 13-20-17-7W4. Higher T_{max} values (av. 440°) at Deer Creek compared to av. 419° in the core are caused by the Eocene igneous intrusions (Lopez, 1995) in the Sweetgrass Hills area.

Wire-line log correlations

In the subsurface, the upper unit is the thickest unit of the Carlile Formation ranging between 10 m in the east to 70 m in the west, and is characterized by an elongated funnel shape log trend. The lower part shows an even to jagged log pattern with relatively constant values on the resistivity and gamma-ray logs. The top is distinctively marked by a low peak on the gamma-ray log and high peak on most other logs (figures 2-5, 2-6 and 2-8). From the photoelectric log it is evident that the peak is of calcite origin (figure 2-8).

In the marginal southern and eastern part of the study area, the upper boundary of the Carlile Formation represents an unconformity with erosional relief of up to 10 m (figures 2-5 and 2-6). The depth of erosion increases in southern and eastern direction, where the upper unit is only a few meters thick and the calcite marker bed is close to the upper formation boundary (figure 2-5). Log correlations suggest increased erosion of the Carlile Formation in the eastern region (figure 2-6). Regional cross-sections of densely spaced resistivity logs clearly show the unconformity between the Carlile and Niobrara formations (see also chapter III).

Age and Correlations of the Carlile Formation

Age

A Middle to Late Turonian age is proposed for the Carlile Formation based on the presence of the *Pseudoclavulina* sp. Zone (Caldwell et al., 1978) and the *Cremnoceramus* spp. Zone at the top of the formation. A lack of macro-fossils in the lower part of the formation was also observed in laterally equivalent strata, which indirectly supports this date (Cobban, 1951; Caldwell et al., 1978; McNeil and Caldwell, 1981).

In the reference section at Deer Creek in Montana, the Carlile Formation is underlain by a calcareous shale containing a mixed fauna of agglutinated and planktic foraminifera with *Hedbergella loetterlei*, *Heterohelix globulosa* and *Trochamina* sp. as the main components. This interval belongs to the Middle Turonian *Hedbergella loetterlei* zone characteristic of the Greenhorn Formation in the US and the Second White Specks Formation in southern Alberta and Saskatchewan (Cobban et al., 1959; Bloch et al., 1993; Schröder-Adams et al., 1996).

The foraminiferal fauna from the Carlile Formation at Deer Creek shows similarities to the Morden Shale in southern Manitoba (McNeil and Caldwell, 1981) and the Haven and Opabin members of the Blackstone Formation in the Alberta Foothills (Wall, 1967b), which belong to the *Pseudoclavulina* sp. Zone. The lower part of the Carlile Formation is almost barren of foraminifera, which is also the case in the Alberta Foothills and Manitoba (McNeil and Caldwell, 1981; Wall, 1967b). All the principal components of this zone (Caldwell et al., 1978; Wall, 1967b) are found in the Deer Creek outcrop and include *Dorothia* sp., *Pseudoclavulina* sp, *Trochammina ribstonensis* and *Haplophragmoides howardense*. The foraminiferal fauna from the upper part of the Carlile Formation at 13-20-17-7W4 is significantly different and still awaits detailed description. The fauna is dominated by the calcareous *Pseudobulimina*, with the agglutinated genera *Trochammina* and *Haplophragmoides* as minor components. Also some planktic foraminifera are seen in the interval.

A bivalve from the top of the Carlile Formation is identified as *Cremnoceramus* sp., characterized of the *Cremnoceramus* spp. Zone of Late Turonian or Coniacian age (Haggart, 2000). Based on the occurrence of this macrofossil, and the foraminiferal zone, the upper boundary lies in the upper Upper Turonian. This is further supported by dating of two bentonites (89.19 and 89.40 Ma) situated directly above the Carlile Formation in the core at 13-20-17-7W4 (pers. comm., Obradovich, 2000,.) (see age and correlation of the Niobrara Formation).

In the western study area, the Jumping Pound sandstone straddles the boundary between the Second White Specks and Carlile formations (figure 2-11). This sandstone

indicates the first significant evidence of the regressive phase of the Greenhorn Cycle and therefore is tentatively included in the Carlile Formation.

Regional Correlations

The Carlile Formation correlates with the older Blackstone and the younger Cardium formations in the southern Alberta Foothills (Wall and Rosene, 1977). The lower unit of the Carlile Formation correlates with the Haven Member of the Blackstone Formation. The middle unit, with its characteristic abundance of siderite concretions, correlates with the Opabin Member of the Blackstone Formation. The coarse grained upper Turonian to lower Coniacian Cardium Formation from the Alberta Foothills (Leckie et al. 1994; Walker and Plint, 1992; Stott, 1963) interfingers with the sand-rich upper unit of the Carlile Formation (figure 2-11). In southwestern Saskatchewan, laterally-equivalent strata to the newly-defined Carlile Formation were also suggested to be named the Carlile Formation (Gilboy 1989; 1993 and 1996; Rice 1981).

The Carlile Formation is equivalent to the Ferdig Member of the Marias River Formation defined in the area of the Sweetgrass Hills in north-central Montana (figure 2-1; Cobban et al., 1959; 1976; Lopez, 1995). The Ferdig Member is correlated with the Carlile Shale in central Montana (Cobban et al., 1976). The Carlile Formation (this study) differs from the Carlile Shale in the mid-central US in the absence of a lower calcareous unit, which is present in the mid-central US (e.g. Fairport Member in Kansas; Hattin, 1975). The sandstones of the upper Carlile Formation, identified in the Deer Creek outcrop (figure 2-4), in the core 13-20-17-7W4 (figure 2-8) and on some logs (figures 2-5 and 2-6), are laterally and lithologically correlative with the Bowdoin sandstones of

northeastern Montana and southern Saskatchewan (Henry, 1979; Gilboy, 1993). Therefore the sandstones of the upper unit of the Carlile Formation are formally named the Bowdoin sandstone beds. These shaly sandstones are major gas producers on the northern flank of the Bowdoin structure in Phillips County, Montana.

The unconformity interpreted at the upper formation boundary in the eastern and southern part of our study area is also documented elsewhere based on missing biozones (Hattin, 1975; North and Caldwell, 1975; Schröder-Adams et al., 1996). A widespread hiatus spanning the middle Turonian to lower Santonian is documented in central and western Saskatchewan (North and Caldwell, 1975). This hiatus includes the entire interval of the Carlile Formation and the lower two members of the Niobrara Formation. The First White Specks Member disconformably overlies a remnant of the Second White Specks Formation in this area (Schröder-Adams et al., 1996; North and Caldwell, 1975). A similar unconformity occurs in the eastern part of the interior seaway in Kansas between the Carlile Shale and the Santonian Niobrara Chalk (Hattin, 1975) and in South and North Dakota (Shurr and Reiskind, 1984). In Canada, the magnitude of the lacuna increases a northeastward.

NIOBRARA FORMATION

General description

The Niobrara Formation is composed of marine shales, siltstones, very fine-grained sandstones, and a few layers of chert pebbles. The formation is subdivided into three members, which in ascending order are: the non-calcareous shaly Verger Member, the sand-rich Medicine Hat Member and the calcareous shaly First White Specks

Member. All members are regionally mappable (figures 2-7B, C, D, E), and have distinctive lithological, geochemical, and petrophysical features. The Niobrara Formation ranges from 250 m in the southwest to less than 80 m thick in the northeast (figure 2-7B). Compared to the underlying Carlile Formation this indicates a reorientation of the basin geometry by almost 45 degrees anticlockwise (see also chapter III). The lower formation boundary with the Carlile Formation is unconformable, especially in the southern and eastern part of the basin and is overlain by an interval rich in bentonites (figures 2-5, 2-6, 2-8 and 2-11). The upper boundary with the overlying Milk River/Lea Park or Alderson formations (figure 2-1) is a sharp boundary separating dark, fine-laminated, calcareous shale of the First White Specks Member from intensely bioturbated, silty sandstones or siltstones.

Type and reference sections of the Niobrara Formation

A 147-m-long core located at 16-04-22-15W4 (figure 2-12) is chosen as a reference section for the Niobrara Formation and type section for the three members in the study area. The core penetrates the upper part of the Verger Member, the entire Medicine Hat and First White Specks members. The core at 13-20-17-7W4 serves as a reference section for the lower Verger Member (figure 2-8). Reference sections displaying typical lateral variations in lithology of the Medicine Hat Member are located at 4-08-13-27W4 and 14-36-13-04W4 (figures 2-13 and 2-14). A reference core for the boundary between the Verger Member and the Medicine Hat Member is at location 08-36-24-13W4 (figure 2-15). An outcrop reference section for the Medicine Hat Member is located at the island of the Ghost Dam Spillway 52 km west of Calgary (figure 2-11).

Type and reference cores are available for public display at the Alberta Energy and Utilities Board's Core Research Centre in Calgary.

Description of the Niobrara Formation

Verger Member

Lithology

The Verger Member is a slightly to moderately bioturbated, silty shale recognized by its abundance of bentonites, mica and pyrite concretions (figures 2-4, 2-8, 2-15). The member's name is taken from the town of Verger located close to the type well 16-04-22-15W4. The member is a relatively homogenous dark gray, platy to slabby shale with few sand beds. In the upper part of the member two pebble layers are present. The few trace fossils found are dominated by small feeding traces of *Gordia, Pilichnus dichotomus* and *Terebellina.*

The lower part of the formation was measured in the core at 13-20-17-7W4 (figure 2-8). At this location, calcareous white speckled shales are inter-laminated with non-calcareous shale. The specks are similar to the specks in the overlying First White Specks Member and are confirmed to be "true white specks fecal pellets" rich in nannofossils (pers. comm., Jim Craig, 1999) with some calcareous benthic and planktic foraminifera. This implies an informal "*middle white specks zone*" in the central and northeastern distal part of the region, due to its similarity to the First White Specks Member and parts of the Second White Specks Formation. The gamma-ray and sonic logs also show responses as observed within the First White Specks Member (figures 2-5, 2-6 and 2-8).

A laterally extensive swarm of seventeen bentonite layers is recognized on logs and in outcrop in the lower part of the Verger Member in the study area. In the core at 13-20-17-7W4 the bentonites occur one meter above the lower member's boundary (figure 2-8). The boundary is placed at the change from thin, intensely bioturbated, lithic greywacke at the top of the Carlile Formation to a thin, dark shale showing an abrupt decrease in the insensitivity of bioturbation.

In the distal parts of the basin, as in core 13-20-17-7W4, the seventeen bentonites are condensed into only 3 m of silty shale, whereas in the proximal part of the basin in northern Montana, eighteen bentonites are observed in about 50 m of shale (figure 2-4; Cobban et al., 1976). Bentonites range from 0.5 cm to 16 cm thick. Due to the distinct petrophysical response of these bentonites, this interval is chosen as the boundary between the Carlile and Niobrara formations (figures 2-5, 2-6 and 2-8).

The upper boundary of the Verger Member is easily recognized on resistivity logs from closely spaced and is interpreted as an onlap surface (see chapter III). Lithologically, the boundary is a lag of well-rounded pebbles separating shales of the Verger Member from the overlying sand-rich Medicine Hat Member (figures 2-12, 2-15 and 2-16). Associated with the pebble layer is a thin layer of calcareous ooids, glauconite, fish and bone debris cemented by siderite. On meter scale, only minor lithological changes are observed across the pebble layer. However, in the three cores analyzed, the abundance of pyrite concretions significantly increases above the boundary. Dominant trace fossils above the boundary are *Gordia* or *Pilichnus dichotomus*. Since the pebble-layer is interpreted as a transgressive lag, it is not expected to be present in the most distal and central part of the basin (see also chapters III and IV).

Geochemistry

The lateral distribution and type of organic matter is highly variable within the member (figure 2-17A). The central part of the study area, represented by the core at 13-20-17-7W4, shows a higher influence of marine organic matter (type II) as expected in the distal part of a basin (figure 2-17A). In the proximal part of the basin to the west (figure 2-17A) and south (figure 2-3) terrestrial organic matter (type III) dominates (figure 2-17 A).

The TOC values of the Verger Member varies from 1.5 % in the proximal setting at 16-4-22-15W4 to 1.9 % in the more distal setting at 13-20-17-7W4. HI values are two and a half times higher in the distal setting than in the proximal setting (figures 2-8 and 2-12; appendix 2-III). The T_{max} values resemble those from the underlying Carlile Formation, and the maturity of the organic matter from the member remains below the oil generation window, close to 420 C^{o}.

Wire-line log correlations

The thickness of the Verger Member ranges from 20 m in the northeast to 120 m in the south and southwest (figure 2-7C). This is geometrically significantly different from the underlying Carlile Formation, which forms a west to east thinning wedge (figure 2-7A). A low resistivity and high gamma-ray log pattern is distinctive for the lower part of the member and is recognized in most of the region, especially in the southern part (figures 2-4, 2-5, 2-8). This log-pattern, reflecting the presence of bentonites, clearly defines the boundary between the Carlile and Niobrara formations. Geographically, the unit shows some variability. In the south-central part of the region towards the border with Montana the bentonite interval is up to 50 m thick with a very low box-shaped

resistivity log signature (figure 2-5). In the distal and northern part of the region the bentonite zone thins to less than 5 m and is only characterized by a thin negative resistivity peak and positive gamma-ray peak (figures 2-5, 2-6 and 2-8). In the western part of the region the bentonite zone becomes less visible (figure 2-6), but is still distinguished by a broader high gamma-ray and lower resistivity log.

The log signature of the upper boundary shows some lateral variation. In the proximal part of the basin the upper boundary is recognized by a change to generally decreasing gamma-ray values, whereas in the distal part the change is seen as a sharp drop in gamma-ray response (figure 2-6). On a tightly spaced cross-section of resistivity logs, the boundary is recognized as a distinct onlap surface (see also chapter III).

Medicine Hat Member

Lithology

The lithological, geochemical and biostratigraphic description of the Medicine Hat Member is based on examination of 81 cores and two outcrops (appendix I). Although the member is relatively laterally homogenous, some variations exist and the region is subdivided into a northern, eastern, and western area (figure 2-7F). The type section is located in the northern area and reference wells are designated for the eastern and western areas (figures 2-13 and 2-14). The Medicine Hat Formation was first discovered in the area of Medicine Hat City. However, that region has no core as long as the one at 16-4-22-15W4, which was therefore chosen as type for the Medicine Hat Member.

The Medicine Hat Member is subdivided into three sand-rich zones using the previously established nomenclature of older "D", middle "C" and youngest "A" sandstone zones. A detailed description of the member is presented including a description of each of the Medicine Hat sandstones and enveloping shales.

Lower Medicine Hat Shale

The lower Medicine Hat shale is only cored in the eastern and northern regions. In these areas, the lateral variability of the 5–10-m-thick shale is minimal. The interval consists of a platy to flaggy, dark gray, silty shale. This lower shale of the Medicine Hat Member is distinguished from the underlying shaly Verger Member by a general lack of bentonites and siderite concretions. The lower shale is slightly to moderately bioturbated with uncommon calcareous white speckled laminae. In the type section and in the eastern reference section the shale grades upward into an intensely bioturbated silty shale with abundant shell debris, mainly of *Inoceramus* and other bivalves (figures 2-12 and 2-14). The dominant trace fossils are *Gordia* and *Pilichnus dichotomus*.

D-sandstone zone

The D-sandstone zone is up to 12 m thick and consists of several individual intensely bioturbated, silty sandstones distributed on the northern, eastern and western flanks of the Bow Island Arch (figures 2-4, 2-5 and 2-18A; chapter IV). In the type core two typical silty sandstones are seen. The generally upwards-coarsening sandstones are characterized as chemically mature, well- to very well-sorted and intensely bioturbated, silty, chert-rich litharenite. The framework grains of quartz and chert are mechanically immature, angular to subrounded, whereas the few heavy mineral grains (mainly zircon)

Glauconite peloids, phosphatic ooids, heavy minerals and feldspar occur in trace (< 1) amounts (pers. comm., El Dein, 1999).

Trace fossils in the sandstones are dominated by *Terebellina*, *Teichichnus* and *Chondrites*. Fish remains are common, especially in the upper part of each sandstone occurring as phosphatic bones or fish scales.

Due to intense bioturbation nearly all of the primary sedimentary structures have been destroyed leaving only few thin beds of lenticular and fine laminated, very fine sandstone. The thickest individual D-sandstone (7 to 8 m thick) occurs in the east and is illustrated in 14-36-13-4W4 (figure 2-14). In core 6-3-24-13W4, small chert pebbles (< 0.5 cm) are observed on the upper surface of the sandstone (figure 2-16).

Shale between C-sandstone zone and D-sandstone zone

The shaly interval between the sandstones of the D-zone and C-zone is up to 20 m thick and consists of dark gray, silty shale (figure 2-12). It has similar lithological features to the shale below the D-sandstone zone, but in the northern and eastern part differences occur in the trace fossil assemblage and concretions.

The dominant trace fossils are *Gordia* and *Pilichnus dichotomus*, but in contrast to the lower shale, *Terebellina* is more common and increases upwards. In the western part of the study area trace fossils are rare and occur as small (<0.5 cm) horizontal to sub-vertical sand infilled burrows. Concretions are relatively common. In the type core (16-4-22-15W4), calcite and siderite concretions are common and in the eastern reference core small pyrite concretions are common. No concretions are observed in the western

vertical sand infilled burrows. Concretions are relatively common. In the type core (16-4-22-15W4), calcite and siderite concretions are common and in the eastern reference core small pyrite concretions are common. No concretions are observed in the western reference core. Throughout all areas macrofossils are common including bivalves, ammonites and brachiopods.

C-sandstone zone

The C-sandstone zone consists of several individual fine-grained sandstones up to 6 m thick. In part of the northern area the individual sandbodies merge to a single sandstone. The sandstones are classified as bioturbated chemically mature chert litharenites. The C-sandstones are distributed on all flanks of the Bow Island Arch. The depo-centre of the sandstones has shifted slightly northwards compared to the D-sandstones (figure 2-18B).

Petrographically, the C sandstone zone is similar to the lower D-sandstone zone, being very well sorted and very fine grained with a framework consisting mainly of monocrystalline quartz (40-50 %), chert (15-20 %) and rock fragments (10-15%). Organic terrestrial material (3-20%) and mica (4-8%) are also relatively common. Feldspar, glauconite and heavy minerals are rare (pers. comm., El Dein, 1999).

In all areas, the C-sandstones are moderately to intensely bioturbated, with the trace fossil assemblage being slightly more diverse than in the D-sandstones. *Siphonites*, *Terebellina*, *Teichichnus*, *Chondrites*, *Zoophycos*, and rare *Asterosoma* and *Teredotes* occur, placing the sandstones within the *Cruziana* ichnofacies. In the lower, most shaly zone *Plioichnus dichotomus* traces were observed. Macrofossils are common, but rarely

intact. Fish remains, mostly scales, and microscopic to small pebble sized coal fragments are abundant across the entire area. Laminae of white specks (fecal pellets) are observed in the eastern part of the region (pers. comm., Jim Craig). Thin bentonites are present and are most common in the east. Associated with a few of the bentonites are calcite cone-on-cone structures as described by Kendall and Simpson (1974)

In the north, small rounded chert pebbles up to one cm in diameter are found in the lower part of the C sandstones. The pebbles are not present in the west, but may correspond to an intensively bioturbated fine sand interval in the reference well of 4-8-27-13W4 (figure 2-13).

Primary sedimentary structures are dominated by thin lenticular bedding and fine lamination indicating a sand-starved environment. Some sharp-based, upwards-fining storm beds are also observed. The lenticular bedding contains both combined flow and unidirectional ripples. All ripples are less than 2 cm high with a wavelength estimated between 10 and 20 cm.

Shale between C-sandstone and A-sandstone zones

The shale between the C-sandstone and A-sandstone zones is relative thin and ranges from 2 to 5 m thick (figures 2-12, 2-13 and 2-14). The shale is lithologically similar to the lower two shales of the Medicine Hat Member, and in areas where the C-sandstones are very thin or missing it can be impossible to distinguish between the two shales.

In general, the shale is flaggy to slabby and has a higher frequency of fine white speckled laminae. Trace fossils are dominated by *Pilichnus dichotomus* and *Gordia*. In

the western area the flaggy shale is slightly bioturbated. Fine lamination and thin lenticular bedding are infrequently present. Shell fragments and shell lags are seen in all areas.

A-sandstone zone

The A-sandstone zone consists of two sandstones and is the most extensive and thickest sandstone of the Medicine Hat Member with up to 15 m of very fine to fine sandstones (figure 2-18C). The sandstones are seen as two large and extensive sand-rich facies flanking the Sweetgrass Arch, but not present on its north-northeast side (figures 2-18C and 2-19). The depocentre of the A-sandstones has moved slightly north of the C and D sandstones (figure 2-18C).

The A-sandstone is a gray, very fine to fine-grained, chemically mature chert-rich litharenite with a few small chert and siderite pebbles. Only very subtle petrographic changes differentiate this sandstone from the C- and D-sandstones. The main component of the framework in the A-sandstones is monocrystalline quartz (38-53%), chert (15-31%) and feldspar (1.8-7.4 %) and are slightly more abundant than in the lower sandstones of C and D. Rock fragments are approximately equally abundant as in C and D (3.5-14%). Mica and terrestrial organic matter is also common, constituting up to 8 and 15% respectively of the framework. Glauconite, heavy minerals and phosphatic bioclasts are rare. The sandstone is generally very well sorted, except in the upper part of the sandstone, which is moderately sorted and contains coarse sand and small pebbles (pers. comm., El Dein, 1999).

With some variation, the upper few meters of the A-sandstone within most of the study area is intensely bioturbated. The trace fossil assemblage resembles that of the C-sandstones, but burrows are slightly larger. Uncommon *Rosselia, Skolithos* and *Ophiomorpha* are also observed. Macro-fossils are uncommon and rarely intact. Most common are *Inoceramus* fragments and thin-shelled bivalves.

The dominant sedimentary structures are small-scale lenticular bedding and fine lamination. A few thin hummocky beds of finely laminated, sub-parallel bedded, fine sand occur in the upper part of the unit. Normally graded thin beds with sharp lower boundaries are also observed. Commonly the upper 1 to 2 m of sandstone are cemented by calcite or dolomite, reducing porosity considerably.

The top of the A-sandstone zone is the boundary between the Medicine Hat and First White Specks members. In most of the region, this boundary is a sharp lithological change from the light-colored, intensely bioturbated, fine sand to a dark gray, calcareous, lightly bioturbated shale with abundant shell fragments and laminae of white specks. Bentonites are rarely preserved in the A-sandstone, but a bentonite overlies the Medicine Hat sandstones in part of the eastern region (Hankel et al., 1989). Mostly based on wire-line logs, but also seen in core (figure 2-20), the boundary is more gradual in the northeastern part of the region. On the crest of the Bow Island Arch where the A-sandstone zone is not present, the top of the member is more difficult to pick. The lithological differences, however, are still traceable, as shown in core 8-26-17-14W4.

Geochemistry

The lowest shale of the member, below the D-sandstone zone, is characterized by high TOC and HI values (figures 2-12, 2-13 and 2-14). The type of organic material from

this lower unit shows a slightly more marine (type II) influence compared to the rest of the Medicine Hat Member (figure 2-17B). The TOC value above this lower shale drops to about 1% and increases upwards within the C-sandstone and shale to values of 1.5 %. This level remains relative constant, with a slight upwards increase to 1.7 % and few peaks of more than 3 %. The HI-Index shows a similar trend to the TOC.

The average TOC values within the Medicine Hat Member are distinguished by a remarkably uniform low value in the entire area ranging from 1.2 to 1.5 % (appendix III). Due to differential diagenesis (Espitalié et al., 1985) the HI values are highly variable in the region. The effect of increased burial and temperature causes a decrease in the OI-index and a slight increase in the HI-index (Espitalié et al., 1985). This is inferred to explain the differences in organic geochemistry between the Medicine Hat Member in the core at 4-8-13-27W4 (western area) and the northern and eastern part (figures 2-17A and B). Keeping this in mind, the Van Krevelen diagrams (figure 2-17) indicate that the organic matter is predominantly of terrestrial origin (III), with a slight tendency for the eastern part to be more marine (type II). Due to burial depth and igneous intrusions the T_{max} varies across the region, lowest in the shallow burial depth of the east and northern part and highest in the western foredeep and close to the intrusions of the Sweetgrass Hills.

Wire-line log correlation

The isopach map of the Medicine Hat Member shows a thickness ranging from 25 to 100 m, thinning from the southwest to the northeast (figures 2-7C and D). Although this wedge shows the same thickness range as the underlying Verger Member the

distribution of sediments is markedly different. The Medicine Hat Member is relative uniform, ranging between 40 and 65 m throughout most of the study area (figure 2-7D).

The general log signature of the member is characterized by several funnel shaped log responses on gamma-ray and resistivity curves (figures 2-5, 2-6, 2-8 and 2-11). The gamma-ray response is commonly lower than in the underlying Carlile Formation and the overlying First White Specks Member. The lower boundary is picked at the onset of the first significant increase in resistivity.

In general, the observed lithology in core correlates well with the resistivity and to some extent on the gamma-ray logs. Due to low compaction, high porosity and a smectite rich, soft shale content (swelling clay), caving is common in this interval and has a profound effect on the accuracy of geophysical logs, especially the gamma-ray and density logs (figure 2-8). This is especially the case in the eastern and northern part of the region, whereas the more deeply buried area is more compacted and less likely to cave. The density log is a widely used log for detection of gas within the Medicine Hat sandstones, but caution should be taken, as caving will reduce the density log response which could be falsely interpreted as gas.

Outcrop reference section

An outcrop at the Ghost River Spillway is the best outcrop reference for the Medicine Hat Member and is correlated directly to the subsurface (figures 2-2, 2-11). The outcrop is located east of the Ghost River Dam, 50 km west of Calgary. For detailed location see Walker and Rosenthal (1982). The Marshybank, Dowling and Thistle members of the Wapiabi Formation are present in the outcrop (Stott, 1963; Walker and

Rosenthal, 1982). The measured outcrop is 30 m thick consisting of two coarsening-upward intervals which are overlain by a dark gray, laminated shale. The lithology and sedimentary facies of the sandstones are similar to facies of the Medicine Hat sandstones found in the subsurface (figures 2-12, 2-13, 2-14, 2-15 and 2-19). As typical of the Medicine Hat sandstones, the upper few meters of the very fine-grained sandstones are intensely bioturbated. The sharp boundary of the Dowling sandstones with the overlying dark gray, laminated shale of the Thistle Member resembles the transition from the Medicine Hat Member to the First White Specks Member.

The subsurface to outcrop correlation is supported by the short distance (2.5 km) between the outcrop and the nearest well. The two sandstones of the Dowling Member are correlated to the two upper sandstones of the Medicine Hat Member, which at this location are interpreted as two of the C-sandstones (see chapter IV).

First White Specks Member

The First White Specks Member refers to what previously was called first white speckled shale or the upper calcareous shale, and is the uppermost unit of the Colorado Group. The name, which is not a locality name, refers to the common term: first white speckled shale, used by government and petroleum industry. The top of this calcareous shale is extensively used as one of the consistent marker horizons in the Upper Cretaceous of the Western Canada Basin. The shales represent the highstand period of the Niobrara Cycle. Within the former first white speckled shale, the Sweetgrass Member was defined in the western part of the region (Schröder-Adams et al., 1997).

The only core with a complete section of the First White Specks Member is its type core at 16-4-22-15W4 (figure 2-12). The cores in 14-26-19-8W4 (figure 2-20) and 4-8-27-13W4 (figure 2-13) contain reference sections of the member, useful in defining its boundaries.

Lithology

The First White Specks Member is a calcareous, dark gray shale with abundant fecal pellets rich in nannofossils (white specks). In certain intervals, especially in the lower part, macrofossils are abundant and are dominated by bivalve fragments, mainly *Inoceramus* and ostreids. Lags of shell hash and sandstone are common and are often associated with sharp based thin, very to fine-grained sandstone beds.

The shale is fissile to platy and is slightly to non-bioturbated. A significant ichnological difference between the First White Specks Member and the underlying shales of the Verger and Medicine Hat members and Carlile Formation is the absence of the feeding traces *Pilichnus dichotomus* and *Gordia*. In the overlying Milk River Formation these traces reappear. Within the uncommon silty and thin sandstone beds of the First White Specks Member traces are dominated by *Siphonites* and *Planolites*. A few brown chert pebbles are present within the middle part of the member in the type core at 16-4-22-15W4, and might be correlate with the sharp-based sand-rich Sweetgrass Member to the west (Schröder-Adams et al., 1997). Thin bentonites (0.5 to 3 cm) are common, which is significantly different from the Second White Specks Formation of the Lower Colorado Group (Bloch et al., 1993) in which bentonites are up to 20 cm thick. Where paleontological data are lacking, the thickness of the bentonites can serve as a means to distinguish the two calcareous shales. Fine lamination, thin graded beds and

small lenticular beds of fine grained litharenite are the dominant sedimentary structures of the member. The upper boundary, marking the top of the Niobrara Formation and Colorado Group, is a sharp lithological change from dark calcareous shale to a sand-rich, bioturbated siltstone of the Milk River/Lea Park formations.

Geochemistry

Organic geochemistry changes significantly across the boundary between the Medicine Hat Member and the First White Specks Member (figures 2-12, 2-13, 2-17A and B and 2-20). Within the First White Specks Member, TOC initially increases upwards to a maximum in the middle, followed by a steady decrease towards the boundary with the Milk River Formation. This trend is most pronounced in the eastern and northern region where values reach an average of 2.5-2.9 % (appendix III). In the western region the TOC rises to an average of 1.72 %. These values are considerably lower than those of the Second White Specks Formation, where values of 4-5 % are common (Bloch et al., 1993). In contrast to the TOC, the HI values are highest in the western part of the region with average values of 283 mg HC/gOC, compared to 206 and 254 mg HC/gOC respectively in the northern and eastern regions.

The T_{max} values of the shales are slightly lower than those of the underlying Medicine Hat Member, ranging from 410 °C in the northern and eastern area to 431 °C in the foredeep of the western region. Organic matter in the First White Specks Member shows higher influence of marine conditions (type II) than in the Medicine Hat Member (figures 2-17B).

Wireline log correlation

Thicknesses of the First White Specks Member range from 20 to 70 m (figure 2-7E). The general trend is a west-east thinning with one anomalous thick in the west central area. The gamma-ray log has a high API-value and is box-shaped due to the sharp boundary with the underlying Medicine Hat Member and the overlying silty to sand-rich Milk River Formation (figures 2-5 and 2-6). The gamma-ray pattern is jagged to irregular with abundant negative and positive peaks. In the west central part of the region the Sweetgrass Member is present and characterized by a sharp lower boundary (Schröder-Adams et al., 1997).

The resistivity is relatively low and shows in general an even pattern with a few negative peaks, and in the area of the Sweetgrass Member a short interval with higher resistivity values (figures 2-5, 2-6 and 2-11). The lower boundary is relatively easy to detect on resistivity logs, unlike the upper boundary, which is best determined on either the gamma-ray or SP-log (figure 2-8).

The sonic velocity is high in the member, which is due to the calcareous cement. A few positive peaks are observed, and are interpreted as minor sandstone, non-calcareous intervals. The caliper log is even and close to bit-size throughout the member, and the cross-plot of the density and neutron log values are characterized by a large positive separation.

Age and regional correlations of the Niobrara Formation

Niobrara Formation

We extend the name Niobrara Formation as derived from southern Manitoba, Saskatchewan (McNeil and Caldwell, 1981; Gilboy, 1989; 1996) and the United States

(McGookey et al. 1972) into southwestern Saskatchewan and southern Alberta. The Niobrara Formation is of Late Turonian to Santonian age based on the presence of the *Trochammina* sp; *Bullopora laevis* and *Globigerinelloides* sp. foraminifera zones (Wall, 1967b; Caldwell et al., 1978; McNeil and Caldwell, 1981; Schröder-Adams et al., 1998). The principal species identified in southern Alberta and southwestern Saskatchewan include agglutinated taxa such as; *Ammobaculites fragmentarius, Ammobaculites tyrrelli, Pseudobolivina rollensis, Dorothia smokyensis, Flabellammina magna, Haplophragmoides crickmayi, Spiroplectammina semicomplanata, Gavelinella henbesti, Saccammina alexanderi, Reophax spp;* the benthic calcareous; *Bullopora laevis Dentalina summitensis, Bolivina elkensis, Gavelinella henbesti, Lenticulina spp* and *Cassidella tegulata;* the planktic *Hedbergella spp.*

Furthermore, dating of two bentonites from the lower part of the Verger Member provides an age of 88.19 and 89.40 Ma (pers. comm., Obradovich, 2000), placing the lower part of the formation in the upper Turonian to lower Coniacian (Obradovich, 1993).

The Niobrara interval is time equivalent to the Wapiabi Formation in the southern Foothills of Alberta (Stott, 1963; Wall, 1967b; Schröder-Adams et al., 1998; Medioli, 1999). In the area of the Sweetgrass Hills, Montana, the Kevin Member of the Marias River Formation is correlative to the Niobrara Formation (figure 2-1; Cobban, 1959; 1976; Lopez, 1995).

Verger Member

The shaly and bentonitic Verger Member overlies the Carlile Formation and underlies the sand-rich Medicine Hat Member. The member is equivalent to the shale of

the Muskiki Member overlying the Cardium Formation in the Alberta Foothills (figure 2-1). In Saskatchewan it might be equivalent to the Govenlock Member of the Niobrara Formation (Gilboy, 1996). It is characterized by abundant bentonites, which have been observed, for example at Highwood River (see chapter IV) and other Alberta foothill sections (Stott, 1962; Cobban et al., 1976). Based on lithological and wireline correlations, the member is equivalent to the lower and middle units of the Kevin Member of the Marias River Formation in northern Montana (figures 2-1, 2-4 and 2-5). In the west-central foothills and plains it correlates to the Muskiki Formation (Plint, 1991).

Medicine Hat Member

The sand-rich Medicine Hat Member overlies the Verger Member. The sandstones of this member are named in ascending order Medicine Hat sandstone zones D, C and A. In contrast to the distribution of the widespread shales of the Colorado Group the Medicine Hat sandstones were more locally deposited on the flanks of the Sweetgrass Arch (figure 2-4; Glass, 1990; Hankel et al. 1989).

The Medicine Hat Member is regionally correlated by Schröder-Adams et al. (1998) who suggested that the lower part of the Medicine Hat shale straddles the Coniacian/Santonian boundary. The upper boundary was placed in the mid Santonian within the *Sphenoceramus patootensis* mollusk zone. Based on this zonation, the Medicine Hat Member correlates to the Marshybank Member and the lower Dowling Member of the southern Alberta Foothills. Correlation to the west-central Alberta Foothills and plains suggests that the Medicine Hat Member is equivalent to the Marshybank and the Bad Heart formations. The thin and very fine grained Dowling

Member of the Wapiabi Formation in the Milk Creek in the southern Alberta Foothills is suggested as being a correlative to the Medicine Hat sandstones (Medioli, 1998).

First White Specks Member

The calcareous, finely laminated First White Specks Member overlying the Medicine Hat Member is time equivalent to the upper part of the Niobrara Formation of the reference section in the Western Interior, USA (McGookey et al., 1972; Merewether et al., 1979) and the upper part of the Kevin Member of the Marias River Formation (figure 2-1). This interval of the Niobrara Formation represents the highest sea-level during the Niobrara cyclothem (Caldwell et al., 1993; McNeil and Caldwell 1981). In the northern portion of the Canadian seaway, this interval is characterized by a lateral faunal change. For example, the time-diagnostic planktic foraminiferal zone of *Globigerinelloides* sp. is not recognized in the study area over the Sweetgrass Arch and its flanks. Transgression of the Niobrara Sea was diachronous from south to north and from west to east (McNeil and Caldwell, 1981; Schröder-Adams et al., 1998).

The First White Specks Shale is abruptly overlain by the Milk River/Lea Park formations. This contact is variable in the study area, and is marked in the western part by an erosional boundary (Myhr and Meijer-Drees 1981; Leckie et al., 1994).

SUMMARY

In the plains of southern Alberta and southwestern Saskatchewan the 120 to 350 m thick interval of the Upper Cretaceous unnamed Colorado Shale has been formally subdivided into the Late Turonian Carlile Formation and the Coniacian to Santonian

Niobrara Formation. A generalized sedimentological log summarizes the integration of all multidisciplinary data used to define the formations (figure 2-21).

The boundary between the Carlile Formation and the underlying Second White Specks Formation is conformable and is easily recognised by a change from calcareous, highly organic (>3 %) shale with common macrofossils to a non-calcareous shale with an organic content generally < 2 % and rare macrofossils. The boundary is visible on most logs, and is in this paper defined as the point on the resistivity log of maximum decline from the high resistivity values of the Second White Specks Formation.

The Carlile Formation is a 30 m (east) to 160 m (west) thick non-calcareous, dark gray, shaly interval with only minor sand partings that is informally subdivided into a lower, middle and upper unit. The lithology of the formation is based mainly on observations from an outcrop along Deer Creek east of the Sweetgrass Hills in Montana, and one core from a well location 13-20-17-7W4. The shale is in general flaggy to slabby and contains few to no macrofossils. It is non- to slightly bioturbated, and has a general upward-coarsening trend. The foraminiferal assemblage found in the formation belongs to the *Pseudoclavulina* sp. Zone (Caldwell et al., 1978), which places the formation into the Late Turonian. The formation is correlative to the Haven and Opabin members of the Blackstone Formation and the Cardium Formation in the southern Foothills.

The lower unit of the Carlile Formation is a 35 to 40 m thick (Deer Creek outcrop) homogenous gray shale with few non-bioturbated sand partings and no macrofossils. The unit includes no microfossils. It's average TOC value is 2.2 %. The middle unit is an approximately 30 m dark gray, slightly bioturbated, silty shale with bands of siderite concretions. A few trace fossils of *Chondrites* and *Gordia* or *Plioichnus* are preserved in

concretions, and except for a few fish scales, no fossils were found in this interval. The average TOC value is 1.4 %. The upper unit is the sandiest of the three units, and in the Deer Creek outcrop and core of 13-20-17-7W4, thin, upwards-coarsening fine sandstone intervals are observed. Some macrofossils and bioturbation occur and the TOC varies between 0.5 and 2.5 %.

The boundary between the Carlile and Niobrara formations is unconformable and is a distinct surface over the entire study area expressed in lithology, petrophysics and microfossil content. Below the boundary is the gray, non calcareous, silty and sand-rich shale of the upper Carlile Formation. Above the boundary is a dark gray, occasionally calcareous shale with abundant bentonites. Detailed wireline cross-sections (figures 2-5 and 2-6; chapter III) show an erosional surface mainly in the southern part tapering to a more conformable surface in the northern area. Biostratigraphically the formation boundary is marked by a change from the *Pseudoclavulina* sp. Zone to the *Trochammina* sp., *Bullopora laevis* zones.

The thickness of the Niobrara Formation varies from 80 m in the northeast to 240 m in the southwest and is subdivided into three mappable members: the shaly Verger, the sand-rich Medicine Hat and the calcareous First White Specks members. In general, the Niobrara Formation is composed of dark gray marine shales, siltstones and very fine, gray sandstones and a few layers of chert pebbles. A common feature of all three members is the occurrence of calcareous laminar and thin beds, although these are most pronounced in the First White Specks Member. This is a significant difference from the underlying Carlile Formation and the overlying Milk River Formation. Macrofossils, mainly ammonites and bivalves, are common in the formation, and bioturbation is widespread

especially in the upper part of the sandstones of the Medicine Hat Member. The foraminifera assemblages found in the formation belong to the *Trochammina* sp., *Bullopora laevis* and *Globigerinelloides* sp. zones (Caldwell et al., 1978), assigning a Coniacian to Santonian age. In the southern Alberta Foothills the lateral equivalent to the Niobrara Formation is the Wapiabi Formation (Wall and Rosene, 1977).

The Verger Member is a 20- (in the northeast) to 120-m- (in the southwest) thick shaly interval, and is named after the town of Verger located close to the type core in well 16-4-22-15W4. The member is slightly bioturbated and has only minor sand partings. In association with the bentonites mica is often present as well as small pyrite concretions. Thin beds of white specks occur and in parts resemble the appearance of the overlying First White Specks Member. TOC values range from 1.5 to 1.9 %, and both macro- and microfossils are abundant in the member.

The Medicine Hat Member is relatively uniform throughout most of the study area with a thickness between 40 and 65 meters. Commercial interest is high in this member due to its proven reserves of shallow biogenic gas and the potential for new discoveries. The member consists of numerous individually fine grained sandstones separated by shale and siltstones. The sandstones are concentrated on the flanks of the Sweetgrass Arch and are divided into three lithostratigraphic units, which are the lower D-sandstones, the middle C-sandstones and the youngest A-sandstones. In general the individual sandstones are lithologically alike, recognized both in cores and on wireline logs as upwards coarsening intervals from shale and silt to very fine to fine grained sandstones with a few layers of pebbles. The foraminifera assemblage of the member is from the *Trochammina*

sp. and *Bullopora laevis* zones which places the member in the earliest Santonian. (The entire range of both zones, is from latest Turonian to earliest Santonian)

The First White Specks Member is the youngest member of the Niobrara Formation, and is a dark gray calcareous shale with abundant fecal pellets rich in nannofossils. Macrofossils, dominated by *Inoceramus*, are common and thin bentonites are widespread. The shale is fissile to platy, slightly to non-bioturbated and contains several thin, sharp based, fine-grained sandstones. One of the thickest sandstones in the First White Specks Member is named the Sweetgrass Member and is situated northwest of the Sweetgrass Arch (Schröder-Adams et al., 1997). The member has a foraminifera assemblage of the *Globigerinelloides* sp. which places the member in the Late Santonian. The member is believed to be equivalent to the Thistle Member of the Wapiabi Formation in the foothills.

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REFERENCES

Beaumont, C., 1981. Foreland basins. *Royal Astronomical Society Geophysical Journal*, vol. 65, p. 291-329.

Bloch, J., Schröder-Adams C., Leckie, D.A., McIntyre, D.J., Craig, J. and Staniland, M., 1993. Revised stratigraphy of the lower Colorado Group (Albian to Turonian), Western Canada. *Bulletin of Canadian Petroleum Geology*, vol. 41, no. 3, p. 325-348.

Caldwell, W.G.E., North B.R., Stelck, C.R., and Wall, J.H., 1978. A foraminiferal zonal scheme for the Cretaceous System in the Interior Plains of Canada. *In:* Western and Arctic Canadian Biostratigraphy, Geological Association of Canada (eds. Stelck, C.R. and Chatterton, B.D.E.). Special Paper 18, p. 495-575.

Cant, D.J., 1992. Subsurface Facies Analysis. *In* Facies Models, Response to sea level change. (eds. Walker R.G. and James N.P.) Geological Association of Canada. p. 27-46.

Gilboy, C., 1993. The Carlile Shale Equivalent (Upper Cretaceous) in Southwestern Saskatchewan: A Wireline-log Study; *in* Summary of Investigations 1993, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 93-4.

Cobban, W.A., Erdmann, C.E., Lemke, R.W. and Maughan, E.K., 1959. Revision of the Colorado Group on the Sweetgrass Arch, Montana. *American Association of Petroleum Geologists Bulletin*, vol. 43, no. 12, p. 2786-2796.

Cobban, W.A., Erdmann, C.E., Lemke, R.W. and Maughan, E.K., 1976. Type sections and stratigraphy of the Blackleaf and Marias River formations (Cretaceous) of the Sweetgrass Arch, Montana. United States Geological Survey, Professional Paper 974, pp. 36-60.

Cobban, W. A., 1951. Colorado Shale of central and northwestern Montana and equivalent rocks of the Black Hills. *American Association of Petroleum Geologists Bulletin*, vol. 35, p. 2170-2198.

Collier, A. J., 1929. The Kevin-Sunburst Oil Field and other possibilities of oil and gas in the Sweetgrass Arch, Montana. U.S. Geological Survey, Bulletin 812-B, Contributions to economic geology, 1929, Part II, p. 57-189.

Dawson, G. M., 1884. Report on exploration from Port Simpson on the Pacific Coast to Edmonton on Saskatchewan River, embracing a portion of the northern part of British Columbia and Peace River Country. Geological and Natural History Survey of Canada. Report of Progress, 1879-1880, part B, 177.

Dowling D. B., 1917. The Southern Plains of Alberta. Geological Survey of Canada, Memoir 93, pp. 200.

Dowling, D.B., Slipper, S. E. and Mclearn F. H., 1919. Investigations in the Gas and Oil Fields of Alberta, Saskatchewan, and Manitoba, Geological Survey of Canada, Memoir 116, pp. 89.

Edwards, A. R., 1963. A preparation technique for calcareous nannoplankton. *Micropaleontology*, vol. 9, p. 103-104.

Espitalié, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J. and Boutefeu, A., 1977. Méthode rapide de caractérisaton des roches de mères de leur potentiel pétrolier et de leur degré d'évolution. *Revue de l'Institute Français du Pétrolier*, vol. 32, p. 23-42.

Espitalié, J., Senga Makadi, K. and Trichet, J., 1984. Role of the mineral matrix during kerogen pyrolysis. *In:* Advances in Organic Geochemistry 1983 (ed. Schenk, P.A.). Pergamon Press, Oxford, p. 365-382.

Espitalié, J., Deroo, G. and Marquis, F., 1985. Rock-Eval pyrolysis and its applications. *Institute Français du Pétrolier* Preprint 33578, pp. 72.

Folk, R.L., 1974. Petrology of Sedimentary Rocks. Hemphills, Austin, Texas, pp. 182.

Gilboy, C.F., 1989. Geology and natural gas production of the Upper Cretaceous Medicine Hat sandstone, Southwestern Saskatchewan. *In: Summary of Investigations 1989*, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 89-4.

Gilboy, C.F., 1993. The Carlile Shale equivalent (Upper Cretaceous) in Southwestern Saskatchewan: A Wireline-log study. *In: Summary of Investigations 1993*, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 93-4.

Gilboy, C.F., 1996. Detailed Log-based Stratigraphic Study of Colorado Group and Milk River Formation Strata (Cretaceous), Southwestern Saskatchewan; *In: Summary*

of Investigations 1996, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 96-4.

Glass, D.J., 1990. Lexicon of Canadian Stratigraphy, Volume 4, Western Canada, including eastern British Columbia, Alberta, Saskatchewan and Southern Manitoba. *Canadian Society of Petroleum Geologists*, pp. 772.

Hancock, W.P. and Glass, D.J., 1968. Medicine Hat - Hatton gas field, Alberta and Saskatchewan. *In* : Natural Gases of North America (ed. Beebe, B.W.). *American Association of Petroleum Geologists*, Memoir 7, p. 732-735.

Hankel, R. C., Davies G. R. and Krouse H. R., 1989. Eastern Medicine Hat gas field: a shallow, Upper Cretaceous, bacteriogenic gas reservoir of southeastern Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 37, no. 1, p. 98-112.

Haggart J.W, 2002. Report on Upper Cretaceous fossils from Kananaskis Lake map-area, Alberta (NTS; 82J) and Montana, USA. Geological Survey of Canada Fossil Report No. JWH-2000-01

Hattin, D.E., 1975. Stratigraphic study of the Carlile-Niobrara (Upper Cretaceous) unconformity in Kansas and northeastern Nebraska. *In:* The Cretaceous System in the Western Interior of North America (ed. Caldwell, W.G.E.). Geological Association of Canada, Special Paper 13, p. 195-210.

Henry, K.C., 1979. Gas Detection in the extremely Shaly Bowdoin Formation of northern Montana. Montana Geological Society. Reprinted courtesy of the Society of Professional Well Log Analysts. SSPWLA 20th Annual Logging Symposium. Special Publications Paper no. 24, p 1-8.

Kaufmann, E.G., 1967. Coloradan macroinvertebrate assemblages, central Western Interior. *In:* Paleoenvironments of the Cretaceous seaway in the Western Interior. Colorado School of Mines, Golden, CO, p. 67-143.

Kendall, A.C. and Simpson, K., 1974. Calcite layers in the uppermost Medicine Hat Sandstone (Upper Cretaceous) of southwestern Saskatchewan. *Bulletin of Canadian Petroleum Geologists*, vol. 22, p. 34-41.

Leckie, D.A., Bhattacharya, J.P., Bloch, J., Gilboy, C.F., Norris, B., 1994. Cretaceous Colorado/Alberta Group of the Western Canada Sedimentary Basin. *In:* Geological Atlas of the Western Canada Sedimentary Basin (compiled by Mossop, G. and Shetson, I.). *Canadian Society of Petroleum Geologists and the Alberta Research Council*, pp. 510.

Leythaeuser, D., 1973. Effects of weathering on organic matter in shales. *Geochim. Cosmochim. Acts*, 37, p. 113-120.

Lopez, L. A., 1995. Geology of the Sweetgrass Hills, North-Central Montana. Montana Bureau of Mines and Geology, Memoir 68, pp. 35.

Lorenz, J.C., 1982. Lithospheric flexure and the history of the Sweetgrass Arch northeastern Montana. Rocky Mountain Association of Geologists - 1982 symposium, p. 77-89.

Lorenz, J.C. and Gavin, W., 1984. Geology of the Two Medicine Formation and the Sedimentology of the dinosaur nesting ground. Montana Geological Society 1984 Field Conference - northwestern Montana, p. 175-186.

Martin, L., 1965. The Medicine Hat Gas Field. *Journal of Canadian Petroleum Technology*, vol. 4, no. 1, p. 23-29.

McGookey, D.P., Haun, J.D., Hale, L. A., Goodell, H. G., McCubbin, D. G., Weimer. R.J., and Wulf, G.R., 1972. Cretaceous System, *In:* Geologic atlas of the Rocky Mountain region: Denver, Colorado (ed. Mallory, W.). *Rocky Mountain Association of Geologists*, pp. 190-228.

McNeil, D.H. and Caldwell, W.G.E., 1981. Cretaceous Rocks and their foraminifera in the Manitoba Escarpment. *Geological Association of Canada*, Special Paper 21, pp. 439.

Merewether, E.A., Cobban, W.A., and Cavanaugh, E.T., 1979. Frontier Formation and equivalent rocks in eastern Wyoming. *Mountain Geologist*, vol. 16, p. 67-101.

Medioli, B.E., 1999. Cenomanian to Santonian sea-level history from a proximal setting in the western Canada sedimentary basin, southern Rocky Mountain Foothills, Alberta: Sedimentology, micropaleontology and organic geochemistry. Unpublished masters thesis, Carleton University, pp. 147.

Meijer-Drees, N.C. and Myhr, D.W., 1981. The Upper Cretaceous Milk River and Lea Park formations in southeastern Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 29, p. 42-74.

Myhr, D.W. and Meijer-Drees, N.C., 1976. The sedimentology of selected clastic oil and gas reservoirs in Alberta. Fourth Canadian Society of Petroleum Geologist core conference. Calgary, Canada.

NACSN (North American Commission on Stratigraphic Nomenclature), 1983. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, vol. 67, p. 841-875.

Nielsen, K. S. and Schröder-Adams, C. J., 1999. Upper Colorado Group lithology and wire line log correlation in southwestern Saskatchewan. *In: Summary of Investigations 1998*, Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 98-4, p. 79-84.

Obradovich, J.D., 1993. A Cretaceous time scale, in Caldwell, W.G.E. and Kauffman, E.G., eds., Evolution of the Western Interior Basin. Geological Association of Canada, Special Paper 39, p. 379-396.

Payenberg, T.H.D., 2002. Litho-, Chrono- and Allostratigraphy of the Santonian to Campanian Milk River and Eagle Formations in southern Alberta and North-central Montana: Implications for differential subsidence in the Western Interior Foreland Basin. Unpubl. Ph.D. Thesis, University of Toronto, Canada. p. 221.

Plint, A.G., 1990. An allostratigraphic correlation of the Muskiki and Marshybank formations (Coniacian-Santonian) in the Foothills and subsurface of the Alberta Basin. *Bulletin of Canadian Petroleum Geology,* vol. 38, no. 3, p. 288-306.

Plint, A.G., Norris, B. and Donaldson, W.S. 1990. Revised definitions for the Upper Cretaceous Bad Heart Formation and associated units in the Foothills and Plains of Alberta and British Columbia. *Bulletin of Canadian Petroleum Geology*, Vol. 38, No.1 p. 78-88.

Plint, A.G., 1991. High-frequency relative sea-level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? *International Association of Sedimentologists*, Spec. Pub. 12, p.409-428.

Podruski, J.A., 1988. Contrasting character of the Peace River and Sweetgrass arches, Western Canada Sedimentary Basin. *Geoscience Canada*, vol. 15, p. 94-97.

Potter, P.E., Maynard, J.B. and Pryor, W.A., 1980. Sedimentology of shale. Springer-Verlag, New York, pp. 306.

Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis. *American Association of Petroleum Geologists Bulletin*, vol. 70, p. 318-329.

Rice, D.D., 1981. Subsurface cross-section from southeastern Alberta, Canada, to Bowdoin Dome area, north-central Montana, showing correlation of Cretaceous rocks and shallow, gas-productive zones in low-permeability reservoirs. *U.S. Geological Survey*, Oil and Gas Investigation, chart OC-112.

Russell L. S. and Landes R. W., 1940. Geology of the Southern Alberta Plains. Geological Survey of Canada Memoir, 221,. p 223.

Schröder-Adams, C.J., Leckie, D.A., Bloch, Craig, J., McIntyre, D.J., and Adams, P.J., 1996. Paleoenvironmental changes in the Cretaceous (Albian to Turonian) Colorado Group of western Canada: microfossil, sedimentological and geochemical evidence. *Cretaceous Research*, v. 17, p. 311-365.

Schröder-Adams, C.J., Adams, P.J., Leckie, D.A., Bloch, J., Craig, J., El-Dien, S.A.S., 1997. Upper Cretaceous Medicine Hat Formation and First White Speckled Shale

in southeastern Alberta: evidence for localized shallow water deposition. *Bulletin of Canadian Petroleum Geology*, vol. 45, no. 3, p. 356-376.

Schröder-Adams, C.J., Adams, P., Haggart, J., Leckie, D.A., Bloch, J., Craig, J., McIntyre, D.J., 1998. An integrated paleontological approach to reservoir problems: Upper Cretaceous Medicine Hat Formation and First White Speckled Shale in southern Alberta, Canada. *Palaios* Vol. 13, p. 361-375..

Shurr, G.W. and Reskind, J., 1984. Stratigraphic framework of the Niobrara Formation (Upper Cretaceous), Montana and South Dakota. *In:* Mesozoic of middle North America (eds. Stott, D.F. and Glass, D.J.). Canadian Society of Petroleum Geologists Memoir. vol.9, p. 205-219.

Shurr, G.W. and Rice, D.D., 1986. Paleotectonic controls on deposition of the Niobrara Formation, Eagle Sandstone, and equivalent rocks (Upper Cretaceous), Montana and South Dakota. *In*: Paleotectonics and sedimentation in the Rocky Mountain region (ed. Peterson, J.A.). American Association of Petroleum Geologists Memoir. vol. 41, p. 193-211.

Simpson, F., 1979a. Low-permeability gas reservoirs in marine, Cretaceous sandstones of Saskatchewan: 1. Project outline and rationale; *Summary of Investigations 1979*, Saskatchewan geological Survey, Miscellaneous Report 79-10, p. 174-180.

Simpson, F., 1979b. Low-permeability gas reservoirs in marine, Cretaceous sandstones of Saskatchewan: 4. Upper Colorado and Montana (Turonian to Campanian) strata of western Saskatchewan; *Summary of Investigations 1979*, Saskatchewan geological Survey, Miscellaneous Report 79-10, p. 191-198.

Simpson, F., 1979. Evolution of a graded Cretaceous Shelf. *In:* Proc. Second International Conference on Basement Tectonics, Newark, Delaware, July 13-17, 1976, p. 43-44.

Simpson, F., 1981: Low-Permeability Gas Reservoirs in Marine Cretaceous Sandstones of Saskatchewan: 11. Well-log Analysis of Medicine Hat Sandstone (Santonian) of Southwestern Saskatchewan and Southeastern Alberta. *In:* Summary of Investigations 1981, *Saskatchewan Geological Survey*, Miscellaneous Report 81-4.

Simpson, F., 1982. Low-permeability gas reservoirs in marine Cretaceous sandstones of Saskatchewan. Summary of Investigations 1982, *Saskatchewan Geological Survey, Miscellaneous Report* 82-4, p. 120-125.

Simpson, F. 1984. Hydrocarbon potential of low permeability marine Cretaceous sandstone's of Saskatchewan, *In:* The Mesozoic of Middle North America. A Selection of Papers from the Symposium on the Mesozoic of Middle North America, Calgary, Alberta, Canada. *Canadian Society of Petroleum Geologists,* p. 513-533.

Spratt, J.G., 1931. Stratigraphy of Colorado Shale in southern plains of Alberta. *American Association of Petroleum Geologists Bulletin*, vol. 15, p. 1171.

Stott, D.F., 1962. Upper Cretaceous marine rocks of Rocky Mountain Foothills. *Alberta Society of Petroleum Geologists Journal*, vol. 10, no. 5, p. 228-240.

Stott D. F., 1963. The Cretaceous Alberta Group and Equivalent Rocks, Rocky Mountain Foothills, Alberta., *Geological Survey of Canada*, Memoir 317, p. 306.

Stott, D.F., 1984. Cretaceous sequences of the foothills of the Canadian Rocky Mountains. *In*: The Mesozoic of North America (eds. Stott, D.F. and Glass, D.J.). *Canadian Society of Petroleum Geologists*, Memoir 9, p. 85-108.

Stower, L.E., 1966. Cretaceous coccoliths and associated nannofossils from France and The Netherlands. *Micropaleontology*, vol. 12, p. 133-167.

The Canadian Gas Potential Committee, 2001. Report from an independent group of geoscience volunteers with industry and government experience who are committed to providing reliable assessments of natural gas resources in Canada. P.O. McAra Printing Limited, Canada

Then, D.R. and Dougherty, B.J., 1983. A new procedure for extracting foraminifera from indurated organic shale: Current Research, part B, *Geological Survey of Canada*, paper 83-1B, p. 313-314.

Tissot, B., Pelet, R. and Ungerer, Ph., 1987. Thermal History of Sedimentary Basins, Maturation Indices, and Kinetics of Oil and Gas Generation: *The American Association of Petroleum Geologists Bulletin*. V. 71. No 12, p. 1445-1466.

Teichmuller, M. and Durand, B., 1983. Fluorescence microscopal rank studies on liptinites and vitrinites in peat and coal and comparison with result of the Rock-Eval pyrolysis. *International Journal of Coal Geology*, vol. 2, p. 197-230.

Uchman, A., 1999. Ichnology of the Rhenodanubian Flysch (Lower Cretaceous-Eocene) in Austria and Germany. *Beringeria* 25: 67-173.

Wall, J.H., 1967a. Microfauna of the Cretaceous Alberta Shale on Deer Creek, International boundary, Great Plains Region. From the Proceedings of the Geological Association of Canada, vol. 18, p. 93-108.

Walker, R. G. and Plint, A. D., 1992. Wave- and shallow-marine systems. *In:* Facies models: response to sea level change (eds. Walker, R.G. and James, N.). *Geological Association of Canada*, St. John's Newfoundland, p. 219-238.

Figure 2-1. Stratigraphic chart, showing the studied interval and its correlations to nearby regions.

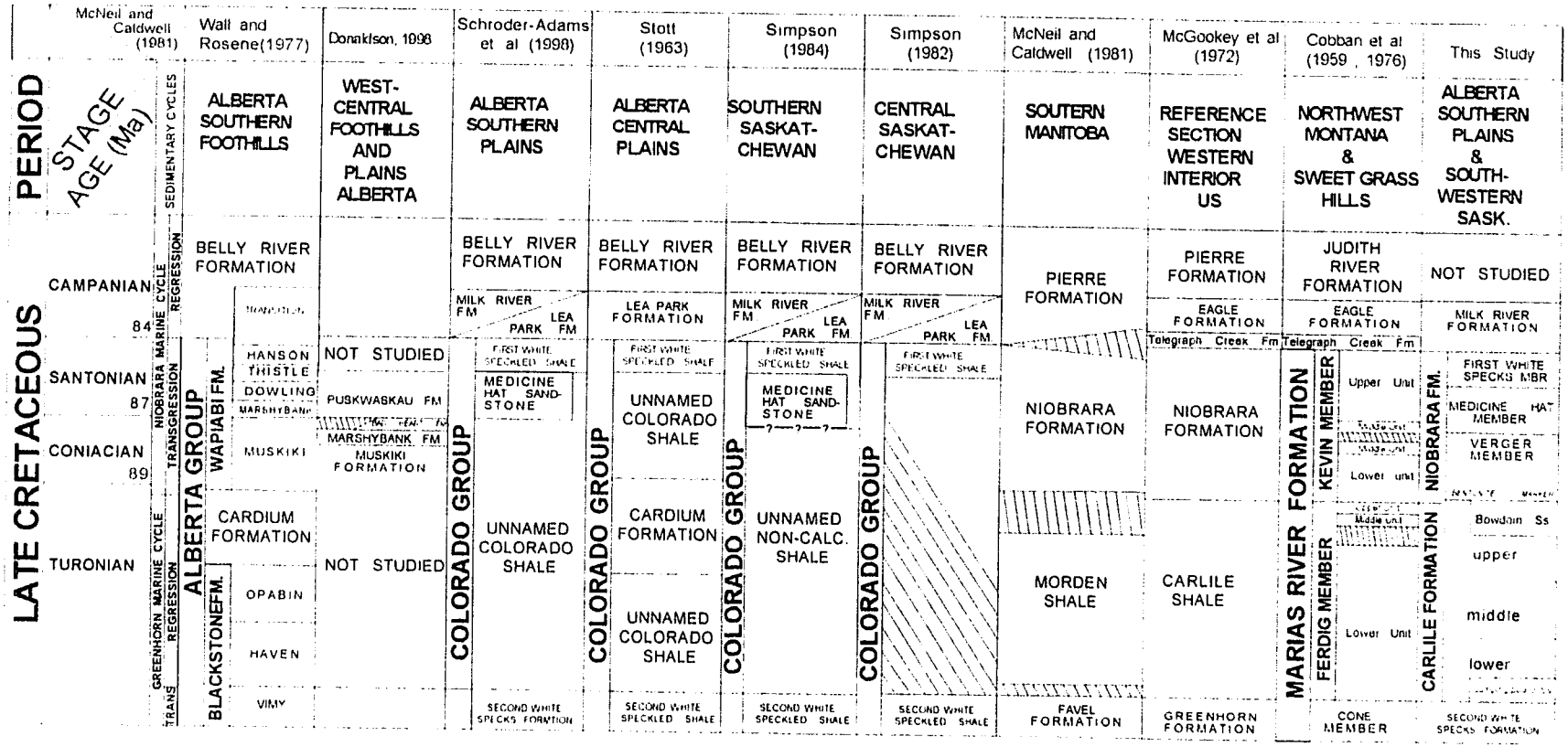

PERIOD
STAGE
AGE (Ma)
SEDIMENTARY CYCLES
LATE CRETACEOUS
CAMPANIAN
84
SANTONIAN
87
CONIACIAN
89
TURONIAN
NIOBRARA MARINE CYCLE
TRANSGRESSION
REGRESSION
GREENHORN MARINE CYCLE
TRANS
REGRESSION
McNeil and Caldwell (1981)
Wall and Rosene(1977)
Donaldson, 1998
Schroder-Adams et al (1998)
Stott (1963)
Simpson (1984)
Simpson (1982)
McNeil and Caldwell (1981)
McGookey et al (1972)
Cobban et al (1959 , 1976)
This Study
ALBERTA SOUTHERN FOOTHILLS
WEST-CENTRAL FOOTHILLS AND PLAINS ALBERTA
ALBERTA SOUTHERN PLAINS
ALBERTA CENTRAL PLAINS
SOUTHERN SASKAT-CHEWAN
CENTRAL SASKAT-CHEWAN
SOUTERN MANITOBA
REFERENCE SECTION WESTERN INTERIOR US
NORTHWEST MONTANA & SWEET GRASS HILLS
ALBERTA SOUTHERN PLAINS & SOUTH-WESTERN SASK.
BELLY RIVER FORMATION
PIERRE FORMATION
JUDITH RIVER FORMATION
NOT STUDIED
MILK RIVER FM
LEA PARK FM
LEA PARK FORMATION
EAGLE FORMATION
Telegraph Creek Fm
MILK RIVER FORMATION
ALBERTA GROUP
WAPIABI FM.
BLACKSTONE FM.
HANSON
THISTLE
DOWLING
MARSHYBANK
MUSKIKI
CARDIUM FORMATION
OPABIN
HAVEN
VIMY
NOT STUDIED
PUSKWASKAU FM
MARSHYBANK FM
MUSKIKI FORMATION
NOT STUDIED
COLORADO GROUP
FIRST WHITE SPECKLED SHALE
MEDICINE HAT SAND-STONE
UNNAMED COLORADO SHALE
SECOND WHITE SPECKS FORMTION
UNNAMED COLORADO SHALE
CARDIUM FORMATION
UNNAMED COLORADO SHALE
SECOND WHITE SPECKLED SHALE
UNNAMED NON-CALC. SHALE
NIOBRARA FORMATION
MORDEN SHALE
FAVEL FORMATION
CARLILE SHALE
GREENHORN FORMATION
MARIAS RIVER FORMATION
KEVIN MEMBER
FERDIG MEMBER
Upper Unit
Lower unit
Middle unit
Lower Unit
CONE MEMBER
NIOBRARA FM.
CARLILE FORMATION
FIRST WHITE SPECKS MBR
MEDICINE HAT MEMBER
VERGER MEMBER
Bowdoin Ss
upper
middle
lower
SECOND WHITE SPECKS FORMATION

Figure 2-1

Figure 2-2. Study area and location of cores and cross-sections. Cross-sections I (A-A') and II (B-B') are shown in figures 2-5 and 2-6. Location of the 2800 wells used for mapping are not shown, but are distributed relatively even over the entire study area.

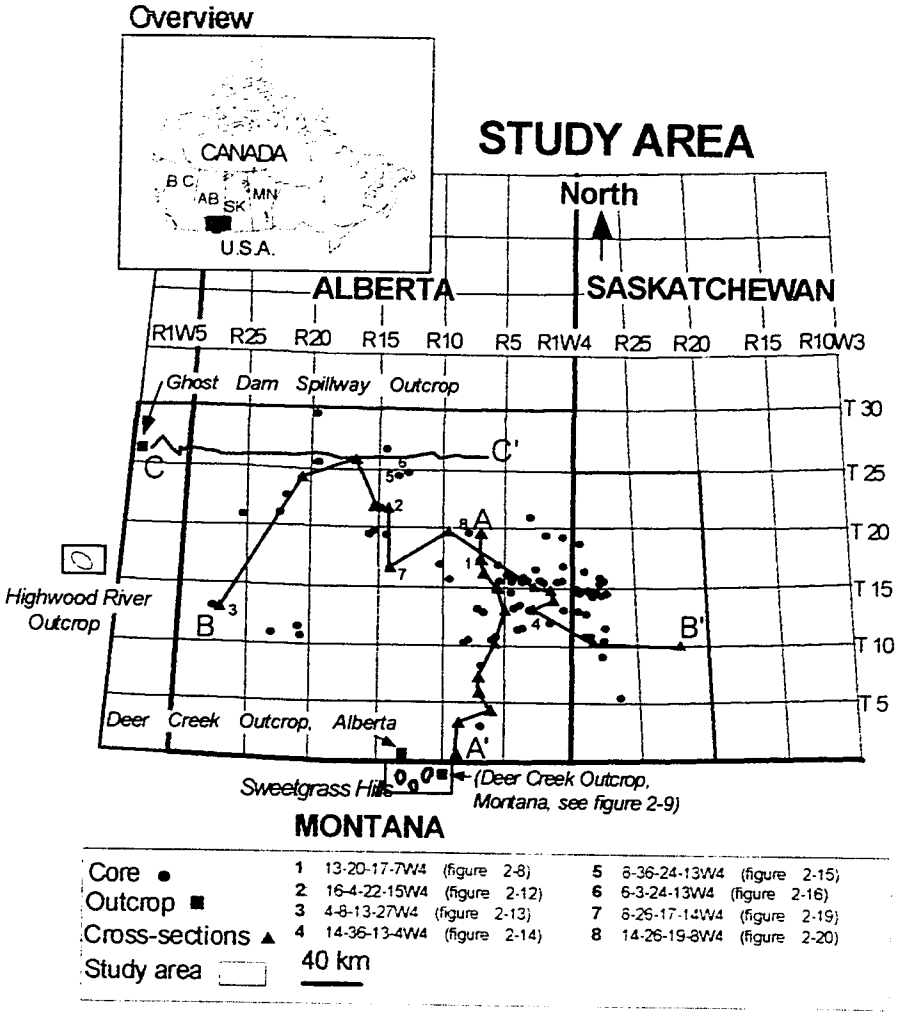

Overview
CANADA
B.C.
AB
SK
MN
U.S.A.
STUDY AREA
North
ALBERTA
SASKATCHEWAN
R1W5 R25 R20 R15 R10 R5 R1W4 R25 R20 R15 R10W3
T 30
T 25
T 20
T 15
T 10
T 5
Ghost Dam Spillway Outcrop
Highwood River Outcrop
Deer Creek Outcrop, Alberta
Sweetgrass Hills
(Deer Creek Outcrop, Montana, see figure 2-9)
MONTANA
A
A'
B
B'
C
C'
Core
Outcrop
Cross-sections
Study area
40 km
1 13-20-17-7W4 (figure 2-8)
2 16-4-22-15W4 (figure 2-12)
3 4-8-13-27W4 (figure 2-13)
4 14-36-13-4W4 (figure 2-14)
5 8-36-24-13W4 (figure 2-15)
6 6-3-24-13W4 (figure 2-16)
7 8-26-17-14W4 (figure 2-19)
8 14-26-19-8W4 (figure 2-20)

Figure 2-2

Figure 2-3. Structural map of the study area and northern Montana. Contours in Alberta and Saskatchewan represent the top Colorado Group (the top of the First White Specks Member of the Niobrara Formation is in meters above sea-level). Structural setting in Montana after Lopez (1995).

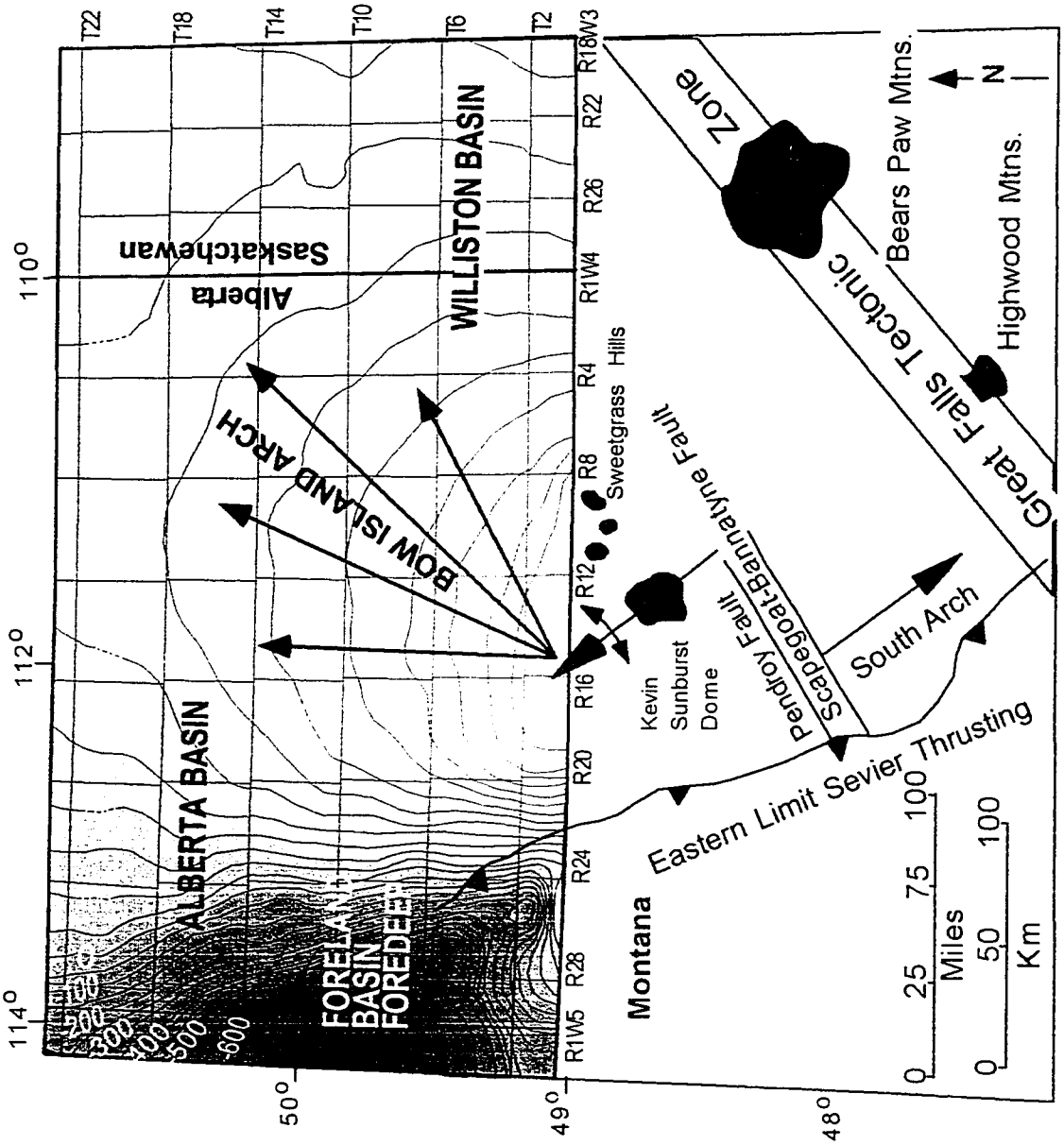

T22
T18
T14
T10
T6
T2
R18W3
R22
R26
R1W4
R4
R8
R12
R16
R20
R24
R28
R1W5
110°
112°
114°
50°
49°
48°
Saskatchewan
Alberta
WILLISTON BASIN
BOW ISLAND ARCH
ALBERTA BASIN
FORELAND BASIN FOREDEEP
Sweetgrass Hills
Kevin Sunburst Dome
Pendroy Fault
Scapegoat-Bannatyne Fault
South Arch
Great Falls Tectonic Zone
Bears Paw Mtns.
Highwood Mtns.
Eastern Limit Sevier Thrusting
Montana
N
0 25 75 100
Miles
0 50 100
Km

Figure 2-3

Figure 2-4. Outcrops along Deer Creek, East Butte, Sweetgrass Hills, Montana. Left sedimentological column shows the type section of the Ferdig Member in northern Montana (Cobban et al., 1976). Middle column is the reference section of the Carlile Formation in the Sweetgrass Hills, northern Montana (this study). The Carlile Formation is correlated to a subsurface wire-line log in Alberta. Outcrop and well location are shown in figure 2-9 and sedimentological legend in figure 2-8.

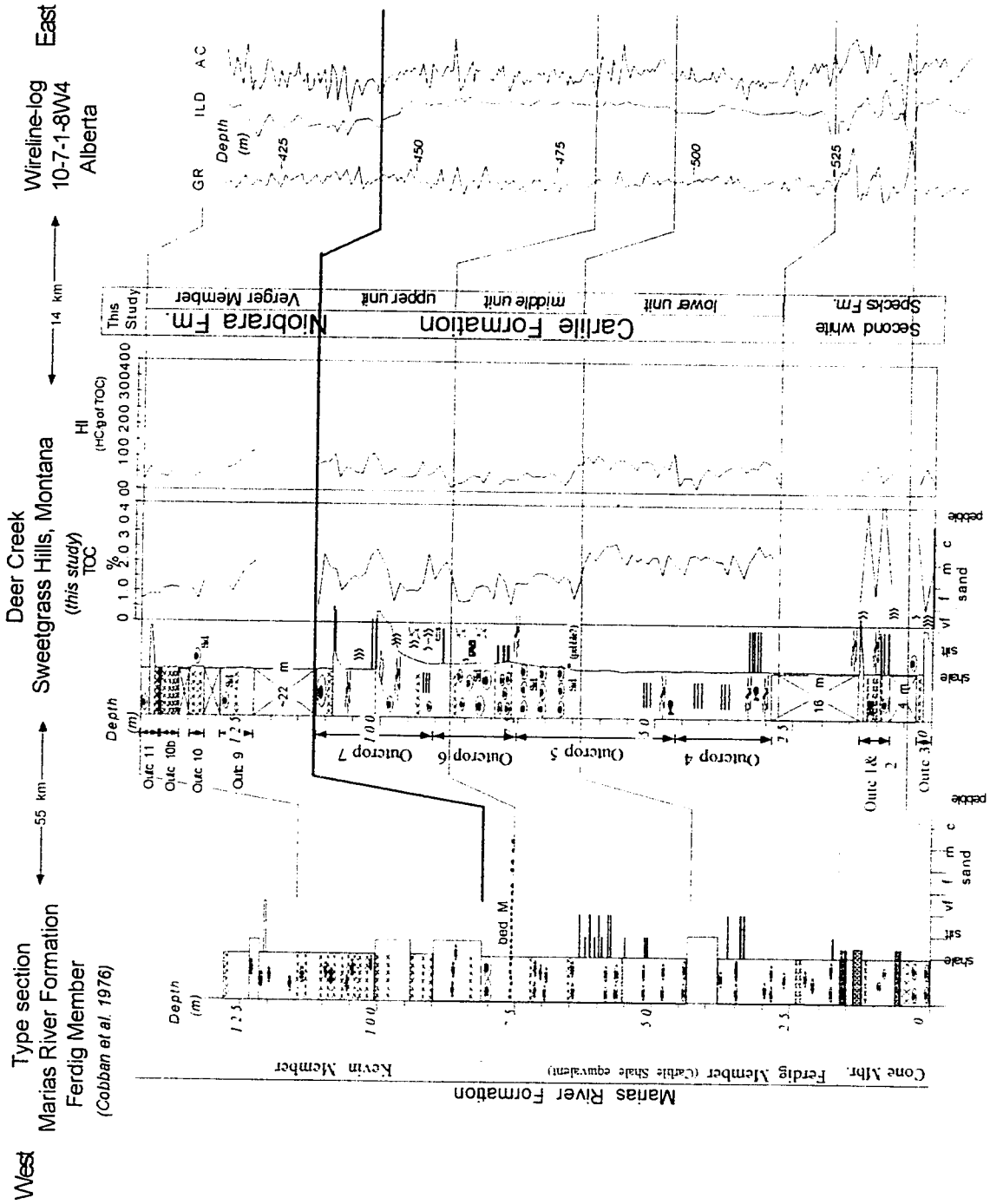

West
Type section
Marias River Formation
Ferdig Member
(Cobban et al. 1976)
55 km
Deer Creek
Sweetgrass Hills, Montana
(this study)
14 km
Wireline-log
10-7-1-8W4
Alberta
East
Depth (m)
TOC %
HI (HC/gof TOC)
This Study
Verger Member
upper unit
middle unit
lower unit
Niobrara Fm.
Carlile Formation
Second white Specks Fm.
Marias River Formation
Kevin Member
Cone Mbr.
Ferdig Member (Carlile Shale equivalent)
Outcrop 7
Outcrop 6
Outcrop 5
Outcrop 4
Outc 11
Outc 10b
Outc 10
Outc 9
Outc 1&2
Outc 3
bed M
GR
ILD
AC
shale
silt
vf f m c sand
pebble

Figure 2-4

Figure 2-5. Cross-sections of wire-line logs are oriented north to south, showing the Carlile and Niobrara formations. Location of wells on figure 2. GR: Gamma Ray log; ILD: Deep Induction log (resistivity) log; ITT: Sonic log. FWSM: The First White Specks Member. Datum: Top of the Second White Specks Formation.

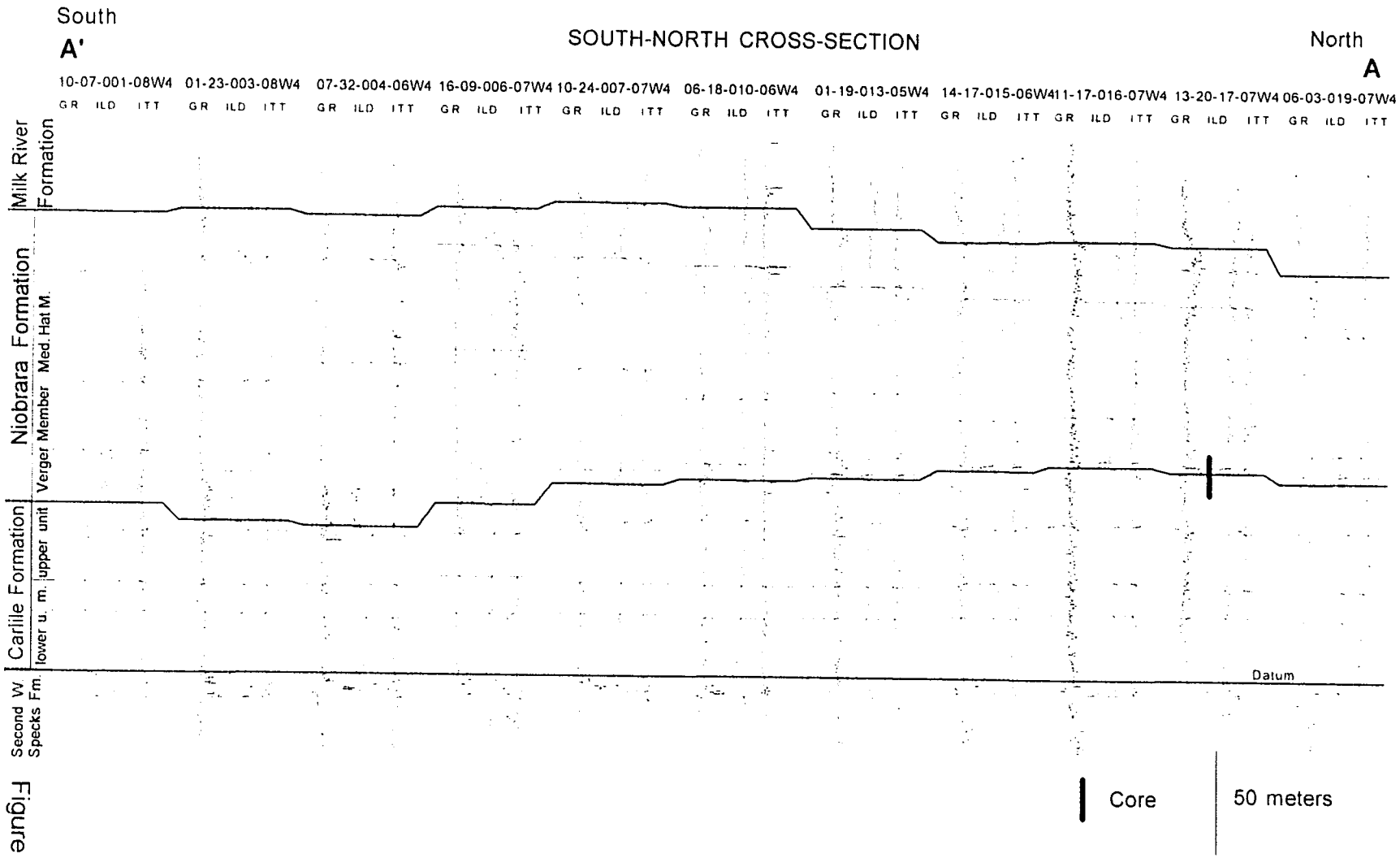

South
A'
SOUTH-NORTH CROSS-SECTION
North
A
10-07-001-08W4
01-23-003-08W4
07-32-004-06W4
16-09-006-07W4
10-24-007-07W4
06-18-010-06W4
01-19-013-05W4
14-17-015-06W4
11-17-016-07W4
13-20-17-07W4
06-03-019-07W4
GR ILD ITT
Milk River Formation
Niobrara Formation
Med. Hat M.
Verger Member
Carlile Formation
upper unit
lower u. m.
Second W Specks Fm.
Datum
Core
50 meters

Figure 2-5

Figure 2-6. Cross-section of wire-line logs are oriented east to west. Location of wells on figure 2-2. GR: Gamma Ray log, ILD: Deep Induction log (resistivity) log. ITT: Sonic log. FWSM: The First White Specks Member. Datum top of the Second White Specks Formation.

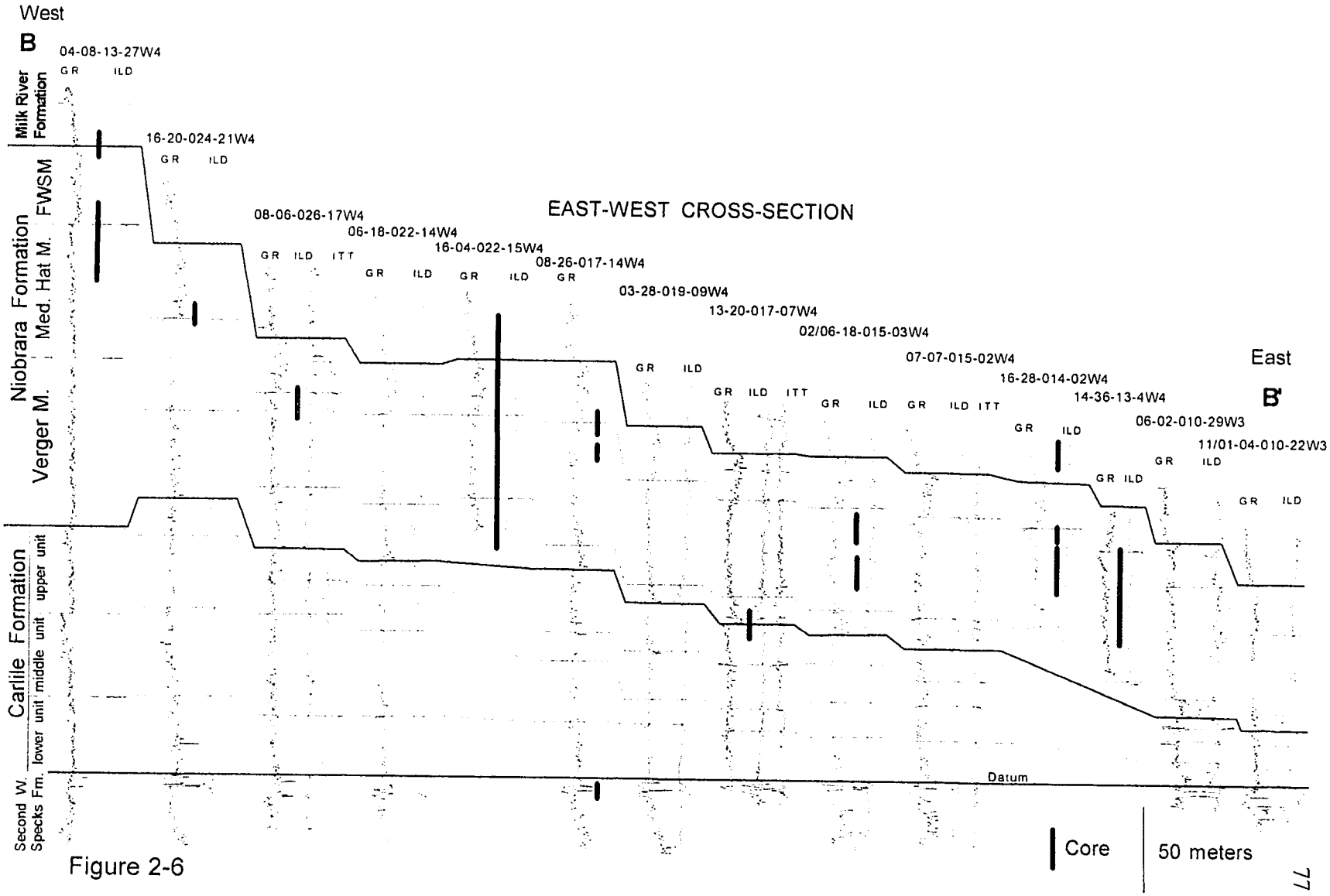

West
B
East
B'
EAST-WEST CROSS-SECTION
04-08-13-27W4
16-20-024-21W4
08-06-026-17W4
06-18-022-14W4
16-04-022-15W4
08-26-017-14W4
03-28-019-09W4
13-20-017-07W4
02/06-18-015-03W4
07-07-015-02W4
16-28-014-02W4
14-36-13-4W4
06-02-010-29W3
11/01-04-010-22W3
GR
ILD
ITT
Milk River Formation
Niobrara Formation
Verger M.
Med. Hat M.
FWSM
Carlile Formation
upper unit
middle unit
lower unit
Second W.
Specks Fm.
Datum
Core
50 meters

Figure 2-6

Figure 2-7A. Isopach map of the Carlile Formation. 10 meters contours. **B**: Isopach map of the Niobrara Formation. Contour lines 20 meters. **C**: Isopach map of the Verger Member. Contour lines 5 meters. **D**: Isopach map of the Medicine Hat Member. Contour lines 5 meters. **E**: Isopach map of the First White Specks Member. Contour lines 5 meters **F**: Subdivision of the study area into western, northern and eastern areas.

ISOPACH CARLILE FORMATION

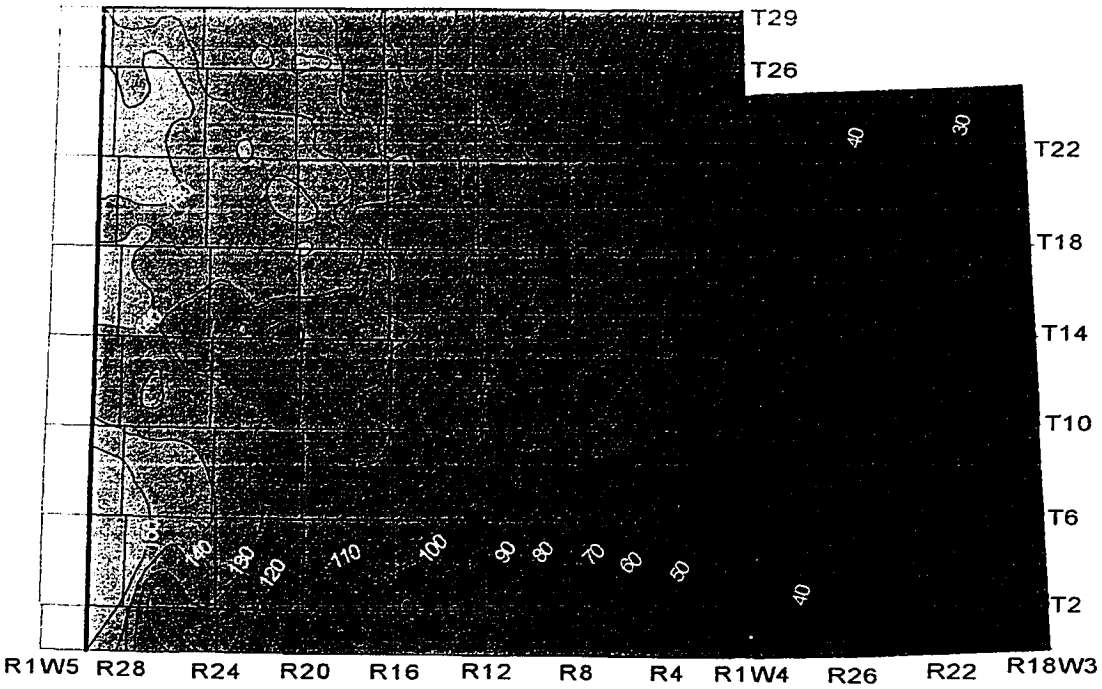


Figure 2-7A

ISOPACH NIOBRARA FORMATION

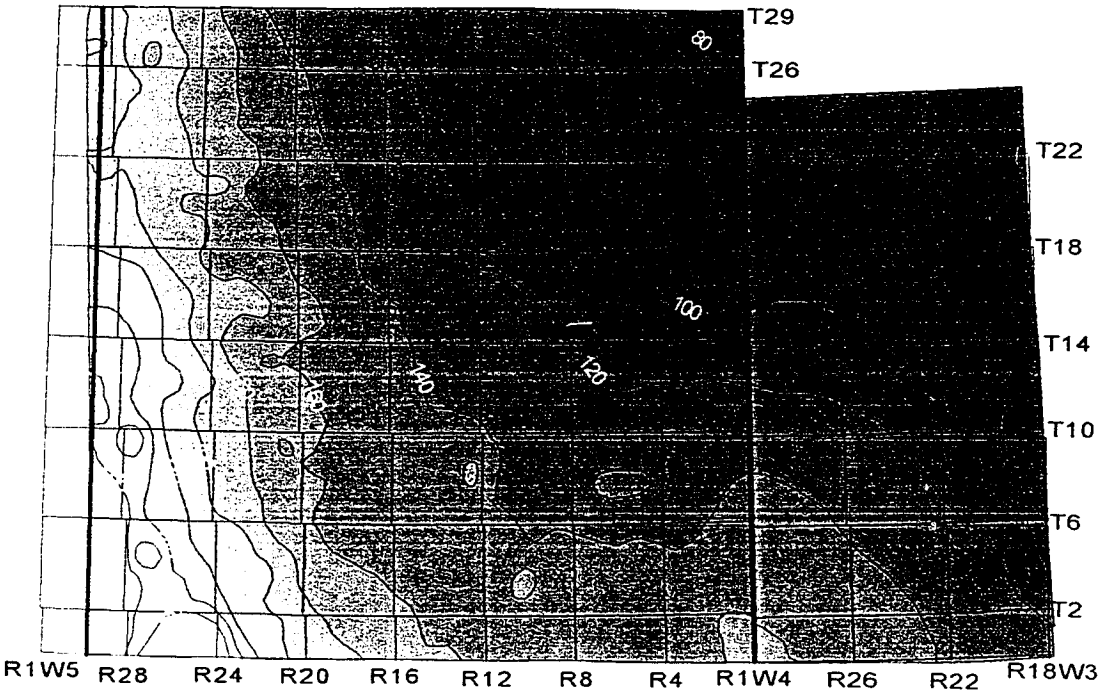


Figure 2-7B

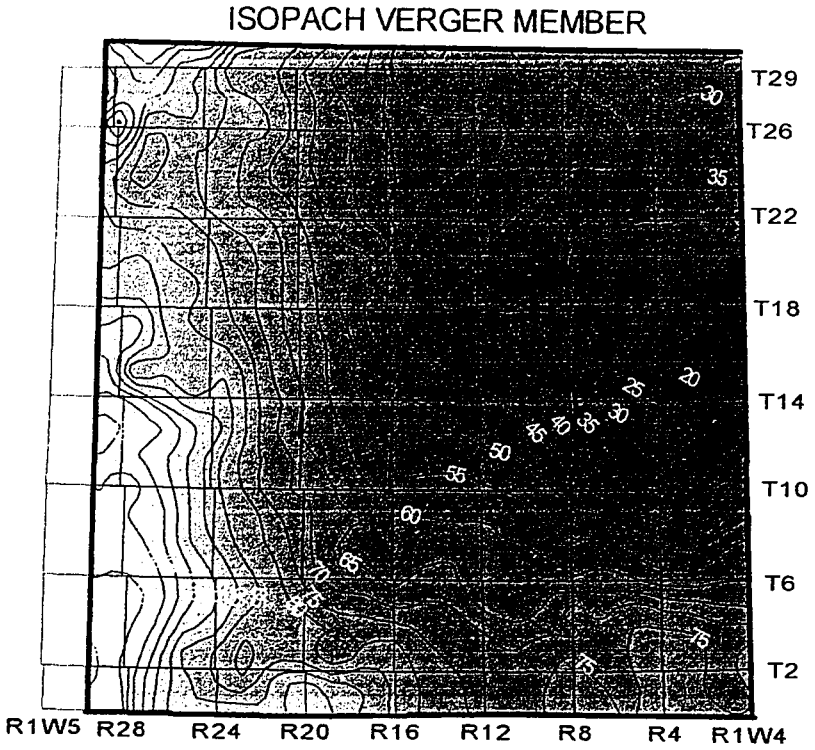


Figure 2-7C

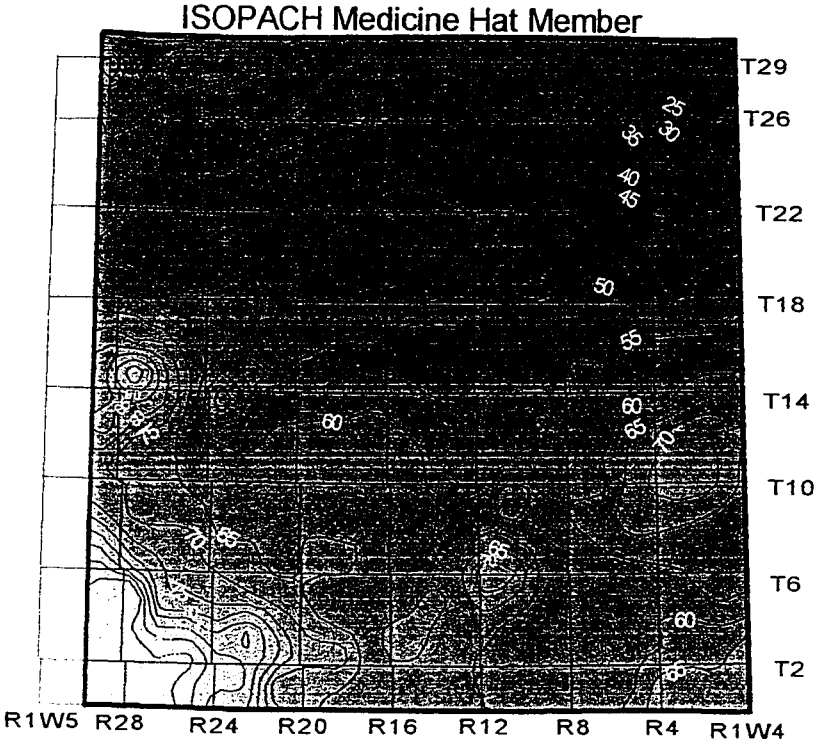


Figure 2-7D

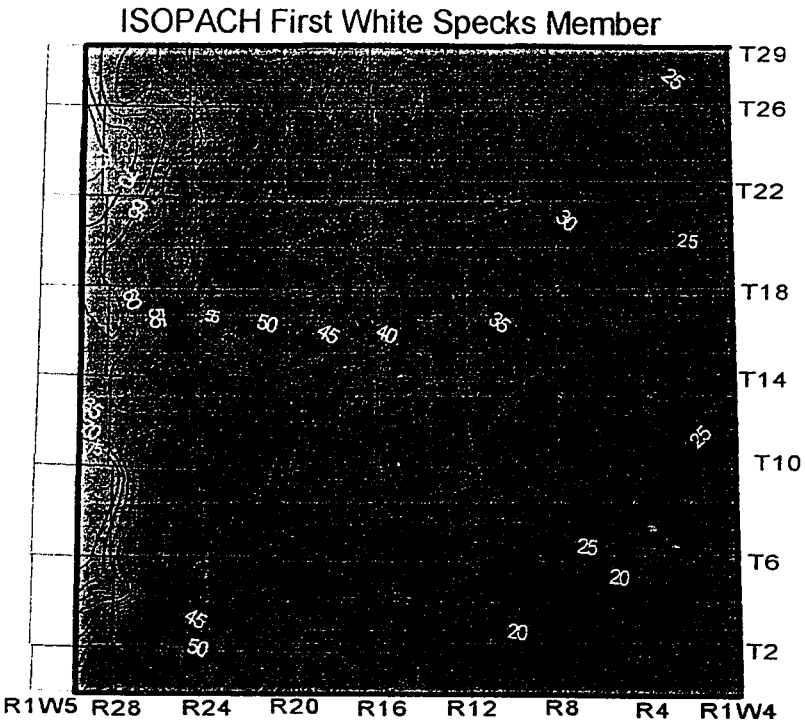


Figure 2-7E

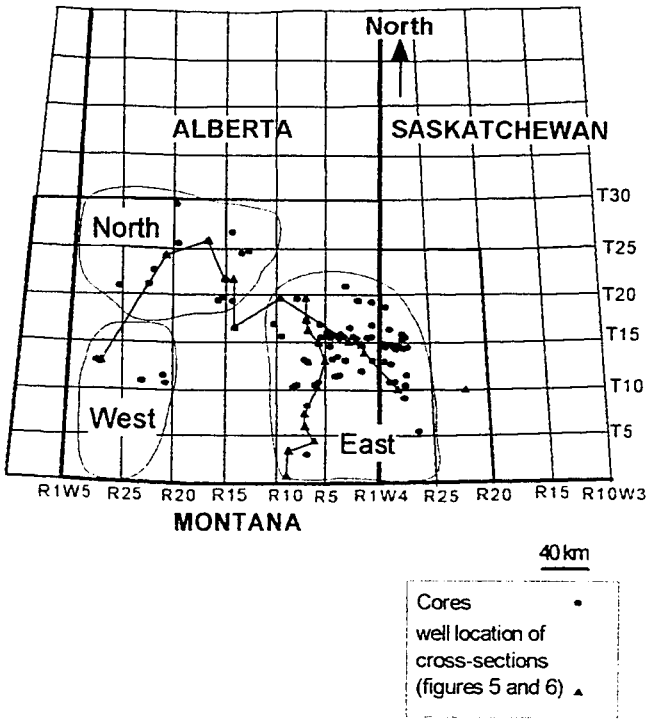


Figure 2-7F

Figure 2-8. **A**: Core 13-20-17-7W4: Reference core of the boundary between the Carlile and Niobrara formations. Core location on figure 9. **B**: Sedimentological legend.

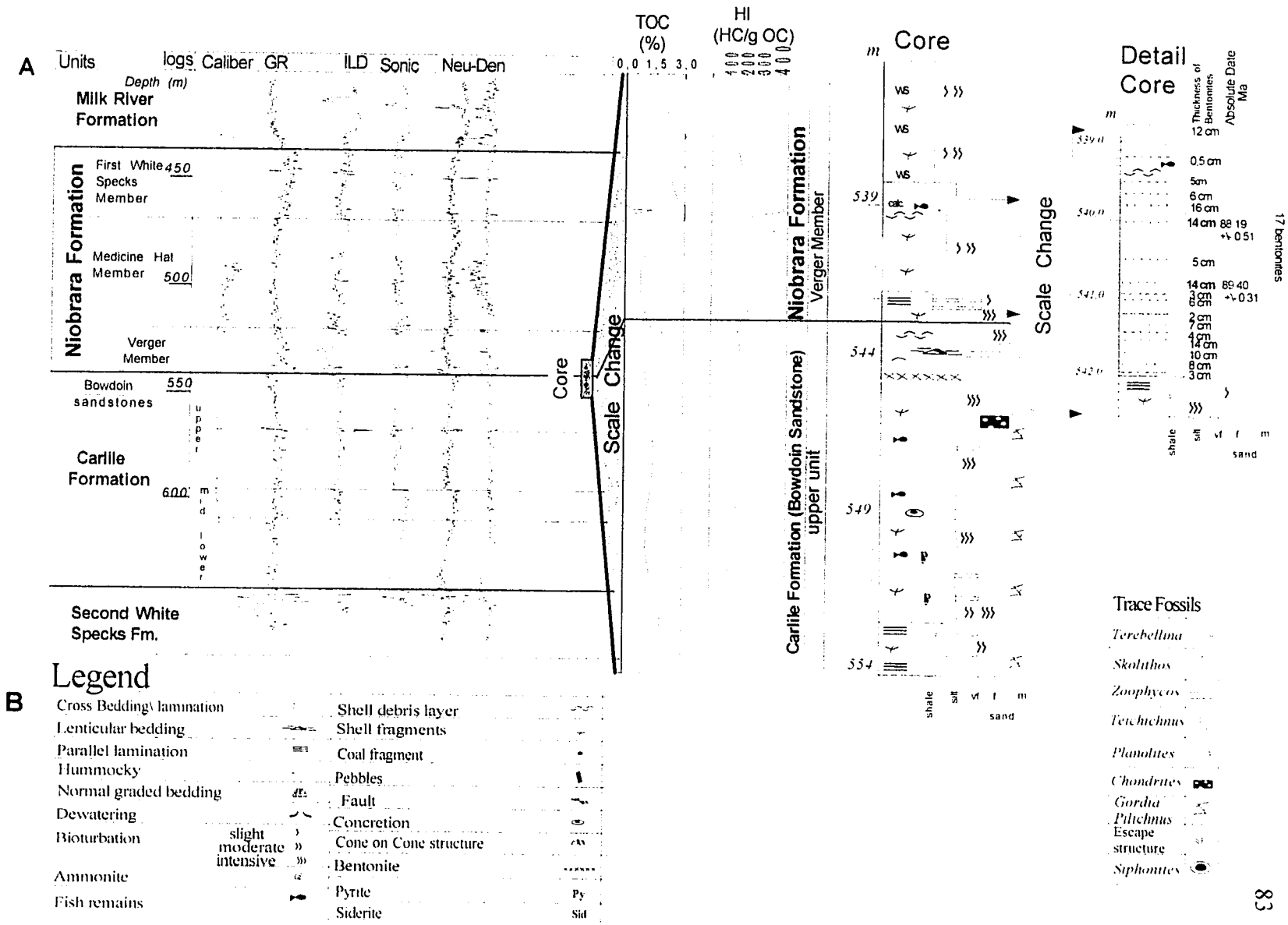
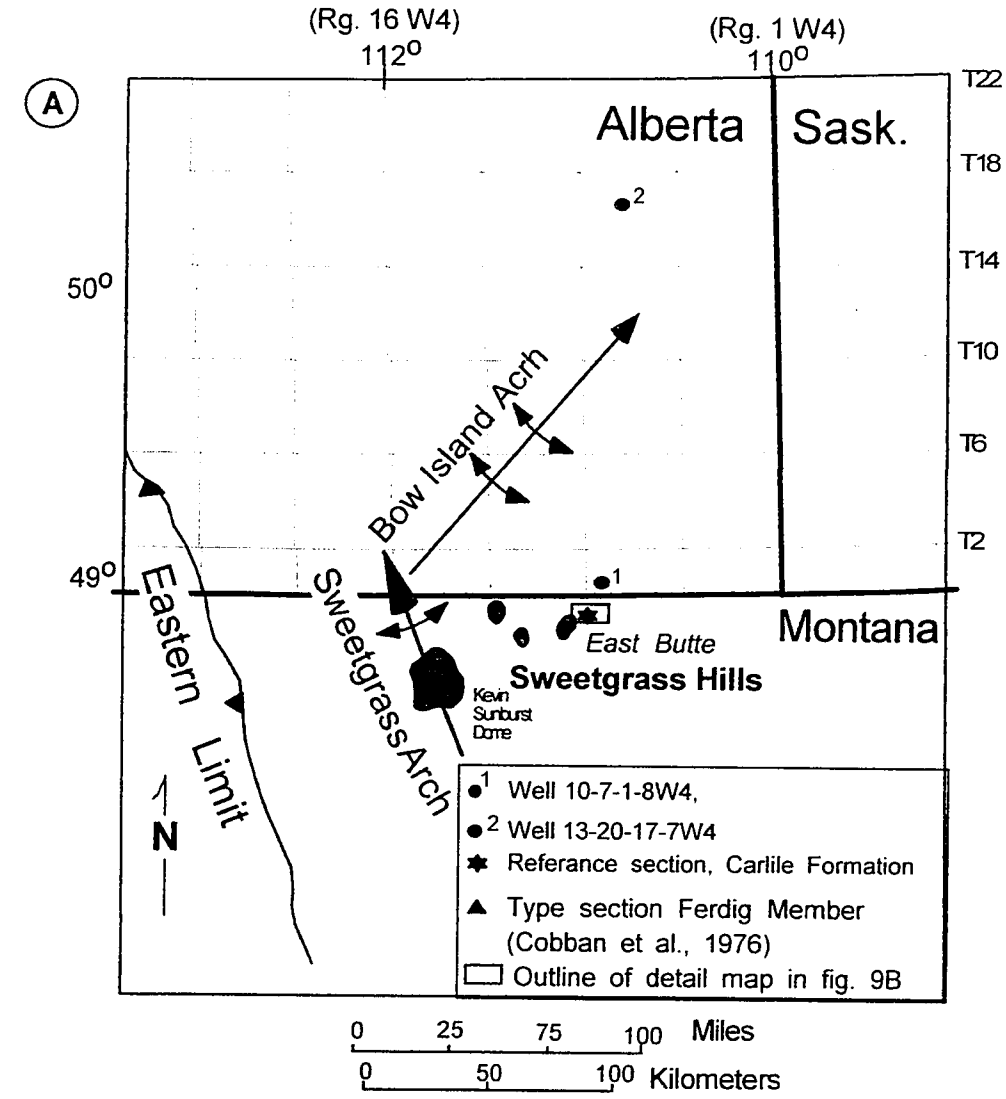

A
Units
logs
Caliber
GR
ILD
Sonic
Neu-Den
Depth (m)
Milk River Formation
Niobrara Formation
First White Specks Member
450
Medicine Hat Member
500
Verger Member
Bowdoin sandstones
550
Carlile Formation
upper
mid
lower
600
Second White Specks Fm.
Core
Scale Change
TOC (%)
0.0 1.5 3.0
HI (HC/g OC)
100
200
300
400
Core
m
Niobrara Formation
Verger Member
Carlile Formation (Bowdoin Sandstone) upper unit
539
544
549
554
shale
silt
vf
f
m
sand
Scale Change
Detail Core
Thickness of Bentonites
Absolute Date Ma
12 cm
0.5 cm
5cm
6 cm
16 cm
14 cm 88.19 +/- 0.51
5 cm
14 cm 89.40 +/- 0.31
17 bentonites
Trace Fossils
Terebellina
Skolithos
Zoophycos
Teichichnus
Planolites
Chondrites
Gordia
Pilichnus
Escape structure
Siphonites
B
Legend
Cross Bedding\ lamination
Lenticular bedding
Parallel lamination
Hummocky
Normal graded bedding
Dewatering
Bioturbation
slight
moderate
intensive
Ammonite
Fish remains
Shell debris layer
Shell fragments
Coal fragment
Pebbles
Fault
Concretion
Cone on Cone structure
Bentonite
Pyrite
Py
Siderite
Sid

Figure 2-8

Figure 2-9. Location maps for the reference section for the Carlile Formation. **A**: Overview of the Sweetgrass Hills with location of the type section of the Ferdig Member, reference section of the Carlile Formation, Wire-line logs at 10-7-1-8W4 and 13-20-17-7W4. **B**: Detailed map of the location of the Deer Creek outcrop.


A
(Rg. 16 W4)
112°
(Rg. 1 W4)
110°
T22
T18
T14
T10
T6
T2
50°
49°
Alberta
Sask.
Montana
Bow Island Arch
Sweetgrass Arch
Eastern Limit
N
East Butte
Sweetgrass Hills
Kevin Sunburst Dome
1 Well 10-7-1-8W4,
2 Well 13-20-17-7W4
Referance section, Carlile Formation
Type section Ferdig Member (Cobban et al., 1976)
Outline of detail map in fig. 9B
0 25 75 100 Miles
0 50 100 Kilometers

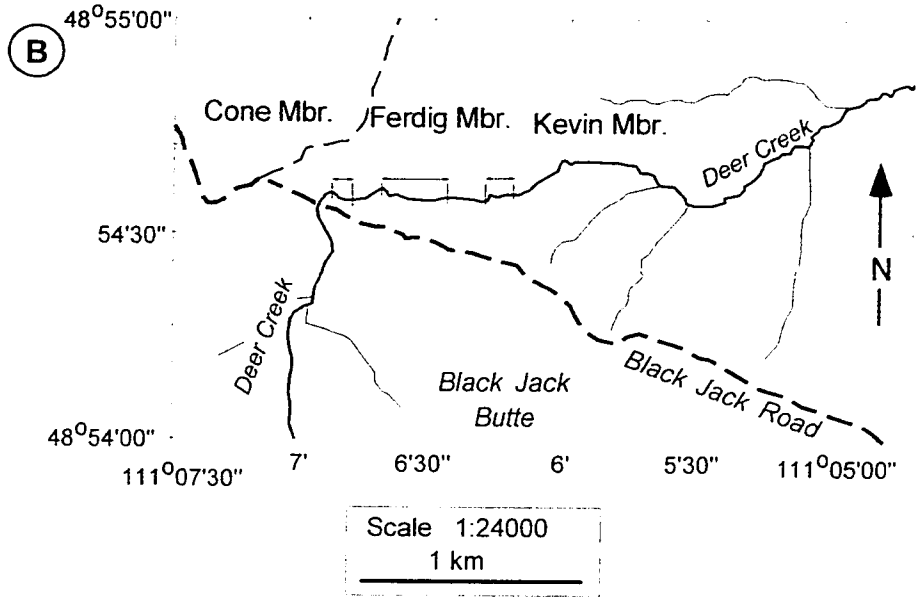
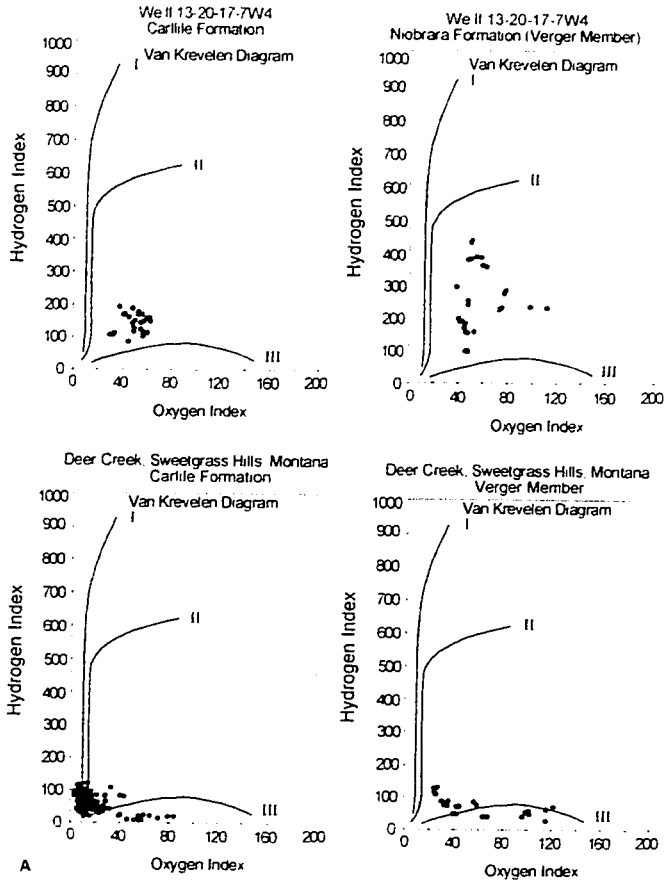

B
48°55'00"
54'30"
48°54'00"
111°07'30"
7'
6'30"
6'
5'30"
111°05'00"
Cone Mbr.
Ferdig Mbr.
Kevin Mbr.
Deer Creek
Deer Creek
Black Jack Butte
Black Jack Road
N
Scale 1:24000
1 km

Figure 2-9

Figure 2-10. **A**: Van Krevelen diagrams of sediments from the Carlile and Niobrara formations sampled at Deer Creek, Montana and from the well 13-20-17-7W4. **B**: Van Krevelen diagram of the three informal units of the Carlile Formation from the Deer Creek outcrop.


Well 13-20-17-7W4
Carlile Formation
Van Krevelen Diagram
Hydrogen Index
Oxygen Index
Well 13-20-17-7W4
Niobrara Formation (Verger Member)
Deer Creek, Sweetgrass Hills, Montana
Carlile Formation
Deer Creek, Sweetgrass Hills, Montana
Verger Member
A

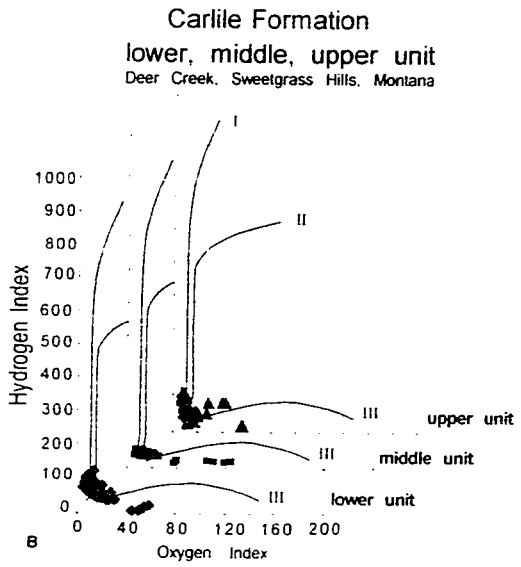

Carlile Formation
lower, middle, upper unit
Deer Creek, Sweetgrass Hills, Montana
Hydrogen Index
Oxygen Index
upper unit
middle unit
lower unit
B

Figure 2-10

Figure 2-11. Correlation between the outcrop-section of the Dowling and Thistle members from the Ghost Dam-Spillway, west of Calgary (Walker and Rosenthal, 1981; Stott, 1963) and a subsurface wire-line cross-section of the Medicine Hat and First White Specks members. All wire-line logs are resistivity logs. Note the short distance of 2.5 km between the outcrop and the cross-section. For location of outcrop and cross-section see figure 2-2. Sedimentological legend see figure 2-8.

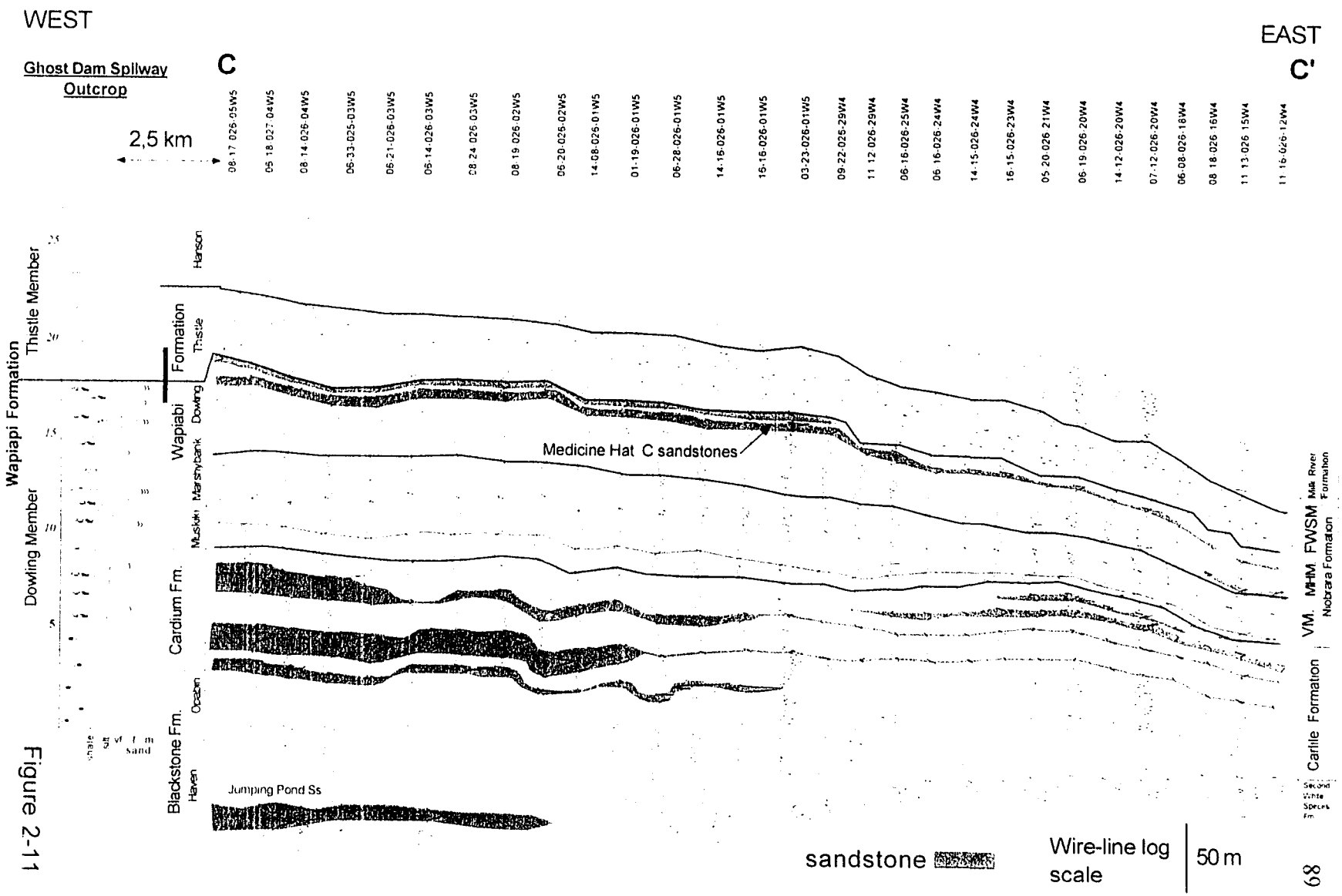

WEST
EAST
Ghost Dam Spillway Outcrop
C
C'
2,5 km
08-17-026-05W5
05-18-027-04W5
08-14-026-04W5
05-33-025-03W5
05-21-026-03W5
05-14-026-03W5
08-24-026-03W5
08-19-026-02W5
05-20-025-02W5
14-08-026-01W5
01-19-026-01W5
06-28-026-01W5
14-16-026-01W5
15-16-026-01W5
03-23-026-01W5
09-22-025-29W4
11-12-026-29W4
06-16-026-25W4
06-16-026-24W4
14-15-026-24W4
16-15-026-23W4
05-20-026-21W4
06-19-026-20W4
14-12-026-20W4
07-12-026-20W4
06-08-026-18W4
08-18-026-16W4
11-13-026-15W4
11-16-026-12W4
Wapiapi Formation
Thistle Member
Dowling Member
Harson
Thistle
Formation
Dowling
Wapiabi
Marshybank
Muskiki
Cardium Fm.
Ocalan
Blackstone Fm.
Haven
Medicine Hat C sandstones
Jumping Pond Ss
VM. MHM. FWSM
Milk River Formation
Nobrara Formation
Carlile Formation
Second White Specks Fm.
sandstone
Wire-line log scale
50 m

Figure 2-11

Figure 2-12. Core 16-4-22-15W4. Reference core of the Niobrara Formation and type core for the Verger, Medicine Hat and First White Specks members. Core location on figure 2-2. For sedimentological legend see figure 2-8.

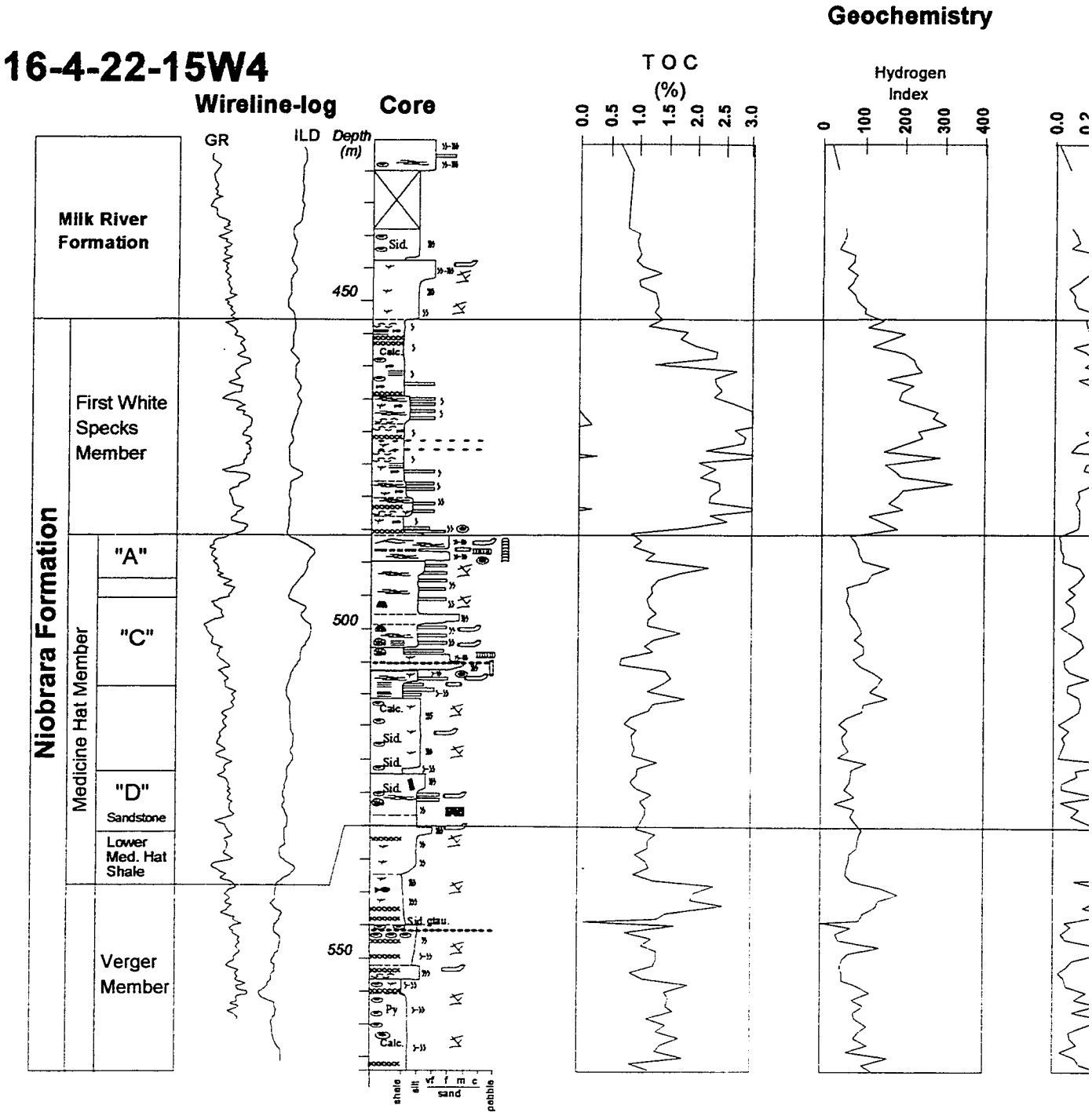

Geochemistry
16-4-22-15W4
Wireline-log
Core
GR
ILD
Depth (m)
TOC (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Hydrogen Index
0
100
200
300
400
Milk River Formation
Niobrara Formation
First White Specks Member
Medicine Hat Member
"A"
"C"
"D"
Sandstone
Lower Med. Hat Shale
Verger Member
450
500
550
Sid.
Calc.
Sid. glau.
Py
shale
silt
vf f m c
sand
pebble

Figure 2-12

91

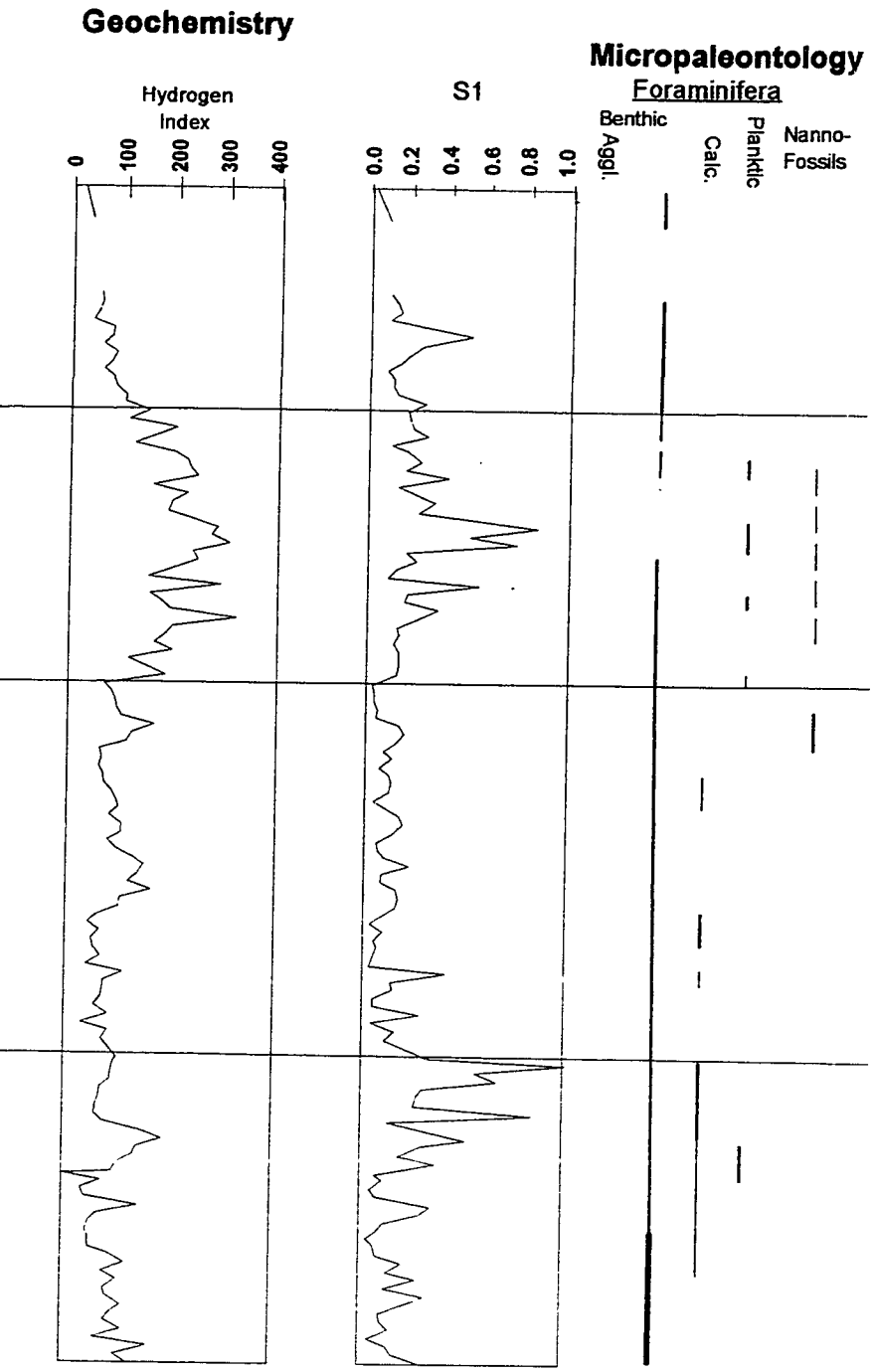


Figure 2-12

Figure 2-13. Core 4-8-27-13W4 representing the Medicine Hat and First White Specks members in the western part of the study area. Core location on figure 2-2. For sedimentological legend see figure 2-8.

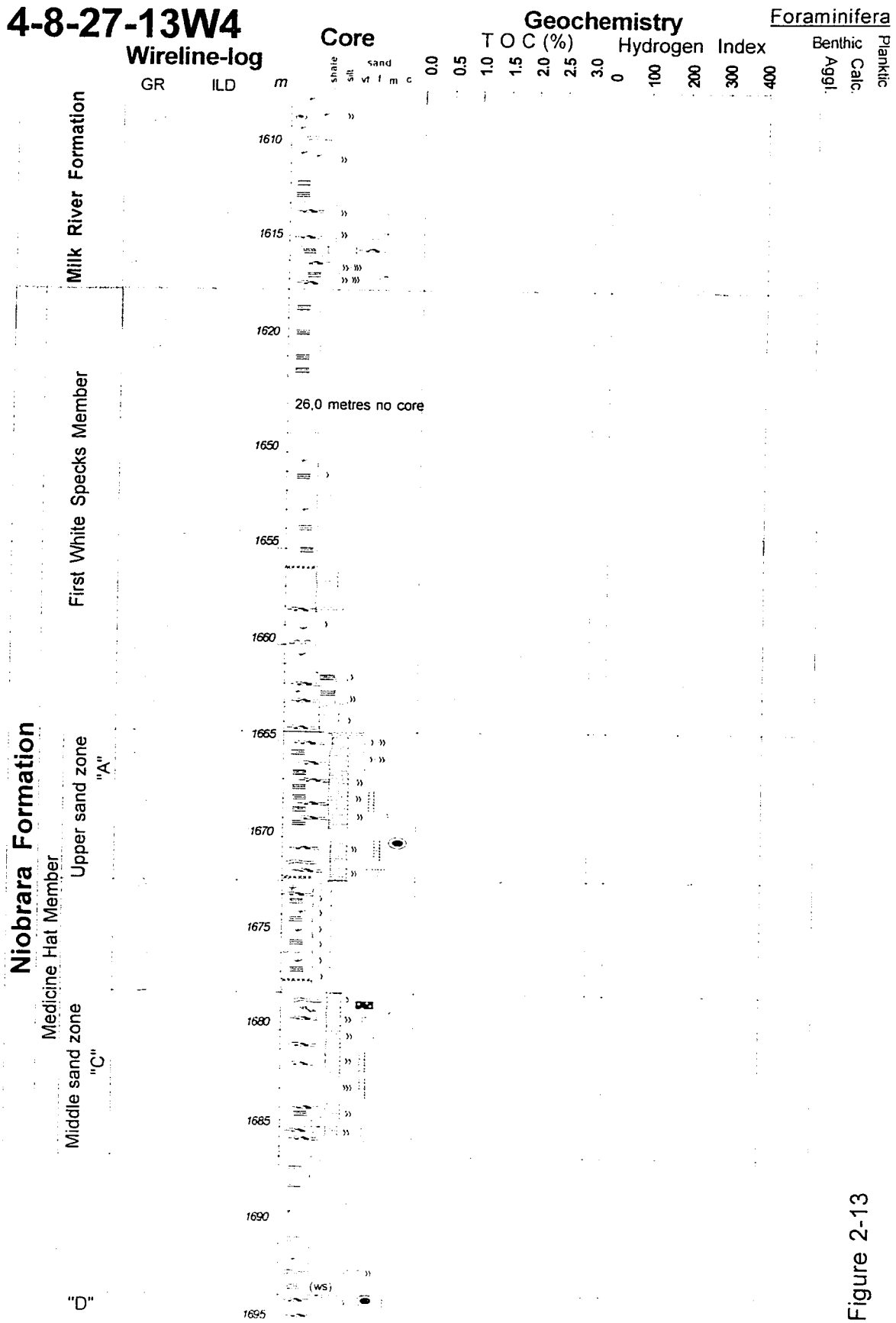

4-8-27-13W4
Wireline-log
GR
ILD
m
Core
shale
silt
sand
vf f m c
Geochemistry
T O C (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Hydrogen Index
0
100
200
300
400
Foraminifera
Benthic
Aggl.
Calc.
Planktic
Milk River Formation
First White Specks Member
Niobrara Formation
Medicine Hat Member
Upper sand zone
"A"
Middle sand zone
"C"
"D"
1610
1615
1620
26,0 metres no core
1650
1655
1660
1665
1670
1675
1680
1685
1690
(ws)
1695

Figure 2-13

Figure 2-14. Core 14-36-13-4W4 representing the Medicine Hat Member in the eastern part of the study area. Core location on figure 2-2. For sedimentological legend see figure 2-8.

14-36-13-4W4

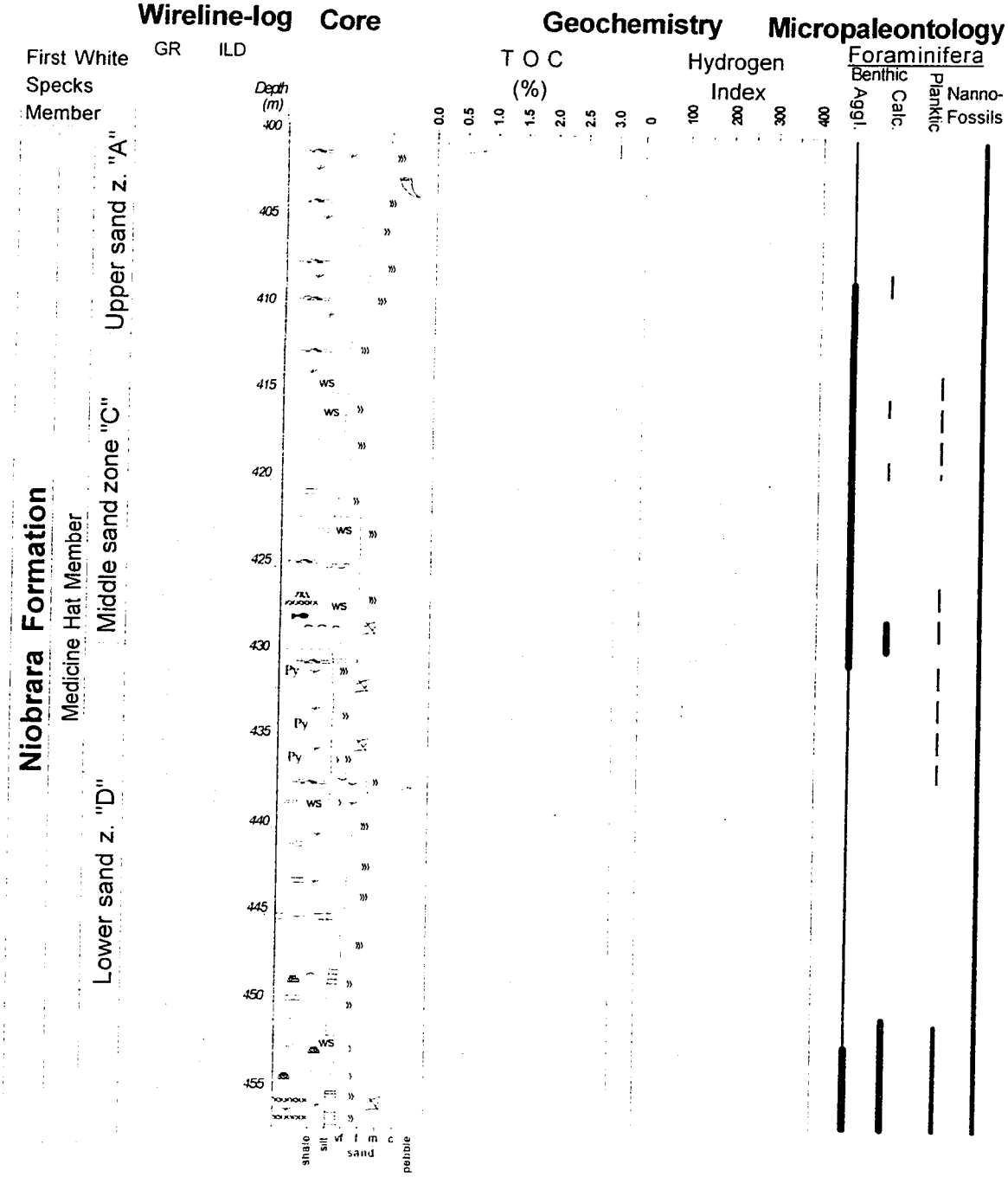


Figure 2-14

Figure 2-15. Core 8-36-24-13W4 illustrating the boundary between the Verger and Medicine Hat members. Core location on figure 2-2. Sedimentological legend see figure 2-8

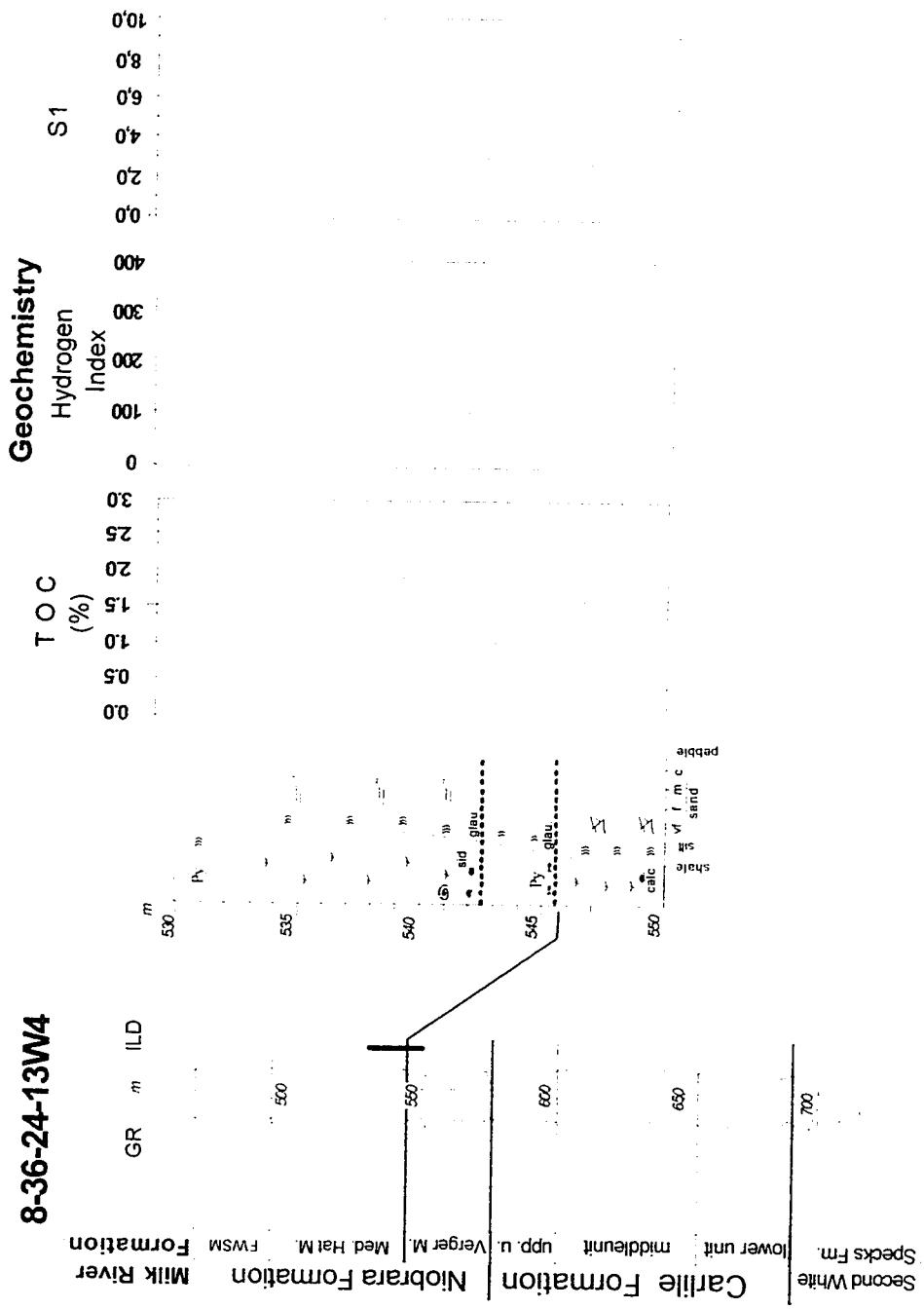

8-36-24-13W4
GR
ILD
Geochemistry
T O C (%)
Hydrogen Index
S1
Milk River Formation
FWSM
Niobrara Formation
Med. Hat M.
Verger M.
Carlile Formation
upp. u.
middleunit
lower unit
Second White Specks Fm.
shale
silt
sand
pebble

Figure 2-15

Figure 2-16. Core 6-3-24-13W4 showing the boundary between the Verger and Medicine Hat members and between the Medicine Hat and First White Specks members. Core location on figure 2-2. For sedimentological legend see figure 2-8

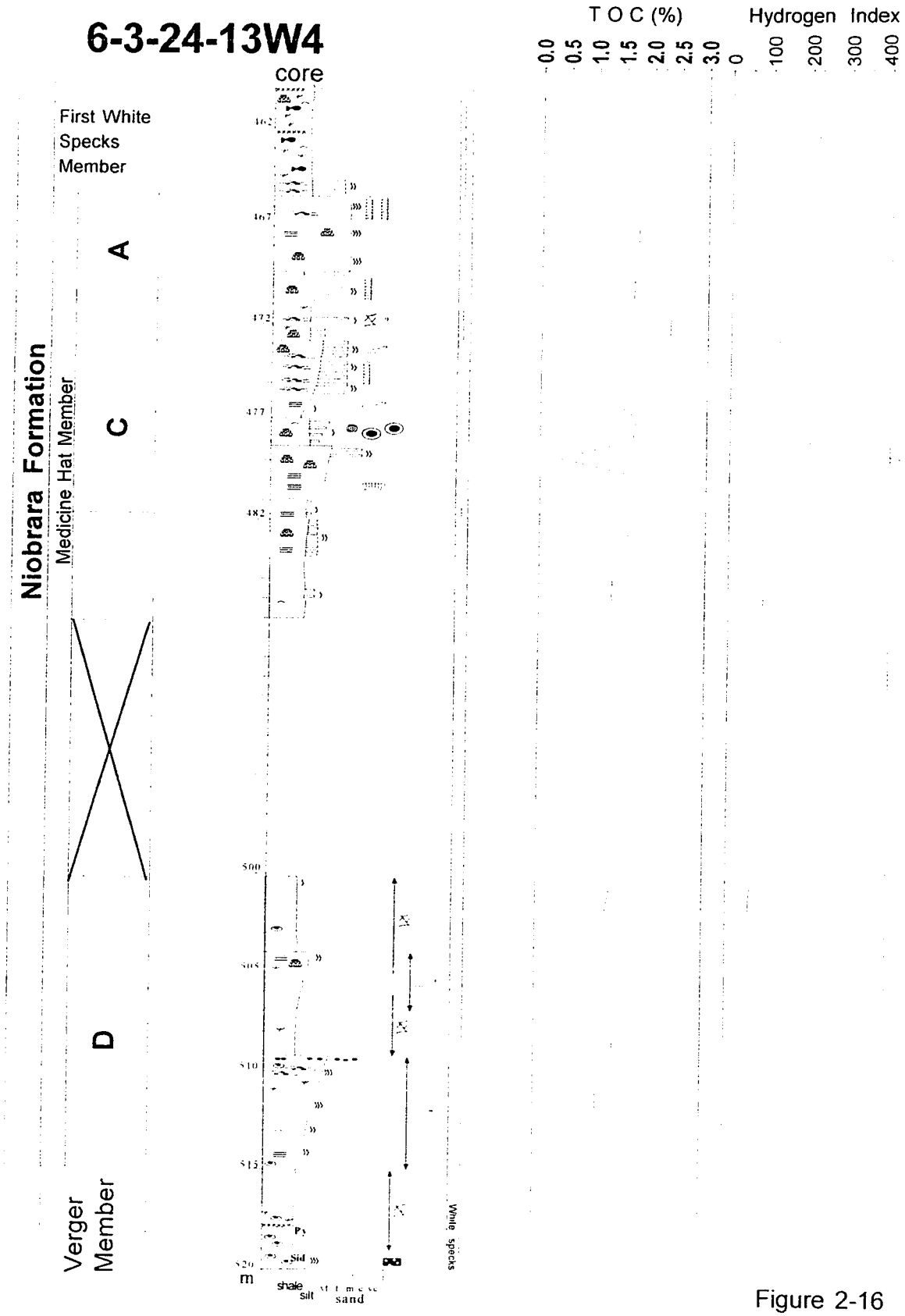

6-3-24-13W4
core
First White Specks Member
Niobrara Formation
Medicine Hat Member
A
C
D
Verger Member
462
467
472
477
482
500
505
510
515
520
m
Py
Sid
shale
silt
sand
White specks
T O C (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Hydrogen Index
0
100
200
300
400

Figure 2-16

Figure 2-17A and B. Geochemistry of the Niobrara Formation illustrated in Van Krevelen diagrams. Examples from the Verger, Medicine Hat and the First White Specks members.

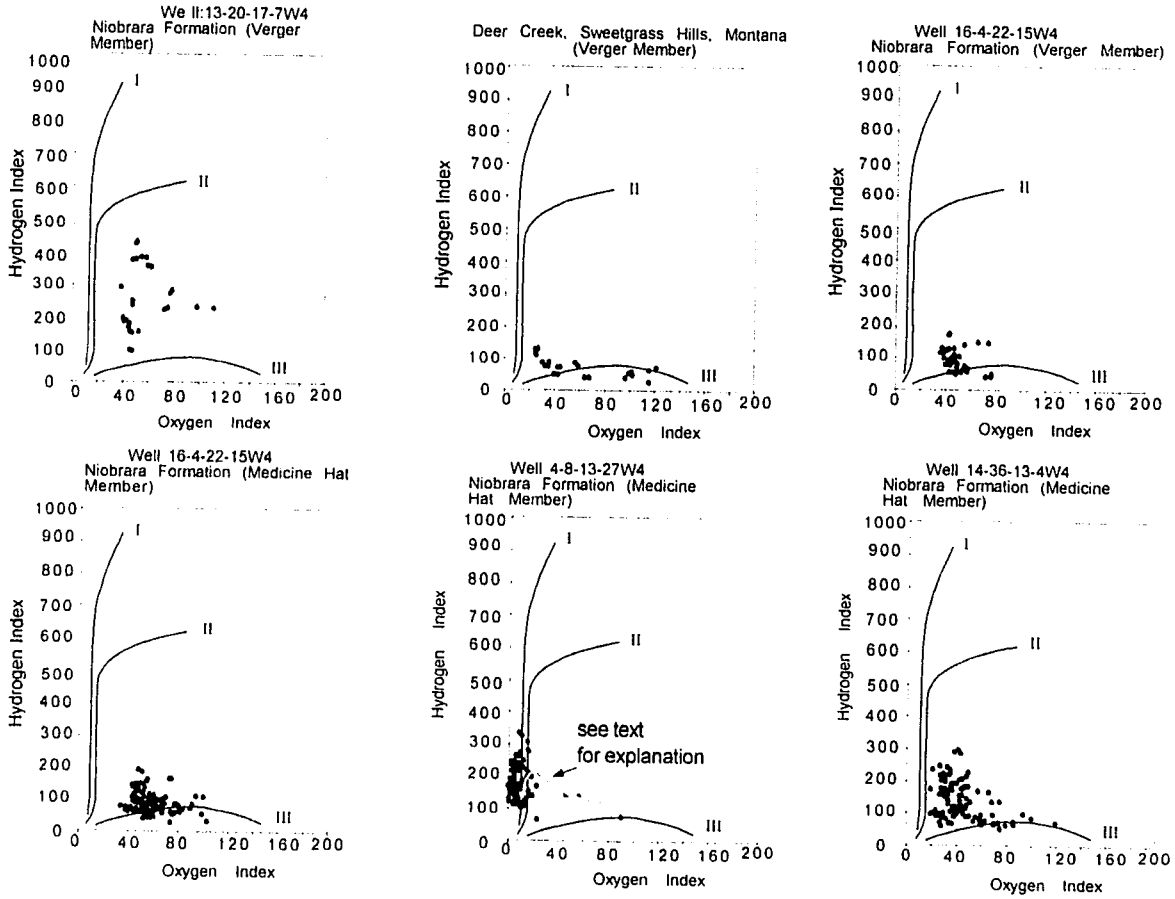

We II:13-20-17-7W4
Niobrara Formation (Verger Member)
Deer Creek, Sweetgrass Hills, Montana (Verger Member)
Well 16-4-22-15W4
Niobrara Formation (Verger Member)
Well 16-4-22-15W4
Niobrara Formation (Medicine Hat Member)
Well 4-8-13-27W4
Niobrara Formation (Medicine Hat Member)
Well 14-36-13-4W4
Niobrara Formation (Medicine Hat Member)
Hydrogen Index
Oxygen Index
0
100
200
300
400
500
600
700
800
900
1000
40
80
120
160
200
I
II
III
see text
for explanation

Figure 2-17A

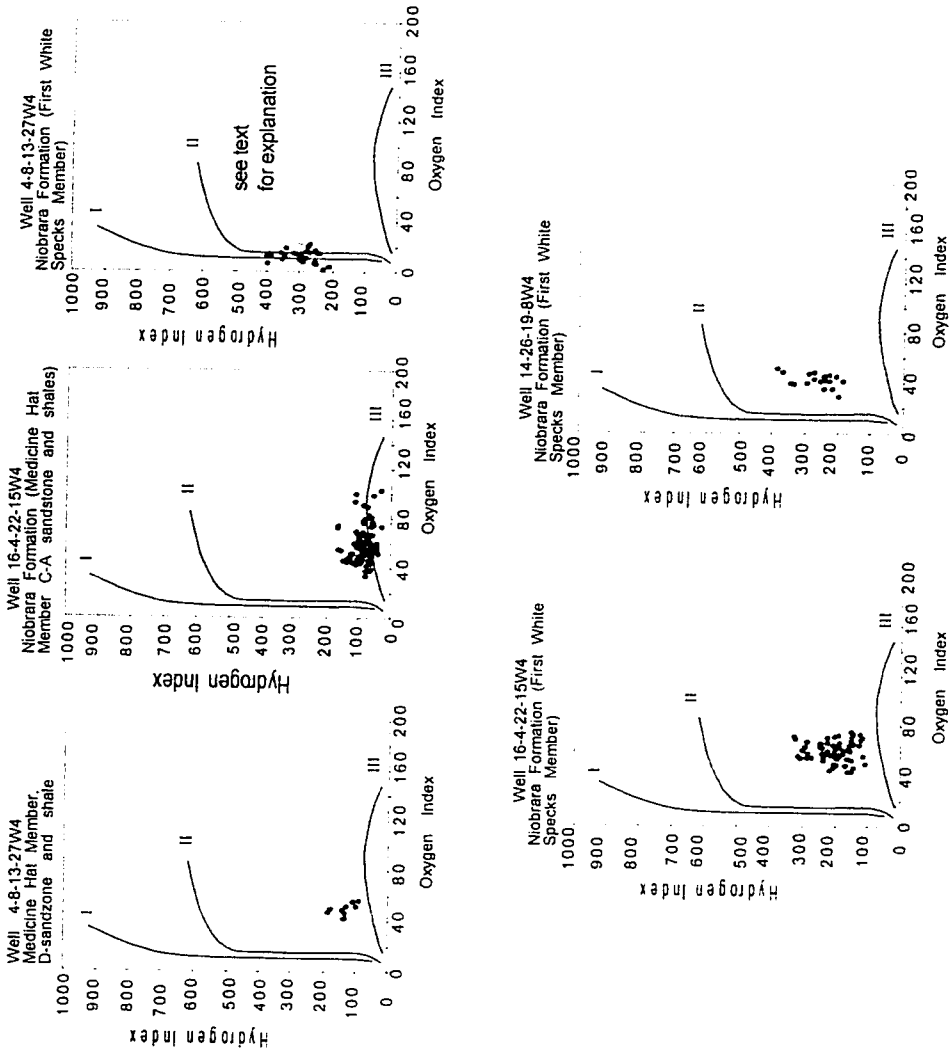
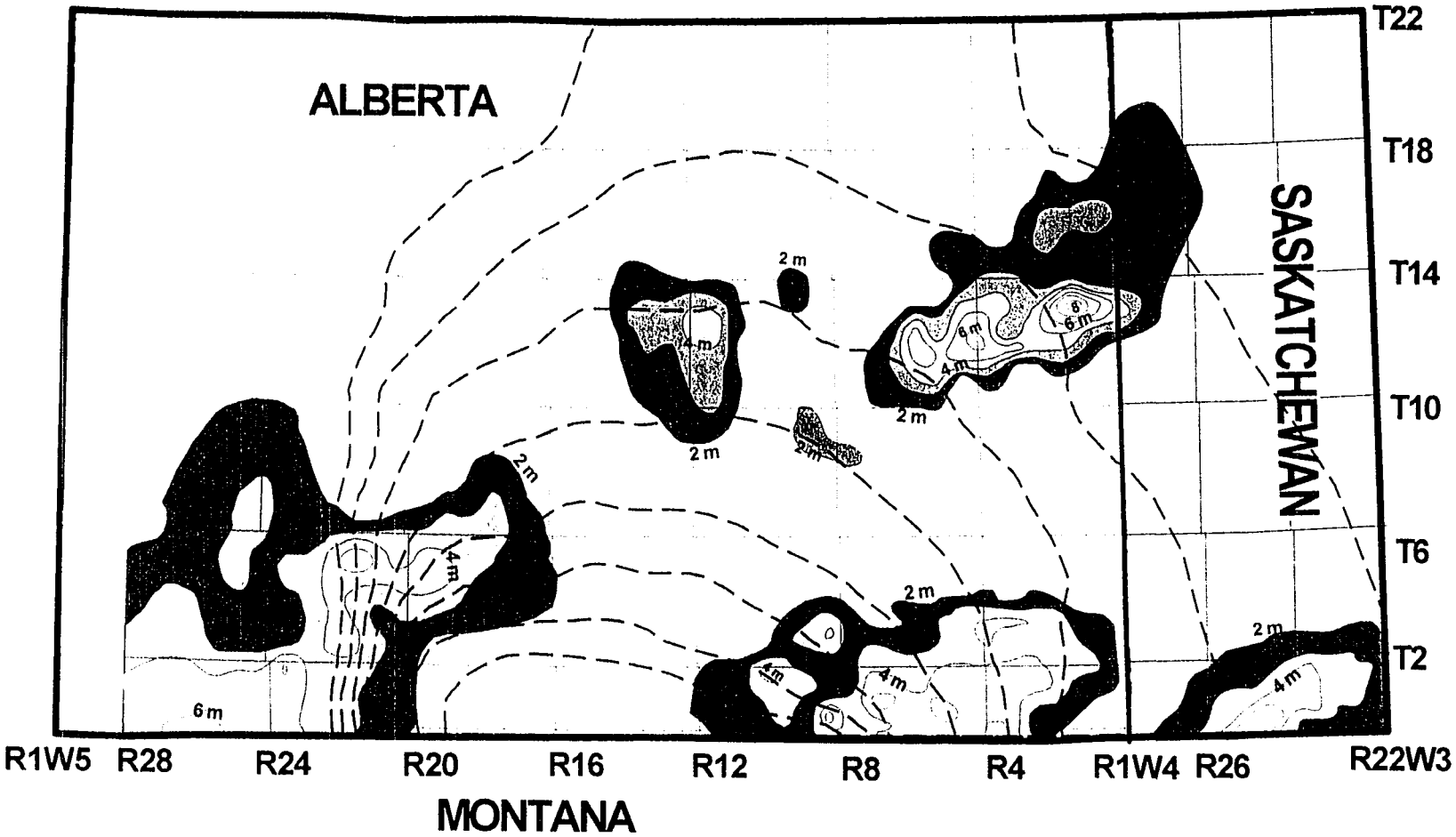

Well 4-8-13-27W4
Medicine Hat Member,
D-sandzone and shale
Well 16-4-22-15W4
Niobrara Formation (Medicine Hat
Member C-A sandstone and shales)
Well 4-8-13-27W4
Niobrara Formation (First White
Specks Member)
Well 16-4-22-15W4
Niobrara Formation (First White
Specks Member)
Well 14-26-19-8W4
Niobrara Formation (First White
Specks Member)
Hydrogen Index
Oxygen Index
I
II
III
see text
for explanation

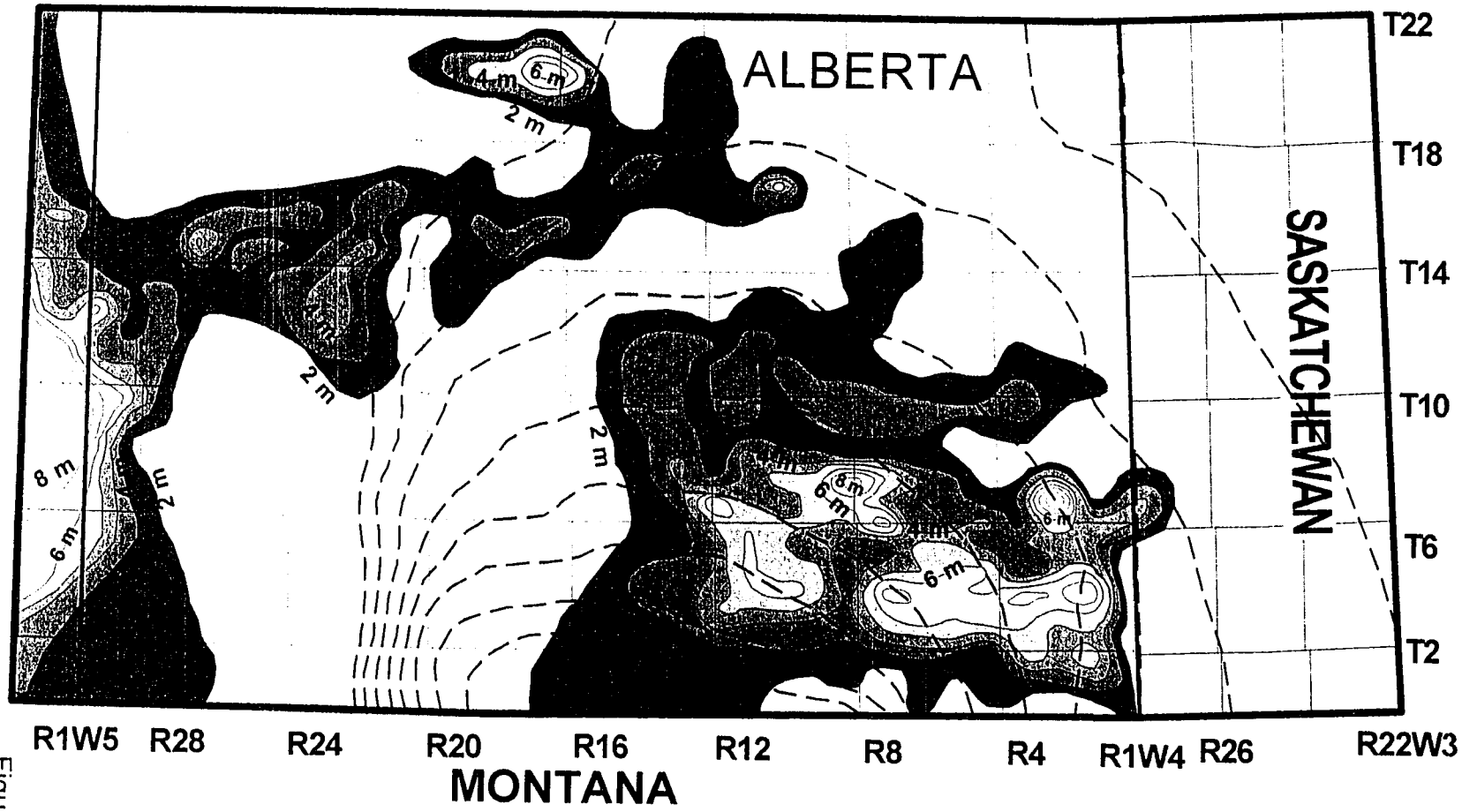
Figure 2-17B

Figure 2-18 A, B and C. Isopach maps of the D, C and A sandstone zones of the Medicine Hat Member. Contour lines in meters. Dashed line illustrates the Sweetgrass Arch in Alberta (see figure 2-3 for details).



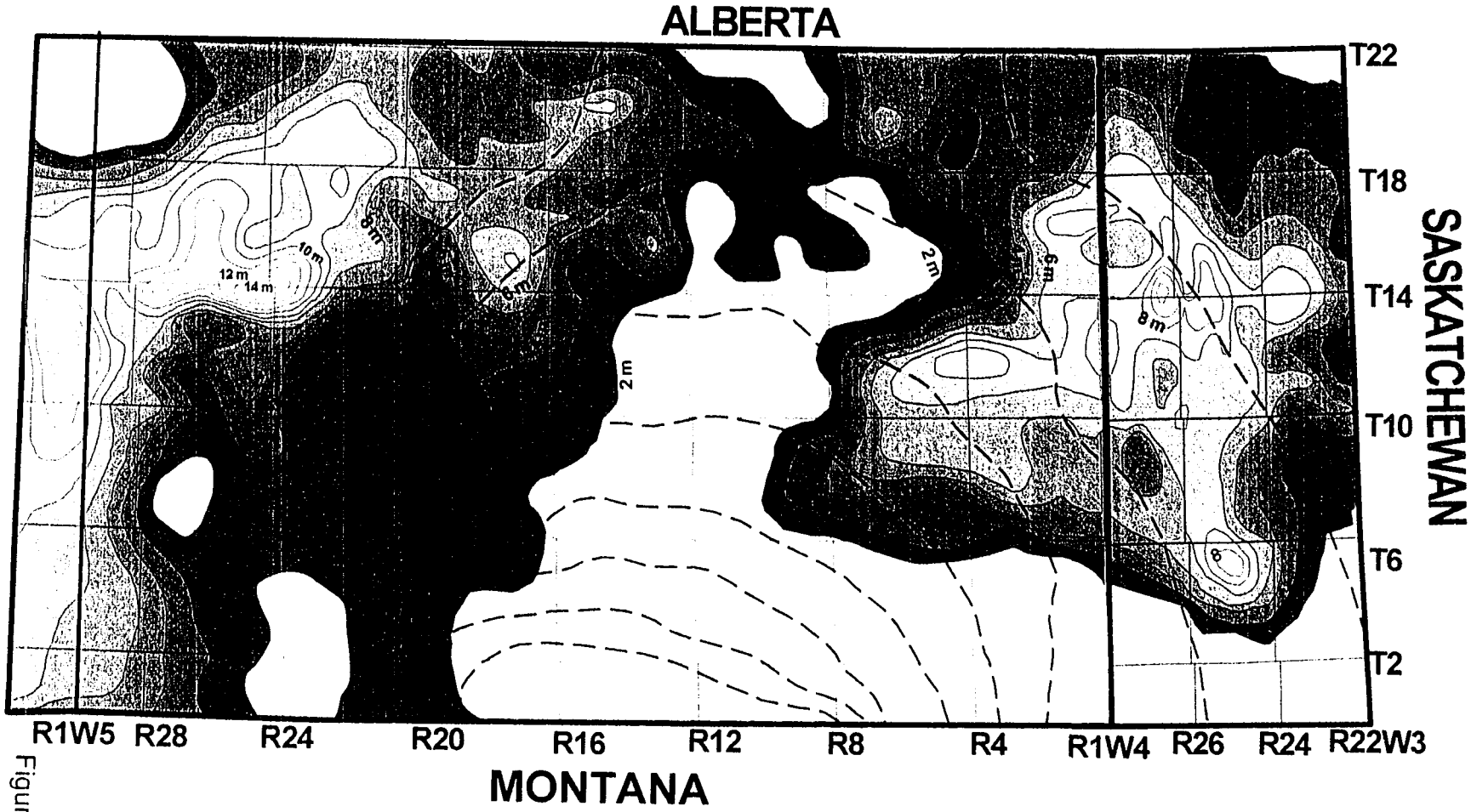
Contours defining Sweet Grass Arch (Bow Island Arch)

Figure 2-18A



Contours defining the Sweet Grass Arch (Bow Island Arch)

Figure 2-18B



Contours defining the Sweet Grass Arch (Bow Island Arch)

Figure 2-18C

Figure 2-19. Core 8-26-17-14W4 illustrating an area with poorly developed sandstones of the Medicine Hat Member. Core location on figure 2-2. For sedimentological legend see figure 2-8.

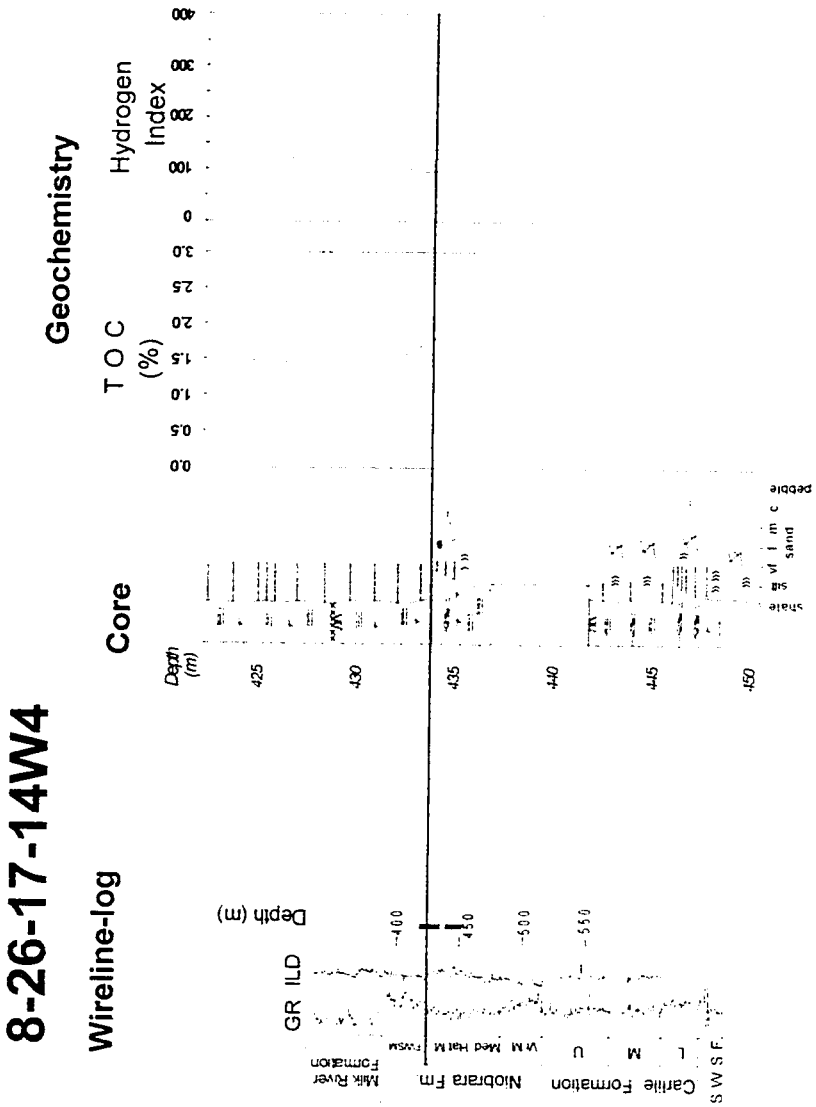

8-26-17-14W4
Wireline-log
Core
Geochemistry
Depth (m)
GR
ILD
Depth (m)
T O C (%)
Hydrogen Index
Milk River Formation
Niobrara Fm
Carlile Formation
S W S F.
shale
silt
vf f m c
sand
pebble

Figure 2-19

Figure 2-20. Core 14-26-19-8W4 showing parts of the Medicine Hat and First White Speeks members. Core location on figure 2-2. Sedimentological legend see figure 2-8.

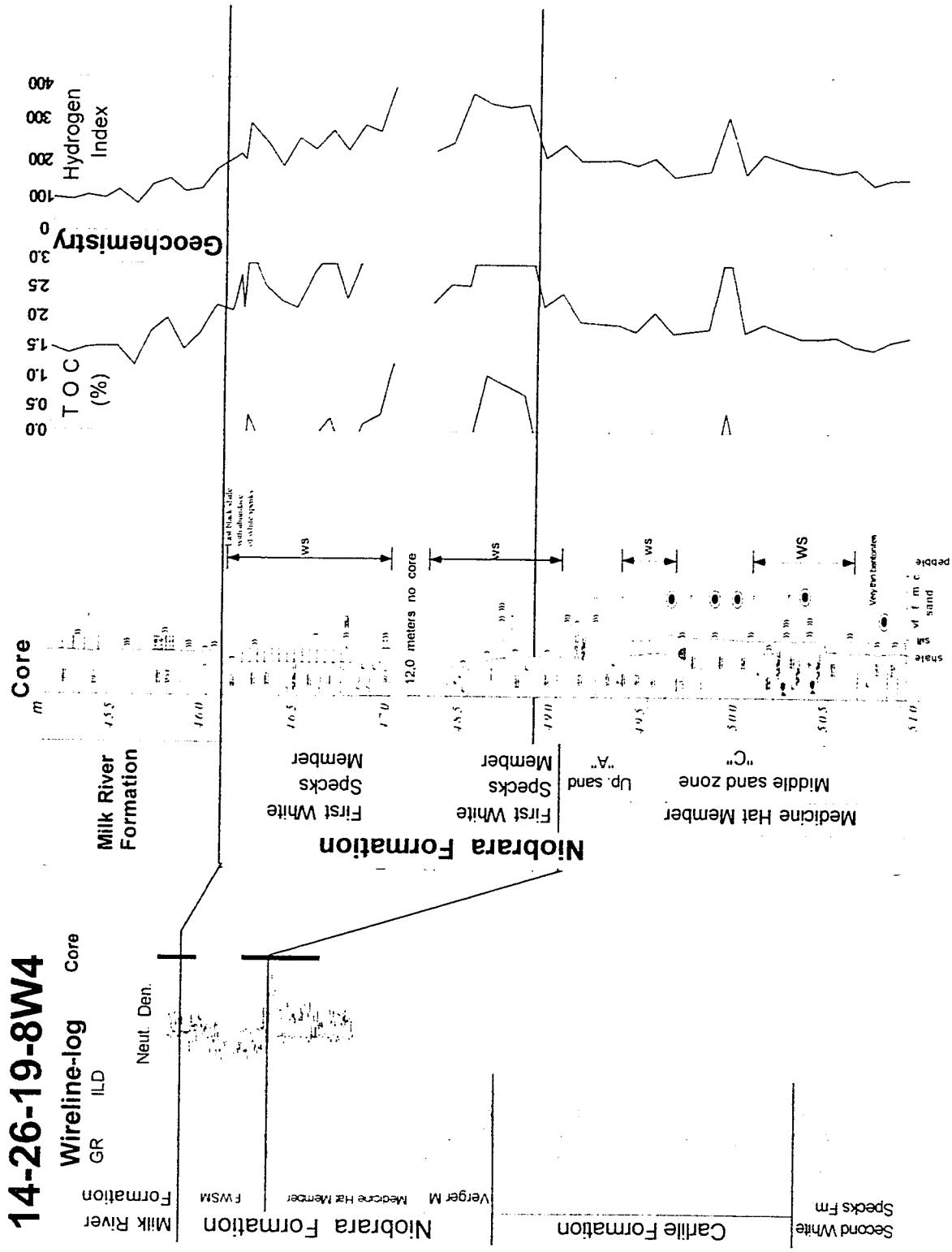

14-26-19-8W4
Wireline-log
GR
ILD
Neut. Den.
Core
Milk River Formation
Niobrara Formation
Carlile Formation
Second White Specks Fm
Milk River Formation
F WSM
Medicine Hat Member
Verger M
Niobrara Formation
Core
Milk River Formation
First White Specks Member
First White Specks Member
Up. sand "A"
Medicine Hat Member
Middle sand zone "C"
12.0 meters no core
WS
Geochemistry
T O C (%)
Hydrogen Index

Figure 2-20

Figure 2-21. Schematic section of the Carlile and Niobrara formations. This section is composed of the most characteristic features using all data of all disciplines. Although some variations exist in the area, this section gives a good guideline to a lithological and geochemical recognition of the two formations.

Cores and outcrops
Lithostratigraphy
Absolute Dating (Ma)
Thick-ness
Milk River Formation
Niobrara Formation
First White Specks M.
SGM
Medicine Hat Member
Verger Member
80 m (northeast) - 240 m (southwest)
Carlile Formation
upper unit
Bowdoin ss
middle unit
lower unit
30 m (east) - 160 m (west)
Second White Specks Formation
14-26-19-8W4 (figure 1-20)
6-3-24-13W4 (figure 1-16)
8-36-24-13W4 (figure 1-15)
14-36-13-4W4 (figure 1-14)
16-4-22-15W4 (figure 1-13)
16-4-22-15W4 (figure 1-12)
Ghost Dam Spillway outcrop (figure 1-11)
13-20-17-7W4 (figure 1-8)
Deer Creek outcrop (figure 1-4)
A
C
D
glau.
Sid.
Py
Sid.
Sid.
89.19
89.40
Bioturbation
Trace fossils
Macro fossils
White Specks
Foraminifera Zones
Trochamina sp.; Bulltopora laevis
Globigerinelloides sp.
Pseudoclavulina sp.
Hedbergella l.
Shale
siltstone
vf f m c vc
sand
congl.

Figure 2-21

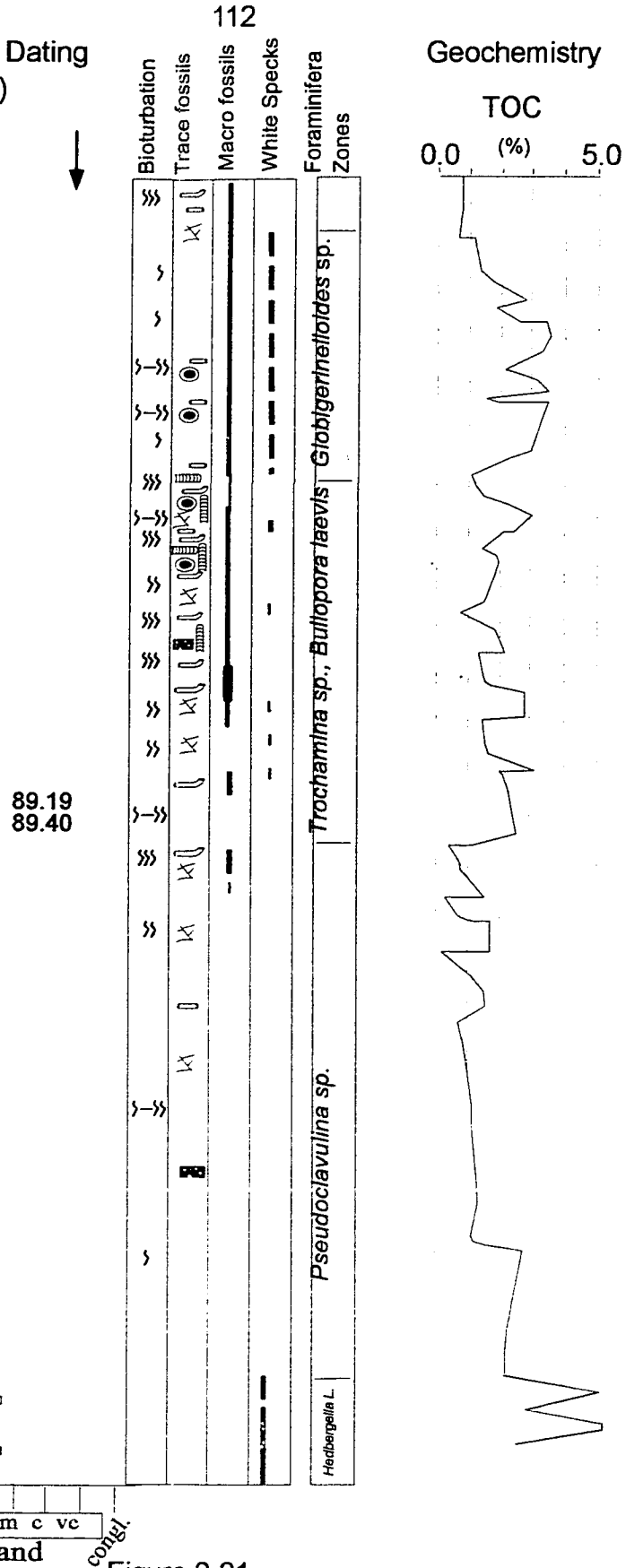
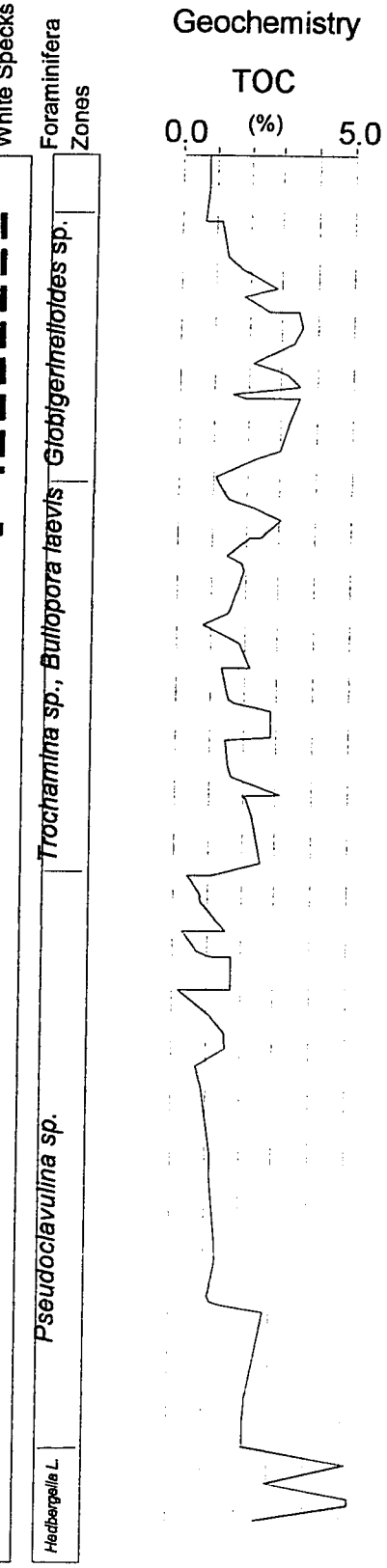


Figure 2-21

Typical section of the Carlile and Niobrara Form in southern Alberta and southwestern Saskatch

Fig



Typical section of the Carlile and Niobrara Formations in southern Alberta and southwestern Saskatchewan.

Figure 2-21

APPENDIX 2-I

CORE LOCATION	Stratigraphic Interval								Geoche.	Micropal.	Nannofossils	Petrology
Alberta Core	Milk R	FW.	Med.	Hat		Verger	Carlile	SwsF				
00/02-09-017-10W4-0									no	yes	no	no
00/04-08-013-27W4-0									yes	yes	yes	yes
00/04-14-008-07W4-0									no	no	no	yes
00/05-03-027-14W4-0									no	no	no	no
00/06-03-024-13W4-0									yes	no	no	no
00/06-05-015-02W4-0									no	no	no	no
00/06-05-019-01W4-0									no	no	no	no
00/06-07-015-02W4-0									no	no	no	no
00/06-08-026-19W4-0									yes	yes	yes	yes
00/06-10-010-08W4-0									no	no	no	no
00/06-10-013-07W4-0									no	no	no	yes
00/06-10-019-14W4-0									no	no	no	yes
00/06-12-013-04W4-0									yes	no	no	no
00/06-23-023-22W4-0									no	no	no	yes
00/06-32-011-20W4-0									no	no	no	no
00/06-35-016-03W4-0									no	no	no	no
00/06-36-020-25W4-0									no	no	no	no
00/07-01-029-19W4-0									no	no	no	no
00/07-09-012-21W4-0									no	no	no	no
00/07-10-014-06W4-0									no	no	no	no
00/07-17-003-07W4-0									no	no	no	no
00/07-19-015-03W4-0									no	no	no	no
00/07-20-011-06W4-0									no	no	no	no
00/07-25-013-01W4-0									no	no	no	yes
00/07-27-020-03W4-0									no	no	no	yes
00/08-06-026-17W4-0									no	no	no	no
00/08-15-019-15W4-0									no	no	no	no
00/08-26-017-14W4-0									yes	no	no	no
00/09-30-014-04W4-0									no	no	no	no
00/10-01-016-05W4-0									no	no	no	no
00/10-10-015-04W4-0									no	no	no	yes
00/10-11-012-04W4-0									no	no	no	no
00/10-13-011-23W4-0									yes	yes	yes	no
00/10-14-015-04W4-0									no	no	no	no
00/10-15-017-01W4-0									yes	yes	yes	no
00/10-17-019-02W4-0									no	no	no	yes
00/10-26-015-04W4-0									no	no	no	yes
00/10-27-012-02W4-0									no	no	no	yes
00/10-28-015-03W4-0									no	no	no	no
00/10-29-011-05W4-0									nn	no	no	no
00/11-11-016-09W4-0									no	no	no	no
00/11-15-012-05W4-0									no	no	no	no
00/11-26-020-23W4-0									yes	no	no	no
00/11-33-016-01W4-0									no	no	no	no

CORE LOCATION	Stratigraphic Interval	Geoche.	Micropal.	Nannofossils	Petrology
Alberta Core	Milk R. / FW. / Med. Hat / Verger / Carlile / SwsF				
00/13-20-017-07W4-0		yes	yes	yes	no
00/14-23-019-15W4-0		no	no	no	no
00/14-26-019-08W4-0		no	no	no	yes
00/14-36-013-04W4-0		yes	yes	yes	no
00/16-04-022-15W4-0		yes	yes	yes	no
00/16-18-013-07W4-0		no	no	no	no
00/16-20-024-21W4-0		no	no	no	no
00/16-23-012-04W4-0		no	no	no	no
00/16-28-014-02W4-0		yes	yes	no	no
02/03-07-013-27W4-0		yes	no	no	no
02/06-18-015-03W4-0		no	no	no	no
02/07-13-010-08W4-0		yes	no	yes	yes
02/16-10-015-01W4-0		no	no	no	no
03/06-26-013-03W4-0		no	no	no	no
02/08-36-024-13W4-0		no	no	no	no
Saskatchewan core					
01/05-21-011-29W3-0		no	no	no	no
01/11-24-013-30W3-0		no	no	no	no
11/13-09-014-28W3-0		yes	no	no	yes
01/04-25-014-28W3-0		no	no	no	no
21/06-13-014-29W3-0		no	no	no	no
01/06-16-014-29W3-0		no	no	no	no
01/06-19-014-29W3-0		no	no	no	no
01/10-23-014-30W3-0		no	no	no	no
21/08-07-015-28W3-0		no	no	no	no
01/03-24-015-28W3-0	?	no	no	no	no
01/10-34-015-28W3-0	?	no	no	no	no
01/13-12-012-28W3-0		no	no	no	no
21/14-29-014-29W3-0		no	no	no	no
01/06-12-014-30W3-0		no	no	no	no
01/11-10-010-28W3-0		no	no	no	no
01/10-03-005-26W3-0		yes	no	no	no
01/07-31-016-29W3-0		yes	yes	no	no
01/06-11-018-29W3-0		no	no	no	no
01/06-33-013-29W3-0		no	no	no	no
01/10-30-011-29W3-0		no	no	no	no
41/07-22-009-28W3-0		no	no	no	no
Outcrops					
Bear Dam, Sweetg.		no	no	no	no
Deer Creek, Sweetg.		yes	yes	yes	no
Kevin, Montana		yes	yes	no	yes
Highwood River		no	yes	yes	yes
Ghost Dam Spilway		no	yes	no	no
Deer Creek, Alberta	?	no	yes	no	no

APPENDIX 2-II

Name (north/south side of creek)	Location	Formation Cobban et al., 1976)	Mea-sured sectio n (m)	Over-lap	Strike/dip of bedding
Deer Creek crossing Black Jack Rd. (location 1)	N48°54'580''; W111°07'000''				
Outcrop 1 (north)	125 meters down steams from location 1	Cone Mbr.	6	-	80°/18°
Outcrop 2 (north)	5 meters down steams from outcrop 1	Cone Mbr.	5	entire outc. 1	76°/18°
Outcrop 3 (south)	5 meters down streams from outcrop 2	Cone Mbr..	3,5	-	68°/16°
Outcrop 4 (north)	N48°54'583''; W111°06'698'' (~60 m. down stream outcrop 3)	Ferdig Mbr.	16,5	-	68°/18°
Outcrop 5 (north)	110 meters down steams from outcrop 4	Ferdig Mbr.	32	-	85°/18°
Outcrop 6 (north)	60 meters down steams from outcrop 5	Ferdig Mbr.	17,5	-	120°/12°
Outcrop 7 (north)	90 meters down steams from outcrop 6	Ferdig Mbr.	22	-	85°/18°
Outcrop 8 (south)	disturbed outcrop, not measured	-	-		-
Outcrop 9 (south)	330 meters down steams from outcrop 7	Kevin Mbr.	6	6 m. with outcro p. 7	70°/14°
Outcrop 10 (north)	15 meters down steams from outcrop 9	Kevin Mbr.	2.5	-	90°/22°
Outcrop 10b (north)	3 meters down steams outcrop from outcrop 10	Kevin Mbr.	3	-	90°/22°
Outcrop 11 (north)	5 meters down steams outcrop 10b	Kevin Mbr.	3,5	-	-

APPENDIX 2-III

Rock eval: Carlile Formation

Rock eval data / Location and Unit	TOC (%) Av. (range)	HI (HC/g TOC Av. (range)	Tmax (C°) Av. (range)	PI Av. (range)
Carlile Formation (general)	1,77 (0,5 - 2,7)	61,2 (9-117)	448 (436-470)	0,26 (0,1-0,6)
Lower unit (Deer Creek outcrop)	2.2 (1,6-2,7)	73,8 (9-117)	446 (436-458)	0,31 (0,1-0,6)
Middle Unit (Deer Creek outcrop)	1,35 (0,6-1,8)	42,4 (15-79)	454 (442-470)	0,2 (0,1-0,4)
Upper Unit (Deer Creek outcrop)	1,47 (0,5-2,5)	57,6 (10-110)	440 (437-451)	0,23 (0,1-0,5)
Upper Unit (13-20-17-7W4 core)	1,39 (0,9-1,9)	144 (85-205)	419 (409-422)	0,17 (0,1-0,3)

Rock eval: Niobrara Formation

Rock eval data / Location and Unit	TOC (%) Av. (range)	HI (HC/g TOC Av. (range)	Tmax (C°) Av. (range)	PI Av. (range)
Verger Member (13-20-17-7W4)	1,9 (0,5-4,3)	263 (95-430)	419 (413-424)	0,07 (0,03-0,04)

(distal)				
Verger Member (16-04-22-15W4) (proximal to distal)	1,4 (0,9-1,9)	93 (50-165)	421 (416-425)	0,1 (0,04-0,25)
Medicine Hat Member (*) (16-04-22-15W4)	1,20 (0,7-2,3)	87 (29-165)	419 (413-424)	-
Medicine Hat Member (14-36-13-4W4)	1,5 (0,6-2,6)	140 (52-294)	421 (411-428)	-
Medicine Hat Member (4-8-27-13W4)	1,3 (0,4-2,0)	174 (64-334)	435 (428-486)	-
Medicine Hat Member *general*	1,33 (0,4-2,3)			-
First White Specks Member (14-29-19-8W4)	2,9 (2,2-4,2)	254 (167-375)	410 (400-418)	-
First White Specks Member (16-4-22-15W4)	2,5 (1,3-3,4)	206 (115-321)	410 (402-420)	-

Chapter III

BASIN-WIDE STRATAL PATTERNS AND SEDIMENT INFILL HISTORY; CRETACEOUS COLORADO GROUP IN WESTERN CANADA. AN APPLIED SEQUENCE STRATIGRAPHIC STUDY

ABSTRACT

The Upper Cretaceous Carlile and Niobrara formations in southern Alberta and southwestern Saskatchewan consists of thirteen sequences. A new method of closely-spaced resistivity wire-line logs allows a detailed interpretation of stratal patterns and facies with high resolution. The first major flooding surface is the most easily recognized surface in the distal marine shale of the two formations and is chosen as the sequence boundary.

The Carlile Formation represents the regressive part of the Greenhorn Cycle and deposited during a long-term fall of sea-level and sediment infill of the Interior Seaway. The Carlile Formation is capped by an angular unconformity, which is coincident with the top of the Cardium Formation in the Alberta Foothills and the Bowdoin sandstones in central Saskatchewan and northern Dakota. The Niobrara Formation represents the transgressive part of the Niobrara Cycle and shows a deepening of the Interior Seaway with major sea-level fluctuations. The Niobrara Formation is overlain by the regressive Milk River Formation (Payenberg, 2002).

The Carlile Formation consists of a sequence-set of seven sequences (F1 to F7), which are characterized on low angled stratal patterns of parallel to sub-parallel sequence

boundaries. The stratal pattern of the lower sequences is eastward dipping, which indicates a general sediment source from the west. The upper two sequences, which were truncated by the Carlile/Niobrara unconformity, are characterized by strata dipping towards east and west. This indicates the narrowing of the Interior Seaway and sediment source; from both west and east.

The Niobrara Formation consists of a sequence-set of six sequences (F8 to F13) that show a composite stratal pattern which changes upwards from generally high angled to very low angled. The lower two sequences (F8 and F9; Verger Member) are each characterized by high-angled highstand progradation, which are capped by thin transgressive pebble lags that indicate subaerial exposure of southern Alberta. The lowstand deposits were deposited outside the study area, in west-central Alberta, and form the coarse-grained Bad Heart Formation. Sequences F10 and F11 (Medicine Hat Member) are dominated by fine-grained isolated shelf sandstones and the stratal pattern illustrates sediment source from both the south and southwest. It is also demonstrated that as transgression occurred in one part of the basin, progradation took place in another part. The upper two sequences F12 and F13 (First White Specks Member) are very low angled and eastward dipping. The Sweetgrass Member is a lowstand deposit of sequence F12 and indicates major sea-level fluctuations in the peak transgressive period of the Niobrara Cycle.

INTRODUCTION

A new method is developed to define stratal geometry of shale-dominated marine basins, using closely-spaced (<2 km) resistivity wire-line logs and sequence stratigraphic principles. These cross-sections illustrate how recognition of key sequence stratigraphic surfaces and stratal patterns unveil basin evolution. This paper is part of a multidisciplinary study of the newly named Upper Cretaceous Carlile and Niobrara formations (Chapter II) in southern Alberta and southwestern Saskatchewan, Canada (figures 3-1 and 3-2).

The Upper Colorado Group is part of the Greenhorn and Niobrara sedimentary cycles (Kauffman and Caldwell, 1993; McNeil and Caldwell, 1981). The two cycles have been studied extensively in the eastern part of the Canadian Interior Seaway (McNeil and Caldwell, 1981; North and Caldwell, 1975; Schröder-Adams et al., 2001) and U.S.A. (Caldwell and Kauffman, 1993; Shurr et al., 1994; Dean and Arthur, 1998), but little has been documented in southern Alberta and southwestern Saskatchewan (Schröder-Adams et al., 1998). The Carlile Formation represents the regressive part of the Greenhorn cycle, which followed the major transgression that deposited the Second White Specks Formation (Schröder-Adams et al., 1996). The Niobrara Formation represents the transgressive part of the Niobrara Cycle with a major sea-level rise, which lasted longer than the transgression of the Greenhorn Cycle, but did not create the same deep water as suggested for the Second White Specks Formation and equivalents (Schröder-Adams et al., 1996; Kauffman and Caldwell, 1993).

In southern Alberta and southwestern Saskatchewan, the Upper Colorado Group, of middle Turonian to upper Santonian age, consists of three marine shaly formations,

which in ascending order are the Second White Specks Formation (Bloch et al., 1993), the Carlile Formation and the Niobrara Formation (Chapter II). Stratal patterns of the latter two formations are assessed using sequence stratigraphical principles and major flooding surfaces as sequence boundaries. Correlations of closely-spaced resisitivity logs allow the use of the terminology and principles of seismic sequence stratigraphy developed by Mitchum et al. (1977), but with a higher degree of resolution and direct ties to core-data. Major flooding surfaces are the most regionally extensive and easiest to recognize in the distal marine setting of the two formations. In contrast to a depositional sequence boundary (Posamentier et al., 1988), the major flooding surface is characterized by a significant sedimentation break (from progradation to retrogradation) and change in sedimentation in the distal setting of a basin, which is reflected lithologically, paleontologically and geochemically.

DATA AND METHODS

Wire-line logs from 2800 wells, organized in cross-sections across southern Alberta and southwestern Saskatchewan (figure 3-2) were used to correlate and map of the Medicine Hat sandstones and Upper Colorado Group shale. Fifty-eight closely spaced cross-sections, each consisting of 25 to 120 wells were constructed to outline the regional stratigraphy. Of these, nine principal regional cross-sections are presented in this paper (figure 3-2). These cross-sections create the main database for correlation and mapping and are tied to 81 cores (9 to 150 m long) and five outcrops for facies control (appendix page 389). Log-facies are calibrated and integrated with core and outcrop facies based on sedimentology, ichnology, micropaleontology and geochemistry. Most cores of the Upper

Colorado Group are situated in the Medicine Hat sandstones providing a good facies control on the main reservoir sandstone.

WIRE-LINE LOGS

The dense hydrocarbon exploration drilling grid in southern Alberta and southwestern Saskatchewan provides a large data base of publicly accessible digital wire-line logs. Correlations are mainly based on resistivity logs supplemented by gamma-ray. sonic and SP logs.

The resistivity log is an excellent indicator of grain-size variations and allows recognition of stratal patterns in a clastic and shale-dominated lithology (Rider. 1986). Correlation of a detailed closely-spaced grid of resistivity log cross-sections allows reconstruction of stratal patterns. which resemble that obtainable on geophysical seismic lines. but with considerably higher vertical resolution. The resistivity log, especially the deep induction log, is less sensitive to caving than many other logs. Caving of bore-holes is a common problem for wire-line logging in the Upper Colorado Group.

As described in detail below. the resistivity log response to bentonites and related smectite-rich sediments is distinctive and indicates a key surface which has chronostratigraphic value. It is important to note that using the resistivity log in a regional study. no absolute cut-off values can be used to define sandstones. The log-curve provides relative readings. One of the main reasons is that the resistivity of formation water. which is one of the main components in the deep resistivity log reading. varies within the studied interval in southern Alberta and southwestern Saskatchewan. Therefore different lithologies can give the same resisitivity value. The resistivity log is also sensitive to the presence of hydrocarbons in sandstones. which gives higher values. The

mapped sandstones are shaly and very fine-grained with low permeability; where gas is present no distinctive water/gas contact is observed. The gas content enhances the signature of the sandstones by increasing the resistivity values and intensifies the stratal pattern. In high permeability sandstones with a water/hydrocarbon contact, caution should be exercised. The gamma-ray, sonic and SP logs are used for interpretation of log-facies and determination of the exact thickness of the sandstones.

BENTONITES

Bentonites are regional facies easily recognized on resistivity and gamma-ray logs. The presence of abundant subsurface bentonite zones is confirmed in the lower Kevin Member of the Marias River Formation outcrops in Montana (Cobban et al., 1976) and in the Muskiki Formation, above the Cardium Formation in the Canadian Rocky Mountain Foothills (Stott, 1962). In the subsurface this zone is best documented in a 8 m long core of well 13-20-17-7W4, where more than 17 bentonite layers are present in a 3 m interval. The bentonite zone has previously been used for wire-line log correlation (Gilboy, 1989; 1996; Leckie et al., 1994), but its character was not documented in core, nor were its lateral extents or stratigraphic significance appreciated.

Bentonites from the Western Interior Seaway are described by numerous authors, dealing with the geochemical aspect used for original composition, correlation (Lerbekmo, 1968; Yen and Goodwin, 1976; Merriam and Bischoff, 1975; Amajor and Lerbekmo, 1980) and paleoenvironmental interpretation (Cadrin et al., 1995; DeCaritat et al., 1994). Regional correlation of bentonites on electrical well logs in the Albian Viking Formation in central Alberta, allowed a subdivision of the formation (Amajor and Lerbekmo, 1980; Glass, 1981).

Bentonites are isochronous geological marker beds as ash falls are considered to be deposited during relative short geological time (days or weeks) (Schoch. 1989; Cadrin et al., 1995). However. ash falls have low preservation potential when deposited in a moderate to high energy environment. but in offshore marine settings preservation potential is high.

On the resistivity log. bentonites or zones of bentonites are recognized by a low resistivity value. The clay mineralogy of the bentonites. a diagenetic product of volcanic ash deposits. makes them a good conductor compared to other clay minerals. Early diagenesis alters the ash deposit to montmorillonite. a subgroup of the smectite clay minerals group (Eslinger and Pevear. 1988; Wolf. 1959). Conductivity is related to the clay mineral-surface area and Cation Exchange Capacity CEC (Rider. 1996; Whitney and Ahlbrandt 1996). CEC is the amount of cations on the surface of the clay mineral through which the electrical current is conducted. The larger the mineral surface area and the higher the CEC. the higher the conductivity. Smectites are extremely fine-grained and therefore characterized by a very high specific surface area (table 6.3 in Rider. 1996). The high surface area of the CEC and large surface area of smectite. and therefore bentonites makes the resistivity log distinctively low (Whitney and Ahlbrandt. 1996).

MICROPALEONTOLOGY

The Carlile and Niobrara formations were sampled for foraminifera and nannofossil analyses in order to establish a biostratigraphic framework and for paleoenvironmental as well as sequence stratigraphic interpretations. The relation between foraminiferal assemblages and modern sequence stratigraphy is not well understood. and has only been used in a small number of publications (e.g. Armentrout.

1996; Loutit et al., 1988; Rey et al. 1993). Biozones are typically only used for biostratigraphic control and correlations. In this paper foraminifera and nannofossils are used biostratigraphically (Chapter II) and in support of sequence stratigraphic interpretation. The foraminiferal assemblages are subdivided into calcareous benthic, agglutinated and planktic groups which reflect different paleoenvironmental conditions (Eicher, 1969; King 1983, 1989; Martinson et al., 1998). Foraminiferal assemblages are not directly related to water depth, but to water masses, defined by ecological parameters such as oxygen content, nutrients, salinity, light, temperature and sedimentation rates (Boltovskoy and Wright, 1976; Leckie, 1989). However, these factors are commonly related to depth and distance from the shoreline, resulting in a link between foraminiferal assemblages and water depth. Planktic foraminifera, which are sensitive to water masses and require stable marine conditions with low sediment input (Martinson et al., 1998), are an indicator of open-marine deep-water conditions. Calcareous benthic foraminifera, which live in a variety of environments, are not as sensitive to environmental variation as planktic foraminifera. However, they are indicative of open-marine conditions saturated with calcium carbonate. Agglutinated foraminifera, which inhabit a variety of marine environments if sufficient oxygen is present, are less sensitive to water masses and calcium carbonate dissolution. Decreased species diversity and abundance of a fossil assemblage also indicate levels of ecological stress. High abundance of only a few taxa reflects a stressed environment with decreased competition, which is commonly found in the marginal part of the marine environment. Nannofossils generally require open-marine conditions similar to that required by planktic foraminifera, but some species are more

tolerant to salinity variations being widespread and occur in shallow-marine environments (pers. comm., Jim Craig, 1999; Schröder-Adams et al., 1998).

The general subdivision of depositional sequences into systems tracts is related to oscillations in relative sea-level (Posamentier et al., 1988). Water depth is the combined effect of relative sea-level and sediment supply (Jervey, 1988; Posamentier et al., 1988). Consequently high or rising relative sea-level does not necessarily mean deep water if the sediment input is sufficiently high. Therefore the use of foraminifera in a sequence stratigraphic analysis can aid interpretation of water masses and paleo water depth. If the rate of sediment input was constant or its variation can be estimated, then the resulting water depth can be used in a sequence stratigraphic analysis.

SEQUENCE STRATIGRAPHY

The method of using cross-sections of closely spaced resistivity wire-line logs in a dense net allows detailed interpretation of depositional stratal patterns. The technique permits an unique method applying the principles and terminology of seismic sequence stratigraphy, where onlap, downlap and offlap surfaces and stratal patterns easily can be identified.

Major first flooding surfaces are used as sequence boundaries (Embry, 1995) in this study to subdivide the Carlile and Niobrara formations into thirteen sequences (F1 to F13). In most sequences this boundary can be recognized throughout the study area making it a key stratigraphic surface (figure 3-3). The Carlile and Niobrara formations were dominated by fully marine upper offshore to shelf sedimentation (chapter IV), which makes it difficult to apply the traditional concepts of a depositional sequence boundary developed for littoral and other near-coastal environments (Van Wagoner et al., 1988,

1990) and genetic sequence boundary (Galloway, 1989). The distal correlative surface to the regressive erosional sequence boundary is difficult to identify and is highly subjective (*this study* and Embry, 1995). The maximum flooding surface could make an alternative choice for a sequence boundary (Galloway, 1989), but is also difficult to identify in a distal marine foreland basin setting. Normally, the maximum flooding surface is identified within the condensed part of a sequence, reflecting starved sedimentation and having a high gamma-ray value. However, the Carlile and Niobrara formations were dominated by offshore and shelf siltstone and shale (see chapter IV) making condensed intervals difficult to identify. In any sequence stratigraphic study it is important to identify those surfaces that work in the specific depositional and tectonic frameworks to avoid forcing data through models that are not suitable (Nystuen, 1998).

Consequently the first major flooding surface is chosen as a sequence boundary in this study as it is the most easily recognised surface in the distal lower-shore face to shelf environment (see chapter IV) of the Carlile and Niobrara formations (figure 3-3). Using a multidisciplinary approach, this boundary is the easiest recognizable surface in a shallow marine siliciclastic basin (figure 3-3). The first major flooding surface has also been used in allostratigraphy, applying the definitions from the North American Stratigraphic Code (1983) (Bhatacharya, 1989, 1993; Boreen and Walker, 1991; Plint and Nummedal, 2000; Plint et al., 2001). On wire-line logs the first major flooding surface is the most easily observed surface in the distal and shaly part of a basin, in which the sequence-sets (Mitchum and Van Wagoner, 1991) of the Carlile Formation were deposited (see chapter IV). In the distal part of the basin with poorly developed lowstand systems tracts, the major flooding surface is recognized at the boundary between shale overlying subtle

upward-coarsening intervals of sandstone (figure 3-3). This lithological change is evident in outcrop and on resistivity and gamma-ray logs (figure 3-3). These distal upward-coarsening intervals have many similarities to parasequences interpreted in more proximal settings (Van Wagoner et al., 1990). Only by placing the sequence stratigraphy into a regional setting is it possible to interpret these upward-coarsening intervals as sequences and not parasequences. All first major flooding surfaces from this study (F1 to F13) can be correlated and mapped throughout study area.

In the more proximal marine settings of the Niobrara Formation from lower shoreface to shelf (see chapter IV), it is possible to interpret the first major flooding surface on the backstepping pattern of parasequences onlapping the transgressive ravinement surface. In the proximal setting, this surface is composed of the regressive subaerial erosional surface and the subsequent submarine erosional surface as the transgressive ravinement (figure 3-3). This surface is identified on the cross-sections of densely spaced resistivity logs as the transgressive systems tract onlaps the sequence boundary in the more proximal setting (figures 3-5 to 3-13). The surface is distinct lithologically, geochemically and micropaleontologically and is observed in cores and outcrops as a transgressive lag with pebbles up to 2 cm in diameter, abundant glauconite, ooids and siderite cement. Changes in organic geochemistry across the boundary are characterized by an increase in total organic matter and a change from terrestrial (type III) dominated to more marine (type II) influence. The foraminiferal fauna changes across the sequence boundary from an agglutinated, shallow-marine assemblage below, to more open marine, mixed calcareous benthic and planktic foraminifera (figure 3-3).

Sequence stratigraphic principles which define the parasequences and their stacking pattern as the main building block of a sequence (Van Wagoner et al., 1990) are applied in this study. In most of the upper five sequences (F8, F9, F10, F13), three systems tracts: lowstand, transgressive and highstand systems tracts are identified (Posamentier et al., 1988), whereas in sequence F 12, the falling stage systems tract (Plint and Nummedal, 2000) is recognized. We acknowledge the value of the falling stage systems tract within a sequence, but only rarely and under specific geological settings is it possible to identify this fourth systems tract. In most cases the sediment deposited during the falling sea-level will be included in the late part of the highstand systems tract.

GEOLOGICAL SETTING AND STRATIGRAPHY

The Greenhorn and Niobrara second order sea-level cycles are described from the Late Cretaceous Interior Seaway in the USA and Canada (e.g. Kaufmann, 1967; McNeil and Caldwell, 1981). The Middle Cenomanian to Late Turonian Greenhorn Cycle was followed by the Coniacian to Santonian Niobrara Cycle (figure 3-1). The Carlile Formation represents the regressive phase of the upper Greenhorn Cycle and is subdivided into three informal units. In southern Alberta and southwestern Saskatchewan (figure 3-2) the Niobrara Formation (see chapter II) and the overlying Milk River Formation represent the Niobrara Cycle. The transgressive part of the Niobrara Cycle encompasses the Niobrara Formation, which is subdivided into the Verger, Medicine Hat and First White Specks members (Chapter II).

The Carlile Formation is a non-calcareous shale with minor fine-grained sandstone beds and abundant siderite concretions in the middle interval. In the Deer Creek outcrop the formation is informally subdivided into a lower, middle and upper unit.

The lower boundary is the top of the calcareous Second White Specks Formation, which is marked by a distinct biostratigraphic and lithological change (Bloch et al., 1993). The upper boundary is sharply marked by the bentonite zone from the lower part of the overlying Verger Member of the lower Niobrara Formation. The formation thickness ranges between 40 to 160 m and thins eastwards. The foraminiferal fauna from the Carlile Formation shows similarities to the Morden Shale in southern Manitoba (McNeil and Caldwell, 1981) and the Haven and Opabin members of the Blackstone Formation in the Alberta Foothills (Wall, 1967b).

The Niobrara Formation is 80 m (northeast) to 240 m (southwest) thick and is subdivided into three mappable members, the shaly Verger, the sand-rich Medicine Hat and the calcareous First White Specks members. Generally the Niobrara Formation is composed of dark gray marine shales, siltstones and very fine-grained gray sandstones and uncommon layers of chert pebbles. Calcareous intervals and thin beds occur in all three members, but are most pronounced in the First White Specks Member. This is in significant contrast to the underlying Carlile Formation and the overlying Milk River Formation. Macrofossils, mainly ammonites and bivalves, are common and bioturbation is widespread especially in the upper part of the sandstones of the Medicine Hat Member. The foraminiferal assemblages belong to the *Trochamina* sp., *Bullopora laevis* and *Globigerinelloides* sp. zones (Caldwell et al., 1978), dating from Coniacian to Santonian.

PHYSIOGRAPHY AND TECTONIC SETTING

Deposition of Late Cretaceous sediments in Western Canada took place in the asymmetrical foreland basin of Western Canada, with maximum subsidence and sediment accumulation rates in the basin foredeep to the west, and declining rates to the east

(Leckie et al., 1994; Shurr and Rice, 1986; Shurr and Reskind, 1984). Foreland basin tectonics in southern Alberta and northern Montana are complicated by the Sweetgrass Arch (figure 3-14). In southern Alberta, this complex structure, also named the Bow Island Arch, trends SW to NE and plunges northwards. The arch divides the Western Canada Basin into the Alberta Basin to the west and the Williston Basin to the east (figure 3-14). The tectonic evolution of the arch is described in detail by Beaumont (1981), Lorenz (1982), Podruski (1988) and is summarized in chapter II.

The effect of the arch on sediment distribution is debatable (Podruski, 1988). It is postulated that subtle facies changes in southern Alberta prior to the Paleogene can not be related to the Bow Island Arch (Podruski, 1988). In contrast, it has been argued that Cretaceous sediment distribution was influenced by the topographic relief of the Sweetgrass Arch (Arnott et al., 1995; Hankel et al., 1989; Myhr and Meijer-Drees 1981; Payenberg, 2002; Schröder-Adams et al., 1997; 1998; Shurr and Rice, 1984; Lorenz 1982; Lorenz and Gavin, 1984 and Cobban et al., 1976). Most authors argue that the southern part of the Sweetgrass Arch (Sunburst-Kevin Dome and South Arch) has been active and affected the sedimentation distribution.

During Santonian time, shoaling over the Sweetgrass Arch caused a change in pelagic conditions compared to deeper marine settings more distal from the arch (Schröder-Adams et al., 1998). Hankel et al. (1989) relates the distribution of the Medicine Hat sandstones to the presence of the underlying Sweetgrass Arch without being specific about the geometry of the arch. Shurr and Rice (1986) relate deposition of Upper Cretaceous sediments to paleotectonic activity on lineament-bound basement blocks in central and northern Montana (e.g. in the area of Bear Paw Mountains, for

location see figure 3-14). Sediment patterns are not directly associated with the Sweetgrass Arch, but lineaments of weakness within the lithosphere have been mapped in the area. Those features correspond to paleo-strandline positions of Santonian strata. Bottom water dysoxia, present in deep basin settings during First White Specks Member time became more oxygenated over the arch, allowing a benthic fauna to persist (Schröder-Adams et al. 1997; 1998).

RESULTS

SEQUENCE-SET (F1 TO F7) OF THE CARLILE FORMATION

General observations

The 40 to 160 m thick Carlile Formation (figure 3-15) consists of a sequence-set of seven sequences (F1 to F7), each topped by a major flooding surface (figures 3-5 to 3-13). An upwards change in stratal pattern is observed throughout the sequence-set: In the lower sequences the dip of the strata is very low with a tendency to very low angle downlap towards the east. In the upper sequences, especially F6 and F7, the stratal pattern changes to a bi-directional dipping of strata both from the west and east towards the central part of the study area (figures 3-6 and 3-7). This is particularly evident in the remnant of sequence F7, which was significantly eroded and capped by the sequence-set boundary F8.

Facies

The facies of the Carlile Formation (see chapter IV) are dominated by low energy distal offshore shale and siltstones. A few slightly upward-coarsening intervals of very

fine-grained and thin sandstone beds are observed throughout the formation (figure 3-16). Facies variations were minor and internal boundaries within each sequence are subtle.

The lower two sequences (F1 and F2) are slightly upward-coarsening intervals. Each sequence develops from a non-calcareous, homogenous dark gray shale to a thinly bedded lenticular sandstone with interlaminated shale. The sandstone lenses and laminae were deposited in a sand-starved environment with abundant disconnected trains of sand-ripples. Macrofossils are rare, and bioturbation is not observed. The sequence boundaries are characterized by a change from lighter gray silty to sandy shale below to a dark gray shale above. The third sequence (F3) is upward-coarsening and is characterized by abundant siderite concretions. The bioturbation in this sequence was dominated by an offshore assemblage of feeding traces with a diameter of less than 1 mm, identified as *Gordia*, *Pilichnus dichotomus* (Uchman, 1999) and *Chondrites*. The fourth sequence is poorly developed and is likely the lower part of the upward-coarsening that forms sequence F5 (figure 3-16). The sixth and seventh sequences (F6 and F7) are present in 13-20-17-7W4 (figure 3-17) and the Deer Creek outcrop. These sequences also show an upwards-coarsening trend from finely laminated shale with few sandstone lenses to a silty fine-grained sandstone. The sandstone beds are dominated by wave rippled lenticular bedding with some thin discontinuous hummocky beds.

Organic Geochemistry

TOC and HI values decrease upwards through the sequence-set, only being interrupted by higher peaks above the sequence boundaries (Chapter II). In the middle of sequence three (F3), a sharp drop in TOC occurs, which corresponds to the first

appearance of siderite concretions. The organic matter is primarily of terrestrial origin (type III), with a slight tendency to become more marine-influenced directly above sequence boundaries. (chapter II).

Stratal Patterns

General Carlile Sequence-set (F1 to F7)

The large scale stratal pattern of sequence-set (F1-F7) of the Carlile Formation is dominated by parallel to sub-parallel strata, outlined especially by the sequence boundaries formed by seven major flooding surfaces (figures 3-5 to 3-13). The sequence-set thins from the west (150 m) to the east and northeast (< 40 m), indicating the dominant sediment input direction was from the west (figures 3-8 and 3-15). The upper sequences (F5, F6 and F7) were truncated by an unconformity forming the upper boundary of the Carlile sequence-set (sequence boundary F8), which is observed on all cross-sections (figures 3-5 to 3-12). The parallel to sub-parallel stratal pattern diverts slightly in the west and east sides of the basin due to higher sedimentation rates of prograding distal shoreface sandstones (figures 3-6, 3-7 and 3-11). This gives the sequence-set an asymmetrical, oblique sigmoid stratal pattern as illustrated in figure 3-4. In the west the sandstones include the fine-grained part of the Cardium sandstones (equivalent to the upper sequences F4 to F7). The distal part of the shaly Bowdoin Sandstone is correlated in the east (figures 3-7 and 3-15).

The internal stratal patterns of the sequences in the Carlile Formation are subtle due to the extreme lateral continuity and low dip-angle of the strata in their distal and

condensed offshore setting. In the west, where sedimentation rates were highest, some marker-beds can be recognized and can be correlated to the rest of the study area.

Sequence F1

Sequence F1 has a remarkably uniform thickness of 35 m in most of the study area (figures 3-5 to 3-12). The lower sequence boundary is distinct with a major decrease in resistivity values. In the west the sequence boundary overlies the Jumping Pound sandstone. The internal stratal pattern is dominated by horizontal to very low (< 0.0001 degree) eastward dipping strata. The lower marker-beds of the sequence downlap towards the sequence boundary in an eastward direction (figures 3-6 and 3-7).

A thin (up to 5 m) transgressive systems tract is present in the west, that thins to below resolution in the central part. This systems tract is overlain by an up to 30 m thick prograding highstand systems tract which downlaps towards the maximum flooding surface lying slightly above the sequence boundary. A five meter thick upwards-coarsening sandstone is located in the highstand systems tract in the west (figures 3-6 and 3-9). Within the highstand systems tract, a few marker-beds offlap from the upper sequence boundary in an eastward direction and indicate subtle progradation. Overlying the highstand systems tract, an up to 7 m thick, upward-coarsening interval is located basinward of the highstand systems tract that represents the lowstand systems tract (figures 3-5 to 3-8). In the central part of the study area the lowstand systems tract is developed as a thin upwards-coarsening sandstone (figure 3-6).

Sequence F2

Sequence F2 is correlated across the entire study area, but varies from the underlying sequence F1 in thickness. The sequence thins from 40 m in the west (60 m in

the NW) to 10 m in the east (figures 3-5 to 3-12). The lower sequence boundary is recognized by a sharp drop in resistivity values. The internal stratal pattern is dominated by eastward, subtle low-angled (<0.0002 degree) dipping marker-beds (figures 3-6 and 3-7). In strike-section running north-south, the marker-beds appear horizontal and no terminations are observed (figure 3-6). In east-west sections, the lower marker-beds downlap eastwards towards the lower sequence boundary (figure 3-6 and 3-7). Westward onlaps on the sequence boundary occurs in the west (cross-section VII, figure 3-11). The upper part of the sequence offlaps from the sequence boundary (figures 3-6 and 3-8).

A wedge-shaped transgressive systems tract thins from 15 m in the west to below resolution eastward (figure 3-6, 3-7 and 3-10). In most proximal areas to the northwest (cross-section VII), this systems tract thins landwards and is outlined by onlap onto the sequence boundary. Overlying the transgressive systems tract is a low-angled (<0.0002 degree), prograding highstand systems tract which is up to 40 m thick, and thins eastwards to below resolution (figures 3-6 and 3-7). In the west, an up to 5 m thick poorly-developed sandstone was deposited in the highstand systems tract (figure 3-6 and 3-9). Marker-beds in the prograding highstands systems tract downlap the transgressive systems tract, or more distally, the lower sequence boundary. Basinwards, an up to 10 m thick lowstand systems tract was deposited over the highstand systems tract. The lowstand has developed an up to 2 m thick upward-coarsening sandstone in the central part of the study area (figure 3-6).

Sequence F3

Sequence F3 is up to 20 m thick in the west-central region and thins rapidly east of range 20W4 to less than 2 m (figures 3-6, 3-7 and 3-10). The lower sequence boundary is

most easily recognized in the west by a significant drop in resistivity, but is traceable in most of the study area. Due to the thin nature of the sequence, few marker-beds outline the stratal pattern, which is dominated by sub-parallel strata that dip eastward at very low angle (<0.0001). The sequence is dominated by eastward downlap towards the lower sequence boundary (figures 3-6, 3-7 and 3-10).

An eastward-thinning transgressive systems tract up to 15 m thick is located in the west that downlaps onto the lower sequence boundary. This system is overlain by a thinner, progradational highstand systems tract, which also downlaps towards the sequence boundary. In the west a well developed sandstone up to 5 m thick was deposited as part of the prograding highstand. The sandstone is the lowest of a number of sandstones observed in the subsequent sequences and might be the distal equivalent of Cardium sandstones observed in the southern Alberta Foothills (Wright and Walker, 1981, figure 3-18). No lowstand systems tracts are observed.

Sequence F4

Sequence F4 is thin and is up to 15 m thick in the west-central region, and thins gradually to the east and north. The sequence is not present north of township 25 and thins eastwards to less than 3 m. Due to the minor thickness the internal stratal pattern is subtle and is only outlined by a few marker-beds (cross-section II and V; figures 3-6 and 3-9). Marker-beds consist of low, east- and northward dipping strata that offlap the upper sequence boundary and downlap toward the lower sequence boundary (figure 3-10). The lower sequence boundary is obvious in the west (figure 3-9) where it overlies the well-developed highstand sandstone of sequence F3. As the sequence thins northward and

eastwards, the sequence boundary is also less visible and merges with the lower boundary of sequence F3 (figures 3-7 and 3-10).

The transgressive systems tract is a distinct low resisitivity interval above the lower sequence boundary. It is up to 10 m thick in the west, wedge-shaped and thins abruptly to 2 to 4 m eastwards. The highstand systems tract, which is up to 10 m thick in the central area is overlying the offlapping and prograding unit. Eastwards of the highstand, a thin (< 5 m) lowstand systems tract is present. No sandstones are observed in any of the systems tracts of this sequence.

Sequence F5

The sequence is present in the entire area, but has significant thickness variations (figures 3-5 to 3-12). In the north-central part, it is up to 35 m thick thinning to 3 m in the east where it finally gets truncated by the Carlile/Niobrara unconformity (figure 3-7). The stratal pattern is low-angled, but slightly steeper (0.002 degree) than in the previous sequences (F1 to F4). Three eastward offlapping parasequences indicate an eastward progradation which downlaps towards the lower sequence boundary (figure 3-6). The lower sequence boundary is subtle, but consistent in the entire region, and is recognized by a drop in resistivity values.

The transgressive systems tract is mainly present in the north and central region and thins to the east to below resolution (<1 m). The systems tract is thickest, up to 7 m, in a north-south trend along Range 25W4 (figure 3-9). The transgressive systems tract is overlain by a prograding highstand systems tract, which is outlined by upwards-coarsening parasequences in the west and central region (figures 3-6 and 3-9). These strata dip to the east and contain poorly developed sandstones (figures 3-6 and 3-7). The

progradation continued eastward of the highstand systems tract and is interpreted as the lowstand systems tract, which also is characterized by a thin (3 m), upwards-coarsening sandstone (figure 3-6). The lowstand is thickest in the southeast where it is up to 10 m thick. In the eastern margin (figures 3-7 and 3-8), the lowstand deposit was eroded and truncated by the Carlile-Niobrara unconformity. Sequence F5 is the oldest deposit to be eroded by this unconformity.

Sequence F6

In contrast to underlying the previous sequences, sequence F6 is relatively thick and its stratal pattern is well defined on most cross-sections. The thickness of the sequence ranges from 45 m in the northwest (figure 3-11) to 25 m in the north-central parts (figure 3-7). Further east, the sequence thickens to 35 m before getting entirely eroded in the far east (figure 3-7). Towards the south and southeast the sequence gradually thins to less than 5 m. The internal stratal pattern of the sequence is more complex than the previous sequences: In most of the area the stratal pattern is dominated by low east- and northeastward dipping strata, however in the northeast and east the uppermost marker-beds dip in the opposite direction; from the northeast towards the southwest (figures 3-5 and 3-8). This is also indicated by the thickness variation described above. The lower sequence boundary is easily recognized in the entire area as it sharply overlie upward-coarsening sandstones in both the highstand and lowstand systems tracts of the previous sequence F5. Within sequence F6, downlap towards the lower sequence boundary is the most common termination, but offlap from the upper sequence boundary is also observed especially in the central and northern regions. Truncations and erosion of the entire sequence is noticed in the east and south.

The transgressive systems tract is characterized by an up to 10 m thick back-stepping stratal pattern that overlies the sequence boundary in the west (figure 3-6). The wedge-shaped system thins abruptly towards the east, where it is below log resolution (< 1 m). The overlying interval is up to 35 m thick and progrades from both west/southwest and northeast. The lower marker-beds of the prograding interval downlap towards the lower sequence boundary. The upper marker-beds merge in the north-central region, which correspond with a thinning of the interval (figure 3-7). The interval is the highstand systems tract with thick upward-coarsening sandstones up to 15 m that are present in the west (figures 3-9 and 3-11). These highstand sandstones are present in outcrops of the southern Alberta Foothills (figure 3-18). On cross-section V (figure 3-9) a thick highstand sandstone body is observed from the middle of the section to the north. This thickening is probably related to syntectonic movement as the strata (sequences) below sequence F6 are down dropped, but the sequences above show no vertical movement (central part of cross-section V, figure 3-9). The highstand systems tract is overlain by a thin (max. 4 m) lowstand deposit in the east-central part of the basin and is recognized by its increased resistivity values (figure 3-11).

Sequence F7

Sequence F7 has its greatest thickness of up to 25 m in the north and northwest and thins to less than 10 m elsewhere. In Saskatchewan, southwestern Alberta and along the western margin, the sequence was entirely eroded (figures 3-5 to 3-12). The stratal pattern of the remaining sequence is dominated by bi-directional dipping strata, from the west and east, merging in the central part of the basin (figure 3-7). The axis of the basin changed from sequence F6 to F7, which is illustrated by the bi-directional stratal pattern

that is moving to the west. The lower sequence boundary is based on a drop in resistivity values and a few marker-beds that downlap onto this surface. Except for the truncations of the sequence margins very few terminations of strata are observed.

A sequence stratigraphic subdivision is difficult as only a small part of the sequence is preserved. However, towards the west a thin transgressive systems tract is identified with a maximum thickness of 5 m, thinning to a thickness below resolution in the central region (figure 3-6 and 3-7). The upper part of the sequence is a remnant of the highstand systems tract and shows the bi-directional stratal pattern, which indicates a sediment source from both west and east. No lowstand deposits were observed; lowstand sediments might have been deposited in the west-central part of Alberta as the Cardium sandstones (Bergman and Walker, 1987).

Micropaleontology of the Carlile Sequence-set

The boundary between the Carlile Formation (or time equivalent strata in the Western Canadian Interior Seaway) and the underlying Second White Specks Formation is characterized by a significant faunal change from the planktic *Hedbergella loetterlei* Zone to the agglutinated fauna of the *Pseudoclavulina* sp. Zone (Caldwell et al., 1978). The lower part of the Carlile Formation, including the two lower sequences are characterized by only a few agglutinated foraminifera, which could be reworked from older deposits. Time equivalent deposits shows similar trends of barren samples of the Alberta Foothills (Wall, 1967a; Brennan-Albert, 1998) and in Manitoba (McNeil and Caldwell, 1981).

The lower part of core 13-20-17-7W4 (554-552 m) (cross-section III) is characterized by a mixed fauna of planktic, agglutinated and calcareous benthic foraminifera (figure 3-17). This interval is interpreted as a distal condensed section from the late transgressive to early highstand deposits of sequence F6. The lower sequence boundary between sequence F5 and F6 is below the cored interval at about 560 m (figure 3-17). The upper part of sequence F6 shows a higher sediment input with shallower water, excluding planktic foraminifera. The fauna was dominated by calcareous benthic and agglutinated foraminifera. This interval is interpreted as the distal part of the latest highstand. Sequence F7 is very thin in both the Sweetgrass Hills (< 4 m) and core at 13-20-17-7W4 (< 1.5 m), and is interpreted as the erosional remnant of the late highstand of sequence F7 in the Carlile Formation (figures 3-16 and 3-17). Sequence F7 is topped by the first major flooding event of the Niobrara Formation, and is recognized by a dark gray shale with few planktic foraminifera.

SEQUENCE-SET (F8 TO F13) OF THE NIOBRARA FORMATION

General observations

The 80 to 250 m thick sequence-set of the Niobrara Formation (figure 3-19) consists of five sequences, each topped by a major flooding event (F8 to F13; figures 3-5 to 3-12 and 20). The Niobrara Formation is subdivided into the Verger, Medicine Hat and First White Specks members (Chapter II). The Verger Member contains the lower two sequences F8 and F9. The Medicine Hat Member consists of sequences F10 and F11, and the First White Specks includes sequences F12 and partly F13. The latter extends into the overlying Milk River Formation and is not fully described in this study.

Sequence-set (F8 and F9) of the Verger Member

Facies

The lower member of the Niobrara Formation is the shale-dominated Verger Member. Each sequence (F8 and F9) consists of several slightly upward-coarsening intervals from a dark gray shale to siltstone with very fine and thin sandstone beds (figure 3-20; Chapter II). The sequence boundary of both sequences are characterized by a thin layer (< 10 cm) of chert pebbles (angular and rounded), glauconite, bone fragments, calcareous ooids and siderite cement. In one outcrop (Kevin in northern Montana), evidence of a paleosol is present (figure 3-18; Chapter III). Sequences F8 and F9 consists of thick shale deposits with relatively high-angled giant clinoforms (100's km long) in sigmoid and tangential sigmoid forms. The height of the clinoforms are up to 50 m (figure 3-8).

Abundant bentonite layers are observed in cores and outcrops in the two sequences (figures 3-5 to 3-13 and 3-17), which make excellent marker-beds, outlining the stratal patterns on resistivity log cross-sections (*see method for details*). Bioturbation ranges from slight to intense and increases upwards in each of the upwards-coarsening intervals. Trace fossils change from being dominated by *Pilichnus dichotomus* and *Gordia* in the lower part of the interval to *Terebellina* and *Chondrites* in the upper part of the upward-coarsening intervals.

Stratal Patterns

Sequence F8

Sequence F8 thins from 110 m in the southwest to 20 m in the east and central part of the region (figure 3-19). This is the thickest sequence studied and its stratal pattern is well defined. The lower sequence boundary is also the formation boundary between the underlying Carlile Formation and the Niobrara Formation. The boundary is easily recognizable in the Upper Colorado Group (figures 3-5 to 3-12), as an unconformity with truncation of sequences F5, F6 and F7, especially on the margins of the basin. On resistivity logs, the boundary is distinct with a major, sharp drop in resistivity values, which represents the first of the numerous bentonites in the sequence (figures 3-5 to 3-12). The internal stratal pattern is dominated by moderate dipping strata (maximum 0.02 degree) to the east and north (figures 3-5 and 3-8). The angle of the dip is significantly different from the low-angled strata of the Carlile Formation. The steepest dipping beds occur in the south, gradually flattening to the north and east (figures 3-5 and 3-6). Terminations are dominated by downlap, offlap or truncation from the upper sequence boundary. No onlap is observed.

The lower part of the sequence is characterized by a south- and southwestward back-stepping stratal pattern outlined by three distinct marker-beds (figures 3-5, 3-6 and 3-8). This pattern represents the transgressive systems tract and is thickest with up to 40 m in the southwest indicating a southern sediment source (figures 3-5, 3-8 and 3-10). The upper boundary of this systems tract is a distinct downlap surface and represents the maximum flooding surface of the sequence. The unit above is dominated by north- and eastward prograding strata with moderate dips (0.02 degree) and is the highstand systems tract. This stratal pattern indicates a dominant sediment source from the south and southwest. The prograding pattern is less pronounced in the north (figure 3-11) and thins

to less than 10 m in the east (figures 3-7 and 3-12). In the south and central areas, the upper part of the prograding highstand is truncated by the overlying sequence boundary. No lowstand deposits are observed in the study area, but correlations to the north (figure 3-13) show that the lowstand deposits are part of the Bad Heart Formation (Donaldson et al., 1998, 1999; Plint, 1991).

Sequence F9

The thickness of sequence F9 ranges from 50 m in the southeast to 10 m in the west and north (figure 3-19). The overall shape of the sequence is lenticular in the southeast and thins to a uniform sheet of ca. 10 m elsewhere. The stratal pattern indicates a sediment source from the south and southwest (figures 3-5, 3-8 and 3-10) and the sediment depo-center shifted eastwards compared to the underlying sequence F8 (figures 3-19 b and c). On the southern and western margins of the region, the lower part of the sequence is slightly back-stepping towards the south (figure 3-5). A moderate to high-angled prograding unit with beds dipping mainly towards the north and northeast overlies the back-stepping unit. However, bi-directional dipping beds are observed in the northeast where some beds dip to the south and southwest (figure 3-5). A few strata onlap the lower sequence boundary in a western and southern direction. In the central part of the region, this onlapping system infilled a broad depression in the previous sequence. The prograding unit downlaps onto the back-stepping unit and towards the lower sequence boundary where the back-stepping unit is not present (figures 3-5 to 3-7). The upper part of the prograding unit is truncated in the south and southwest and gradually thins to the north (figure 3-8).

The sequence stratigraphic subdivision of sequence F9 resembles of sequence F8. Only two systems tracts are observed in the study area and the stratal pattern is dominated by moderate to high angle dipping strata (dip 0.01 to 0.02 degree) and truncation of the upper part of the sequence. The back-stepping unit observed in the south and central part of the region is the transgressive systems tract, which onlaps the lower sequence boundary and is characterized by low resistivity values. In the north-central part the transgressive systems tract infilled a 25 km wide depression, which could indicate that the first part of the transgressive sea flooded an elongated embayment. The sandstone bodies of Verger 1, 2 and 3 were deposited in the highstand systems tract and are each up to 7 m thick (figures 3-5 to 3-13, 3-21a). The progradation of the highstand systems tract is from the south and southwest to the north with relatively steep clinoforms of up to 0.05 degree in the southeast region. The upper part of the highstand systems tract is truncated, which is most evident in the southeast (figures 3-5 and 3-8). As in sequence F8, no lowstand deposits were seen in the study area, but correlations to the north indicate that the lowstand systems tract is likely the upper part of the Bad Heart Formation (Donaldson et al., 1998; Plint, 1991).

Micropaleontology

Sequences F8 and F9 were sampled from three cores and the Deer Creek outcrop (figures 3-16 and 3-20). Cores represent the distal to middle shelf, whereas the outcrop are from a more proximal part (see chapter IV).

The fauna found in the lower part of core 13-20-17-7W4 (figure 3-17) comprise calcareous and agglutinated benthic and planktic foraminifera. This thin interval is

interpreted as the distal part of the major flooding event overlying sequence F7 of the underlying Carlile Formation.

The principle of bio-event correlation (Armentrout, 1996) is used in cores from 16-4-22-15W4 and 13-20-17-7W4 (figures 3-17, 3-20, 3-22 and 3-23). In the two wells a similar vertical succession of benthic and planktic foraminiferal assemblages are observed in sequence F8 that indicates the same stratigraphic interval, an isochronal interval. The assemblage is abundant and rich in large agglutinated foraminifera (mainly *Ammobaculites* ssp.). In both wells a thin interval interrupts the agglutinated assemblage and changes to a fauna dominated by planktic and calcareous benthic taxa. Based on the assemblage, the interval is interpreted as the distal part of a highstand period with low sediment input. The planktic assemblage could indicate a renewed rise in sea-level (minor transgression) in the overall highstand period. The bio-correlation clarifies that the proximal prograding upper part of sequence F8 seen in the core at 16-4-22-15W4 was deposited at the same time as the distal sediments in the core at 13-20-17-7W4 (figure 3-22). The distal sediments seen in the latter well are part of a major lenticular structure, mapped and correlated by wire-line-log and could have been interpreted as a separate event, if the bio-correlation did not show the relation to the sediments of 16-4-22-15W4.

The major flooding event creating the upper boundary of sequence F8 is supported by the presence of planktic foraminifera and high TOC values of up to 4.5 % (figures 3-17 and 3-20).

Sequence-set (F10 and F11) of the Medicine Hat Member

The sequence-set of the Medicine Hat Member consists of sequences F10 and F11 and the combined isopach map shows a relatively consistent thickness of the sequences. ranging from 40 to 60 m (figure 3-19). The Medicine Hat Member is distinguished by its abundance of fine-grained sandstones. Isopach maps of thirteen sandstones are shown in figure 3-21. and their stratigraphic position is incorporated into the facies and stratal pattern sub-chapters.

Facies

The lower sequence boundary of F10 is identified in three cores in the north central part of the region (figure 3-20) and is described in detail in the previous chapter. Overlying the sequence boundary, two parasequences are identified that show a back-stepping trend. The lower parasequence is a coarsening-upwards fine-grained sandstone overlain by a thin pebble lag (figure 3-20). The upper parasequence is characterized as a silty, dark gray shale coarsening upward to a silty to very fine-grained sandstone. The two parasequences are overlain by the maximum flooding surface characterized by a thin shale with calcareous benthic foraminifera. The overlying progradational part of sequence F10 is characterized by silty to fine sandstone intervals. In the core at 16-4-22-15W4 parasequences are unrecognizable in the intensely bioturbated upper facies of the sequence (figure 3-23). To the east in the area of the Medicine Hat gas field. the upper progradational part is considerably thicker. and five parasequences are identified in the core at 14-36-13-4W4 (Chapter II and IV).

The progradational upper interval is characterized by an abundance of siderite concretions and many bivalve fragments. The dominant trace fossils in the upper and lower intervals are *Gordia*, *Plioichnus* and *Terebellina*. Throughout the sequence, primary sedimentary structures were commonly destroyed by bioturbation, but are, in the lower part of the parasequences, dominated by fine sand lamination and thin lenticular bedding. The upper part is typically thinly interbedded shale with silty to fine sand laminae and lenticular bedding. Normally graded, thin beds also occur in this facies.

Stratal Patterns

Sequence F10

Sequence F10 is the oldest of the Niobrara Formation to have major fine-grained sandstones deposited in southern Alberta and southwestern Saskatchewan (figure 3-21). The sequence is up to 40 m thick in the south and west and thins to between 15 and 20 m in the north and east (figures 3-5 to 3-12). The sequence thickens locally to up to 50 m in southeastern Alberta near the Medicine Hat City (Tw. 10 - Rg. 4), which is also observed on the combined isopach map of sequences F10 and F11 (figure 3-19c). The six sandstones mapped in the sequence (figure 3-21) enhance the recognition of the stratal pattern as key terminations and stratigraphic surfaces are easier to recognize. The stratal pattern of the sequence is subdivided into two parts: A lower one up to 25 m thick, that is dominated by low resistivity values and shows a back-stepping pattern of parasequences towards the south and west. This unit is wedge-shaped and thickest in a northwest-southeast trend through the west-central part of the study area (figure 3-6). The back-stepping system infills the 40 km broad depression in sequence F9 (figure 3-7). The overlying unit is prograding and downlaps towards the back-stepping interval and more

distally onto the lower sequence boundary. The prograding unit has bi-directional dip mainly from the west but also from the northeast (figure 3-7). The dip of the strata in both the back-stepping and prograding intervals are low to very low (< 0.002 degree), which is significantly different from the moderate to high-angled stratal pattern in the underlying Verger Member. In most cross-sections, the marker-beds and parasequences are sub-horizontal. Terminations of strata are mainly onlaps on the sequence boundary towards the south and west, and downlaps on the top of the back-stepping system. Offlap from the upper part of the sequence is also observed.

The sequence stratigraphic subdivision of F10 includes all three systems tracts. The lower back-stepping system in the south and west is the onlapping transgressive systems tract, which is up to 25 m thick. In this system two transgressive sandstones were deposited (Medicine Hat sandstones 1 and 1a; figure 3-21). These isolated sandstones have a northeast to southwest trend in the north and east. As in sequence F9, it appears that a broad elongated embayment in the north was flooded during the initial transgression of the region. Overlying the transgressive systems tract an up to 35 m prograding highstand systems tract was deposited thick in the northwest. Outlined by parasequences the progradation was mainly from the south and southwest. Two parasequences in the highstand systems tract developed into fine-grained sandstones (Medicine Hat sandstone 2 and 3; figure 3-21) in the west and central part of the region (figures 3-6 and 3-9). Overlying the highstand systems tract the progradation continued towards the east where a fine-grained sandstone was deposited. This sandstone (Medicine Hat sandstone 4; figure 3-21) represents the early lowstand deposit in a distal setting of the basin. The sandstone coarsens upwards to very fine sand up to 7 m thick; it was

deposited in the area where the sequence has its maximum thickness of 50 m. Overlying this sandstone, a late lowstand sandstone (Medicine Hat sandstone 5) was deposited to the south and southwest (figure 3-21). This sandstone is trending east-west and is a up to 8 m thick.

Sequence F11

Sequence F11 has its greatest thickness in the area of Medicine Hat City where it is 40 m thick as seen in the combined isopach map of sequence F10 and F11 (figure 3-19c). To the south and east it thins to less than 15 to 25 m. In the southwest the sequence is 35 m and thins to the northwest to 10 to 20 m (figures 3-8 and 3-9). This thickness distribution differs from the other sequences, which generally are thinning from west to east. The thickest part of the sequence is in southeast Alberta, which was locally controlled by structure (see chapter IV). The lower sequence boundary is easily recognized by a significant drop in resisitivity values above the upper sandstones of sequence F10.

Internally the stratal pattern is complex, but is generally characterized by a thick, up to 35 m, lower back-stepping and low resisitivity interval overlain by a thinner (up to 15 m) prograding unit. The complexity of the stratal pattern lies in the timing of the back-stepping and prograding units, which is diachronous within the region. The thick, back-stepping interval is present in most of the study area where it onlaps the sequence boundary towards the south and west. In the upper part a back-stepping stratal pattern is still seen in the northwest (figure 3-7), but towards the south (figure 3-5) it merges with a northward prograding sand-rich interval. This reflects two different scenarios in the basin - back-stepping and onlapping strata in the northwest and progradation and offlap in the

southeast. The stratal pattern changes upwards northwestwards to a prograding system similar to that in the south. The prograding system was dominated by eastwards and northwards low-angled (0.002 degree) dipping strata with widespread sandstones (Medicine Hat sandstones 6a, 8 and 9) that cover up to 3000 km^2.

The sequence stratigraphic subdivision is complicated by the complex and diachronous nature of the boundary between the back-stepping and the prograding intervals and shows how sedimentary systems can vary within a basin. The back-stepping unit is up to 30 m thick in the north and central region. The diachronous surface thins dramatically to the south and west to less than 5 m. Two sharp-based transgressive sandstones (Medicine Hat sandstones 6 and 7; figure 3-21) distinctly outline the back-stepping pattern in the northwest. A transgressive northeast-southwest oriented sandstone is also observed in the southwest (Medicine Hat sandstone 7a; figure 3-21). Based on wire-line correlations, the overlying prograding unit was deposited somewhat earlier in the south than in the northwest, and is subdivided into a southern and western highstand systems tract and an eastern lowstand systems tract. The highstand systems tract is dominated by progradation from the south and southwest and is outlined by the two extremely widespread sandstones (Medicine Hat sandstones 6a and 8; respectively 3000 and 2000 km^2). The isolated Medicine Hat sandstone 6a covers most of southern Alberta and crosses the crest of the Bow Island Arch (figures 3-14 and 3-21). The Medicine Hat sandstone 8 was deposited on the west and northwest flank of the Bow Island Arch. This sandstone of the Medicine Hat Member might be the only one connected to a western shoreline and therefore represents the distal shoreface (see chapter IV). The lowstand systems tract of the sequence was deposited in the eastern part of the region and its main

component is the Medicine Hat sandstone 9, which corresponds to the A-sandstone in the lithostratigraphic subdivision (Chapter II). This sandstone covers almost 1000 km^2 and is the best developed of the Medicine Hat sandstones. It was deposited on the northeast and east side of the Bow Island Arch (figure 3-14) and progradation from the northwest indicates continuation of the sediment source that feeds Medicine Hat sandstone 8. The Medicine Hat sandstone 9 is especially thick in the area of Medicine Hat City, which is believed to be due to the local Medicine Hat syncline (see chapter IV).

Sequence-set (F12 and F13) of the First White Specks Member

The sequence-set of the calcareous First White Specks Member consists of the sequences F12 and the lower transgressive part of sequence F13 (figure 3-19). The upper part and regressive part of sequence F13 belongs to the overlying Milk River Formation. The First White Specks Member thins from 70 to 20 m generally from west to east (figure 3-19). Within the First White Specks Member, the sand-rich Sweetgrass Member was deposited in the northwest of the region (Schröder-Adams et al., 1997).

Facies

The First White Specks Member, which is the upper member of the Niobrara Formation, is a calcareous dark gray shale with numerous bentonites, common macrofossils and a few thin sandstones in southern Alberta and southwestern Saskatchewan (Chapter II). The paleoenvironment was dominated by a low-energy regime and the results of this study indicate that the member was deposited in a lower offshore to shelf setting (see chapter IV).

Stratal Patterns

Sequence F 12

This sequence is the lower part of the First White Specks Member. The stratal pattern of the member is subtle and generally very low-angled. Sequence F12 has a relatively constant thickness of 20 to 35 m in the region and is thinning very gently from west to east. The thickening observed in sequence F10 and F11 in the Medicine Hat City area, is not observed in sequence F-13. The internal stratal pattern on the resistivity logs is very subtle, which is related to lack of lithological contrasts and the extreme lateral continuation of these distal shale deposits (see chapter IV). Marker-beds all dip eastwards with a very low angle (< 0.001 degree). The few terminations in the central and east areas are low-angled downlaps toward the lower sequence boundary. Towards the top of the sequence a few offlaps occur (figures 3-6 and 3-7). The lower sequence boundary is the top of the major and extensive sandstones of the underlying sequence F11 and is characterized by a significant drop in resistivity values. The wedge-shaped lower part of the sequence has low resistivity values and downlaps towards the sequence boundary in the central to eastern region. A sharp-based sandstone is observed in this interval on the northwest margin of the basin (figure 3-11). An up to 20 m thick prograding interval is overlies this interval, which dips very gently to the east where it thins gradually to 2 m. In the west a thin sandstone is observed in the lower part of the interval (figure 3-7). The most distinctive sandstone deposited in the west and northwest of the region is overlying this prograding system (figures 3-6 to 3-9), which is the Sweetgrass Member (Schröder-Adams et al., 1997).

The transgressive systems tract of sequence F12 is the up to 10 m thick, wedge-shaped interval overlying the sequence boundary. One unmapped thin transgressive sandstone occurs in the west with the characteristic sharp base onlapping the lower sequence boundary. Above, is the extremely low-angled, prograding highstand systems tract, which downlaps the transgressive system or more distal the lower sequence boundary. Overlying the distal highstand systems tract is the lowstand systems tract of the Sweetgrass Member (figures 3-7 to 3-9). This sandstone is up to 6 m thick and varies from being sharp-based to upwards-coarsening. The lowstand systems tract was deposited in the western part of the region, which is landwards of the lowstands in the previous sequences, indicating a major relative sea-level rise in the First White Specks Member.

Sequence F13

Only the lower transgressive part of sequence F13, which is part of the Niobrara Formation, was studied. The regressive part of the sequence was deposited in the regressive part of the Niobrara Cycle in the Milk River Formation. The transgressive systems tract of sequence F13 ranges from 2 to 15 m in the western and northern part of the region. The stratal pattern is dominated by sub-horizontal to very low dipping strata. The lower boundary is easily recognized in the northwest region where it overlies the Sweetgrass Member. In the rest of the study area similar thin sandstones are observed at the same stratigraphic level (figure 3-5; in the south) as the Sweetgrass Member, which makes it possible to trace the lower sequence boundary. The upper boundary is also the formation boundary between the Niobrara Formation and the Milk River Formation, which is best observed on gamma-ray logs (figure 3-20).

The deposits below the boundary of the Niobrara and Milk River Formation are the transgressive systems tract and possibly of the early highstand systems tract. The distinct change from black calcareous shale of the First White Specks Member to the silty bioturbated sediments of the Milk River Formation represents a major drop in relative sea-level and marks the change to the late highstand or lowstand systems tracts.

DISCUSSION

RATIONALE OF THE METHOD

Correlations on closely spaced resistivity logs illustrate stratal patterns and the sediment infill history of the Upper Colorado Group. The technique shows that the Upper Cretaceous shaly basin was complex with clinoforms and sediment input from several directions. Marker-beds and parasequences can be correlated for 10's to 100's of kilometers. To interpret the stratal pattern of this type of shelf environment, an important aspect of the technique has been to establish the right proportion between the horizontal scale of the logs and the vertical scale. At a certain ratio, by trial and error, the stratal pattern stands out and a sequence stratigraphic interpretation is possible using the principles of seismic stratigraphy (Mitchum et al., 1977).

The advantages of this technique compared to seismic are a higher vertical resolution and a direct tie to cores and drill-cuttings for lithology and facies control. The gamma-ray and other wire-line logs are more sensitive to secondary features such as caving of the well bore and minor local variations in lithology (e.g. diagenetic alterations of clay mineralogy) and do not illustrate the stratal pattern as well as the resistivity logs. Assuming that the formation water is constant, the resistivity log is the best tool to

determine grain size variations and is perfect for stratal pattern correlations in low permeability sand-rich and shaly intervals.

STRATAL PATTERN AND SEDIMENT INFILL HISTORY

The Upper Colorado Group consists of two sequence-sets, each with a specific set of stratal patterns that reflect a distinct sediment infill history. The lower sequence-set consists of seven sequences (F1to F7), which are dominated by low-angled strata that form the regressive Carlile Formation. The upper sequence-set consists of six sequences (F8 to F13) with a complex stratal pattern, forming the transgressive Niobrara Formation.

The Carlile sequence-set

The Carlile Formation sequence-set (F1-F7) is dominated by low-angled stratal patterns having parallel to sub-parallel sequence boundaries in the overall regressive regime of the Greenhorn Cycle. The lower five sequence boundaries converge slightly eastwards, which is also reflected in an overall eastward thinning from 150 m to 50 m. The stratal pattern changes upwards through the sequence-set from dipping towards the east to bi-directional dips from both west and east. This indicates that in the lower part, a general sediment input direction was from the west, changing upwards in response to sediment input both from west and east.

The basal sequence boundary of each sequence is overlain by a thin (up to 5 m thick) transgressive shaly interval that eastward downlaps onto the sequence boundary. In the west (e.g. figure 3-9), approximately one third of the sediments from each sequence were deposited in the transgressive systems tract (e.g. F2, F4 and F6). In the east (figures 3-5 and 3-7) the transgressive systems tracts are very thin and below log resolution (<1 m). The transgressive systems tracts are overlain by very low-angle prograding units that

downlap onto the maximum flooding surfaces (top of transgressive systems tract). The progradation is seen on the east-west cross-sections (dip-direction) whereas the north-south cross-sections (strike-direction) show parallel strata. The prograding unit is subdivided into the highstand systems tracts and lowstand systems tracts. The boundary between these two systems, which is the correlative sequence boundary (Posamentier et al., 1988), is extremely difficult to pick in this very subtle and low-dipping, distal stratal pattern, making the choice of boundary highly subjective. This is the main reason to chose the first major flooding surface as the sequence boundary, which is picked more objectively (*see sequence stratigraphy for discussion*). The highstand systems tracts are normally observed at the basin margin directly above, and downlap onto the transgressive systems tracts. In the marginal marine setting to the west these highstand deposits are characterized by gently upward-coarsening sandstones (parasequences) that pinch out eastwards. The sandstones increase upwards in frequency and thickness and are known as the Cardium sandstone in the Foothill region of southern Alberta (Wall, 1967b; Wright and Walker, 1981). In the east, only the upper two sequences F6 and F7 show sandstone development forming the Bowdoin sandstones (see chapter IV). The boundary to the lowstand deposits is chosen on the basis of the stratal pattern and lithology and is characterized as a prograding unit basinward of the prograding highstands.

In the lower five sequences (F1 to F5), all low-angled strata dip eastwards indicating a sediment source from the west in a wide shallow sea where the basin axis was east of the study area (see chapter IV). During this time southern Alberta and southwestern Saskatchewan were located too far from the east coast of the interior seaway to receive any significant sediments from this side of the basin. This changes in

the upper two sequences, which have bi-directional strata-dips (F6 and F7). Sequence F6 is thinnest in the east-central region with marker-beds dipping from the east and west towards the central region. This is the first indication within the studied stratigraphic interval of a westward shift in the basin axis of the Interior Seaway, with a new sediment source from the east (Canadian Shield). Sequence F7 is also characterized by bi-directional downlap and the basin axis has moved westward compared to sequence F6. It is likely that this westward movement of the basin-center took place for the lower sequences (F1-F5) as well, but east of the study area. In the lower sequences, the eastern shore line was so far to the east that it did not affect sedimentation in the study area.

The westward shift of the basin-center, indicated by stratal patterns and sandstones developed in both the east (Bowdoin sandstone) and the west (Cardium sandstone) illustrate the sediment infill of the basin in a regressive setting. The relative sea-level fluctuations and cyclicity represented by the seven sequences (F1 to F7) were probably due to minor tectonic events in the west, and overall the interval of the Carlile Formation (Late Turonian) is considered as a relatively quiet tectonic period. The basin gradually infilled during the seven relative sea-level cycles of the Carlile Formation. The lower five sequences reflect an offshore to shelf environment. In the upper two sequences, the facies pattern changed to a slightly more proximal setting indicating that the basin infilled with sediments from both the east and west.

The boundary between the Carlile and Niobrara sequence-sets

The boundary between the Carlile and Niobrara sequence-sets is a regional disconformity overlain by a major flooding event. Erosion and truncation of the Carlile sequence-set is observed in all marginal parts of the Alberta Basin. The erosion is seen as

marker-beds and parasequences were truncated by the regional unconformity. In the south, towards the border of Montana, up to 25 m of sequence F7 and partly sequence F6 were eroded (figure 3-5). In the west and northwest, where the prograding Cardium sandstones were deposited, up to 15 m of sequence F7 have been eroded (figures 3-6 and 3-13). In the east about 20 m were eroded from close to the Saskatchewan border region and eastwards (figures 3-6 and 3-7).

The boundary between the two sequence-sets is documented in one core (13-20-17-7W4) and two outcrops (Deer Creek, Montana, and Highwood River, Alberta Foothills). The boundary is characterized by a major change in lithology, sedimentology, geochemistry and micropaleontology (Chapter II). Two features are especially important in the recognition of the boundary: 1) truncation of marker-beds and sequences as described in the previous paragraph is obvious on long regional cross-sections but is difficult to observe on log or outcrop scale and 2) The abundance of bentonites above the boundary, which is easily observed in cores, outcrops and resistivity wire-line. In the core 14-20-17-7W4, 17 bentonites, ranging from 0.5 to 16 cm, were deposited in a 3 m interval above the sequence-set boundary. The same is the case in the Sweetgrass Hills area, Montana where 17 bentonites were deposited above the boundary, but here in a 50 m thick shaly interval (Cobban et al., 1976). In the Alberta Foothills, in the Highwood River outcrop, the interval above the boundary (top of the Cardium Formation) is also characterized by bentonites (figure 3-18). This is also observed elsewhere in the Alberta Foothills (Stott, 1962) confirming the significance of bentonite swarms in correlations. The bentonites mark the boundary between the two formations and indicates elevated volcanic activity, coincident with major tectonic episode in the Cordillera. The tectonic

event, which was probably due to renewed thrusting south and southwest of southern Alberta changed the basin geometry, sediment source and caused the change in lithology, sedimentology, geochemistry and micropaleontology across the formation boundary. However, with distance to origin of the bentonites, the recognition and stratigraphic use of the bentonites become limited. In the Cold Lake area in northeastern Alberta, core data of this interval show no distinct bentonite swarm, and other methods such as micropaleontology are needed to establish stratigraphic correlations (per. comm. Claudia Schröder-Adams).

The Niobrara Sequence set

The stratal patterns and the sedimentary facies of the Niobrara sequence-set are markedly different from the Carlile sequence-set (figures 3-24a and b). The Niobrara sequence-set is dominated by a stratal pattern which evolved from moderate high-angled in the lower sequences, to low-angled in the upper sequences. Sedimentary facies change upwards from shale and bentonite-rich in the lower sequences to more sandstone-rich in the middle sequences to calcareous and shaly in the upper sequence. In general, accommodation space and sediment input rate was higher in the Niobrara sequence-set and the individual systems tracts are commonly thicker than in the Carlile sequence-set (figures 3-25a and b). Isopachs of the Niobrara sequence-set indicate a general thinning from 250 m to less than 80 m from the west and south towards the east and northeast and indicate the prevalent sediment input direction from the south and west towards the north and northeast.

Individual sequences of the Niobrara Formation

The lower two sequences of the Verger Member (F8 and F9) are characterized by thick prograding shale units with high-angled stratal patterns and well defined onlap and downlap surfaces. Also, these sequences generally lack lowstand deposits within the study area. Neither the stratal pattern, or the sedimentary facies indicate any lowstands and as illustrated by one cross-section, lowstand deposits are believed to have been deposited north of the study area, (figure 3-13; see chapter IV).

Sequences F8 and F9 have comparable stratal patterns through each individual sequence (figures 3-5 to 3-12). At each sequence, and especially sequence F8, accommodation space increased significantly across the sequence boundary, resulting in a major flooding event, which pushed facies landwards towards the western and eastern margins of the basin and no sand-rich facies are observed (figures 3-25a and b). For both sequences, the transgressive systems tract above the first major flooding surface (sequence boundary) is a generally back-stepping system, which fines upwards and is topped by the maximum flooding surface. Subsequently, and still in a regime of high accommodation, a high sedimentation rate of shale caused progradation into the basin from several directions (figures 3-25a and b). The shaly highstand of sequence F8 prograded from the west and southwest whereas the main progradation within sequence F9 is mainly from the south. The highstand systems tracts consist of high-angled stratal patterns, which downlapped the maximum flooding surface. The highstand of sequence F9 is characterized by offlaps and truncated strata from the upper sequence boundary as sediments were bypassed and built out in north/northeast direction. This is one of the main criteria for the falling stage systems tracts (Plint and Nummedal, 2000). However,

in this study this part of the sequence is regarded as part of the latest stage of the highstand systems tract.

No sandstones are observed in sequence F8, which is dominated by shale and bentonites. In sequence F9, three sandstones (Verger 1, 2 and 3) are mapped in the highstand systems tracts (figure 3-21a). These sandstones show progradation from the south and southwest forming elongate ridges.

Sequences F8 and F9 lacks lowstand systems tracts in the study area (figures 3-5 to 3-13). From the stratal pattern and facies interpreted from wire-line logs and cores, the prograding highstands of the two sequences show no sign of an overlying lowstand, but indirect evidence for an eroded lowstand exists in cores. At 8-36-24-13W4; 6-3-24-13W4; 16-4-22-15W4 (Figures 3-20 and 3-23) and two outcrops (Kevin and Highwood River; figure 3-2) the upper sequence boundaries of the two sequences are characterized by reworked layers of chert pebbles, bone fragments and ooids, and are interpreted as a transgressive lag (Chapter II; figure 3-20). A petrographic study of this layer not only revealed the presence of chert pebbles, ooids and bone fragments, but also indicated the presence of a paleosol (pers. comm., El Dein, 1999). The widespread pebble layer and the paleosol are indicators of subaerial exposure in southern Alberta and northern Montana and subsequent erosion during transgressive ravinement. The ravinement eroded the southern and western part of the lowstands systems tracts and the upper part of the highstands systems tracts. The preserved lowstands are believed to be present north of the study area, in the west-central part of Alberta represented by the Bad Heart Formation (Donaldson et al., 1998; Plint, 1990; Plint and Norris 1991). Correlations show that the flooding surfaces, capping at least two of the Bad Heart sandstones, correspond to the two

major flooding surfaces (sequence boundaries) of sequences F8 and F9 (figure 3-13). In southern Alberta and Montana the only evidence of lowstands is the transgressive lag. since no major erosion has occurred, it is believed that the exposed shelf profile was low-angled and near equal to the gradient of the alluvial hinterland. This would mean that no nick-point was developed and the development of incised valleys would be more unlikely (Posamentier, 2001). Instead the broad exposed shelf developed as a lowstand bypass channel system (Posamentier and Allen, 1999; Posamentier, 2001) where only minimal erosion occurred and the limited accommodation space resulted in thin sediment accumulation. This scenario implies deposition of a thin alluvial and fluvial system in southern Alberta and northern Montana, which was subsequently reworked by the transgression resulting in a pebble lag.

After deposition of sequences F8 and F9 the stratal patterns and sedimentary facies changed again (figure 3-19). The thick progradational part of sequences F8 and F9 were mainly deposited in the south and west (figure 3-19), which changed the distribution of available accommodation in this part of the basin. Accumulation of sediments in the west and south, and thereby loading of the crust, was not compensated by subsidence. That resulted in less accommodation space and a shift in the sediment depocenter towards the north as indicated by the isopach map of sequences F10 and F11 (figures 3-19; 3-25a and b). The sediment input changes from shaly in F8 and F9 to silty and fine-grained sand-rich sediments in F10 and F11. The fluctuation in sedimentation rates increases in the two upper sequences, but remains relatively high compared to the Carlile Formation (figures 3-25a and b).

The stratal pattern also changed from the high-angled stratal pattern of sequence F8 and F9 to generally low-angled in sequence F10 and F11 (figures 3-5 to 3-13). The increased occurrence of interbedded fine-grained sandstones and shale of sequence F10 and F11 enhances recognition of the stratal pattern, with terminations in the form of onlap, downlap and offlap. A total of thirteen isolated shaly marine sandstones are mapped in these two sequences, with some being extremely extensive, covering up to half of the study area (up to 3000 km^2).

Sequence F10 is dominated by relatively thick onlapping and transgressive sediments, which are thickest in the north and east of the depocenter of sequences F8 and F9. This area had more accommodation space than in the west and south where the transgressive systems tracts were thin due to lower accommodation space, slightly lower water-depth and sediment bypass. The onlapping transgressive systems tract of sequence F10 includes the stratigraphically oldest sandstone considered as the Medicine Hat sandstone. This sandstone is 4 m thick and onlaps the lower sequence boundary of sequence F10 (figures 3-7 and 3-11). The sandstone is mapped and named Medicine Hat-sandstone 1. It is elongated and oriented northeast-southwest (figure 3-21b), which would have been parallel to sub-parallel (Leckie and Krystinik, 1989) to the transgressive shoreline (see chapter IV). The thickened section of the transgressive systems tract in a depression of the previous sequence (F9) could indicate the area which was first flooded after the lowstand of sequence F9.

A highstand systems tract that prograded mainly from the west and southwest, overlies and downlaps the thick transgressive systems tract. The highstand systems tract contains five upwards-coarsening sandstones which have the character of parasequences

(see chapter IV: Van Wagoner et al.. 1990). Three of these sandstone bodies are mapped (Medicine Hat sandstones 3. 3a and 4: figures 3-21b and c). Three sandstones prograded from the west. and two from the east (figure 3-7). This could be explained by: 1) a bi-directional input of sediments from both the west/southwest and the east and/or 2) the influence of the Bow Island Arch. In the latter case. it is possible that the arch acted as a subtle submarine topographic high. which decreased accommodation space. and resulted in distribution of fine sandstone deposits on the flanks of the arch. but not on the crest. Following the prograding highstand. the first major sandstones (up to 11 m) of the Medicine Hat Member (Medicine Hat sandstone 4) were deposited as a lowstand systems tract in the east-central part of the study area. just west of the Saskatchewan/Alberta border (figure 3-21b). This was the first lowstand systems tract of the Niobrara sequence-set to be deposited in the study area and is one (lithostratigraphic sandstone Medicine Hat D-sandstone; Chapter II) of the three gas producing sandstones in the Medicine Hat Gas Field. The Medicine Hat 4 sandstone is the lower sandstone of a major lowstand wedge. and is overlain by the Medicine Hat 5 sandstone. This sandstone was deposited south and southwest of the Medicine Hat 4 sandstone. which is slightly landwards and shows the late lowstand stage when relative sea-level was slightly rising. The Medicine Hat 5 sandstone is overlain by a major flooding surface. which is the lower sequence boundary of sequence F11.

Sequence F11 contains the thickest and most extensive fine-grained sandstones (Medicine Hat sandstones 6. 6a. 7. 7a. 8 and 9: figures 3-21d. e and f). This sandy shelf was created during a sea-level cycle of relatively low accommodation space. which allowed the sand to migrate far out on the shelf (figures 3-25a and b). The systems tract

subdivision of the sequence is complex and illustrates how transgression was possible in one direction of the basin as progradation occurred simultaneously elsewhere in the basin.

The three lower sandstones of sequence F11 (Medicine Hat 6, 7 and 7a) are transgressive and onlap the lower sequence boundary of sequence F11 in a back-stepping pattern towards the northwest and southwest (figures 3-7 and 3-10). These fine-grained sandstones are sharp-based and relatively thin with a maximum thickness of 4 m (figures 3-20, 3-21d and 3-23). In the northwest, overlying a thick shaly transgressive interval, the northwest back-stepping pattern of sandstones 6 and 7 illustrates the rising relative sea-level and the increased accommodation space in this part of the basin (figure 3-7). However, in the south no back-stepping sandstones are observed in this interval. Instead, a thin shaly transgressive systems tract is overlain by the prograding and upwards-coarsening Medicine Hat 6a sandstone (figure 3-5). The thin transgressive shale in the south correlates to the thick shaly lower part of the transgressive system in northwestern direction. The differences occur in the upper part of the transgressive systems tract, where the isopachs and cross-sections (figure 3-5) indicate that the sandstone in the south (Medicine Hat sandstone 6a) was a northward prograding sandstone. This sandstone merges with the transgressive sandstone of Medicine Hat 6 and 7 in the east-central part of the study area (figures 3-21 d and e). Consequently, northwest transgression coincides with southern progradation.

Progradation of the Medicine Hat 6a sandstone from the south was extensive and covered all of southern Alberta with an area of 3000 km^2 indicating a major source of fine-grained sediments into the area. This sandstone is the first major sandstone of the highstand systems tract. This sandstone shows no influence of the Bow Island Arch on

sedimentation pattern (figure 3-21d), which is markedly different from the overlying sandstones of the Medicine Hat Member. Medicine Hat 6a sandstone is overlain by a thick upwards-coarsening sandstone body (Medicine Hat sandstone 8), which prograded northwards and northeastwards (figure 3-21e). This sandstone is the thickest sandstone (up to 12 m) of the Medicine Hat Member and is characterized by an upwards-coarsening fine-grained sandstone with a "high energy" layer at its base (see chapter IV). Overlying Medicine Hat sandstone 8 and deposited basinward of this sandstone, the lowstand sandstone (Medicine Hat sandstone 9) of sequence F11 is located in the eastern and central part of the study area (figure 3-21f). This sandstone is detached and up to 10 m thick. This lowstand sandstone is fine-grained, upwards-coarsening and prograded from the south and southwest, which is in contrast to the highstand Medicine Hat 8 sandstone which prograded from the west. The two latest and thickest sandstones (Medicine Hat sandstones 8 and 9) flank the western, northern and eastern part of the Bow Island Arch (figures 3-14 and 3-21f), which suggests the arch had some influence on the sediment distribution (see chapter IV).

During deposition of the youngest two sequences F12 and F13, available accommodation space was high and sedimentation rate was low (figures 3-25a and b). Sequence F12 is the lower of the two sequences in the First White Specks Member. The Medicine Hat sandstones 8 and 9 are overlain by a major flooding event that formed the sequence boundary to sequence F12, which is a part of the First White Specks Member (Chapter II). This flooding event was the most extensive of the Niobrara sea-level cycle and abruptly changed the lithology from the sand-rich sequences of F10 and F11 to a calcareous shale-dominated interval (figures 3-25a and b). The stratal pattern of sequence

F12 and F13 is extremely low-angled (< 0.002 degree). Furthermore, as facies contrasts are limited within the sequence and dominated by homogenous shale, the stratal pattern is subtle and difficult to interpret. The sedimentary facies and micropaleontological content of the First White Specks Member indicate that water-depth increased significantly and that the deposition of these shales took place in a distal offshore setting. This makes a sequence stratigraphic subdivision difficult. However, the lower thin (maximum 5 m) part of the sequence belongs to the transgressive systems tract. A subtle downlap of overlying prograding strata indicates a maximum flooding surface which tops the transgressive systems tract. The very low-angled prograding interval of shale is the highstand. No sandstones are observed in the highstand. Above the highstand systems tract a 4-6 m thick sandstone was deposited as the lowstand deposit. This sandstone is observed in the southeastern (figures 3-5 and 3-8) and northwestern regions (figures 3-7 and 3-9). The latter sandstone is mapped and formally named the Sweetgrass Member (Schröder-Adams et al., 1997). This lowstand sandstone was deposited landwards of the previous lowstand from sequence F11, which was deposited in the east-central part of the study area. This indicates a landwards shift of all systems tracts and their facies, and lowstand deposits of sequence F12 were deposited on top of lowstand deposits of the underlying sequences. A major regression in sequence F13 is signaled by the boundary to the overlying Milk River Formation, which marks the end of the transgressive part of the Niobrara cycle (Kauffman and Caldwell, 1993). The lower part of sequence F13 is the transgressive and early highstand deposits of the sequence.

Water depth in the Carlile and Niobrara Formations

Stratal patterns. sedimentary facies and micropaleontology indicates that the water-depth increased significantly during deposition of the Niobrara sequence-set compared to the Carlile sequence-set. During the initial stage of the Niobrara flooding, sedimentation could not keep up with increase of accommodation resulting in deeper water over the entire study area. This is indicated in the central part of the basin by a condensed section of dark grey shale with high TOC values up to 4.5 %. Planktic foraminifera and nannofossils confirming deeper water. Informally the lower part of the Niobrara sequence-set could be called the middle white specks zone (Chapter II).

CONCLUSIONS

The Carlile and Niobrara formations are subdivided into 13 third-order sequences in southern Alberta and southwestern Saskatchewan. The first major flooding surface is used as sequence boundary and is mainly recognized on resistivity wire-line logs using a new method of densely spaced logs (figures 3-5 to 3-13). The boundary is readily recognized sedimentologically, micropaleontologically and geochemically (figure 3-20).

The **Carlile Formation** consists of a sequence-set of seven sequences (F1 to F7), which is characterized on a stratal pattern of parallel to sub-parallel sequence boundaries. The internal stratal patterns of these sequences are shingled with very low-angle dipping strata. The lower five sequences (F1 to F5) are dominated by eastward dipping marker-beds and parasequences, whereas the upper two sequences (F6 and F7) have bi-directional dipping strata. In the lower sequences (F1 to F5) the sediment-input was mainly from the west. In the upper two sequences the dip is both from the west and east

and indicates a narrowing of the Interior Seaway with sediment-input from both the eastern and western margin (figures 3-5 to 3-12). The relative sea-level was lowered during the deposition of the Carlile sequence-set, which represents the regressive part of the Greenhorn Cycle (Kauffman and Caldwell, 1993). The seven sequences are subdivided into transgressive, highstand and lowstand systems tracts. The transgressive systems tracts are generally thin (< 5 m) and wedge-shaped thinning to the east. The highstand systems tracts prograde towards the center of the basin and are thickest in the western region, where the Carlile Formation interfingers with the distal part of the Cardium Formation. Therefore, it is interpreted that most of the Cardium sandstones in southern Alberta Foothills were deposited during a prograding highstand period. Overlying the highstand system tract are thin shaly and fine-grained sandstones deposited in the central and eastern part of the region.

The boundary between the Carlile and Niobrara sequence-sets is a regional unconformity, that is recognized throughout the entire study area. On the densely spaced resistivity logs (figures 3-5 to 3-13) the boundary is observed as an angular unconformity, with erosion of up to 20 m in the south and east of the region. One core intersects this boundary (figure 3-17) and shows the boundary to the sharp contact between lithic sandstones overlain by a dark grey shale with a major swarm of bentonite layers. Micropaleontologically the boundary is also distinct and marks the boundary between the *Pseudoclavulina* sp. Zone and *Trochammina* sp; *Bullopora laevis* Zone (Chapter II).

The **Niobrara Formation** consists of a sequence-set of six sequences (F8 to F13) and has a complex stratal pattern with a general upwards-decrease in dip of strata. Each

of the three members (Verger, Medicine Hat and First White Specks) of the Niobrara Formation consists of two sequences.

The lower two sequences (F8 and F9) consist of thick shale deposits with relatively high-angled giant clinoforms (100's km long) in a sigmoid and tangential sigmoid forms. The height of the clinoforms are up to 50 m. The dip is towards the northeast and east and indicates a general sediment input from the south and southwest forming a 45 degree rotation of sediment input direction compared to the underlying Carlile sequence-set. The transgressive and back-stepping systems tract of each of the two sequences is overlain by these high-angled clinoforms, that belong to the highstand system tracts. Some of these clinoforms were either truncated or off-laps from the upper sequence-boundaries and were probably deposited during falling relative sea-level and would be candidates for the newly defined falling stage systems tract (Plint and Nummedal, 2000). However, in this study these deposits are classified as late highstand deposits. Correlations to west-central Alberta show that sandstones of the Bad Heart Formation are most likely the lowstand systems tract to sequence F8 and F9 (figure 3-13). This is supported by the presence of a transgressive ravinement surface with chert pebbles at the upper sequence boundaries. Sequence F8 is the first sequence deposited in the transgressive part of the second order Niobrara Cycle (Kauffman and Caldwell, 1993).

The stratal patterns and sediments of sequences F10 and F11 are significantly different from the underlying sequences F8 and F9. The strata dip-angle is lower and all three systems tracts are found within the study area. Stratal dip is mainly from the west, northwest and south. The increased occurrence of interbedded fine-grained sandstones and shale of sequences F10 and F11 enhance recognition of the stratal pattern.

terminations in the form of onlap, downlap and offlap. Numerous (13) isolated shaly marine sandstones are mapped in these two sequences, with some being extensive covering up to half of the study area (up to 3000 km^2; figure 3-21). Sequence F11 shows an example of complex sequence stratigraphy in a large region, which experienced different levels and timing of the relative sea-level change. While the stratal pattern indicates transgression in the northwest region, time-equivalent strata show progradation in the southeastern region. This is possible due to differential changes in tectonic activity of the rising Cordillera Mountains to the west. The two latest and thickest sandstones (Medicine Hat sandstones 8 and 9) flank the western, northern and eastern part of the Bow Island Arch (figures 3-14 and 3-21f), which suggest the arch had some influence on the sediment distribution (see chapter IV). These two sandstones were deposited during the lowest relative sea-level of the Medicine Hat Member. The other sandstones of the Medicine Hat Member were partly or entirely deposited on the arch. This indicates that the Bow Island arch only had an effect on the sedimentation during low relative sea-level. During deposition of most of the Medicine Hat sandstones and all the interbedded shaly intervals of the Verger and Medicine Hat members, the arch had no effect. The differential availability of accommodation space across the Arch was only significant during low sea-level.

Sequences F12 and F13 are characterized by a subtle stratal pattern of eastwards directed very low-angled strata. The lithology consists of dark gray shale with thin bentonites and an abundance of shell fragments. The sequences are dominated by transgressive and highstand systems tracts. The Sweetgrass Member in the northwestern part of the region is the only lowstand system tract mapped in the region (Schröder-

Adams et al. 1997). This lowstand deposit is located west (landwards) of all previous lowstand deposits (F1 to F12) and indicates a significant rise in sea-level. However, micropaleontology indicates that the water-depth probably never got as deep as in the Second White Specks Formation (Schröder-Adams et al., 1996; see chapter IV).

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REFERENCES

Amajor, L.C. and Lerbekmo, J.R., 1980. Subsurface correlation of bentonite beds in the Lower Cretaceous Viking Formation of south-central Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 28, no. 2, p. 149-172.

Armentrout, J.M., 1996. High resolution sequence biostratigraphy: examples from the Gulf of Mexico Plio-Pleistocene. *In:* High Resolution Sequence Stratigraphy: Innovations and Applications (eds. Howell, J.A. and Aitken J.F.). The Geological Society of London, Special Publication no. 104, p. 65-86.

Arnott, R.W.C., Hein, F.J. and Pemberton, S.G., 1995. Influence of the ancestral Sweetgrass Arch on sedimentation of the Lower Cretaceous Bootlegger Member, north-central Montana. *Journal of Sedimentary Research*, vol. B65, no. 2, p. 222-234.

Bergman, K.M. and Walker, R.G., 1987. The importance of sea-level fluctuations in the formation of linear conglomerate bodies; Carrot Creek Member of Cardium Formation, Cretaceous Western Interior Seaway, Alberta, Canada. *Journal of Sedimentary Petrology*, vol. 57, p. 651-665.

Beaumont, C., 1981. Foreland basins. *Royal Astronomical Society Geophysical Journal*, vol. 65, p. 291-329.

Bhatacharya, J.P., 1993. The expression and interpretation of marine flooding surfaces and erosional surfaces in core; examples from the Upper Cretaceous Dunvegan Formation, Alberta foreland basin, Canada. *In:* Sequence Stratigraphy and Facies

Associations (eds. Posamentier, H.W., Summerhayes, C.P., Haq, B.U. and Allen G.P.). Blackwell Scientific Publications, Special Publication no. 18, p. 125-160.

Bhatacharya, J.P., 1989. Allostratigrahy and river and wave-dominated depositional systems of the Upper Cretaceous (Cenomanian) Dunvegan Formation, Alberta. Ph.D. thesis, McMaster University, Hamilton, Ontario, pp. 588.

Bloch, J., Schröder-Adams C., Leckie, D.A., McIntyre, D.J., Craig, J. and Staniland, M., 1993. Revised stratigraphy of the lower Colorado Group (Albian to Turonian), Western Canada. *Bulletin of Canadian Petroleum Geology*, vol. 41, no. 3, p. 325-348.

Boltovskoy, E. and Wright R., 1976. Recent Foraminifera. The Hague, W. Junk p. 95-160.

Boreen, T. and Walker, G.R., 1991. Definition of allomembers and their facies assemblages in the Viking Formation, Willesden Green area, Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 39, no. 2, p. 123-144.

Brennan-Alpert, P., 1998. A reference section for the Cretaceous hydrocarbon-bearing Second White Specks Formation at Highwood River, Southern Alberta Foothills. Unpublished Honors Thesis, Carleton University, pp. 44.

Cadrin, A.A.J., Kyser, T.K., Caldwell, W.G.E. and Longstaffe, F.J., 1995. Isotopic and chemical compositions of bentonites as paleoenvironmental indicators of the Cretaceous Western Interior Seaway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, no.119, Elsevier, p. 301-320.

Caldwell, W.G.E., North B.R., Stelck, C.R. and Wall, J.H., 1978. A foraminiferal zonal scheme for the Cretaceous System in the Interior Plains of Canada. *In:* Western

and Arctic Canadian Biostratigraphy (eds. Stelck, C.R. and Chatterton, B.D.E.). Geological Association of Canada. Special Paper no. 18, p. 495-575.

Cobban, W.A., Erdmann, C.E., Lemke, R.W. and Maughan, E.K., 1976. Type sections and stratigraphy of the Blackleaf and Marias River formations (Cretaceous) of the Sweetgrass Arch, Montana. United States Geological Survey, Professional Paper no. 974, p. 36-60.

Dean, W.E. and Arhur, M.A., 1998. Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA. SEPM Concepts in Sedimentology and Paleontology No. 6., SEPM, pp. 255.

DeCaritat, P., Bloch, J.D., Hlutcheon, I.E. and Longstaffe, R.J., 1994. Compositional trends of a Cretaceous Foreland Basin shale (Belle Fourche Formation, Western Canada Sedimentary Basin: diagenetic and depositional controls. *Clay minerals*, V. 24, p. 503-526.

Donaldson, W.S., Plint, A.G. and Longstaffe, F.J., 1998. Basement tectonic control on the distribution of the shallow marine Bad Heart Formation: Peace River Arch area, NW Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 46, p. 576-598.

Donaldson, W.S., Plint, A.G. and Longstaffe, F.J., 1999. Tectonic and eustatic control on deposition and preservation of Cretaceous ooidal ironstone and associated facies: Peace River Arch area, NW Alberta, Canada. *Sedimentology*, vol. 46, p. 1159-1182.

Eicher, D.L., 1969. Paleobathymetry of Cretaceous Greenhorn Sea in Eastern Colorado. *American Association of Petroleum Geologist Bulletin*, vol. 53, no. 5, p. 1075-1090.

Embry, F.E., 1995. Sequence boundaries and sequence hierarchies: problems and proposals. *In:* Sequence stratigraphy: Advances and Applications for Exploration and Producing in Northwest Europe (eds. Steel, R.J., Felt, V.L., Johannessen, E.P. and Mathieu, C.). Norwegian Petroleum Society (NPF), Special Publication 5, Elsevier, p. 1-11.

Eslinger, E. and Pevear, D., 1988. Clay Minerals. Society of Economic Paleontologists and Mineralogists. Short course notes no. 22, chapter 3, p. 3-1 to 3-20.

Galloway, W. E., 1989: Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units. *American Association of Petroleum Geologists Bulletin,* vol. 73, no. 2, p. 125-142.

Gilboy, C.F., 1989. Geology and Natural Gas Production of the Upper Cretaceous Medicine Hat Sandstone, Southwestern Saskatchewan. *Summary of Investigations 1989*, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report no. 89-4.

Gilboy, C.F., 1996. Detailed log-based stratigraphic study of Colorado Group and Milk River Formation Strata (Cretaceous), Southwestern Saskatchewan; *In: Summary of Investigations 1996*, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report no. 96-4.

Glass, D.E., 1981. Subsurface correlation of bentonite beds in the Lower Cretaceous Viking Formation of south-central Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 29, no. 3, p. 426-429.

Glass, D.J., 1990. Lexicon of Canadian Stratigraphy, Volume 4, Western Canada, including eastern British Columbia, Alberta, Saskatchewan and Southern Manitoba. Canadian Society of Petroleum Geologists, pp. 772.

Hankel, R. C., Davies G. R. and Krouse H. R., 1989. Eastern Medicine Hat gas field: a shallow, Upper Cretaceous, bacteriogenic gas reservoir of southeastern Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 37, no. 1, p. 98-112.

Haq, B. U., Hardenbol, J. and Vail, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. *In:* Sea-level Changes: an Integrated Approach (eds. Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Roos, C. A. and Van Wagoner, J. C.). Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, p. 71-108.

Jervey, M.T., 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expresssion. *In*: Sea-level Changes: an Integrated Approach (eds. Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Roos, C. A. and Van Wagoner, J. C.). Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, p. 47-70.

Kaufmann, E.G., 1967. Coloradan macroinvertebrate assemblages, central Western Interior. *In:* Paleoenvironments of the Cretaceous Seaway in the Western Interior. Colorado School of Mines, Golden, CO, p. 67-143.

Kauffman, E.G. and Caldwell, W.G.E., 1993. The Western Interior Basin in space and time. *In:* Evolution of the Western Interior Basin (eds. Caldwell, W.G.E. and Kauffman, E.G.). Geological Association of Canada, Special Paper no. 39, p. 1-30.

King, C., 1983. Cainozonic micropaleontological biostratigraphy of the North Sea. *Rep. Inst. Geol. Sci.* No. 82/7,p. 1-40, 6 pl.

King, C., 1989. Cenozoic of the North Sea. *In*: Stratigraphical Atlas of Fossil Foraminifera (eds. Jenkins, D. G. and Murray, J.W.). Second edition. Ellis Horwood Lrd., Chichester, p. 418-489.

Leckie, D.A., Bhattacharya, J.P., Bloch, J., Gilboy, C.F., Norris, B., 1994. Cretaceous Colorado/Alberta Group of the Western Canada Sedimentary Basin. *In:* Geological atlas of the Western Canada Sedimentary Basin (compiled by Mossop, G. and Shetson, I.). Canadian Society of Petroleum Geologists and the Alberta Research Council, pp. 510.

Leckie, D.A. and Krystinik, L.F., 1989. Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle shelf deposits? *Journal of Sedimentary Petrology*, vol. 59, p. 862-870.

Leckie, R.M., 1989. A paleoceanographic model for the early evolutionary history of planktonic foraminifera. *Palaeogeography, Palaeoclimatology, palaeoecology*, vol. 73, p. 107-138.

Lerbekmo, J.F., 1968. Chemical and modal analyses of some Upper Cretaceous and Paleocene bentonites from western Alberta. *Canadian Journal of Earth Sciences*, vol. 5, p. 1505-1511.

Lorenz, J.C., 1982. Lithospheric flexure and the history of the Sweetgrass Arch northeastern Montana. *Rocky Mountain Association of Geologists* - 1982 symposium, p. 77-89.

Lorenz. J.C. and Gavin. W., 1984. Geology of the Two Medicine Formation and the Sedimentology of the dinosaur nesting ground. Montana Geological Society - 1984 Field Conference - northwestern Montana, p. 175-186.

Loutit. T.S., Hardenbol. J., Vail, P.R. and Baum, G.R., 1988. Condensed sections: the key to age dating and correlation of continental margin sequences. *In*: Sea-level Changes: an Integrated Approach (ed. Wilgus. C.K., Hastings. B.S., Kendall, C.G.St.C., Posamentier, H.W., Roos, C.A. and Van Wagoner, J.C.). Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, p. 183-216.

Ludvigson. G.A., Witzke. B.J., Gonzalez, L.A., Hammond, R.H. and Plocher, O.W., 1994. Sedimentology and carbonate geochemistry of concretions from the Greenhorn marine cycle (Cenomanian - Turonian), eastern margin of the Western Interior Seaway. *In*: Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin (eds. Shurr, G.W., Ludvigson, G.I. and Hammond R.H.). The Geological Society of America, Special Paper no. 287, p. 145-174.

Martinson. V.S., Heller, P.L. and Frerichs, W.E., 1998. Distinguishing middle Late Cretaceous tectonic events from regional sea-level change using foraminiferal data from the U.S. Western Interior. *GSA Bulletin*, v. 110: no. 2, p. 259-268.

McNeil. D.H. and Caldwell. W.G.E., 1981. Cretaceous rocks and their foraminifera in the Manitoba Escarpment. *Geological Association of Canada*, Special Paper no. 21, pp. 439.

Merriam. R. and Bischoff J.L., 1975. Bishop Ash: a widespread volcanic ash extended to southern California. *Journal of Sedimentary Petrology*, vol. 45, no. 1, p. 207-211.

Mitchum, R.M. and Van Wagoner J.C., 1991. High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles. *Sedimentary Geology*, vol. 70, p. 131 -160

Mitchum, R.M., Vail, P.R. and Thompson III, S., 1977. Part 2: The Depositional sequence as a basic unit for stratigraphic analysis. *In*: Seismic stratigraphy - Applications to Hydrocarbon Exploration (ed. Payton, C. E.). *American Association of Petroleum Geologists*, Memoir no. 26, Tulsa, Oklahoma.

Meijer-Drees, N.C. and Myhr, D.W., 1981. The Upper Cretaceous Milk River and Lea Park formations in southeastern Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 29, p. 42-74.

NACSN (North American Commission on Stratigraphic Nomenclature), 1983. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, vol. 67, p. 841-875.

North, B.R. and Caldwell, W.G.E., 1975. Illustrations of Canadian fossils. Cretaceous foraminifera from Saskatchewan and Manitoba: *Geological Survey of Canada*, Paper 74-38, pp. 35.

Nystuen, J.P., 1998. History and development of sequence stratigraphy. *In:* Sequence stratigraphy - concepts and applications (eds Gradstein, K.O. and Milton, N. J.). *Norwegian Petroleum Society (NPF)*, Special Publication 8, Elsevier Science, Amsterdam. p. 31-116.

Payenberg, T.H.D., 2002. Litho-, Chrono- and allostratigraphy of the Santonian to Campanian Milk River and Eagle formations in southern Alberta and north-central

Montana: Implications for differential subsidence in the Western Interior Foreland Basin. Unpublished Ph.D. Thesis, University of Toronto, Canada. pp. 221.

Plint, A.G., 1990. An allostratigraphic correlation of the Muskiki and Marshybank formations (Coniacian-Santonian) in the Foothills and subsurface of the Alberta Basin. *Bulletin of Canadian Petroleum Geology,* vol. 38, no. 3, p. 288-306.

Plint, A.G and Norris, B., 1991. Anatomy of a ramp margin sequence: facies successions, paleogeography and sediment dispersal patterns in the Muskiki and Marshybank formations, Alberta Foreland Basin. *Bulletin of Canadian Petroleum Geology*, vol. 39, p. 18-42.

Plint, A.G., 1991. High-frequency relative sea-level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? *International Association of Sedimentologists*, spec. publ. 12, p.409-428.

Plint, A.G. and Nummedal, D., 2000. The falling stage systems tract: Recognition and importance in sequence stratigraphic analysis. *In*: Sedimentary responses to forced regressions, (eds. Hunt, D. and Gawthorpe, R.L.G.). *Geological Society of London*, Special Publication no. 172, p. 1-17.

Plint, A.G., McCarthy, P.J. and Faccini, U.F., 2001. Nonmarine sequence stratigraphy: updip expression of sequence boundaries and systems tracts in a high-resolution framework, Cenomanian Dunvegan Formation, Alberta foreland basin, Canada. *American Association of Petroleum Geologists Bulletin*, vol. 85, p. 1967-2001.

Podruski, J.A., 1988. Contrasting character of the Peace River and Sweetgrass arches, Western Canada Sedimentary Basin. *Geoscience Canada*, vol. 15, p. 94-97.

Posamentier, H.W., and Allen, G.P., 1999. Siliciclastic sequence stratigraphy: concepts and applications: *Society of Economic Paleontologists and Mineralogists*, Concepts in Sedimentology and Paleontology, vol. 9, p. 210.

Posamentier, H.W. and Vail, P.R., 1988. Eustatic controls of clastic deposition II. In: *Sea-Level Changes: An Integrated Approach* (eds. Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Roos, C. A. and Van Wagoner, J. C.). *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 42, p. 125-154.

Posamentier, H.W., 2001. Lowstand alluvial bypass systems: Incised vs. unincised. *American Association of Petroleum Geologists Bulletin*, vol. 85, p. 1771-1793.

Rey, J., Cubaynes, R., Qajoun, A. and Ruget, C., 1993. Foraminifera indicators of systems tracts and global unconformities. *In:* Sequence stratigraphy and facies associations (eds. Posamentier, H.W., Summerhayes, C.P., Haq, B.U. and Allen G.P.). *Blackwell Scientific Publications*, Special Publication no. 18, p. 109-124.

Rider, M. H., 1986. The Geological Interpretation of Well Logs. Blackie, Halsted Press New York. Pp. 172.

Schoch, R. M., 1989. Stratigraphy: principles and methods. Van Nostrand Reinhold, New York. pp. 278.

Schröder-Adams, C.J., Leckie, D.A., Bloch, Craig, J., McIntyre, D.J., and Adams, P.J., 1996. Paleoenvironmental changes in the Cretaceous (Albian to Turonian) Colorado Group of western Canada: microfossil, sedimentological and geochemical evidence. *Cretaceous Research*, vol. 17, p. 311-365.

Schröder-Adams, C.J., Adams, P.J., Leckie, D.A., Bloch, J., Craig, J., El-Dein, S.A.S., 1997. Upper Cretaceous Medicine Hat Formation and First White Speckled Shale in southeastern Alberta: evidence for localized shallow water deposition. *Bulletin of Canadian Petroleum Geology*, vol. 45, p. 356-376.

Schröder-Adams, C.J., Adams, P., Haggart, J., Leckie, D.A., Bloch, J., Craig, J., McIntyre, D.J., 1998. An integrated paleontological approach to reservoir problems: Upper Cretaceous Medicine Hat Formation and First White Speckled Shale in southern Alberta, Canada. *Palaios*, Vol. 13, p. 361-375.

Schröder-Adams C.J., Cumbaa, S.L., Bloch, J., Leckie, D.A., Craig, J., Seif El-Dein, S.A., Simons, D. H.A.E. and Kenig, F. 2001. Late Cretaceous (Cenomanian to Campanian) paleoenvironmental history of the Eastern Canadian margin of the Western Interior Seaway: bonebeds and anoxic events. *Palaeogeography, Palaeoclimatology, Palaeoecology* V. 170, p. 261-289.

Shurr, G.W. and Reskind, J., 1984. Stratigraphic framework of the Niobrara Formation (Upper Cretaceous), Montana and South Dakota. *In:* Mesozoic of middle North America (eds. Stott, D.F. and Glass, D.J.). *Canadian Society of Petroleum Geologists Memoir*, vol. 9, p. 205-219.

Shurr, G.W. and Rice, D.D., 1986. Paleotectonic controls on deposition of the Niobrara Formation, Eagle Sandstone, and equivalent rocks (Upper Cretaceous), Montana and South Dakota. *In*: Paleotectonics and sedimentation in the Rocky Mountain region (ed. Peterson, J.A.). *American Association of Petroleum Geologists Memoir*, vol. 41, p. 193-211.

Shurr, G.W., Ludvigson, G.A. and Hammond, R.H. 1994. Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin. Special Paper 287. The Geological Society of America. pp. 264.

Stott, D.F., 1962. Upper Cretaceous marine rocks of Rocky Mountain Foothills. *Alberta Society of Petroleum Geologists Journal*, vol. 10, no. 5, p. 228-240.

Uchman, A., 1999. Ichnology of the Rhenodanubian Flysch (Lower Cretaceous-Eocene) in Austria and Germany. *Beringeria* 25: 67-173.

Van Wagoner, J. C., Mitchum, R., Campion, K., and Rahmanian, V. D., 1990. Silciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. *American Association of Petroleum Geologist., Methods in Exploration Series*, vol. 7, Tulsa, Oklahoma, pp. 55.

Van Wagoner, J.C., Posamentier, H.W., Vail, P.R., Sarg, J.F. and Loutit, T.S., 1988. An overview of the fundamentals sequence stratigraphy and key definitions. *In*: Sea-Level Changes: An Integrated Approach (eds. Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Roos, C. A. and Van Wagoner, J. C.). *Society of Economic Paleontologists and Mineralogists*, Special Publication no. 42, p. 39-46.

Wall, J.H., 1967a. Paleoecology of Cretaceous marine microfaunas in the Rocky Mountain Foothills of Alberta and British Columbia. *In*: Paleoenvironments of the Cretaceous Seaway in the Western Interior. Colorado School of Mines, Golden, Colorado, p. 173-194.

Wall, J.H., 1967b. Cretaceous Foraminifera of the Rocky Mountain Foothills, Alberta. *Research Council Alberta*, Bulletin 20, p. 185.

Whitney, G. and Ahlbrandt, T.S., 1996. Effects of clays on resistivities of clastic rocks and reservoir performance. *In:* Hydrocarbon production from low contrast, low resistivity reservoirs Rocky Mountain and Mid-Continent regions log examples of subtle pays (eds. Dolly, E.D. and Mullarkey, J.C.). *Rocky Mountain Association of Geologists*, Denver. p. 43-52.

Wolf, K.H., 1959. Bentonite. *Journal of the Alberta Society of Petroleum Geologists*, vol. 7, No. 1, p. 13-15.

Wright, M.E. and Walker, R.G., 1981. Cardium Formation (U. Cretaceous) at Seebee, Alberta – storm transported sandstones and conglomerates in shallow marine depositional environments below fairweather wave base. Canadian Journal of Earth Sciences, vol. 18, p. 795-809.

Yen, F.S. and Goodwin, J.H., 1976. Correlation of tuff layers in the Green River Formation, Utah using Biotite compositions. *Journal of Sedimentary Petrology*, vol. 46, no. 2, p. 345-354.

Figure 3-1. Stratigraphic chart of the Upper Colorado Group in southern Alberta, southwest Saskatchewan and northern U.S.A

PERIOD	STAGE / AGE (Ma)	Wall and Rosene (1977) ALBERTA SOUTHERN FOOTHILLS	Chapter II ALBERTA SOUTHERN PLAINS & SOUTH-WESTERN SASK.	McNeil and Caldwell (1981) SOUTHERN MANITOBA	McGookey et al. (1972) REFERENCE SECTION WESTERN INTERIOR US	Kauffman (1976) SEDIMENTARY CYCLES	
LATE CRETACEOUS	CAMPANIAN 84	BELLY RIVER FORMATION	NOT STUDIED	PIERRE FORMATION	PIERRE FORMATION	REGRESSION	NIOBRARA MARINE CYCLE
		TRANSITION	MILK RIVER FORMATION		EAGLE FORMATION		
					Telegraph Creek Fm		
	SANTONIAN 87	ALBERTA GROUP; WAPIABI FM.: HANSON, THISTLE, DOWLING, MARSHYBANK	NIOBRARA FORMATION: FIRST WHITE SPECKS MBR	NIOBRARA FORMATION	NIOBRARA FORMATION	TRANSGRESSION	
	CONIACIAN 89	MUSKIKI	MEDICINE HAT MEMBER; VERGER MEMBER; BENTONITE MARKER				
	TURONIAN	CARDIUM FORMATION	CARLILE FORMATION	MORDEN SHALE	CARLILE SHALE	REGRESSION	GREENHORN MARINE CYCLE
		BLACKSTONE FM: OPABIN, HAVEN, VIMY	SECOND WHITE SPECKS FORMTION	FAVEL FORMATION	GREEN HORN FORMATION	TRANS GRESSION	

Figure 3-1

Figure 3-2. Study area showing well control, outcrops and wire-line cross-sections.

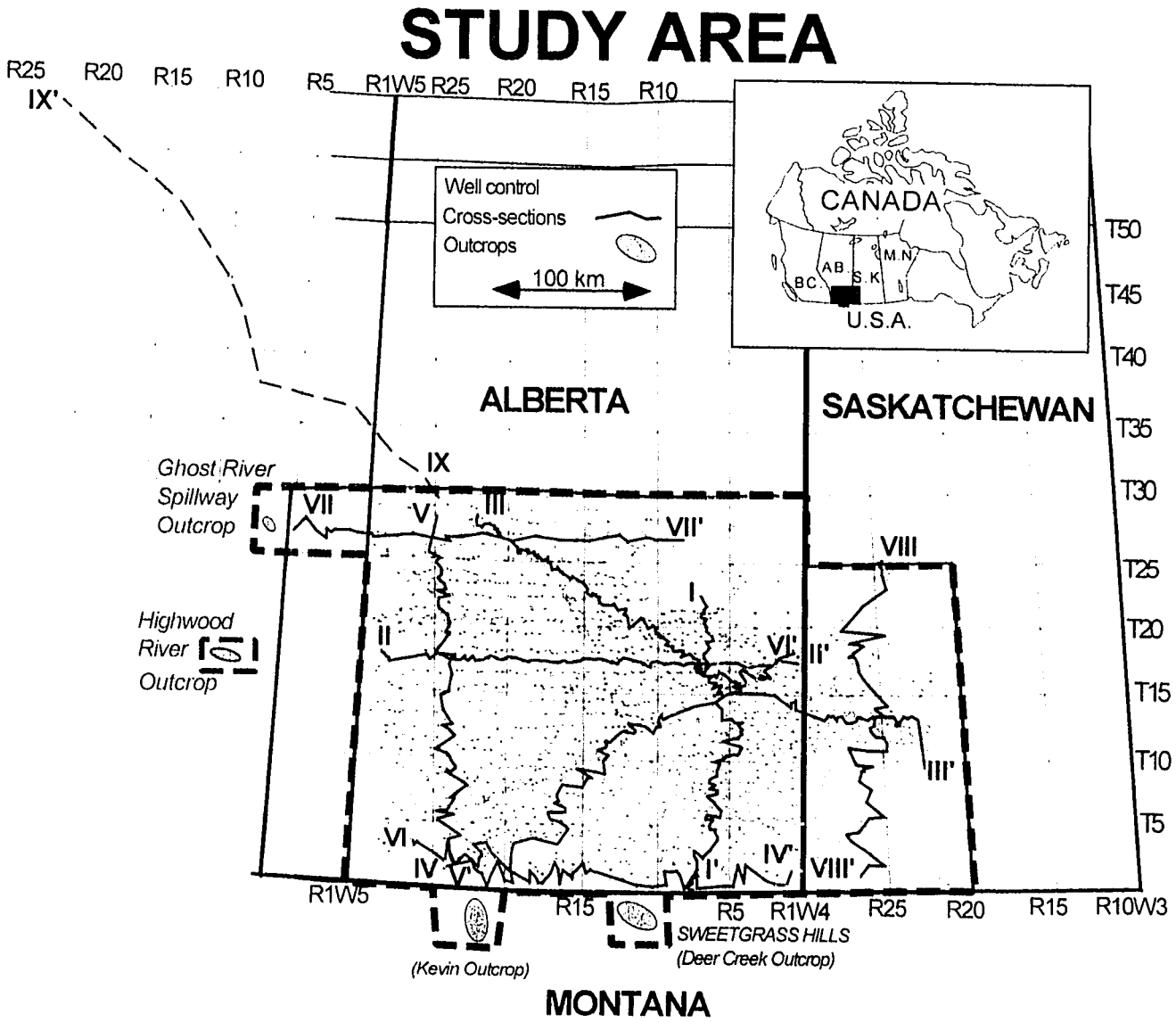
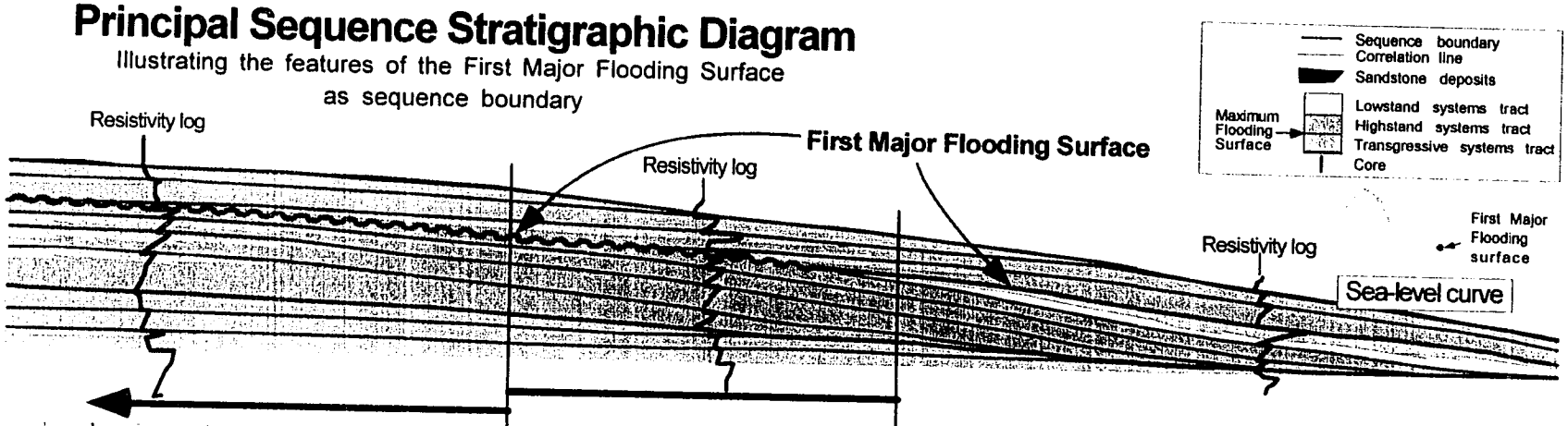

STUDY AREA
R25
R20
R15
R10
R5
R1W5
R25
R20
R15
R10
IX'
Well control
Cross-sections
Outcrops
100 km
CANADA
BC
AB
S.K
M.N
U.S.A.
ALBERTA
SASKATCHEWAN
T50
T45
T40
T35
T30
T25
T20
T15
T10
T5
Ghost River
Spillway
Outcrop
Highwood
River
Outcrop
IX
VII
V
III
VII'
VIII
I
II
VI'
II'
III'
VI
IV
I'
IV'
VIII'
R1W5
R15
R5
R1W4
R25
R20
R15
R10W3
(Kevin Outcrop)
SWEETGRASS HILLS
(Deer Creek Outcrop)
MONTANA

Figure 3-2

Figure 3-3. Principal diagram illustrating and explaining how to recognize the First Major Sequence Boundary, which is used as sequence boundary in this study. The changes across the boundary are explained sedimentologically, geochemically and paleontologically. Typical wire-line log patterns from the resistivity tool are illustrated on the diagram at three different locations along a dip-section.

Principal Sequence Stratigraphic Diagram

Illustrating the features of the First Major Flooding Surface as sequence boundary

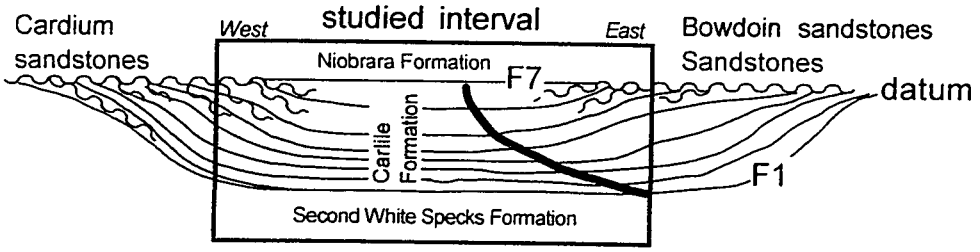


First Major Flooding Surface	Composite Erosional Surface	Erosional Transgressive Flooding Surface	First Major Flooding Surface
Expression of	Composite regressive and transgressive erosional and revinement surface. **SB / FS**	Transgressive ravinement surface. **FS**	Distal marine flooding surface. Starved sand sedimentation. Dominated by suspension sedimentation **FS**
Characterized by: Sedimentological and surface relations	Common pebble layer. Glauconite Significant erosion	Possible pebble layer on contact surface Enriched in Glauconite Onlap of backstepping parasequences	Only significant surface Top of upward coaseming intervals Low relief of boundary Parallel to sub-parallel sequence boundaries
Geochemistry (Rock-Eval Analysis)	Marked increase in TOC above the boundary Change from terrestial (type III) to marine (type II) organic matter.	Marked increase in TOC about the boundary Change from terrestial (type III) to marine (type II) organic matter.	Increase in TOC above the boundary Change from terrestial (type III) to marine (type II) organic matter.
Micro-paleontology	Change from a agglutinated benthic dominatly assemblage below the boundary to a calcareous benthic and planktic assemblage above.	Change from a agglutinated and calcareous benthic dominatly assemblage below the boundary to a calcareous benthic and planktic assemblage above.	Change from dominantly agglutinated assamblage below the boundary to a calcareous benthic and planktic assemblage above.

Figure 3-3

Figure 3-4. Schematic representation of the stratal pattern of the Carlile sequence-set from sequence F1 to F7. The shift of the basin axis is also illustrated, see text for detailed explanation.

Schematic representation of the stratal pattern of the sequence-set of the Carlile Formation



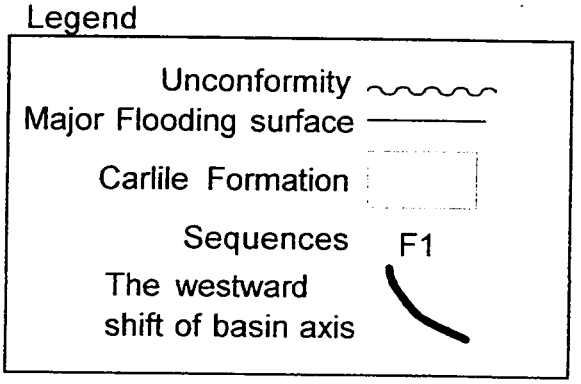
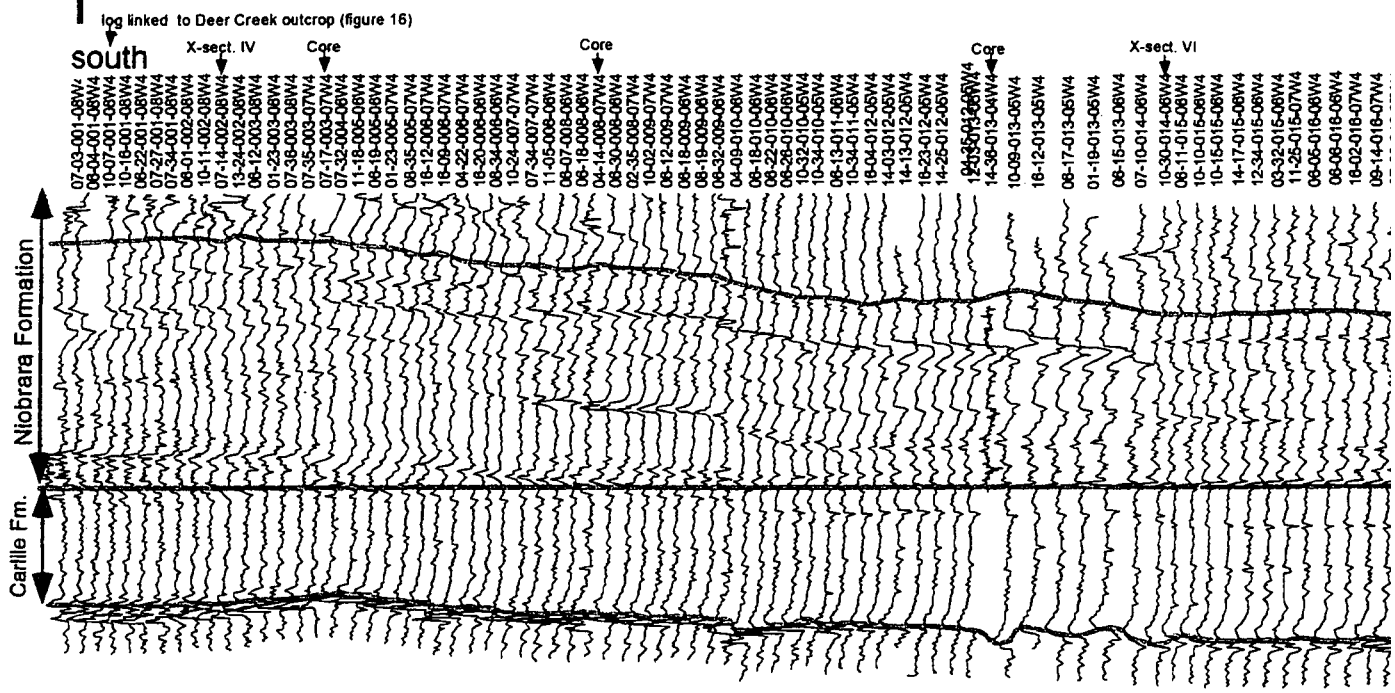


Figure 3-4

Figure 3-5. Cross-section I: A north-south resistivity wire-line cross-section in the east-central region. For location of cross-section see figure 3-2.

Cross-section I



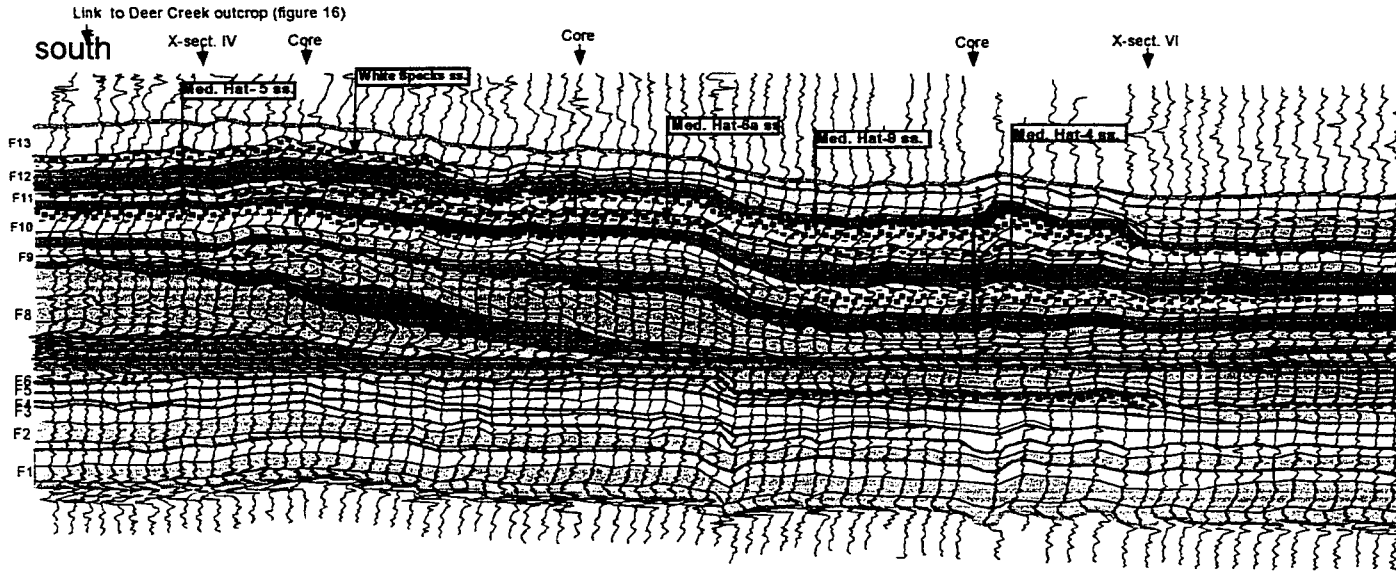
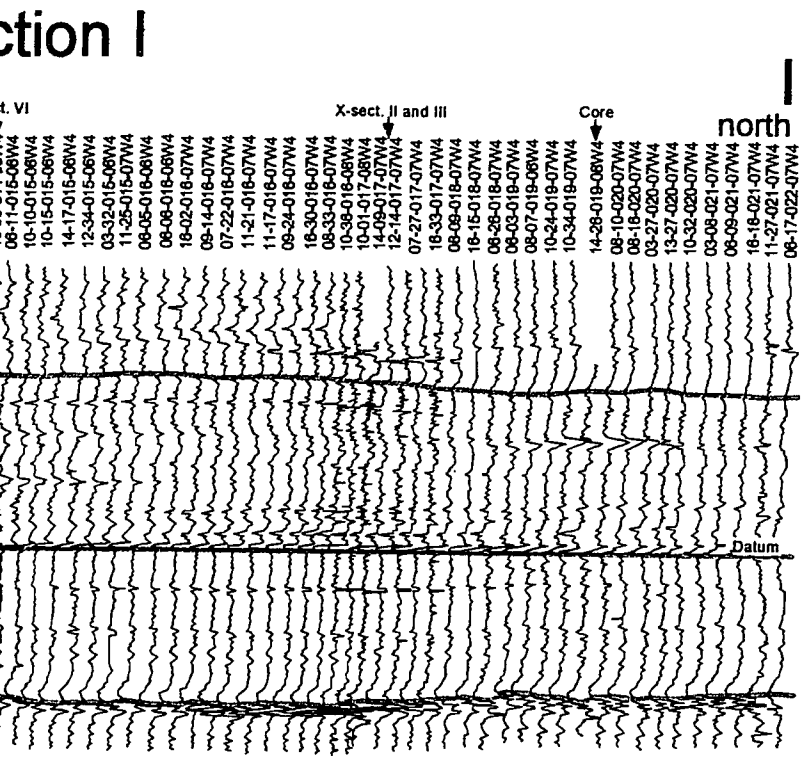
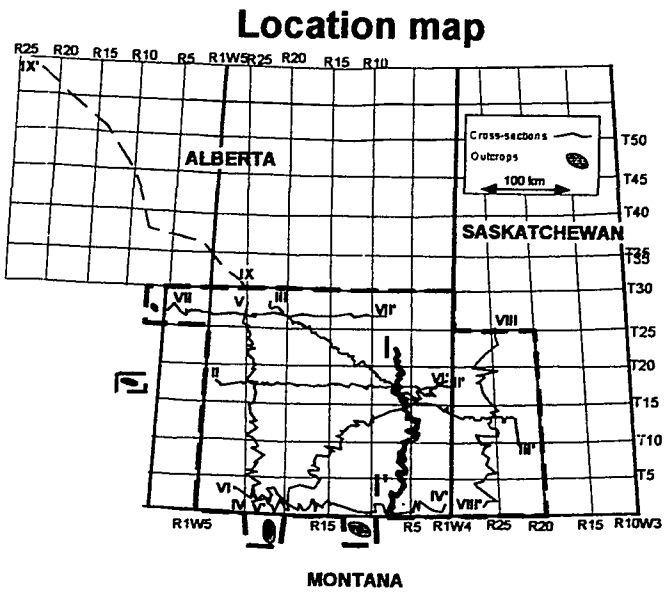
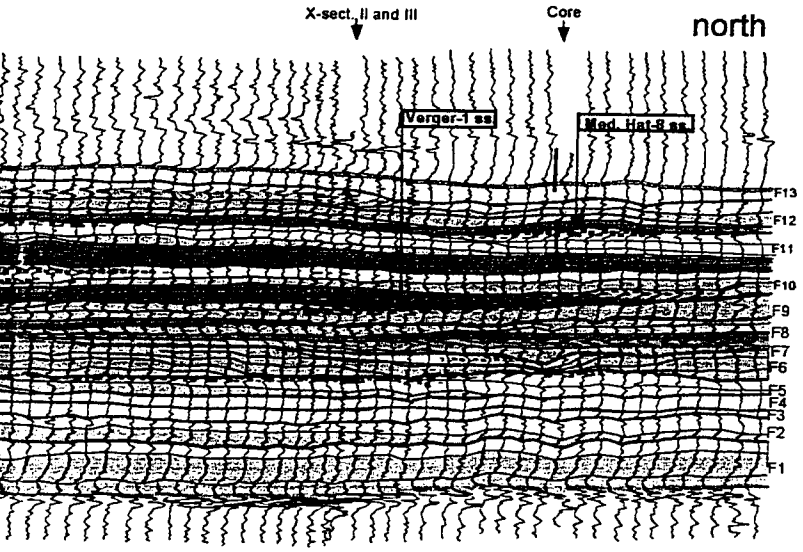


Figure 3-5

197







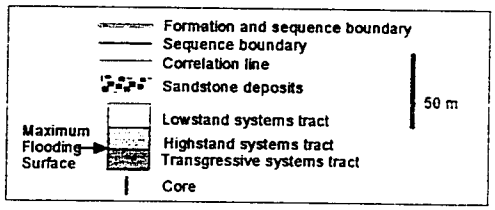


Figure 3-5

Figure 3-6. Cross-section II: An east-west resistivity wire-line cross-section in the central region. For location of cross-section see figure 3-2. Legend on figure 3-5.

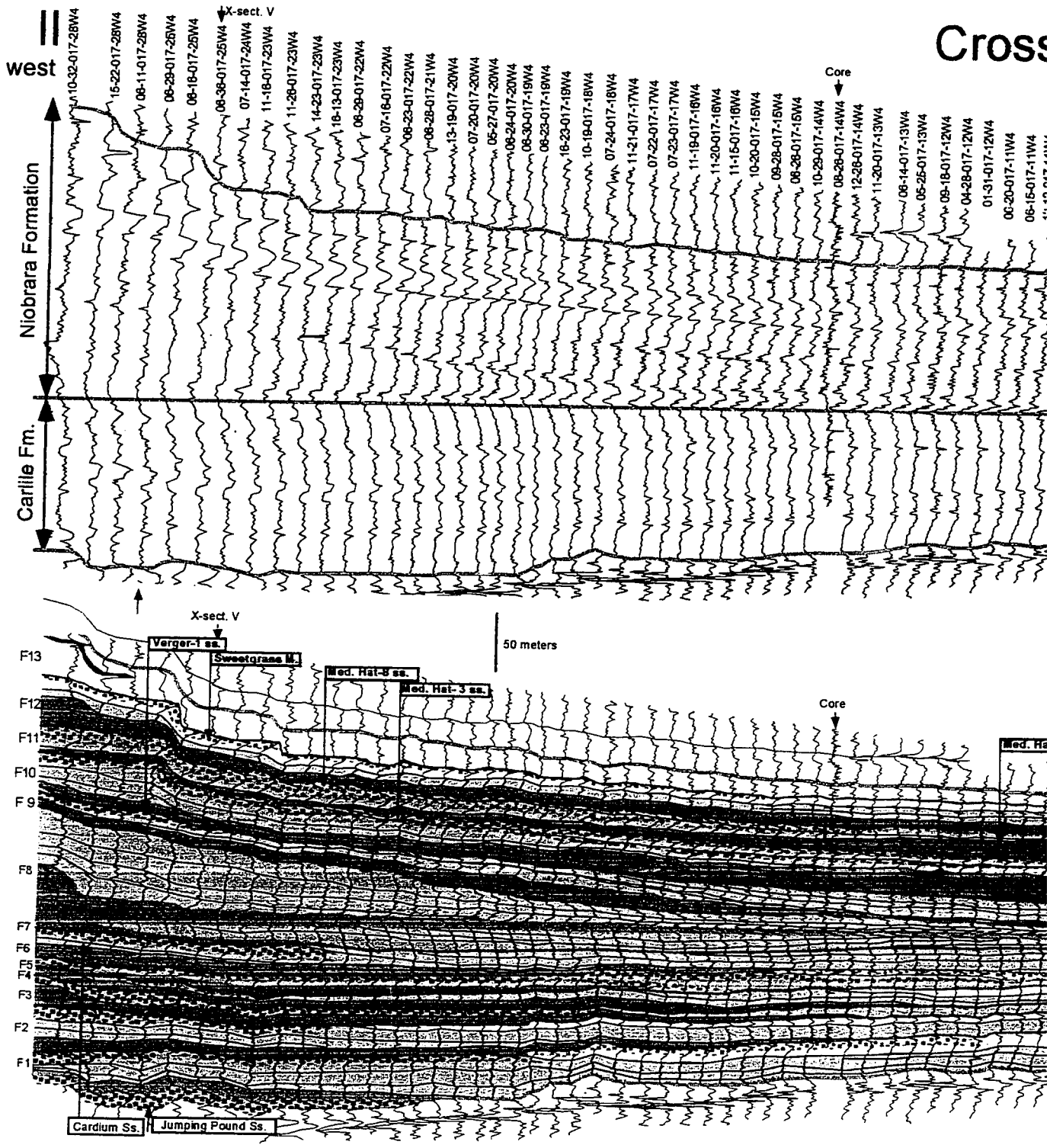
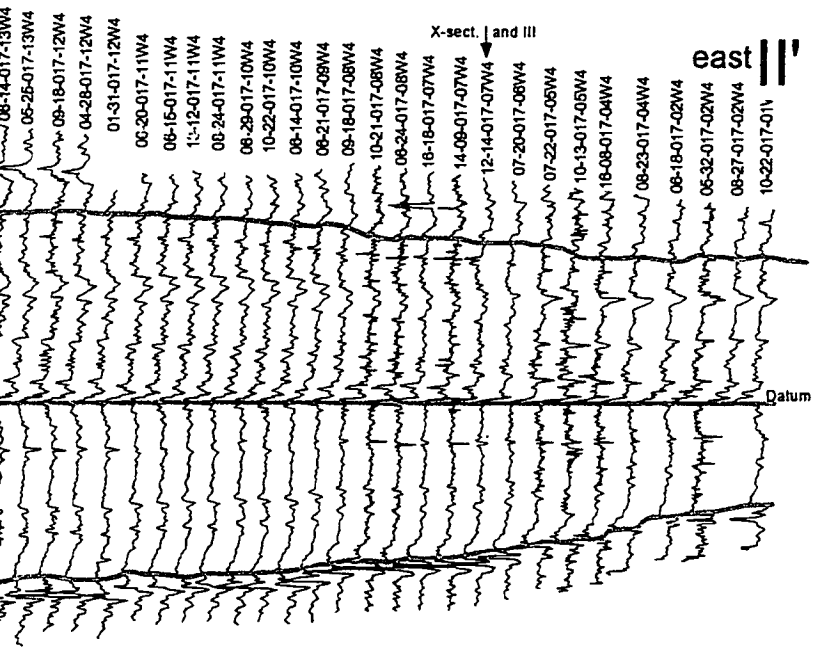
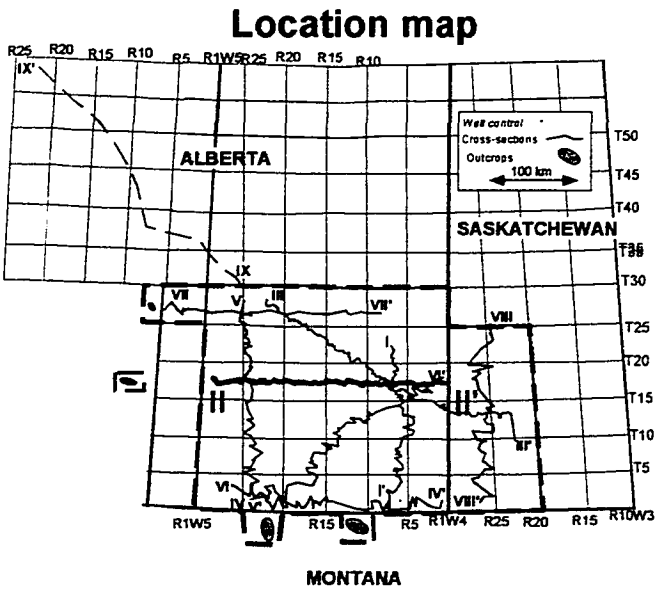

Cross
west
X-sect. V
Core
Niobrara Formation
Carlile Fm.
50 meters
Verger-1 ss.
Sweetgrass M.
Med. Hat-5 ss.
Med. Hat-3 ss.
F13
F12
F11
F10
F 9
F8
F7
F6
F5
F4
F3
F2
F1
Cardium Ss.
Jumping Pound Ss.

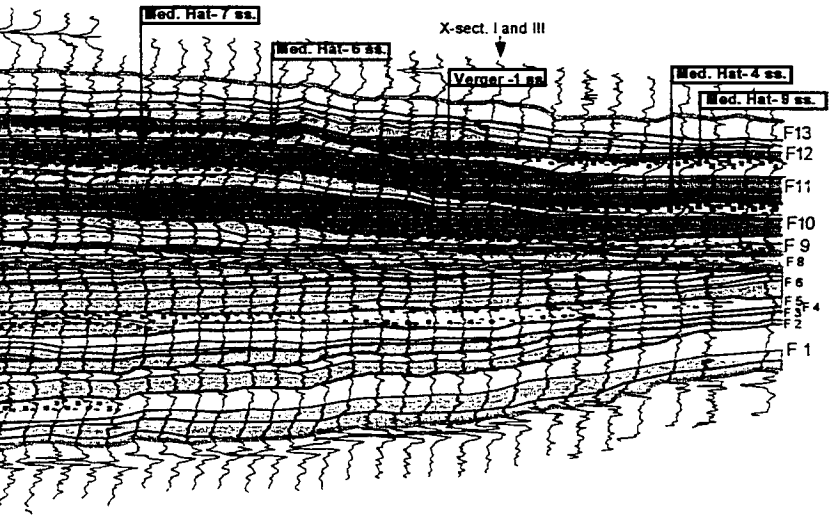
Figure 3-6

199

Cross-section II







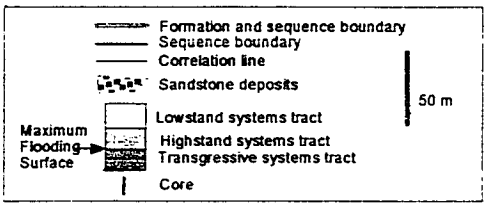


Figure 3-7. Cross-section III: A northwest-southeast resistivity wire-line cross-section. For location of cross-section see figure 3-2. Legend on figure 3-5.

Cross-section II

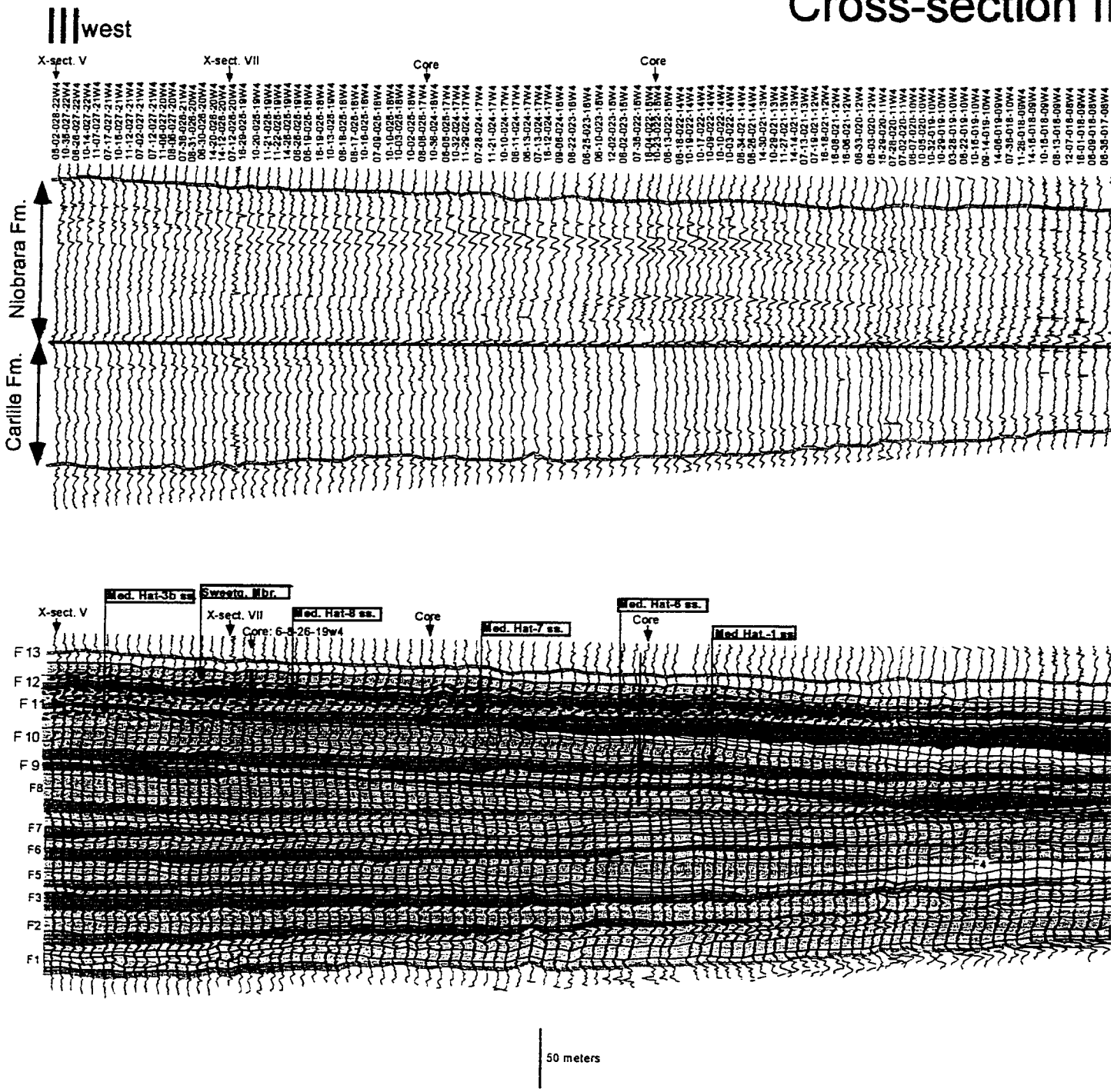
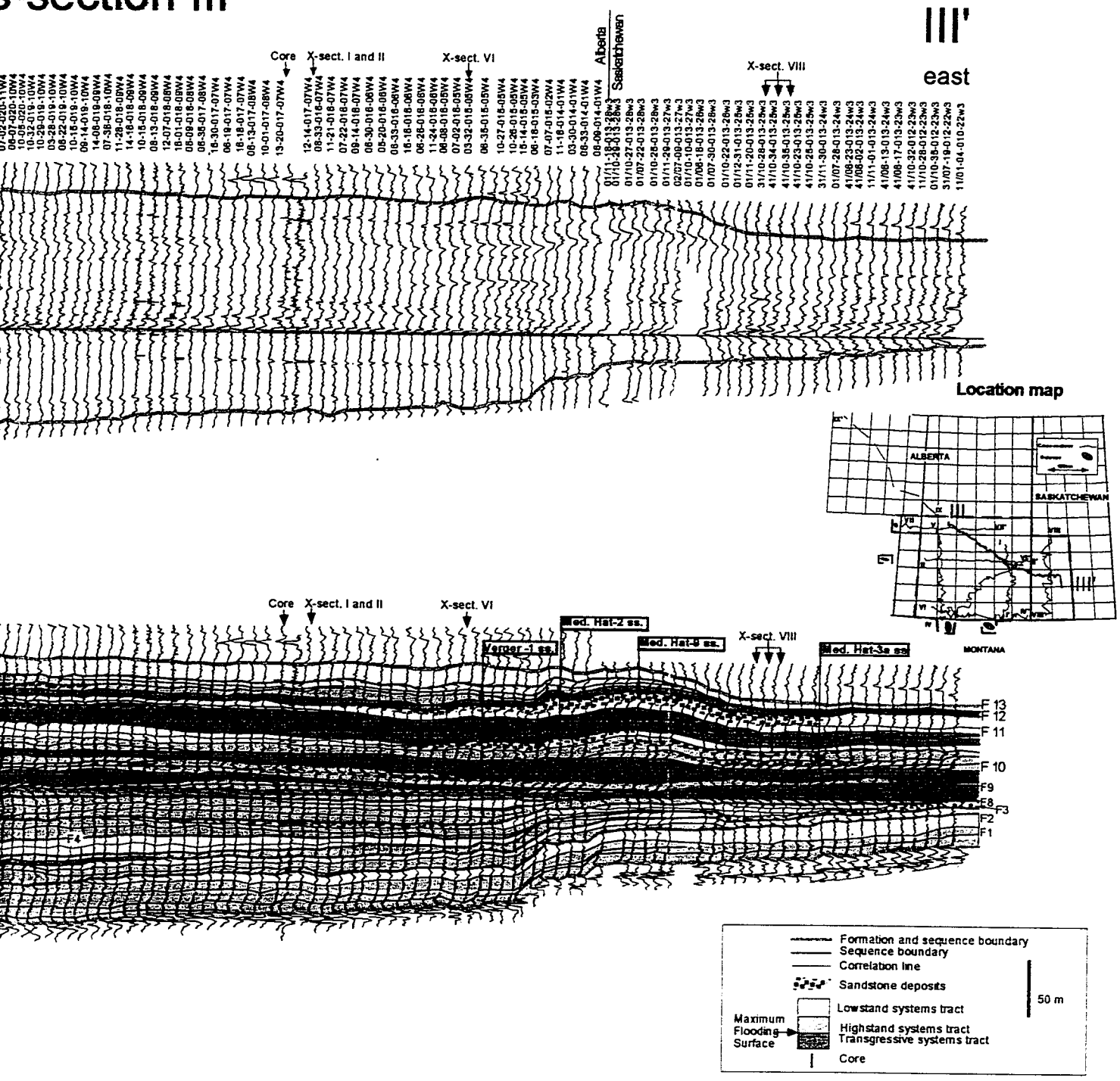


Figure 3-7

201

s-section III



re 3-7

Figure 3-7

Figure 3-8. Cross-section IV: An east-west resistivity wire-line cross-section along the Montana-Alberta border. For location of cross-section see figure 3-2. Legend on figure 3-5.

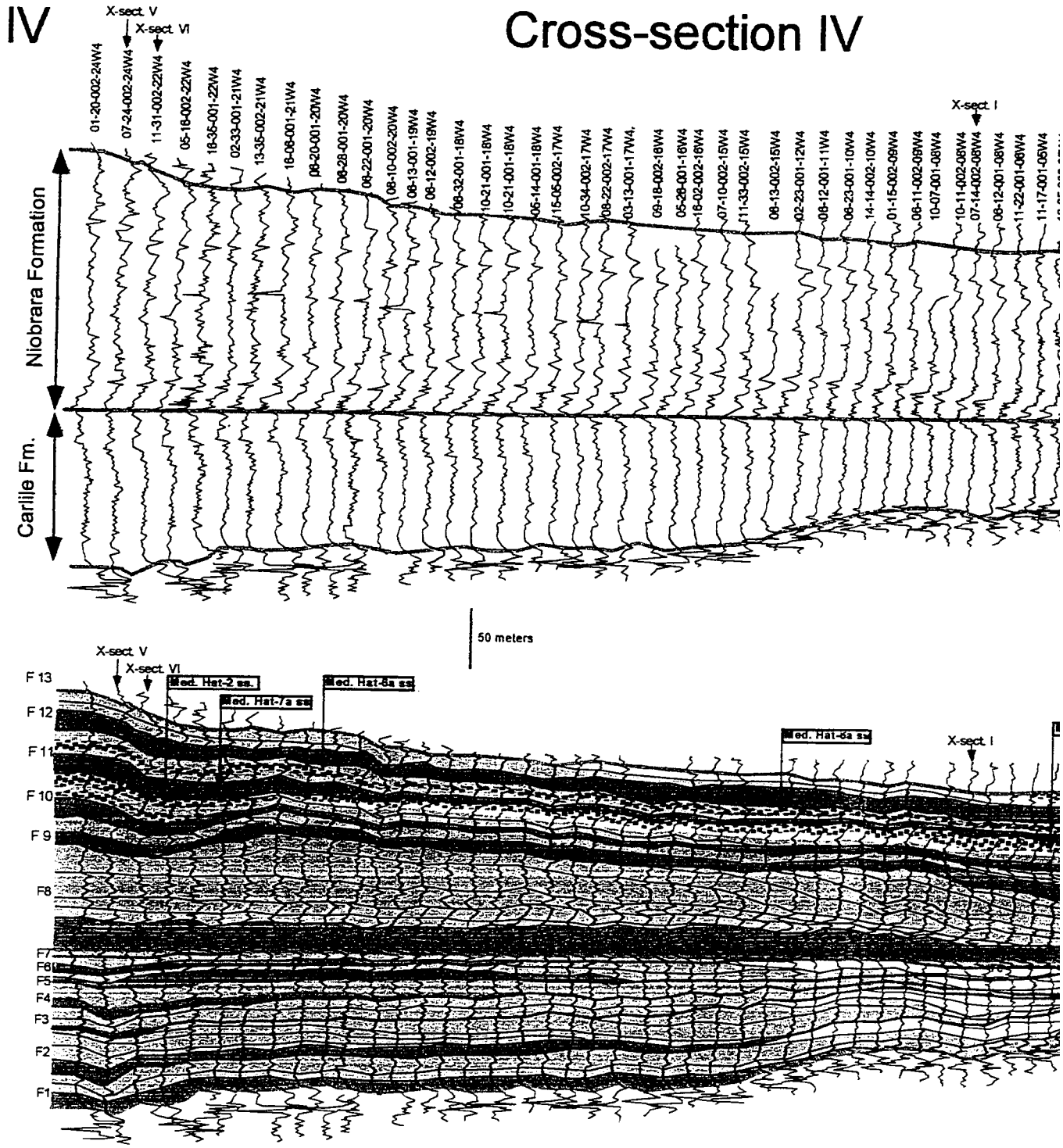
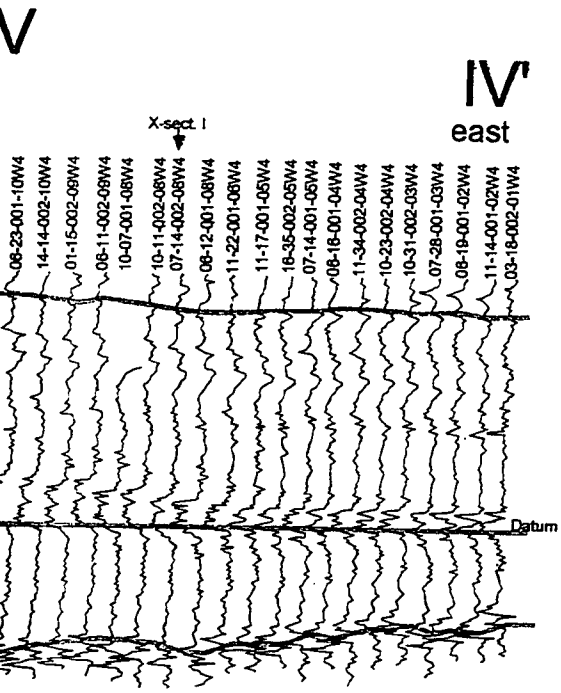
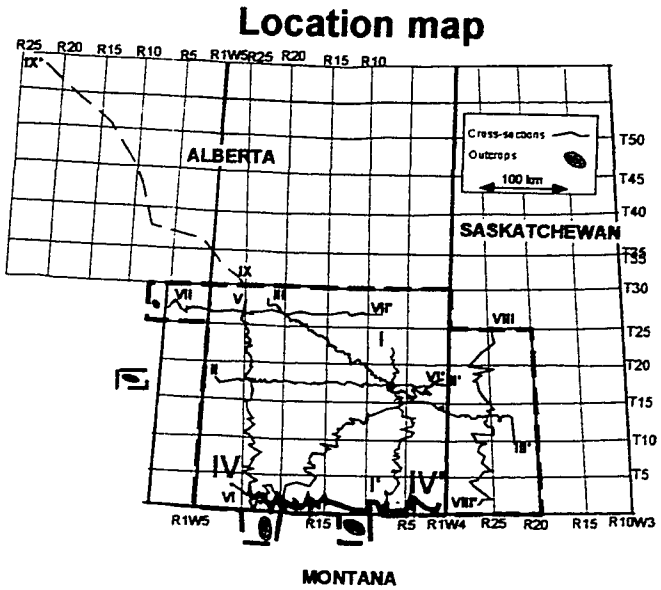
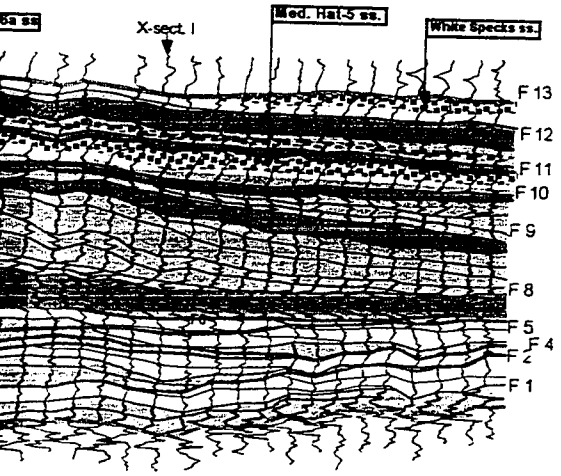

IV
Cross-section IV
X-sect. V
X-sect. VI
X-sect. I
Niobrara Formation
Carlile Fm.
50 meters
Med. Hat-2 ss.
Med. Hat-7a ss.
Med. Hat-6a ss.
F 13
F 12
F 11
F 10
F 9
F8
F7
F6
F5
F4
F3
F2
F1

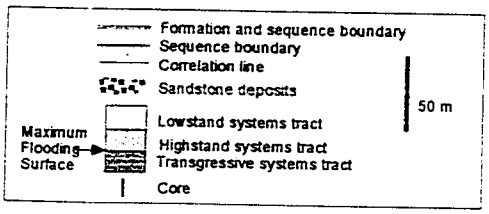
Figure 3-8

203









re 3-8

Figure 3-8

Figure 3-9. Cross-section V: A north-south resistivity wire-line cross-section in the west region. For location of cross-section see figure 3-2. Legend on figure 3-5.

Cross-section V

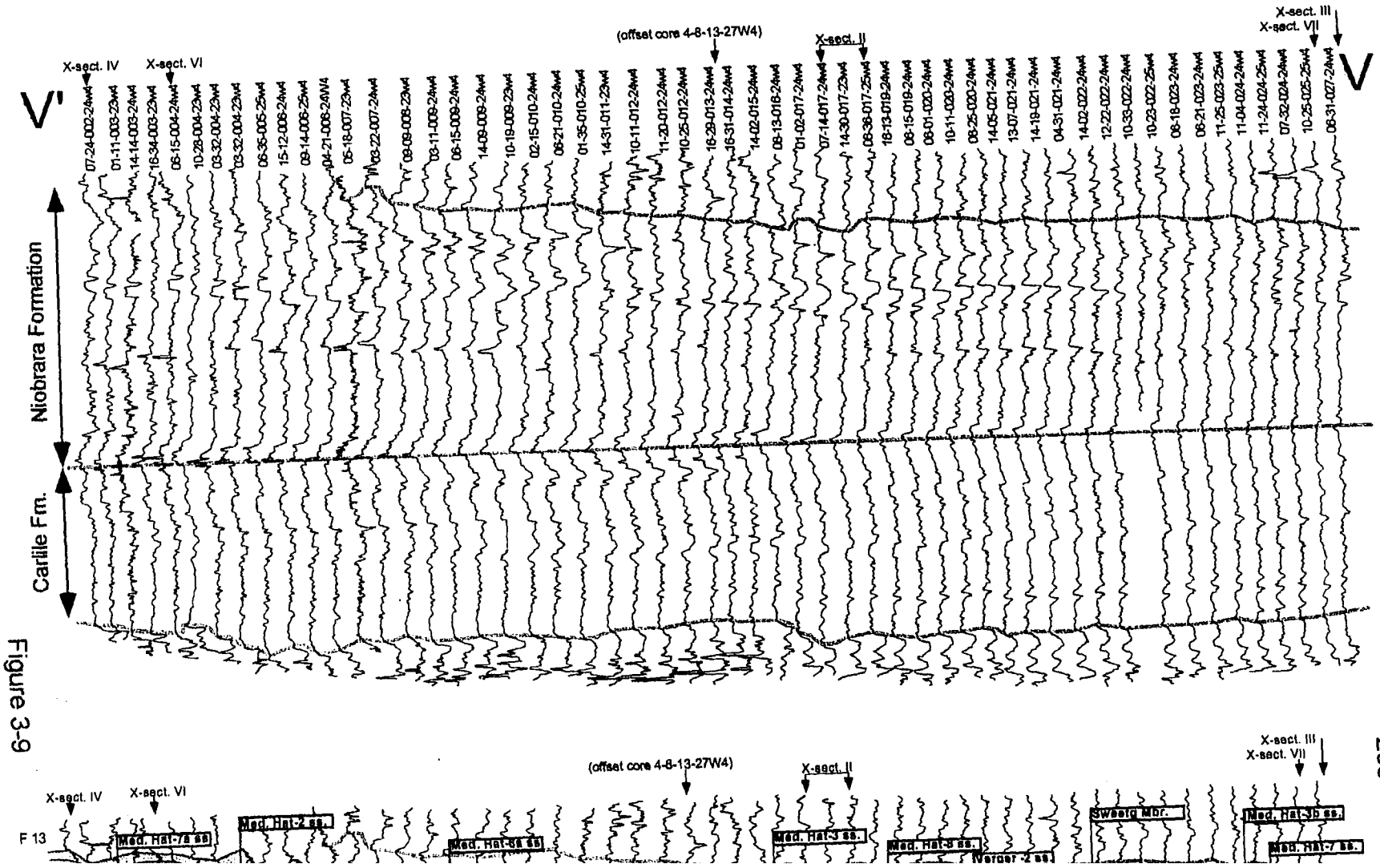
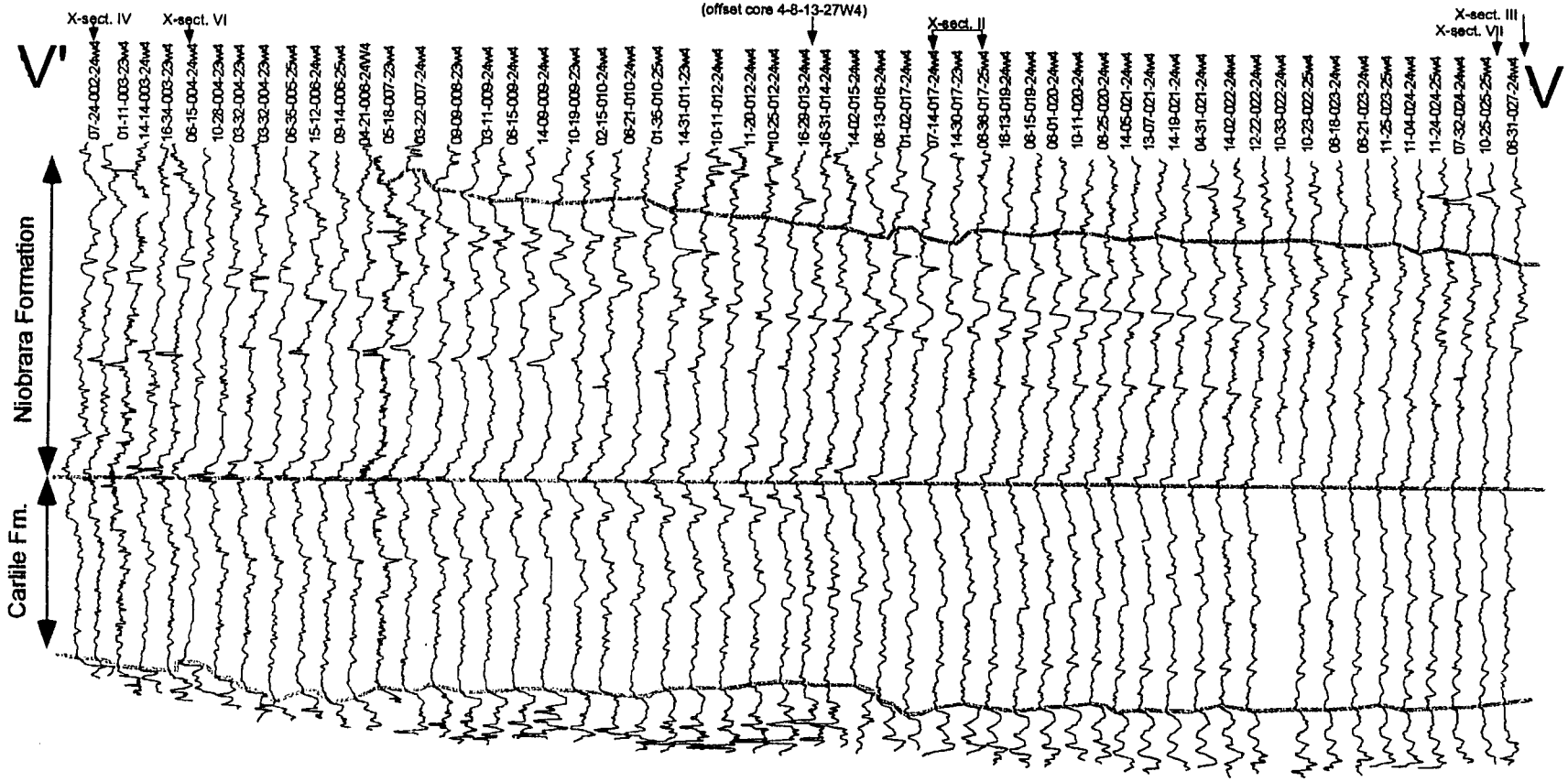


Figure 3-9

Cross-section V



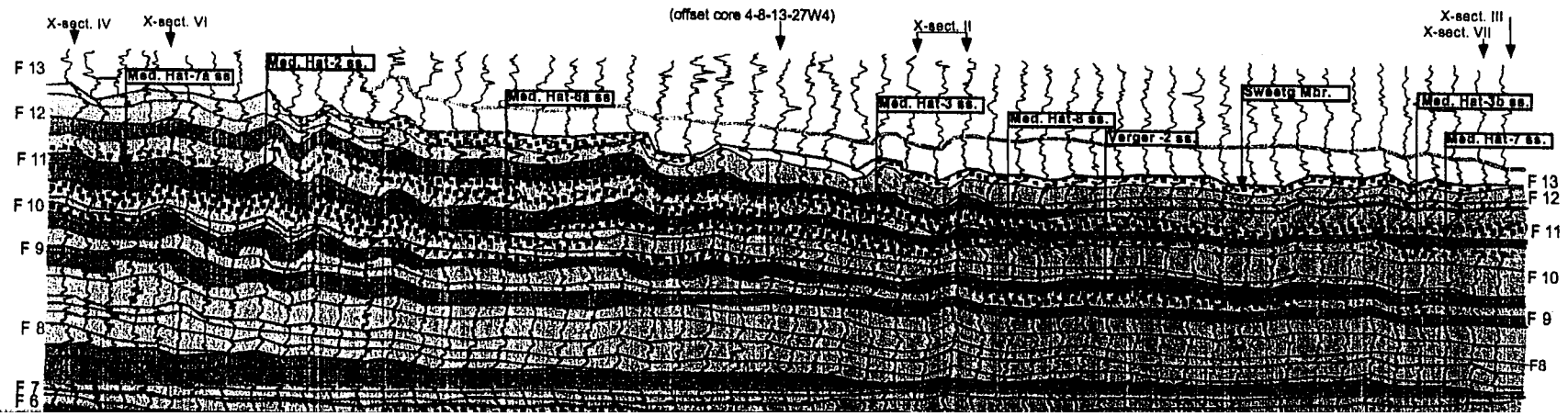
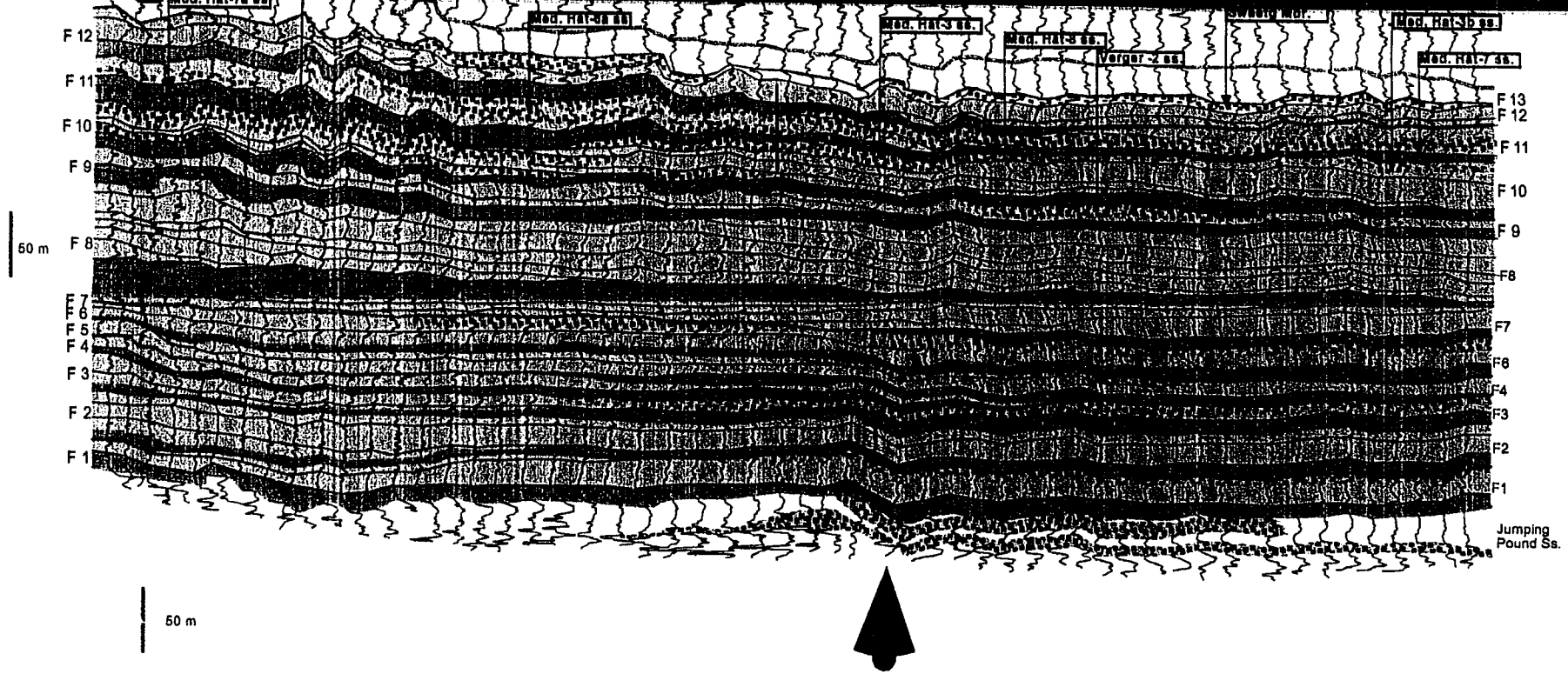
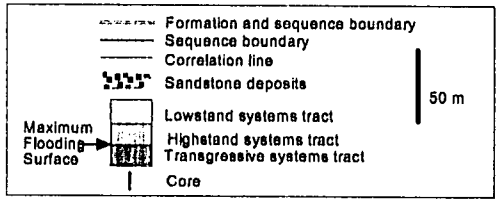


Figure 3-9



Zone of change in all sequences in the Carlile formation. Except the upper sequence F7. Might be a tectonic movement filled with F6 lowstand deposits. Very little seen in Niobrara formation at this location.



Location map

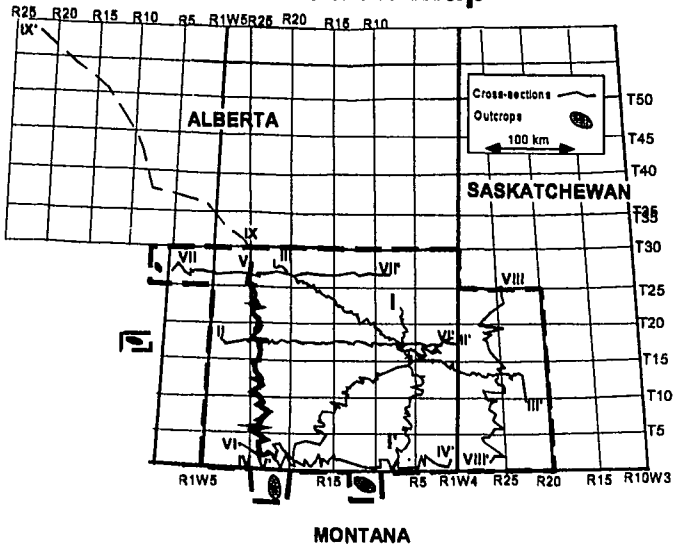


Figure 3-9

Figure 3-10. Cross-section VI: A southwest-northeast resistivity wire-line cross-section in the south-central region. For location of cross-section see figure 3-2. Legend on figure 3-5.

Cross-section VI

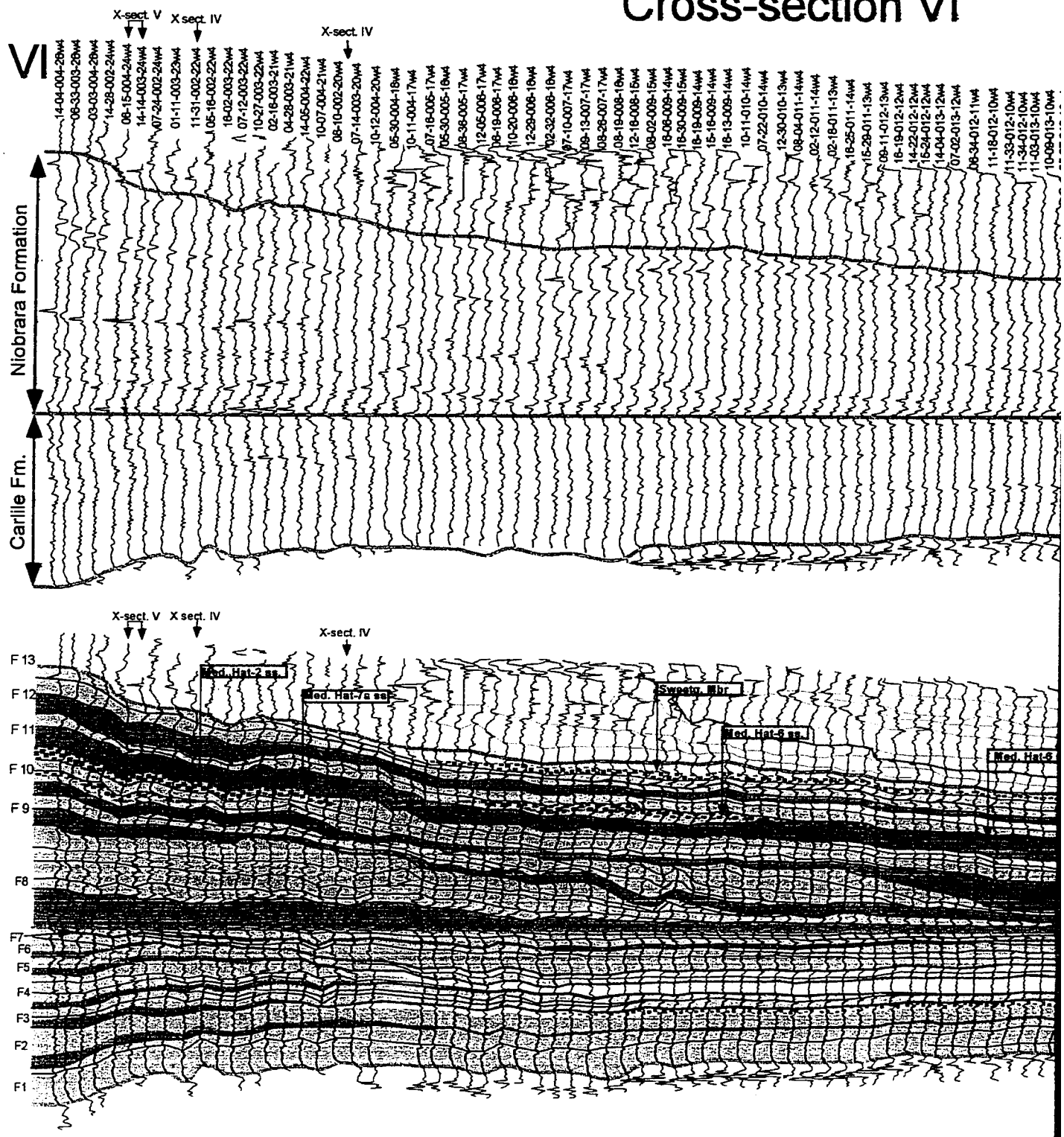
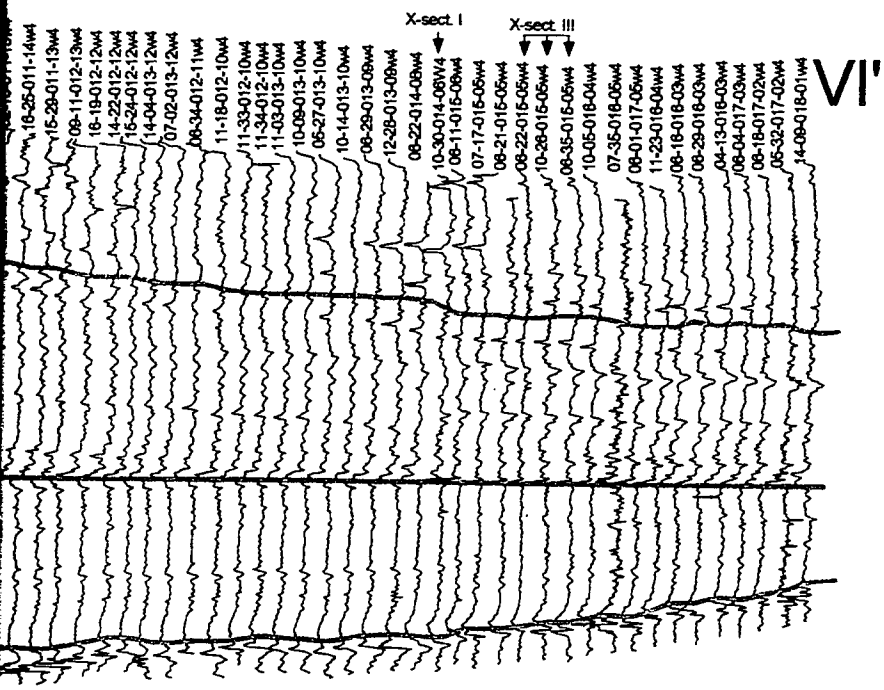
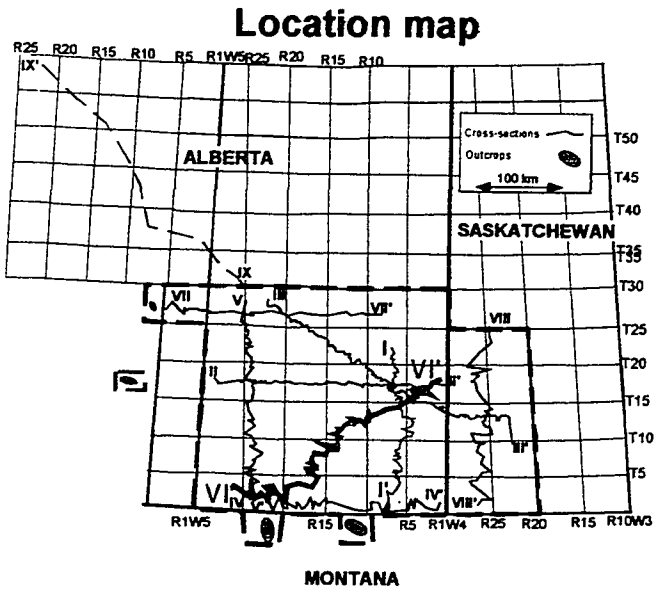


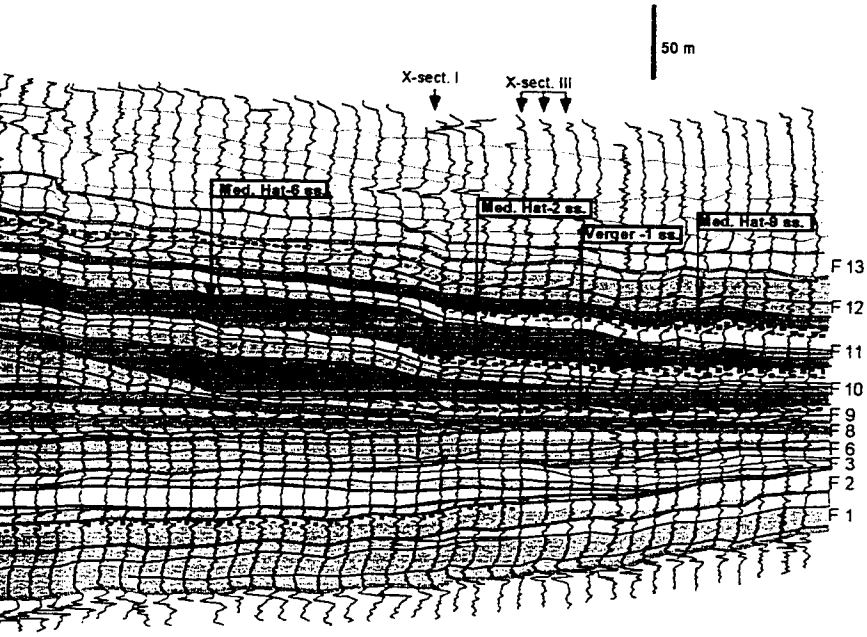
Figure 3-10

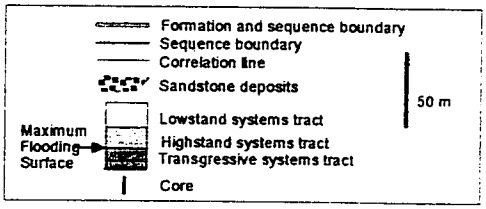
207

tion VI





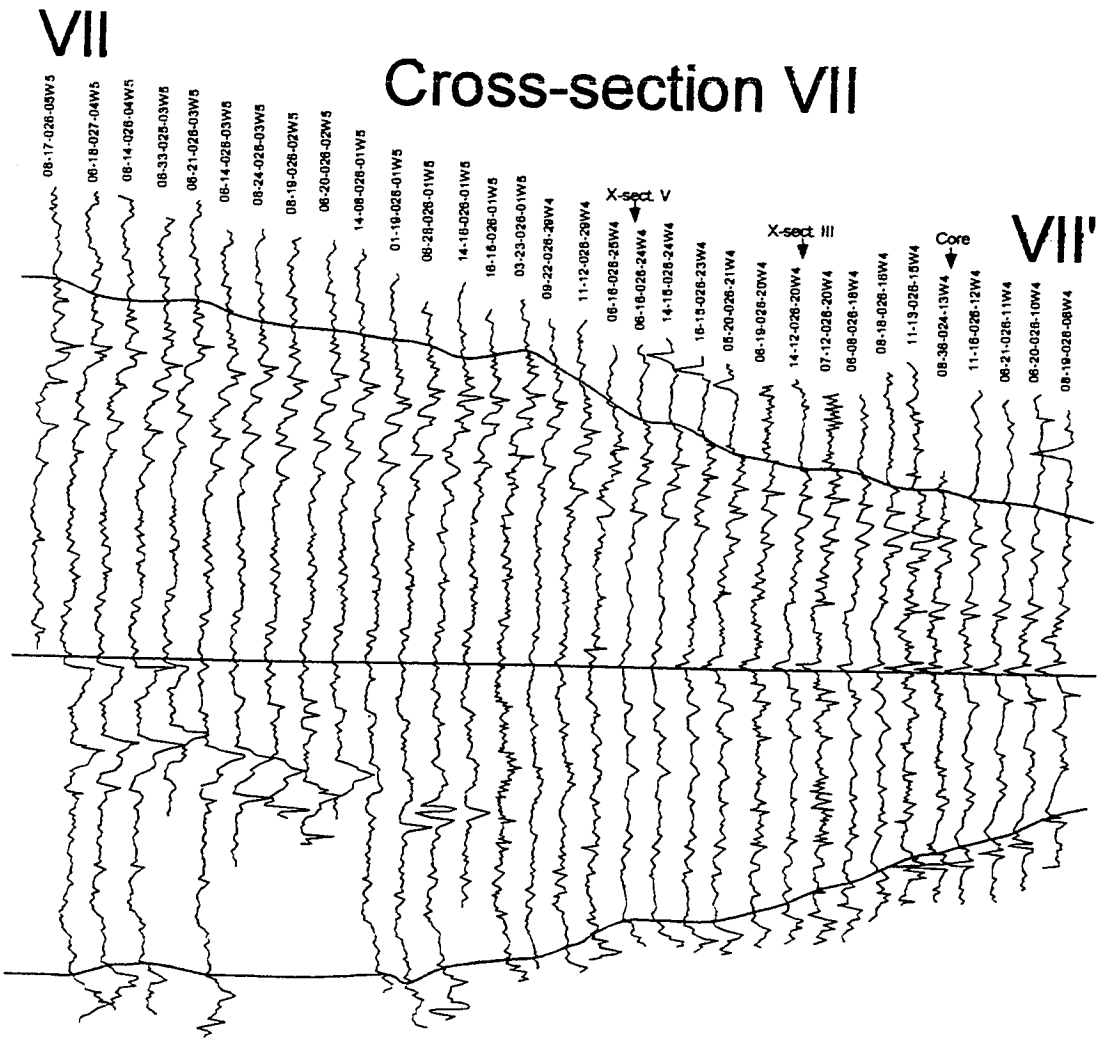


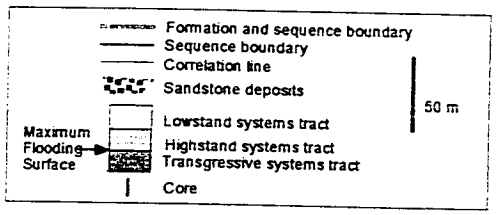


ure 3-10

Figure 3-10

Figure 3-11. Cross-section VII: An east-west resistivity wire-line cross-section in the north and northwestern region. The cross-section is tied to an outcrop section of the Medicine Hat and First White Specks members at the Ghost Dam Spillway (chapter II). For location of cross-section and outcrop see figure 3-2. Legend on figure 3-5.


VII
Cross-section VII
VII'
X-sect. V
X-sect. III
Core


Formation and sequence boundary
Sequence boundary
Correlation line
Sandstone deposits
50 m
Lowstand systems tract
Highstand systems tract
Transgressive systems tract
Maximum Flooding Surface
Core

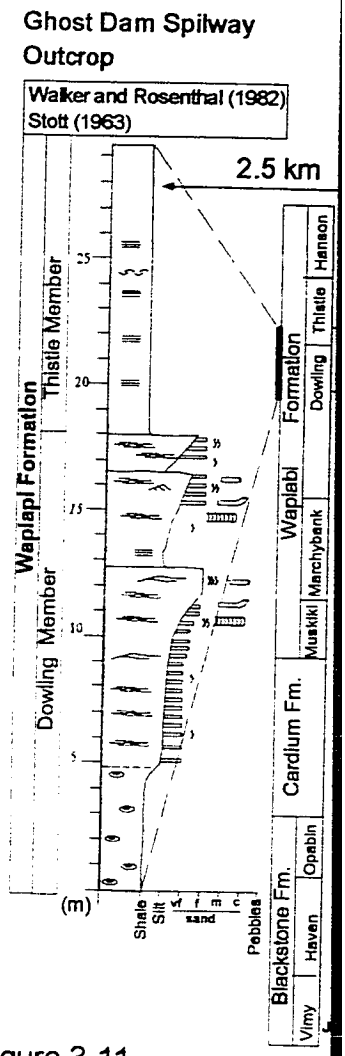
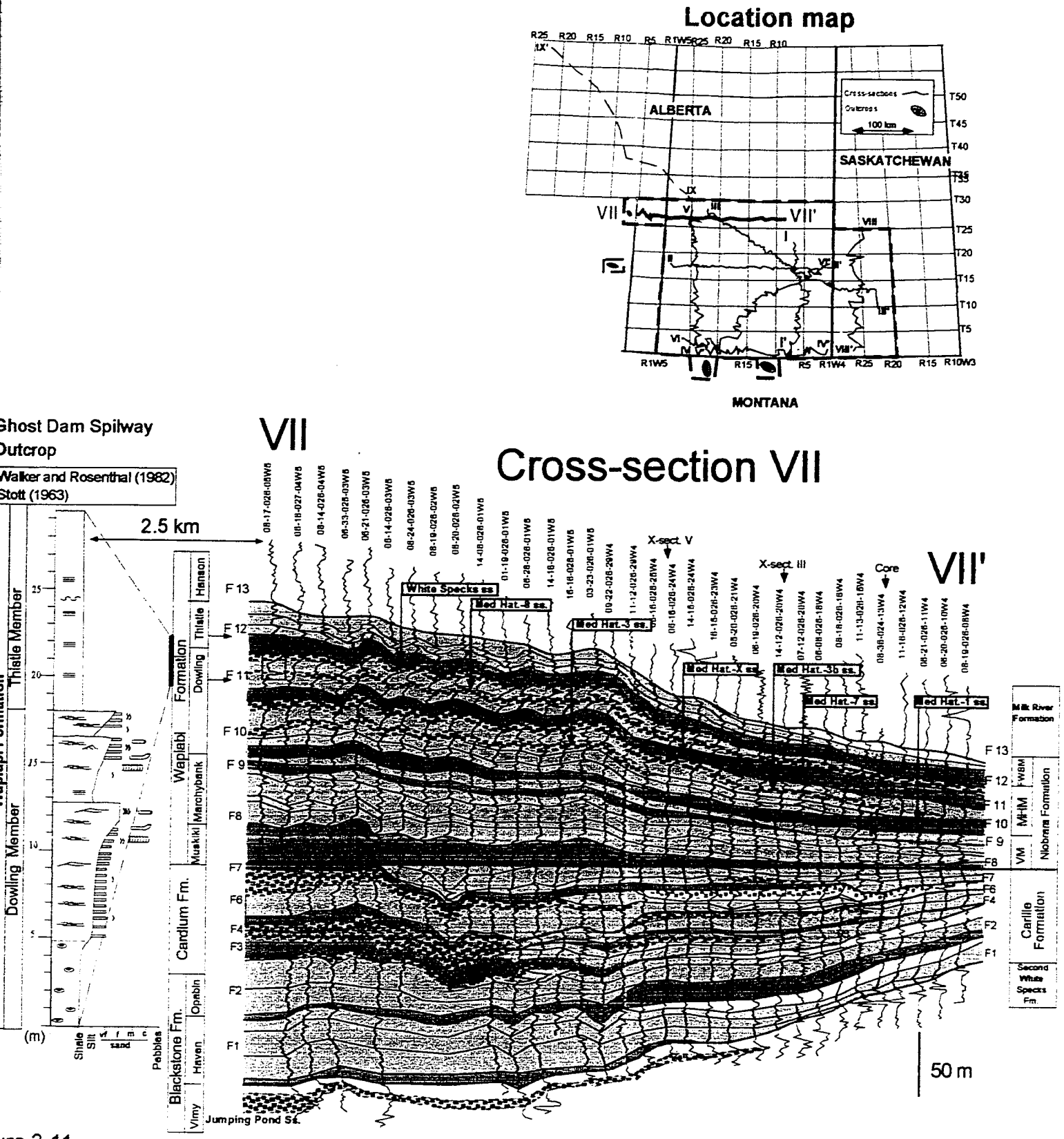

Ghost Dam Spilway Outcrop
Walker and Rosenthal (1982)
Stott (1963)
2.5 km
Waplapl Formation
Thistle Member
Dowling Member
Waplabi Formation
Dowling
Thistle
Hanson
Marchybank
Muskiki
Cardium Fm.
Blackstone Fm.
Opabin
Haven
Vimy
(m)
Shale
Silt
sand
Pebbles

Figure 3-11

209

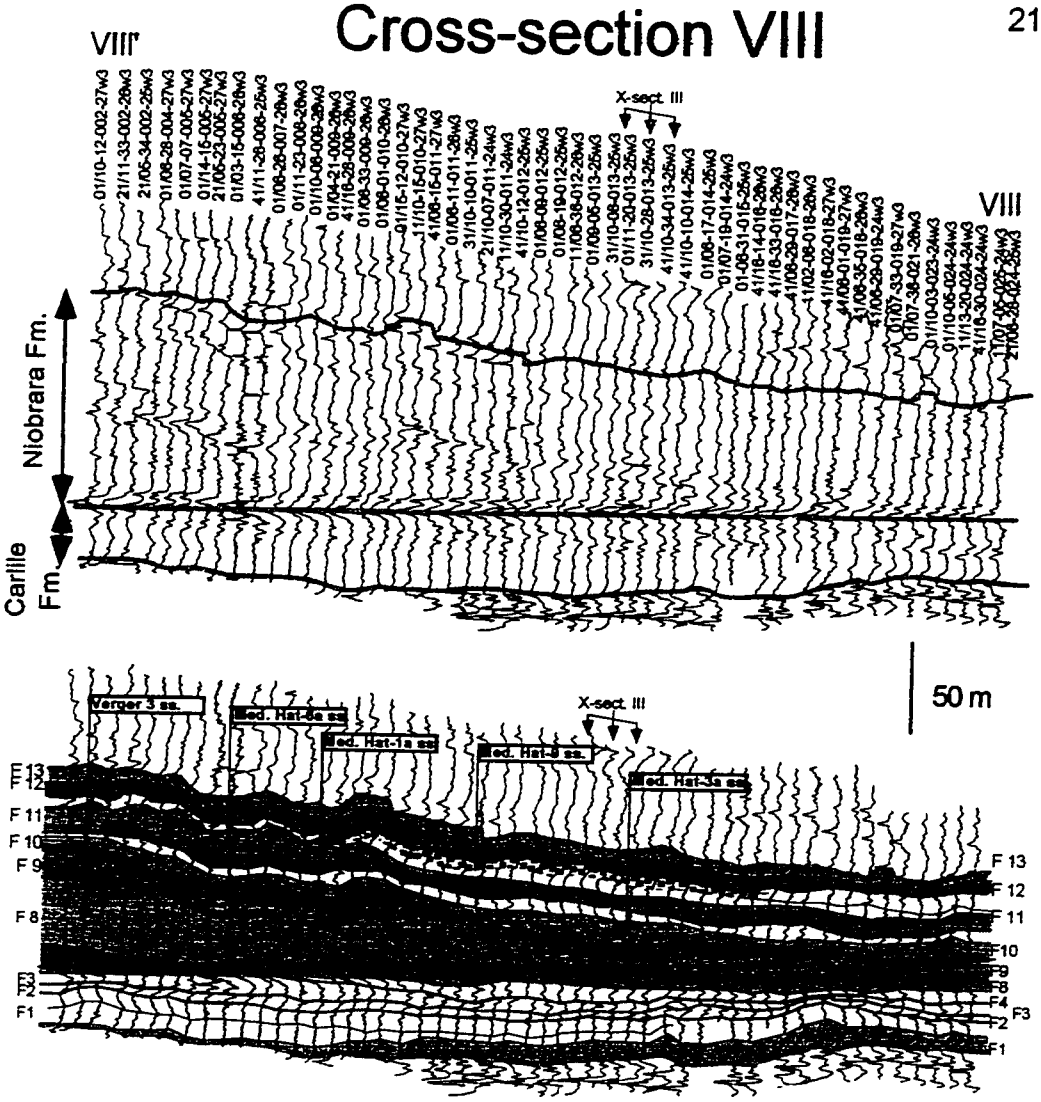


ure 3-11

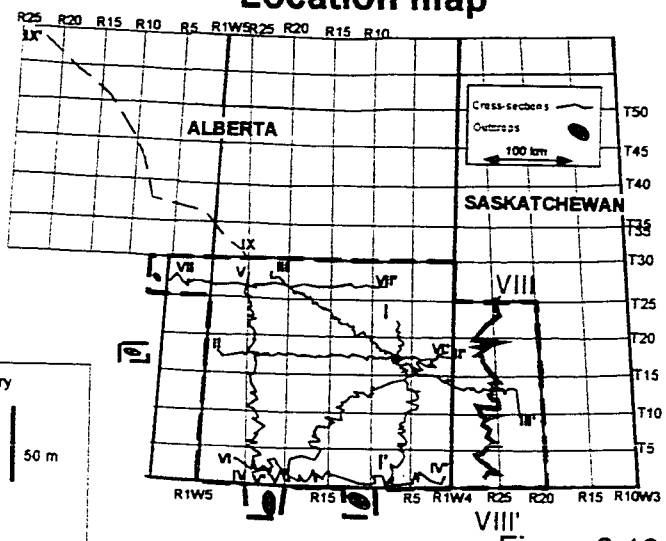
Figure 3-11

Figure 3-12. Cross-section VIII: A north-south cross-section in the east region in Saskatchewan. For location of cross-section see figure 3-2. Legend on figure 3-5.

Cross-section VIII



Location map



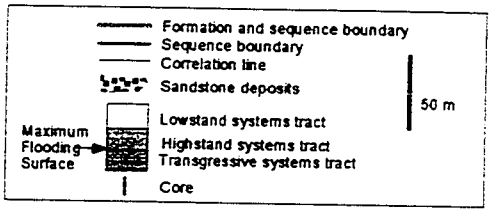


Figure 3-12

Figure 3-13. Cross-section XI: A northwest-southeast cross-section that links the study area with the west-central region of Alberta. The cross-section illustrates the correlation between Carlile and Niobrara sequence-sets and the deposits of the Kaskapau. Cardium Muskiki. Marchybank. Bad Heart and Puskwaskau formations. The correlation of sequences F8 and F9 is especially interesting as they correlate to the lowstand deposits of the Bad Heart Formation. For location of cross-section see figure 3-2. Legend on figure 3-5.

Correlation from southen Alberta to Bad Heart Formation in West-central Alberta

Cross-section IX

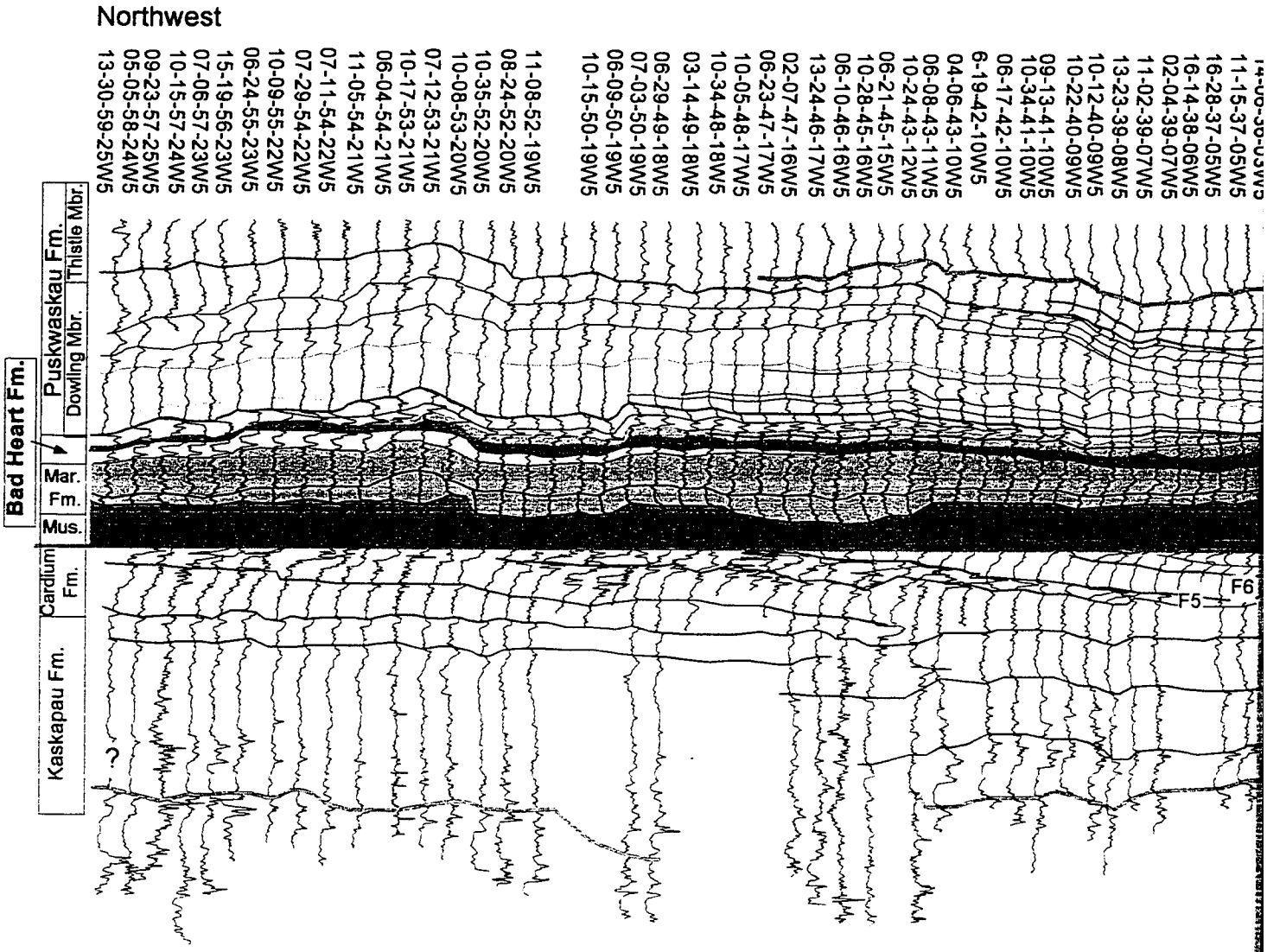
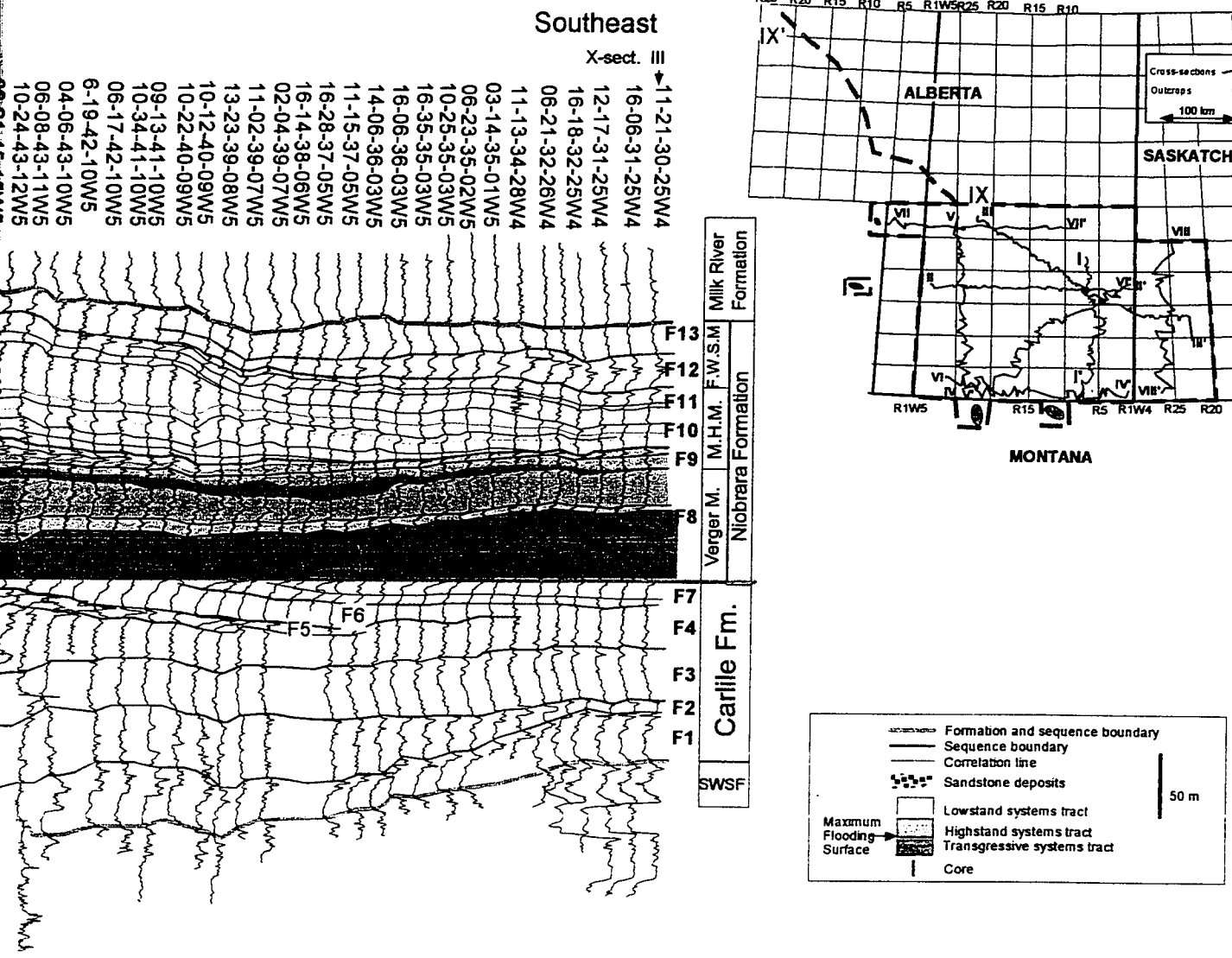


Figure 3-13

213

en Alberta
est-central Alberta



re 3-13

Figure 3-13

Figure 3-14. Structural map of the study area and north-central Montana. The map shows the major structural elements of the area including the foreland basin deep to the west, the northeast plunging Bow Island Arch, which divides the Alberta Basin to the west and the Williston Basin to the east. Major structures in Montana after Lorenz (1982).

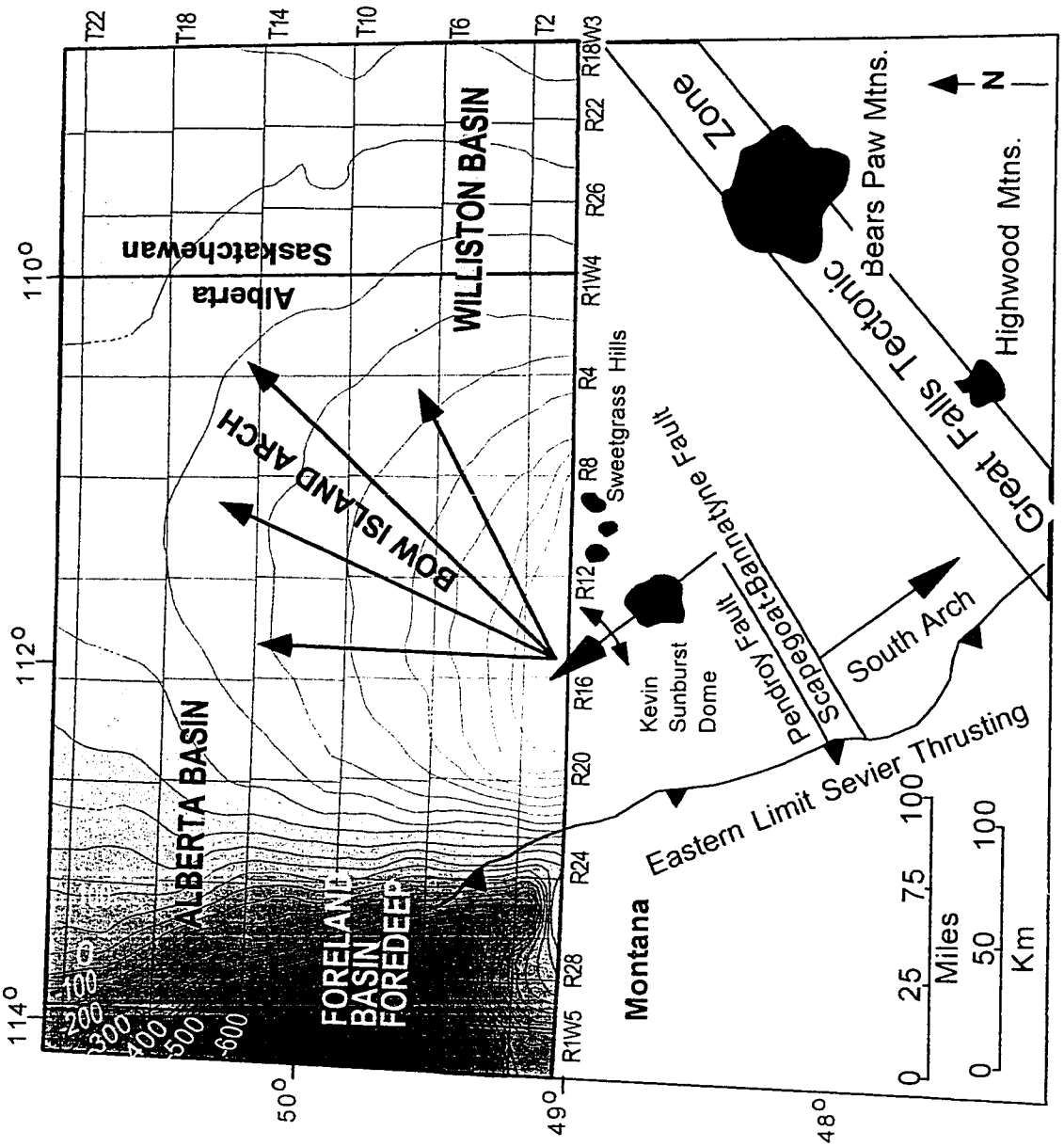

T22
T18
T14
T10
T6
T2
R18W3
R22
R26
R1W4
R4
R8
R12
R16
R20
R24
R28
R1W5
114°
112°
110°
50°
49°
48°
Alberta
Saskatchewan
WILLISTON BASIN
BOW ISLAND ARCH
ALBERTA BASIN
FORELAND BASIN FOREDEEP
100
0
100
200
300
400
500
600
Sweetgrass Hills
Kevin Sunburst Dome
Pendroy Fault
Scapegoat-Bannatyne Fault
South Arch
Eastern Limit Sevier Thrusting
Montana
Great Falls Tectonic Zone
Bears Paw Mtns.
Highwood Mtns.
N
0 25 75 100
Miles
0 50 100
Km

Figure 3-14

Figure 3-15. Isopach map of the sequence-set (F1 to F7) of the Carlile Formation in southern Alberta and southwestern Saskatchewan. Generally the sediment input directions are from the west. Sediment input from the east is observed from the upper two sequences (F6 and F7).

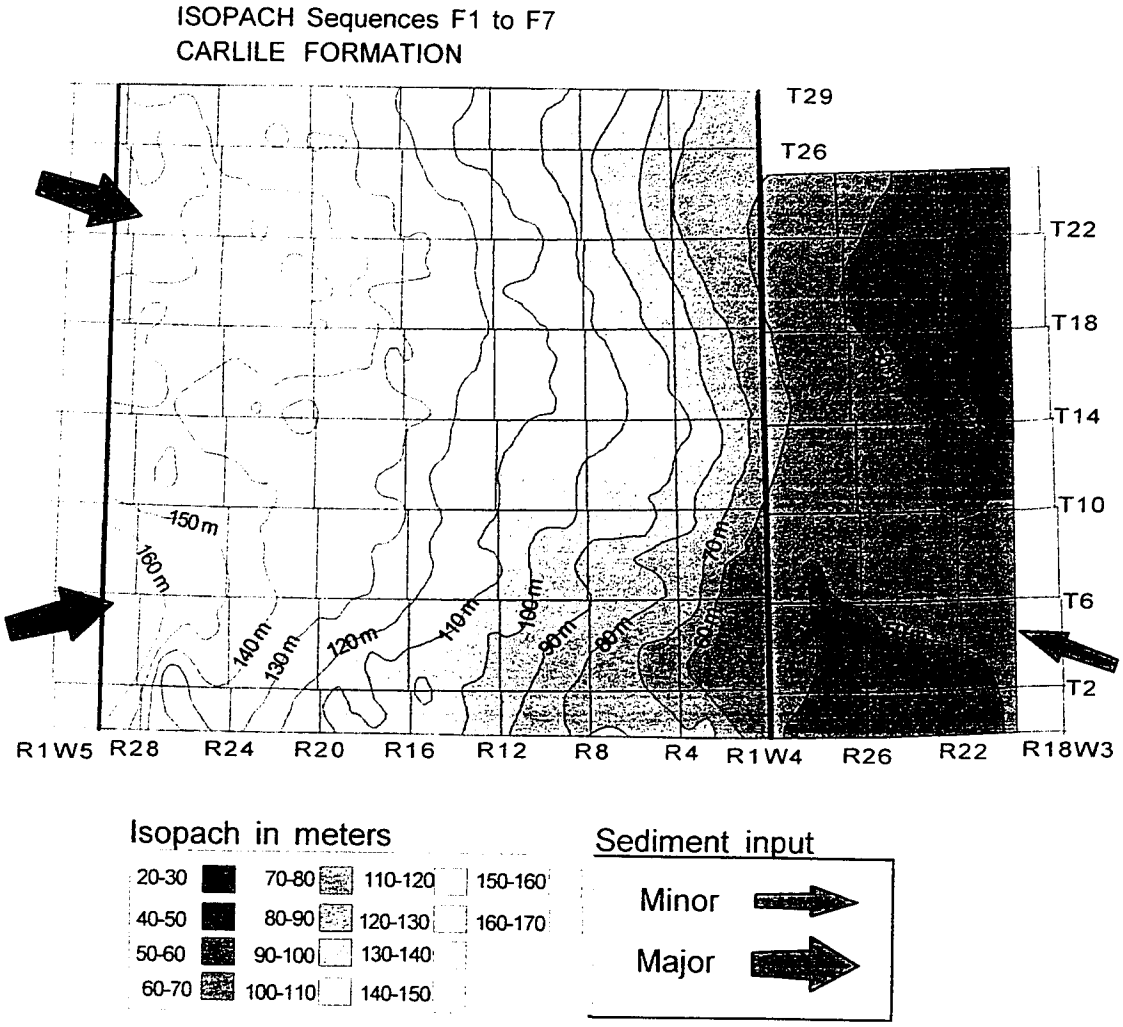

ISOPACH Sequences F1 to F7
CARLILE FORMATION
T29
T26
T22
T18
T14
T10
T6
T2
R1W5
R28
R24
R20
R16
R12
R8
R4
R1W4
R26
R22
R18W3
150m
160m
140m
130m
120m
110m
100m
90m
80m
70m
Isopach in meters
20-30
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
130-140
140-150
150-160
160-170
Sediment input
Minor
Major

Figure 3-15

Figure 3-16. The Deer Creek outcrop section of the Carlile Formation and the lower part of the Niobrara Formation. The composite outcrop section from the Sweetgrass Hills, Montana (chapter II) is correlated to a wire-line log in Alberta (10-7-1-8W4). This log is located on the cross-section I (figure 3-5). All seven sequences are present in the Deer Creek outcrop.

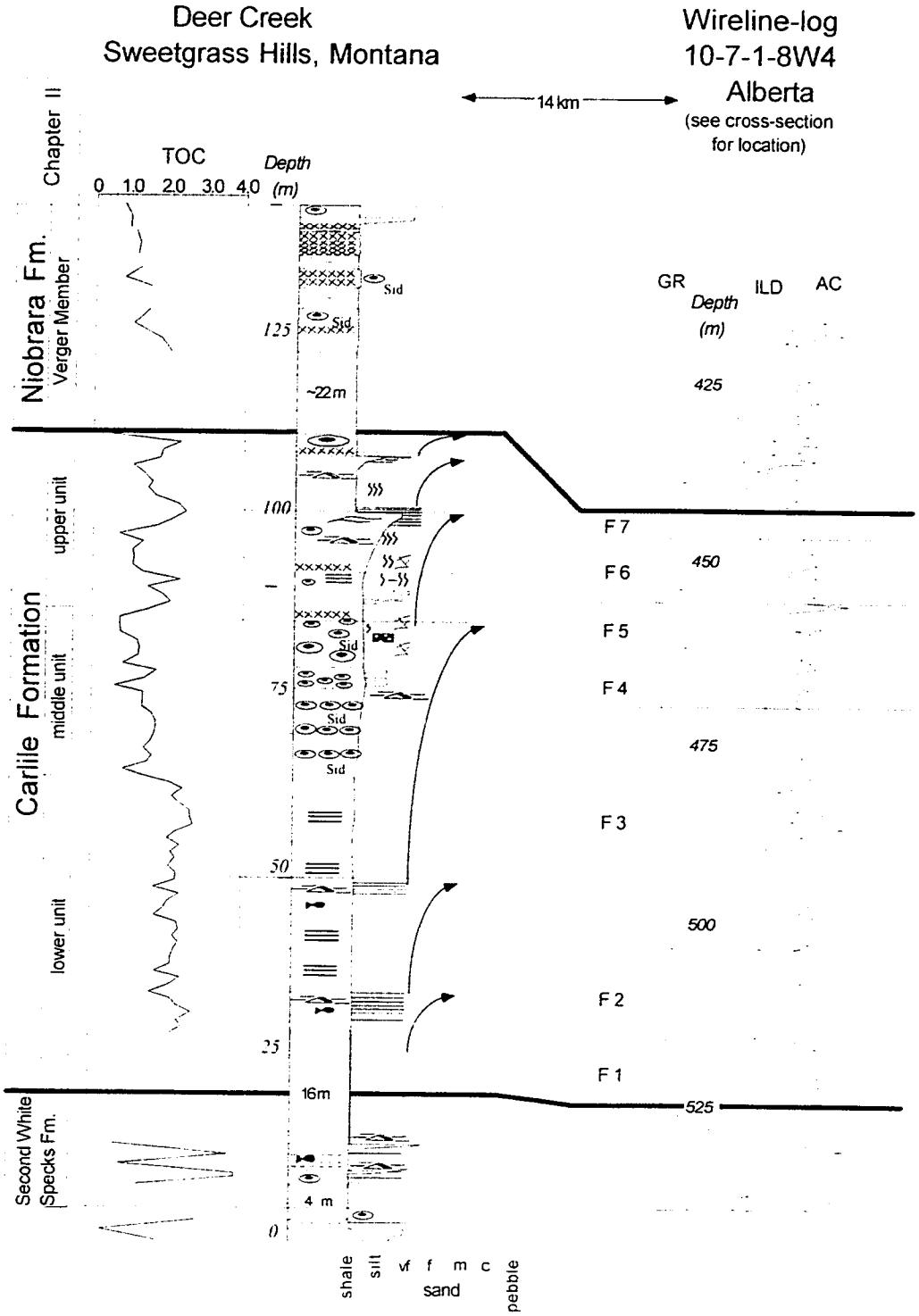

Deer Creek
Sweetgrass Hills, Montana
Wireline-log
10-7-1-8W4
Alberta
(see cross-section for location)
14 km
Chapter II
TOC
0 1.0 2.0 3.0 4.0
Depth (m)
Niobrara Fm.
Verger Member
Sid
125
~22m
GR
ILD
AC
Depth (m)
425
upper unit
100
F 7
F 6
450
Carlile Formation
middle unit
F 5
F 4
75
475
F 3
50
lower unit
500
F 2
25
F 1
16m
525
Second White Specks Fm.
4 m
0
shale
silt
vf f m c
sand
pebble

Figure 3-16

Figure 3-17. Well 13-20-17-7W4 and a core cut on the boundary between the Carlile and Niobrara formations. The sedimentology, ichnology, geochemistry and micropaleontology are shown beside the core and represent the upper part of sequence F6, F7 and lower part of F8.

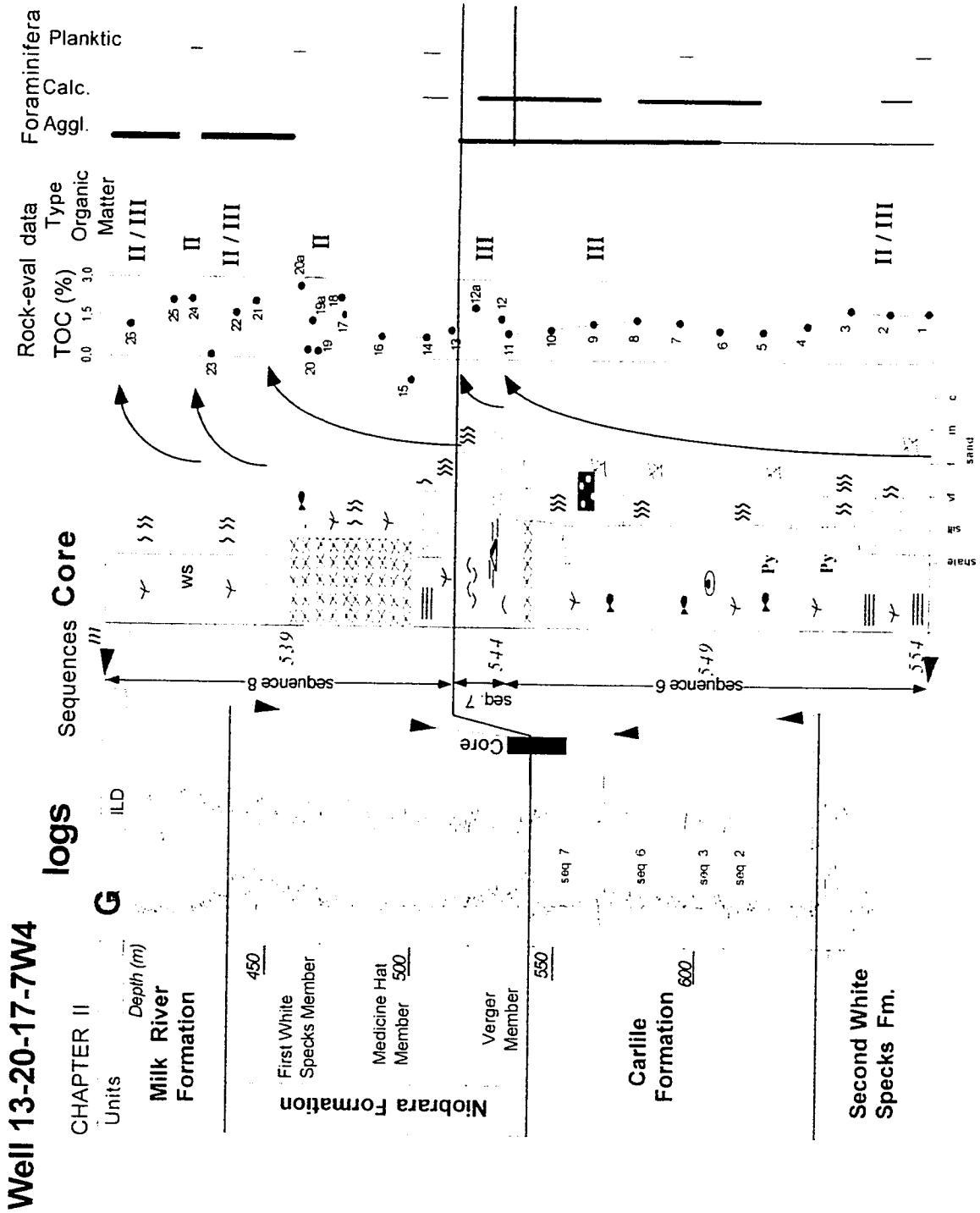

Well 13-20-17-7W4
CHAPTER II
Units
Depth (m)
G
logs
ILD
Sequences
Core
Rock-eval data
TOC (%)
Type Organic Matter
Foraminifera
Planktic
Calc.
Aggl.
Milk River Formation
First White Specks Member
Medicine Hat Member
Verger Member
Niobrara Formation
Carlile Formation
Second White Specks Fm.
sequence 8
sequence 6
seq 7
Core
seq 7
seq 6
seq 3
seq 2
450
500
550
600
II / III
II
III
ws
Py
shale
silt
sand

Figure 3-17

Figure 3-18. Outcrop to subsurface correlation of the Niobrara Formation and equivalent strata. Correlations illustrate the regional continuity of the two pebble layers in the upper part of the Verger Member.

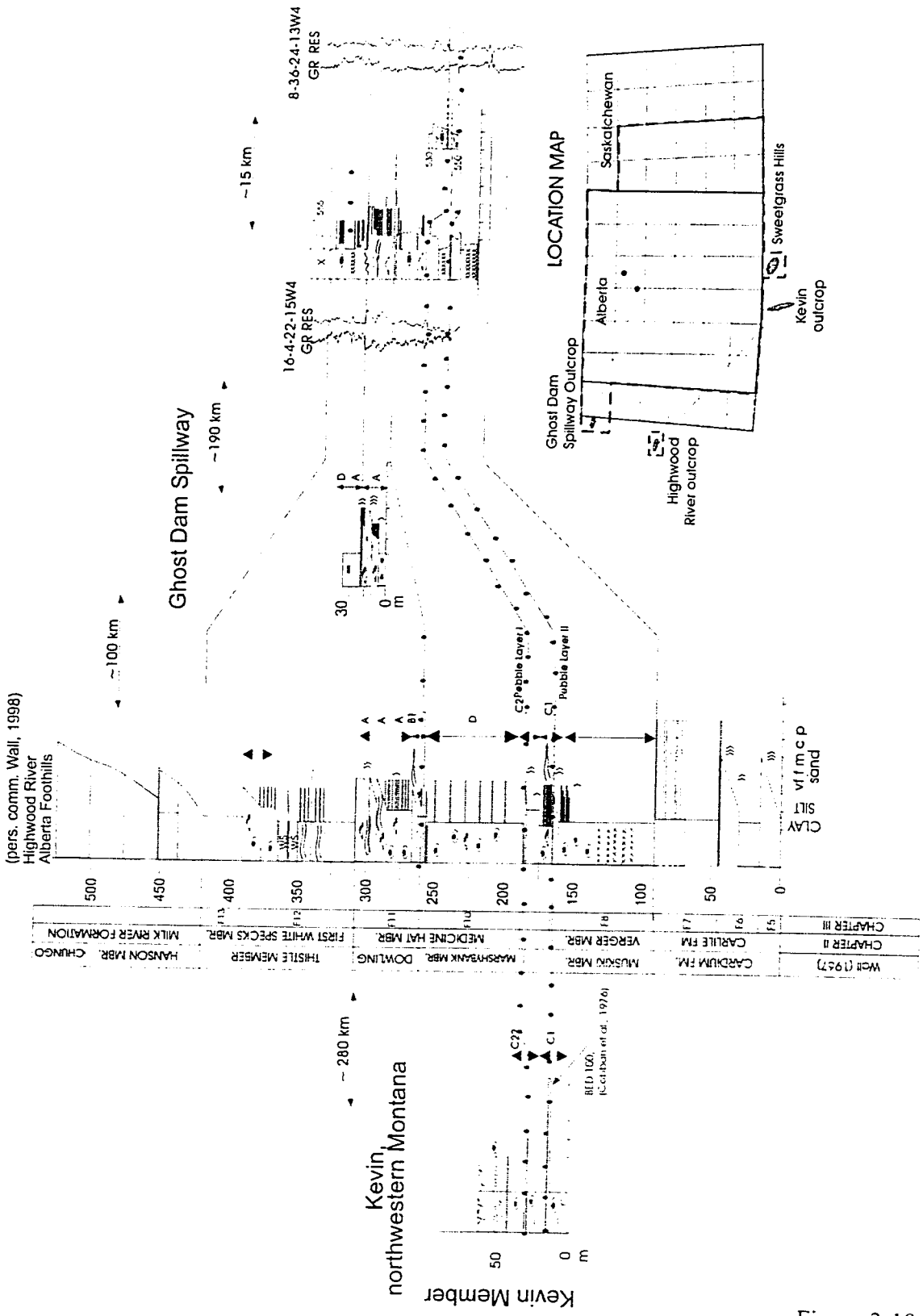

(pers. comm. Wall, 1998)
Highwood River
Alberta Foothills
~100 km
Ghost Dam Spillway
~190 km
16-4-22-15W4
GR RES
~15 km
8-36-24-13W4
GR RES
LOCATION MAP
Saskatchewan
Alberta
Sweetgrass Hills
Kevin outcrop
Ghost Dam Spillway Outcrop
Highwood River outcrop
Pebble Layer I
Pebble Layer II
CLAY
SILT
vf f m c p
sand
500
450
400
350
300
250
200
150
100
50
0
CHUNGO
HANSON MBR.
MILK RIVER FORMATION
THISTLE MEMBER
FIRST WHITE SPECKS MBR.
DOWLING
MARSHBANK MBR.
MEDICINE HAT MBR.
MUSKIN MBR.
VERGER MBR.
CARLILE FM.
CARDIUM FM.
Wall (1967)
CHAPTER II
CHAPTER III
~ 280 km
Kevin,
northwestern Montana
Kevin Member
50
0
m

Figure 3-18

Figure 3-19. **a**) Isopach map of the Niobrara sequence-set (F8 to F13) in southern Alberta and southwestern Saskatchewan. The general sediment input direction is from the southwest and south. **b**) Isopach map of sequence F8 from the lower part of the Verger Member in southern Alberta. The sequences thin from southwest to east and northeast and indicate a major sediment input from the southwest. **c**) Isopach map of sequence F9 from the upper part of the Verger Member with depo-center in the southeast. The stratal pattern indicates a sediment input direction from the southwest (figure 3-5 and 3-8). **c**) Isopach map of the two sequences F10 and F11 from the Medicine Hat Member. The isopach shows a different pattern than the previous sequences F8 and F9 as the thickness variations are limited and most of the two sequences are between 40 and 60 m thick. **d**) Isopach map of sequences F11 and F12 of the First White Specks Member showing a general thinning towards the east. This pattern is disrupted in the south by a thinning of the two sequences over the Bow Island Arch. The general sediment input direction was from the west.

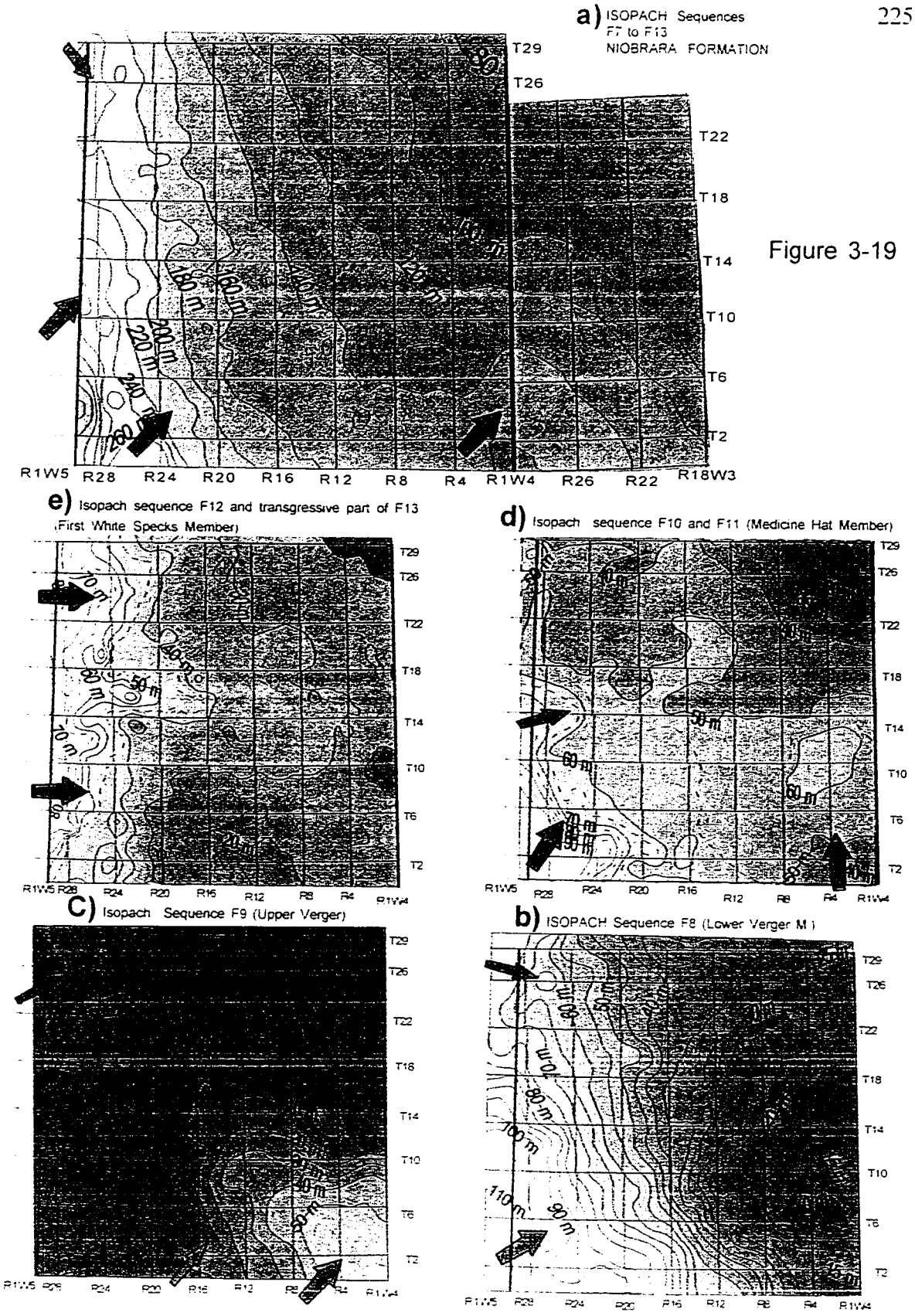
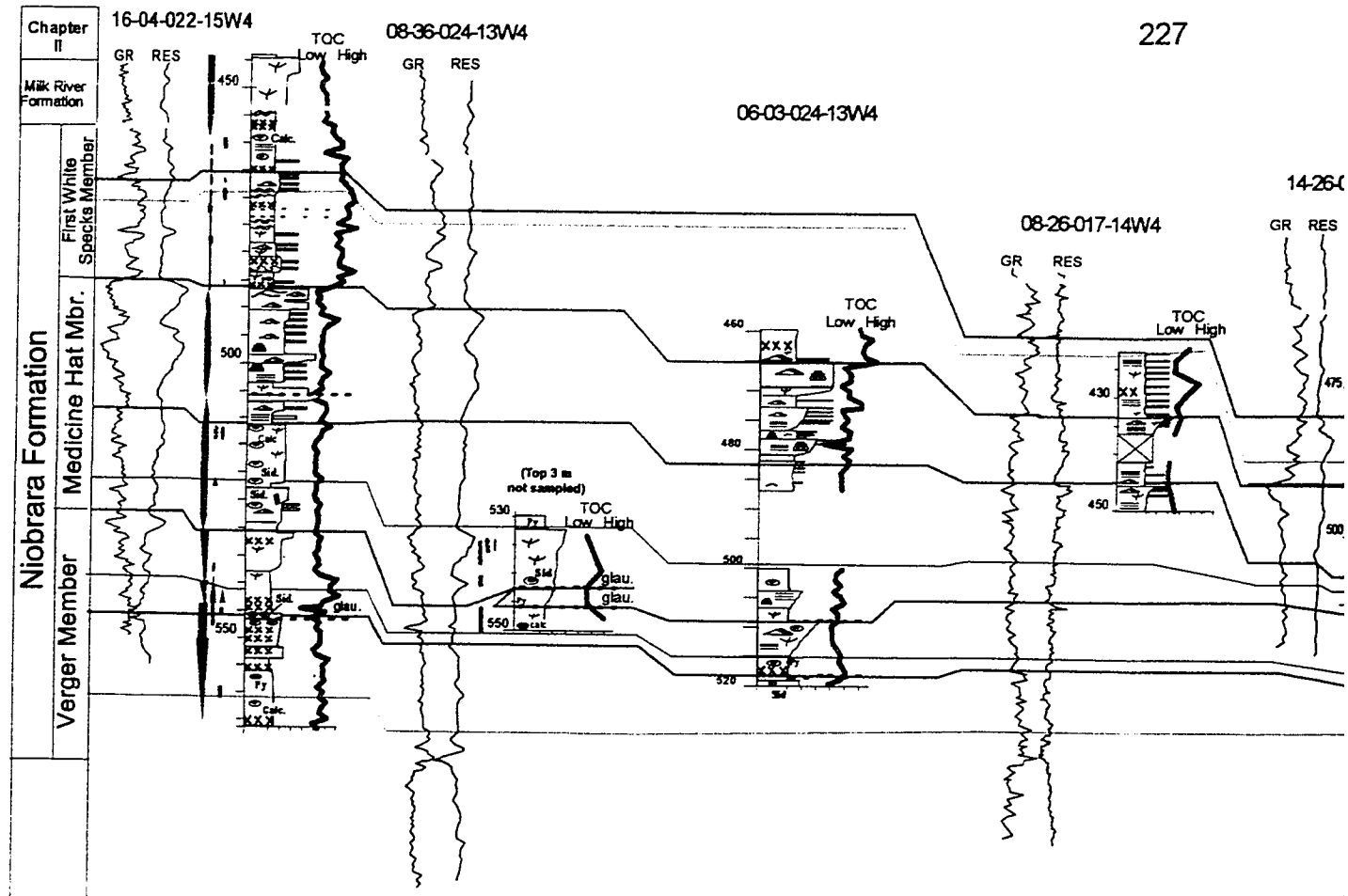

a) ISOPACH Sequences F7 to F13 NIOBRARA FORMATION
T29
T26
T22
T18
T14
T10
T6
T2
R1W5
R28
R24
R20
R16
R12
R8
R4
R1W4
R26
R22
R18W3
e) Isopach sequence F12 and transgressive part of F13 (First White Specks Member)
d) Isopach sequence F10 and F11 (Medicine Hat Member)
C) Isopach Sequence F9 (Upper Verger)
b) ISOPACH Sequence F8 (Lower Verger M.)

Figure 3-19

Figure 3-20. Cores and outcrop (Deer Creek) cross-section of the Carlile and Niobrara formations. The section shows the correlation of the upper 6 sequences (F8 to F13) and the lower sequences (F1 to F7) in the Deer Creek outcrop. The pebble layer at the lower boundary of sequences F9 and F10 are illustrated with the logs and cores from location: 16-4-22-15W4. 8-36-24-13W4 and 6-3-24-13W4.



Sedimentology

Cross Bedding\ lamination		Shell debris layer	
Lenticular bedding		Shell fragments	
Parallel lamination		Coal fragment	
Hummocky		Pebbles	
Normal graded bedding or lamination		Fault	
Dewatering		Concretion	
Bioturbation	slight / moderate / intensive	Cone on Cone structure	
Ammonite		Bentonite	
Fish remains		Pyrite	Py
		Siderite	Sid

Geochemistry and boundaries

High Low

Total Organic Content (TOC)

Formation and sequence boundary

First Major Flooding surface and Sequence boundary

Maximum Flooding Surface

Micropaleontology

Relatively abundances of Foraminifera

Agglutinated

Calcareous Benthic

Planktic

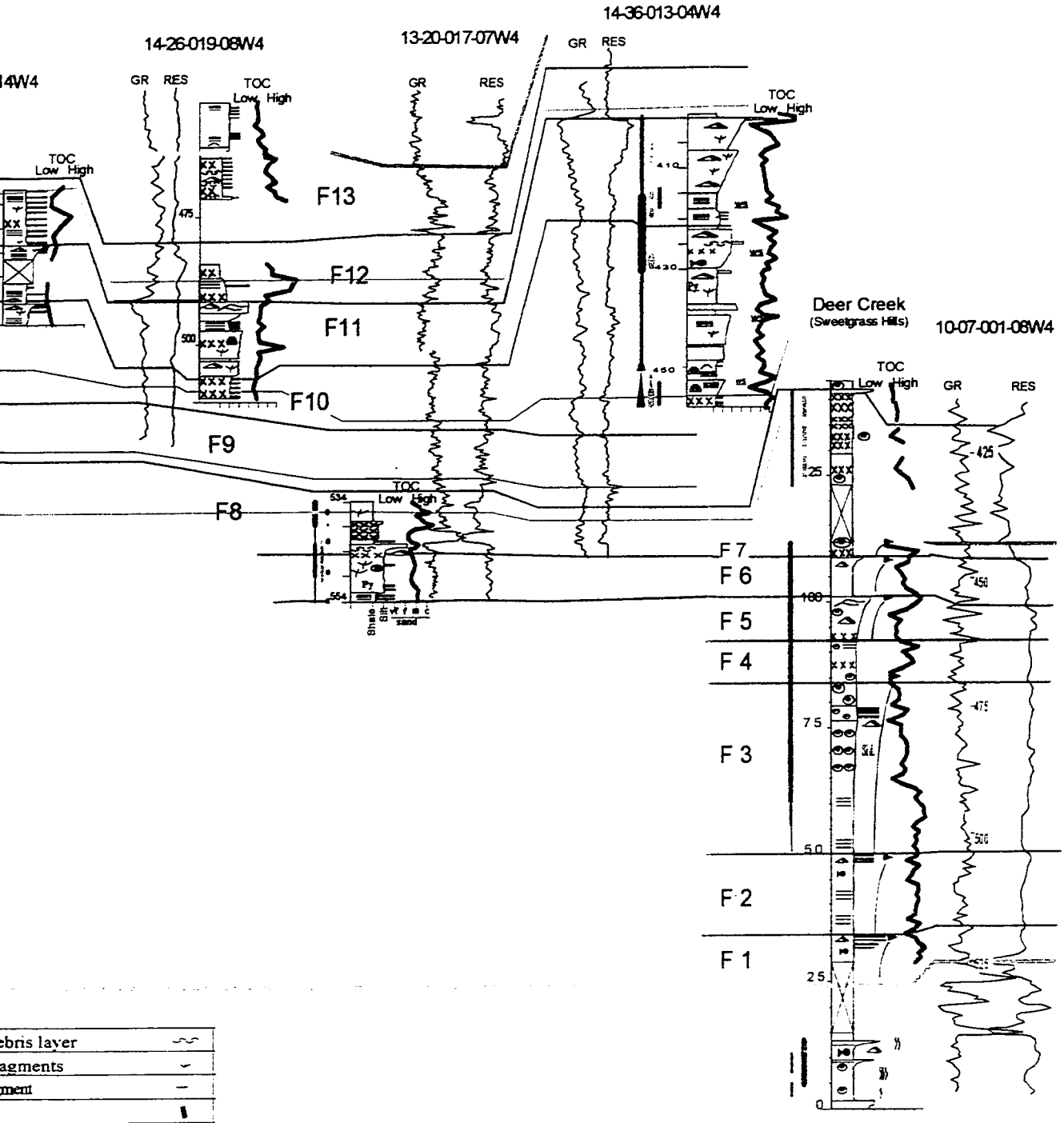
abundant

common

few

Figure 3-20

227



ebris layer	
agments	
ment	
tion	
Cone structure	
ite	
	Py
	Sid

e 3-20

Figure 3-20

Figure 3-21. Isopach maps of sandstones from sequences F9 to F11 from the upper Verger Member and Medicine Hat Member. **a**) Isopach map of the three sandstones from sequence F9; Verger 1, 2 and 3, which all are deposited in the highstand system tract. **b**) Isopach map of the Medicine Hat sandstones 1, 1a, 2 and 4 in sequence F10. Medicine Hat sandstones 1 and 1a are deposited within the transgressive system tract and are elongated and orientated southwest-northeast. Medicine Hat sandstone 4 is an early lowstand deposit. **c**) Isopach map of the Medicine Hat sandstones 3, 3a and 5 in sequence F10. The sandstones 3 and 3a are deposited in the highstand systems tract and sandstone 5 is a late lowstand deposit. **d**) Isopach of the Medicine Hat sandstones 6 and 6a. Sandstone 6 was deposited in the transgressive system tract and is composed of a south and north portion. Sandstone 6a is a major sandstone orientated east-west and covers most of southern Alberta below township 14. **e**) Isopach maps of Medicine Hat sandstones 7 and 7a are both deposited in the transgressive systems tract. **f**) Isopach map of the two major sandstones of the Medicine Hat Member; Sandstones 8 and 9. Medicine Hat sandstone 8 was a highstand deposit, which might be connected to a shoreline in the west (chapter III). Medicine Hat sandstone 9 in the east was a lowstand deposit and is the main gas producing sandstone of the Medicine Hat Member.

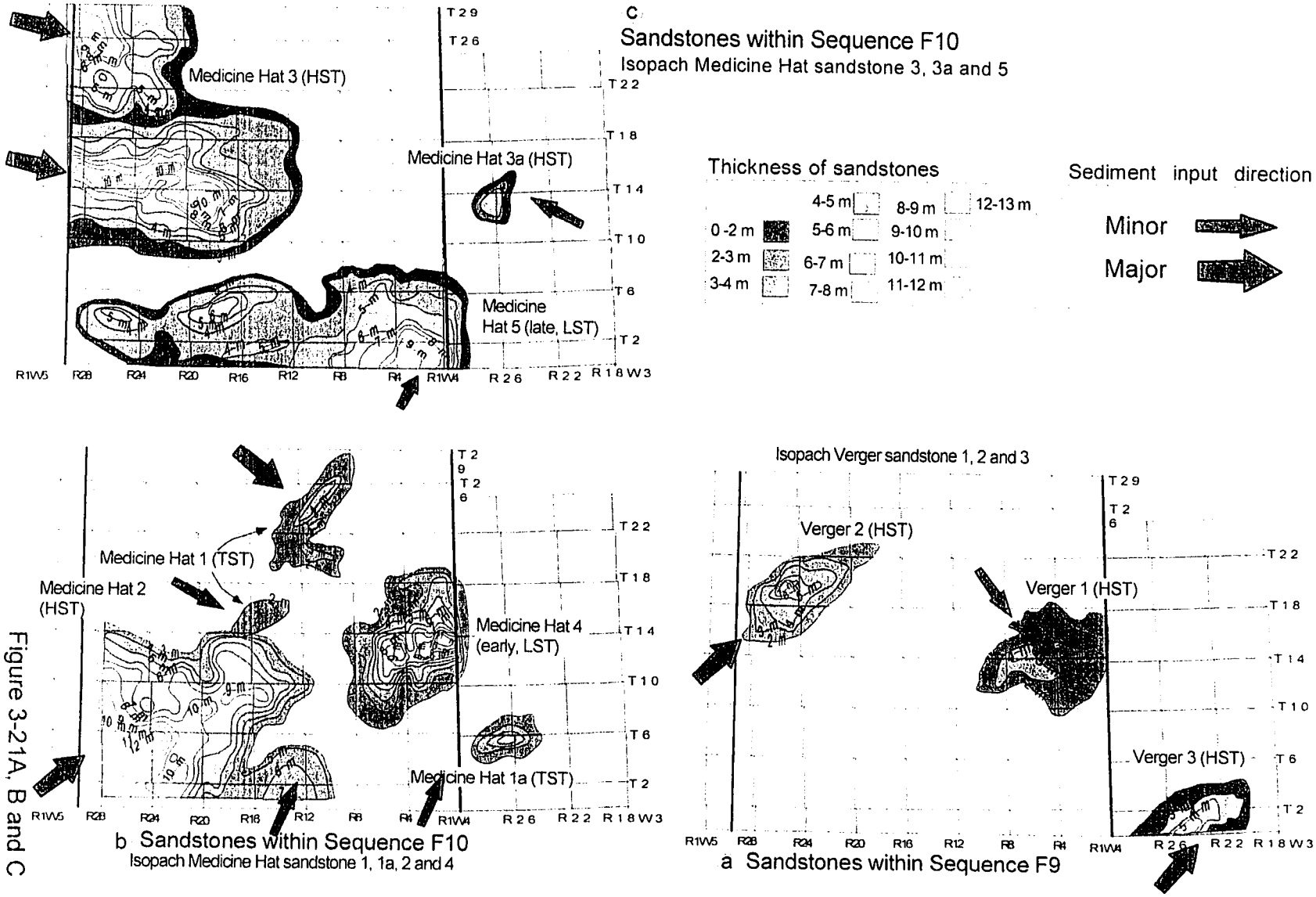
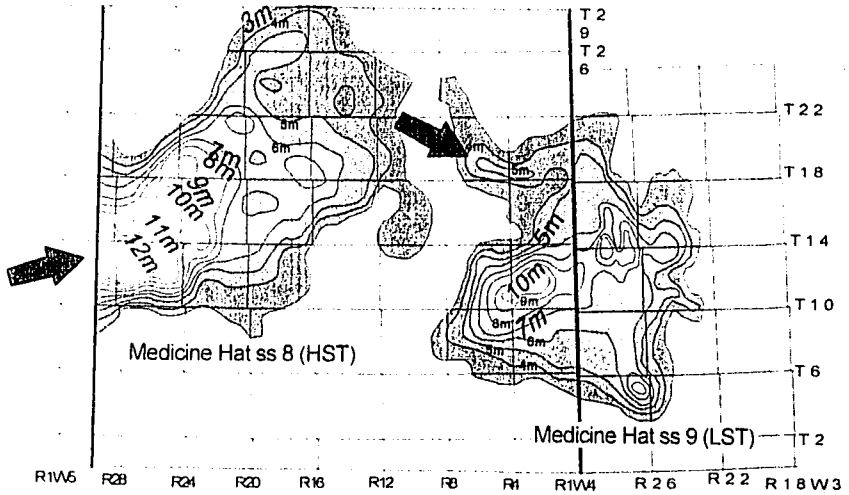


Figure 3-21A, B and C



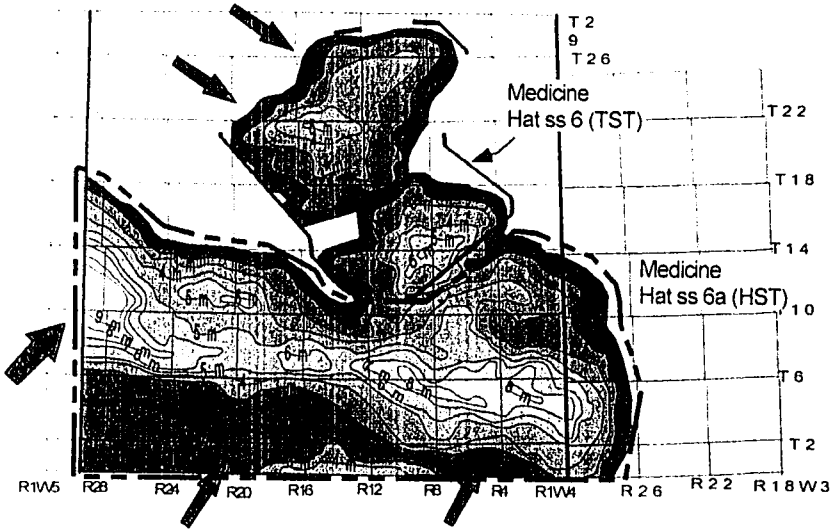
f Sandstones within Sequence F11
Isopach Medicine Hat sandstone 7 and 8

Thickness of sandstones

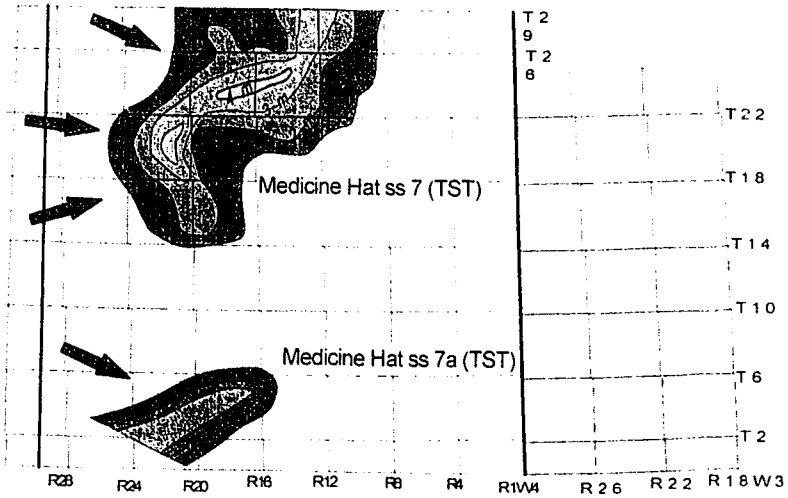
0-2 m
2-3 m
3-4 m
4-5 m
5-6 m
6-7 m
7-8 m
8-9 m
9-10 m
10-11 m
11-12 m
12-13 m

Sediment input direction

Minor
Major



d Sandstones within Sequence F11
Isopach Medicine Hat sandstone 6 and 6a



e Sandstones within Sequence F11
Isopach Medicine Hat sandstone 7 and 7a

Figure 3-21D, E and F

Figure 3-22. Bio-event correlation between the cores 16-4-2215W4 and 13-20-17-7W4 helps the wire-line correlations on cross-section III (figure 3-7) and enhances to interpret the stratal pattern of sequence F8.

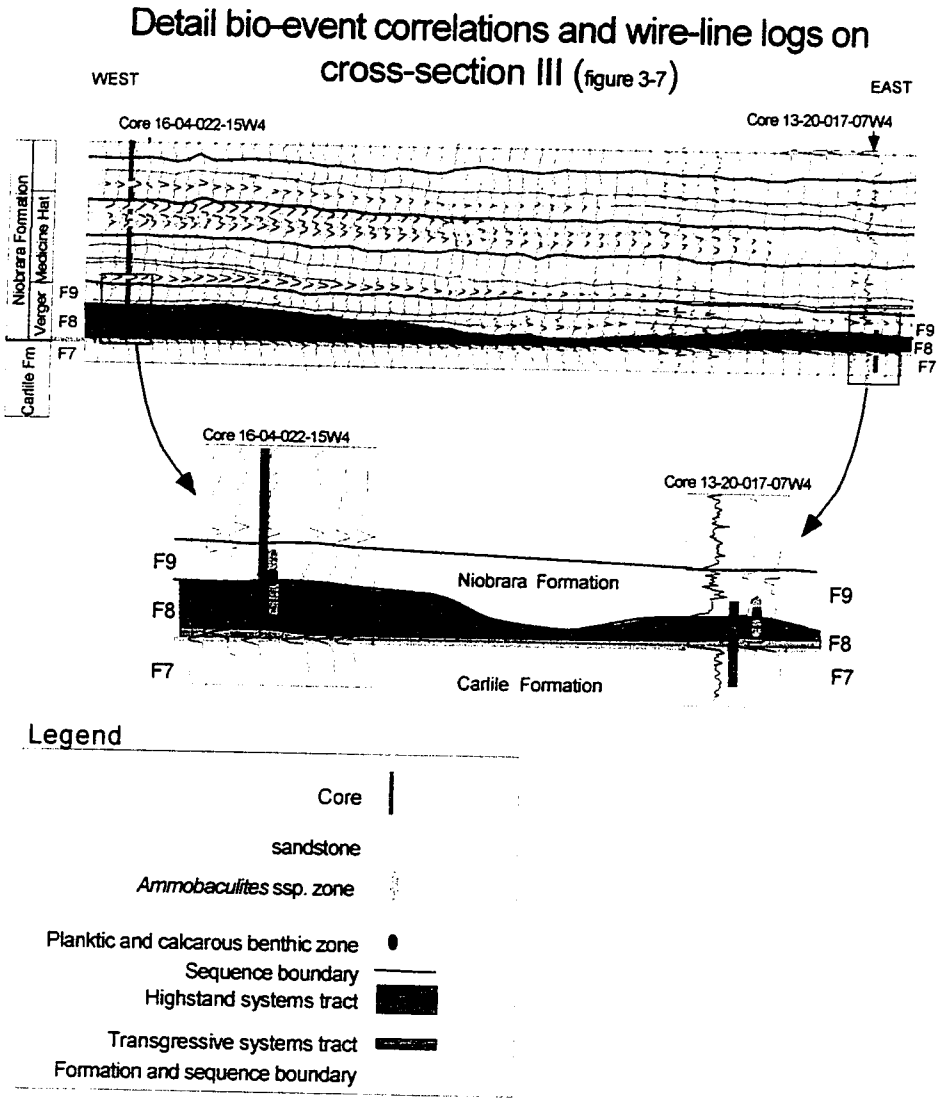

Detail bio-event correlations and wire-line logs on cross-section III (figure 3-7)
WEST
EAST
Core 16-04-022-15W4
Core 13-20-017-07W4
Niobrara Formation
Medicine Hat
Verger
Carlile Fm
F9
F8
F7
Niobrara Formation
Carlile Formation
Legend
Core
sandstone
Ammobaculites ssp. zone
Planktic and calcarous benthic zone
Sequence boundary
Highstand systems tract
Transgressive systems tract
Formation and sequence boundary

Figure 3-22

Figure 3-23. Core 16-4 22-15W4 is the most complete representation of the Niobrara Formation and is a reference core in southern Alberta and southwestern Saskatchewan. It also serves as type core for the Verger, Medicine Hat and First White Specks members (chapter II). The sequence stratigraphic subdivision illustrates the upper five sequences of the Niobrara sequence-set (F9 to F13).

16-4-22-15W4 Type core of the Niobrara Formation (*Chapter II*)

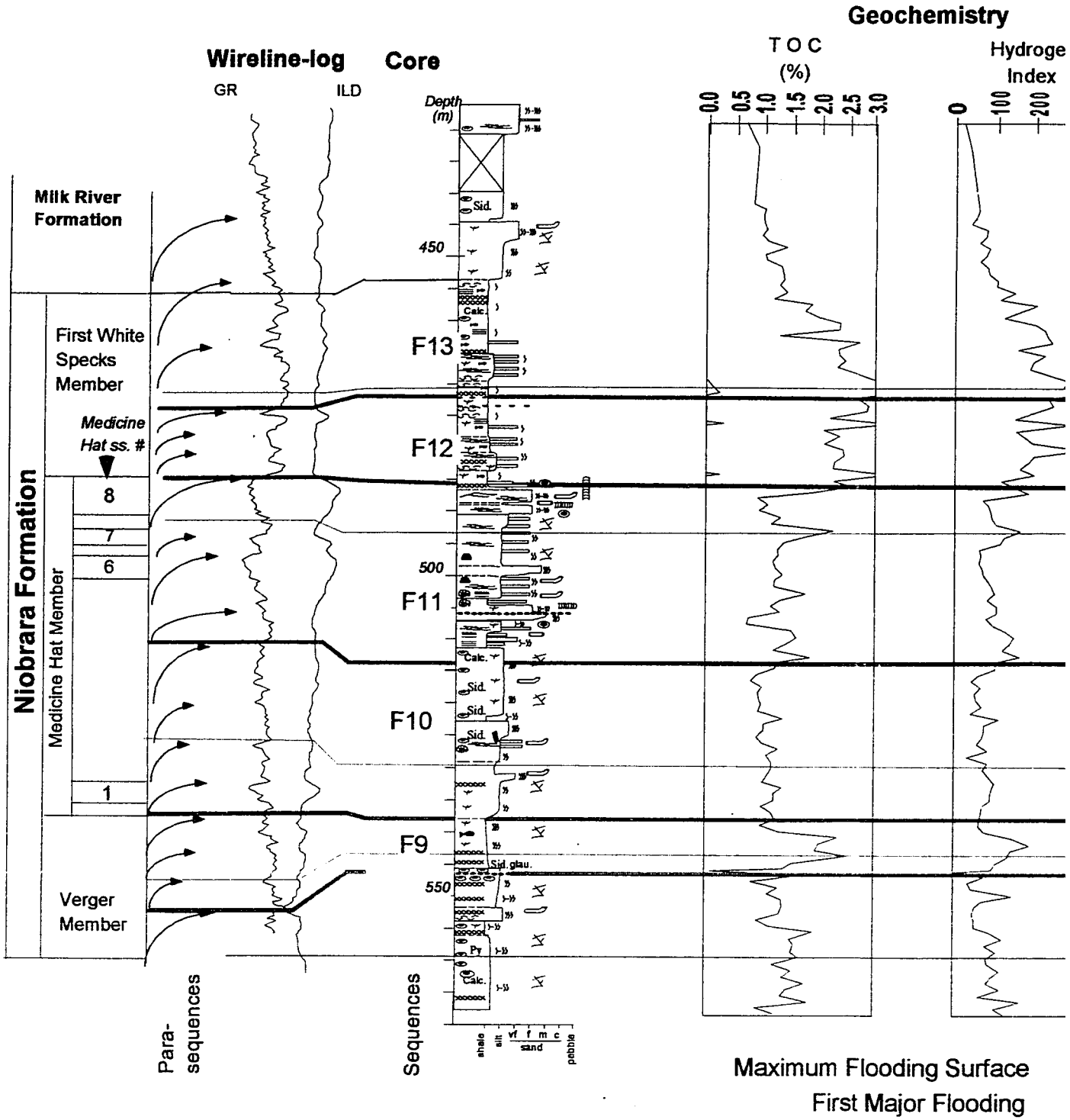


Figure 3-23

234

r II)

Geochemistry

Micropaleontology

Foraminifera

Benthic

Hydrogen Index

0 100 200 300 400

2.5 3.0

Aggl. Calc. Planktic

Nanno-Fossils

Flooding Surface

st Major Flooding

e 3-23

Figure 3-23

Figure 3-24 a and b. General east-west (**a**) and north-south (**b**) oriented stratal pattern of the Carlile (F1 to F7) and Niobrara sequence-sets (F8 to F13). The diagram simplifies the stratal patterns and shows major correlation trends and the differences in stratal patterns between the two sequence-sets. The Carlile sequence-set is dominated by parallel to sub-parallel sequence boundaries whereas the Niobrara sequence-set is more complex showing a variety of high-angled and low-angled strata.

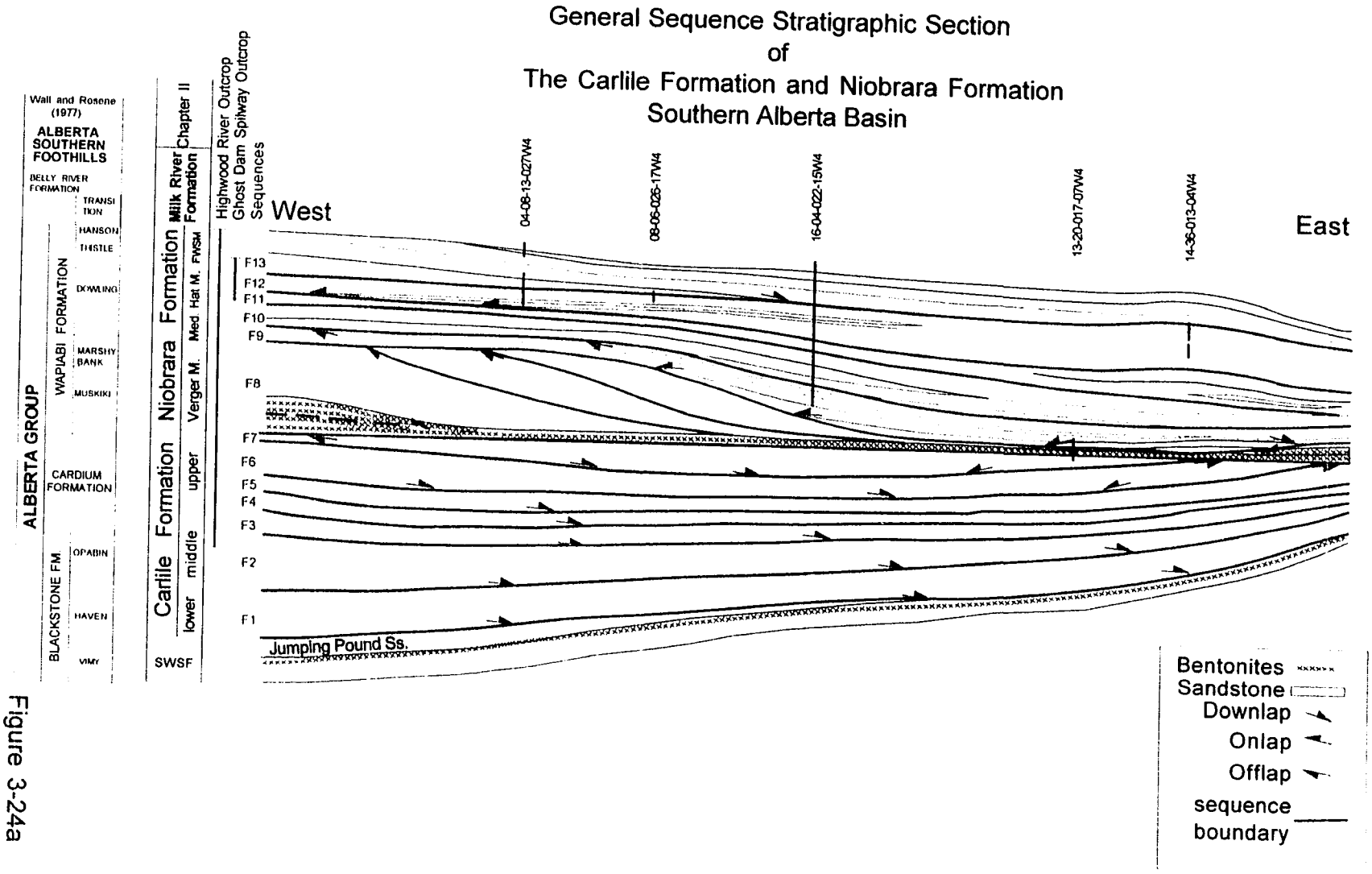

General Sequence Stratigraphic Section
of
The Carlile Formation and Niobrara Formation
Southern Alberta Basin
Wall and Rosene (1977)
ALBERTA SOUTHERN FOOTHILLS
BELLY RIVER FORMATION
ALBERTA GROUP
WAPIABI FORMATION
TRANSITION
HANSON
THISTLE
DOWLING
MARSHY BANK
MUSKIKI
CARDIUM FORMATION
BLACKSTONE FM
OPABIN
HAVEN
VIMY
Carlile Formation
Niobrara Formation
Milk River Formation
Chapter II
lower
middle
upper
Verger M.
Med. Hat M.
FWSM
SWSF
Highwood River Outcrop
Ghost Dam Spillway Outcrop
Sequences
West
East
04-08-13-027W4
08-06-026-17W4
16-04-022-15W4
13-20-017-07W4
14-36-013-04W4
F13
F12
F11
F10
F9
F8
F7
F6
F5
F4
F3
F2
F1
Jumping Pound Ss.
Bentonites
Sandstone
Downlap
Onlap
Offlap
sequence boundary

Figure 3-24a

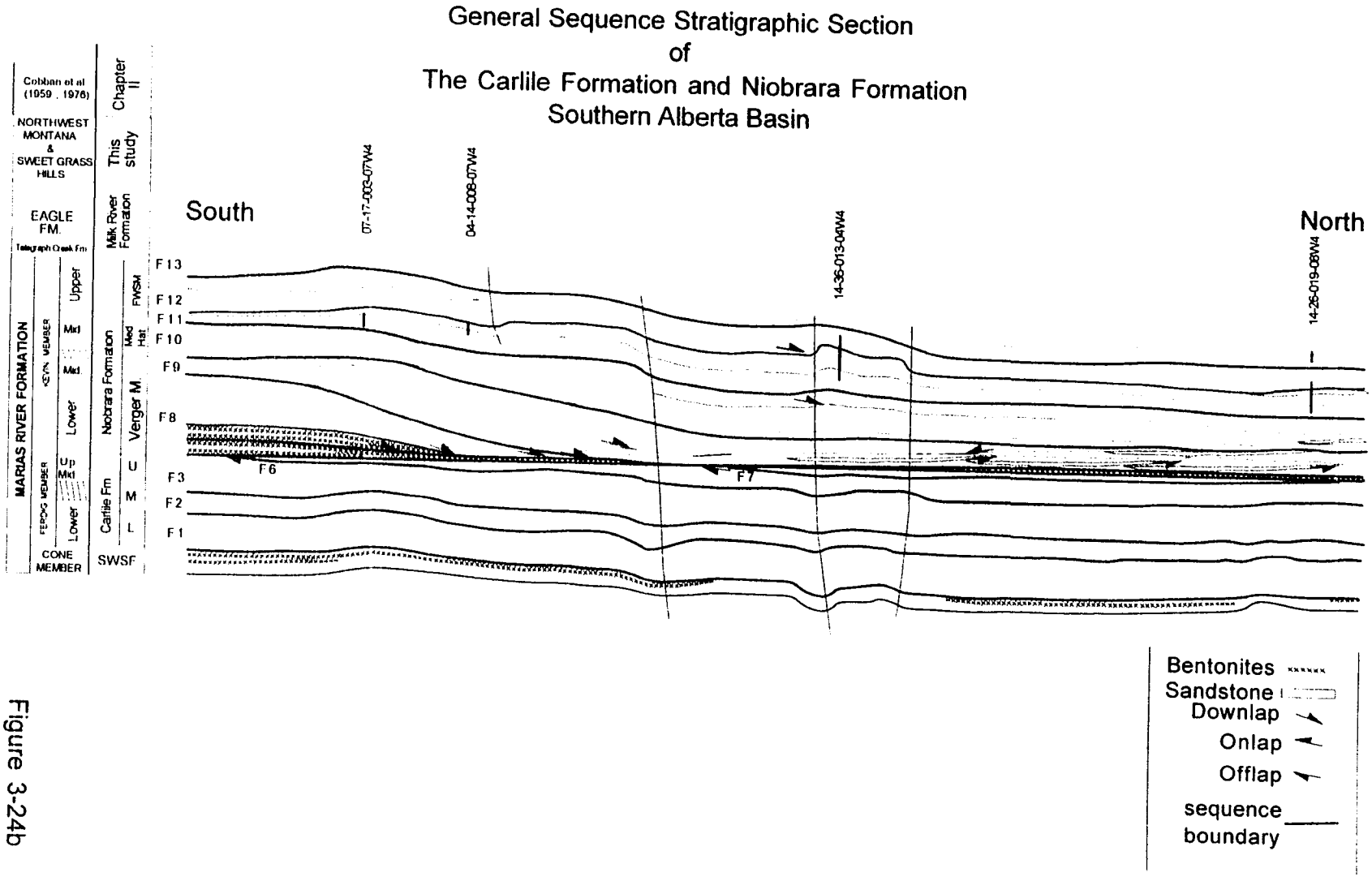

General Sequence Stratigraphic Section
of
The Carlile Formation and Niobrara Formation
Southern Alberta Basin
Cobban et al (1959 , 1976)
NORTHWEST MONTANA & SWEET GRASS HILLS
EAGLE FM.
Telegraph Creek Fm
MARIAS RIVER FORMATION
KEYA MEMBER
FERDIG MEMBER
CONE MEMBER
Upper
Mid
Mid.
Lower
Up Mid
Lower
Chapter II
This study
Milk River Formation
Niobrara Formation
Carlile Fm
SWSF
FWSM
Med Hat
Verger M.
U
M
L
South
North
07-17-003-07W4
04-14-008-07W4
14-36-013-04W4
14-26-019-06W4
F13
F12
F11
F10
F9
F8
F6
F7
F3
F2
F1
Bentonites
Sandstone
Downlap
Onlap
Offlap
sequence boundary

Figure 3-24b

Figure 3-25 a and b. Variation in accommodation space and relative rates of sediment input for the Carlile and Niobrara sequence-sets are illustrated in an east-west (a) and a north-south (b) cross-section. To illustrate the changes in water masses through time. the presence of planktic foraminifera is indicated as well. It is notable that through the Carlile time no planktic foraminifera were found whereas especially the underlying Second White Specks Formation. but also the overlying Niobrara Formation have an assemblage of planktic foraminifera. The thick bentonite swarm overlying the formation boundary between Carlile and Niobrara formations is also indicated.

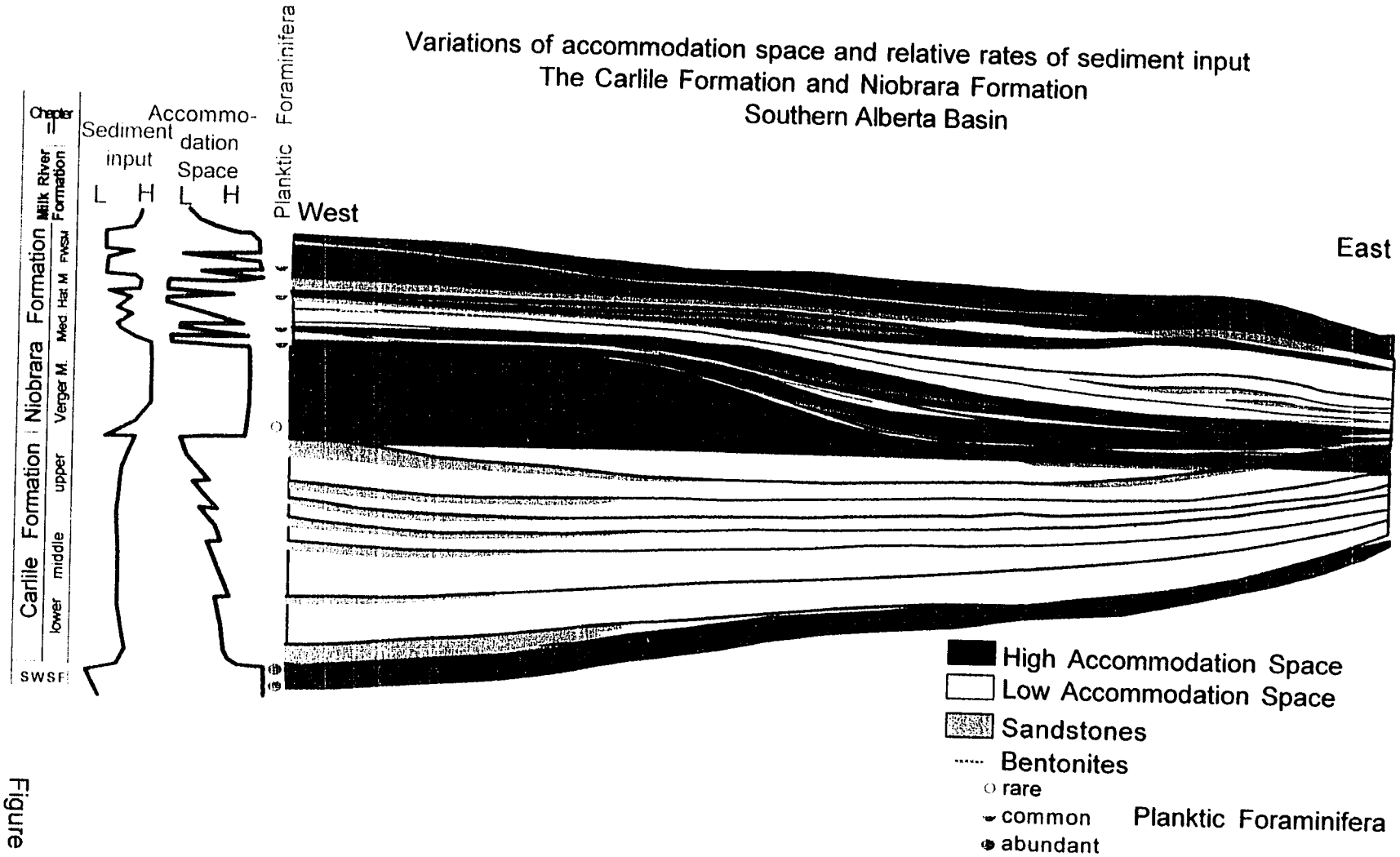

Variations of accommodation space and relative rates of sediment input
The Carlile Formation and Niobrara Formation
Southern Alberta Basin
Chapter II
Carlile Formation
Niobrara Formation
Milk River Formation
lower
middle
upper
Verger M.
Med. Hat M.
FWSM
SWSF
Sediment input
L H
Accommo-dation Space
L H
Planktic Foraminifera
West
East
High Accommodation Space
Low Accommodation Space
Sandstones
Bentonites
rare
common
abundant
Planktic Foraminifera

Figure 3-25a

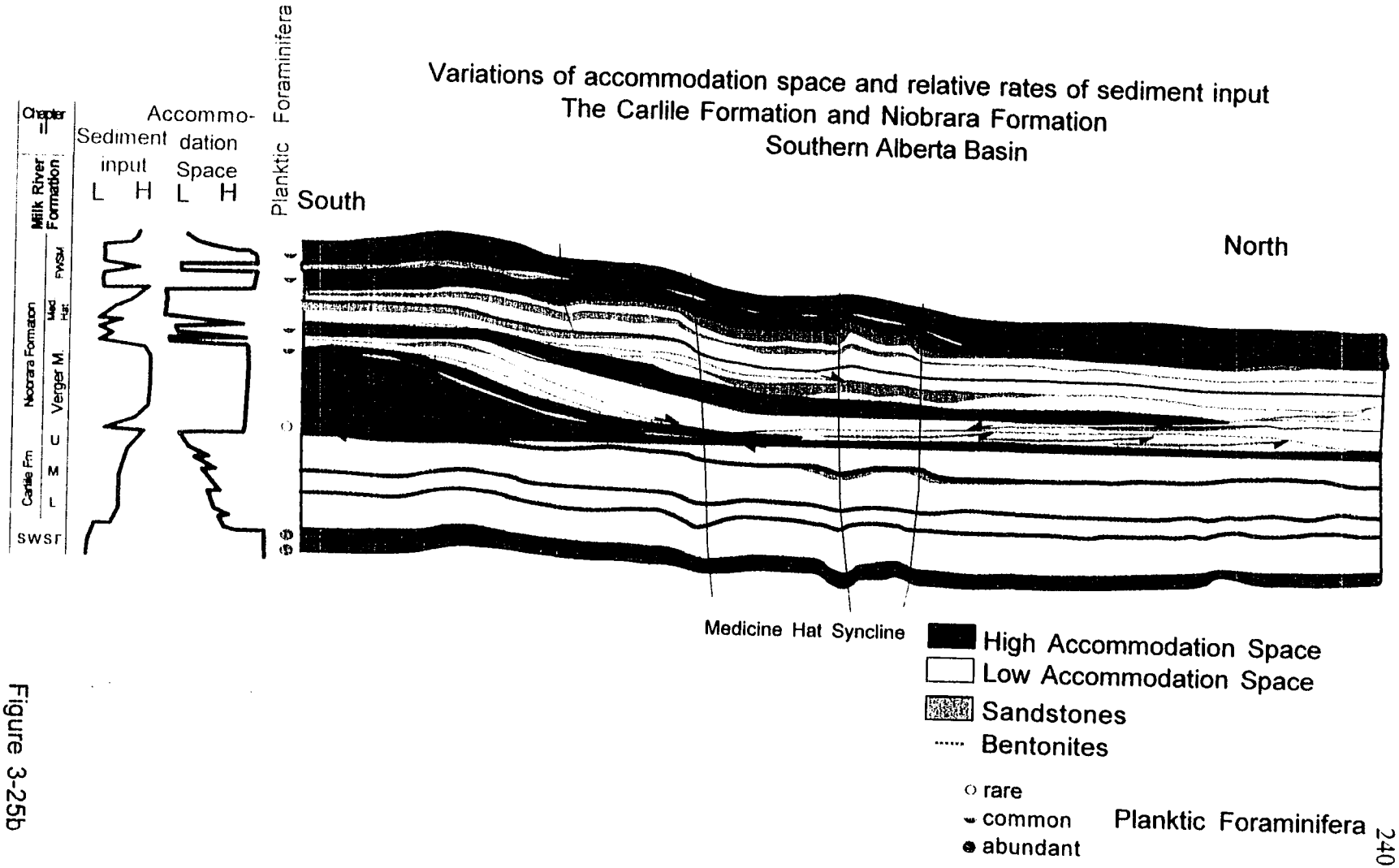

Variations of accommodation space and relative rates of sediment input
The Carlile Formation and Niobrara Formation
Southern Alberta Basin
Chapter II
Milk River Formation
Niobrara Formation
Carlile Fm.
Verger M.
Med Hat
PWSM
U
M
L
SWST
Sediment input
L H
Accommo-dation Space
L H
Planktic Foraminifera
South
North
Medicine Hat Syncline
High Accommodation Space
Low Accommodation Space
Sandstones
Bentonites
rare
common
abundant
Planktic Foraminifera

Figure 3-25b

Chapter IV

PALEOENVIRONMENT OF THE CARLILE AND NIOBRARA FORMATIONS IN SOUTHERN ALBERTA AND SOUTHWESTERN SASKATCHEWAN

ABSTRACT

The Late Cretaceous Upper Colorado Group, including the Carlile and Niobrara formations, reveals a complex and dynamic basin system in southern Alberta and southwestern Saskatchewan. An integrated study of the lower offshore to shelf environment, including sedimentology, geochemistry, petrophysics and micro-paleontology indicates that relative sea-level fluctuations played a major role in the facies distribution and paleogeography of the Interior Seaway.

Nine paleogeographic maps illustrate the facies of the north-central part of the Interior Seaway of North America from Late Turonian to Santonian. The maps are based on our study of southern Alberta and southwestern Saskatchewan and integrated with regional studies of the same interval in Western Canada and northwestern states of the US. The maps show a gradual infill of the basin during the regressive part of the Greenhorn Cycle, represented by the Carlile Formation. The Interior Seaway reached its maximum extension during the peak transgression of the Greenhorn cycle (Middle Turonian) and the basin was gradually infilled during the Carlile Formation. The boundary between the Carlile and Niobrara formations is an angular unconformity (see chapter III) where up to 20 m of the upper Carlile Formation was eroded. At this time (late Late Turonian) the Interior Seaway was a narrow Seaway of a few hundred

kilometers with its axis in eastern Alberta. Marginal marine sandstones were deposited in western Alberta (Cardium Formation) and central Saskatchewan (Bowdoin sandstone).

The overlying transgressive part of the Niobrara Cycle shows multiple dramatic basin changes, with two examples of complete lowstand drainage implied by the Verger Member (Coniacian time). These lowstand events occurred in-between shale deposition which indicate fully marine distal conditions. During the deposition of the Medicine Hat Member (Santonian), changes from a shaly to a sandy shelf took place with deposition of thirteen sandstones in the vicinity of the Bow Island Arch of southern Alberta. During lowstand periods with low accommodation space, the Bow Island Arch affected sedimentation, whereas during high accommodation space, the arch had no influence. A subtle syncline is the primary reason for deposition of the main gas producing sandstone of the Medicine Hat Member. The maximum extension of the Interior Seaway occurred during the Niobrara Cycle with the deposition of the First White Specks Member (Late Santonian).

INTRODUCTION

Paleoenvironments of the Late Turonian to Late Santonian Carlile and Niobrara formations in Alberta and Saskatchewan (see chapter II and figures 4-1 and 4-2) are interpreted in a multidisciplinary study. Fine-grained sandstones and pebble layers in a basin generally dominated by shales and siltstones gives evidence of a dynamic sedimentary system. This paper is part of a study describing in detail the Upper Colorado Group (see chapter II and III) whereas Bloch et al. (1993) addressed the stratigraphy of the Lower Colorado Group.

Integration of several geo-disciplines demonstrate the complex evolution of the Western Interior Seaway of Canada and part of the northern United States during the Late Cretaceous. New techniques in chapter III and an extensive data-set allow illustration of highly variable stratal patterns that outline a multi-event infill history of the basin. Sedimentology, geochemistry, micropaleontology and stratal geometry reveal a complex paleoenvironmental history.

The paleoenvironment of the Upper Colorado Group of southern Alberta and southwestern Saskatchewan is poorly understood and previously interest has mainly been focused on the sandstone deposits within the interval (Martin, 1965; Hancock and Glass, 1968; Hankel et al., 1989; Schröder-Adams et al., 1997). The objective of this study is a paleoenvironmental analysis of the entire Upper Colorado Group from Late Turonian to Santonian including the shaly and silty intervals. The value of shale and siltstone is often ignored, but contain valuable information that can explain the depositional environment of the adjacent sandstones, by including especially micropaleontology, geochemistry and ichnology. The multidisciplinary approach allows us to reconstruct facies distribution,

sediment input directions, depocenter migration and the general physiographic evolution of the Interior Seaway.

The discussion on the origin of isolated shelf sandstones has been ongoing for the last 20 years and is still controversial (Johnson and Baldwin, 1986; Plint, 1988; Tillman et al., 1985; Swift and Thorne, 1991; Walker and Plint, 1992; Snedden and Bergman, 1999; Galloway, 2002). The Medicine Hat Member of the Niobrara Formation contains 13 mappable isolated fine-grained sandstones, which have great value to the petroleum industry due to their biogenetic gas, but their paleoenvironments have never been addressed. Few good modern or ancient analogues exist for these widespread (up to 3000 km^2) fine-grained sandstones (Palmer and Scoot, 1984; Swift et al., 1976; Swift et al., 1986; Swift and Rice, 1984; Rice, 1984; Galloway, 2002) and the origin and geological setting of these sandy shelf deposits needs still to be resolved. With little knowledge of the paleo-shoreline at the time of sandstone deposition, I am using indirect data such as the predominate stratal patterns, facies associations, micropaleontology and geochemistry to reconstruct the most likely setting of the interior seaway in southern Alberta and southwestern Saskatchewan.

The Upper Colorado Group or its equivalent have been analyzed in several regions bordering our study area, in both Western Canada and the northern United States (Stott, 1962; Cobban et al., 1994; Williams and Stelk, 1975; Lang and McGookey, 1988; Schröder-Adams et al., 1998; Hattin, 1975; McNeil and Caldwell, 1981; Wright and Walker, 1981; Park, 1965; Cobban et al., 1976; Wall, 1967a; Wall and Rosene, 1977; North and Caldwell, 1975; Plint and Norris, 1991; Longman et al., 1994; Hu, 1997).

Correlation of these studies with our results have concluded in nine new paleogeographic maps of western Canada and northern United States covering Late Turonian to Santonian.

DATA

Wire-line logs from 2800 wells, organized in closely spaced cross-sections in southern Alberta and southwestern Saskatchewan (figure 4-1), are used to correlate and map the Carlile and Niobrara formations (see chapter III). For facies control, the cross-sections are tied to 81 cores and 5 outcrops, the latter from the Rocky Mountain Foothills and northern Montana (see appendix in chapter II). Where cores are available, log-facies are interpreted from an integrated facies analysis including sedimentology, ichnology, micropaleontology and organic geochemistry. Most cores are situated in sandstones of the Medicine Hat Member providing good facies control on the main hydrocarbon reservoir sandstones of the Niobrara Formation. Detailed lithological descriptions of the formations are available in chapter II, and the stratal pattern outlines and the sequence stratigraphic subdivision are illustrated in chapter III.

METHODS

The methodology integrates sedimentology, micropaleontology, organic geochemistry and petrophysical wire-line correlations. For micropaleontological and geochemical analysis, samples were collected at one meter intervals. For micropaleontology, 540 samples were processed from 11 cores and 5 outcrops. A total of 810 samples were processed for organic geochemistry from 24 cores and 2 outcrops (appendix in chapter II). For petrographic analysis 45 samples were collected from primarily sandstones, which were classified and their chemical and physical maturity

determined (pers. comm., El Dein,, 1999). In general, sample spacing was decreased in intervals of specific interest, such as lithological and sequence stratigraphic boundaries.

Samples for foraminiferal analysis were prepared using the standard method of Then and Dougherty (1983). The existing general foraminiferal zonation of Caldwell et al. (1978) in the Western Interior Seaway has been used to establish a biostratigraphic subdivision of the interval. Selected core samples were examined for their nannofossil content, and are incorporated into the paleoenvironmental framework (pers. comm. Jim Craig, 1999). Macrofossils were identified by J. Haggert (GSC, Vancouver) and C. Collom (Mount Royal College, Calgary).

Rock-Eval pyrolysis was used to characterize the maturity and type of organic matter deposited in the sediments. Using the technique and methods of Espitalié et al. (1977; 1984); Peters (1986) and Tissot et al. (1987), the samples were processed and analyzed for their total organic carbon content (TOC), Hydrogen Index (HI) and level of thermal maturity (T_{max}, S1, S2, S3). Effects of weathering on the organic geochemistry of outcrop samples were corrected based on methods outlined by Espitalié et al. (1984) and Leythaeuser (1973). For details see chapter II.

Densely spaced resistivity wire-line logs are chosen for correlations in the marine upper Colorado Group (see chapter III). The gamma-ray, sonic and density logs are important for lithology interpretations, but are more affected by borehole caving, which increases the risk of misinterpretation. It is therefore recommended to use resistivity logs for correlations in this interval and use of the gamma-ray only with caution. Standard descriptive terminology for log trends and patterns are used (Cant, 1992).

The paleogeographic maps presented in this paper are based on results from our study and closely integrated with published paleoenvironmental data from the region including the central and southern Interior Seaway in Canada and the northern states of America. Precise locations of marginal marine and coastline environments throughout the Upper Cretaceous time are poorly known, especially on the eastern margin. Where unknown or non-preserved coastlines of these environments were estimated and extrapolated from the existing and commonly more distal sedimentation. I primarily concentrated and interpreted the facies within the detailed study area, and then compared and correlated to the surrounding regions.

GEOLOGICAL SETTING AND STRATIGRAPHY

The Greenhorn and Niobrara second order sea-level cycles are described from the Late Cretaceous Interior Seaway in the US and Canada (Kaufmann, 1967; McNeil and Caldwell, 1981; Caldwell et al., 1993). The Carlile Formation represents the regressive phase of the upper Greenhorn Cycle, whereas the transgressive part of the Niobrara Cycle encompasses the Niobrara Formation consisting of the Verger, Medicine Hat and First White Specks members (figures 4-2 and 4-3; see chapter II).

The Carlile Formation is an eastward thinning, 40 to 160 m thick, non-calcareous shale (figure 4-4) and is informally subdivided into a lower, middle and upper unit based on lithology (see chapter II). The lower boundary of the Carlile Formation is the top of the calcareous Second White Specks Formation marked by a distinct biostratigraphic and lithological change (Bloch et al., 1993). The upper boundary is marked sharply by the bentonite zone at the base of the overlying Verger Member. The foraminiferal fauna from

the Carlile Formation shows similarities with the Morden Shale in southern Manitoba (McNeil and Caldwell, 1981) and the Haven and Opabin members of the Blackstone Formation in the Alberta Foothills (Wall, 1967b).

The Niobrara Formation is a northeastwards thinning 80 to 240 m thick unit (figure 4-5), which is subdivided into three mappable members, the shaly Verger, the sand-rich Medicine Hat and the calcareous First White Specks members. The foraminifera assemblages belong to the *Trochamina* sp., *Bullopora laevis* and *Globigerinelloides* sp. zones (Caldwell et al., 1978), dating it from Coniacian to Santonian and locally to Early Campanian. The Verger Member is a 20 (northeast) to 120 m (southwest) thick shaly interval. The member is slightly bioturbated with minor sand beds and contains at least two pebble layers near the top. Thin beds of white specks occur, resembling the appearance of the overlying First White Specks Member. The Medicine Hat Member is between 40 and 65 m thick and consists of fine-grained sandstone beds separated by shale and siltstone. The foraminifera assemblage represents the *Trochamina* sp. - *Bullopora laevis* Zone, which places the member in the Santonian (Caldwell et al., 1978). The 20 to 80 m thick First White Specks Member is the youngest member of the Niobrara Formation, and is a dark gray calcareous shale with abundant fecal pellets rich in nannofossils. One of the thickest sandstones in the First White Specks Member is named the Sweetgrass Member, situated northwest of the Sweetgrass Arch (Schröder-Adams et al., 1997). The member has a foraminiferal assemblage of the *Globigerinelloides* sp. Zone providing a Late Santonian age (Caldwell et al., 1978; McNeil and Caldwell 1981; Schroder-Adams et al., 1998).

Deposition of Late Cretaceous sediments in Western Canada took place in the asymmetrical foreland basin of Western Canada, with maximum subsidence and sediment accumulation rates in the basin foredeep to the west and declining rates to the east (Leckie et al., 1994). Voluminous sediment input was derived from the rising Cordillera in the west (Leckie et al., 1994; McNeil and Caldwell, 1981; Shurr and Rice 1986). Consequently the overall geometry of the Upper Colorado Group is wedge shaped, thinning eastwards (Leckie et al., 1994). Foreland basin tectonics were locally complicated by the Sweetgrass Arch (figure 4-6). In southern Alberta this complex high, also named the Bow Island Arch, trends SW to NE and plunges northwards. The arch divides the Western Canada Basin into the Alberta Basin to the west and the Williston Basin to the east (figure 4-6).

FACIES DESCRIPTION

Individual facies are described and related to their depositional environment in table 4-1 and figure 4-7. The facies are identified based on lithology, sedimentary structures, micropaleontology, organic geochemistry and ichnofossils. The facies are fully marine shelf sediments ranging from lower shoreface to open shelf, with one exception, a paleosol interpreted from one outcrop in northern Montana. In general, all other facies are dominated open marine processes and most facies are laterally extensive for up to several hundred kilometers. Strata range from shale with no interbedded sandstone, to silty intrebedded sandstone with 10 to 50% shale (litharenite to lithic greywacke (Tucker, 1991).

Normally, facies analysis in marine deposits is related to the relative position of the sediments between the marine shoreline and the open shelf (Walker and Plint, 1992; Reading, 1986). A frequently used term is shoreface deposits (lower, middle or upper), which are shoreline connected deposits (Leckie and Krystinik, 1989; Elliott, 1986; Walker and Plint, 1992). It will be shown that most of the Medicine Hat sandstones were shoreline detached isolated shelf sandstones, with facies characters comparable to those in lower to middle shoreface settings. These sandstones are the result of the same processes and energy levels as lower or middle shoreface deposits resulting in comparable facies character (figure 4-7). Only one sandstone the Medicine Hat Member (sandstone 8), deposited in the west region, might have been connected to an unknown upper shoreface further west. For this reason, we subdivide the facies into a succession of energy levels rather than into proximal to distal settings (table 1 and figure 4-7). The chosen terms of energy levels and their related facies are described by Clifton (1986), and are used to interpret the paleoenvironments. For sediments deposited in low to moderate energy regimes, which includes most of the two formations, a threefold subdivision is chosen (MacEachern et al., 1999). This subdivision includes: 1) Upper offshore, dominated by low energy with frequent moderate energy events; 2) Lower offshore, characterized by low energy with infrequent moderate energy events; and 3) Shelf environments characterized by only low energy events. No strata interpreted to be deposited in the upper shoreface were observed. However, the lag facies VII is evidence of a high energy regime. Pebbles associated with the lag deposits originated from a terrestrial high energy environment (e.g., fluvial system) and were subsequent reworked by a transgressive high energy sea.

The following facies are observed:

Facies

I : Fine laminated calcareous shale.

II : Bioturbated and non-calcareous shale.

III : Shaly siltstone.

IV : Siltstone interbedded with fine sandstones.

V : Thin-bedded, fine-grained shaly sandstones.

VI : Bioturbated fine-grained shaly sandstones.

VII : Lag and related facies.

VIII : Paleosol.

FACIES ASSOCIATIONS

Four major facies associations are recognized as the main building blocks of the sediment infill of the basin (figure 4-8). They represent fully marine sedimentary successions in a low to moderate energy regime generally coincident with a in a middle shoreface to offshore regime, only interrupted by a few high energy pebble layers. The latter indicates that non-marine or marginal facies were present, but were subsequently eroded, leaving the lag behind. All other facies show different versions of upward-coarsening successions, and are relatively uncomplicated. Most facies boundaries are gradational with a few exceptions as the top of the upward-coarsening intervals in facies association A and D indicates (figure 4-8). The facies boundaries associated with facies VII (lag and related facies) and VIII (paleosol) are sharp and show a dramatic change in

environment or/and erosion. Where correlatable in the entire region, the latter surface qualifies as a sequence boundary (see chapter III).

Facies association A: Upwards-coarsening parasequence (low to moderate energy) (figure 4-8A)

Parasequences (Van Wagoner et al., 1988; 1990) are the most common facies association observed in the Niobrara Formation. A parasequence is a gradational upwards-coarsening facies succession including most of the facies described in table 1. The facies boundaries are gradational with the exception of the top boundary of the parasequence.

The lower part of the parasequence is the shaly facies of either I or II, which is overlain by the silty and bioturbated facies III. That is followed by facies IV, which is characterized by thin sand beds interbedded with siltstone and overlain by the sand-rich facies of V and VI. In some cases, only one of facies V or VI are present. The parasequence may be topped by facies VII, the pebble layer and associated facies, and is always overlain by facies I or II.

Interpretation of facies association A

A parasequence is a relatively conformable succession of genetically related beds or bedsets bounded by a marine-flooding surface or correlative surfaces (Van Wagoner et al., 1990). This definition meets the description of facies association A. The association is an upwards-coarsening unit that reflects a progradational sedimentary system (Van Wagoner et al., 1990) from a low energy environment at the base to a moderate energy level at the top. This is normally interpreted as a function of a lowering of the relative sea-level and a gradual approach to the shoreline and shallowing of the water depth (Van

Wagoner et al, 1990). However, facies association A is locally mapped as isolated deposits surrounded by offshore or shelf shale without obvious erosion of a contiguous nearshore facies. This indicates that facies association A reflects an upwards increase in the paleoenvironmental energy level, but is not necessarily an expression of proximity to the shoreline. Only regional mapping and the overall stratal pattern reveal the origin of the facies association.

Facies association B: Lower shoreface (moderate energy) with basal erosion (high energy) surfaces (figure 4-8B)

The facies association B is an upward-coarsening unit topped by the shaly facies I or II, with one or more high-energy events (facies VII, hummocky bed or broken shell-debris) in the lower part of sand-rich facies V or VI. The lower part of the facies association is a gradational upwards-coarsening of silty facies III and IV overlying shaly facies I and II. In the overlying sand-rich facies V or VI, at least one thin pebble layer (facies VII) occurs. The pebble layer, hummocky bed, or shell-debris layer is typically less than 3 cm thick. These layers indicate an erosional event, but is thought not to be significant as the facies below (I, II and III) are always preserved. The facies association's upper facies are characterized by a commonly bioturbated sand-rich facies overlain by a shaly facies I or II.

Examples: core 6-8-26-19W4, 852-843 m; 8-6-26-17W4; 774-771 m; 4-8-13-27W4, 5410-5400 ft; Highwood River outcrop, at 260 m mark.

Interpretation of facies association B

The lower shoreface association with erosion surfaces (B) represents a progradational event during relative sea-level fall. The difference from facies association

A is the presence of a "higher energy layer" in the lower part of the sand-rich interval. This layer, consisting of pebble, hummocky beds or shell-debris, represent the marine regressive erosional surface due to a lowering of relative sea-level (Plint, 1988; Plint and Nummedal, 2000). As sea-level was lowered on a relatively low-angled shelf, storm-wave base (high energy) was also lowered and eroded into a lower shoreface basinwards of the prograding upper shoreface. This resulted in an abrupt lower boundary of the prograding shoreface, which is observed both in core and wire-line logs. This facies association is rare, and is mainly observed in the western part of the study area.

Facies association C: Transgressive lag enclosed in shale and siltstone (episode of high energy enclosed in low energy sediments); (figure 4-8C)

The facies association consists of thin (<10 cm) chert pebble layers and related facies of bone fragments, ooids and siderite cement (facies VII), which are enclosed in shale and siltstones (facies I, II or III). The lower part of the association is typically dominated by the offshore to outer lower shoreface shaly facies II or III. In some cases, facies II is directly overlain by the pebble layer (VII), but in most instances a thin remnant of the silty facies III is present. The lower contact of the lag is sharp.

Above the pebble layer (facies VII), shaly facies I or II are present, which develops into silty facies III. Micropaleontologically, a significant change is observed across the pebble layer. Below the layer, the fauna is dominated by agglutinated foraminifera whereas above (few meters above pebble layer), a mixed assemblage of agglutinated and calcareous benthic foraminifera and minor occurrences of planktic foraminifera occur.

Thin sections of the pebble layer and its calcareous cement show evidence of calcareous nodules, intraclasts, rootlets and ooids at the Kevin outcrop in northern Montana (figure 4-1; pers. comm., El Dein, 1999). The calcareous mudstone matrix (calcrete) shows sparry-filled micro-fractures and tubules, which possibly were formerly occupied by rootlets (Shanley and McCabe, 1994; Leckie et al., 1989).

Interpretation of facies association C

The lag deposit in the facies association C is a transgressive lag resulting from the wave ravinement of older deposits by a transgressing sea. The shale and siltstone facies below and above the pebble layer are low energy offshore and distal deposits, in contrast to the high energy nature implied by the pebble layers. The pebble lag and associated facies reveal that the eroded older deposits had a distinctive different facies than the shale and silty facies now enclosing it. A dense grid of wire-line logs shows the regional picture, with a minimum depth of erosion of 20 m towards the south and east of the study area (see chapter III). As indicated by a possible paleosol and the pebble layers, these lags represent the remnant of a terrestrial environment, which developed as thin lowstand bypass channel systems on a broad exposed shelf ((see chapter III); Allen and Posamentier, 1999; Posamentier, 2001). The reason why no thicker lowstand deposits were deposited is likely due to the lack of a nick-point on the shelf. Instead of incised valleys, a thin facies of pebble filled shallow channels (braided river system) with interfluves having possible soil formation developed, which would have been easily eroded by the transgressive sea, leaving only a lag behind.

Examples of facies C: Kevin outcrop, northern Montana; Highwood river outcrop (figure 4-24); core 16-4-22-15W4; 546 m (figure 4-11); core 8-36-24-13W4, 545 m (figure 4-11); 6-3-24-13W4, 520 m (figure 4-11).

Facies association D: Distal lower shoreface to offshore (low energy);(figure 4-8D)

This distal lower shoreface to offshore facies association dominates throughout much of the studied interval. The lower facies is shaly facies I or II, which might be slight to intensively bioturbated. Calcareous benthic or planktic foraminifera may be present in this shale and the TOC values are moderate to high (1.0 to 4.0 %). Gradually, facies I or II changes to facies III with a shaly siltstone facies along with common thin (< 3 cm) lenticular sandstone beds and concretions. Facies III is sharply overlain by facies II and this contact is the most notable boundary of facies association D. No pebbles were observed at the top of facies III.

Interpretation of facies association D

The facies association is part of the distal lower shoreface and offshore deposits and only subtle facies changes are observed. The upwards change from facies III to facies I/II is the most distinct boundary and is used as the sequence boundary (see chapter III), indicating a major flooding event.

Examples of D: Carlile Formation in Deer Creek, Sweetgrass, Montana; Verger Member and First White Specks Member of the Niobrara Formation.

RESULTS

PALEOENVIRONMENT OF THE CARLILE FORMATION

The facies association of the non-calcareous Carlile Formation (figure 4-4) is based on a composite outcrop in Deer Creek, Sweetgrass Hills, Montana and the core from 20-13-17-7W4 (figures 4-9 and 4-10). These facies are extrapolated to the rest of the basin using correlation of densely spaced resistivity log cross-sections (see chapter III). The sediments of the Carlile Formation are dominated by shales and siltstones and were deposited in a low-energy regime, which changed upwards from open shelf environment to lower offshore. The foraminiferal fauna consists mainly of agglutinated species, however, calcareous benthic and few planktic foraminifera are observed in the central part of the basin. The Carlile Formation overlies the Second White Specks Formation (Schröder-Adams et al., 1996), which represents the highest sea-level in the Interior Seaway during the Cretaceous (Caldwell and Kaufmann, 1993).

Facies Associations

Strata of the Carlile Formation are dominated by shale (facies II) and siltstone (facies III), and the only facies association present is D (figures 4-9 and 4-10). This facies association is repeated seven times in the study area as illustrated by the deposits at the Deer Creek outcrop and correspond to some of the sequences (figures 4-9 and 11) from the Carlile Formation (see chapter III).

The lower two facies associations (D1 and D2; each 10-15 m thick) are characterized by homogenous shale units with a few trains of starved lenticular sand beds of facies III. Neither concretions, macrofossils, bentonites or any other sedimentary

features are observed. The third facies association (D3) is 30 to 40 m thick and is characterized by a homogenous non-calcareous lower facies II overlain by facies III. which contains numerous sideritic concretions. some silty beds and a few thin bentonites. The fourth facies association D. about 15 m thick. includes sediments from sequence F4 and F5 and is a shale with few concretions and sandstone beds. The upper part of association D4 represents the most sand-rich part of the Carlile Formation. and is characterized by a silty shale with thin lenticular sand beds and rare thin. discontinuous mini hummocky beds. A few concretions are observed. including calcareous septarian and sideritic concretions. Facies association D5 is about 8 m thick in both the Deer Creek outcrop and core 13-20-17-7W4. Pyrite and abundant fish scales occur in the core of 13-20-17-7W4 (figure 4-10). which is missing in the Deer Creek outcrop, (figures 4-9). The overlying facies association D6 is thin and only a remnant is preserved. In the Deer Creek outcrop facies II is capped by a horizon composed of thick yellowish silty concretions. In the core 13-20-17W4 D6. is represented by a thin (2 m) shaly sandstone.

The facies associations of D4. D5 and D6 (including sequence F4 to F7). inferred from wire-line logs. has the most well-developed sandstones in the western part of the study area towards the southern Alberta foothills (see chapter III). No cores exist in this area. Correlations based on wire-line logs suggest that the upper part of these sandstones are facies IV or V and represent the distal part of the shoreface sandstones of the Cardium Formation in southwest Alberta (Walker and Rosenthal. 1982: Wall. 1975: Medioli. 1999).

Organic Geochemistry

The organic content of the Carlile Formation is characterized by low to moderate TOC values ranging from 0.7 to 2.5 % (figure 4-9 and see chapter II). The organic content is dominated by type III terrestrial material (Deer Creek: figure 4-12), but in core 13-20-17-7W4 is slightly more of marine origin (type II) (figures 4-9 and 4-10).

Micropaleontology and Ichnology

An agglutinated foraminifera assemblage characterizes the Carlile Formation, which evolves upwards throughout the formation from poor to a moderately diverse and abundant assemblage. The Carlile Formation is represented by the *Pseudoclavulina* sp. Zone (chapter II: Caldwell et al.,1978). No nannofossils were observed in the Carlile Formation, which are abundant in the underlying Second White Specks Formation. (figure 4-11; Schröder-Adams et al., 1996; pers. comm., Jim Craig, 1999).

The lower part of the formation, including facies association D1 and D2 is characterized by barren to very few and poorly preserved specimens of mainly *Trochammina* spp. and *Haplophragmoides howardense*. No bioturbation and only few macrofossils are observed in the lower part of the Carlile Formation or equivalent strata (figure 4-2; Cobban et al., 1951; McNeil and Caldwell, 1981). This implies inhospitable conditions for living organisms.

Foraminifera of the *Pseudoclavulina* sp. Zone appear gradually in facies II of facies association D3. This is also consistent with the first appearance of siderite concretions and siltstone interbedded with thin sandstone beds. In the Deer Creek outcrop, the following assemblage is typical of facies association D3, D4, D5 and D6. A total of 20 species were identified with up to 75 specimens per sample. The dominant

taxa are *Haplophragmoides howardense*, *Haplophragmoides bonanzaense*, *Trochammina* spp., *Pseudobolovina variana* and *Ammobaculites* ssp.

Facies association D3 contains the most diverse assemblage with up to 6 species per sample, but with low total abundances ranging from 5-30 specimens. Slight bioturbation is observed in the silty upper part of D3, but is restricted to small *Chondrites*, *Gordia* and *Pilichnus dichotomus* (Uchman, 1999, see chapter II). The upper facies associations D4, D5 and D6 are dominated by *Haplophragmoides howardense*, *H. bonanzaense and P. variana* and most samples contain more than 50 specimens. In the upper part of the D4 to D6 bioturbation increases from moderate to intensive burrowing in the sand-rich part of facies III (figure 4-9).

The assemblage of facies association D5 and D6, represented in core 13-20-17-7W4 differs from the assemblage in the Deer Creek outcrop. The assemblage in the core is a combination of agglutinated and calcareous benthic and some planktic specimens, which differs from the established *Pseudoclavulina* sp. Zone for this interval (Late Turonian, Caldwell et al., 1978). The most abundant species is *Neobulimina albertensis*, some specimens of *Trochammina* and *Haplophragmoides* and a few planktic species.

Bioturbation was intense in the upper part of facies association D5 and D6, dominated by *Chondrites*, *Gordia* and *Pilichnus dichotomus*, which indicates an ichnofacies of distal Cruziana (Pemberton et al., 1992).

Paleoenviroment and Paleogeographic maps

Second White Specks Formation

Widespread regional lithological and paleontological changes from the calcareous Second White Specks Formation (Schröder-Adams et al., 1996) to the lower part of the

non-calcareous Carlile Formation indicate a major paleoceanographic change within the interior seaway (figure 4-13 and 4-14; Wall, 1967b; McNeil and Caldwell, 1981). The interior seaway is believed to have experienced maximum width during the deposition of the Second White Specks Formation, which coincides with the peak transgression of the Greenhorn cycle (Kauffman and Caldwell, 1993; figure 4-13). The sediment deposited during this period is dominated by calcareous shale in the northern region (including the study area) and chalky shale in the south and southeast regions (Kauffman, 1984). The shorelines of the Second White Specks Formation along the western and eastern margins are mainly speculative as these sediments are either eroded (east) or have not been observed (west). The only correlated shoreline deposits observed of the Second White Specks Formation occur in northern British Columbia (Stott, 1962). However, based on the lithologies and micropaleontological data it is generally believed that the shorelines were pushed significantly to the east and west as indicated in figure 4-13 (Kauffman, 1984). During the peak transgression of the Greenhorn, a connection between the Pacific ocean and the Interior Seaway is suggested to have formed in the borderland between Montana and Alberta (Lang and McGugan, 1987; figure 4-13).

The Jumping Pound sandstone straddles the boundary between the Second White Specks and Carlile formations in southwestern Alberta (Brennan-Alpert, 1998; (see chapter III)), and indicates the first evidence of a drop in relative sea-level and the regressive phase of the Greenhorn cycle. During the Second White Specks Formation, the axis and the deepest part of the basin was east of the study area in either Saskatchewan or Manitoba (figure 4-13).

The boundary between the Second White Specks Formation and the Morden Shale (time-equivalent to the Carlile Formation) is described as a disconformity in Manitoba and Saskatchewan (Schröder-Adams et al., 2001; McNeil and Caldwell, 1981; North and Caldwell, 1975). The lack of cores and outcrops in southern Alberta and southwestern Saskatchewan makes it difficult to analysis the boundary between the two formations. On densely spaced wire-line logs the boundary appears as a concordant contact with no erosion detectable (see chapter III).

Lower Carlile Formation

The transition from the Second White Specks Formation to the Carlile Formation is reflected in a significant decrease in TOC and the disappearance of nannoplankton and planktic foraminifera (see chapter II; Schröder-Adams et al., 1996). It is not clear why a sea-level fall could cause this change and several options are possible. The drop in sea level changed the geographical and physical outline of the Interior Seaway (compare figures 4-13 and 4-14) and possibly created silled sub-basins with restricted water mass circulation creating anoxic bottom water conditions (Arthur and Sageman, 1994; Hay et al., 1993). However, correlations suggest in figure 4-14, that no obvious sub-basin was created in the study area, but instead a more than 1000 km wide basin. The stratal pattern of the lower sequences of the Carlile Formation also indicates a wide basin, and is dominated by continuous parallel to sub-parallel strata thinning slightly to the east (see chapter III). Another possibility for the disappearance of nannoplankton and planktic foraminifera is that stratification of the water column, resulting in dysoxic bottom water conditions, continued from the Second White Specks Formation into the lower part of the Carlile Formation (facies association D1 and D2). This has been proposed in the northern

part of the Interior Seaway in the United States (Caldwell et al. 1993). The lowering of sea-level would expose more dry land and possible cause higher freshwater input via river discharge, which is observed in the time-equivalent Morden Shale in Manitoba (Schröder-Adams et al., 2001) and Iowa and South Dakota (Ludvigson et al., 1994). This lighter freshwater would decrease salinity and possibly carry suspended clay from turbid river plumes in the surface water layer creating unfavorable conditions for planktic foraminifera and most nannofossils (Hay et al., 1993). Bottom water conditions would be dysoxic, but not anoxic as in the Second White Specks Formation and some oxidation of organic material, lowering the TOC compared to the SWSF values, would take place.

The dysoxic conditions prevailed until the lower part of the third sequence (F3) where an agglutinated foraminifera assemblage slowly developed, bioturbation was slight and TOC values were lowered to about 1.0 %. The change was related to the continuous lowering of sea-level, causing wave activity to mix water masses providing increased oxygen to bottom water. River discharge would have lowered salinity, and wave activity causing turbidity conditions at or near seafloor, further resulting in suspended clay. In marine environments, these conditions are favored by agglutinated foraminifera with little need for calcareous cement (Boltovskoy and Wright, 1976), which is correlated also with observations in the remaining upper part of the Carlile Formation in the Deer Creek outcrop.

The low angled shingled stratal pattern of the lower Carlile Formation (see chapter III), could indicate a low sedimentation rate in a relatively shallow sea (Reading, 1986), allowing waves and related currents to disperse sediments relatively evenly on the shelf, creating a low-angle stratal pattern. However, micropaleontology indicates that the

central part of the basin in core 13-20-17-7W4 (figure 4-10) might have been deeper the influenced by warm water from the south. The dominance of the benthic infaunal foraminifera *Neobulimina albertensis* and the presence of some planktic foraminifera are evidence for dysoxic or anoxic environments in the upper part of the Carlile Formation. In the southwestern part of the U.S. Interior seaway this fauna has been related to relatively deep, warm and low oxygenated water masses derived from the southern Tethyan Sea (Leckie et al., 1998). It is therefore likely that during short transgressions in the Upper Carlile Formation these warm southern water masses reached the southern part of Alberta and Saskatchewan.

Time-equivalent to the Lower Carlile Formation are the marine, shaly Haven and Opabin members of the Blackstone Formation, deposited in the southern Alberta Foothills (Wall, 1967a; Wall and Rosene, 1977), which indicates that the paleo-shoreline was further to the west in eastern British Columbia. In north-central Montana the marine shale of the Ferdig Member was deposited with a coeval shoreline in the western part of Montana (Cobban et al., 1976; Cobban et al., 1994). In southern Montana the shoreline was represented by the Turner Sand-rich Member of the Carlile Shale and in Wyoming the Frontier Formation contains shoreface sandstone (Cobban et al., 1994; figure 4-14). In Kansas and northern Nebraska, the facies of the lower Carlile is chalky shale to calcareous shale indicating open oceanic conditions (Hattin, 1975). In Manitoba, the Morden Shale was deposited as a black shale, with high TOC values, few nannofossils and rare benthic and planktic foraminifera (McNeil and Caldwell, 1981; Schröder-Adams et al., 2001). This indicates a sea with restricted watermass circulation and freshwater

input (Schröder-Adams et al., 2001) and it is postulated that the, now eroded, paleo-shoreline was just east of the Manitoba Escarpment.

Upper Carlile Formation

The final Late Turonian stage of the Carlile Formation, shows a narrow seaway with upper offshore or distal shoreface facies associations in the western and eastern part of the study area (figure 4-15). As indicated by the stratal pattern (see chapter III), the axial part of the basin was located within the study area in Alberta. The stratal pattern changes upwards to slightly sigmoidal, possibly as the result of higher sedimentation rates. The stratal pattern shows bi-directional sediment input from west and east (see chapter III).

The core at 13-20-17-7W4 represents the upper part of the Carlile Formation with a faunal assemblage including few agglutinated, abundant benthic calcareous and few planktic foraminifera (facies II), indicating fully marine condition in the lower offshore to shelf environment. The planktic foraminifera are of restricted abundance and are mainly found in facies II in the lower part of facies association D5; however they indicate the presence of stable normal-marine salinity water masses during periods of high sea-level in the central part of the basin. This is also observed in the correlative Blue Hill Shale in Colorado, U.S.A. (Caldwell et al., 1993).

Figure 4-15, summarizing paleoenvironments late Turonian age, indicates a narrow seaway with the deposition of the marginal marine Cardium Formation in the west of Alberta (Wall, 1975; Wright and Walker, 1981; Stott, 1963; Leckie et al., 1994), and the Frontier sandstone in southwestern Montana and northern Wyoming (Krystinik and Desjarnett, 1995; McGookey et al., 1972). In the east, the Bowdoin sandstone was

deposited east of the study area, mainly in south-central Saskatchewan and northern North Dakota (Gilboy, 1993). The origin of this sandstone, which is a fully marine, shaly fine-grained sandstone, is not fully understood, but is suggested to be related to significant erosion of the Carlile Formation in northern and central Saskatchewan. The "pinch out" or erosion of the entire Carlile shale in northern central Saskatchewan has been observed by Park, (1965), Simpson (1975), Gilboy (1993), Jellicoe (1991) and Schröder-Adams et al. (1996). The disconformity is marked by a thin layer of the Second White Specks Formation directly overlain by the First White Specks Member of the Niobrara Formation (Park, 1965; Schröder-Adams et al 1996). These observations are paralleled by an eastward increase of erosion within the upper Carlile Formation in southeastern Alberta and southwestern Saskatchewan (see chapter III). East of central Saskatchewan, in Manitoba, the correlative Morden Shale is present and shows no sign of erosion at the upper boundary, but at the lower boundary (McNeil and Caldwell, 1981; Schroder-Adams et al., 2001). In southern Nebraska and northern Kansas significant erosion is also documented between the Carlile Shale and Niobrara Formation (Hattin, 1975). The lowered sea-level, combined with a tectonic uplift (*forebulge*; Allen and Allen, 1990) would have subaerially exposed or created very shallow-marine conditions in the northern and central part of Saskatchewan and eroded the entire Carlile Formation and parts of the Second White Specks Formation (figures 4-3 and 4-15). The fine-grained Bowdoin sandstone was derived from erosion of the low relief Canadian Shield and eroded Carlile Formation in northern Saskatchewan. A southward longshore coastal current could have transported and deposited this sandstone in southern Saskatchewan and northern Montana.

PALEOENVIRONMENT OF THE NIOBRARA FORMATION

The paleoenvironmental study of the Niobrara Formation (figure 4-1) is subdivided into three parts using the three members as major paleogeographic scenarios (figures 4-16, 20, 27, 28, 29 and 31). Each member has distinct facies associations (figure 4-8). The Verger Member is dominated by facies association C and D. The Medicine Hat Member is mainly composed of facies association A and the First White Specks Member is dominated by facies association D. The microfauna and flora are composed of an abundant and diverse assemblage of agglutinated, calcareous benthic and planktic foraminifera and nannofossils.

Verger Member

The Verger Member, the lowest member of the Niobrara Formation, is a slightly to moderately bioturbated silty shale with a few very fine-grained sandstones (see chapter II). Three thin shaly sandstones are mapped; Verger 1, 2 and 3 (figure 4-17 and see chapter III). The member is sequence stratigraphically subdivided into two sequences (F8 and F9), each modified by significant relative sea-level fluctuations (see chapter III). The thickness of the Verger Member ranges from 20 m in the northeast to 120 m in the south and southwest (figure 4-5).

Facies associations

One of the most characteristic features of the Verger Member is an abundance of bentonites. Up to 20 bentonites are observed in outcrops and cores (figure 4-10 and see chapter II). In outcrops (northern Montana), these bentonites are interbedded in 50 m of

shale (Cobban et al., 1976; see chapter II), whereas further north in core 13-20-17-7W4 (figure 4-10) they are condensed into only 3 m of shale.

Sediments of the Verger Member are dominated by facies I, II and III and a few examples of facies VI. Facies VII (pebbles) and VIII (paleosol) are also present in cores and outcrops (figure 4-18). These facies compose facies associations C and D (figure 4-11). Facies association C is observed in two intervals (C1 and C2) and marks the upper boundaries of sequences F8 and F9 (see chapter III). However, shaly facies association D dominates and only subtle facies boundaries are observed in these sediments. Examples of the facies associations will be illustrated below:

In cores, facies association D is recognized in two cases and named D7 and D8 (figure 4-11). Wire-line log correlations indicate that facies associations D is present in most of the study area. This is also confirmed in the western outcrop of Highwood River, where a thick facies II (70 m) indicates the presence of low energy facies association D (figure 4-18).

Two examples of facies association C, including pebble lags, are present in the upper part of the member (C1 and C2) and are recognized in subsurface of southern Alberta and in outcrops in the southern Alberta Foothills and northwestern Montana (figures 4-11 and 4-18), which indicates a significant regional extent of these facies associations.

Geochemistry

The geochemistry of the Verger Member (figures 4-11 and 4-19A+B) is dominated by moderate TOC values (2-2 %) with a few high values (3-4%, in core 13-20-17-7W4). The type of organic material varies across the area with a dominance of type III

(terrestrial) in the south at Deer Creek outcrop (figure 4-1). A dominance of type III, but with slight influences of type II, occurs in the north at 16-4-22-15W4, 8-36-24-13W4 and 6-3-24-13W4 (figure 4-19 and see chapter II). In the eastern core 13-20-17-7W4, sediments are dominated by type II (marine), with slight indications of type III (figure 4-10).

Micropaleontology and ichnology

The faunal and floral assemblage of the Verger Member is abundant and diverse and is composed of both agglutinated, benthic calcareous, planktic foraminifera, ostracodes and nannofossils.

The facies associations D7 and D8 are characterized by an assemblage where the most abundant agglutinated species are *Ammobaculites tyrrelli*, *Marssonella oxycona*, *Reophax* ssp, *Trochammina ribstonensis* and *Haplophragmoides ssp.*, *Spiroplectammina* sp. and the calcareous species *Bullopora laevis* and *Neobulimina albertensis*,. A few planktic foraminifera such as *Heterohelix pulchra*, *Hedbergella delrioensis* and *Hedbergella* ssp. are also observed. In the core 16-4-22-15W4, the upper part of facies association D8 just below facies association C1 (below facies VII, pebble) are dominated by *Ammobaculites* ssp. and *Marssonella oxycona*. Above the lags, the fauna changes to a mixed agglutinated, calcareous benthic and planktic assemblage that indicate deepening and increased marine influence.

Bioturbation varies from no bioturbation in facies I to total bioturbation in some of facies II or III. The trace fossil assemblage is dominated by *Gordia*, *Terrebellina* and *Pilichnus dichotomus* and belongs to the distal Cruziana ichnofacies (Pemberton et al., 1992).

Paleogeographic maps

Two paleogeographic maps illustrate the two end scenarios throughout the evolution of the Verger Member (figures 4-16 and 4-20). The Verger Member represents the initial transgressive stage of the Niobrara sea-level cycle (Kauffman and Caldwell, 1993), which follows the final lowstand stage of the Carlile Formation. However, as illustrated below, this transgression is complex and interrupted by two major relative sea-level falls.

A significant transgression of the interior seaway resulted in a major paleoenviromental change across the Carlile - Niobrara boundary, which is documented in sedimentology, geochemistry and paleoecological data presented above. The initial stage of the expanded seaway was represented by lower offshore to shelf deposits. This stage is followed by the combined effect of high sedimentation rate of shale and siltstone combined with high available accommodation space creating a high-angled (~0.05°) prograding stratal pattern from the south and southwest (see chapter III). The diverse and abundant fauna of the Verger Member, especially the presence of planktic foraminifera such as species *Heterohelix pulchra*, *Hedbergella delrioensis* and *Hedbergella* ssp. (Leckie, 1987) and its shale-rich facies associations D confirm the fully marine setting of these sediments. These planktic genera are surface dwelling foraminifera typical for shallow epicontinental seas (Eider, 1969; Leckie 1987). Their presence, however, within finely laminated, non-bioturbated shale with abundant white specks (nannofossils) and pyrite concretions indicate similar conditions such as indicated by the Second White Specks Formation and First White Specks Member. During transgressive or highstand

conditions of the Verger Member dysoxic bottom water conditions inhibited benthic fauna.

A paleoenvironmental map (figure 4-16) of Late Turonian to early Coniacian age, representing deposits of the lower Verger Member at peak transgression and highstand (sequence F8 and F9), illustrates the expanded seaway that followed the lowstand stage of the Upper Carlile Formation (figure 4-15). A regional correlation of these fine-grained deposits (facies association D) reveals that offshore and shelf deposits were widespread, and no marginal or nearshore deposits existed in the vicinity of the study area. This makes it difficult to draw an accurate shoreline and therefore the extent and width of the seaway should be seen as a minimum, and is justified by extrapolation from the studies described below (figure 4-16).

The transgressive and highstand systems tract of sequence F8 is correlated to the marine shale of the Muskiki Member in the southern Alberta Foothills (Stott, 1962; Wall and Rosene, 1977; Wall, 1967), the marine shale of the Muskiki Formation in the west-central Alberta Foothills (Plint et al, 1990; Plint and Norris, 1991), the shaly Govenlock unit in southwestern Saskatchewan (Gilboy, 1996) and the shaly part of the lower calcareous unit of the Niobrara Formation in Manitoba (McNeil and Caldwell, 1981). These correlative shale units are fully marine without known shorefaces. In northwest Montana, shale and siltstone interbedded with 17 bentonites indicates fully marine conditions in the 50 m of the lower unit of the Kevin Member (Cobban et al., 1976). The main progradation of the Verger Member is from northern Montana and the bentonites outline perfectly the stratal pattern (see chapter III). Longman et al. (1998) inferred that a shoreline was expected in the most western part of Montana or eastern Idaho. McGookey

(1972) implies volcanic activity in northwestern Idaho and southwestern Montana, which is suggested to be the source of bentonites in northern Montana (Cobban et al., 1976), southern Alberta and southwestern Saskatchewan (see chapter II and III; Stott, 1962).

The paleoenvironment during the relative sea-level lowstands during the Verger Member is illustrated in figure 4-20. The two lag deposits (C1 and C2) in the upper part of the Verger Member, capping sequence F8 and F9 respectively, are interpreted as the result of transgressive ravinement of previous deposits. On densely spaced resistivity log cross-sections, these two surfaces are characterized by westward marine onlap (figure 4-18; see chapter III). Two pebble layers are also interpreted in the time equivalent strata of the lower Kevin Member in northern Montana (figure 4-20, and Cobban et al., 1976). There, these layers have an extent of several hundred square miles, covering all of northwestern Montana from the Rocky Mountains in the west to the Bearpaw Mountains in the east, and southwards to south-central Montana (figure 4-18; Cobban et al., 1976). Erosion of up to 24 m has been estimated in relation to the pebble layers in Montana, creating a hiatus in the *Clioscaphites choteauensis* Zone (Cobban et al., 1976). In the north of our study area, the lags are observed in three wells that penetrate the upper part of the Verger Member (figures 4-11 and 4-18). In the Highwood River outcrop in the southern Alberta Foothills, two pebble layers occur in the time-equivalent Muskiki Member (figures 4-1 and 4-18). How far the ravinement surface extended to the east is difficult to predict as no core or outcrop data are available and densely spaced resisitivity log cross-section do not reveal this (see chapter III). Also it is difficult to determine if these surfaces are eastwards ravinement surfaces or correlative non-erosive surfaces. In Manitoba, the lower calcareous unit of the Niobrara Formation contains some sand-rich

intervals (McNeil and Caldwell, 1981), that may be the eastern basin margin response to the western lowstand deposits of sequence F8 and F9 (figure 4-20).

The pebble layers are the remains of a reworked lowstand deposit of a low relief fluvial system, which drained most of Montana and southern Alberta (see chapter III). The drainage seems to have been mostly northwards where the lowstand deposits are found in the Bad Heart Formation (figure 4-20). Wireline log correlations connect the two lag deposits in southern Alberta and northern Montana to the top of two of the main sandstones in the Bad Heart Formation (figure 3-14 *in* chapter III). No detailed correlations have been carried out, but these sandstones may correlate to the two Allomembers 1 and 2 of the Bad Heart Formation (Donaldson et al., 1999). The Bad Heart Formation was previously interpreted as a shallow marine lowstand deposit overlying the Marshybank Formation in the west-central Foothills of Alberta (Plint, 1990; Plint, 1991; Plint and Norris, 1991; Donaldson et al., 1998; 1999). The Bad Heart Formation is characterized by its abundant ooidal ironstone sediments deposited in a shallow marine environment. The two lag deposits (C1 and C2; figures 4-11 and 4-18) in our study area are also characterized by oolites interbedded with sideritic concretions, which is unique to the interval studied.

Medicine Hat Member

The Medicine Hat Member, the central member of the Niobrara Formation, consists of fine-grained sandstone interbedded with shale (see chapters II and III). Detailed sequence stratigraphic mapping of the sandstones resulted in recognition of thirteen individual sandstones deposited within two sequences (F10 and F11) (see chapter

III). The lower seven sandstones are deposited in sequence F10 and the upper five in sequence F11. The Medicine Hat Member is relatively uniform in thickness with an average of 50 meters (figure 4-5). The paleoenvironment of most of the member reflects a fine-grained sandy shelf; most sandstones are mapped as isolated shelf sandstones not connected from the coeval shoreline.

Facies associations

The Medicine Hat Member is dominated by facies association A (figure 4-8), but also facies associations B and D (figure 4-8) are present. Thirteen fine-grained sandstones (Medicine Hat sandstones; 1, 1a, 2, 3, 3a, 4, 5, 6, 6a, 7, 7a, 8, 9) (figures 4-17 and 4-21) are mapped within the Medicine Hat Member and are associated with facies association A, B and C. Eight of the mapped sandstones were deposited in highstand system tracts, three sandstones are from the lowstand system tract and five are transgressive sandstones (see chapter III).

The Medicine Hat highstand (Medicine Hat sandstones. 2. 3. 3a and 6a) and lowstand (Medicine Hat sandstones 4, 5 and 9) sandstones show similar facies associations of a gradually upwards-coarsening succession of facies association A (figure 4-8). For most of these sandstones, the facies association is inferred from wire-line logs as core data is scattered and mainly concentrated in four of the thirteen sandstones (Medicine Hat sandstones 4. 6. 8 and 9). Using mainly the gamma-ray and resistivity logs, a gentle upward-coarsening succession has been interpreted based on a funnel shaped log trend (Cant, 1992). Medicine Hat sandstone 9 is the main gas producer in the Medicine Hat Gas field in southeastern Alberta and therefore also the most cored. For a

detailed lithological description of this sandstone. see discussion of Medicine Hat A sandstone in chapter II.

Facies association A, characteristic of most Medicine Hat sandstones, shows a coarsening-upwards succession from a variably bioturbated gray shale (facies I and II) into thin siltstone transitional zone (facies III) and further up into siltstones with thin interbedded sandstones (facies IV) (figures 4-22 and 4-23). The upper part is dominated by facies VI, which is a moderately to intensely bioturbated, very fine to fine sandstone. Remains of the sedimentary structures indicate thin-bedded sandstone interlaminated with shale and siltstone.

A few of the highstand sandstones in the west have a "high energy layer" of pebbles, hummocky or sharp lower boundary in the lower part representing facies association C (figure 4-8). Some sandstones may have a sharp lower boundary in one area that changes to a gradational boundary in another. The major Medicine Hat sandstone 8 (figures 4-21 and 4-24), has a sharp lower boundary (see chapter II). In core 6-8-26-19W4 (figure 4-24) and the Highwood River outcrop (figure 4-18), the lower boundary of the Medicine Hat sandstone 8 is also characterized by a thin pebble layer, shell debris and thin hummocky beds. In the outcrop reference section of the Medicine Hat Member in Ghost Dam Spillway (see chapter III), four crestline orientations were measured from wave ripples from Medicine Hat 8a sandstone. Ripple crestline orientation ranged between 58°N and 63°N.

The sandstones of the transgressive system tracts are documented in a few cores and are best described by facies association C. The lower transgressive sandstone in sequence F11 (Medicine Hat sandstone 6) has a sharp lower boundary with small pebbles

and shell debris (facies VII). The sandstone is thin and overlain by a thin, finely laminated shale (facies I/II), which is overlain by a transgressive sharp-based sandstone (Medicine Hat sandstone 7; figures 4-11 and 4-21). This sandstone lacks pebbles or "high energy layers" and is interpreted as the more distal part of a transgressive sandstone. The overlying shaly interval contains the maximum flooding surface. A second example of a transgressive deposit with similar facies evolution is observed in core 8-36-24-13W4 (figure 4-11) where the sequence boundary F10 and it's overlying transgressive sandstone Medicine Hat sandstone 1 is cored.

Shale-rich facies association D is present in part of the transgressive and distal highstand deposits of sequences F10 and F11 (figures 4-11 and 4-22 and 4-24). These deposits are dominated by shale (facies I or II) have a gradual upwards-coarsening to siltstone, occasionally with thin interbedded very fine sandstone.

Geochemistry

The TOC values of the Medicine Hat Member are low, ranging between 1.0 to 2.0 %. In general TOC values are lower in the sandstone facies (IV, V and VI) and higher in the shale facies (I, II and III); however exceptions occur in Medicine Hat sandstone 4 in the core of 14-36-13-4W4 (figure 4-22). Here the lower shaly facies (II and III) have a TOC content of 1.3 % and the upper sandstone facies have an average TOC value of 1.8%. The shales interbedded between the Medicine Hat sandstones show an upwards increase in TOC values (figures 4-11 and 4-22; see chapter II). This is especially the case east of the Bow Island Arch (figure 4-11), whereas to the west the average TOC is almost constant throughout the member (core 4-8-13-27W3 in chapter II).

In all wells a general trend of increased TOC values and slight increase in marine type organic matter takes place above the sequence boundaries F10 and F11. The geographic distribution of organic material shows very subtle changes and shows no anomalies (figures 4-6 and 4-25).

Due to a differential burial temperature and pressure history of the sediments (from Foothills to Plains). it is difficult to determine if the type of organic matter has a geographical distribution (see chapter II). These factors affect the HI/OI ratio and in general with increased burial depth the OI decreases and the HI increases (Espitalié et al., 1985). This is especially critical for the western core 4-8-13-27W4 (see chapter II). which is buried twice as deep as the other wells. In summary. when the affect of differential burial temperature and pressure history is removed, the type of organic matter does not change much throughout the study area.

Micropaleontology and ichnofacies

The Medicine Hat Member is part of the *Bullopora laevis* Zone (Caldwell et al., 1978; Schröder-Adams et al., 1998; see chapter II) and in the east. possibly. the lower part of the *Globigerinelloides* sp. Zone. The micro-fauna is dominated by a moderately diverse and abundant agglutinated foraminifera assemblage. but with some intervals of significant amounts of calcareous benthic and planktic foraminifera (figure 4-9). The asssemblage includes the following agglutinated taxa: *Ammobaculites fragmentarius. Ammobaculites tyrrelli. Pseudobolivina rollensis. Dorothia smokyensis. Flabellammina magna. Haplophragmoides crickmayi. Spiroplectammina semicomplanata. Gavelinella henbesti. Saccammina alexanderi. Reophax* spp., the benthic calcareous: *Bullopora laevis Dentalina summitensis. Bolivina elkensis. Gavelinella henbesti. Lenticulina* spp. and the

planktic taxa *Hedbergella loetterlei*, *Heterohelix* spp. Eastwards planktic foraminifera are most common indicating increasing oceanic conditions (Boltovsky and Wright 1976; Lipps, 1979), which is also confirmed by abundant white speckled layers of nannofossils (figure 4-26; pers. comm., Jim Craig, 1999). The geographic distribution of relative abundances of agglutinated, benthic calcareous, planktic foraminifera and nannofossils is shown in figure 4-25. It shows that the east and northeast is dominated by a mixed foraminiferal fauna and nannofossils. In the west, no nannofossils were observed and only a sparse agglutinated assemblage was found.

In general, ichnofossils are diverse and abundant in sandstones of the Medicine Hat Member. However, in the west, in the core at 4-8-13-27W4 (see chapter II), the Medicine Hat sandstones are only slightly to moderately bioturbated. The same is observed in the eastern margin of Medicine Hat sandstone 9 (Medicine Hat A; figure 4-26).

The ichnofacies of the Medicine Hat sandstones includes mainly *Terebellina*, *Teichichnus*, *Chondrites*, *Siphonites*, *Zoophycos and Planolites* which places them in the Cruziana ichnofacies (Pemberton et al., 1992). The upper sandstone, Medicine Hat 9, has a slightly more diverse assemblage including rare examples of small *Skolithos*, *Ophiomorpha*, and rare *Rosselia*, *Asterosoma* and *Teredolites*. These traces indicate a proximal Cruziana ichnofacies or the distal part of the marginal marine Skolithos facies. The shale and siltstone are dominated by the traces of *Pilichnus dichotomus* and *Gordia*.

Paleoenvironment and paleogeographic maps

The geological setting of the Medicine Hat Member is unusual as only a few examples of modern or ancient analogues have been documented of lateral extensive

marine sandstone bodies are surrounded by shale (Swift et al., 1976; Swift et al., 1986; Swift and Rice, 1984; Rice, 1984; Galloway, 2002). The majority of the Medicine Hat sandstones are extensive and widespread, covering 1000 to 3000 km^2, that terms like ridges, shoals or bars are insufficient descriptors to use. Therefore the most suitable description of the paleoenvironment during Medicine Hat Member is a sandy offshore and shelf environment. Modern analogues for the Medicine Hat sandstones may be part of the transgressive mid North American shelf, (Swift et al., 1976; Swift et al., 1986). Ancient examples of widespread sandstones in the Cretaceous Seaway are the Belle Fourche and Mosby sandstones (Swift and Rice, 1984 and Rice, 1984). The Miocene Utsira Formation in the North Sea basin is a very widespread shelf sandstone coving up to 6000 km^2 deposited in a narrow epicontinental basin (Galloway, 2002), which is similar to the setting of the Medicine Hat Member. The stratal pattern of the Utsira Formation is similar to the Medicine Hat Member with low-angled shingled strata, caused by extensive reworking of allochthonous sediment supplied to the shallow sea (Galloway, 2002). The sandstones of the Medicine Hat Member consist of very fine to fine-grained sandstones and originated from coastal erosion or deltaic input.

The Medicine Hat sandstones are fine-grained, and coastal currents, swells and storm events would have been able to move these sediments out on the shelf from the coastal regions with waves having an orbital velocity of less than 50 cm/s, which is created by most storm currents and coastal currents (Clifton, 1986). One mechanism for transporting the fine-grained sediments of the Medicine Hat Member could have been bottom currents in the coastal zone, which were directed offshore (Swift et al., 1986). Another modern analogue for bringing sand to the shelf is the wave dominated delta of

the Nile delta, which has a broadly arcuate outline with cuspate headlands. The sand is brought to the shoreline by the river and transported onto the shelf by a seaward deflection of eastward flowing coastal currents (Palmer and Scott, 1984).

After deposition of the Verger Member and the lowstand deposits of the Bad Heart Formation (Plint, 1991; Donaldson et al., 1998), a major transgression occurred and marine shale was deposited above sequence boundary F10 (figure 4-27). The transgression is evident in the Medicine Hat Member and represented by the lower shale (facies I/II) to siltstone (facies III). This lower shale has an abundant and diverse foraminifera fauna of agglutinated, calcareous benthic and planktic species. In west-central Alberta the transgression is observed as the shaly Puskwaskau Formation overlying, basinwards, the Bad Heart Formation and, landwards, the Marshybank Formation (Plint, 1990; Hu, 1997). In the southern Alberta Foothills, the transgression is documented with a similar foraminifera fauna as found in our study, and was deposited as the shaly part of the Dowling Member (Wall, 1967). In Manitoba, this major transgression may be represented by the change from calcareous shale to the chalky Niobrara Formation (McNeil and Caldwell, 1981). In northwestern Montana the marine shaly middle unit of the Kevin Member was deposited. In summary, regional relationships demonstrate that the study area and the region surrounding it was fully marine in an offshore to shelf setting (figure 4-27).

During the initial transgression, the first Medicine Hat sandstones were deposited in southern Alberta and southwestern Saskatchewan. Sedimentation of sandstones in an offshore environment at this time (early Santonian) was concentrated in southern Alberta and southwestern Saskatchewan as no sandstones are described or mapped elsewhere.

The sandstones described in north-central Montana as the Martin sandstones (Rice, 1981) are the southern edge of some of the Medicine Hat sandstones mapped in southern Alberta and southern Saskatchewan (e.g. Medicine Hat sandstone 5, 6a and Verger sandstone 3 (see chapter III). Thirteen major Medicine Hat sandstones are mapped and their paleoenvironment is addressed below.

Medicine Hat sandstones were deposited in lowstand, transgressive and highstand system tracts (figures 4-28 and 4-29; see chapter III). Most sandstones were deposited in the upper offshore to shelf environment and form facies association A to D. One exception is the thick western Medicine Hat 8 highstand sandstone (figure 4-18). This sandstone has a thin pebble layer in the lower part and is interpreted as a lower shoreface sandstone with a sharp marine erosive base as defined by Plint (1988). This sandstone continues to the west of the study area where it may be connected to a shoreline.

The transgressive sandstones show a preferred NE-SW orientation and are elliptical in shaped somewhat resembling a shelf ridge, but much larger (Med. Hat 1, 1a, 6, 7 and 7a). They are typical facies association A or C, 30-40 km wide and more than 100 km long. These transgressive sandstones could be broad shelf ridges as described by Snedden and Dalrymple (1999). However, these are described as being at maximum a few kilometers wide, with a significantly more complex architecture, high energy sedimentary structures and common lithologies coarser than seen in transgressive sandstones of the Medicine Hat Member.

All evidence points to a low energy offshore to shelf environment of the Medicine Hat Member. Petrology of the sandstones (47 samples representing eight of the Medicine Hat sandstones) indicate both physically and chemically mature sandstones likely

resulting from long transportation (pers. comm., El Dein, 1999). A few small sideritic pebbles are found within and on top of some of the sandstones. These pebbles are interpreted as being the result of reworking of intrabasinal siderite concretions at moderate energy levels in the upper offshore environment.

The majority of the sandstones consist of gentle upward-coarsening successions (facies association A). The sedimentary structures indicate an environment with low to moderate energy (Clifton, 1986) and a sand starved sea-bed. Storms would either have generated hummocky beds, mega-ripples (Leckie and Krystinik, 1989) or erosional surfaces (if no sand available), and none of these structures are present.

The sandstones were deposited in a wave-dominated low to moderate energy regime around storm wave base. The small scale sedimentary structures are the result of wave activity and the storm generated currents in a distal setting (Niedoroda et al., 1989). Contourites or their shallow version of the deep water contour currents may have reworked the sediments (Stow et al., 1998; Hay et al., 1993). Most of the sandstones were deposited on the flanks of the Bow Island Arch. If the arch was a subtle submarine high of less than 10 m water depth, then shallow water and flank restricted contourites (Stow et al., 1998) could have distributed the sediments around the arch (figure 4-29).

Geographically, the sedimentary facies change within and between the sandstones is minor. However, the degree of bioturbation varies significantly and is moderate to intensive east and north of the Bow Island Arch, but slight to moderate in the west and eastern margin of the sandstones. The explanation for this pattern is best viewed in association with the organic geochemical and micropaleontological data which is addressed below.

The organic matter of the Medicine Hat Member is dominated by the terrestrial type III. The amount of type III organic material illustrates the significance of river discharge transporting terrestrial organic matter into the basin and possible coastal erosion of land areas especially during transgression. The increased TOC values can either be due to deeper water with slightly more dysoxic conditions and therefore more organic material preserved. Lower sedimentation rates could be another reason, which would increase the TOC/sediment ratio. This deepening of the basin is a continuation of the Niobrara transgression, which was initiated in the Verger Member. The organic geochemical data indicate a deeper basin to the east with more dysoxic conditions at the seafloor or lower sedimentation rates as a function of distance from the sediment source.

The micro fauna indicates a fully marine environment thoughout the deposition of the Medicine Hat Member. The fauna is dominated by agglutinated foraminifera, however the presence of calcareous benthic and planktic foraminifera in some intervals indicates periods with water masses of normal marine salinity and low suspended material (Boltovsky and Wright 1976; Lipps, 1979; Eicher, 1969). The geographic faunal distribution indicate that fully-marine conditions were more prevalent in the east as the fauna from cores in Saskatchewan have significant amounts of nannofossils (white specks) and some planktic foraminifera (figure 4-30). Westwards the white speckled layers gradually diminishes and no white specks are observed in the most western core of 4-8-13-27W4 or in the outcrops of Highwood River, Ghost Dam Spillway and Mill Creek (pers. comm., Jim Craig, 1999; Medioli, 1999).

The Sweetgrass Arch

The influence of the Sweetgrass Arch on the depositional environment in the Cretaceous strata is illustrated in several studies (Arnott et al.,1995; Hankel et al., 1989; Schröder-Adams et al., 1997, 1998; Myhr and Meijer-Drees, 1976; Lorenz, 1982; Lorenz and Gavin, 1984; Payenberg, 2002). Deposition of the Upper Colorado Group reveals that the arch had no or limited effect on the depositional environment during times of high accommodation, but did influence sedimentation during low accommodation space. Although the arch was present as a subtle high at all times, distal marine environments were not affected. At times of high relative sea-level with water depth of 50-100 m, an elevation of 3-5 m would have little or no effect on sedimentation, whereas, at low sea-level of 10-30 m, such a feature would influence sedimentation patterns. These shallow depths are possible during deposition of the two major sandstones of the Medicine Hat Member (Medicine Hat sandstones 8 and 9), which were deposited on the flanks of the arch (figure 4-29). Possible oceanic currents were directed by the arch and the preservation potential for sandstone on the shallow water high of the arch would have been low. The combined effect of "shallow-water contourites" (Stow et al., 1998) and high energy on top of the arch would have deposited the sandstone on the flanks. With a sediment source from the southwest or west and the current going north on the east side of the arch, as indicated by the stratal pattern, the sediments would be deposited west and northwest of the arch forming the highstand Medicine Hat sandstone 8 (figure 4-21). During the subsequent lowstand the sandstone may have been deposited north and east of the arch by a southwards-directed oceanic current (figure 4-29; Slingerland et al., 1996).

The isopach maps of the Carlile Formation and the Niobrara Formation including the Verger. Medicine Hat members or their individual sequences, reveal no relation to the arch (figures 4-5). This is in contrast to the First White Specks Member, which shows a thinning over the arch and a possible influence of the arch on the sedimentation pattern (*see the chapter First White Specks Member for details*). The Medicine Hat Member shows thickening on the west and east side of the Arch, that can be explained without the presence of the arch. To the west, the member is thicker due to a more proximal position to the sediment source which affected the shale and sandstone deposits. To the east, the Medicine Hat Member thickens and is a result of the local east-west oriented Medicine Hat Syncline described in the next section. No variation in isopach maps were observed in a regional study of the Cretaceous in both Montana and southern Alberta (Podruski, 1988).

The Medicine Hat Syncline

The influence of a secondary structural feature in southeast Alberta and southwestern Saskatchewan affected the deposition of the thick Medicine Hat sandstones 4 and 9 (Medicine Hat sandstone. A and D in chapter II). A subtle east-west trending syncline is indicated (figures 4-31 and 4-32) in southeastern Alberta and southwestern Saskatchewan. The isopach map of the Medicine Hat Member (figure 4-5) indicates a thicker section in this area and illustrates that the syncline was synsedimentary with the Medicine Hat Member. This is also recognized in the Belle Fouche Formation, Second White Specks Formation and Niobrara Formation (figure 4-13 and Gilboy, 1988). The east-west trending syncline is possibly related to two faults, one on the south side and one on the north side of the syncline forming a subtle "graben structure" (figure 4-13). In the

syncline, the Medicine Hat 4 and 6 sandstones have their maximum thickness, contrasting the thickness of the bentonite marker beds of the Verger Member, which thin abruptly into the syncline (figure 4-10; see chapter III) The bentonites of the Second White Specks Formation show similar trend (figure 4-32) and dramatically thin in the syncline. This could indicate a repeated and systematic reactivation of the structure where increased accommodation space occurred during extension of the structure and decreased accommodation space during compression. As argued in this paper, the sandstones are offshore to shelf deposits, which were transported mainly by storm generated currents and other oceanic currents. Transported along the flanks of the Bow Island Arch, areas with increased rates of accommodation would accumulate the fine sandstones and have the highest preservation potential. Consequently, this implies that the deposits probably never had a "ridge" morphology, but were a relatively low relief sand-sheet (figure 4-32). The time of deposition of the sandstones is believed to be coincident with the extensional component of the structure. The opposite is observed in the deep water Second White Specks Formation and the Verger Member. In the area of the syncline, these bentonites are not preserved. At the time of Second White Specks and Verger Member deposition, the structure had a compressional component, creating a subtle structural high. Here the very fine deposits of volcanic ash were eroded due to a slightly decreased water depth over the structure and thereby increased wave and current energy.

The origin of the Medicine Hat Syncline is not fully understood, but Gilboy (1988) suggested that dissolution of Devonian salt deposits could have created the feature. Another possibility could be reactivated subtle faulting in relation to thrusting in the Cordillera in the west (Lemieux, 1999). The importance of subtle faulting in the

plains of both southern Alberta and Montana has also been emphasized by Ridgley (2001) and in South Dakota by Shurr et al. (1994). I propose to name the structure the Medicine Hat Syncline.

First White Specks Member

The First White Specks Member, the upper member of the Niobrara Formation, is a calcareous, dark gray shale with numerous bentonites, abundant macrofossils and a few thin sandstones in southern Alberta and southwestern Saskatchewan (see chapter III). The member is in general an eastward-thinning wedge from 80 to 20 m thick (figure 4-5). The paleoenvironment was dominated by a low energy regime in a lower offshore to shelf setting.

Facies associations

The sediments of the First White Specks Member are dominated by facies association D, and consist almost entirely of facies I (figures 4-8 and 4-11). This facies is a dark gray, fine laminated shale with common white speckled laminae or thin beds. Bivalves and rare ammonites occur and form in places debris layers. Bentonites are present, and are less than five cm thick. Shale of the First White Specks Member are interbedded by a few thin fine-grained sandstones. One of these sandstones, the Sweetgrass Member, is a fine-grained sandstone interlaminated with shale (Schröder-Adams et al., 1997). Rare siltstones and thin sandstone beds are commonly associated with thin lags of broken bivalves, are normal graded and finely laminated or thin lenticular.

The stratal pattern of the First White Specks Member described in chapter III, is subtle due to homogenous lithological characters and extreme lateral continuity of the individual marker-beds. This results in a stratal pattern, which is low angled with few terminations and disconformaties.

Micropaleontology and ichnofacies

The time-diagnostic planktic foraminiferal zone of *Globigerinelloides* sp. Zone, which is recognized in time equivalent intervals elsewhere in the basin (Caldwell et al. 1978; 1993), is not fully recognized in the study area over the Sweetgrass Arch and its flanks (*this study* and Schröder-Adams et al., 1998). Planktic foraminifera of the Niobrara cycle are also less diverse in the Canadian part of the seaway compared to the U.S. part (Caldwell et al., 1993).

Bioturbation is sparse and is mostly observed in thin sandstones, whereas the fine lamination is preserved in shale. Within the infrequent siltstone and thin sandstone beds, traces are dominated by *Siphonites* and *Planolites*. *Gordia* and *Pilichnus dichotomus* which are typical of the shale in the underlying Verger and Medicine Hat member are not present in the First White Specks Member.

Geochemistry

The TOC content increases significantly across the boundary between the Medicine Hat Member and First White Specks Member accompanied by an increase of marine derived organic matter (figures 4-11 and 4-21; see chapter II). The vertical succession of TOC values is near symmetrical in the member, with an increase to ca. 3% in the middle of the member, followed by a decrease to about 1 % in the upper part. This trend is most pronounced in the eastern and northern region where values reach an

average of 2.5-2.9 %. In the western region, the TOC rises to an average of 1.72 %. Compared to the Second White Specks Formation (TOC 4-5%, in Bloch et al., 1993) the TOC values are considerably lower in the First White Specks Member. The First White Specks Member shows a higher influence of marine organic matter (type II) than in the Medicine Hat Member.

Paleoenvironment and paleogeographic maps

The abrupt change from the Medicine Hat Member to the First White Specks Member indicates a renewed major transgression of the interior seaway (figure 4-31; Caldwell et al., 1993; Kauffman, 1984). In the Alberta Foothills, the First White Specks Member is equivalent to the calcareous Thistle Member of the Wapiabi Formation, which has some planktic foraminifera present (Wall, 1967 and Stott, 1963). In Saskatchewan, the First White Specks Member is recognized by a more diverse planktic foraminifera assemblage (Park, 1965) and in Manitoba, the upper chalky shale of the Niobrara Formation is partly equivalent to the First White Specks Member. Although combined evidence in our study area indicates that the First White Specks Member represents the peak transgression and highstand period of the Niobrara Cycle, the exact timing is still debatable when put into a regional context (McNeil and Caldwell, 1981). The facies associations of the First White Specks Member indicate the most distal and low energy environment of both the Niobrara and Carlile formations. A significant lateral biofacies change across the southern part of the Canadian interior seaway was shown by Schröder-Adams et al. (1998) who suggested a possible shallowing of the seaway in the area of the Sweetgrass Arch. My study confirms that the rich fauna of planktic foraminifera and nannofossils, which is documented elsewhere in the basin, is not found in the First White

Specks Member in the plains of southern Alberta and southwestern Saskatchewan. The isopach map of the First White Specks Member (figure 4-5) also confirms an influence of the arch as a 15 to 20 m thinning is observed. This could be related to lower accommodation over the arch during the deposition of the lowstand deposits or the Sweetgrass Member. However, the faunal change may not only be related to a lateral variation of accommodation and related water depth. Planktic fauna and flora reflect the conditions of water masses, which are defined by salinity, temperature, light, pH, suspended material, oxygen concentration, $CaCO_2$ content and nutrients (Boltovskoy and Wright, 1976; Hay et al., 1993). In general, planktic foraminifera and nannofossils are more abundant and diverse in a warm, normal salinity water mass with high or normal $CaCO_2$ concentrations (Boltovskoy and Wright, 1976; Lipps, 1979). Using the circulation model for the interior seaway (Slingerland, 1996), it is possible that relatively cold water masses with a low concentration of $CaCO_2$ were traveling southwards along the west side of the interior seaway. The Cordilleran highland in the west is likely to have had a higher influx of river discharge than the low lands of the east (Longman et al., 1998). This could have created a more brackish southern current in the west and a more marine northern current in the east. This combination of effects might have been responsible for a major lateral faunal change from east to west and between south and north of the interior seaway (figure 4-31).

DOMINATING FACTORS IN BASINAL EVOLUTION

The Greenhorn and Niobrara sedimentary cycles (Kauffman and Caldwell, 1993) are the expression of two major second order sea-level fluctuations during Late Turonian

to Santonian time (Haq et al., 1988). Third-order sea-level fluctuations modified these cycles, caused mainly by tectonic thrusting and displacement of the accreted terraces in the Cordillera to the west (Kauffman and Caldwell, 1993). Higher order eustatic sea-level change may also have had an influence (Plint, 1991). Recent studies in the U.S. Western Interior Seaway, using foraminiferal correlations, illustrate that tectonically-controlled cyclicity and related subsidence may have been as short termed as eustatic-glacio sea-level changes (Martinson et al., 1998), which complicates the interpretation of the dominating factors of the interior seaway's basin evolution. In this study, repeated lithological successions with imprints of volcanic activity and significant changes in sediment input direction also indicate a strong influence of tectonic activity. In the Late Cretaceous, four cycles repeat the succession of a gradational upwards-coarsening interval followed by an abrupt change to fine-grained sediments (shale) with abundant bentonites. These four cycles are in ascending order (figure 4-33); 1) the silty and sand-rich Belle Fouche Formation sharply overlain by the Second White Specks Formation with abundant bentonites (Schröder-Adams et al., 1996); 2) the general upwards-coarsening of the Carlile Formation abruptly overlain by the bentonite enriched and shaly Verger Member (*this study*); 3) the sand-rich Medicine Hat Member overlain by the calcareous shale of the First White Specks Member which have numerous thin interbedded bentonites (*this study*); 4) the sand-rich Milk River Formation overlain by the Claggett shale with numerous thick bentonites (Payenberg, 2002). The repeat of these events suggest a cyclicity which is likely related to plate tectonic, volcanic activity and thrusting in the Cordillera (Leckie and Smith, 1992; Bally and Snelson, 1980; Allen and Allen, 1990). The shales overlying the sand-rich intervals are all characterized by

abundant bentonites, and may be associated with the start of a new thrusting (Flemings and Jordan, 1990) and increased subsidence in the foreland basin. The bentonites are due to volcanic activity related to burial and heating of the progressive Pacific plate under the continental North American plate. Bentonites have a higher preservation potential in condensed shaly intervals, which may partly account for the abundant bentonites in the shales (Loutit et al., 1988). Following thrusting, a quiet tectonic period, where the thrust is gradually eroded, promotes infilling the newly developed accommodation space in the foreland basin. The hinge zone (Leckie and Smith, 1992) of the foreland basin likely experience isostatic rebound during the thrusting creating a forebulge (Allen and Allen, 1990) on the eastern side of the basin. This rebound can be so substantial that it can create an unconformity, which slowly moves towards the thrust belt (westwards) (Flemings and Jordan, 1990). This could explain the unconformity between the Second White Specks and Carlile formations in Manitoba and Saskatchewan (Schröder-Adams et al., 2001; McNeil and Caldwell, 1981; North and Caldwell, 1975) and later the unconformity between the Carlile and Niobrara formations in central Saskatchewan (figure 4-3; Park, 1965).

Subtle syntectonic movements in the plains are thought to have had an influence on the sediment distribution even in the eastern margin distant from the western Cordillera. (Shurr et al., 1994; Lemieux, 1999; Ridgley, 2001; Anna, 1986; Gilboy 1996). These are subtle block-fault movements that results from the Cordilleran pressure regime (Lemieux, 1999). Dissolution of deeper deposited Devonian salts (Gilboy, 1996), might have directed sediment patterns or created or diminished accommodation space. The Medicine Hat Syncline is a structure defined in southeast Alberta and southwest

Saskatchewan that influenced accumulation of thick deposits of Medicine Hat sandstones 4 and 8 and sandstones in the Belle Fourch Formation (figure 4-31). This structure, which was reactivated by periods of uplift and subsidence during the Late Cretaceous is probably due to extensional and compressional movements related the Cordilleran tectonics (Lemieux, 1999). Salt dissolution would only cause subsidence, not repeated events of uplift and subsidence, but only repetitive subsidence effect.

CONCLUSIONS

Detailed analysis of the upper Colorado Group, including the Carlile and Niobrara formations, reveals a complex and dynamic basin system far removed from the Cordillera. A multidisciplinary approach has resulted in interpretation of paleo-environmental changes, which are depicted in comparison to other studies and outlines facies distribution of various Late Cretaceous time-slices. The two formations represent significantly different basin histories, both in terms of paloegeographic outline, facies distribution and sea-level history.

The deposits of the non-calcareous **Carlile Formation** are a regressive succession, which gradually infilled the basin during Late Turonian time (~ 90? Ma to 89 Ma; Haq et al., 1988; Obradovich, 1993). This corresponds to the third order cycle (3.1) of Haq et al. (1988) and a major sea-level fall in the Interior Seaway (Kauffman and Caldwell, 1993). Seven sequences (F1 to F7) of fourth order were deposited during this period with an average of 140 000 years per cycle. Although the length of these cycles a proximally corresponds to Milankovitch cycles (Fischer, 1993; Park and Herbert, 1987),

it is believed that Cordilleran tectonics in the west are more likely to have a dominant influence on the sea-level cyclicity.

The partly calcareous **Niobrara Formation** was deposited as an overall transgressive succession, which experienced major sea-level fluctuations during the Coniacian and Santonian (89.0 Ma to 83.5 Ma; Obradovich 1993). Six sequences (F8-F13) are interpreted from this interval, which gives an average duration of 915 000 years, considerable longer than the regressive sequences of the Carlile Formation. The period of the Niobrara Formation corresponds to the two third order cycles (3.2 and 3.3) of Haq et al (1988). In the interior seaway three major sea-level cycles are observed in this interval (Kauffman and Caldwell, 1993; Longman et al., 1998). Plint (1991) suggested glacio-eustatic control on the origin of the high-frequency cycles in the Coniacian to lower Santonian Marshybank and Bad Heart formations in west-central Alberta. Our study shows that the lowstand of the Bad Heart Formation (Donaldson et al., 1998) drained most of the Western Canadian Interior Seaway and parts of northern Montana. Major events like these, which can be traced for more than 1500 km, are unlikely to have been solely controlled by tectonic events or sediment rate fluctuations, which support the glacio-eustatic control suggested by Plint (1991).

The sandstones of the Medicine Hat Member were deposited in a sand-rich shelf environment (figures 4-3, 4-27, 4-28 and 4-29). Most sandstones are distal, isolated fine-grained sandstones that were transported to the offshore setting by storms and shelf currents. Shale interbedded between the sandstones has a microfauna that indicates a fully marine and distal depositional environment. No nearshore deposition is known in the vicinity of the study area, therefore in order to create an accurate paleoenvironmental map

of the interior seaway the proposed shoreline and nearshore environment is inferred based on the distal nature of the known sediments. (figures 4-28 and 4-29). The two sequences mapped in the Medicine Hat Member show a repeat of the same stratal pattern and reflect relative sea-level changes in the distal fine-grained environment of a shelf (see chapter III). The vertical facies change of the interval (figure 4-3) shows how tongues of eastern calcareous shale containing white specks (nannofossils) interfinger with non-calcareous shale in the west. The figure also illustrates why Simpson (1981) placed the Medicine Hat sandstones in the First White Speckled Shale; white specks are present below, within and above the sandstones (figure 4-26). Westward, the white specks layers below and within the Medicine Hat sandstone becomes less common and occur mainly above the Medicine Hat Member (Schröder-Adams et al., 1997).

The general stratigraphic framework of the Carlile and Niobrara formations is illustrated in a east-west cross-section in the southern part of the Canadian Interior Seaway (figure 4-3). The diagram shows the general stratal pattern and facies characteristics for the formations and members. The diagram correlates to central Saskatchewan (North and Caldwell, 1975; Park, 1965) and Manitoba (McNeil and Caldwell, 1981) and illustrates the regional lateral facies changes. The major unconformity between the Carlile and Niobrara formations in central Saskatchewan is possibly related to a forebulge developed in the hinge zone of the foreland basin during thrusting in the Cordillera. The unconformity between the Favel Formation (Second White Specks Formation) and the Morden Shale (Carlile Formation) in Manitoba (McNeil and Caldwell, 1981; Schröder-Adams et al., 2001) is not observed in southern Alberta or southwestern Saskatchewan. Two major unconformities are present in the

Verger Member, and the Medicine Hat Member is characterized by the present of thirteen mappable fine grained sandstones. The eastern margin of the sandstones is the east margin of the Bow Island Arch from where the water depth increased significantly. The First White Specks Member is a calcareous shale with few fine-grained sandstones with a very low angled stratal pattern.

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REFERENCES

Anna. L.O.. 1986. Structural influences on Cretaceous sedimentation. northern great plains. *In.* Peterson, J.A. (eds.). Paleotectonics and sedimentation in the Rocky Mountain Regions. United States. AAPG Memoir 41. P. 173-191.

Allen. P.A. and Allen, J.R., 1990. Basin Analysis: Principles and Applications. Blackwell Scientific Publications. Oxford, pp. 451.

Arnott, R.W.C., Hein, F.J. and Pemberton, S.G., 1995. Influence of the ancestral Sweetgrass Arch on sedimentation of the Lower Cretaceous Bootlegger Member. North-Central Montana. *Journal of Sedimentary Research*, vol. B65, no. 2, p. 222-234.

Arthur, M.A. and Sageman, B.B., 1994. Marine Black Shales: Depositional mechanisms and environments of ancients deposits. *Annu. Ref. Earth Planet. Sci.* p. 499-551.

Bally, A.W. and Snelson, S., 1980. Realms of subsidence. *In* A.D. Miall, (eds.) Facts and Principles of World Petroleum Occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 9-75.

Bloch. J., Schröder-Adams C., Leckie. D.A.. McIntyre. D.J.. Craig. J. and Staniland. M., 1993. Revised stratigraphy of the lower Colorado Group (Albian to Turonian). Western Canada. *Bulletin of Canadian Petroleum Geology*, vol. 41, no. 3. p. 325-348.

Boltovsky. E. and Wright. R.. 1976. Recent foraminifera: The Hague. Dr. W. Junk. pp. 515.

Brennan-Alpert. P.. 1998. A reference section for the Cretaceous hydrocarbon-bearing Second White Specks Formation at Highwood River. Southern Alberta Foothills. Unpublished Honors Thesis. Carleton University. Ottawa. pp. 44.

Caldwell. W.G.E.. North B.R.. Stelck. C.R. and Wall. J.H.. 1978. A foraminiferal zonal scheme for the Cretaceous System in the Interior Plains of Canada. *In:* Western and Arctic Canadian Biostratigraphy (eds. Stelck. C.R. and Chatterton. B.D.E.). Geological Association of Canada. Special Paper 18. p. 495-575.

Caldwell. W.G.E.. Diner. R.. Eicher. D.L.. Fowler. S.P.. Stelck. C.R. and von Holdt Wilhelm. L.. 1993. Foraminiferal biostratigraphy of Cretaceous marine cycloterms. *In*: Evolution of the Western Interior Basin (eds. Caldwell. W.G.E. and Kauffman. E.G.). Geological Association of Canada. Special Paper 39. p. 477-520.

Cant. D.J.. 1992. Subsurface facies analysis. *In:* Facies Models: response to sea level change (eds. Walker. R.G. and James. N.P.). Geological Association of Canada. p. 27-46.

Clifton. H.E.. 1986. Interpreting paleoenergy levels from sediment deposited on ancient wave-dominated shelves. *In*: Shelf Sands and Sandstones (eds. Knight. R.J. and McLean. J.R.). Canadian Society of Petroleum Geologists. Memoir 11. p. 181-191.

Cobban. W. A.. 1951. Colorado shale of central and northwestern Montana and equivalent rocks of the Black Hills. *American Association o Petroleum Geologists Bulletin*. vol. 35. p. 2170-2198.

Cobban. W.A.. Erdmann. C.E.. Lemke. R.W. and Maughan. E.K.. 1976. Type sections and stratigraphy of the Blackleaf and Marias River formations (Cretaceous) of the Sweetgrass Arch. Montana. United States Geological Survey. Professional Paper 974. pp. 36-60.

Cobban. W.A.. Merewether. E.A.. Fouch. T.D. and Obradovich. J.D.. 1994. Some Cretaceous shorelines in the Western Interior of the United States. *In:* Mesozoic Systems of the Rocky Mountain Region. USA (eds. Caputo. M.V.. Peterson. J.A. and Franczyk. K.J.). *Rocky Mountain Section. SEPM*. p. 393 - 413.

Donaldson. W.S.. Plint. A.G. and Longstaffe. F.J.. 1998. Basement tectonic control on the distribution of the shallow marine Bad Heart Formation: Peace River Arch area. NW Alberta. *Bulletin of Canadian Petroleum Geology*. vol. 46. p. 576-598.

Donaldson. W.S.. Plint. A.G. and Longstaffe. F.J.. 1999. Tectonic and eustatic control on deposition and preservation of Cretaceous ooidal ironstone and associated facies: Peace River Arch area. NW Alberta. Canada. *Sedimentology*. vol. 46. p. 1159-1182.

Eicher. D.L.. 1969. Paleobathymetry of Cretaceous Greenhorn Sea in Eastern Colorado. *AAPG Bulletin*. vol. 53/5. p. 1075-1090.

Elliott. T.. 1986. Siliciclastic shorelines. *In*: Sedimentary Environments and Facies (ed. Reading. H.G.). 2nd edition. Boston. *Blackwell Scientific Publications*. p. 155-188.

Espitalié. J.. Laporte. J.L.. Madec. M.. Marquis. F.. Leplat. P.. Paulet. J. and Boutefeu. A.. 1977. Méthode rapide de caractérisaton des roches de mères de leur potentiel pétrolier et de leur degré d'évolution. *Revue de l'Institute Français du Pétrolier*. vol. 32. p. 23-42.

Espitalié, J., Senga Makadi, K. and Trichet, J., 1984. Role of the mineral matrix during kerogen pyrolysis. *In:* Advances in Organic Geochemistry 1983 (ed. Schenk, P.A.). Pergamon Press, Oxford, p. 365-382.

Espitalié, J., Deroo, G. and Marquis, F., 1985. Rock-Eval pyrolysis and its applications. *Institute Français du Pétrolier*. Preprint 33578, pp. 72.

Fischer, A.G., 1993. Cyclostratigraphy of Cretaceous chalk-marl sequences. *In*: Evolution of the Western Interior Basin. (eds. Caldwell, W.G.E. and Kauffman, E.G.). Geological Association of Canada, Special Paper 39, p. 283-295.

Flemings, P.B. and Jordan, T.E., 1990. Stratigraphic modeling of foreland basins: Interpreting thrust deformation and lithosphere rheology. *Geology*, v. 18, p. 430-434.

Galloway, W. E., 2002. Paleogeographic setting and depositional architecture of a sand-dominated shelf depositional system, Miocene Utsira Formation, North Sea Basin. *Journal of Sedimentary Research*, Vol. 72, No. 4, p. 476-490.

Gilboy, C.F., 1987. Aspects of the regional geological framework of low-permeability shallow gas reservoirs in Upper Cretaceous strata (Colorado and Montana Groups), southwestern Saskatchewan: *In: Summary of Investigations 1987*, Saskatchewan Geological Survey, Miscellaneous Report 87-4, p. 199-213.

Gilboy, C.F., 1988. Geology and natural gas production of the Upper Cretaceous Second White-Speckled shale, southwestern Saskatchewan: *In*: Summary of Investigations 1988, Saskatchewan Geological Survey; Saskatchewan Energy and Mines, Miscellaneous Report 88-4.

Gilboy, C.F., 1993. The Carlile Shale equivalent (Upper Cretaceous) in Southwestern Saskatchewan: a wireline-log study. *In:* Summary of Investigations 1993. Saskatchewan Geological Survey; Saskatchewan Energy and Mines. Miscellaneous Report 93-4.

Gilboy, C.F., 1996. Detailed log-based stratigraphic study of Colorado Group and Milk River Formation strata (Cretaceous). Southwestern Saskatchewan; *In: Summary of Investigations 1996*. Saskatchewan Geological Survey; Saskatchewan Energy and Mines. Miscellaneous Report 96-4.

Haggert J.W. 2002. Report on Upper Cretaceous fossils from Kananaskis Lake map-area. Alberta (NTS: 82J) and Montana, USA. Geological Survey of Canada Fossil Report No. JWH-2000-01.

Hancock, W.P. and Glass, D.J., 1968. Medicine Hat - Hatton gas field, Alberta and Saskatchewan. *In* : Natural Gasses of North America (ed. Beebe, B.W.). *American Association of Petroleum Geologists*, Memoir 7, p. 731-735.

Hankel, R. C., Davies G. R. and Krouse H. R., 1989. Eastern Medicine Hat gas field: a shallow, Upper Cretaceous, bacteriogenic gas reservoir of southeastern Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 37, no. 1, p. 98-112.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. *In*: Sea Level Changes: An Integrated Approach (eds. Wilgus, C.K. et al.). Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, p. 71-108.

Hattin, D.E., 1975. Stratigraphic study of the Carlile-Niobrara (Upper Cretaceous) unconformity in Kansas and northeastern Nebraska. *In:* The Cretaceous System in

the Western Interior of North America (ed. Caldwell. W.G.E.). Geological Association of Canada. Special Paper 13. p. 195-210.

Hay. W.W.. Eicher. D.L. and Diner. R.. 1993. Physical oceanography and water masses in the Cretaceous Western Interior Seaway. *In*: Evolution of the Western Interior Basin (eds. Caldwell. W.G.E.. and Kauffman. E.G.). Geological Association of Canada. Special Paper 39. p. 297-318.

Hu. Y.. 1997. High-resolution sequence stratigraphic analysis of the Upper Cretaceous Puskwaskau Formation of west-central Alberta and adjacent B.C. Outcrop and Subsurface. Unpublished Ph.D. Thesis. University of Western Ontario. London. Canada.

Jellicoe. B.C. and Kyser. T.K.. 1991. Paleoenvironmental reconstruction of the Niobrara marine cyclothem in southeastern Saskatchewan. (abstract). Geological Association of Canada. Joint Annual Meeting with Society of Economic Geologists. Toronto.

Johnson. H.D. and Baldwin C.T. 1989. Shallow siliciclastic seas. in (eds. Reading H.G.) cap. 9: Sedimentary Environments and Facies. Second edition. Blackwell Scientific Publications. p. 229-282.

Kauffman. E.G.. 1967. Coloradan macroinvertebrate assemblages. central Western Interior. *In:* Paleoenvironments of the Cretaceous seaway in the Western Interior. Colorado School of Mines. Golden. CO. p. 67-143.

Kauffman. E.G.. 1984. Paleogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America. *In*: Jurassic-Cretaceous

Biochronology and Paleogeography of North America. (ed. Westerman. G.E.G.). Geological Association of Canada. Special Paper 27. p. 273-306.

Kauffman. E.G. and Caldwell. W.G.E.. 1993. The Western Interior Basin in space and time. *In*: Evolution of the Western Interior Basin. (eds. Caldwell. W.G.E. and Kauffman. E.G.). Geological Association of Canada. Special Paper 39. p.1-30.

Krystinik. L.F. and Desjarnett. B.B.. 1995. Lateral variability of sequence stratigraphic framework in the Campanian and Lower Maastrichtian of the Western Interior Seaway. *In*: Sequence Stratigraphy of Foreland Basin Deposits (eds. Van Wagoner. J.C. and Bertram. G.T.). American Association of Petroleum Geologists. Memoir 64. p. 11-27.

Lang. H.R. and McGugan. A.. 1987. Cretaceous (Albian-Turonian) foraminiferal biostratigraphy and paleogeography of northern Montana and southern Alberta. *Canadian Journal of Earth Sciences*. vol. 25. p. 316-342.

Leckie. D.A.. Bhattacharya. J.P.. Bloch. J.. Gilboy. C.F.. Norris. B.. 1994. Cretaceous Colorado/Alberta Group of the Western Canada Sedimentary Basin. *In:* Geological Atlas of the Western Canada Sedimentary Basin (compiled by Mossop. G. and Shetson. I.). *Canadian Society of Petroleum Geologists and the Alberta Research Council*. pp. 510.

Leckie. D.A. and Krystinik. L.F.. 1989. Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle shelf deposits? *Journal of Sedimentary Petrology*. vol. 59. p. 862-870.

Leckie, D.A. and Fox, C. and Tarnocai, C., 1989. Multiple paleosols of the late Albian Boulder Creek Formation, British Columbia, Canada. *Sedimentology*, vol. 36, p. 307-323.

Leckie, D.A. and Smith, D.G., 1992. Regional setting, evolution, and depositional cycles of the Western Canada Foreland Basin. *in* (ed. Macqueen, W. R. & Leckie, D. A.), Foreland Basins Belts, AAPG Memoir *55*, p. 9 - 46.

Leckie, R.M., Yuretich, R.F., West, O.L.O., Finkelstein, D. and Schmidt, M., 1998. Paleoceanography of the southwestern western interior sea during the time of the Cenomanian-Turonian boundary (Late Cretaceous). *In* Dean, W.E. Walter and Arthur, M.A. (eds.) Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA. SEPM Concepts in Sedimentology and Paleontology, No. 6, p. 101-126.

Lemieux, S. 1999. Seismic reflection expression and tectonic significance of Late Cretaceous extensional faulting of the Western Canada Sedimentary Basin in southern Alberta. *Bulletin of Canadian Petroleum Geology*, vol. 47, no. 4, p. 375-390.

Lipps, J.H., 1979. The ecology and Paleoecology of Planktic Foraminifera. *In:* Foraminiferal ecology and paleoecology (eds. Lipps, J.H., Berger, W.H., Buzas, M.A., Douglas, R.G. and Ross, C.A). *Society of Economic Paleontologists and Mineralogists* short course, vol. 6, p. 62-104.

Leythaeuser, D., 1973. Effects of weathering on organic matter in shales. *Geochim. Cosmochim. Acts*, 37, p. 113-120.

Longman, M.W., Luneau, B.A. and Landon, S.M., 1998. Nature and distribution of Niobrara lithologies. *In*: the Cretaceous Western Interior Seaway of the Rocky Mountain Region. *The Mountain Geologist*, vol. 35, no. 4, p. 137-170.

Lorenz, J.C., 1982. Lithospheric flexure and the history of the Sweetgrass Arch northeastern Montana. *Rocky Mountain Association of Geologists* - 1982 Symposium, p. 77-89.

Lorenz, J.C. and Gavin, W., 1984. Geology of the Two Medicine Formation and the sedimentology of the dinosaur nesting ground. Montana Geological Society - 1984 Field Conference - northwestern Montana, p. 175-186.

Loutit, T.S., Hardenbol, J., Vail, P.R. and Baum, G.R., 1988. Condensed sections: the key to age dating and correlation of continental margin sequences. *In*: Sea-level Changes: An Integrated Approach (ed. Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Roos, C.A. and Van Wagoner, J.C.). Society of Economic Paleontologists and Mineralogists, Special Publication no. 42, p. 183-216.

Ludvigson, G.A., Witzke, B.J., Gonzalez, L.A., Hammond, R.H. and Plocher, O.W., 1994. Sedimentology and carbonate geochemistry of concretions from the Greenhorn marine cycles (Cenomanian-Turonian), eastern margin of the Western Interior Seaway. *in* Shurr, G.W., Ludvigson, G.A., and Hammond, R.H., (eds.). Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin: Geological Society of America Special Paper 287, p. 145-173.

MacEachern, J.A., Stelck, C.R. and Pemberton S.G., 1999. Marine and marginal marine mudstone deposition: paleoenvironmental interpretations based on the integration

of ichnology, palynology and foraminiferal paleoecology. *In*: Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation (eds. Bergman, K.M and Snedden, J.W.). Society of Economic Paleontologists and Mineralogists. Special Publication 64, p. 205-225.

Martin, I., 1965. The Medicine Hat Gas Field. *Journal of Canadian Petroleum Technology*. vol. 4, no. 1, p. 23-29.

Martinson, V.S., Heller, P.L. and Frerichs, W.E. 1998. Distinguishing middle Late Cretaceous tectonic events from regional sea-level change using foraminiferal data from the U.S. Western Interior. *GSA Bulletin*, v. 110; no. 2, p. 259-268.

McGookey, D.P., Haun, J.D., Hale, L.A., Goodell, H.G., McCubbin, D.G., Weimer, R.J. and Wulf, G.R., 1972. Cretaceous system. *In:* Geologic Atlas of the Rocky Mountain Region: Denver, Colorado (ed. Mallory, W.). Rocky Mountain Association of Geologists, p. 190-228.

McNeil, D.H. and Caldwell, W.G.E., 1981. Cretaceous rocks and their foraminifera in the Manitoba Escarpment. Geological Association of Canada, Special Paper 21, pp. 439.

Medioli, B.E., 1999. Cenomanian to Santonian sea-level history from a proximal setting in the western Canada sedimentary basin, southern Rocky Mountain Foothills, Alberta: Sedimentology, micropaleontology and organic geochemistry. Unpublished Masters Thesis, Carleton University, pp. 147.

Myhr, D.W. and Meijer-Drees, N.C., 1976. Geology of the southeastern Alberta Milk River. The sedimentology of selected clastic oil and gas reservoirs in Alberta: Calgary, *Canadian Society of Petroleum Geologists Bulletin*.

Niedoroda. A.W., Swift, D.J.P. and Thorne. J.A. 1989. Modeling shelf storm beds: Controls of bed thickness and bedding sequence. GCSSEPM Foundation Seventh Annual Research Conference Proceedings. P. 15-39.

Nielsen. K. S. and Schröder-Adams, C. J., 1999. Upper Colorado Group lithology and wire line log correlation in southwestern Saskatchewan. *In: Summary of Investigations 1998*. Saskatchewan Geological Survey. Saskatchewan Energy Mines. Miscellaneous Report 98-4, p. 79-84.

North. B.R. and Caldwell. W.G.E., 1975. Illustrations of Canadian fossils. Cretaceous Foraminifera from Saskatchewan and Manitoba: Geological Survey of Canada. Paper 74-38. pp. 35.

Obradovich, J.D., 1993. A Cretaceous time scale, *In*: Evolution of the Western Interior Basin (eds. Caldwell , W.G.E. and Kauffman, E.G.). Geological Association of Canada, Special Paper 39, p. 379-396.

Palmer, J. J. and Scott. A. J. 1984. Stacked Shoreline and Shelf Sandstone of La Ventana Tougue (Campanian), Northwestern New Mexico. *AAPG Bulletin* V. 68. No. 1. p. 74-91.

Park, J.M., 1965. Biostratigraphy of the Upper Cretaceous White Speckled Shales in central Saskatchewan. Unpublished Master Thesis. University of Saskatchewan. pp. 78

Park. J. and Herbert. T.D., 1987. Hunting for paleoclimatic periodicities on a geologic time series with an uncertain time scale. *Journal of Geophgysical Research*. vol. 92. p. 14027-14040.

Payenberg, T.H.D., 2002. Litho-, Chrono- and allostratigraphy of the Santonian to Campanian Milk River and Eagle formations in southern Alberta and north-central Montana: Implications for differential subsidence in the Western Interior Foreland Basin. Unpublished Ph.D. Thesis. University of Toronto, Canada. pp. 221.

Pemberton, S.G., MacEachern, J.A. and Frey, R.W., 1992. Trace fossil facies models: environmental and allostratigraphic significance. *In*: Facies Models: response to sea-level change (eds.Walker, R.G. and James, N.P.). Geological Association of Canada, p. 47-72.

Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis. *American Association of Petroleum Geologists Bulletin*, vol. 70, p. 318-329.

Plint, A.G., 1988. Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta. *In*: Sea-Level Changes: An Integrated Approach (eds. Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C.). Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 357-370.

Plint, A.G., 1990. An allostratigraphic correlation of the Muskiki and Marshybank formations (Coniacian-Santonian) in the Foothills and subsurface of the Alberta Basin. *Bulletin of Canadian Petroleum Geology*, vol. 38, no. 3, p. 288-306.

Plint, A.G., 1991. High-frequency relative sea-level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? *International Association of Sedimentology*, vol. 12, p.4 09-428.

Plint, A.G. and Norris, B., 1991. Anatomy of the ramp margin sequence: facies successions, paleogeography, and sediment dispersal patterns in the Muskiki and Marshybank formations, Alberta foreland basin. *Canadian Petroleum Geology Bulletin*, vol. 39, p. 18-42.

Plint, A.G. and Nummedal, D., 2000. The falling stage systems tract: Recognition and importance in sequence stratigraphic analysis. In: Sedimentary Responses to Forced Regressions (eds. Hunt, D. and Gawthorpe, R.L.G.). Geological Society of London, Special Publication 172, 1-17.

Plint, A.G., Norris, B. and Donaldson, W.S. 1990. Revised definitions for the Upper Cretaceous Bad Heart Formation and associated units in the Foothills and Plains of Alberta and British Columbia. *Bulletin of Canadian Petroleum Geology*, vol. 38, no. 1, p. 78-88.

Podruski, J.A., 1988. Contrasting character of the Peace River and Sweetgrass arches, Western Canada Sedimentary Basin. *Geoscience Canada*, vol. 15, p. 94-97.

Posamentier, H.W., 2001. Lowstand alluvial bypass systems: Incised vs. unincised. *American Association of Petroleum Geologists Bulletin*, vol. 85, no. 10, p. 1771-1793.

Reading, H.G., 1986. Facies. *In:* Sedimentary Environments and Facies (ed. Reading, H.G.). Blackwell Scientific Publications p. 4-19.

Ridgley, J.L., McNeil, D.H., Gilboy, C.F., Condon, S.M., Obradovich, J.D., 2001. Structural and stratigraphic controls on sites of shallow biogenic gas accumulations in the Upper Cretaceous Belle Fourche and Second White Specks-Greenhorn formations of southern Alberta, Saskatchewan and northern Montana.

in Gas in the Rockies (eds.) Anderson, D.S, Robinson J.W., Estes-Jackson, J.E., Coalson, E.B. The Rocky Mountain Association of Geologists pp. 241-270.

Rice, D.D., 1984. Widespread, shallow-marine, storm-generated sandstone units in the Upper Cretaceous Mosby Sandstone, Central Montana. *In*: Siliciclastic Shelf Sediments (eds.Tillman, R.W. and Seimers, C.T.). Tulsa, Society for Sedimentary Geology (Society of Economic Paleontologists and Mineralogists), Special Publication 34, p. 143-161

Schröder-Adams, C.J., Adams, P.J., Leckie, D.A., Bloch, J., Craig, J. and El-Dien, S.A.S., 1997. Upper Cretaceous Medicine Hat Formation and First White Speckled Shale in southeastern Alberta: evidence for localized shallow water deposition. *Bulletin of Canadian Petroleum Geology*, vol. 45, no. 3, p. 356-376.

Schröder-Adams, C.J., Adams, P., Haggart, J., Leckie, D.A., Bloch, J., Craig, J. and McIntyre, D.J., 1998. An integrated paleontological approach to reservoir problems: Upper Cretaceous Medicine Hat Formation and First White Speckled Shale in southern Alberta, Canada. *Palaios*, vol. 13, p. 361-375.

Schröder-Adams C.J., Cumbaa, S.L., Bloch, J., Leckie, D.A., Craig, J., Seif El-Dein, S.A., Simons, D. H.A.E. and Kenig, F. 2001. Late Cretaceous (Cenomanian to Campanian) paleoenvironmental history of the Eastern Canadian margin of the Western Interior Seaway: bonebeds and anoxic events. *Palaeogeography, Palaeoclimatology, Palaeoecology* V. 170, p. 261-289.

Schröder-Adams, C.J., Leckie, D.A., Bloch, Craig, J., McIntyre, D.J. and Adams, P.J., 1996. Paleoenvironmental changes in the Cretaceous (Albian to Turonian)

Colorado Group of western Canada: microfossil, sedimentological and geochemical evidence. *Cretaceous Research*, vol. 17, p. 311-365.

Shanley, K. W. and McCabe, P.J. 1994. Perspectives on the sequence stratigraphy of continental strata. *AAPG Bulletin*, Vol. 78, no. 4. p. 544-568.

Shurr, G.W. and Rice, D.D., 1986. Paleotectonic controls on deposition of the Niobrara Formation, Eagle Sandstone, and equivalent rocks (Upper Cretaceous), Montana and South Dakota. *In*: Paleotectonics and sedimentation in the Rocky Mountain region (ed. Peterson, J.A.). *American Association of Petroleum Geologists*, Memoir 41, p. 193-211.

Shurr, G.W., Hammond, R.H. and Bretz, R.F., 1994. Cretaceous paleotectonism and postdepositional tectonism in south-central South Dakota: An example of epeirogenic tectonism in continental lithosphere, *in* Shurr, G.W., Ludvigson, G.A., and Hammond, R.H., (eds.). Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin: Geological Society of America Special Paper 287, p. 237-256.

Simpson, F., 1975. Marine lithofacies and biofacies of the Colorado Group (Middle Albian to Santonian) in Saskatchewan; *in* Caldwell, W.G.E. (eds.), The Cretaceous System in the Western Interior of North America; Geol. Assoc. Can., Spec. Pap. 13, p. 553-587.

Simpson, F., 1981: Low-permeability gas reservoirs in marine Cretaceous sandstones of Saskatchewan: 11. Well-log analysis of Medicine Hat Sandstone (Santonian) of southwestern Saskatchewan and southeastern Alberta. *In: Summary of*

Investigations 1981, Saskatchewan Geological Survey, Miscellaneous Report 81-4.

Simpson, F., 1982. Low-permeability gas reservoirs in marine Cretaceous sandstones of Saskatchewan. *Summary of Investigations 1982*, Saskatchewan Geological Survey, Miscellaneous Report 82-4, p. 120-125.

Simpson, F., 1984. Hydrocarbon potential of low permeability marine Cretaceous sandstones of Saskatchewan, *In:* The Mesozoic of Middle North America. A selection of papers from the symposium on the Mesozoic of Middle North America, Calgary, Alberta, Canada. *Canadian Society of Petroleum Geologists,* p. 513-533.

Slingerland, R., Kump, L.R., Arthur, M.A., Fawcett, P.J., Sageman, B.B, and Barron, E.J., 1996. Estuarine circulation in the Turonian Western Interior Seaway of North America. *G.S.A. Bulletin*, vol. 108, no. 7, p. 941-952.

Snedden, J.W. and Bergman, K.M. 1999. Isolated shallow marine sand bodies: Deposits for all interpretations. *in* Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation. (eds. Bergman K.M. and Snedden J.W.) SEPM Special Publication No. 64, p. 1-12.

Snedden, J.W. and Dalrymple, R.W., 1999. Modern Shelf Sand Ridges: From historical perspective to a unified hydrodynamic and evolutionary model. *In:* Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation (eds. Bergman, K.M. and Snedden, J.W.). Society of Economic Paleontologists and Mineralogists. Special Publication 64, p. 13-28.

Stott, D.F., 1962. Upper Cretaceous marine rocks of Rocky Mountain Foothills. *Alberta Society of Petroleum Geologists Journal*, Vol. 10, no. 5, p. 228-240.

Stott , D.J., 1963. The Cretaceous Alberta Group and equivalent rocks, Rocky Mountain Foothills, Alberta. Geological Survey of Canada, Memoir 317, pp. 306.

Stow, D.A.V., Faugeres, J., Viana, A. and Gonthier, E. 1998. Fossil contourites: a critical review. *Sedimentary Geology*, vol. 115, p. 3-331.

Swift, D. J. P. and Thorne, J. A., 1991. Sedimentation on continental margin I: a general model for shelf sedimentation, Article I, V and VI. *In*: Shelf Sand and Sandstone Bodies, Geometry, Facies and Sequence Stratigraphy (Swift, D.J.P., Oertel, G.F., Tillman, R.W. and Thorne, J.A., eds.). International Association of Sedimentologists, Special Publication 14, p. 3-31.

Swift, J.P., Freeland, G.L., Gadd, P.E., Han, G., Lavell, J.W. and Stubblefield, W.L., 1976. Morphologic evolution and coastal sand transport, New York - New Jersey Shelves. Middle Atlantic Continental Shelf and the New York Bight Special Symposia, vol. 2, p. 69-89.

Swift, D.J.P. and Rice, D.D., 1984. Sand bodies on Muddy shelves: A model for sedimentation in the Western Interior Cretaceous Seaway, North America. *In*: Siliciclastic Shelf Sediments (eds. Tillman, R.W. and Seimers, C.T.). Tulsa, Society for Sedimentary Geology (Society of Economic Paleontologists and Mineralogists) Special Publication 34, p. 43-?

Swift, D.J.P., Thorne, J. and Oertel, G.F., 1986. Fluid processes and sea-floor response on a modern storm-dominated shelf: Middle Atlantic shelf of North America. Part II: Response of the shelf floor. *In:* Shelf Sands and Sandstones (eds. Knight, R.J.

and McLean, J.R.). Canadian Society of Petroleum Geologists, Memoir 11,. p. 191-213.

Then, D.R. and Dougherty, B.J., 1983. A new procedure for extracting foraminifera from indurated organic shale: Current Research, part B. Geological Survey of Canada, paper 83-1B, p. 313-314.

Tillman, R.W., Swift, D.J.P. and Walker, R.G., 1985. Shelf Sands and Sandstones: Tulsa, SEPM, Short Course Notes 13, pp. 708

Tissot, B., Pelet, R. and Ungerer, Ph., 1987. Thermal History of Sedimentary Basins, Maturation Indices, and Kinetics of Oil and Gas Generation: *American Association of Petroleum Geologists Bulletin*, vol. 71, no. 12, p. 1445-1466.

Tucker, M.E., 1991. Sedimentary Petrology. An introduction to the Origin of Sedimentary Rocks. Blackwell Scientific Publications, pp. 259.

Uchman, A., 1999. Ichnology of the Rhenodanubian Flysch (Lower Cretaceous-Eocene) in Austria and Germany. *Beringeria* 25: 67-173.

Van Wagoner, J.C., Mitchum, R.M., Campton, K.M. and Rahmanian, V.D., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops. American Association of Petroleum Geologists, Methods in Exploration Series, no. 7, pp. 55.

Van Wagoner, J.C., Posamentier, H.W., Vail, P.R., Sarg, J.F. and Loutit, T.S., 1988. An overview of the fundamentals sequence stratigraphy and key definitions. *In*: Sea-Level Changes: An Integrated Approach (eds. Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Roos, C. A. and Van Wagoner, J. C.).

Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 39-46.

Walker, R.G. and Rosenthal, L.R.P., 1982. Wapiabi Formation at Ghost Dam, Bow River, Alberta. *In:* Clastic Units of the Front Ranges, Foothills and Plains in the area Between Field, B.C. and Drumheller, Alberta (ed. Walker, R.G.). IAS excursion 21A, p. 144-150.

Walker, R.G. and Plint, A.D., 1992. Wave- and shallow-marine systems, *In:* Facies Models: Response to Sea Level Change (eds. Walker, R.G. and James, N.). Geological Association of Canada, St. John's Newfoundland, p. 219-238.

Wall, J.H., 1967a. Paleoecology of Cretaceous marine microfaunas in the Rocky Mountain Foothills of Alberta and British Columbia. *In*: Paleoenvironments of the Cretaceous Seaway in the Western Interior. Colorado School of Mines, Golden, Colorado, p. 173-194

Wall, J.H., 1967b. Cretaceous Foraminifera of the Rocky Mountain Foothills, Alberta. *Research Council Alberta*, Bulletin 20, p. 185.

Wall, J.H. and Rosene, R.K., 1977. Upper Cretaceous Stratigraphy and micropaleontology of the Crowsnest Pass - Waterton Area, southern Alberta Foothills. *Bulletin of Canadian Petroleum Geology*, vol. 25, no. 4, p. 842-867.

Williams, G.D. and Stelck, C.R., 1975. Speculations on the Cretaceous paleogeography of North America. *In*: The Cretaceous System in the Western Interior of North America (ed. Caldwell, W.G.E.). Geological Association of Canada, Special Paper 13, p. 1-20.

Wright, M.E. and Walker, R.G., 1981. Cardium Formation (U. Cretaceous) at Seebee, Alberta – storm transported sandstones and conglomerates in shallow marine depositional environments below fair-weather wave base. *Canadian Journal of Earth Sciences*, vol. 18, p. 795-809.

Table 4-1 Facies Description

No.	Facies	Description				Interpretation Paleo-environment
		Sedimentology	Micro-paleontology	Organic Geochemistry	Ichnofossils	
I	Fine laminated calcareous shale	Dark grey shale. Finely laminated and minor to no bioturbation. Thin (1-5 mm) lenticular sand lenses and normal graded very fine sand beds may be present. Macro-fossils may be present and unbroken. White specks are common. Concretions are rare.	Dominated by calcareous benthic and planktic foraminifera. ranging from abundance to rare. Agglutinated taxa may be common, but have low diversity. White specks layers contain nannofossils	High TOC values (2.5-5.0 %) and dominated by organic material II/III (marine-terrestrial).	Ichnofossils are rare.	Very low energy at all times. Dominated by out of suspension sedimentation Offshore, possible dysoxic bottom-water, normal at surface.
II	Bioturbated non-calcareous shale	Medium to dark gray shale. Most laminar and thin sedimentary structures destroyed due to bioturbation. Remains of lamination and thin sand-beds may be present. Concretions common, mainly sideritic. Abundant macrofossils are mainly unbroken.	Dominated by agglutinated foraminifera normally with high abundances and diversity. Calcareous benthic foraminifera may be present and can be dominating. Nanno-fossils may be present, but in poor preservation	Moderate TOC values (1.0-3.0 %). Organic material dominated by terrestrial type III with minor amounts of type II.	Bioturbation moderate to intensive. *Gordia, Plioichnus, Chondrites*, small *Planolites* and *Terrebellina*	Low energy with few periods of moderate energy levels. Offshore to lower shoreface. Normal oxygen and salinity through water column.

III	Shaly Siltstone	Medium gray siltstone with abundance of shale laminar. Mainly homogenous and structure-less with only few visible silty laminar features. Concretions may be present. Abundance of macro-fossils, both broken and unbroken.	Dominated by agglutinated foraminifera. Diversity and abundances moderate to high. Calcareous benthic foraminifera may be present. Nannofossils are not present	Moderate TOC values (0.5-2 %). Organic material mainly terrestrial type III.	Moderate to strongly bioturbated. Gordia, Plioichnus, planolites terrebellina Teichichnus	Low energy with periods of moderate energy. As lower shoreface facies with normal oxygen and salinity
IV	Siltstone interbedded with fine sandstone	Medium gray siltstone interbedded with light gray thin sandstone beds (05-25 mm). Sandstone beds are lenticular, normal graded or thin hummocky beds. Lenticular beds are both current and wave rippled. Concretions are rare. Macrofossils are common	Dominated by agglutinated foraminifera. Diversity and abundances are moderate. Calcareous benthic foraminifera may be present. Nannofossils are not present	Moderate TOC values (0.5 - 2.0%). Organic material mainly terrestrial type III	Slight to strongly bioturbated. *Siphonites, Terebellina, Teichichnus, Chondrites, Zoophycos,*	Moderate and high energy with periods of low energy. Alike lower to middle shoreface with storm and shelf currents as the dominating depositional feature.
V	Thin bedded fine grained shaly sandstone	Thin bedded sandstone with thin interbedded shale laminar. Very fine to fine and well sorted sandstone. General composition of matrix (60 %): Ca. 50% quartz, 20 % chert, 10 % rock fragments, organic material 5%, mica 4 %, feldspar 4 %. Chemically and physically mature. Sedimentary structures as in facies IV, but more frequent and thicker (5- 50 mm). Concretions and macro-fossils	Agglutinated foraminifera with low diversity and abundances Nannofossils are normally not present, but may occur in the interbedded shale laminar.	Low to moderate TOC values (0.5 -1.5 %). Organic material terrestrial type III.	Slightly bioturbated *Terebellina, Teichichnus*	High energy followed by a period of moderate to low energy, where biosphere had time to bioturbated sandstone.

		may occur.				
VI	Bioturbated Fine grained shaly sandstone	Original facies V, but now intensively bioturbated. Bed thickness up to 1 m of bioturbated homogenous very fine to fine sandstone. Concretions rare and few broken macro fossil.	Agglutinated foraminifera with low diversity and abundances. No nannofossils.	Low to moderate TOC values (0.5 -1.5 %). Organic material terrestrial type III.	Intensively bioturbated *Siphonites*, *Terebellina*, *Teichichnus*, *Chondrites*, *Zoophycos*, and rare *Asterosoma* and *Teredolites*	High energy and erosive.
VII	Lag and related facies	Black and white chert pebbles in size from 5 mm to 20 mm. Pebbles are rounded and mainly matrix supported. Associated are bone fragments and ooids. The zone is often cemented by siderite. Matrix may either be shale or sandstone.	Dominated by agglutinated, low in diversity and abundances. Few calcareous benthic are observed. No nannofossils.	Low to moderate TOC values (0.5 -1.5 %). Organic material terrestrial type III.	No bioturbation observed.	N/A
VIII	Paleosoil	Calcrete, 80 % calcite, 5 % anhydrite, 4 % authigenic chert and 6 % quartz, 5 % others. Structure-less with calcareous ooids and nodules. Rootlets observed. (pers. Comm. Seif El Dein, 1999)	No microfossils or nannofossils	N/A	No bioturbation	

Figure 4-1. Study area in southern Alberta, southwestern Saskatchewan and northern Montana.

STUDY AREA

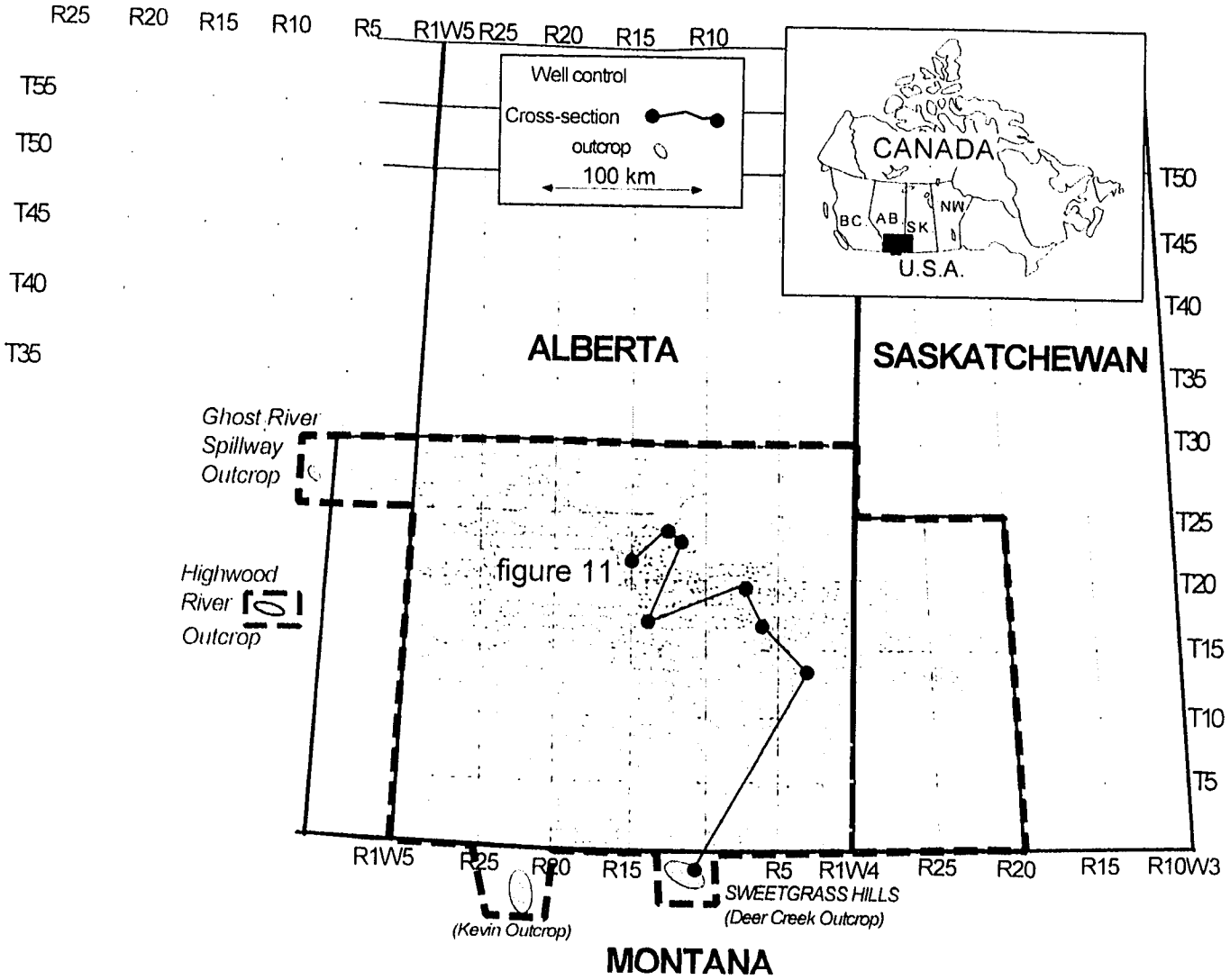


Figure 4-1

Figure 4-2. Stratigraphic chart showing the interval of the Carlile and Niobrara formations and correlations to adjacent regions.

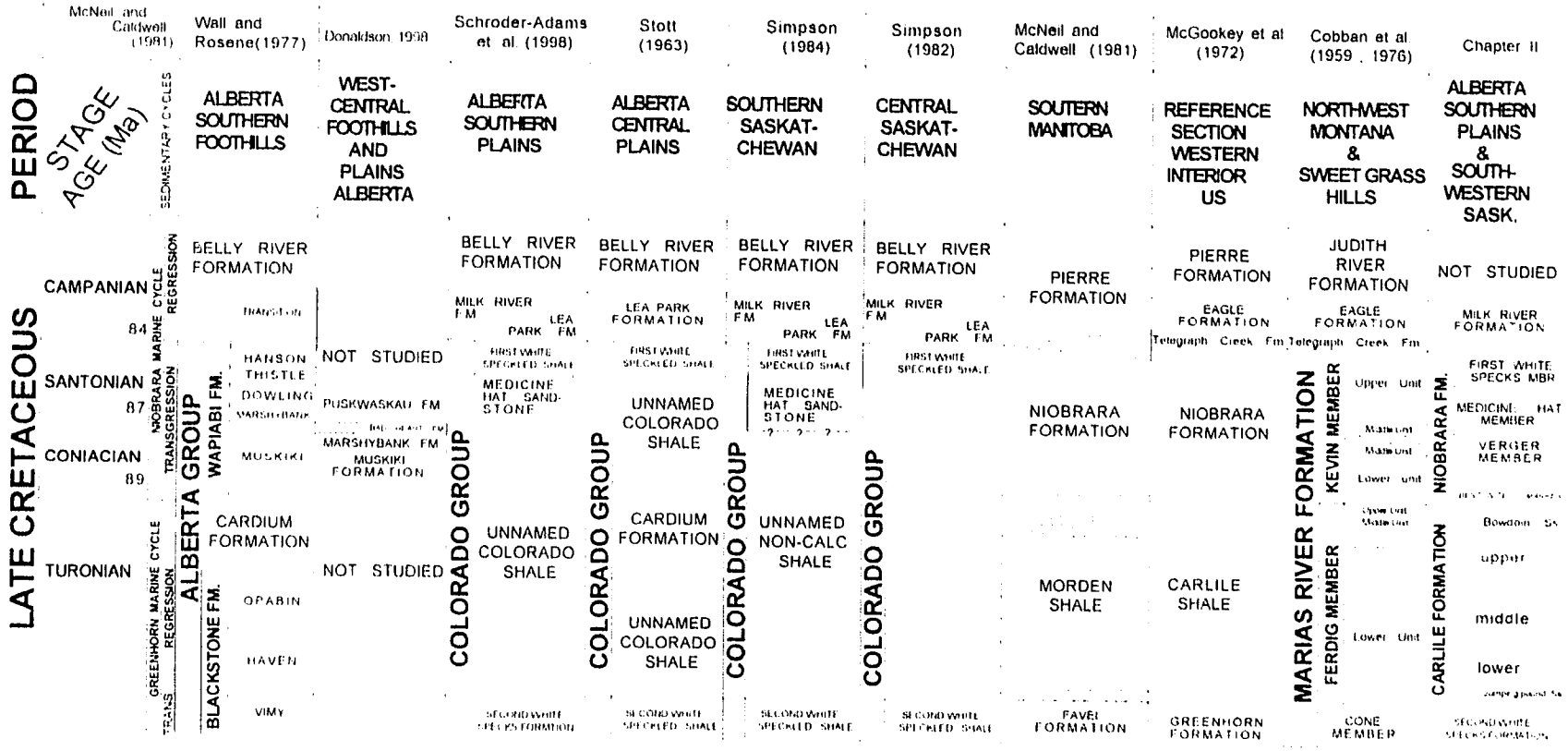

PERIOD
STAGE
AGE (Ma)
SEDIMENTARY CYCLES
LATE CRETACEOUS
CAMPANIAN
84
SANTONIAN
87
CONIACIAN
89
TURONIAN
MARINE CYCLE
REGRESSION
TRANSGRESSION
GREENHORN MARINE CYCLE
REGRESSION
TRANS
McNeil and Caldwell (1981)
Wall and Rosene(1977)
ALBERTA SOUTHERN FOOTHILLS
BELLY RIVER FORMATION
HANSON
THISTLE
DOWLING
MUSKIKI
CARDIUM FORMATION
OPABIN
HAVEN
VIMY
ALBERTA GROUP
WAPIABI FM.
BLACKSTONE FM.
Donaldson 1998
WEST-CENTRAL FOOTHILLS AND PLAINS ALBERTA
NOT STUDIED
PUSKWASKAU FM
MARSHYBANK FM
MUSKIKI FORMATION
NOT STUDIED
Schroder-Adams et al. (1998)
ALBERTA SOUTHERN PLAINS
BELLY RIVER FORMATION
MILK RIVER FM
LEA PARK FM
FIRST WHITE SPECKLED SHALE
MEDICINE HAT SAND-STONE
UNNAMED COLORADO SHALE
SECOND WHITE SPECKS FORMATION
COLORADO GROUP
Stott (1963)
ALBERTA CENTRAL PLAINS
BELLY RIVER FORMATION
LEA PARK FORMATION
FIRST WHITE SPECKLED SHALE
UNNAMED COLORADO SHALE
CARDIUM FORMATION
UNNAMED COLORADO SHALE
SECOND WHITE SPECKLED SHALE
COLORADO GROUP
Simpson (1984)
SOUTHERN SASKAT-CHEWAN
BELLY RIVER FORMATION
MILK RIVER FM
LEA PARK FM
FIRST WHITE SPECKLED SHALE
MEDICINE HAT SAND-STONE
UNNAMED NON-CALC SHALE
SECOND WHITE SPECKLED SHALE
COLORADO GROUP
Simpson (1982)
CENTRAL SASKAT-CHEWAN
BELLY RIVER FORMATION
MILK RIVER FM
LEA PARK FM
FIRST WHITE SPECKLED SHALE
SECOND WHITE SPECKLED SHALE
COLORADO GROUP
McNeil and Caldwell (1981)
SOUTERN MANITOBA
PIERRE FORMATION
NIOBRARA FORMATION
MORDEN SHALE
FAVEL FORMATION
McGookey et al (1972)
REFERENCE SECTION WESTERN INTERIOR US
PIERRE FORMATION
EAGLE FORMATION
Telegraph Creek Fm
NIOBRARA FORMATION
CARLILE SHALE
GREENHORN FORMATION
Cobban et al (1959 , 1976)
NORTHWEST MONTANA & SWEET GRASS HILLS
JUDITH RIVER FORMATION
EAGLE FORMATION
Telegraph Creek Fm
MARIAS RIVER FORMATION
KEVIN MEMBER
Upper Unit
Lower unit
FERDIG MEMBER
Lower Unit
CONE MEMBER
Chapter II
ALBERTA SOUTHERN PLAINS & SOUTH-WESTERN SASK.
NOT STUDIED
MILK RIVER FORMATION
NIOBRARA FM.
FIRST WHITE SPECKS MBR
MEDICINE HAT MEMBER
VERGER MEMBER
Bowdoin Sh
CARLILE FORMATION
upper
middle
lower
SECOND WHITE SPECKS FORMATION

Figure 4-2

Figure 4-3. A west-east representation of the stratigraphic framework of the Carlile and Niobrara formations and regional correlations. The cross-section is based on regional cross-sections in chapter II.

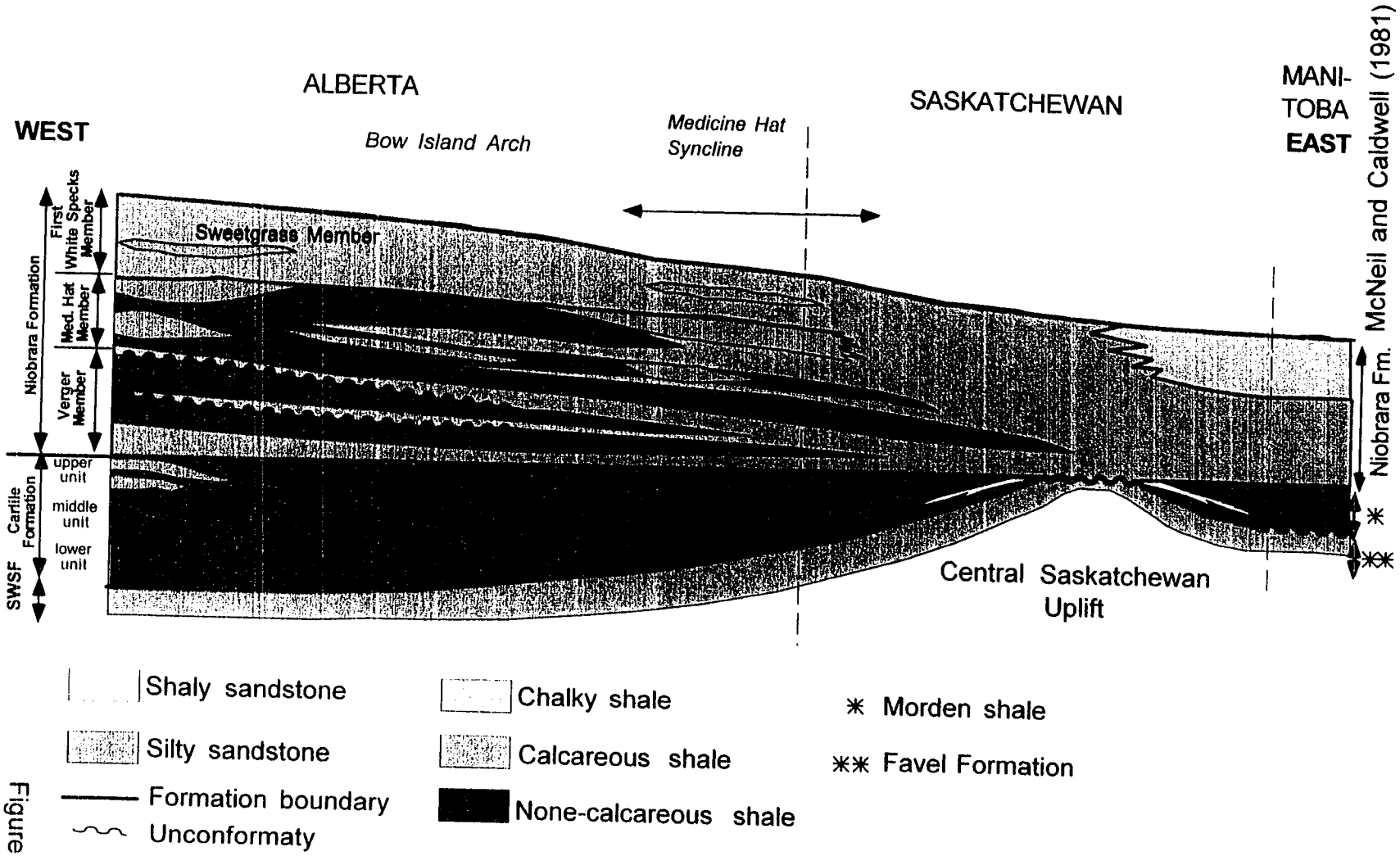

ALBERTA
SASKATCHEWAN
MANI-
TOBA
WEST
EAST
Bow Island Arch
Medicine Hat
Syncline
Sweetgrass Member
Niobrara Formation
First
White Specks
Member
Med. Hat
Member
Verger
Member
Carlile
Formation
upper
unit
middle
unit
lower
unit
SWSF
Niobrara Fm.
McNeil and Caldwell (1981)
*
**
Central Saskatchewan
Uplift
Shaly sandstone
Silty sandstone
Formation boundary
Unconformaty
Chalky shale
Calcareous shale
None-calcareous shale
* Morden shale
** Favel Formation

Figure 4-3

Figure 4-4. Isopach map of the Carlile Formation in southern Alberta and southwestern Saskatchewan. For well and outcrop location see figure 4-1.

ISOPACH Sequence F1 to F7 (chapter III)
CARLILE FORMATION

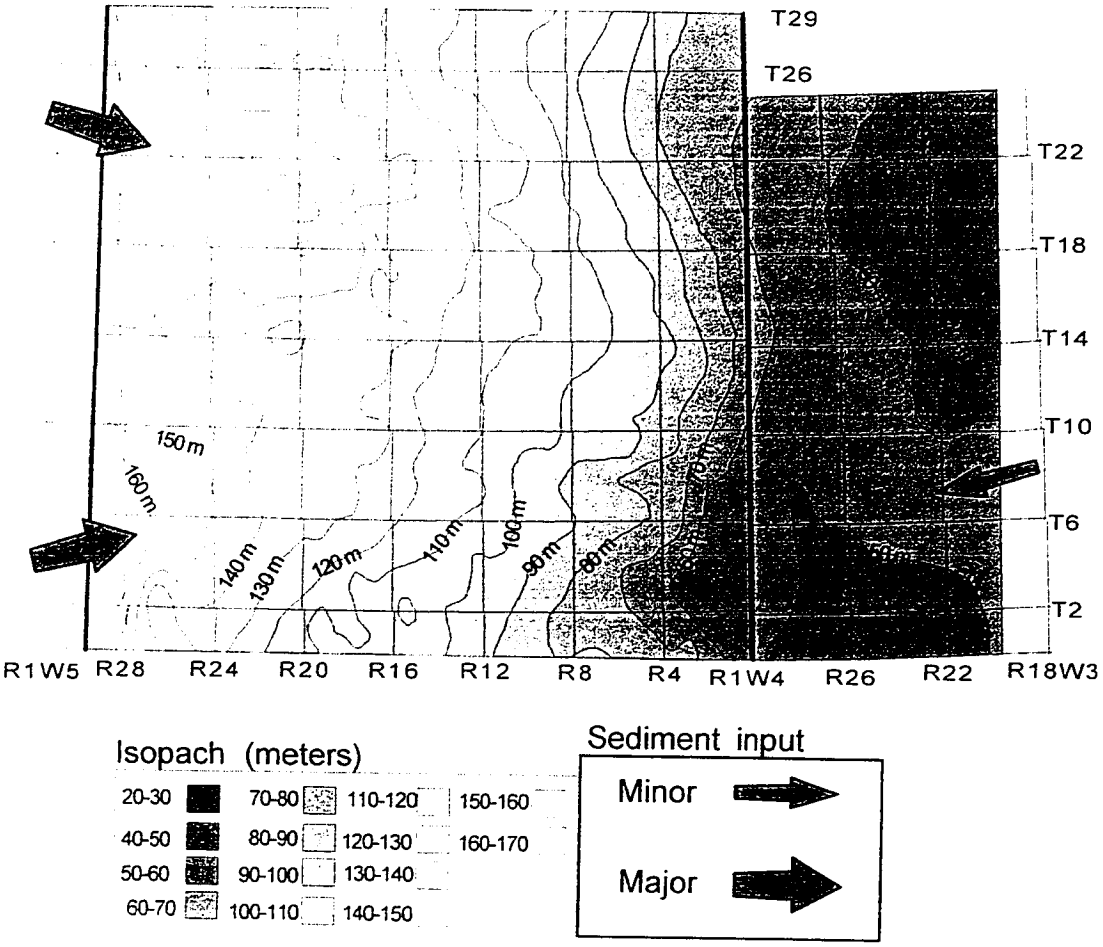


Figure 4-4

Figure 4-5. Isopach map of the Niobrara Formation and its members in southern Alberta and southwestern Saskatchewan. For well and outcrop location see figure 4-1. From chapter III. Contours are in meters above sea-level.

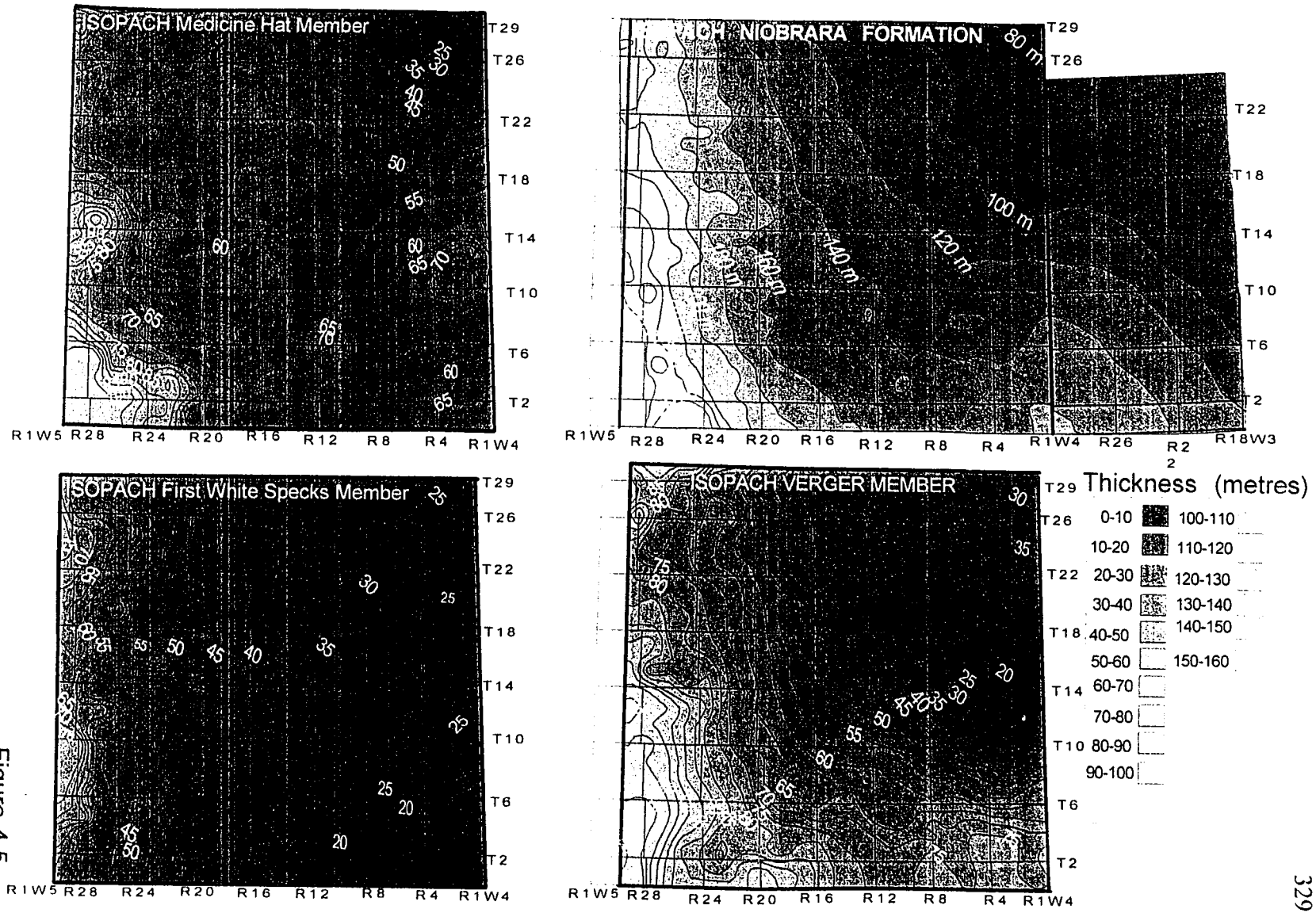

ISOPACH Medicine Hat Member
ISOPACH NIOBRARA FORMATION
ISOPACH First White Specks Member
ISOPACH VERGER MEMBER
T29
T26
T22
T18
T14
T10
T6
T2
R1W5
R28
R24
R20
R16
R12
R8
R4
R1W4
R26
R2
2
R18W3
80 m
100 m
120 m
140 m
160 m
Thickness (metres)
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
130-140
140-150
150-160

Figure 4-5

Figure 4-6. Regional structural map of the top Colorado Group in southern Alberta and southwestern Saskatchewan. The major structural elements are also outlined in northern Montana (after Lorenz, 1982).

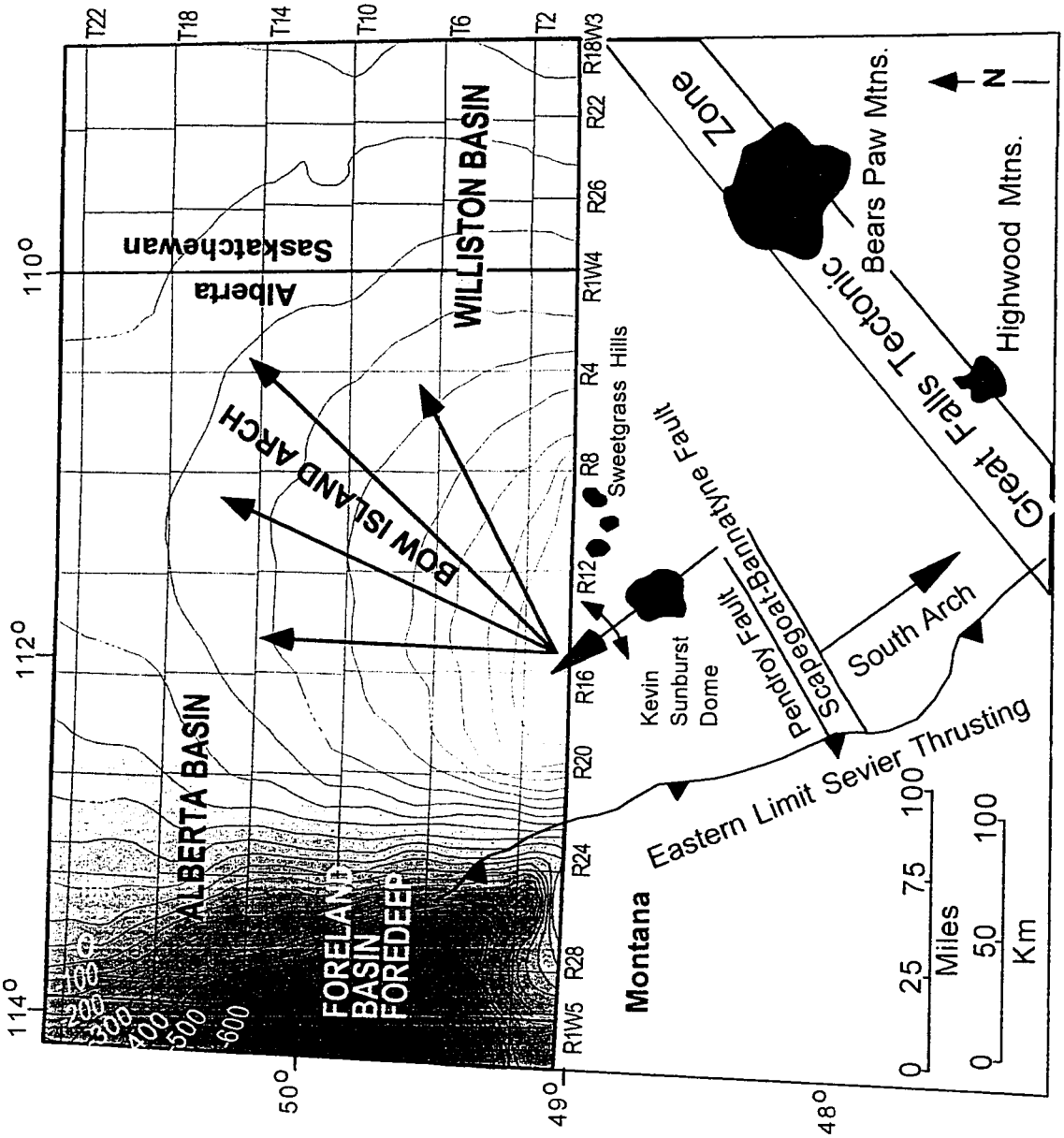

T22
T18
T14
T10
T6
T2
R18W3
R22
R26
R1W4
R4
R8
R12
R16
R20
R24
R28
R1W5
110°
112°
114°
50°
49°
48°
Saskatchewan
Alberta
WILLISTON BASIN
BOW ISLAND ARCH
ALBERTA BASIN
FORELAND BASIN FOREDEEP
100
200
300
400
500
600
Sweetgrass Hills
Kevin Sunburst Dome
Pendroy Fault
Scapegoat-Bannatyne Fault
South Arch
Eastern Limit Sevier Thrusting
Montana
Great Falls Tectonic Zone
Bears Paw Mtns.
Highwood Mtns.
N
0 25 75 100
Miles
0 50 100
Km

Figure 4-6

Figure 4-7. Schematic representation of the seven facies observed in the Carlile and Niobrara formations. The facies are related to the energy regime of Clifton (1986) and Ichnofacies from Pemberton et al., (1992).

Facies of the Carlile and Niobrara formations

High energy
"Proximal"

Low energy
"Distal"

	"Terrestial" facies	Upper shoreface	Middle shoreface	Lower shoreface		Upper Offshore	Lower Offshore	Shelf
Facies	**VII** and **VIII**	N/A	N/A	**VI**	**V**	**IV**	**III**	**II and I**
Energy level (after Clifton, 1986)	High energy (VII) Low energy (VIII)	N/A	N/A	Moderate energy with infrequent moderate to high energy		Low energy with frequent episode of moderate energy	Low energy with infrequent episode of moderate energy	Low energy
Ichno facies (after Pemberton et al., 1992)	N/A	N/A	N/A	*Skolithos/Cruziana*		*Cruziana* Proximal	*Cruziana* Distal	*Zoophycos*

Figure 4-7

Figure 4-8. Facies associations recognized in the Carlile and Niobrara Formations. Facies association A: **Upwards-coarsening parasequence (low to moderate energy)**. Facies association B: **Lower shoreface (moderate energy) with basal erosional surfaces (high energy)**. Facies association C: **Transgressive lag enclosed in shale and siltstone (episode of high energy enclosed in low energy sediments)**. Facies association D: **Distal lower shoreface to offshore (low energy)**. For trace-fossil assemblage see table 4-1.

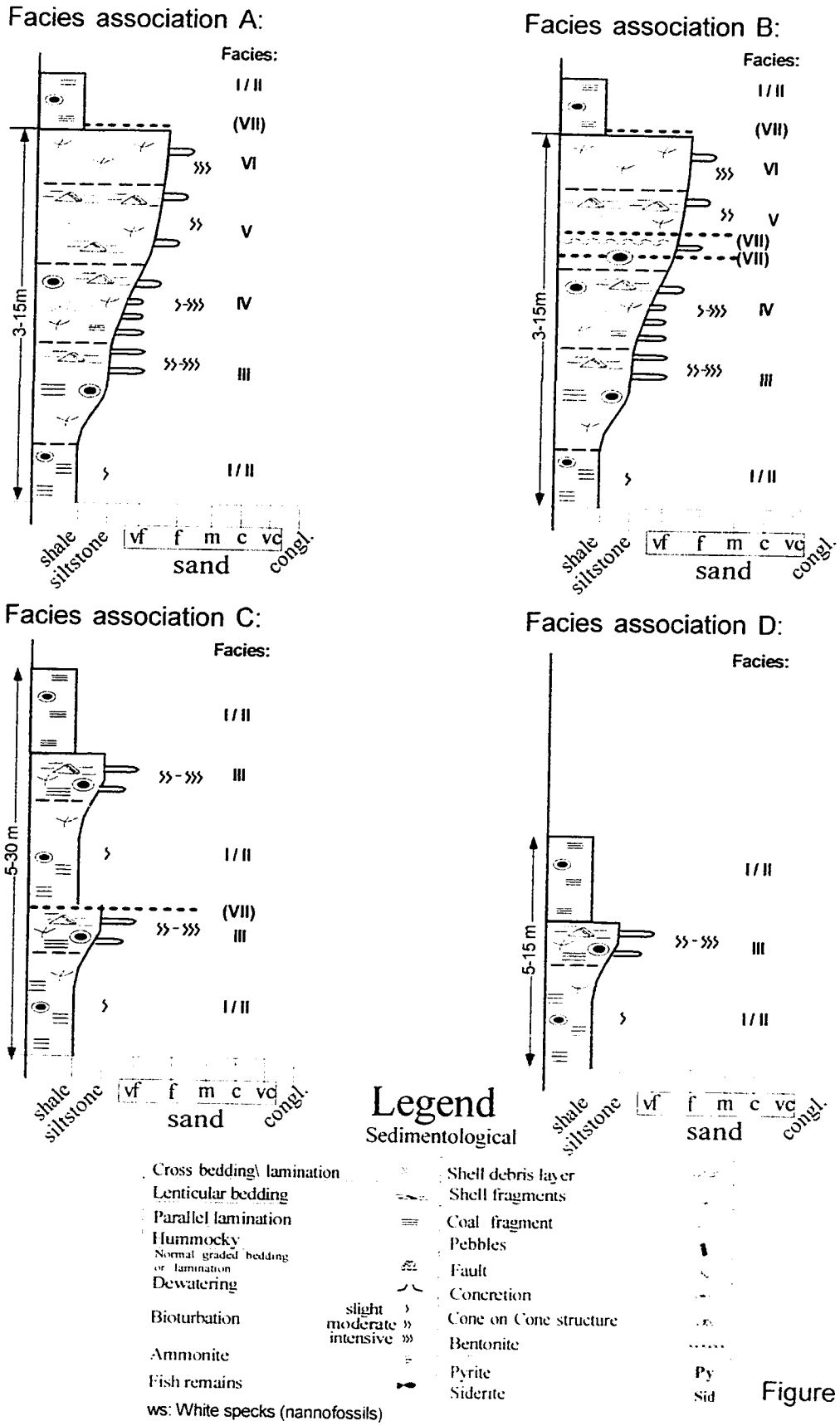

Facies association A:
Facies association B:
Facies association C:
Facies association D:
Facies:
I / II
(VII)
VI
V
IV
III
3-15m
5-30 m
5-15 m
shale
siltstone
vf f m c vc
sand
congl.
Legend
Sedimentological
Cross bedding\ lamination
Lenticular bedding
Parallel lamination
Hummocky
Normal graded bedding or lamination
Dewatering
Bioturbation
slight
moderate
intensive
Ammonite
Fish remains
ws: White specks (nannofossils)
Shell debris layer
Shell fragments
Coal fragment
Pebbles
Fault
Concretion
Cone on Cone structure
Bentonite
Pyrite
Py
Siderite
Sid

Figure 4-8

Figure 4-9. Outcrop section of the Carlile Formation in the Deer Creek outcrop on the east side of East Butte, Sweetgrass Hills, Montana. From chapter III. Location of outcrop is shown on figure 4-1 and sedimentological legend on figure 4-8.

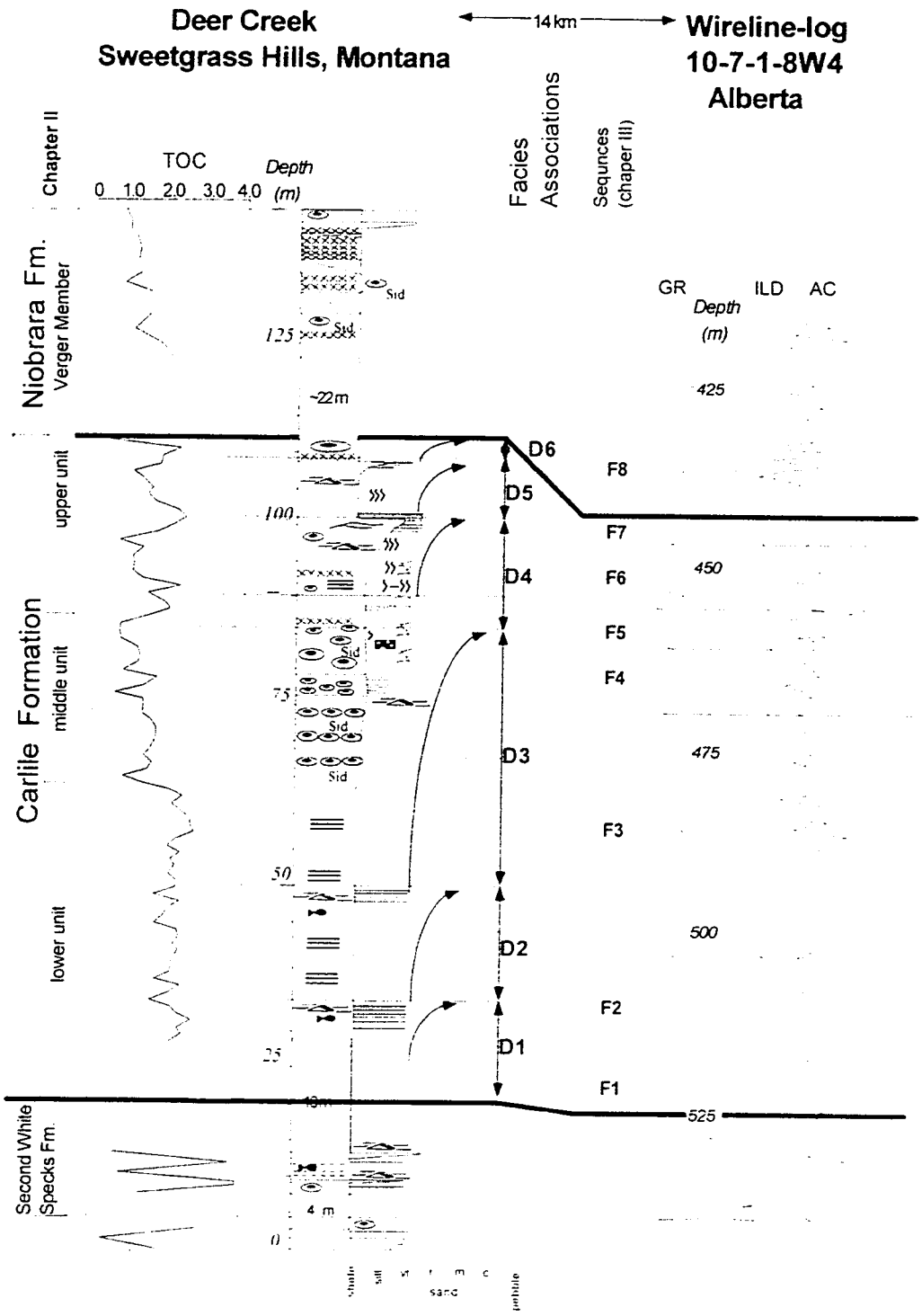
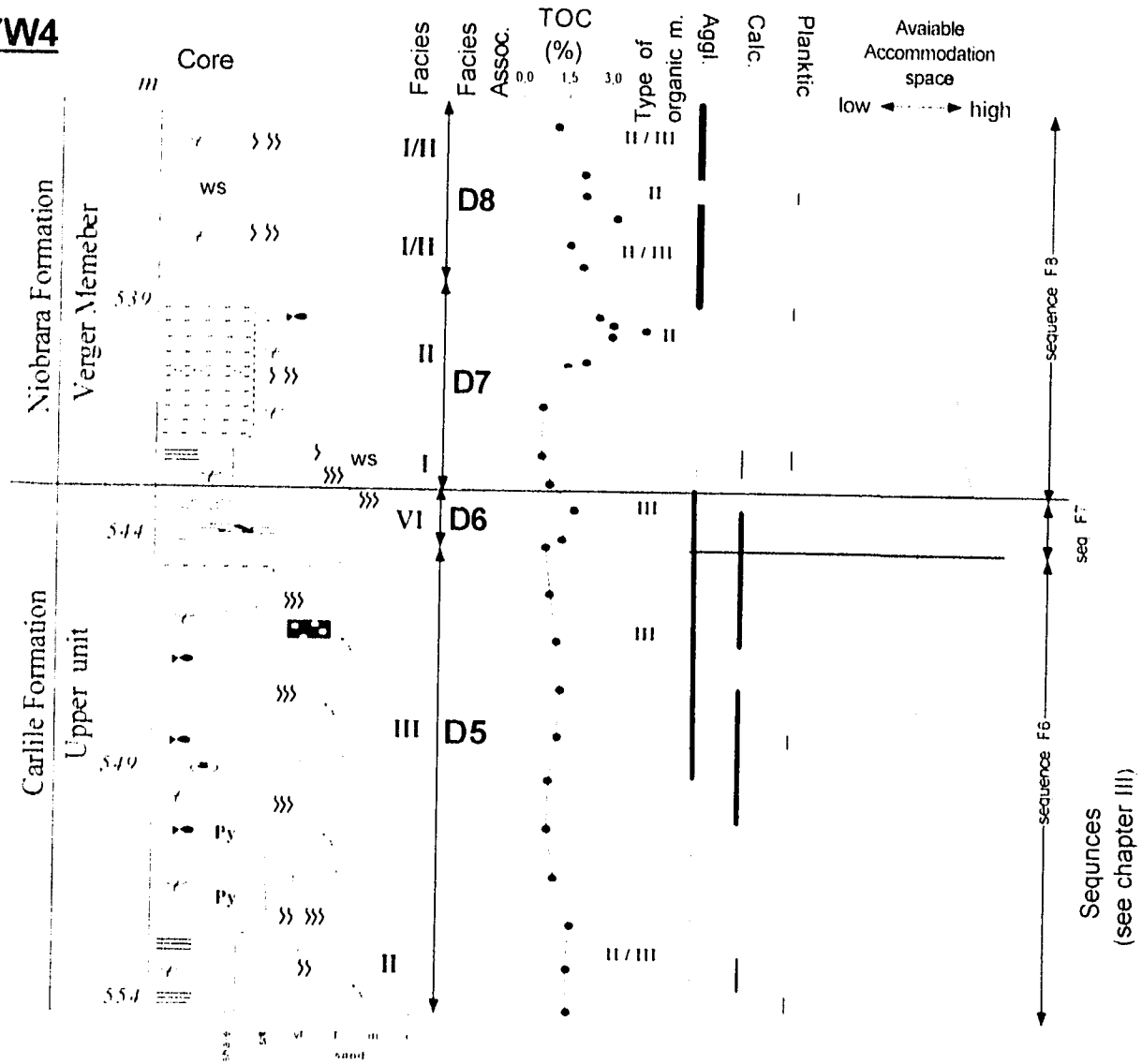

Deer Creek
Sweetgrass Hills, Montana
14 km
Wireline-log
10-7-1-8W4
Alberta
Chapter II
TOC
0 1.0 2.0 3.0 4.0
Depth (m)
Facies Associations
Sequnces (chaper III)
GR
ILD
AC
Depth (m)
Niobrara Fm.
Verger Member
Carlile Formation
upper unit
middle unit
lower unit
Second White Specks Fm.
Sid
125
100
75
50
25
0
~22m
13m
4 m
425
450
475
500
525
D6
D5
D4
D3
D2
D1
F8
F7
F6
F5
F4
F3
F2
F1
sand

Figure 4-9

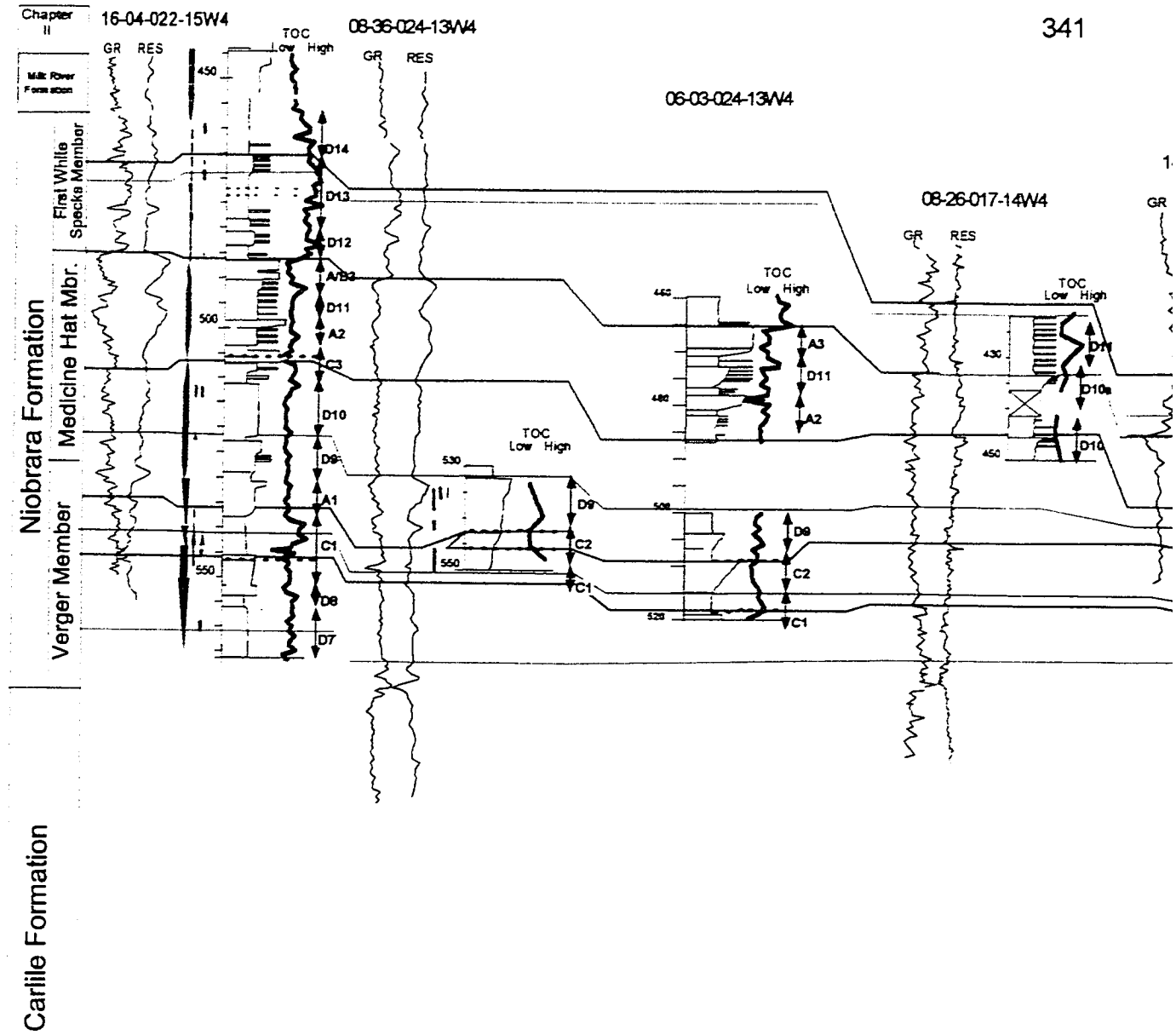
Figure 4-10. Core 13-20-17-7W4. Facies associations on the boundary between the Carlile and Niobrara Formation in a distal setting. Location on figure 4-1 and legend on figure 4-8.



Type of organic material (Espitalie, 1984)
Type II: Marine
Type III: Terrestrial

Figure 4-10

Figure 4-11. Cores and outcrop cross-section from southern Alberta and northern Montana. Lithology. TOC values and quantitative micropaleontological data are illustrated. For description of facies association see figure 4-3 to 4-8 and the text. The lithological subdivision is from chapter II. the sequence stratigraphic subdivision is from chapter III. For wells and outcrop location see figure 4-1 and sedimentological legend see figure 4-8.



Geochemistry and boundaries

High Low

Total Organic Content (TOC)

Formation and sequence boundary

First Major Flooding surface and Sequence boundary

Maximum Flooding Surface

D7 Facies Association (D7)

Micropaleontology

Relatively abundances of Foraminifera

Agglutinated

Calcareous Benthic

Planktic

abundant

common

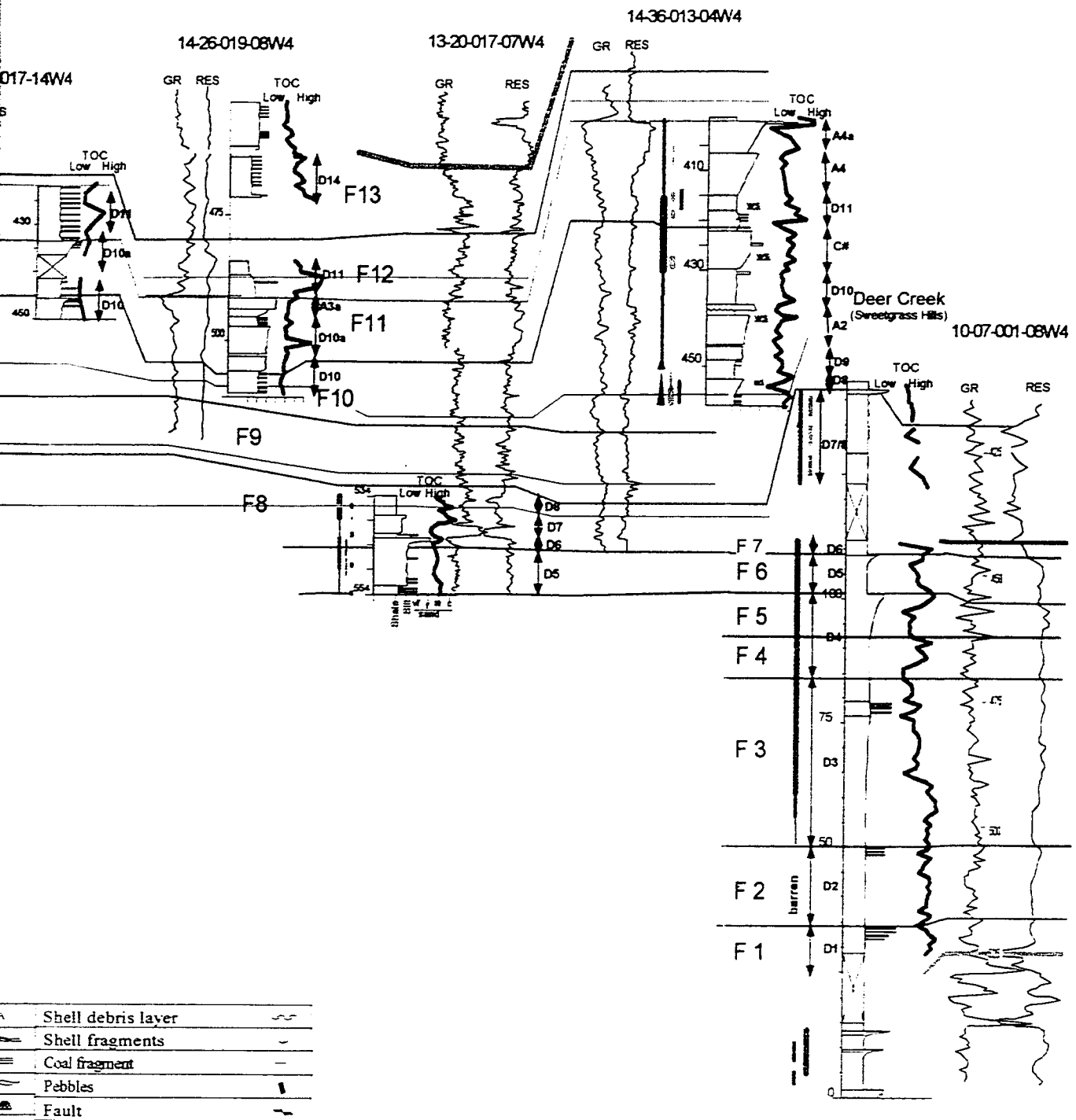
few

Sedimentology

Cross Bedding lamination		Shell debris layer
Lenticular bedding		Shell fragments
Parallel lamination		Coal fragment
Hummocky		Pebbles
Normal graded bedding or lamination		Fault
Dewatering		Concretion
Bioturbation	slight, moderate, intensive	Cone on Cone structu
Ammonite		Bentonite
Fish remains		Pyrite
		Siderite

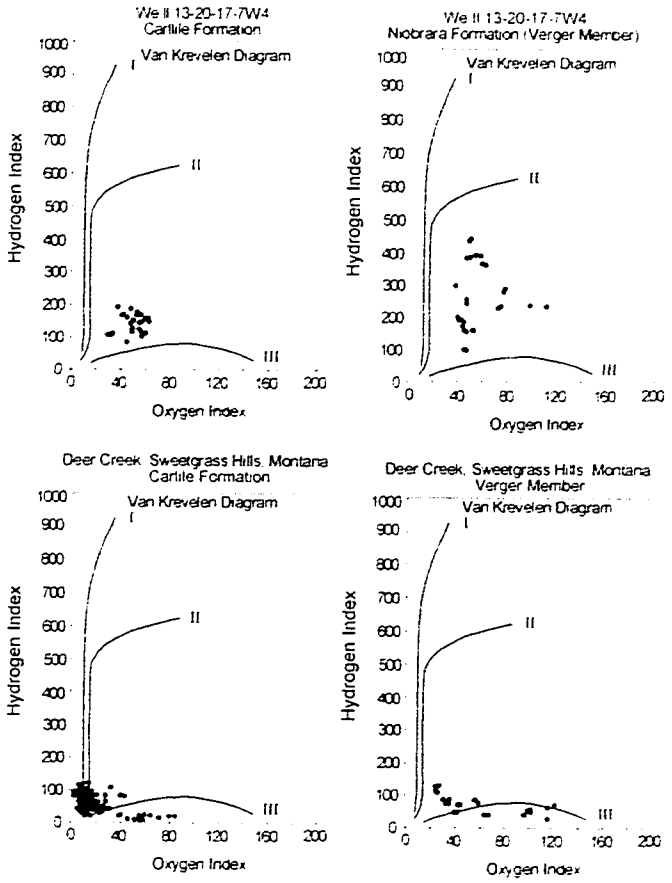
Figure 4-11

341



Shell debris layer	
Shell fragments	
Coal fragment	
Pebbles	
Fault	
Concretion	
Cone on Cone structure	
Bentonite	
Pyrite	Py
Siderite	Sid

Figure 4-12. Organic geochemistry of the Carlile Formation and the lower member (Verger) of the Niobrara Formation. The Van Krevelen diagrams illustrate the stratigraphic and paleogeographic changes in organic matter.



Carlile Formation
lower, middle, upper unit
Deer Creek, Sweetgrass Hills, Montana

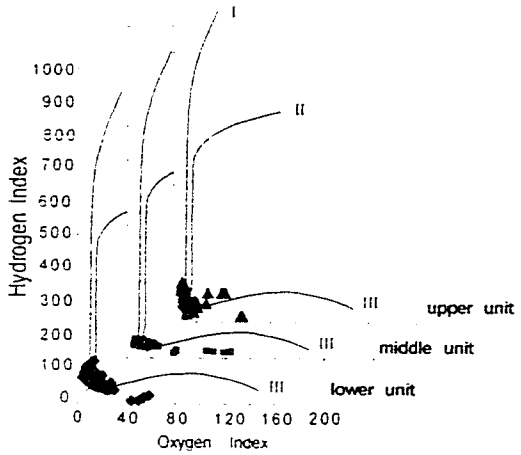


Figure 4-12

Figure 4-13. Paleogeographic map from the Second White Specks Formation (Bloch et al., 1993) (early Late Turonian) in the study area and the larger region of western Canada and northwestern US. **1)** Stott (1962), **2)** Williams and Stelk (1975); **3)** Lang and McGugan (1987); **4)** Kauffman (1984); **5)** Schröder-Adams et al. (1996); **6)** McNeil and Caldwell (1981); **7)** McGookey et al. (1972).

Figure 4-14. Paleogeographic map from the Lower Carlile Formation (Late Turonian) in the study area and the larger region of western Canada and northwestern US. **1)** Wall and Rosene (1977); **2)** McGookey et al. (1972); **3)** Stott (1963); **4)** Hattin (1975); **5)** McNeil and Caldwell, (1981); **6)** Schröder-Adams et al. (2001); **7)** Cobban et al. (1976); **8)** Brennan-Alpert (1998); **9)** Cobban et al. (1994). **10)** Caldwell et al. (1993). See legend on figure 4-13.

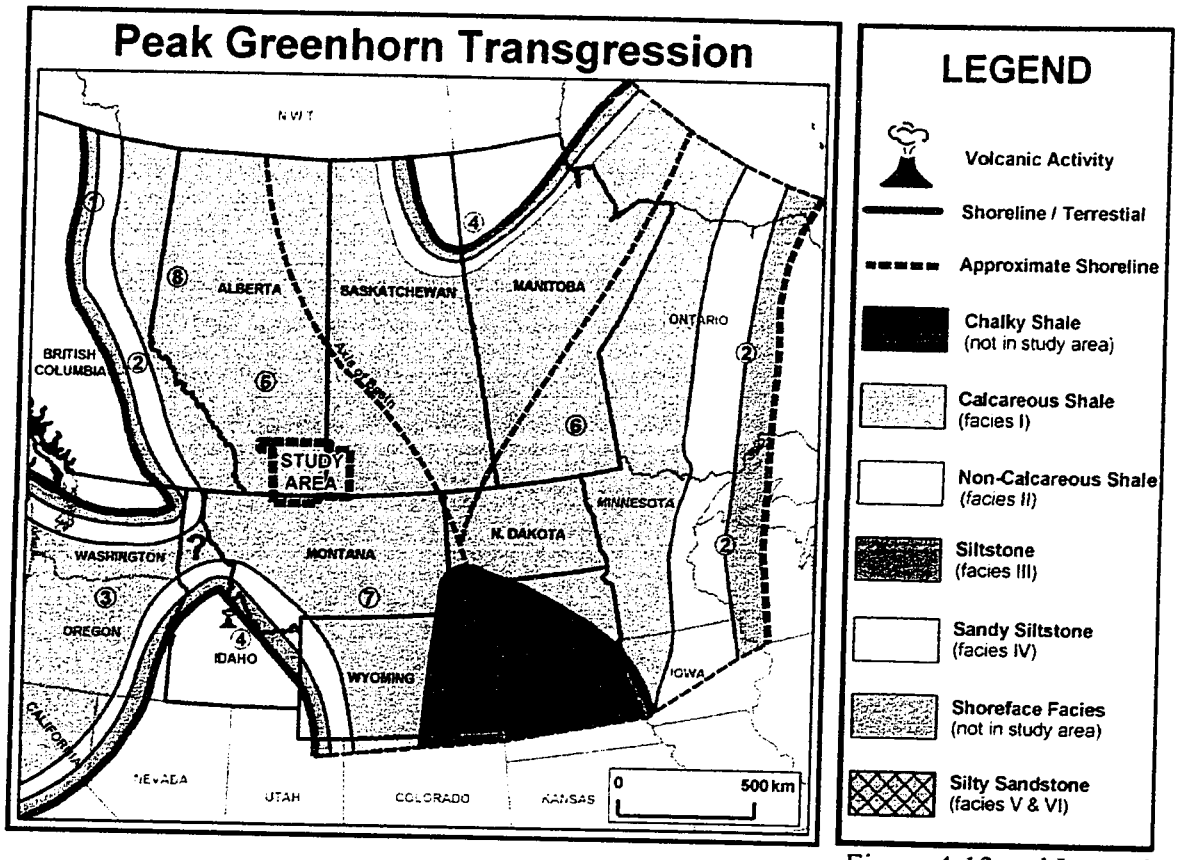


Figure 4-13 and Legend

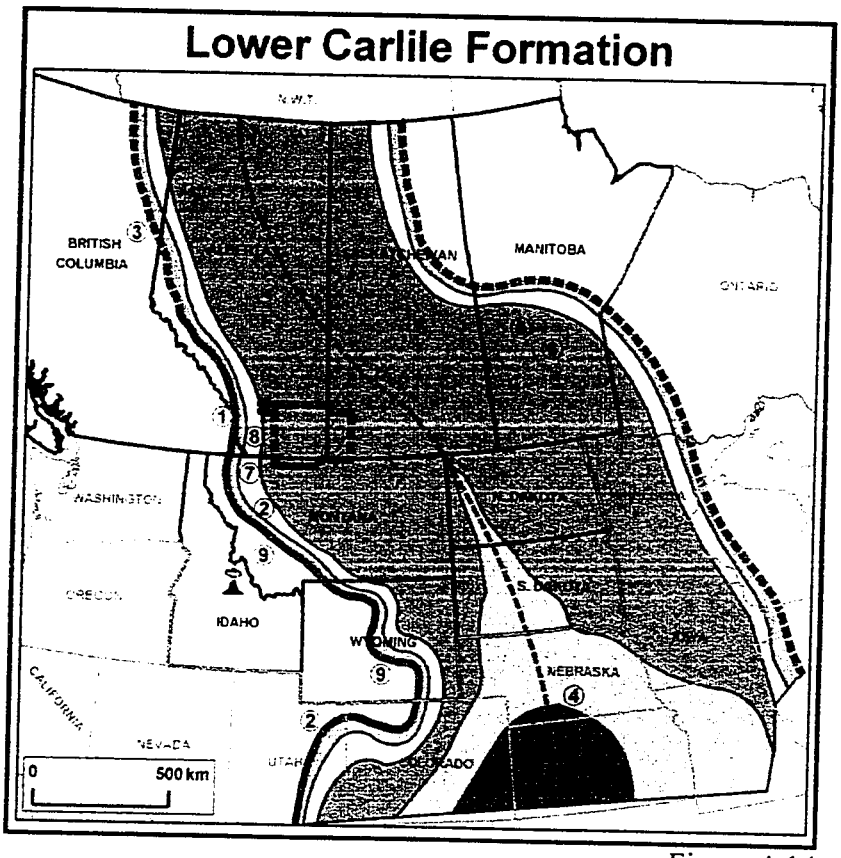


Figure 4-14

Figure 4-15. Paleogeographic map from the Upper Carlile Formation (Late Turonian) in the study area and the larger region of western Canada and northwestern US. **1)** Wall and Rosene (1977); **2)** Wright and Walker (1981); **3)** Stott (1963); **4)** Leckie et al. (1994); **5)** Gilboy (1993); **6)** Park (1965); **7)** McGookey et al. (1972); **8)** North and Caldwell (1975); **9)** Cobban et al. (1976); **10)** Caldwell et al. (1993). See legend on figure 4-13.

Figure 4-16. Paleogeographic map from the Verger Member (maximum transgressions) of the Niobrara Formation in the study area and the larger region of western Canada and northwestern US. **1)** McNeil and Caldwell (1981); **2)** Longman et al. (1998); **3)** McGookey et al (1972); **4)** Stott (1962); **5)** Stott (1963); **6)** Wall and Rosene (1977); **7)** Plint and Norris (1991); **8)** Cobban et al. (1976). See legend on figure 4-13.

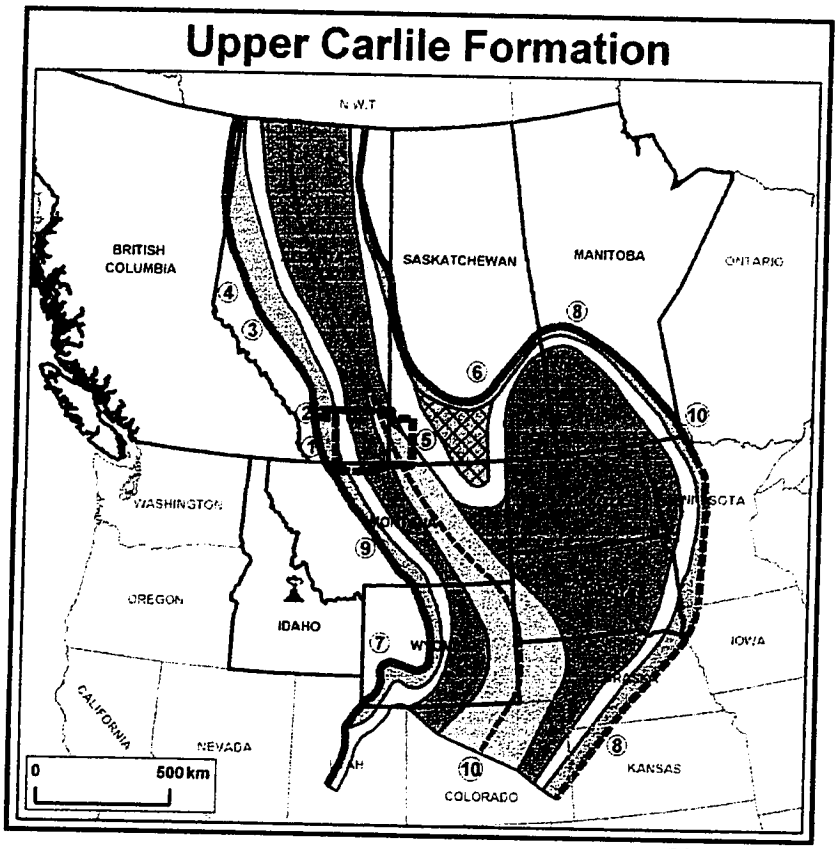


Figure 4-15

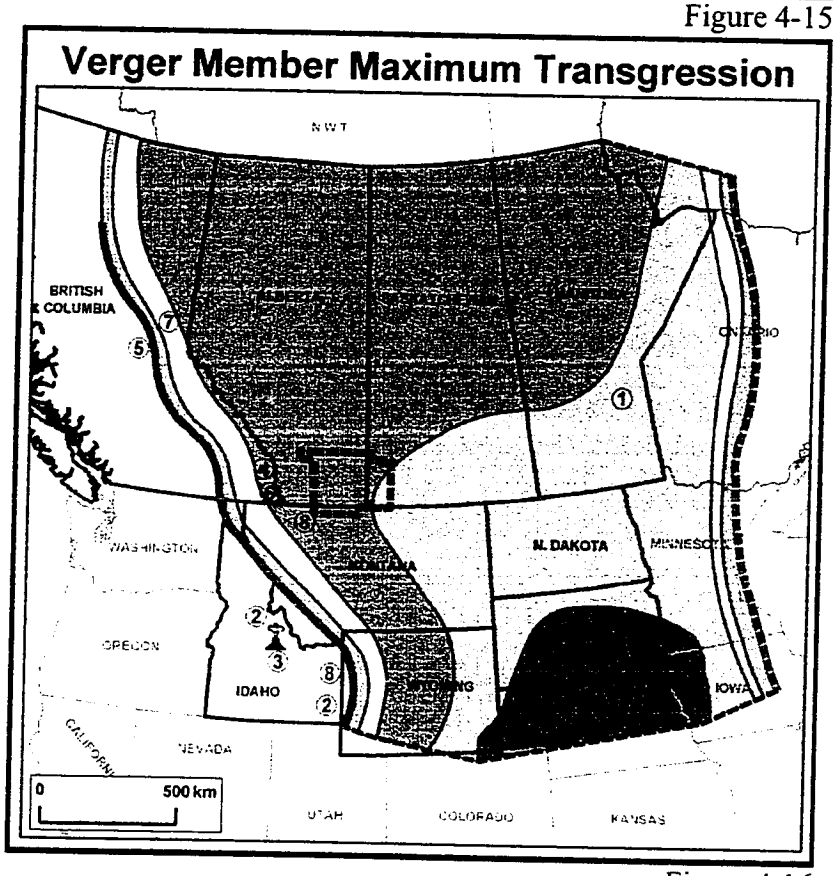


Figure 4-16

Figure 4-17. Isopach maps of the Verger sandstones 1, 2 and 3 and Medicine Hat sandstones 1, 1a, 2, 3, 3a, 4 and 5 in southern Alberta and southwestern Saskatchewan. For well and outcrop location see figure 4-1.

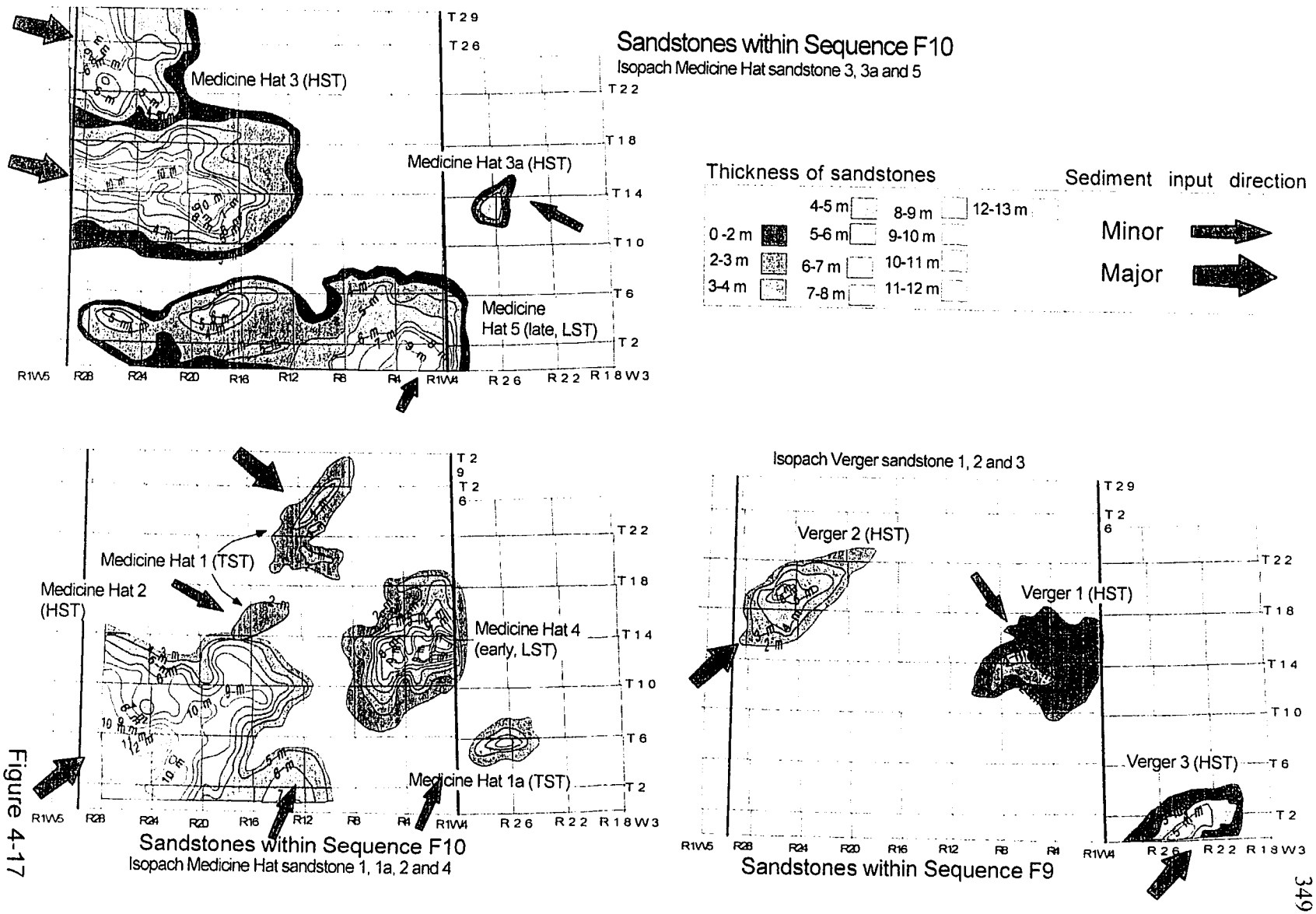

Sandstones within Sequence F10
Isopach Medicine Hat sandstone 3, 3a and 5
Medicine Hat 3 (HST)
Medicine Hat 3a (HST)
Medicine Hat 5 (late, LST)
Thickness of sandstones
0-2 m
2-3 m
3-4 m
4-5 m
5-6 m
6-7 m
7-8 m
8-9 m
9-10 m
10-11 m
11-12 m
12-13 m
Sediment input direction
Minor
Major
Medicine Hat 1 (TST)
Medicine Hat 2 (HST)
Medicine Hat 4 (early, LST)
Medicine Hat 1a (TST)
Sandstones within Sequence F10
Isopach Medicine Hat sandstone 1, 1a, 2 and 4
Isopach Verger sandstone 1, 2 and 3
Verger 2 (HST)
Verger 1 (HST)
Verger 3 (HST)
Sandstones within Sequence F9
T29
T26
T22
T18
T14
T10
T6
T2
R1W5
R28
R24
R20
R16
R12
R8
R4
R1W4
R26
R22
R18W3

Figure 4-17

Figure 4-18. Outcrop to subsurface correlation of the Niobrara Formation and equivalent strata. The regional correlations illustrate the regional continuity of the two pebble layers in the upper part of the Verger Member. For locations of outcrops and cores see figure 4-1 and sedimentological legend on figure 4-8.

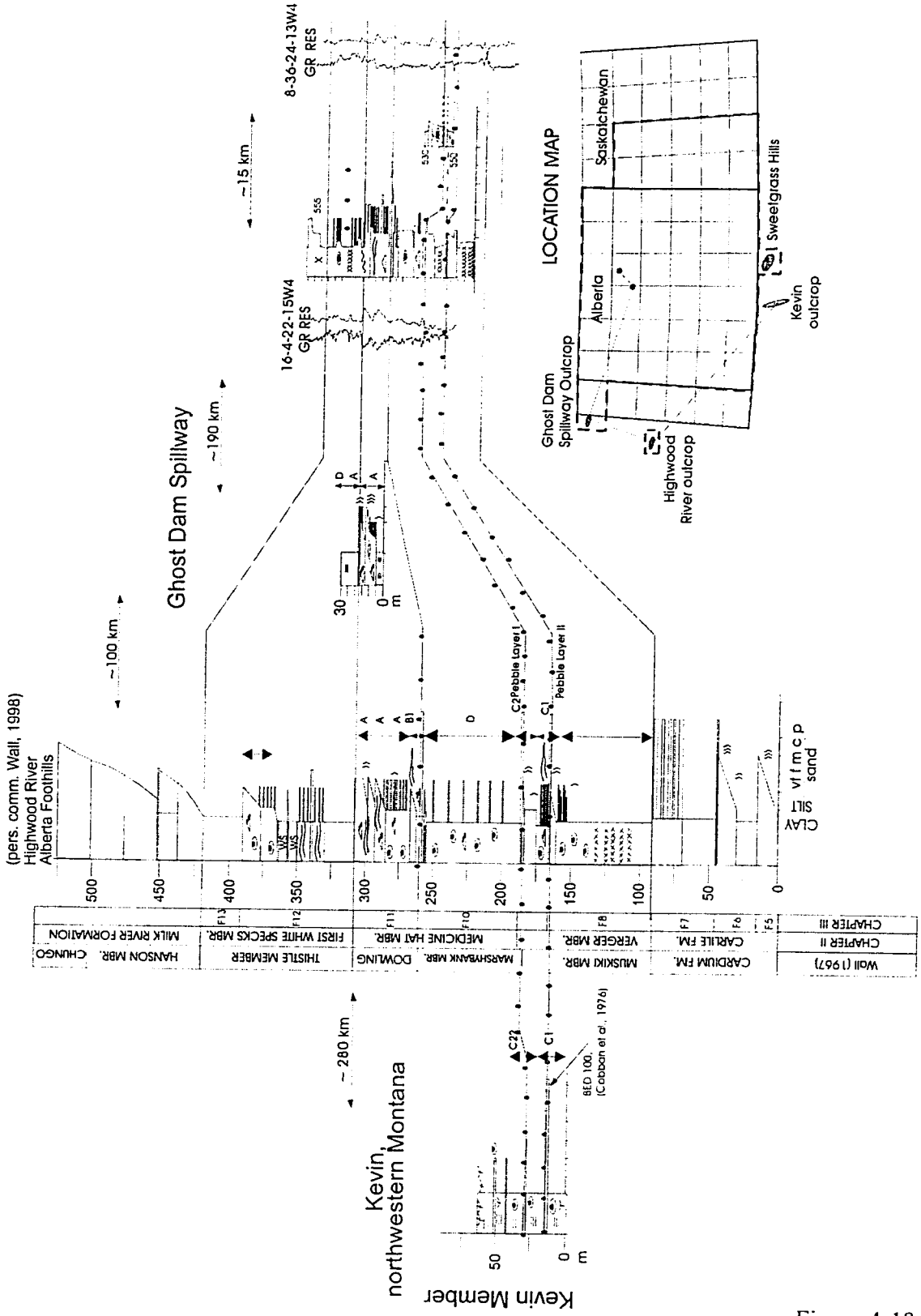

(pers. comm. Wall, 1998)
Highwood River
Alberta Foothills
~100 km
Ghost Dam Spillway
~190 km
~15 km
16-4-22-15W4
GR RES
8-36-24-13W4
GR RES
LOCATION MAP
Saskatchewan
Alberta
Sweetgrass Hills
Kevin outcrop
Ghost Dam Spillway Outcrop
Highwood River outcrop
Pebble Layer I
Pebble Layer II
CLAY
SILT
vf f m c p
sand
500
450
400
350
300
250
200
150
100
50
0
MILK RIVER FORMATION
CHUNGO
HANSON MBR.
THISTLE MEMBER
FIRST WHITE SPECKS MBR.
DOWLING
MEDICINE HAT MBR.
MARSHBANK MBR.
MUSKIKI MBR.
VERGER MBR.
CARDIUM FM.
CARLILE FM.
CHAPTER III
CHAPTER II
Wall (1967)
~ 280 km
Kevin,
northwestern Montana
Kevin Member
BED 100,
(Cobban et al., 1976)

Figure 4-18

Figure 4-19A and B. Organic geochemistry of the Carlile Formation and the Niobrara Formation.

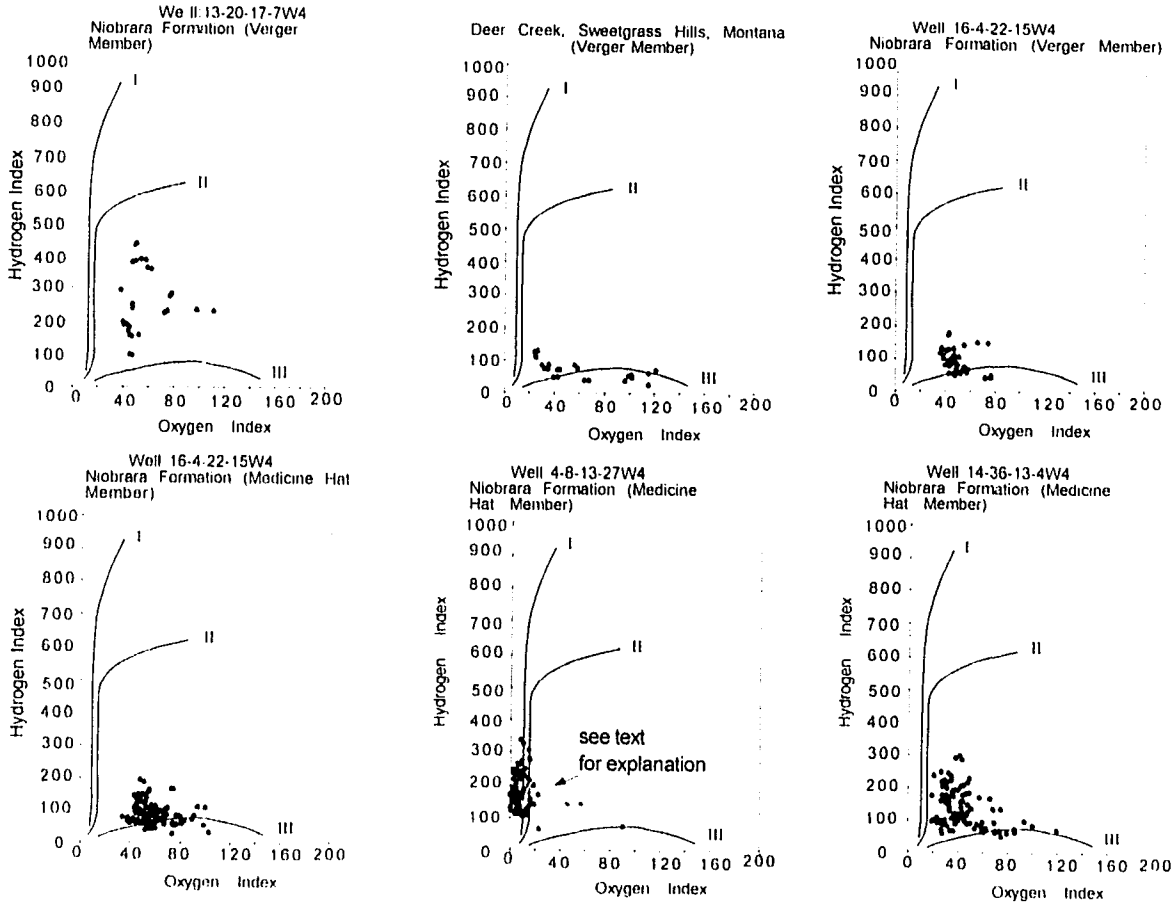

Well 13-20-17-7W4
Niobrara Formation (Verger Member)
Deer Creek, Sweetgrass Hills, Montana (Verger Member)
Well 16-4-22-15W4
Niobrara Formation (Verger Member)
Well 16-4-22-15W4
Niobrara Formation (Medicine Hat Member)
Well 4-8-13-27W4
Niobrara Formation (Medicine Hat Member)
Well 14-36-13-4W4
Niobrara Formation (Medicine Hat Member)
Hydrogen Index
Oxygen Index
I
II
III
see text for explanation

Figure 4-19A

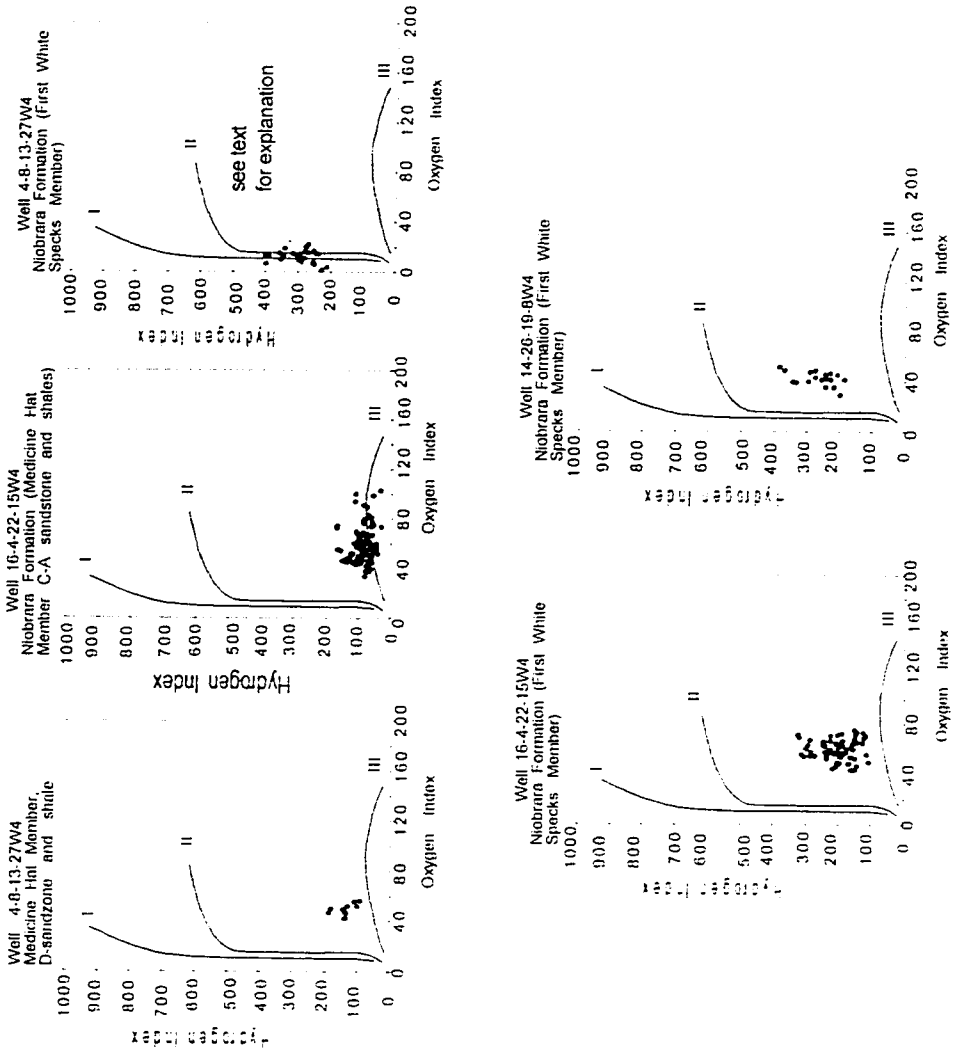

Well 4-8-13-27W4
Medicine Hat Member,
D-sandzone and shale
Well 16-4-22-15W4
Niobrara Formation (Medicine Hat
Member C-A sandstone and shales)
Well 4-8-13-27W4
Niobrara Formation (First White
Specks Member)
see text
for explanation
Well 16-4-22-15W4
Niobrara Formation (First White
Specks Member)
Well 14-26-19-8W4
Niobrara Formation (First White
Specks Member)
Hydrogen Index
Oxygen Index
I
II
III

Figure 4-19B

Figure 4-20. Paleogeographic map from the Verger Member (maximum regressions) of the Niobrara Formation in the study area and the larger region of western Canada and northwestern US. **1)** Cobban et al. (1976): **2)** Plint and Norris (1991): **3)** Donaldson et al.. (1998): **4)** McNeil and Caldwell (1981). See legend on figure 4-13.

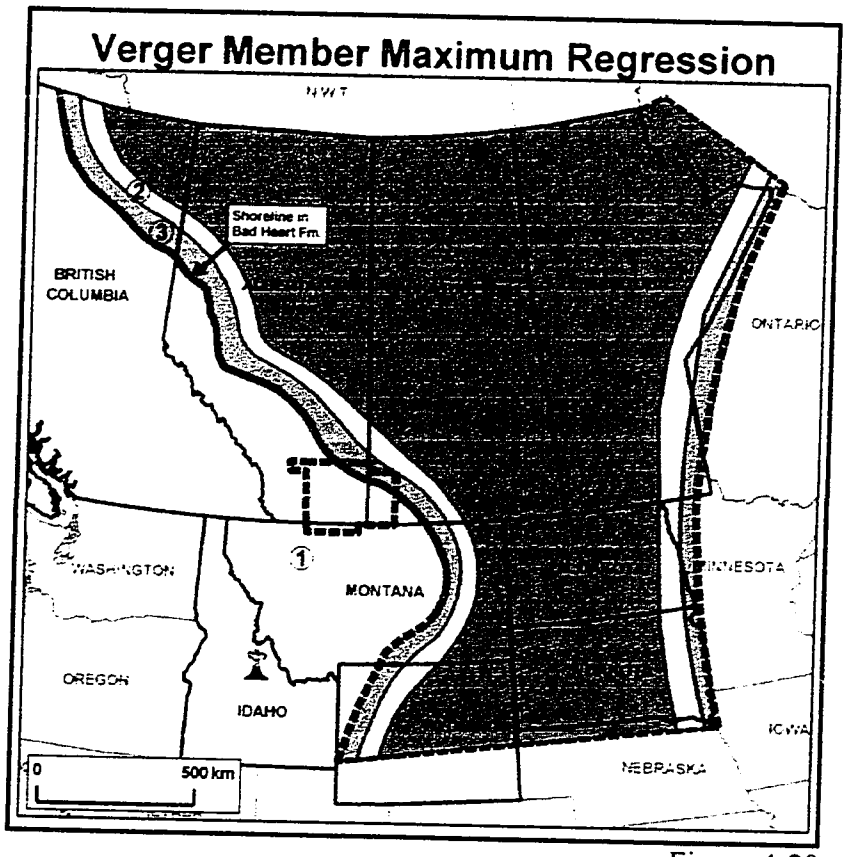
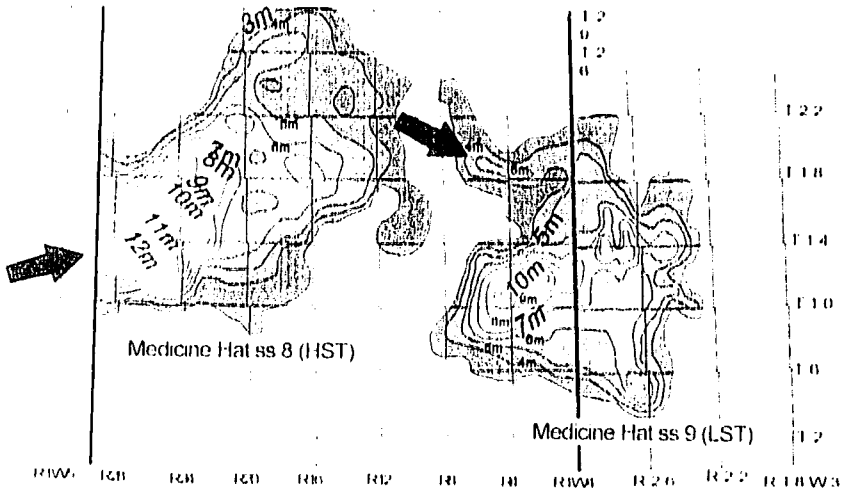

Verger Member Maximum Regression
NWT
Shoreline in Bad Heart Fm.
BRITISH COLUMBIA
ONTARIO
WASHINGTON
MONTANA
MINNESOTA
OREGON
IDAHO
IOWA
NEBRASKA
0
500 km

Figure 4-20

Figure 4-21. Isopach maps of the Medicine Hat sandstone 6. 6a. 7. 7a. 8 and 9 in southern Alberta and southwestern Saskatchewan.



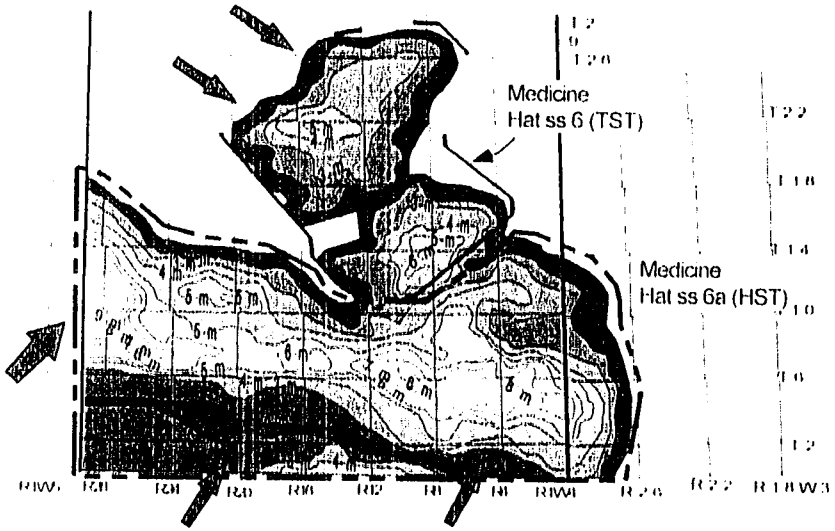
Sandstones within Sequence F11
Isopach Medicine Hat sandstone 7 and 8

Thickness of sandstones

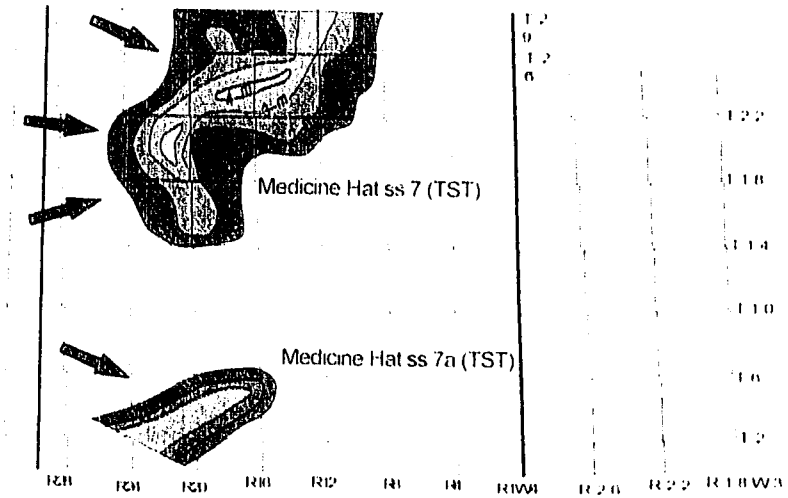
0-2 m
2-3 m
3-4 m
4-5 m
5-6 m
6-7 m
7-8 m
8-9 m
9-10 m
10-11 m
11-12 m
12-13 m

Sediment input direction

Minor
Major



Sandstones within Sequence F11
Isopach Medicine Hat sandstone 6 and 6a



Sandstones within Sequence F11
Isopach Medicine Hat sandstone 7 and 7a

Figure 4-21

Figure 4-22. Core 14-36-13-4W4. Facies associations of the Medicine Hat Member in southeastern Alberta. Modified from chapter II. For well and outcrop locations see figure 4-1.

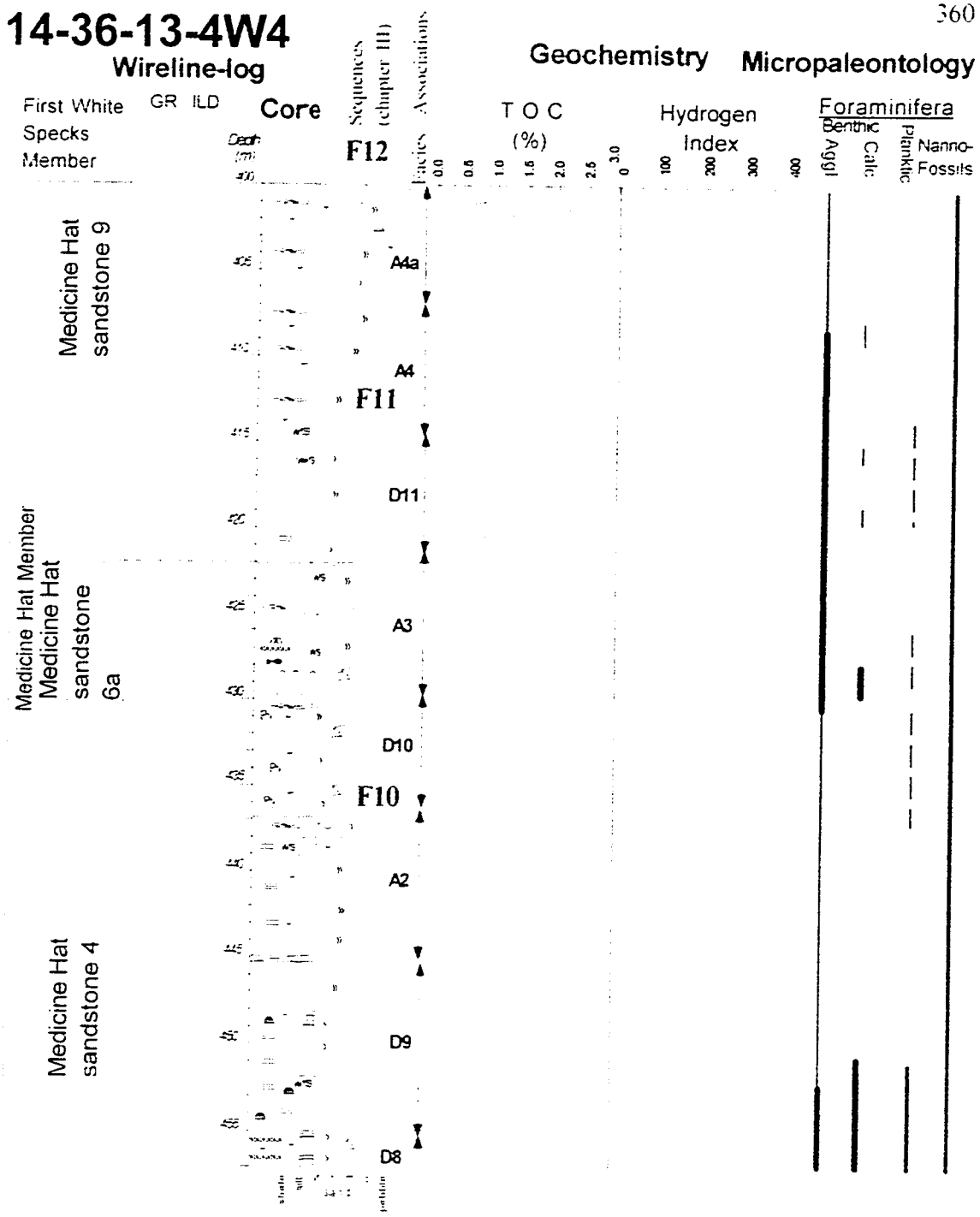

14-36-13-4W4
Wireline-log
First White Specks Member
GR
ILD
Core
Depth (m)
Sequences (chapter III)
Facies Associations
F12
F11
F10
A4a
A4
D11
A3
D10
A2
D9
D8
Geochemistry
T O C (%)
Hydrogen Index
Micropaleontology
Foraminifera
Benthic
Agglt
Calc
Planktic
Nanno-Fossils
Medicine Hat sandstone 9
Medicine Hat Member
Medicine Hat sandstone 6a
Medicine Hat sandstone 4

Figure 4-22

Figure 4-23. Core 10-28-15-3W4. Illustration of the facies association (A) of the upper part of the Medicine Hat Member in southeastern Alberta. For well and outcrop location see figure 4-1.

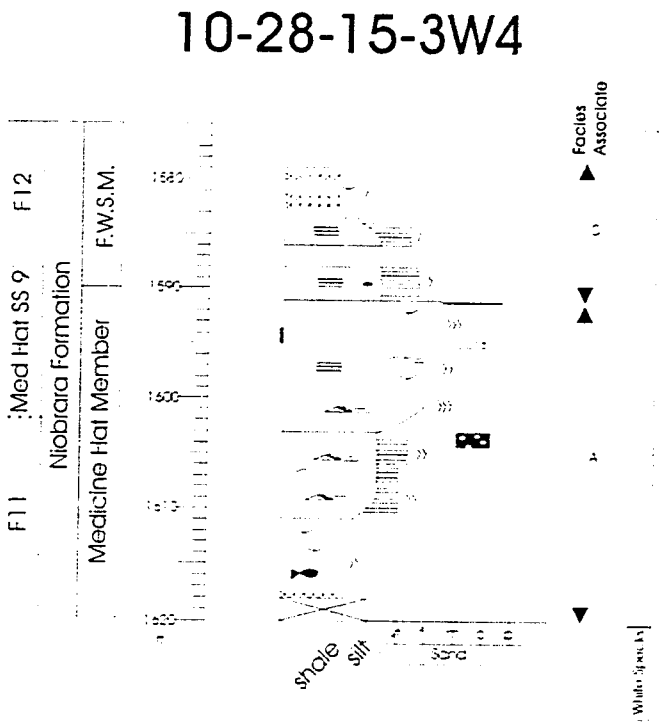

10-28-15-3W4
F11
Med Hat SS 9
F12
Niobrara Formation
Medicine Hat Member
F.W.S.M.
1580
1590
1600
1610
1620
shale
silt
sand
Facies Associate

Figure 4-23

Figure 4-24. Core 6-8-26-19W4. Facies association of the upper part of Medicine Hat Member (sandstone 8) and the First White Specks and Sweetgrass members. For well and outcrop location see figure 4-1.

6-8-26-19W4

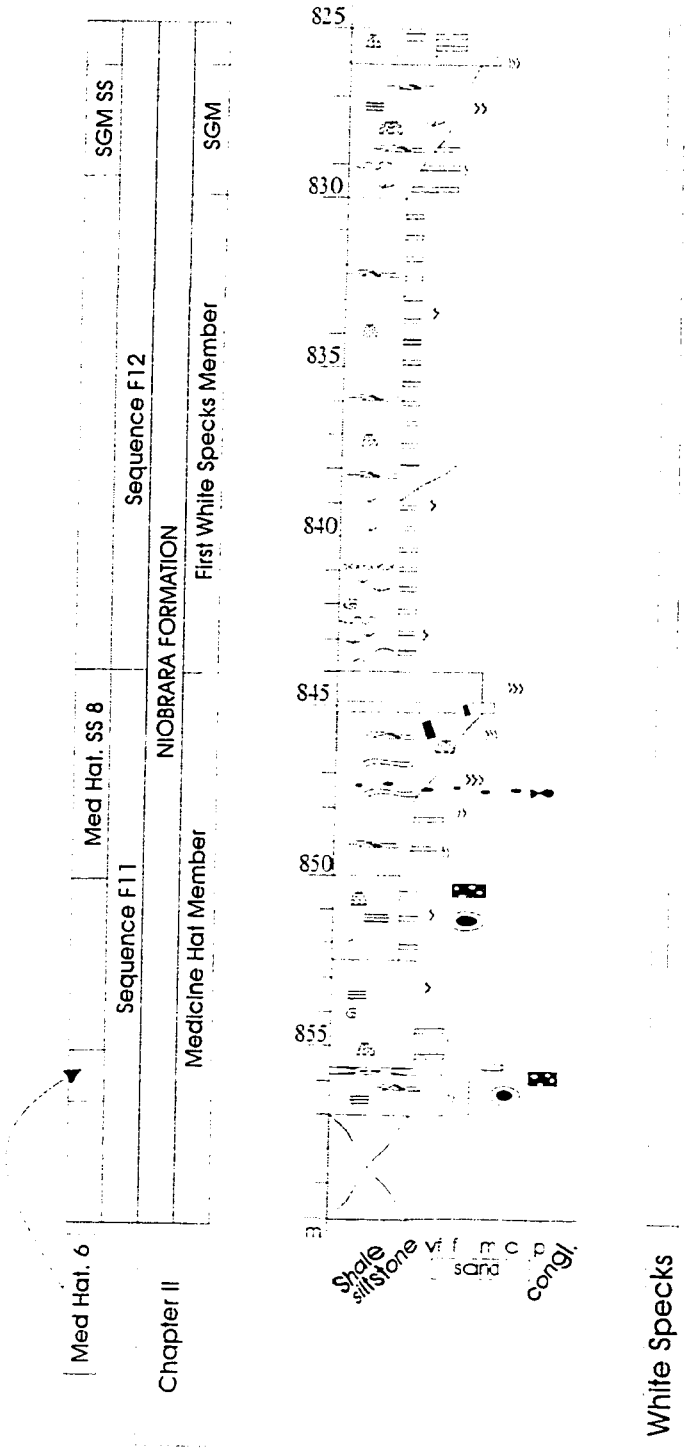


Figure 4-24

Figure 4-25. Relative distribution of the micropaleontology assemblage and TOC in southern Alberta and southwestern Saskatchewan. Paleontological content is subdivided into nannofossils, agglutinated foraminifera, calcareous benthic foraminifera and planktic foraminifera. The TOC values are an average for the entire Medicine Hat Member, or as much as the individual cores have recovered of the member (see appendix in chapter II).

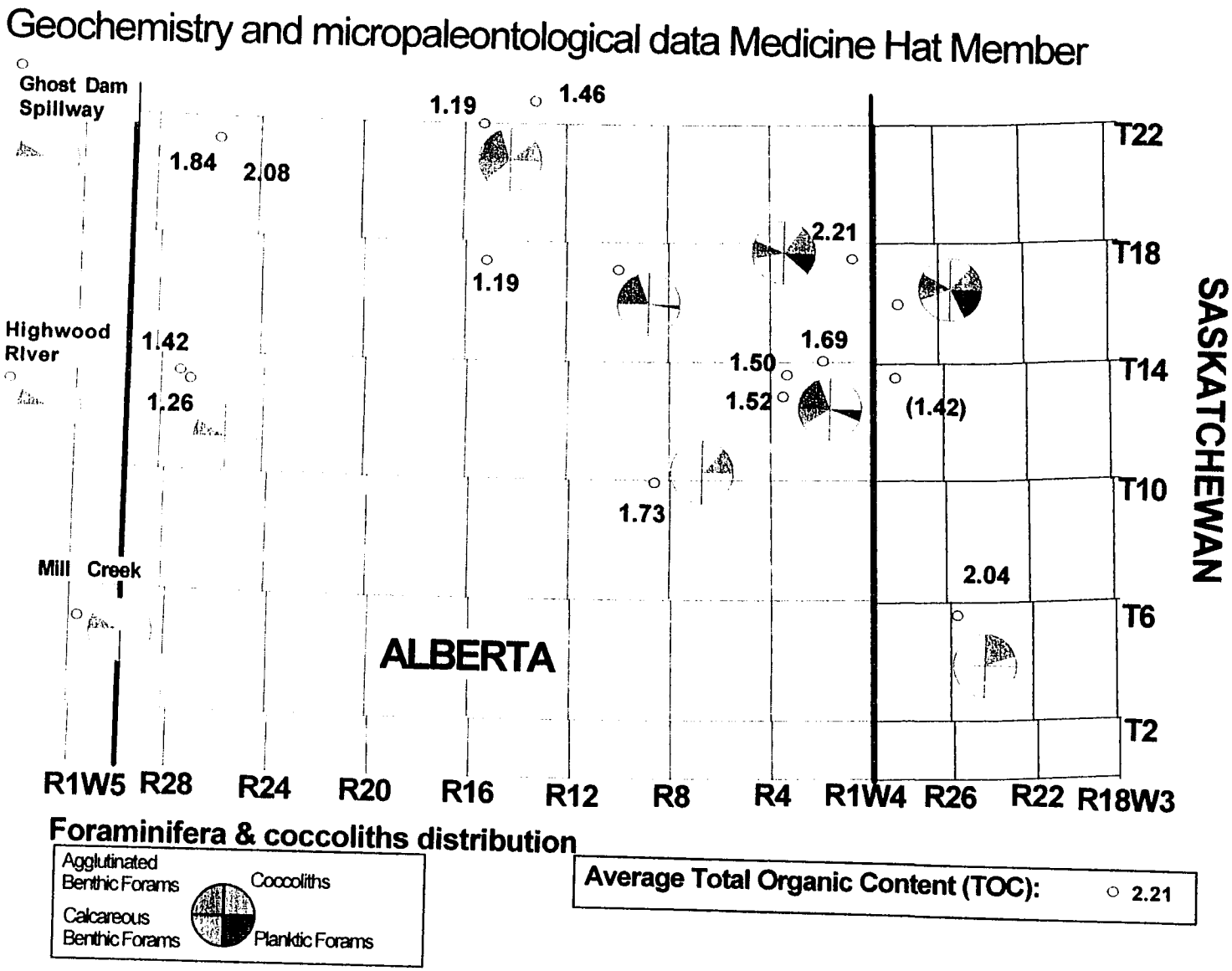

Geochemistry and micropaleontological data Medicine Hat Member
Ghost Dam Spillway
Highwood River
Mill Creek
1.84
2.08
1.42
1.26
1.19
1.46
1.19
2.21
1.69
1.50
1.52
(1.42)
1.73
2.04
ALBERTA
SASKATCHEWAN
T22
T18
T14
T10
T6
T2
R1W5
R28
R24
R20
R16
R12
R8
R4
R1W4
R26
R22
R18W3
Foraminifera & coccoliths distribution
Agglutinated Benthic Forams
Coccoliths
Calcareous Benthic Forams
Planktic Forams
Average Total Organic Content (TOC):
2.21

Figure 4-25

Figure 4-26. Core cross-section in southwestern Saskatchewan of the upper part of the Medicine Hat Member and First White Specks Member. Modified from Nielsen and Schröder-Adams (1998).

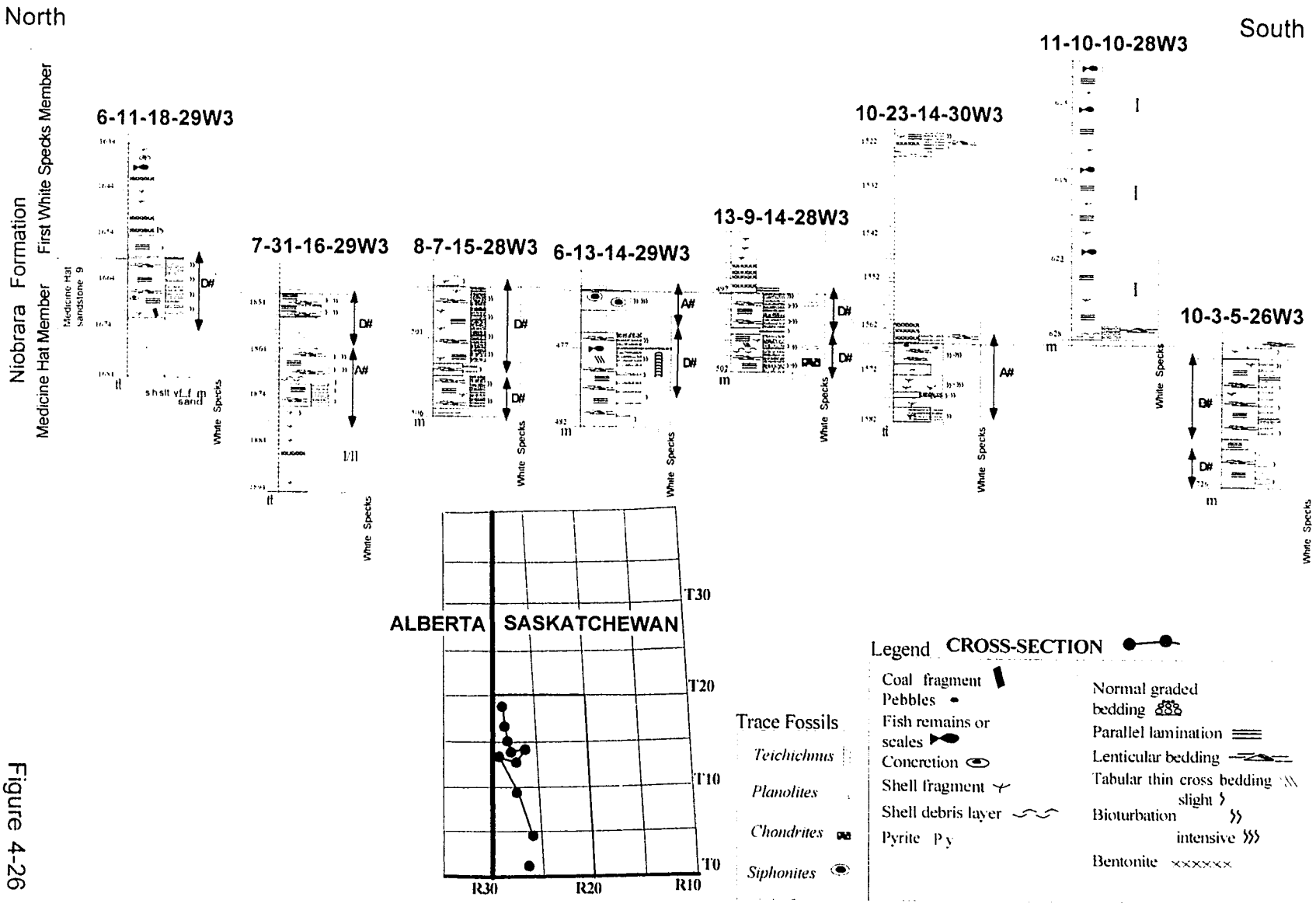

North
South
Niobrara Formation
Medicine Hat Member
First White Specks Member
6-11-18-29W3
7-31-16-29W3
8-7-15-28W3
6-13-14-29W3
13-9-14-28W3
10-23-14-30W3
11-10-10-28W3
10-3-5-26W3
White Specks
D#
A#
ALBERTA
SASKATCHEWAN
T30
T20
T10
T0
R30
R20
R10
Trace Fossils
Teichichnus
Planolites
Chondrites
Siphonites
Legend CROSS-SECTION
Coal fragment
Pebbles
Fish remains or scales
Concretion
Shell fragment
Shell debris layer
Pyrite Py
Normal graded bedding
Parallel lamination
Lenticular bedding
Tabular thin cross bedding
Bioturbation slight
intensive
Bentonite

Figure 4-26

Figure 4-27. General paleogeographic map from the Medicine Hat Member of the Niobrara Formation in the study area and the larger region of western Canada and northwestern US. **1)** Plint (1991); **2)** Cobban et al. (1976); **3)** Medioli (1999); **4)** Wall (1967a); **5)** McNeil and Caldwell (1981); **6)** Gilboy (1987); **7)** McGookey et al. (1972). See legend on figure 4-13.

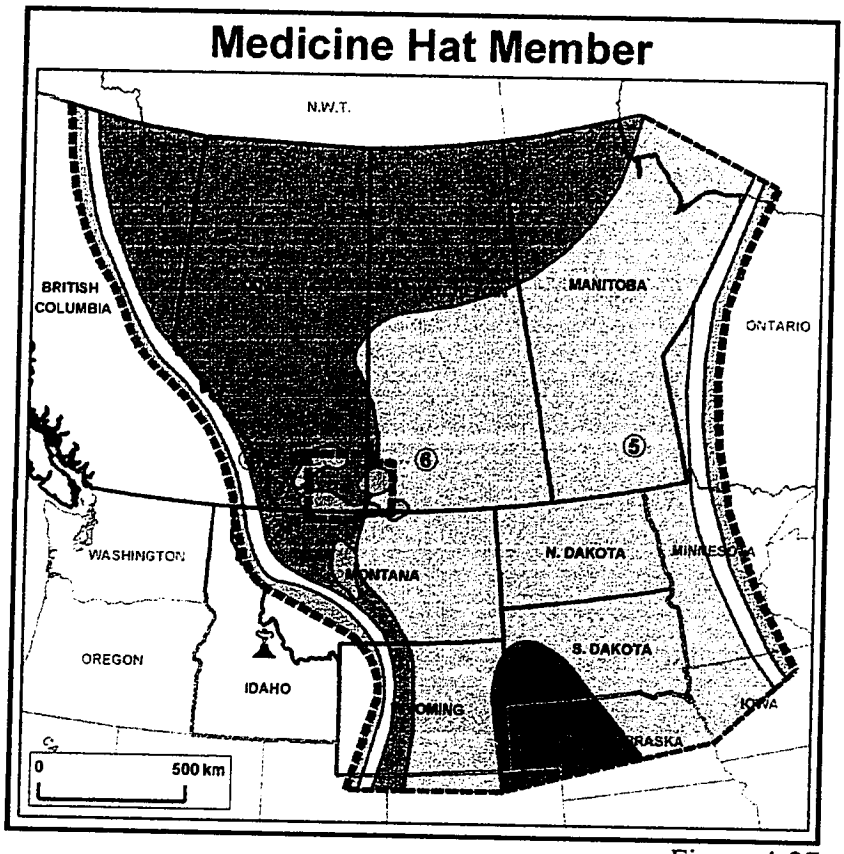

Medicine Hat Member
N.W.T.
BRITISH COLUMBIA
MANITOBA
ONTARIO
WASHINGTON
N. DAKOTA
MONTANA
OREGON
IDAHO
S. DAKOTA
0
500 km

Figure 4-27

Figure 4-28. Detailed paleogeographic map of the lower sequence (F10) of the Medicine Hat Member of the Niobrara Formation (chapter III). For isopach maps of the individual sandstones see figure 4-17.

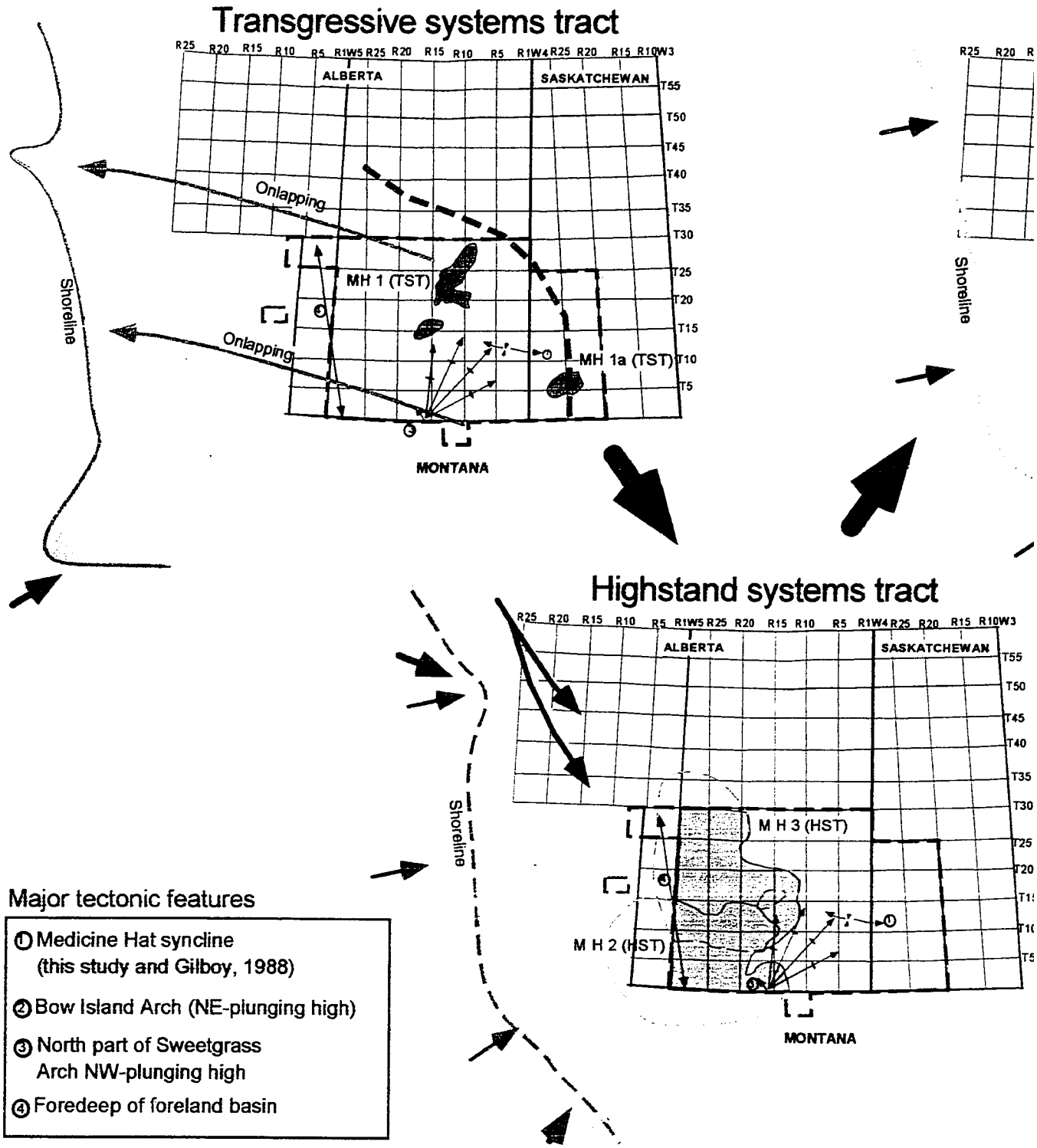
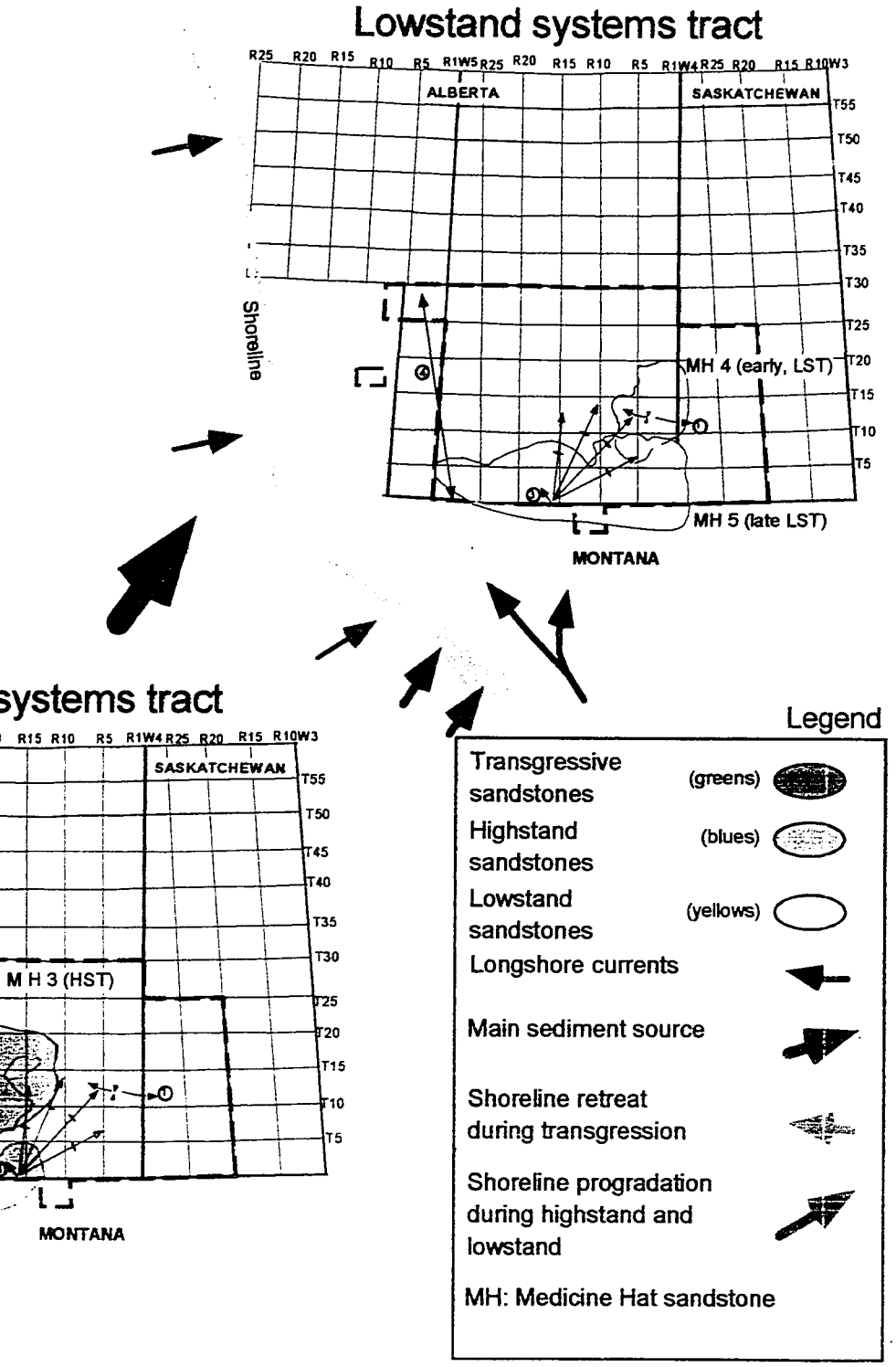

Transgressive systems tract
ALBERTA
SASKATCHEWAN
MONTANA
Onlapping
Onlapping
MH 1 (TST)
MH 1a (TST)
Shoreline
Highstand systems tract
ALBERTA
SASKATCHEWAN
MONTANA
M H 3 (HST)
M H 2 (HST)
Shoreline
Major tectonic features
① Medicine Hat syncline (this study and Gilboy, 1988)
② Bow Island Arch (NE-plunging high)
③ North part of Sweetgrass Arch NW-plunging high
④ Foredeep of foreland basin

Figure 4-28

372



e 4-28

Figure 4-28

Figure 4-29. Detailed paleogeographic map of the lower sequence (F11) of the Medicine Hat Member of the Niobrara Formation (chapter III). For isopach maps of the individual sandstones see figure 4-21.

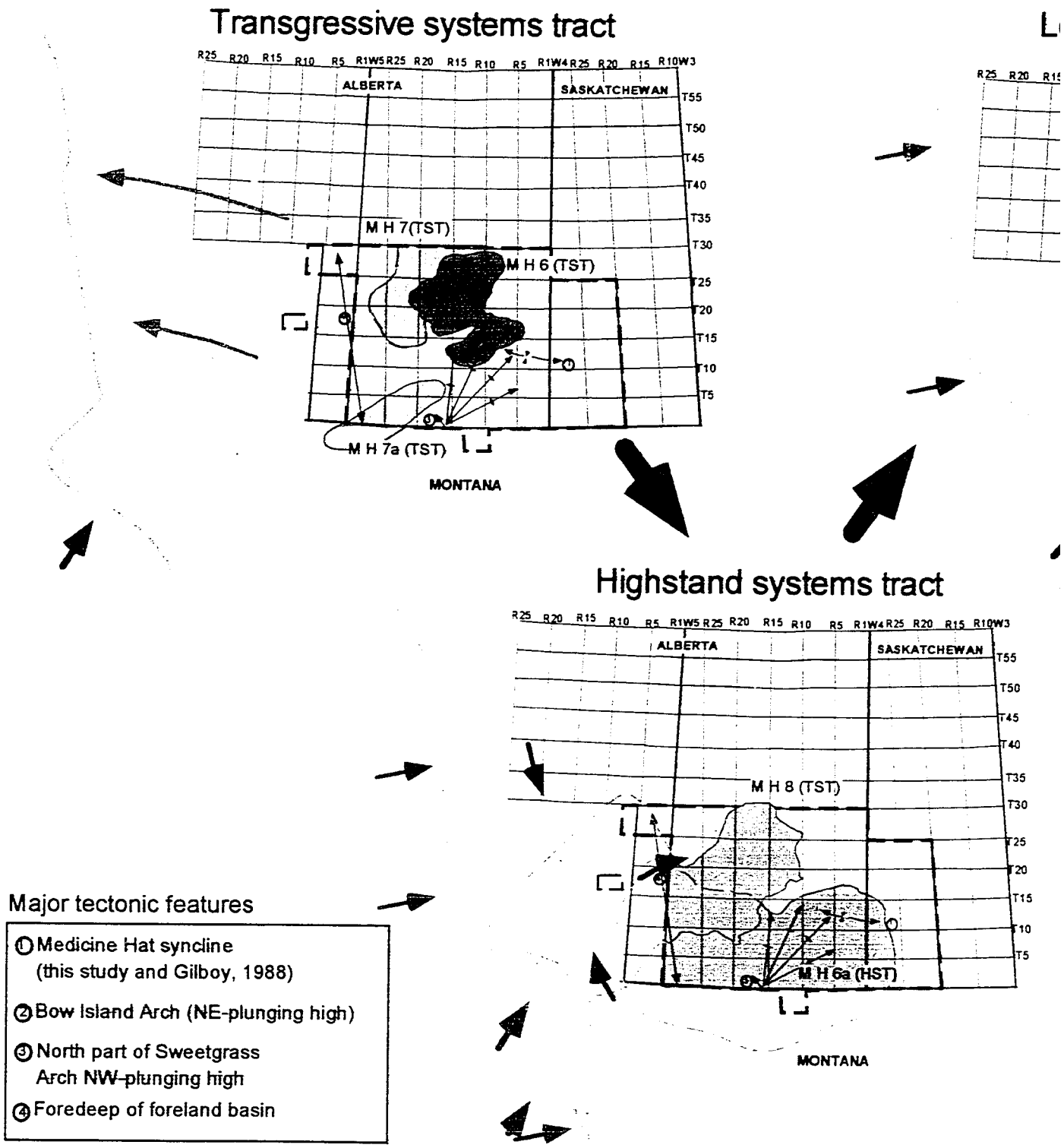
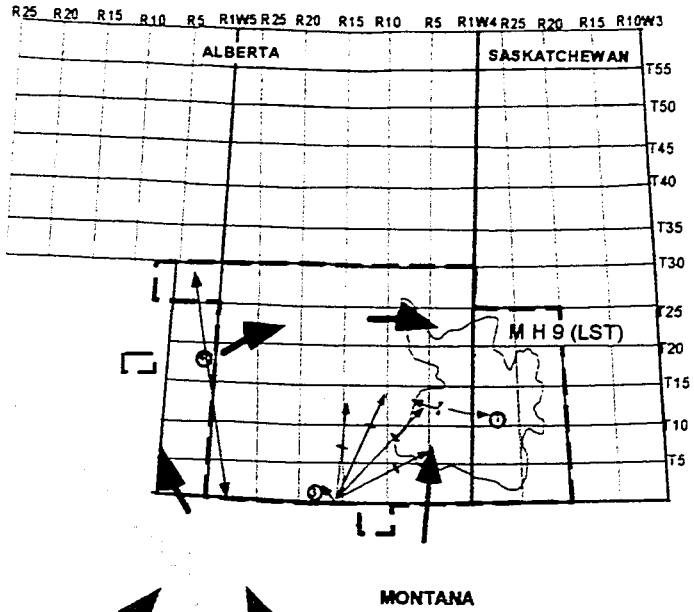

Transgressive systems tract
ALBERTA
SASKATCHEWAN
M H 7(TST)
M H 6 (TST)
M H 7a (TST)
MONTANA
Highstand systems tract
ALBERTA
SASKATCHEWAN
M H 8 (TST)
M H 6a (HST)
MONTANA
Major tectonic features
① Medicine Hat syncline (this study and Gilboy, 1988)
② Bow Island Arch (NE-plunging high)
③ North part of Sweetgrass Arch NW-plunging high
④ Foredeep of foreland basin

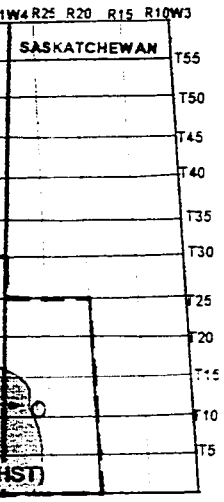
Figure 4-29

374

Lowstand systems tract



s tract



Legend

Transgressive sandstones	(greens)	
Highstand sandstones	(blues)	
Lowstand sandstones	(yellows)	
Longshore currents		
Main sediment source		
Shoreline retreat during transgression		
Shoreline progradation during highstand and lowstand		

MH: Medicine Hat sandstone

Figure 4-29

Figure 4-30. Wire-line cross-section of the Medicine Hat and First White Specks members in southwestern Saskatchewan. Note that the well. 8-7-15-28W3 illustrate the increased thickness of the Medicine Hat Member in the Medicine Hat Syncline. The Medicine Hat sandstone 9 is relatively thick with up to 12 m in Saskatchewan. However. the sandstone is generally more shaly and contains more white specks laminar than observed on the Alberta side. (modified from Nielsen and Schröder-Adams. 1998). Well location on figure 4-26.

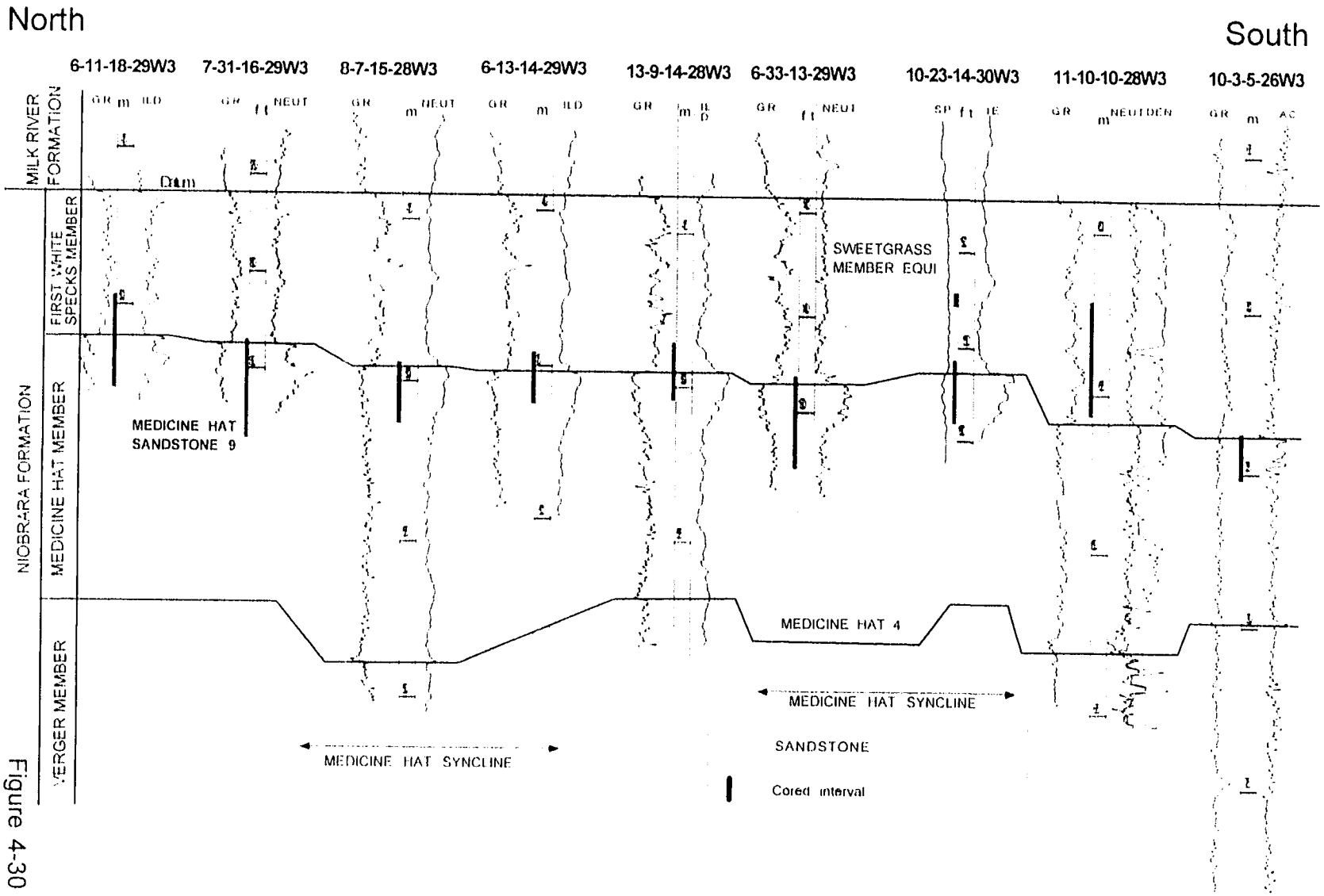

North
South
6-11-18-29W3
7-31-16-29W3
8-7-15-28W3
6-13-14-29W3
13-9-14-28W3
6-33-13-29W3
10-23-14-30W3
11-10-10-28W3
10-3-5-26W3
MILK RIVER FORMATION
NIOBRARA FORMATION
FIRST WHITE SPECKS MEMBER
MEDICINE HAT MEMBER
VERGER MEMBER
SWEETGRASS MEMBER EQUI
MEDICINE HAT SANDSTONE 9
MEDICINE HAT 4
MEDICINE HAT SYNCLINE
MEDICINE HAT SYNCLINE
SANDSTONE
Cored interval

Figure 4-30

Figure 4-31. Paleogeographic map of the First White Specks Member of the Niobrara Formation in the study area and the larger region of western Canada and northwest US **1**) Wall (1967a): **2**) McNeil and Caldwell (1981): **3**) Longman et al. (1994): **4**) Park (1965): **5**): North and Caldwell (1975). See legend on figure 4-13.

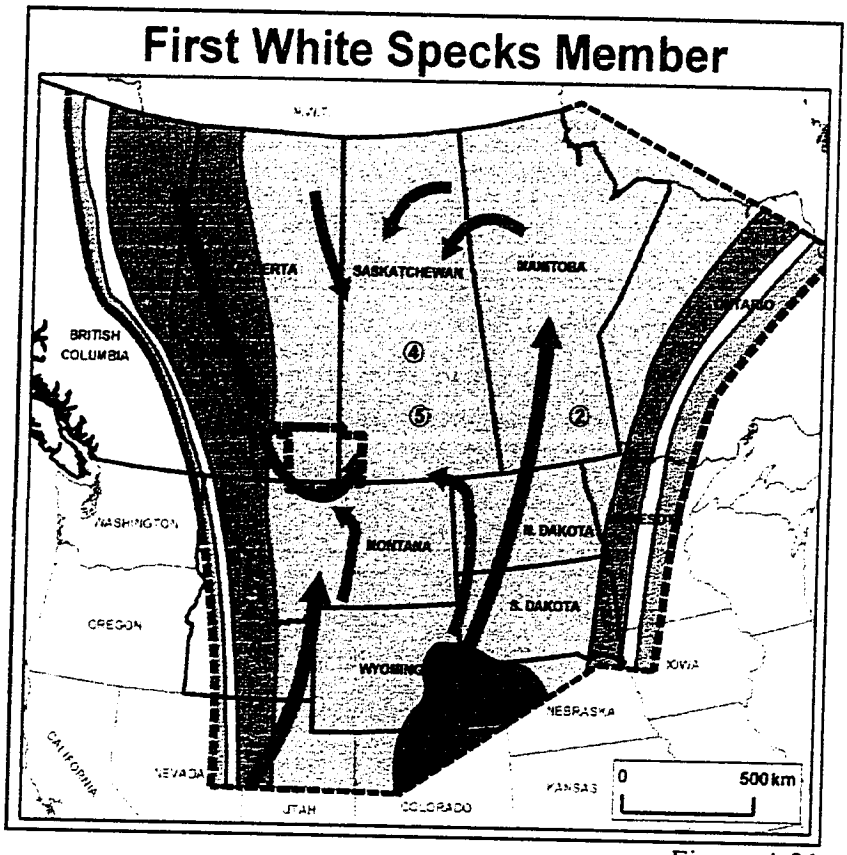

First White Specks Member
SASKATCHEWAN
MANITOBA
BRITISH COLUMBIA
④
⑤
②
MONTANA
N. DAKOTA
S. DAKOTA
OREGON
NEBRASKA
KANSAS
COLORADO
0
500 km

Figure 4-31

Figure 4-32. Densely spaced resistivity log correlation of the Carlile and Niobrara formations in southeastern Alberta and southwestern Saskatchewan. The two cross-sections illustrate the Medicine Hat Syncline in cross-sections and its distribution.

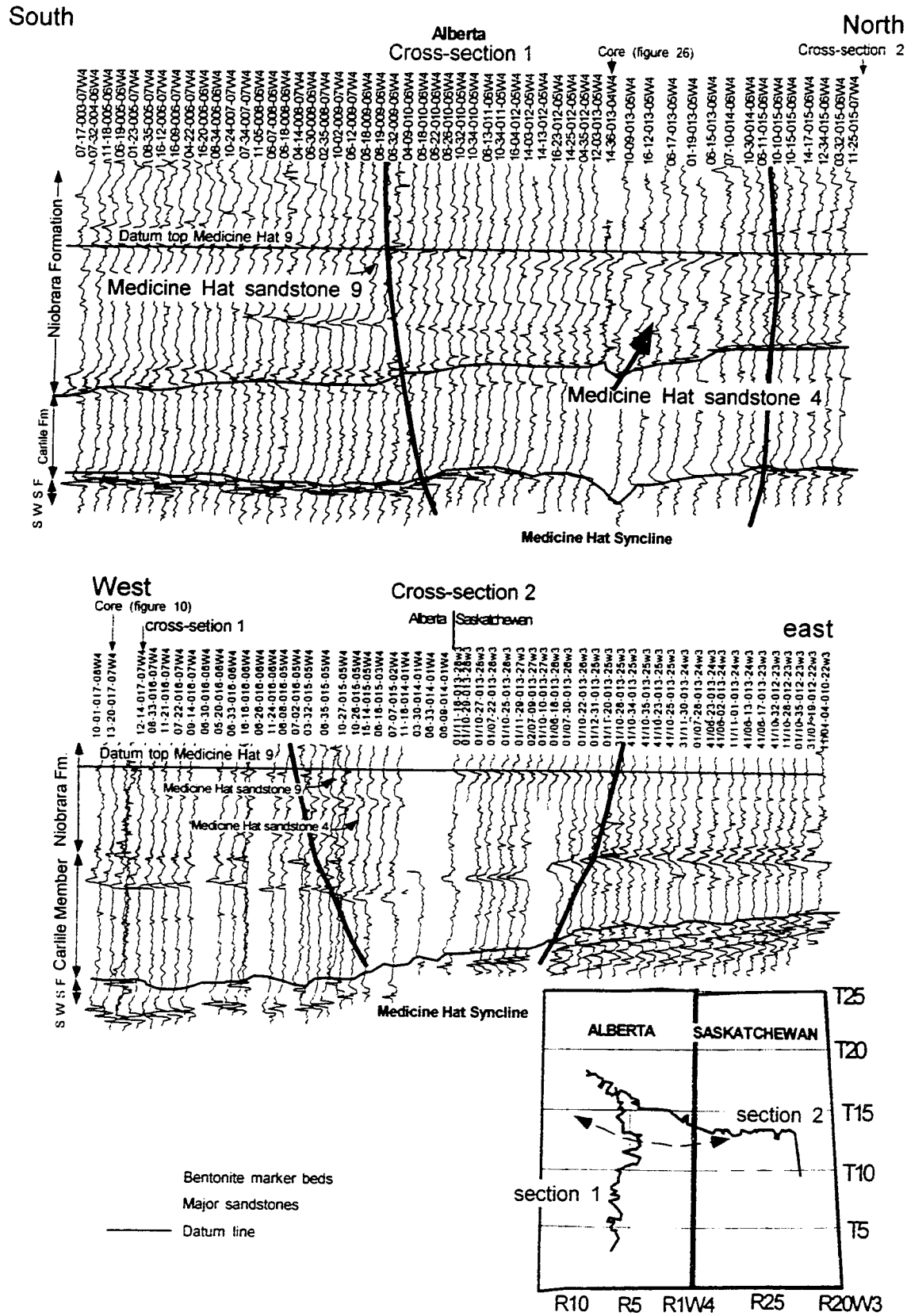
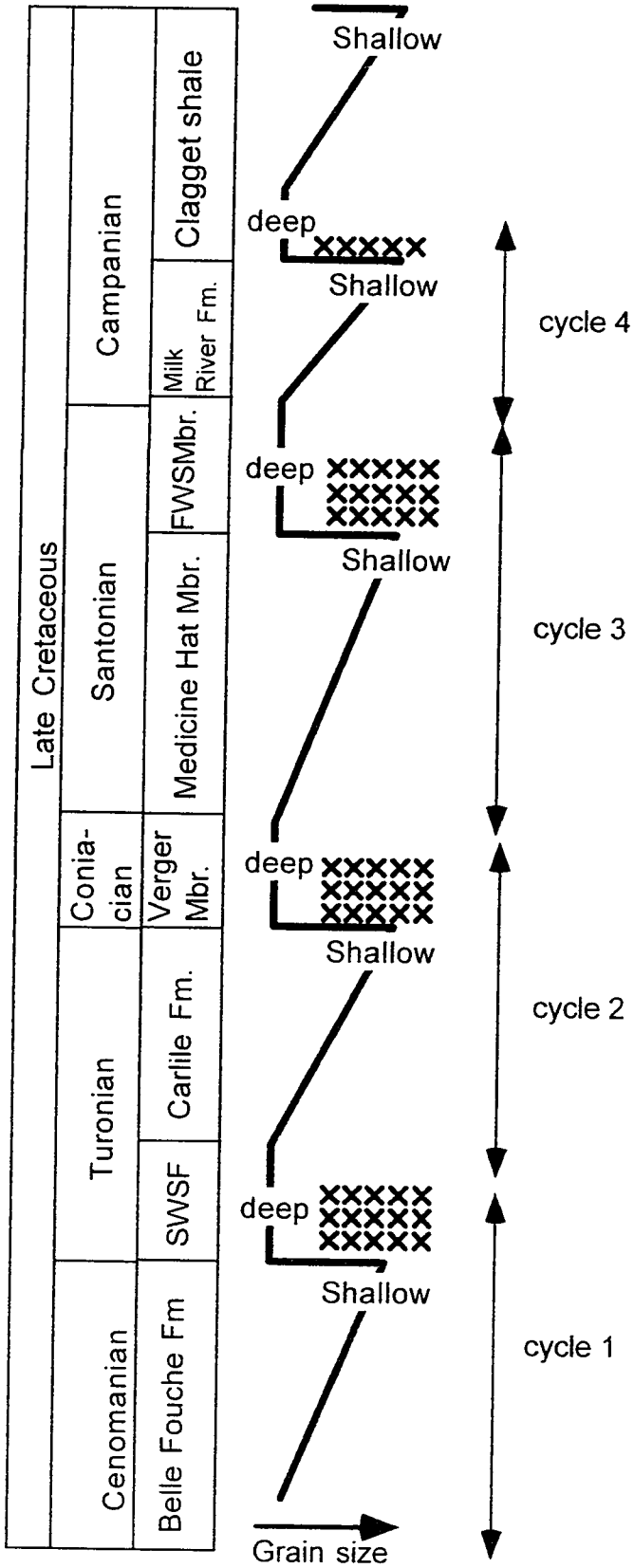

South
North
Alberta
Cross-section 1
Core (figure 26)
Cross-section 2
Niobrara Formation
Datum top Medicine Hat 9
Medicine Hat sandstone 9
Medicine Hat sandstone 4
Carlile Fm
S W S F
Medicine Hat Syncline
West
Core (figure 10)
cross-setion 1
Cross-section 2
Alberta
Saskatchewan
east
Niobrara Fm.
Carlile Member
Datum top Medicine Hat 9
Medicine Hat sandstone 9
Medicine Hat sandstone 4
Medicine Hat Syncline
ALBERTA
SASKATCHEWAN
section 2
section 1
T25
T20
T15
T10
T5
R10
R5
R1W4
R25
R20W3
Bentonite marker beds
Major sandstones
Datum line

Figure 4-32

Figure 4-33. Repeated events in Late Cretaceous time in southern Alberta and southwestern Saskatchewan. The four events are: 1) The silty and sandy Belle Fouche Formation sharply overlain by the Second White Specks Formation with abundant bentonites (Schröder-Adams et al., 1996); 2) The general upwards-coarsening of the Carlile Formation abruptly overlain by the bentonite enriched and shaly Verger Member (*this study*); 3) The sandy Medicine Hat Member overlain by the calcareous shale of the First White Specks Member which have numerous thin interbedded bentonites (*this study*). 4) The sandy Milk River Formation overlain by the Clagget shale with numerous and thick bentonites (Payenberg, 2002).



Bentonites: XXXXX

Figure 4-33

Chapter V

CONCLUSIONS

A multidisciplinary study of the Upper Colorado Group in southern Alberta and southwestern Saskatchewan resulted in a new formal stratigraphic subdivision and a better understanding of the paleoenvironment and sea-level fluctuations though Late Turonian to Santonian time. Integration of detailed sedimentology, micropaleontology, geochemistry and regional log correlations indicates a complex sea-level history that affected the paleoenvironment and the outline of the Western Cretaceous Interior Seaway. The following conclusions are drawn from this thesis.

LITHOSTRATIGRAPHY

• The 120 to 350 m thick Late Cretaceous Upper Colorado Group is formally subdivided into the lower Carlile Formation and upper Niobrara Formation. The Carlile Formation is a non-calcareous shale with minor occurrences of fine sandstone beds and a middle interval characterized by abundant siderite concretions. The boundary between the Carlile Formation and the underlying Second White Specks Formation is conformable and is easily distinguished by the change from a calcareous and highly organic (> 3 %) shale with common macrofossils to a non-calcareous shale with an organic content normally less than 2%, and rare macrofossils. The boundary between the Carlile and Niobrara formations is unconformable and forms a distinctive surface throughout the study area.

• The Niobrara Formation is composed of dark gray marine shales, siltstones and very fine, gray sandstones and a uncommon layers of chert pebbles and is subdivided into

three mappable members: The shaly Verger, the sand-rich Medicine Hat and the calcareous First White Specks members. The Niobrara Formation is overlain by the Milk River Formation.

• The Verger Member is a 20- (in the northeast) to 120-m- (in the southwest) thick shaly interval, named after the town of Verger located close to the type core in well 16-4-22-15W4. The sand-rich Medicine Hat Member is relatively uniform throughout most of the study area with a thickness between 40 and 65 meters. The First White Specks Member is the youngest member of the Niobrara Formation, and is a dark gray, calcareous shale with abundant fecal pellets rich in nannofossils and a rare interbedded fine-grained sandstones.

• The foraminiferal assemblage found in the Carlile Formation belongs to the *Pseudoclavulina* sp. Zone, which places the formation into the Late Turonian. The foraminifera assemblages found in the Niobrara Formation belong to the *Trochammina* sp., *Bullopora laevis* and *Globigerinelloides* sp. zones, assigning a Coniacian to Santonian age.

• Two bentonites from the lower Verger Member of the Niobrara Formation give ages of 89.19 and 89.40 Ma (core from 13-20-17-7W4). This indicates an age of late Late Turonian for the boundary between the Carlile and Niobrara formations.

SEQUENCE STRATIGRAHPY

• A new method is developed to define stratal geometry of shale-dominated marine basins, using closely-spaced (<2 km) resistivity wire-line logs and sequence stratigraphic principles. These cross-sections illustrate how recognition of key sequence stratigraphic surfaces, especially the first major flooding surface, which is used as sequence boundary,

can unveil basin evolution. Thirteen sequences are interpreted from the Carlile and Niobrara formations.

- The **Carlile Formation** consists of a sequence-set of seven sequences (F1 to F7), which is characterized by a low-angled stratal pattern of parallel to sub-parallel sequence boundaries. Overall the relative sea level was falling during deposition of the Carlile sequence-set, which represents the regressive part of the Greenhorn. Sediment supply was mainly from the west, but in the upper two sequences (F6 and F7) to bi-directional from both west and east. The upper part of the Carlile Formation includes fine-grained sandstones, which are laterally equivalent to the Cardium sandstones in the southern Alberta Foothills and Bowdoin sandstones in Saskatchewan and North Dakota. Based on wire-line correlations, the shoreface sandstones of the Cardium Formation were deposited during a prograding highstand period and the thin sandstones of the Carlile Formation in the plains are distal lowstand sandstones.

- The **Niobrara Formation** consists of a sequence-set of six sequences (F8 to F13) and has a complex stratal pattern with a general upward-decrease in dip angle of strata. The Formation represents the transgressive part of the Niobrara Cycle and is characterized by a general rise in sea-level. Sediment input was mainly from the south, southwest and west. The six sequences are subdivided into three groups (F8/F9; F10/F11; F12/F13), which have specific stratal patterns:

- The lower two sequences (F8/F9) consists of thick shale deposits with relatively high-angled giant clinoforms (up to 0.05 degree). The sequences reveals major highstand progradation and sediment input from the south and southwest. No lowstand deposits are present in the region. Correlation into west-central Alberta show that the

coarse-grained Bad Heart Formation is likely the lowstand deposit to sequences F8 and F9, and that most of southern Alberta was subaerially exposed during this time.

- The stratal patterns of F10 and F11 are dominated by low angled strata, which consists of interbedded shale and fine-grained sandstones. All three systems tracts are observed within the study area, and are distinguished on stratal pattern, key surfaces and lithology. Fine-grained sandstones occur in all systems tracts, and the lowstand and highstand sandstones are characterized as gradual upward-coarsening units, whereas the transgressive sandstones are sharp based and generally thinner than lowstand and highstand sandstones. Thirteen isolated shaly marine sandstones are mapped in sequence F10 and F11, with some being extensive covering up to half of the study area (up to 3000 km^2; figure 21).

- Sequence F12 and F13 are characterized by a very subtle stratal pattern of eastern very low-angled strata. The lowstand systems tract of sequence F12 is the fine-grained Sweetgrass Member which was deposited northwest of the Bow Island Arch and landwards of the lowstands of the Medicine Hat Member. This indicates a general rise in relative sea-level and indicates that the sequences F12 represents the highest sea-level of the Niobrara cycle in southern Alberta.

PALEOENVIRONMENT

- Detailed analysis of the upper Colorado Group, including the Carlile and Niobrara formations, reveals a complex and dynamic basin system far removed from the Cordillera. The two formations represent significantly different basin histories, both in terms of paloegeographic outline, facies distribution and sea-level history. Nine paleogeographic maps illustrate the facies of the north-central part of the Interior Seaway

and its possible shoreline positions from Late Turonian to Santonian time. Maps are based on this study of southern Alberta and southwestern Saskatchewan and integrated with regional studies of the same interval in Western Canada and northwestern United States. The maps show a gradual infill of the basin during the regressive part of the Greenhorn Cycle, represented by the Carlile Formation. The overlying transgressive part of the Niobrara Cycle shows multiple dramatic basin changes, with two examples of complete marine drainage of the study area.

- **Carlile Formation** is a regressive succession, which gradually infilled the basin during Late Turonian time. Generally the water depth was shallower than in the underlying Second White Specks Formation and most of the overlying Niobrara Formation.

- The partly calcareous **Niobrara Formation** was deposited as an overall transgressive event, that experienced major sea-level fluctuations during the Coniacian and Santonian. This resulted in interfingering of tongues of eastern calcareous shale containing white specks (nannofossils) with non-calcareous shale in the west (figure 3-3). Transgressive pulses deepened the basin significantly, which is evident from the occurrence of calcareous benthic and planktic foraminifera and nannofossils that require fully marine shelf conditions.

- The lowstand periods of sequence F8 and F9 (correlative to the Bad Heart Formation), drained most of the western Canadian Interior Seaway and parts of northern Montana. Major events like these, which can be traced for more than 1500 km are unlikely solely controlled by tectonic events or sediment rate fluctuations, which indicates some eustatic sea-level control during Coniacian time.

- The sandstones of the Medicine Hat Member were deposited in a sand-rich, upper offshore to shelf environment. Most sandstones are distal, isolated fine-grained sandstones that were transported to the offshore setting by storms and shelf currents. Shale interbedded between the sandstones has a microfauna that indicates a fully marine and distal depositional environment. The sandstones were deposited in a wave-dominated low to moderate energy regime around storm wave base. The sediments are dominated by small-scale sedimentary structures, which are the result of wave activity and storm generated currents in a distal setting. Contourites or their shallow version of the deep water contour currents may have reworked the sediments.

- The Medicine Hat Syncline is a local structure defined in southeastern Alberta and southwestern Saskatchewan. Isopach maps of the Medicine Hat Member and individual sandstones indicate a thicker section in this area and illustrate a synsedimentary structure. The east-west trending syncline is possibly related to two faults, one on the south side and one on the north side of the syncline forming a subtle "graben structure".

- Deposition of the Upper Colorado Group reveals that the Sweetgrass Arch had no or limited effect on the depositional environment during times of high accommodation space, but did influence sedimentation during low accommodation space. Only during lowstand times as during deposition of the major Medicine Hat sandstones 8 and 9, it is likely that the arch had an affect on the sedimentary environment.

APPENDIX A

LIST OF CORES AND OUTCROPS WITH ROCK-EVAL ANALYSIS

- **8-36-24-13W4**
- **8-26-17-14W4**
- **7-31-16-29W3**
- **7-25-13-01W4**
- **7-13-10-08W4**
- **6-03-14-13W4**
- **6-26-13-3W4**
- **6-12-13-4W4**
- **6-10-13-7W4**
- **4-8-13-27W4**
- **3-7-13-27W4**
- **16-28-14-2W4**
- **16-10-15-1W4**
- **14-36-13-4W4**
- **14-26-19-8W4**
- **13-9-14-28W3**
- **13-20-17-7W4**
- **11-26-20-23W4**
- **11-10-10-28W3**
- **10-3-5-26W3**
- **10-15-17-1W4**
- **10-1-16-5W4**
- **10-10-15-4W4**
- **16-4-22-15W4**
- **6-3-24-13W4**
- **Deer Creek outcrop, Montana**
- **Ghost Dam Spillway**

Legend and explanation for Rock-eval terms and indexes.	
Qty	Quantitative sample size (mg)
TOC	Total Organic Carbon Content (in weight %)
S1	The amount of free HC's (gas or oil) that are volatilised for 2 minutes at 300 degree Celsius.
S2	The amount of HC's coming from kerogen cracking between 300 and 600 degree C. and from heavy extractable compounds such as resins and asphaltenes.
S3	The amount of CO2 trapped separately during kerogen cracking
HI	Hydrogen Index
OI	Oxygen Index
PI	Production Index (S1/S1+S2), free hydrocarbons in relation to the total amount of HC..
Tmax	The average of 20 temperature measurements made on both sides of the top of peak S2. Indicator of organic matter maturation.
RC	Residual Carbon
PC	Pyrolyzable carbon (RC+PC)= TOC
%minc.	Mineral Carbon
S4CO	An measurement of CO yielded during the oxidation step.
KFID	The FID calibration constant

Well: 8-36-24-13W4

Depth (m)	Qty (mg)	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
534	100.0	426	4.05	0.91	0.21	0.82	4.33	0.42	1.09	83	19
540	100.3	427	6.78	2.75	0.34	0.71	8.09	0.80	2.06	133	17
542.7	100.6	425	2.60	0.98	0.29	0.73	3.38	0.31	1.05	93	28
545.5	100.1	424	2.32	1.18	0.22	0.66	5.36	0.30	1.12	105	20
548	100.6	420	3.19	4.14	0.46	0.44	9.00	0.63	2.23	186	21

Well: 8-26-17-14W4

Depth (m)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
422	100.30	0.17	4.83	0.01	0.03	0.64	416	461	0.51	0.44	2.40	1.96	202	21
424	100.60	0.10	1.65	0.00	0.06	0.81	423	468	0.30	0.16	1.49	1.33	111	20
426	100.80	0.08	1.67	0.01	0.05	0.74	419	464	0.29	0.16	1.41	1.25	119	21
428	100.20	0.13	8.72	0.02	0.01	1.21	412	457	0.63	0.76	3.15	2.39	277	20
430	100.40	0.09	5.26	0.01	0.02	0.54	417	462	0.52	0.47	2.25	1.78	234	23
432	100.50	0.04	1.40	0.01	0.03	0.46	416	461	0.29	0.13	1.52	1.39	93	19
434	100.70	0.08	1.82	0.01	0.04	0.54	422	467	0.37	0.17	1.84	1.67	99	20
436	100.20	0.10	1.81	0.00	0.05	0.72	423	468	0.29	0.17	1.47	1.30	123	20
441.5	100.70	0.01	0.03	0.00	0.27	7.31	435	480	0.15	0.01	0.05	0.04	60	300
442	99.60	0.04	0.73	0.01	0.05	0.58	429	474	0.24	0.08	1.15	1.07	64	21
444	100.00	0.02	0.45	0.00	0.05	0.32	421	466	0.24	0.05	1.04	0.99	43	23
446	100.10	0.02	0.62	0.00	0.03	0.34	425	470	0.22	0.06	1.10	1.04	56	20
448	100.00	0.06	1.04	0.01	0.05	1.39	427	472	0.28	0.10	1.34	1.24	78	21
450	100.10	0.12	1.53	0.01	0.07	0.61	423	468	0.27	0.15	1.51	1.36	102	18

Well: 7-31-16-29W3

DEPTH (ft)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
1845.00	100.40	420	0.81	2.36	0.63	0.26	3.74	0.26	1.63	144	38
1845.00	100.60	422	0.78	2.31	0.63	0.25	3.66	0.25	1.61	143	39
1852.00	100.10	422	0.48	1.71	0.64	0.22	2.67	0.18	1.48	115	43
1852.00	99.90	425	0.48	1.79	0.60	0.21	2.98	0.18	1.46	122	41
1868.00	100.60	417	0.46	2.52	0.67	0.15	3.76	0.24	1.90	132	35
1868.00	100.40	418	0.44	2.49	0.71	0.15	3.50	0.24	1.96	127	36
1876.00	100.60	424	0.56	4.03	1.09	0.12	3.69	0.38	2.48	162	43
1876.00	99.70	425	0.56	3.95	1.07	0.12	3.69	0.37	2.49	158	42
1879.00	100.80	423	0.27	2.07	0.71	0.12	2.91	0.19	1.72	120	41
1879.00	100.80	423	0.27	2.11	0.75	0.11	2.81	0.19	1.77	119	42
1882.00	100.00	425	0.68	6.58	1.31	0.09	5.02	0.60	3.12	210	41
1882.00	100.80	423	0.68	6.69	1.25	0.09	5.35	0.61	3.13	213	39
1885.00	100.40	425	0.35	6.39	1.46	0.05	4.37	0.56	3.18	200	45
1885.00	100.50	426	0.38	6.73	1.47	0.05	4.57	0.59	3.28	205	44
1888.00	99.80	421	0.62	4.85	1.00	0.11	4.85	0.45	2.73	177	36
1888.00	99.90	425	0.64	5.27	1.05	0.11	5.01	0.49	2.80	188	37
1891.00	100.60	420	0.16	1.44	0.67	0.10	2.14	0.13	1.74	82	38
1891.00	100.10	421	0.16	1.41	0.66	0.10	2.13	0.13	1.74	81	37
1894.00	100.50	422	1.00	10.00	1.55	0.09	6.45	0.91	4.09	244	37
1894.00	100.10	424	1.01	10.13	1.49	0.09	6.79	0.92	4.06	249	36

Well: 7-25-13-1W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
448	100.6	0.11	2.28	0.00	0.04	1.19	416	459	0.57	0.22	2.00	1.78	114	29
449	100.1	0.28	6.04	0.00	0.04	1.50	413	456	0.50	0.55	2.70	2.15	224	19
450	100.8	0.08	2.04	0.00	0.04	0.80	416	459	0.47	0.20	1.80	1.60	113	26
451	100.0	0.15	1.88	0.00	0.07	0.77	422	465	0.41	0.19	1.64	1.45	115	25
452	100.5	0.10	2.03	0.00	0.05	1.16	419	462	0.40	0.19	1.66	1.47	122	24
453	100.7	0.12	2.36	0.00	0.05	1.11	415	458	0.50	0.23	1.89	1.66	125	26
454	100.3	0.15	5.59	0.00	0.03	1.34	409	452	0.52	0.50	2.25	1.75	248	23
455	100.1	0.16	4.21	0.00	0.04	1.52	417	460	0.61	0.39	2.46	2.07	171	25
456	100.8	0.10	3.15	0.00	0.03	0.93	417	460	0.53	0.29	2.08	1.79	151	25
457	100.4	0.19	5.69	0.00	0.03	1.31	412	455	0.58	0.51	2.75	2.24	207	21
458	100.0	0.28	2.96	0.00	0.09	0.81	417	460	0.52	0.29	1.97	1.68	150	26
459	100.2	0.06	1.77	0.00	0.03	0.99	408	451	0.75	0.18	2.00	1.82	89	38
460	99.9	0.12	3.72	0.00	0.03	0.99	413	456	0.49	0.34	2.20	1.86	169	22
561	99.8	0.07	1.38	0.00	0.05	0.88	410	453	0.62	0.15	1.79	1.64	77	35
462	100.3	0.11	2.95	0.00	0.04	1.39	417	460	0.50	0.28	1.95	1.67	151	26
9107	100.1	0.83	10.21	0.05	0.07	0.72	441	484	0.34	0.94	4.95	4.01	207	7
463	100.7	0.12	2.17	0.00	0.05	1.03	409	452	0.76	0.22	2.22	2.00	98	34
464	99.9	0.06	1.55	0.00	0.04	0.86	413	456	0.58	0.16	1.82	1.66	85	32
465	100.3	0.02	0.40	0.00	0.06	0.50	412	455	0.33	0.05	1.01	0.96	40	33
466	100.4	0.13	2.00	0.00	0.06	0.80	415	458	0.54	0.20	1.71	1.51	117	32

Well 7-13-10-8W4

Depth (m)	Qty (ng)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
313	99.9	408	0.42	3.14	1.11	0.12	2.82	0.29	1.81	173	61
314	101.1	413	0.62	7.74	1.62	0.07	4.77	0.69	3.06	252	52
314.6	101.1	417	0.48	3.41	1.17	0.12	2.91	0.32	1.62	210	72
315	100.3	419	0.42	4.04	1.26	0.09	3.20	0.37	1.89	213	66
315.8	99.8	414	0.64	6.92	1.40	0.08	4.94	0.63	2.87	241	48
316	99.7	423	0.05	0.03	0.76	0.62	0.03	0.00	0.06	50	1266
316.1	100.9	418	0.71	6.41	1.68	0.10	3.81	0.59	2.68	239	62
317	100.0	419	0.58	2.22	1.48	0.21	1.50	0.23	1.63	136	90
318	100.7	419	0.77	3.70	1.39	0.17	2.66	0.37	2.16	171	64
319	101.1	418	0.24	1.02	0.83	0.19	1.22	0.10	0.97	105	85
320	100.7	419	0.55	2.98	1.34	0.16	2.22	0.29	1.97	151	68
321	99.7	416	0.52	2.85	1.60	0.15	1.78	0.28	1.75	162	91
322	99.7	420	0.71	2.38	0.93	0.23	2.55	0.25	1.62	146	57
323	100.4	421	0.65	3.96	1.21	0.14	3.27	0.38	2.02	196	59
324	101.0	417	0.44	2.49	0.92	0.15	2.70	0.24	1.77	140	51
325	99.8	417	0.46	2.03	0.89	0.19	2.28	0.20	1.57	129	56

WELL: 6-3-24-13W4 (page 1/2)

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I
459.2	100.3	410	3.31	4.91	0.99	0.40	4.95	0.68	2.21	222
460	99.6	415	2.87	5.45	0.92	0.34	5.92	0.69	2.29	237
461	100.4	415	4.34	5.95	1.40	0.42	4.25	0.85	2.81	211
462	100.8	416	2.98	5.48	1.06	0.35	5.16	0.70	2.49	220
463	100.1	414	2.63	4.97	0.93	0.35	5.34	0.63	2.34	212
464	101.0	413	4.58	5.12	1.12	0.47	4.57	0.80	2.55	200
465	100.6	414	3.86	9.64	1.29	0.29	7.47	1.12	3.16	305
465.4	101.0	417	3.14	3.59	0.85	0.47	4.22	0.56	2.03	176
465.8	100.2	418	1.97	1.84	0.69	0.52	2.66	0.31	1.38	133
466	100.2	415	1.96	2.26	0.66	0.46	3.42	0.35	1.54	146
467	100.0	416	5.84	2.44	0.73	0.71	3.34	0.69	1.74	140
468	100.4	415	1.99	2.10	0.73	0.49	2.87	0.34	1.73	121
469	100.0	418	1.83	1.14	0.54	0.62	2.11	0.24	1.25	91
470	100.6	417	2.21	2.21	0.79	0.50	2.79	0.36	1.63	135
471	100.4	419	2.59	1.89	0.66	0.58	2.86	0.37	1.67	113
472	100.3	418	2.67	4.51	1.08	0.37	4.17	0.59	2.33	193
472.7	100.2	418	3.13	4.30	0.98	0.42	4.38	0.61	2.30	186
473	100.7	417	2.77	1.52	0.55	0.65	2.76	0.35	1.30	116
474	100.6	419	1.82	1.69	0.56	0.52	3.01	0.29	1.43	118
475	99.6	419	2.40	2.10	0.66	0.53	3.18	0.37	1.58	132
476	100.1	416	2.01	1.50	0.47	0.57	3.19	0.29	1.25	120
477	100.4	421	2.55	2.81	0.66	0.48	4.25	0.44	1.72	163
478	100.6	417	1.99	2.66	0.84	0.43	3.16	0.38	1.68	158
479	101.1	419	2.36	1.61	0.51	0.60	3.15	0.33	0.33	487
480	101.0	418	2.89	3.09	0.64	0.48	4.82	0.49	1.77	174
481	100.0	420	2.19	1.81	0.52	0.55	3.48	0.33	1.42	127
482	100.4	419	3.20	2.74	0.66	0.54	4.15	0.49	1.73	158
483	100.1	418	2.99	1.77	0.54	0.63	3.27	0.39	1.58	112
484	101.0	419	1.97	1.54	0.48	0.56	3.20	0.29	1.35	114

485	99.8	425	1.96	1.32	0.50	0.60	2.64	0.27	1.32	100

WELL: 6-3-24-13W4 (page 2/2)

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I
486	101.2	424	1.80	1.10	0.54	0.62	2.03	0.24	1.30	84
487	100.4	425	2.32	1.10	0.53	0.68	2.07	0.28	1.36	80
500.15	100.1	426	3.45	1.10	0.55	0.76	2.00	0.37	1.61	68
501	99.7	426	2.98	0.65	0.56	0.82	1.16	0.30	1.30	50
502	100.2	424	2.68	0.68	0.48	0.80	1.41	0.28	1.23	55
503	100.5	424	2.56	1.54	0.86	0.62	1.79	0.34	1.55	99
504	100.5	418	2.54	0.63	0.39	0.80	1.61	0.26	1.16	54
505	100.8	422	3.15	1.45	0.76	0.68	1.90	0.38	1.54	94
506	100.3	421	2.99	2.02	0.79	0.60	2.55	0.41	1.74	116
507	100.6	423	2.33	0.72	0.49	0.77	1.46	0.25	1.12	64
508	100.1	422	3.08	1.30	0.53	0.70	2.45	0.36	1.45	89
509	100.2	420	3.01	1.07	0.54	0.74	1.98	0.34	1.40	76
510	100.5	422	2.18	1.15	0.45	0.66	2.55	0.27	1.03	111
511	100.4	419	2.21	1.21	0.58	0.65	2.08	0.28	1.09	111
512	100.1	421	2.14	1.12	0.46	0.66	2.43	0.27	1.09	102
513	100.1	423	2.88	1.06	0.50	0.73	2.12	0.32	1.17	90
514	99.7	420	2.66	1.47	0.55	0.65	2.67	0.34	1.39	105
515	100.2	423	3.64	1.49	0.65	0.71	2.29	0.42	1.56	95
516	99.9	422	2.95	1.32	0.67	0.69	1.97	0.35	1.48	89
517	100.5	422	1.94	2.07	0.99	0.48	2.09	0.33	1.68	123
518	100.5	423	3.09	2.54	0.99	0.55	2.56	0.46	1.84	138
519	101.2	416	1.73	1.28	0.81	0.58	1.58	0.25	1.56	82
520	100.2	421	1.83	0.68	0.59	0.73	1.15	0.20	0.94	72

Well: 6-26-13-3W4

Depth (m)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
474	100.8	0.12	2.40	0.00	0.05	0.69	416	459	0.46	0.23	1.65	1.42	145	28
475	99.9	0.38	6.40	0.01	0.06	1.61	418	461	0.51	0.59	2.66	2.07	241	19
476	100.1	0.14	4.29	0.00	0.03	1.18	418	461	0.59	0.39	2.28	1.89	188	26
9107	100.3	0.88	11.49	0.05	0.07	0.72	440	483	0.32	1.04	4.96	3.92	233	6
477	100.0	0.08	2.16	0.00	0.04	0.91	417	460	0.60	0.21	1.77	1.56	122	34
478	100.3	0.12	2.70	0.00	0.04	0.84	420	463	0.49	0.26	1.82	1.56	148	27
479	100.6	0.08	2.12	0.00	0.04	0.79	417	460	0.48	0.20	1.76	1.56	120	27
480	100.0	0.07	1.17	0.00	0.06	0.58	420	463	0.38	0.12	1.34	1.22	87	28
481	100.4	0.13	2.18	0.00	0.06	1.00	407	450	0.74	0.22	2.07	1.85	105	36

WELL: 6-12-13-4W4 (page 1/2)

Depth (m)	QTY (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
405	100.6	412	0.60	7.64	1.80	0.07	4.24	0.68	2.88	265	62
406	100.6	415	0.71	8.37	2.04	0.08	4.10	0.75	2.95	283	69
407	100.8	413	1.25	6.60	1.78	0.16	3.70	0.65	2.70	244	65
408	100.7	405	0.62	7.90	1.96	0.07	4.03	0.71	3.27	241	59
409	100.9	414	1.08	5.30	1.60	0.17	3.31	0.53	2.49	212	64
410	99.9	412	1.03	6.23	1.56	0.14	3.99	0.60	2.54	245	61
411	99.9	415	0.60	4.65	1.86	0.11	2.50	0.43	2.47	188	75
412	101.1	412	1.25	7.03	1.66	0.15	4.23	0.69	2.83	248	58
413	100.1	414	1.09	10.21	1.93	0.10	5.29	0.94	3.16	323	61
414	100.6	411	0.90	14.58	2.26	0.06	6.45	1.29	4.02	362	56
415	100.2	409	0.75	12.60	1.93	0.06	6.52	1.11	3.54	355	54
416	100.0	409	0.86	11.11	2.04	0.07	5.44	0.99	3.47	320	58
423	101.0	406	0.33	5.14	1.33	0.06	3.86	0.45	2.46	208	54
423.2	100.6	409	0.57	9.53	1.74	0.06	5.47	0.84	3.29	289	52
423.38	100.3	414	0.66	12.96	2.25	0.05	5.76	1.13	3.88	334	57
423.59	100.0	414	0.77	12.88	2.16	0.06	5.96	1.13	3.92	328	55
424	101.3	417	0.39	2.96	1.40	0.12	2.11	0.27	1.99	148	70
425	100.8	420	0.20	1.69	0.96	0.11	1.76	0.15	1.35	125	71
426	100.2	418	0.24	1.18	0.82	0.17	1.43	0.11	1.19	99	68
427	100.5	417	0.19	0.82	0.70	0.19	1.17	0.08	0.97	84	72
428	100.7	420	0.10	0.45	0.51	0.19	0.88	0.04	0.63	71	80
429	100.9	418	0.17	0.66	0.69	0.21	0.95	0.06	0.82	80	84
430	100.5	414	3.08	2.21	0.66	0.58	3.34	0.44	1.47	150	44
431	100.0	410	9.57	5.04	0.94	0.66	5.36	1.21	2.51	200	37
447	100.8	416	0.22	2.36	0.91	0.09	2.59	0.21	1.66	142	54
448	100.8	418	0.17	1.69	0.73	0.09	2.31	0.15	1.38	122	52
449	100.4	418	0.19	2.25	0.94	0.08	2.39	0.20	1.69	133	55
450	101.0	411	0.25	2.95	1.47	0.08	2.00	0.26	2.43	121	60
451	100.7	422	0.51	2.15	0.76	0.19	2.82	0.22	1.68	127	45

452	100.8	417	0.32	4.17	1.07	0.07	3.89	0.37	2.24	186	47

WELL: 6-12-13-4W4 (page 2/2)

Depth (m)	QTY (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
453	99.9	418	0.20	1.80	0.97	0.10	1.85	0.16	1.55	116	62
454	100.4	421	0.15	2.05	1.11	0.07	1.84	0.18	1.51	135	73
455	99.9	420	0.21	0.82	0.64	0.21	1.28	0.08	1.16	70	55
456	100.9	420	0.17	0.98	0.69	0.15	1.42	0.09	1.27	77	54
457	100.2	423	0.39	1.28	0.89	0.23	1.43	0.13	1.37	93	64

Well: 6-10-13-7W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
1209	100.0	0.13	0.37	0.00	0.26	0.46	415	458	0.19	0.05	0.55	0.50	67	35
1215	99.8	0.16	0.90	0.00	0.15	0.54	419	462	0.30	0.10	1.05	0.95	86	29
1221	99.7	0.09	0.92	0.00	0.09	0.61	415	458	0.33	0.10	1.16	1.06	79	28
1224	100.0	0.10	0.15	0.00	0.40	0.21	415	458	0.06	0.02	0.39	0.37	38	15
1227	100.6	0.14	1.64	0.00	0.08	0.70	417	460	0.41	0.17	1.56	1.39	105	26
1230	100.5	0.08	0.96	0.00	0.08	0.63	416	459	0.38	0.10	1.27	1.17	76	30
1233	100.2	0.14	1.66	0.00	0.08	0.76	417	460	0.49	0.17	1.64	1.47	101	30
1236	100.9	0.14	2.13	0.00	0.06	0.71	418	461	0.51	0.21	1.82	1.61	117	28
1239	99.6	0.13	0.80	0.00	0.14	0.44	416	459	0.36	0.09	1.00	0.91	80	36
1242	100.9	0.22	2.11	0.00	0.10	0.77	420	463	0.45	0.21	1.73	1.52	122	26
1251	99.9	0.15	2.60	0.00	0.06	0.77	421	464	0.42	0.25	1.66	1.41	157	25
1254	99.9	0.08	0.87	0.00	0.08	0.39	419	462	0.26	0.09	0.97	0.88	90	27
1257	100.2	0.12	2.80	0.00	0.04	1.02	418	461	0.58	0.27	1.89	1.62	148	31
9107	100.3	0.89	11.06	0.04	0.07	0.71	438	481	0.24	1.01	4.97	3.96	223	5
1260	100.6	0.25	3.51	0.00	0.07	1.46	418	461	0.70	0.34	2.45	2.11	143	29
1263	99.9	0.11	1.25	0.00	0.08	0.59	419	462	0.30	0.13	1.33	1.20	94	23
1266	99.8	0.13	1.51	0.00	0.08	0.61	417	460	0.48	0.16	1.47	1.31	103	33
1269	100.7	0.24	3.31	0.00	0.07	1.23	416	459	0.66	0.32	2.27	1.95	146	29
1272	100.9	0.14	1.46	0.00	0.09	0.66	422	465	0.33	0.15	1.45	1.30	101	23
1275	100.7	0.15	2.05	0.00	0.07	0.68	418	461	0.36	0.20	1.58	1.38	130	23
1278	99.7	0.12	1.94	0.00	0.06	0.72	417	460	0.54	0.19	1.71	1.52	113	32
1281	100.5	0.11	2.22	0.00	0.05	0.73	416	459	0.54	0.22	1.75	1.53	127	31
1284	99.6	0.14	2.37	0.00	0.06	0.68	418	461	0.51	0.23	1.58	1.35	150	32
9107	100.6	0.90	10.93	0.01	0.08	0.68	440	483	0.27	0.99	4.93	3.94	222	5

Well: 4-8-13-27W4 (page 1/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5225	99.8	438	0.06	0.74	0.00	0.07	0.00	0.06	0.97	76	0
5225	101.3	434	0.06	0.90	0.00	0.06	0.00	0.08	0.99	90	0
5227	100.7	435	0.05	0.83	0.00	0.06	0.00	0.07	0.99	83	0
5227	100.6	440	0.05	0.87	0.00	0.05	0.00	0.07	0.97	89	0
5230	100.1	432	0.05	0.80	0.00	0.06	0.00	0.07	0.94	85	0
5230	100.5	441	0.04	0.71	0.00	0.05	0.00	0.06	0.91	78	0
5233	100.5	436	0.02	0.48	0.13	0.04	3.69	0.04	0.87	55	14
5233	100.7	438	0.05	0.62	0.15	0.08	4.13	0.05	0.89	69	16
5236	100.8	439	0.06	0.72	0.00	0.08	0.00	0.06	1.09	66	0
5236	100.8	439	0.06	0.75	0.03	0.07	25.00	0.06	1.03	72	2
5239	100.6	436	0.05	0.61	0.03	0.08	20.33	0.05	0.88	69	3
5239	101.0	436	0.05	0.56	0.10	0.08	5.60	0.05	0.87	64	11
5242	100.6	431	0.44	3.67	0.11	0.11	33.36	0.34	1.71	214	6
5242	99.6	434	0.45	3.78	0.05	0.11	75.60	0.35	1.68	225	2
5245	100.0	435	0.15	1.30	0.06	0.10	21.66	0.12	1.22	106	4
5245	99.9	435	0.15	1.40	0.02	0.10	70.00	0.12	1.21	115	1
5248	100.4	433	0.16	0.38	0.01	0.30	38.00	0.04	0.53	71	1
5248	100.7	436	0.16	0.36	0.02	0.31	18.00	0.04	0.54	66	3
5251	100.1	435	0.18	1.15	0.08	0.14	14.37	0.11	1.1	104	7
5251	100.1	437	0.17	1.12	0.12	0.13	9.33	0.10	1.07	104	11

Well: 4-8-13-27W4 (page 2/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5254	101.1	439	0.20	1.84	0.10	0.10	18.40	0.17	1.15	160	8
5254	100.8	436	0.22	1.93	0.08	0.10	24.12	0.17	1.19	162	6
5257	101.2	433	0.10	0.86	0.13	0.10	6.61	0.08	0.96	89	13
5257	100.7	437	0.09	0.83	0.16	0.10	5.18	0.07	0.94	88	17
5260a	100.4	430	0.55	6.36	0.18	0.08	35.33	0.57	1.92	331	9
5260a	100.8	429	0.56	6.25	0.16	0.08	39.06	0.56	2.05	304	7
5260b	100.3	433	0.08	0.36	0.08	0.18	4.50	0.03	0.45	80	17
5260b	100.0	433	0.09	0.34	0.18	0.21	1.88	0.03	0.44	77	40
5263	100.2	430	0.54	4.96	0.21	0.10	23.61	0.45	1.79	277	11
5263	100.5	430	0.53	4.92	0.14	0.10	35.14	0.45	1.73	284	8
5266	100.7	431	0.51	3.60	0.24	0.12	15.00	0.34	1.53	235	15
5266	101.0	433	0.50	3.93	0.25	0.11	15.72	0.36	1.63	241	15
5269	100.5	428	0.65	5.97	0.32	0.10	18.65	0.55	2.07	288	15
5269	99.7	429	0.66	5.81	0.23	0.10	25.26	0.53	1.99	291	11
5272	100.7	434	0.42	3.21	0.11	0.12	29.18	0.30	1.29	248	8
5272	99.5	435	0.43	3.28	0.10	0.12	32.80	0.30	1.31	250	7
5275	100.6	432	0.43	3.03	0.06	0.12	50.50	0.28	1.45	208	4
5275	99.8	429	0.50	3.35	0.03	0.13	111.66	0.32	1.5	223	2
5366	100.5	438	0.44	3.02	0.21	0.13	14.38	0.28	1.22	247	17
5366	100.4	435	0.46	3.01	0.20	0.13	15.05	0.28	1.26	238	15

Well: 4-8-13-27W4 (page 3/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5369	100.7	430	0.78	6.69	0.28	0.10	23.89	0.62	1.93	346	14
5369	100.6	432	0.73	6.51	0.19	0.10	34.26	0.60	1.86	350	10
5372	99.9	430	0.62	4.79	0.17	0.11	28.17	0.45	1.62	295	10
5372	99.9	430	0.61	4.57	0.15	0.12	30.46	0.43	1.56	292	9
5375	101.0	430	0.83	6.78	0.30	0.11	22.60	0.63	1.92	353	15
5375	100.1	430	0.79	6.37	0.37	0.11	17.21	0.59	1.9	335	19
5378	100.0	432	0.78	8.10	0.15	0.09	54.00	0.74	2.05	395	7
5378	100.0	433	0.76	7.84	0.30	0.09	26.13	0.71	2.01	390	14
5381	100.3	432	0.94	9.71	0.33	0.09	29.42	0.88	2.45	396	13
5381	99.8	430	0.98	9.64	0.34	0.09	28.35	0.88	2.5	385	13
9107	100.1	441	1.10	11.53	0.68	0.09	16.95	1.05	4.95	232	13
5384	99.8	430	0.55	4.87	0.43	0.10	11.32	0.45	1.84	264	23
5384	100.9	429	0.56	5.03	0.40	0.10	12.57	0.46	1.87	268	21
5387	100.7	431	0.71	6.74	0.24	0.10	28.08	0.62	1.97	342	12
5387	101.1	431	0.68	6.81	0.28	0.09	24.32	0.62	1.99	342	14
5390	101.2	434	0.72	5.70	0.27	0.11	21.11	0.53	1.88	303	14
5390	100.5	429	0.73	6.21	0.30	0.11	20.70	0.57	1.99	312	15
5393	100.3	431	0.67	5.00	0.31	0.12	16.12	0.47	1.88	265	16
5393	100.4	429	0.68	5.07	0.32	0.12	15.84	0.47	1.85	274	17

Well: 4-8-13-27W4 (page 4/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5396	100.9	432	0.61	5.16	0.21	0.11	24.57	0.48	1.75	294	12
5396	100.1	433	0.62	5.00	0.17	0.11	29.41	0.46	1.73	289	9
5399	100.2	433	0.58	4.34	0.15	0.12	28.93	0.41	1.75	248	8
5399	100.2	432	0.59	4.41	0.12	0.12	36.75	0.41	1.8	245	6
5402	100.1	435	0.55	4.70	0.15	0.10	31.33	0.43	1.76	267	8
5402	100.0	435	0.55	4.62	0.12	0.11	38.50	0.43	1.76	262	6
5405	100.0	433	0.97	2.11	0.14	0.31	15.07	0.25	1.27	166	11
5405	100.7	432	0.98	2.17	0.12	0.31	18.08	0.26	1.26	172	9
5408	99.8	433	0.24	0.65	0.03	0.27	21.66	0.07	0.47	138	6
5408	100.4	432	0.22	0.65	0.07	0.26	9.28	0.07	0.45	144	15
5411	100.0	440	0.25	1.86	0.01	0.12	186.00	0.17	0.99	187	1
5411	99.8	438	0.25	1.81	0.02	0.12	90.50	0.17	0.99	182	2
5414	99.7	436	0.27	1.86	0.12	0.13	15.50	0.17	1.02	182	11
5414	99.9	435	0.28	1.82	0.13	0.13	14.00	0.17	1.12	162	11
5417	99.8	435	0.31	2.94	0.11	0.10	26.72	0.27	1.25	235	8
5417	100.7	435	0.33	2.96	0.05	0.10	59.20	0.27	1.35	219	3
5420	100.5	432	1.00	1.01	0.10	0.50	10.10	0.16	0.9	112	11
5420	100.3	433	1.00	1.18	0.12	0.46	9.83	0.18	0.87	135	13
5423	101.6	435	0.40	1.36	0.15	0.23	9.06	0.14	1.01	134	14
5423	100.2	435	0.39	1.54	0.16	0.20	9.62	0.16	1	154	16

Well: 4-8-13-27W4 (page 5/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5426	99.7	434	0.41	2.96	0.12	0.12	24.66	0.28	1.35	219	8
5426	100.9	436	0.39	2.89	0.06	0.12	48.16	0.27	1.27	227	4
5429	99.8	432	0.80	1.94	0.15	0.29	12.93	0.22	1.11	174	13
5429	100.3	431	0.77	1.89	0.25	0.29	7.56	0.22	1.12	168	22
5432	100.2	434	0.37	3.25	0.03	0.10	108.33	0.30	1.35	240	2
5432	100.0	439	0.34	2.97	0.07	0.10	42.42	0.27	1.24	239	5
5435	100.3	435	0.33	2.50	0.06	0.12	41.66	0.23	1.23	203	4
5435	100.6	434	0.34	2.78	0.07	0.11	39.71	0.26	1.25	222	5
5438	100.7	431	0.97	3.52	0.18	0.22	19.55	0.37	1.54	228	11
5438	100.8	432	0.93	3.55	0.14	0.21	25.35	0.37	1.56	227	8
5441	100.9	433	0.34	2.02	0.10	0.14	20.20	0.19	1.32	153	7
5441	100.8	434	0.32	2.16	0.13	0.13	16.61	0.20	1.29	167	10
5444	100.7	486	0.27	3.46	0.04	0.07	86.50	0.31	1.44	240	2
5444	101.2	438	0.41	3.31	0.15	0.11	22.06	0.31	1.46	226	10
5447	100.0	430	0.57	5.87	0.19	0.09	30.89	0.53	1.79	327	10
5447	100.8	430	0.60	6.08	0.15	0.09	40.53	0.55	1.82	334	8
5450	100.5	431	0.58	4.59	0.23	0.11	19.95	0.43	1.88	244	12
5450	100.3	433	0.57	5.02	0.17	0.10	29.52	0.46	1.86	269	9
5453	100.4	432	0.36	2.76	0.22	0.12	12.54	0.26	1.4	197	15
5453	100.6	433	0.35	2.77	0.26	0.11	10.65	0.26	1.4	197	18

Well: 4-8-13-27W4 (page 6/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5456	100.4	433	0.47	3.24	0.24	0.13	13.50	0.30	1.56	207	15
5456	100.6	431	0.50	3.48	0.23	0.13	15.13	0.33	1.61	216	14
5459	100.5	433	0.56	5.58	0.31	0.09	18.00	0.51	2.02	276	15
5459	99.9	431	0.58	6.21	0.31	0.09	20.03	0.56	2.04	304	15
5462	99.6	437	0.16	1.65	0.10	0.09	16.50	0.15	1.14	144	8
5462	100.1	436	0.15	1.54	0.22	0.09	7.00	0.14	1.13	136	19
5465a	100.4	431	0.48	1.26	0.41	0.28	3.07	0.14	0.88	143	46
5465a	100.6	433	0.47	1.19	0.49	0.28	2.42	0.13	0.87	136	56
5465b	100.1	428	0.24	0.31	0.37	0.44	0.83	0.04	0.41	75	90
5465b	100.2	428	0.25	0.27	0.10	0.48	2.70	0.04	0.42	64	23
5468	99.7	433	0.59	2.70	0.14	0.18	19.28	0.27	1.52	177	9
5468	100.2	433	0.55	2.42	0.12	0.19	20.16	0.24	1.49	162	8
5471	100.3	435	0.34	2.44	0.12	0.12	20.33	0.23	1.41	173	8
5471	100.8	436	0.34	2.31	0.07	0.13	33.00	0.22	1.29	179	5
5474	101.4	435	0.41	2.16	0.12	0.16	18.00	0.21	1.34	161	8
5474	101.1	433	0.45	2.17	0.13	0.17	16.69	0.21	1.37	158	9
5477	99.8	435	0.24	1.60	0.07	0.13	22.85	0.15	1.2	133	5
5477	100.0	435	0.23	1.54	0.11	0.13	14.00	0.14	1.22	126	9
5480	101.5	437	0.19	2.12	0.04	0.08	53.00	0.19	1.33	159	3
5480	100.4	436	0.21	2.12	0.03	0.09	70.66	0.19	1.38	153	2

Well: 4-8-13-27W4 (page 6/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5483	100.5	434	0.37	1.21	0.10	0.23	12.10	0.13	1.11	109	9
5483	100.0	433	0.38	1.27	0.05	0.23	25.40	0.13	1.1	115	4
5486	100.2	436	0.14	1.48	0.00	0.09	0.00	0.13	1.09	135	0
5486	101.2	436	0.12	1.28	0.00	0.09	0.00	0.11	1.01	126	0
5489	100.3	437	0.20	2.29	0.01	0.08	229.00	0.20	1.36	168	0
5489	100.9	438	0.18	2.24	0.05	0.07	44.80	0.20	1.26	177	3
5492	100.5	435	0.20	2.47	0.12	0.08	20.58	0.22	1.42	173	8
5492	100.1	435	0.19	2.38	0.03	0.07	79.33	0.21	1.39	171	2
5495	100.8	434	0.20	2.36	0.03	0.08	78.66	0.21	1.38	171	2
5495	100.0	436	0.19	2.21	0.05	0.08	44.20	0.20	1.34	164	3
5498	99.8	435	0.18	1.48	0.06	0.11	24.66	0.13	1.25	118	4
5498	100.4	433	0.19	1.68	0.12	0.10	14.00	0.15	1.24	135	9
5501	101.3	434	0.16	1.48	0.02	0.10	74.00	0.13	1.23	120	1
5501	100.1	437	0.14	1.48	0.01	0.09	148.00	0.13	1.2	123	0
5504	100.5	437	0.13	1.33	0.09	0.09	14.77	0.12	1.12	118	8
5504	100.3	438	0.14	1.56	0.00	0.08	0.00	0.14	1.15	135	0
5507	100.7	435	0.22	1.16	0.06	0.16	19.33	0.11	1.04	111	5
5507	100.7	432	0.23	1.31	0.00	0.15	0.00	0.12	1.07	122	0
5510	100.7	437	0.18	2.05	0.08	0.08	25.62	0.18	1.3	157	6
5510	100.3	437	0.15	1.93	0.07	0.07	27.57	0.17	1.31	147	5

Well: 4-8-13-27W4 (page 7/7)

Depth (ft)	QTY(mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
5513	99.8	433	0.29	1.35	0.08	0.18	16.87	0.13	1.12	120	7
5513	100.1	434	0.28	1.21	0.15	0.19	8.06	0.12	1.13	107	13
5515	101.3	432	0.23	1.80	0.15	0.11	12.00	0.16	1.3	138	11
5515	100.2	433	0.22	1.77	0.17	0.11	10.41	0.16	1.26	140	13

Well: 3-7-13-27W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
5521	100.20	0.17	1.59	0.01	0.09	0.22	428	473	0.17	0.15	1.28	1.13	125	13
5526	100.10	0.23	3.05	0.01	0.07	0.28	430	475	0.24	0.28	1.88	1.60	163	13
5531	100.80	0.15	2.16	0.01	0.07	0.24	430	475	0.22	0.20	1.67	1.47	130	13
5536	101.30	0.12	1.55	0.01	0.07	0.22	430	475	0.20	0.15	1.35	1.20	116	15
5541	100.60	0.10	1.85	0.01	0.05	0.18	438	483	0.18	0.17	1.36	1.19	137	13
5546	99.80	0.14	1.73	0.01	0.08	0.22	433	478	0.19	0.16	1.40	1.24	124	14
5551	100.50	0.20	2.51	0.01	0.07	0.26	432	477	0.19	0.23	1.80	1.57	140	11
5556	100.10	0.18	1.99	0.01	0.08	0.25	431	476	0.20	0.19	1.60	1.41	125	13
5561	100.10	0.17	2.47	0.01	0.06	0.17	435	480	0.14	0.23	1.74	1.51	143	8
5566	100.20	0.14	2.74	0.01	0.05	0.28	434	479	0.22	0.25	1.83	1.58	150	12
5571	100.00	0.24	2.58	0.01	0.08	0.28	432	477	0.28	0.25	1.95	1.70	133	14
5576	100.60	0.23	0.53	0.00	0.30	0.15	435	480	0.12	0.07	0.66	0.59	80	18
5581	100.60	0.38	1.85	0.01	0.17	0.22	430	475	0.13	0.19	1.35	1.16	138	10
5586	100.00	0.29	2.27	0.01	0.11	0.29	430	475	0.11	0.22	1.57	1.35	145	7
5591	100.30	0.69	2.39	0.01	0.22	0.64	428	473	0.14	0.26	1.24	0.98	194	11
5596	100.10	0.32	2.13	0.01	0.13	0.29	427	472	0.17	0.21	1.36	1.15	157	13
5601	100.80	0.35	4.39	0.01	0.07	0.28	427	472	0.17	0.40	1.98	1.58	222	9
5606	100.80	0.33	2.58	0.01	0.11	0.26	429	474	0.21	0.25	1.62	1.37	160	13
5611	100.70	0.30	3.48	0.01	0.08	0.21	432	477	0.21	0.32	1.88	1.56	186	11
5616	100.40	0.33	3.96	0.01	0.08	0.25	428	473	0.22	0.37	1.95	1.58	204	11
5621	100.70	0.27	3.37	0.01	0.07	0.21	429	474	0.23	0.31	1.80	1.49	188	13
5625	100.60	0.04	0.09	0.00	0.31	0.18	451	496	0.09	0.01	0.45	0.44	20	20
5626	100.00	0.05	0.19	0.00	0.21	0.28	435	480	0.13	0.03	0.56	0.53	34	23

Well:16-28-14-2W4

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I	H I
467	101.0	421	0.26	3.16	0.67	0.08	4.71	0.28	1.97	160	34	160
468	100.3	418	0.19	2.47	0.57	0.07	4.33	0.22	1.91	129	29	129
469	99.5	421	0.11	1.16	0.44	0.09	2.63	0.10	1.32	87	33	87
470	100.2	422	0.21	3.02	0.83	0.07	3.63	0.26	2.10	143	39	143
471	100.8	424	0.19	2.57	0.80	0.07	3.21	0.23	1.79	143	44	143
472	100.0	419	0.11	1.22	0.52	0.08	2.34	0.11	1.29	94	40	94
473	101.1	419	0.29	0.74	0.40	0.28	1.85	0.08	1.03	71	38	71
473.5	101.0	422	0.13	1.21	0.42	0.10	2.88	0.11	1.30	93	32	93
474	99.7	426	0.11	1.15	0.54	0.09	2.12	0.10	1.43	80	37	80
476	100.6	422	0.32	3.74	0.88	0.08	4.25	0.33	2.09	178	42	178
477	100.0	421	0.16	1.65	0.46	0.09	3.58	0.15	1.34	123	34	123
478	100.7	421	0.22	3.72	0.93	0.06	4.00	0.32	2.14	173	43	173
479	99.9	423	0.34	3.66	0.95	0.08	3.85	0.33	2.02	181	47	181
480	100.4	419	0.29	6.76	1.18	0.04	5.72	0.58	2.83	238	41	238
481	100.5	421	0.30	6.01	1.28	0.05	4.69	0.52	2.91	206	43	206
482	100.3	423	0.17	1.96	0.52	0.08	3.76	0.17	1.54	127	33	127
483	101.1	423	0.23	6.18	1.40	0.04	4.41	0.53	2.62	235	53	235
484	100.8	423	0.12	2.08	0.60	0.05	3.46	0.18	1.62	128	37	128
485	101.3	413	0.18	2.65	0.83	0.06	3.19	0.23	2.00	132	41	132
499	100.5	420	0.07	1.17	0.59	0.06	1.98	0.10	1.40	83	42	83
500	100.4	426	0.09	0.72	0.51	0.11	1.41	0.06	1.00	72	51	72
501	100.4	427	0.10	0.91	0.56	0.10	1.62	0.08	1.18	77	47	77
502	100.9	425	0.14	1.04	0.41	0.12	2.53	0.09	1.25	83	32	83
503	100.4	419	0.04	0.92	0.52	0.04	1.76	0.08	1.35	68	38	68
504	100.3	424	0.10	0.70	0.33	0.12	2.12	0.06	1.06	66	31	66
505	99.7	422	0.17	1.69	0.57	0.09	2.96	0.15	1.55	109	36	109
506	100.5	422	0.18	3.42	0.78	0.05	4.38	0.30	2.04	167	38	167
507	100.1	421	0.10	1.59	0.58	0.06	2.74	0.14	1.64	96	35	96
508	100.2	422	0.16	1.45	0.66	0.10	2.19	0.13	1.54	94	42	94

16-10-15-1W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
1767	100.1	0.34	5.45	0.00	0.06	1.12	416	459	0.68	0.51	2.60	2.09	210	26
1770	100.3	0.35	7.62	0.00	0.04	1.41	417	460	0.62	0.69	2.88	2.19	265	22
1773	100.2	0.32	7.27	0.00	0.04	1.31	410	453	0.76	0.66	2.67	2.01	272	28
1775	100.3	0.25	5.65	0.00	0.04	1.41	415	458	0.73	0.52	2.49	1.97	227	29
1781.5	100.4	0.23	1.42	0.00	0.14	0.87	415	458	0.44	0.16	1.46	1.30	97	30
1796	100.8	0.32	1.71	0.00	0.16	0.70	414	457	0.41	0.19	1.47	1.28	116	28
1802	100.7	0.66	6.73	0.01	0.09	1.91	414	457	0.91	0.65	3.04	2.39	222	30

Well: 14-36-13-4W4 (page 1/2)

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
400	100.7	422	0.58	5.11	0.46	0.10	11.10	0.47	2.18	234	21
401	100.3	419	0.98	7.28	1.53	0.12	4.75	0.68	3.80	191	40
402	100.9	422	0.20	0.44	0.24	0.31	1.83	0.05	0.65	67	36
403	100.7	421	0.51	1.52	0.40	0.25	3.80	0.16	1.19	127	33
403.75	100.8	424	0.46	2.65	0.56	0.15	4.73	0.25	1.68	157	33
406	101.1	414	0.90	6.07	0.93	0.13	6.52	0.58	2.14	283	43
407	100.6	421	0.40	2.06	0.48	0.16	4.29	0.20	1.45	142	33
408	100.2	419	0.22	1.15	0.33	0.16	3.48	0.11	1.18	97	27
409	100.1	421	0.31	1.07	0.41	0.22	2.60	0.11	1.50	71	27
410	100.1	419	0.36	1.21	0.26	0.23	4.65	0.13	1.25	96	20
410.5	100.6	421	0.40	1.33	0.35	0.23	3.80	0.14	1.33	100	26
415	100.6	423	0.57	2.63	0.56	0.18	4.69	0.26	1.53	171	36
416	100	422	0.54	3.40	0.67	0.14	5.07	0.32	1.80	188	37
417	100.5	421	0.49	2.61	0.48	0.16	5.43	0.25	1.51	172	31
418	100.1	423	0.82	4.81	0.78	0.15	6.16	0.46	2.17	221	35
419	100.4	422	0.60	4.82	0.68	0.11	7.08	0.45	2.02	238	33
420	99.9	424	0.69	7.52	1.02	0.08	7.37	0.68	2.58	291	39
420.75	100.1	422	0.63	1.47	0.39	0.30	3.76	0.17	0.83	177	46
423	100.2	421	0.56	3.82	0.74	0.13	5.16	0.36	2.03	188	36
424	100.5	417	0.38	2.75	0.54	0.12	5.09	0.26	1.61	170	33
425	100	421	0.69	4.23	0.68	0.14	6.22	0.41	1.95	216	34
426	99.5	419	0.48	2.88	0.53	0.14	5.43	0.28	1.71	168	30
427	101.2	425	0.64	2.79	0.45	0.19	6.20	0.28	1.60	174	28
428	100.2	425	0.92	4.30	0.57	0.18	7.54	0.43	1.99	216	28
429	100.6	425	0.69	2.99	0.42	0.19	7.11	0.30	1.49	200	28
430	100.8	425	0.69	2.68	0.51	0.21	5.25	0.28	1.66	161	30
430.25	100.2	421	0.35	1.33	0.42	0.21	3.16	0.14	1.37	97	30
431	100	421	0.50	1.08	0.39	0.32	2.76	0.13	1.25	86	31
432	100.7	427	0.40	1.42	0.62	0.22	2.29	0.15	1.39	102	44

433	100.5	426	0.45	1.28	0.59	0.26	2.16	0.14	1.30	98	45

Well: 14-36-13-4W4 (page 2/2)

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
434	99.8	426	0.28	1.31	0.35	0.18	3.74	0.13	1.37	95	25
435	100	426	0.29	1.72	0.60	0.14	2.86	0.16	1.47	117	40
436	100.5	422	0.41	3.62	1.00	0.10	3.62	0.33	2.01	180	49
437	100.2	424	0.19	1.04	0.45	0.16	2.31	0.10	1.18	88	38
438	100	418	0.15	0.68	0.76	0.18	0.89	0.06	1.02	66	74
439	100.2	422	0.30	1.91	0.61	0.14	3.13	0.18	1.40	136	43
439.25	100.7	416	0.38	4.38	0.94	0.08	4.65	0.39	2.13	205	44
440	100	417	0.15	1.05	0.80	0.12	1.31	0.10	1.36	77	58
441	100.5	416	0.12	0.73	0.71	0.14	1.02	0.07	1.17	62	60
442	100.4	416	0.16	0.92	0.53	0.15	1.73	0.09	1.05	87	50
443	100.2	420	0.14	1.20	0.80	0.10	1.50	0.11	1.32	90	60
444	100.3	415	0.07	0.66	0.78	0.10	0.84	0.06	0.90	73	86
445	100.4	414	0.15	0.70	0.80	0.18	0.87	0.07	1.13	61	70
446	100.1	419	0.24	1.25	0.94	0.16	1.32	0.12	1.35	92	69
447	100.6	418	0.09	0.68	0.72	0.12	0.94	0.06	1.02	66	70
448	100.2	423	0.22	2.28	0.92	0.09	2.47	0.20	1.39	164	66
449	99.9	423	0.21	1.85	1.06	0.10	1.74	0.17	1.41	131	75
450	99.7	412	0.10	0.86	0.75	0.10	1.14	0.08	1.18	72	63
451	100.5	425	0.33	4.17	0.96	0.07	4.34	0.37	1.97	211	48
452	100.4	425	0.18	1.93	0.74	0.09	2.60	0.17	1.45	133	51
453	100.1	424	0.16	0.59	0.58	0.22	1.01	0.06	0.62	95	93
454	101.3	428	0.27	1.93	0.76	0.12	2.53	0.18	1.58	122	48
455	100.3	424	0.27	2.81	0.80	0.09	3.51	0.25	1.82	154	43
456	100.1	424	0.68	1.81	0.60	0.27	3.01	0.20	1.53	118	39
457	100.1	423	0.28	1.53	0.55	0.16	2.78	0.15	1.50	102	36

Well: 14-26-19-8W4 (page 1/3)

Depth (m)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	TOC	RC%	HI	OICO
449	100.3	0.62	1.22	0.00	0.34	0.72	419	462	1.47	1.30	83	20
450	100.0	0.68	1.05	0.00	0.39	0.58	423	466	1.37	1.21	77	20
451	100.1	0.88	1.33	0.00	0.40	0.62	417	460	1.47	1.27	90	22
452	100.6	0.73	1.23	0.00	0.37	0.55	423	466	1.49	1.31	83	20
453	100.0	1.24	1.53	0.00	0.45	0.52	419	462	1.48	1.24	103	18
454	100.0	0.57	0.79	0.00	0.42	0.38	422	465	1.15	1.03	69	19
455	100.5	0.89	2.08	0.00	0.30	0.57	423	466	1.77	1.51	118	16
456	100.2	0.82	2.64	0.00	0.24	0.75	421	464	1.99	1.69	133	19
457	100.5	0.55	1.49	0.00	0.27	0.49	421	464	1.46	1.28	102	20
458	100.6	0.45	1.91	0.00	0.19	0.58	418	461	1.73	1.52	110	24
459	100.3	0.38	3.61	0.00	0.09	0.79	413	456	2.25	1.89	160	25
9107	100.6	0.90	11.59	0.05	0.07	0.72	439	482	4.97	3.92	234	5
460	100.5	1.20	4.02	0.00	0.23	0.73	410	453	2.15	1.69	187	25
460.5	100.3	0.62	5.53	0.00	0.10	1.05	408	451	2.80	2.27	198	20
460.7	100.7	0.87	4.10	0.00	0.17	0.75	411	454	2.22	1.79	185	14
461	100.0	1.50	9.09	0.00	0.14	1.28	410	453	3.26	2.36	279	18
462	100.2	0.82	5.85	0.00	0.12	1.17	413	456	2.58	2.01	227	17
463	100.4	0.51	3.88	0.00	0.12	0.96	405	448	2.32	1.94	167	17
464	100.8	0.98	5.28	0.00	0.16	0.91	410	453	2.20	1.66	240	26
465	99.8	0.55	6.04	0.00	0.08	1.16	400	443	2.83	2.26	213	18
9107	100.5	0.89	11.52	0.05	0.07	0.79	441	484	5.04	3.99	230	5
9107	100.1	0.97	11.52	0.05	0.08	0.83	440	483	5.00	3.95	231	5
466	99.8	0.72	8.41	0.00	0.08	1.39	408	451	3.23	2.45	260	19
467	100.3	0.84	5.04	0.00	0.14	1.11	410	453	2.39	1.88	211	21
468	99.8	1.31	8.60	0.00	0.13	1.47	408	451	3.13	2.28	275	17
469	100.6	0.95	8.53	0.01	0.10	1.58	411	454	3.29	2.48	260	17
469 9	99.8	1.19	15.72	0.01	0.07	2.14	411	454	4.20	2.76	375	18
483	100.0	0.87	4.70	0.00	0.16	0.81	408	451	2.29	1.81	205	17
484	99.9	0.71	6.01	0.00	0.11	0.92	415	458	2.62	2.04	229	21

Well: 14-26-19-8W4 (page 2/3)

Depth (m)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	TOC	RC%	HI	OICO
485	99.9	1.94	9.34	0.00	0.17	1.25	412	455	2.62	1.66	356	21
486	100.7	1.43	13.24	0.01	0.10	1.57	411	454	4.01	2.76	330	18
487	100.5	1.79	12.25	0.00	0.13	1.49	410	453	3.82	2.63	321	17
488	100.1	1.02	11.99	0.00	0.08	1.41	411	454	3.63	2.52	330	17
489	100.8	1.28	4.23	0.00	0.23	1.01	415	458	2.23	1.75	190	21
490	99.7	1.52	5.62	0.00	0.21	1.06	418	461	2.50	1.89	225	14
491	100.4	3.53	3.62	0.00	0.49	0.58	417	460	1.98	1.37	183	16
9107	100.3	0.93	11.78	0.05	0.07	0.76	441	484	5.01	3.94	236	5
493	100.5	1.87	3.55	0.00	0.34	0.65	416	459	1.92	1.45	185	21
494	100.3	0.75	3.12	0.00	0.19	0.66	416	459	1.80	1.46	173	23
495	100.6	0.81	4.11	0.00	0.17	0.82	416	459	2.15	1.72	191	24
496	100.1	0.92	2.55	0.00	0.27	0.62	414	457	1.77	1.47	144	21
498	100.7	0.68	2.95	0.00	0.19	0.67	415	458	1.86	1.54	159	19
499	100.2	2.63	9.95	0.01	0.21	1.36	416	459	3.33	2.26	299	14
500	99.8	1.46	2.69	0.00	0.35	0.57	417	460	1.79	1.43	150	20
501	100.2	1.13	3.93	0.00	0.22	0.74	414	457	1.95	1.51	202	23
503	100.5	2.18	2.91	0.00	0.43	0.48	415	458	1.69	1.26	172	17
9107	100.0	0.87	10.88	0.05	0.07	0.72	441	484	4.93	3.94	222	6
504	100.8	1.06	2.75	0.00	0.28	0.54	414	457	1.67	1.34	165	23
505	99.7	1.03	2.64	0.00	0.28	0.51	418	461	1.71	1.39	154	19
506	100.6	0.61	2.50	0.00	0.20	0.57	419	462	1.53	1.26	163	14
507	100.8	0.86	1.84	0.00	0.32	0.49	417	460	1.49	1.25	123	17
508	100.9	1.02	2.24	0.00	0.31	0.55	419	462	1.64	1.35	137	23
509	100.0	1.03	2.34	0.00	0.30	0.54	414	457	1.69	1.39	138	25
661	100.2	1.24	14.19	0.00	0.08	1.15	413	456	4.01	2.70	354	18
662	99.7	1.13	17.41	0.01	0.06	1.51	412	455	4.48	2.90	389	20
663	100.4	1.75	20.17	0.01	0.08	1.72	409	452	4.75	2.90	425	16
664	100.6	1.22	13.70	0.01	0.08	1.44	408	451	3.12	1.86	439	16
665	100.1	3.73	27.30	0.02	0.12	2.42	408	451	6.16	3.54	444	15

Well: 14-26-19-8W4 (page 3/3)

Depth (m)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	TOC	RC%	HI	OICO
9107	100.4	0.88	11.04	0.05	0.07	0.77	441	484	4.98	3.97	223	7
9107	100.5	0.95	11.06	0.04	0.08	0.79	439	482	4.96	3.95	224	5
666	100.1	2.36	23.22	0.01	0.09	2.42	408	451	5.50	3.34	422	15
667	100.1	2.41	26.71	0.02	0.08	2.38	407	450	6.03	3.57	443	15
668	100.3	2.82	32.30	0.01	0.08	2.34	408	451	6.92	3.96	467	15
669	100.8	2.67	26.82	0.00	0.09	1.76	406	449	5.83	3.35	460	15
670	100.0	0.70	1.51	0.00	0.32	0.50	411	454	0.83	0.63	182	33
671	100.3	2.10	14.57	0.00	0.13	1.21	406	449	3.88	2.47	376	16
672	99.8	1.67	15.37	0.00	0.10	1.39	403	446	4.40	2.95	349	17

Well: 13-9-14-28W3

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
493.00	99.90	421	0.47	8.84	2.02	0.05	4.37	0.77	3.98	222	50
494.00	100.10	423	0.54	5.68	1.70	0.09	3.34	0.51	3.12	182	54
495.00	100.10	422	0.48	11.54	2.85	0.04	4.04	1.00	4.35	265	65
496.00	100.90	428	0.53	8.12	2.06	0.06	3.94	0.72	3.67	221	56
496.90	100.40	425	0.52	4.11	1.51	0.11	2.72	0.38	2.75	149	54
497.00	100.00	426	0.22	1.20	0.76	0.15	1.57	0.11	1.24	96	61
497.10	100.90	425	0.21	1.41	0.96	0.13	1.46	0.13	1.29	109	74
498.00	100.30	429	0.24	2.11	1.06	0.10	1.99	0.19	1.96	107	54
499.00	100.40	427	0.27	1.65	0.83	0.14	1.98	0.16	1.60	103	51
500.00	100.40	426	0.15	0.45	0.38	0.25	1.18	0.05	0.61	73	62
501.00	99.60	424	0.32	1.98	0.87	0.14	2.27	0.19	1.63	121	53
502.00	100.40	427	0.25	1.68	0.73	0.13	2.30	0.16	1.60	105	45

WELL: 13-20-17-7W4

Depth (m)	SAMPLE ID.	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
535	26	100.2	424	0.10	1.12	0.54	0.08	2.07	0.10	1.17	95	46
536	25	100.6	422	0.31	3.83	0.81	0.07	4.72	0.34	1.98	193	40
536.5	24	100.7	415	0.33	7.37	1.30	0.04	5.66	0.64	2.09	352	62
537	23	100.0	419	0.34	8.65	1.16	0.04	7.45	0.74	3.00	288	38
537.5	22	100.9	422	0.17	2.35	0.71	0.07	3.30	0.21	1.52	154	46
538	21	100.6	425	0.26	3.73	0.87	0.07	4.28	0.33	2.02	184	43
539	20.1	100.2	415	0.45	9.51	1.46	0.05	6.51	0.83	2.51	378	58
539.1	20	100.6	0	0.01	0.00	0.18	0.00	0.00	0.00	0.02	0	900
539.4	19.1	100.2	413	0.71	18.51	2.15	0.04	8.60	1.60	4.29	431	50
539.5	19	100.5	417	0.07	1.17	0.58	0.06	2.01	0.10	0.51	229	113
539.8	18	100.6	0	0.05	0.00	0.42	1.00	0.00	0.00	0.01	0	4200
540	17.2	100.4	416	0.44	8.19	1.04	0.05	7.87	0.71	2.20	372	47
540.1	17.1	100.5	421	0.37	3.85	0.74	0.09	5.20	0.35	1.56	246	47
541	16	100.1	418	0.12	1.66	0.56	0.07	2.96	0.14	0.76	218	73
541.7	15	100.5	0	0.02	0.00	0.37	1.00	0.00	0.00	0.00	0	0
542	14	100.4	416	0.29	2.07	0.58	0.12	3.56	0.19	0.74	279	78
543	12	100.4	419	0.60	1.80	0.71	0.25	2.53	0.20	1.14	157	62
543.2	13	100.5	409	0.26	2.83	0.88	0.08	3.21	0.25	1.86	152	47
543.8	12.1	100.6	420	0.33	2.56	0.86	0.11	2.97	0.24	1.52	168	56
544	11	100.4	418	0.38	1.02	0.55	0.27	1.85	0.11	0.91	112	60
545	10	100.3	422	0.29	1.26	0.62	0.19	2.03	0.12	1.07	117	57
546	9	100.4	421	0.23	1.39	0.41	0.14	3.39	0.13	1.29	107	31
547	8	100.5	420	0.49	2.04	0.72	0.19	2.83	0.21	1.47	138	48
548	7	100.8	421	0.42	2.00	0.78	0.17	2.56	0.20	1.36	147	57
549	6	99.8	420	0.30	1.89	0.60	0.14	3.15	0.18	1.12	168	53
550	5	100.1	420	0.28	1.28	0.38	0.18	3.36	0.13	1.13	113	33
551	4	100.3	422	0.41	1.73	0.66	0.19	2.62	0.17	1.34	129	49
552	3	100.1	420	0.41	3.15	0.78	0.12	4.03	0.29	1.85	170	42
553	2	100.6	420	0.64	3.29	0.67	0.16	4.91	0.32	1.74	189	38
554	1	100.3	417	0.46	3.31	0.85	0.12	3.89	0.31	1.76	188	48

Well: 11-26-20-23W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
2991	100.60	0.56	4.38	0.01	0.11	0.58	421	466	0.46	0.43	2.20	1.77	200	21
2993	100.60	0.59	3.92	0.01	0.13	0.54	420	465	0.43	0.39	2.12	1.73	185	20
2998	100.70	0.16	0.99	0.00	0.14	0.22	417	462	0.26	0.11	0.58	0.47	171	45
3003	99.90	0.10	0.57	0.00	0.15	0.25	418	463	0.15	0.06	0.76	0.70	75	20
3008	100.30	0.10	0.29	0.00	0.25	0.20	422	467	0.14	0.04	0.49	0.45	59	29
3013	100.40	0.07	1.04	0.01	0.07	0.65	415	460	0.48	0.11	1.90	1.79	55	25
3018	99.80	0.10	0.27	0.00	0.27	0.22	423	468	0.10	0.03	0.51	0.48	53	20
3023	100.30	0.21	1.39	0.01	0.13	0.41	421	466	0.30	0.15	1.46	1.31	96	21
3028	100.20	0.29	2.75	0.01	0.10	0.51	423	468	0.28	0.27	1.92	1.65	144	15
3033	100.40	0.18	2.83	0.01	0.06	0.57	422	467	0.47	0.27	2.00	1.73	142	24
3038	100.60	0.17	3.24	0.01	0.05	0.53	421	466	0.39	0.30	2.03	1.73	160	19
3043	100.10	0.53	3.03	0.01	0.15	0.51	422	467	0.39	0.31	2.01	1.70	151	19
3048	100.10	0.17	2.35	0.01	0.07	0.45	423	468	0.34	0.22	1.86	1.64	127	18
3053	100.30	0.33	4.82	0.01	0.06	0.62	422	467	0.42	0.45	2.36	1.91	205	18

WELL: 11-1010-28W3

Depth (ft)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
611	100.2	417	0.38	6.41	1.85	0.06	3.46	0.56	2.84	225	65
612	100.8	417	0.37	6.39	1.94	0.05	3.29	0.56	2.77	230	70
613	100.5	415	0.59	8.78	2.50	0.06	3.51	0.78	3.30	266	75
614	100.6	421	0.31	6.14	1.90	0.05	3.23	0.53	2.79	220	68
615	100.0	415	0.35	7.20	1.82	0.05	3.95	0.62	2.94	244	61
616	100.4	410	0.45	6.73	1.51	0.06	4.45	0.59	2.62	256	57
617	100.5	419	0.27	5.22	1.77	0.05	2.94	0.45	2.49	209	71
618	100.3	416	0.33	5.23	1.65	0.06	3.16	0.46	2.58	202	63
619	100.3	418	0.49	8.72	2.23	0.05	3.91	0.76	2.93	297	76
620	100.2	418	0.44	8.55	1.97	0.05	4.34	0.74	2.96	288	66
621	100.8	415	0.33	4.40	1.72	0.07	2.55	0.39	2.26	194	76
622	100.3	417	0.46	7.07	1.77	0.06	3.99	0.62	2.59	272	68
623	100.5	415	0.63	14.85	2.70	0.04	5.50	1.29	4.08	363	66
624	100.6	423	0.34	5.07	1.49	0.06	3.40	0.45	2.18	232	68
625	100.5	413	0.83	15.77	2.82	0.05	5.59	1.38	3.94	400	71
626	100.6	419	0.56	13.10	2.40	0.04	5.45	1.13	3.74	350	64
627	100.3	417	0.27	3.98	1.54	0.06	2.58	0.35	2.08	191	74
628	100.7	417	0.49	9.70	2.06	0.05	4.70	0.84	2.91	333	70

WELL: 10-3-5-26W3

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I	H I
717	100.4	421	0.18	4.12	0.95	0.04	4.33	0.35	2.15	191	44	191
718	100.2	425	0.19	4.03	0.92	0.05	4.38	0.35	2.04	197	45	197
719	100.1	423	0.19	4.98	1.22	0.04	4.08	0.43	2.77	179	44	179
720	100.0	417	0.34	9.50	1.83	0.03	5.19	0.82	3.03	313	60	313
721	100.5	414	0.15	2.15	0.69	0.07	3.11	0.19	1.25	172	55	172
722	100.4	421	0.12	2.82	0.61	0.04	4.62	0.24	2.07	136	29	136
723	100.9	422	0.16	4.35	0.89	0.04	4.88	0.37	2.38	182	37	182
724	100.7	415	0.17	2.97	0.50	0.05	5.94	0.26	1.79	165	27	165
725	100.8	419	0.16	3.04	0.55	0.05	5.52	0.26	1.94	156	28	156
726	100.2	418	0.12	1.51	0.68	0.07	2.22	0.13	1.13	133	60	133
859	100.7	413	0.31	10.06	1.44	0.03	6.98	0.86	2.79	360	51	360
860	100.1	408	0.50	26.49	2.09	0.02	12.67	2.24	5.56	476	37	476
861	100.4	414	0.31	11.21	1.45	0.03	7.73	0.96	3.27	342	44	342
862	100.3	417	0.16	4.55	0.79	0.03	5.75	0.39	1.65	275	47	275
863	100.7	416	0.23	10.77	1.30	0.02	8.28	0.91	2.98	361	43	361
864	100.6	414	0.39	14.27	1.55	0.03	9.20	1.22	4.23	337	36	337
865	100.1	415	0.18	6.67	1.06	0.03	6.29	0.57	2.43	274	43	274
866	99.7	416	0.24	7.81	0.93	0.03	8.39	0.67	3.40	229	27	229
867	100.6	413	0.15	3.51	0.52	0.04	6.75	0.30	1.89	185	27	185
868	100.4	416	0.17	3.62	0.54	0.04	6.70	0.31	1.61	224	33	224

WELL: 10-15-17-1W4

Depth (ft)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
1707	100.6	412	1.50	15.37	1.59	0.09	9.66	1.40	3.62	424	43
1709	100.4	413	0.94	12.32	1.47	0.07	8.38	1.10	3.24	380	45
1712	100.3	413	0.97	13.73	1.93	0.07	7.11	1.22	3.59	382	53
1715	100.2	0	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0	0
1718	100.4	411	1.13	15.47	1.81	0.07	8.54	1.38	3.85	401	47
1721	100.4	412	0.95	14.34	1.89	0.06	7.58	1.27	3.98	360	47
1724	100.5	411	0.80	12.96	1.48	0.06	8.75	1.14	3.36	385	44
1727	100.4	413	0.99	11.58	1.71	0.08	6.77	1.04	3.27	354	52
1730	100.5	418	0.74	6.89	1.42	0.10	4.85	0.63	2.51	274	56
1733	100.3	419	0.91	7.78	1.53	0.10	5.08	0.72	2.71	287	56
1736	100.8	418	1.24	7.35	1.21	0.14	6.07	0.71	2.33	315	51
1739	100.3	414	1.24	7.62	1.40	0.14	5.44	0.73	2.50	304	56
1742	100.0	420	0.68	5.31	1.18	0.11	4.50	0.49	2.32	228	50
1745	100.5	417	0.58	2.51	0.79	0.19	3.17	0.25	1.44	174	54
1748	100.4	417	0.35	0.90	0.53	0.28	1.69	0.10	0.81	111	65
1751	100.3	419	0.87	3.22	0.88	0.21	3.65	0.34	1.78	180	49
1757	100.4	421	0.29	0.48	0.32	0.38	1.50	0.06	0.59	81	54
1760	99.8	418	0.68	1.45	0.59	0.32	2.45	0.17	1.10	131	53

Well: 10-1-16-5W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
1465	100.6	10.88	26.57	0.00	0.29	0.69	341	384	0.34	3.12	4.58	1.46	580	7
1466	100.0	0.35	1.66	0.00	0.17	0.66	418	461	0.37	0.18	1.29	1.11	129	29
1469	100.1	0.14	1.22	0.00	0.10	0.86	421	464	0.43	0.13	1.37	1.24	89	31
1472	100.5	0.11	2.01	0.00	0.05	1.09	419	462	0.60	0.20	1.85	1.65	109	32
1475	100.0	0.07	1.06	0.00	0.06	0.67	423	466	0.37	0.11	1.30	1.19	82	28
1478	100.3	0.09	1.83	0.00	0.05	1.40	423	466	0.37	0.18	1.75	1.57	105	21
1481	99.9	0.04	0.54	0.00	0.07	0.56	423	466	0.27	0.06	0.98	0.92	55	28
9107	99.9	0.87	11.56	0.05	0.07	0.72	439	482	0.28	1.05	4.95	3.90	235	6
1484	100.4	0.06	0.53	0.00	0.10	0.63	423	466	0.30	0.06	1.06	1.00	50	28
1487	100.5	0.10	0.99	0.00	0.09	0.73	417	460	0.46	0.11	1.33	1.22	74	35

Well: 10-10-15-4W4

Depth (ft)	Qty (mg)	S1	S2	S'2	PI	S3CO2	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO
1600	100.5	0.08	0.64	0.00	0.11	0.65	422	465	0.34	0.07	1.23	1.16	52	28
1603	99.8	0.11	0.78	0.00	0.13	0.65	421	464	0.34	0.09	1.21	1.12	64	28
1606	100.7	0.10	0.88	0.00	0.10	0.63	423	466	0.30	0.09	1.15	1.06	77	26
1612	100.3	0.09	0.51	0.00	0.15	0.49	422	465	0.19	0.06	0.97	0.91	53	20
1615	100.2	0.13	1.71	0.00	0.07	1.51	424	467	0.36	0.17	1.32	1.15	130	27
1618	100.0	0.08	1.07	0.00	0.07	0.68	422	465	0.40	0.11	1.35	1.24	79	30
1621	100.4	0.10	1.28	0.00	0.08	0.75	422	465	0.46	0.13	1.46	1.33	88	32
1624	100.7	0.11	1.11	0.00	0.09	0.64	422	465	0.34	0.12	1.39	1.27	80	24
1699	100.8	0.10	0.98	0.00	0.09	0.79	423	466	0.35	0.10	1.28	1.18	77	27

Well 16-4-22-15W4 (page 1/5)

Depth (m)	Qty (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
426	100.00	443	0.04	0.14	0.47	0.22	0.29	0.01	0.68	20	69
430	100.20	425	0.09	0.32	1.55	0.22	0.20	0.03	0.89	35	174
439	100.40	425	0.10	0.44	0.82	0.19	0.53	0.04	0.82	53	100
440	100.00	424	0.14	0.57	0.48	0.20	1.18	0.05	1.02	55	47
441	100.30	425	0.13	0.48	0.49	0.22	0.97	0.05	0.98	48	50
442	99.80	424	0.09	0.37	0.48	0.20	0.77	0.03	0.99	37	48
443	100.30	422	0.26	0.81	0.47	0.25	1.72	0.08	1.04	77	45
444	101.00	423	0.50	0.72	0.39	0.41	1.84	0.10	0.97	74	40
445	100.20	420	0.26	0.62	0.51	0.30	1.21	0.07	1.07	57	47
446	100.20	416	0.21	1.16	0.67	0.15	1.73	0.11	1.39	83	48
447	100.60	416	0.17	0.76	0.60	0.18	1.26	0.07	1.02	74	58
448	101.10	419	0.09	0.61	0.86	0.13	0.70	0.05	1.05	58	81
449	100.50	419	0.13	1.02	0.86	0.11	1.18	0.09	1.30	78	66
450	100.90	423	0.12	1.13	0.93	0.10	1.21	0.10	1.34	84	69
451	100.30	423	0.16	1.41	1.03	0.10	1.36	0.13	1.36	103	75
452	100.70	423	0.28	1.32	0.62	0.17	2.12	0.13	1.29	102	48
453	100.30	415	0.20	2.09	0.63	0.09	3.31	0.19	1.42	147	44
454	100.90	420	0.19	1.29	0.67	0.13	1.92	0.12	1.18	109	56
455	100.30	414	0.21	3.79	0.89	0.05	4.25	0.33	1.87	202	47
456	100.00	412	0.28	2.77	0.78	0.09	3.55	0.25	1.74	159	44
457	100.30	407	0.11	2.42	1.49	0.04	1.62	0.21	2.00	121	74
458	100.00	414	0.25	4.80	1.21	0.05	3.96	0.42	2.39	200	50
459	100.00	413	0.30	5.27	1.43	0.05	3.68	0.46	2.37	222	60
460	100.50	418	0.18	2.96	0.76	0.06	3.89	0.26	1.29	229	58
461	100.80	417	0.39	6.62	1.82	0.06	3.63	0.58	2.74	241	66
462	100.20	405	0.13	3.68	1.48	0.03	2.48	0.31	2.35	156	62
463	100.40	414	0.25	5.30	1.60	0.05	3.31	0.46	2.38	222	67
464	99.70	408	0.35	4.82	1.23	0.07	3.91	0.43	2.48	194	49
465	100.40	414	0.25	4.36	1.51	0.05	2.88	0.38	2.34	186	64

466	100.80	410	0.38	6.25	1.48	0.06	4.22	0.55	2.69	232	55

Well 16-4-22-15W4 (page 2/5)

Depth (m)	Qty (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
467	100.30	410	0.81	8.59	1.77	0.09	4.85	0.78	3.04	282	58
468	100.60	410	0.48	8.45	1.74	0.05	4.85	0.74	3.11	271	55
469	100.90	411	0.69	9.85	1.78	0.07	5.53	0.87	3.24	304	54
470	101.00	411	0.21	6.35	1.54	0.03	4.12	0.54	2.70	235	57
471	100.30	409	0.26	7.08	1.87	0.04	3.78	0.61	2.90	244	64
472	99.60	403	0.16	5.74	1.70	0.03	3.37	0.49	2.87	200	59
473	99.60	402	0.11	3.28	1.68	0.03	1.95	0.28	2.20	149	76
474	100.00	409	0.60	9.71	2.16	0.06	4.49	0.85	3.36	288	64
475	101.20	411	0.21	3.16	1.36	0.06	2.32	0.28	2.07	152	65
476	100.60	412	0.19	4.15	1.39	0.04	2.98	0.36	2.37	175	58
477	101.30	412	0.35	4.04	1.21	0.08	3.33	0.36	2.10	192	57
478	100.00	412	0.24	7.74	1.72	0.03	4.50	0.66	2.43	318	70
479	100.20	403	0.14	4.84	1.77	0.03	2.73	0.41	2.45	197	72
480	99.80	410	0.16	4.21	1.55	0.04	2.71	0.36	2.28	184	67
481	100.70	408	0.11	3.68	1.23	0.03	2.99	0.31	2.26	162	54
482	100.30	402	0.15	6.39	2.01	0.02	3.17	0.54	3.25	196	61
483	99.90	407	0.17	2.60	1.62	0.06	1.60	0.23	2.27	114	71
484	100.60	409	0.14	3.81	1.88	0.04	2.02	0.32	2.58	147	72
485	100.50	417	0.17	3.41	1.26	0.05	2.70	0.29	1.86	183	67
486	100.40	419	0.02	0.62	0.61	0.03	1.01	0.05	0.90	68	67
487	100.10	421	0.04	0.89	0.84	0.04	1.05	0.07	1.07	83	78
488	100.50	420	0.04	0.85	0.63	0.05	1.34	0.07	0.94	90	67
489	99.90	418	0.06	1.22	0.81	0.05	1.50	0.10	1.31	93	61
490	99.90	419	0.06	1.17	0.79	0.05	1.48	0.10	1.15	101	68
491	100.70	420	0.16	3.67	1.66	0.04	2.21	0.31	2.25	163	73
492	100.90	418	0.19	2.17	0.92	0.08	2.35	0.19	1.76	123	52
493	100.50	418	0.15	1.54	0.84	0.09	1.83	0.14	1.38	111	60
494	100.30	421	0.09	0.77	0.72	0.10	1.06	0.07	1.26	61	57
495	100.00	418	0.12	0.82	0.77	0.13	1.06	0.07	1.28	64	60

Well 16-4-22-15W4 (page 3/5)

Depth (m)	Qty (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
496	101.20	422	0.05	0.70	0.70	0.07	1.00	0.06	1.18	59	59
497	100.30	423	0.11	0.82	0.76	0.12	1.07	0.07	1.22	67	62
498	100.30	419	0.12	0.95	0.83	0.11	1.14	0.08	1.34	70	61
499	100.30	421	0.12	1.00	0.69	0.11	1.44	0.09	1.20	83	57
500	100.40	418	0.04	1.11	0.67	0.04	1.65	0.09	1.19	93	56
501	99.70	419	0.13	1.73	0.89	0.07	1.94	0.15	1.75	98	50
502	100.20	420	0.17	1.06	0.70	0.14	1.51	0.10	1.30	81	53
503	100.00	421	0.16	1.18	0.53	0.12	2.22	0.11	1.13	104	46
504	100.30	418	0.13	1.33	0.62	0.09	2.14	0.12	1.29	103	48
505	100.70	420	0.06	0.58	0.40	0.09	1.45	0.05	0.74	78	54
506	100.70	418	0.06	0.67	0.45	0.08	1.48	0.06	0.71	94	63
507	101.10	415	0.09	1.87	0.71	0.05	2.63	0.16	1.49	125	47
508	100.40	416	0.23	2.38	0.74	0.09	3.21	0.21	1.60	148	46
509	100.60	418	0.09	2.02	0.71	0.04	2.84	0.17	1.47	137	48
510	100.80	418	0.07	1.41	0.54	0.05	2.61	0.12	1.19	118	45
511	100.20	413	0.20	2.98	1.03	0.06	2.89	0.26	1.85	161	55
512	100.10	424	0.17	1.35	0.79	0.11	1.70	0.12	1.30	103	60
513	99.60	422	0.17	1.22	0.70	0.12	1.74	0.11	1.22	100	57
514	100.10	417	0.10	0.54	0.68	0.16	0.79	0.05	0.91	59	74
515	100.80	421	0.03	0.34	0.47	0.08	0.72	0.03	0.80	42	58
516	100.50	422	0.09	0.65	0.47	0.12	1.38	0.06	1.01	64	46
517	100.60	421	0.04	0.46	0.50	0.08	0.92	0.04	0.92	50	54
518	99.80	424	0.06	0.50	0.71	0.11	0.70	0.04	0.94	53	75
519	101.00	424	0.06	0.65	0.54	0.09	1.20	0.05	0.98	66	55
520	100.50	419	0.03	0.38	0.49	0.07	0.77	0.03	0.93	40	52
521	100.10	419	0.46	1.49	1.27	0.24	1.17	0.16	1.35	110	94
522	100.30	421	0.15	0.75	0.92	0.17	0.81	0.07	1.02	73	90
523	100.60	422	0.15	0.73	0.68	0.17	1.07	0.07	1.01	72	67
524	100.20	421	0.04	0.62	0.49	0.06	1.26	0.05	0.90	68	54

Well 16-4-22-15W4 (page 4/5)

Depth (m)	Qty (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
525	101.20	418	0.05	0.56	1.00	0.08	0.56	0.05	1.01	55	99
526	100.90	422	0.13	1.03	0.86	0.11	1.19	0.09	1.27	81	67
527	101.10	416	0.04	0.35	1.11	0.11	0.31	0.03	1.07	32	103
528	100.40	422	0.15	0.96	0.91	0.14	1.05	0.09	1.17	82	77
529	100.70	422	0.11	0.82	0.60	0.12	1.36	0.07	1.16	70	51
531.25	100.20	417	0.38	1.01	0.63	0.28	1.60	0.11	1.01	100	62
532	99.70	419	1.06	1.26	0.60	0.46	2.10	0.19	1.34	94	44
533	100.30	421	0.69	1.09	0.55	0.39	1.98	0.14	1.21	90	45
534	100.00	421	0.69	1.07	0.63	0.39	1.69	0.14	1.21	88	52
535	99.70	424	0.32	0.68	0.46	0.32	1.47	0.08	0.98	69	46
536	100.60	422	0.26	0.79	0.45	0.25	1.75	0.08	1.17	67	38
537	100.40	419	0.25	0.76	0.49	0.25	1.55	0.08	1.22	62	40
538	99.80	414	0.84	0.58	0.48	0.59	1.20	0.11	0.96	60	50
539	100.00	420	0.14	0.98	0.50	0.12	1.96	0.09	1.30	75	38
540	100.60	409	0.32	3.40	1.18	0.09	2.88	0.31	2.36	144	50
541	100.70	418	0.52	3.83	0.98	0.12	3.90	0.36	2.03	188	48
542	100.80	418	0.32	2.75	0.86	0.10	3.19	0.25	1.96	140	43
543	100.10	412	0.17	3.35	1.34	0.05	2.50	0.29	2.52	132	53
544	100.20	423	0.37	1.57	0.81	0.19	1.93	0.16	1.52	103	53
545	100.60	422	0.19	1.27	0.78	0.13	1.62	0.12	1.36	93	57
545.3	100.50	0	0.07	0.00	0.26	1.00	0.00	0.00	0.08	0	325
546	99.80	409	0.12	1.22	0.94	0.09	1.29	0.11	1.68	72	55
547	101.10	415	0.05	0.28	0.87	0.16	0.32	0.02	0.80	35	108
548	100.60	413	0.09	0.55	0.98	0.14	0.56	0.05	1.27	43	77
549	101.20	426	0.35	1.58	0.73	0.18	2.16	0.16	1.09	144	66
550	100.20	420	0.29	0.91	0.77	0.24	1.18	0.10	1.36	66	56
551	100.30	416	0.12	0.72	0.79	0.14	0.91	0.07	1.37	52	57
552	99.90	421	0.08	0.61	0.64	0.12	0.95	0.05	1.31	46	48
553	100.60	421	0.03	0.47	0.45	0.06	1.04	0.04	0.91	51	49

Well 16-4-22-15W4 (page 5/5)

Depth (m)	Qty (mg)	Tmax	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I
554	99.80	421	0.08	0.57	0.53	0.12	1.07	0.05	1.13	50	46
555	100.00	418	0.09	1.71	0.84	0.05	2.03	0.15	1.91	89	43
556	101.00	424	0.19	1.80	0.62	0.10	2.90	0.16	1.50	120	41
557	100.70	418	0.11	1.21	0.69	0.08	1.75	0.11	1.58	76	43
558	100.70	423	0.26	1.63	0.60	0.14	2.71	0.15	1.54	105	38
559	100.80	421	0.13	1.33	0.70	0.09	1.90	0.12	1.65	80	42
560	99.80	425	0.33	1.00	0.54	0.25	1.85	0.11	1.19	84	45
561	100.50	422	0.25	1.73	0.56	0.13	3.08	0.16	1.53	113	36
562	100.10	420	0.09	1.30	0.62	0.07	2.09	0.11	1.37	94	45
563	100.40	417	0.11	1.42	0.77	0.07	1.84	0.12	1.75	81	44
564	100.60	424	0.18	1.67	0.56	0.10	2.98	0.15	1.44	115	38
565	100.20	416	0.05	0.83	0.74	0.06	1.12	0.07	1.35	61	54
566	100.20	421	0.17	2.99	0.77	0.05	3.88	0.26	1.82	164	42
567	100.10	422	0.16	0.90	0.46	0.15	1.95	0.08	0.89	101	51
568	100.40	420	0.21	1.52	0.46	0.12	3.30	0.14	1.22	124	37

WELL: 6-3-24-13W4 (page 1 of 2)

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I
459.2	100.3	410	3.31	4.91	0.99	0.40	4.95	0.68	2.21	222
460	99.6	415	2.87	5.45	0.92	0.34	5.92	0.69	2.29	237
461	100.4	415	4.34	5.95	1.40	0.42	4.25	0.85	2.81	211
462	100.8	416	2.98	5.48	1.06	0.35	5.16	0.70	2.49	220
463	100.1	414	2.63	4.97	0.93	0.35	5.34	0.63	2.34	212
464	101.0	413	4.58	5.12	1.12	0.47	4.57	0.80	2.55	200
465	100.6	414	3.86	9.64	1.29	0.29	7.47	1.12	3.16	305
465.4	101.0	417	3.14	3.59	0.85	0.47	4.22	0.56	2.03	176
465.8	100.2	418	1.97	1.84	0.69	0.52	2.66	0.31	1.38	133
466	100.2	415	1.96	2.26	0.66	0.46	3.42	0.35	1.54	146
467	100.0	416	5.84	2.44	0.73	0.71	3.34	0.69	1.74	140
468	100.4	415	1.99	2.10	0.73	0.49	2.87	0.34	1.73	121
469	100.0	418	1.83	1.14	0.54	0.62	2.11	0.24	1.25	91
470	100.6	417	2.21	2.21	0.79	0.50	2.79	0.36	1.63	135
471	100.4	419	2.59	1.89	0.66	0.58	2.86	0.37	1.67	113
472	100.3	418	2.67	4.51	1.08	0.37	4.17	0.59	2.33	193
472.7	100.2	418	3.13	4.30	0.98	0.42	4.38	0.61	2.30	186
473	100.7	417	2.77	1.52	0.55	0.65	2.76	0.35	1.30	116
474	100.6	419	1.82	1.69	0.56	0.52	3.01	0.29	1.43	118
475	99.6	419	2.40	2.10	0.66	0.53	3.18	0.37	1.58	132
476	100.1	416	2.01	1.50	0.47	0.57	3.19	0.29	1.25	120
477	100.4	421	2.55	2.81	0.66	0.48	4.25	0.44	1.72	163
478	100.6	417	1.99	2.66	0.84	0.43	3.16	0.38	1.68	158
479	101.1	419	2.36	1.61	0.51	0.60	3.15	0.33	0.33	487
480	101.0	418	2.89	3.09	0.64	0.48	4.82	0.49	1.77	174
481	100.0	420	2.19	1.81	0.52	0.55	3.48	0.33	1.42	127
482	100.4	419	3.20	2.74	0.66	0.54	4.15	0.49	1.73	158
483	100.1	418	2.99	1.77	0.54	0.63	3.27	0.39	1.58	112
484	101.0	419	1.97	1.54	0.48	0.56	3.20	0.29	1.35	114

485	99.8	425	1.96	1.32	0.50	0.60	2.64	0.27	1.32	100

WELL: 6-3-24-13W4 (page 2 of 2)

Depth (m)	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I
486	101.2	424	1.80	1.10	0.54	0.62	2.03	0.24	1.30	84
487	100.4	425	2.32	1.10	0.53	0.68	2.07	0.28	1.36	80
500.15	100.1	426	3.45	1.10	0.55	0.76	2.00	0.37	1.61	68
501	99.7	426	2.98	0.65	0.56	0.82	1.16	0.30	1.30	50
502	100.2	424	2.68	0.68	0.48	0.80	1.41	0.28	1.23	55
503	100.5	424	2.56	1.54	0.86	0.62	1.79	0.34	1.55	99
504	100.5	418	2.54	0.63	0.39	0.80	1.61	0.26	1.16	54
505	100.8	422	3.15	1.45	0.76	0.68	1.90	0.38	1.54	94
506	100.3	421	2.99	2.02	0.79	0.60	2.55	0.41	1.74	116
507	100.6	423	2.33	0.72	0.49	0.77	1.46	0.25	1.12	64
508	100.1	422	3.08	1.30	0.53	0.70	2.45	0.36	1.45	89
509	100.2	420	3.01	1.07	0.54	0.74	1.98	0.34	1.40	76
510	100.5	422	2.18	1.15	0.45	0.66	2.55	0.27	1.03	111
511	100.4	419	2.21	1.21	0.58	0.65	2.08	0.28	1.09	111
512	100.1	421	2.14	1.12	0.46	0.66	2.43	0.27	1.09	102
513	100.1	423	2.88	1.06	0.50	0.73	2.12	0.32	1.17	90
514	99.7	420	2.66	1.47	0.55	0.65	2.67	0.34	1.39	105
515	100.2	423	3.64	1.49	0.65	0.71	2.29	0.42	1.56	95
516	99.9	422	2.95	1.32	0.67	0.69	1.97	0.35	1.48	89
517	100.5	422	1.94	2.07	0.99	0.48	2.09	0.33	1.68	123
518	100.5	423	3.09	2.54	0.99	0.55	2.56	0.46	1.84	138
519	101.2	416	1.73	1.28	0.81	0.58	1.58	0.25	1.56	82
520	100.2	421	1.83	0.68	0.59	0.73	1.15	0.20	0.94	72

Deer Creek samples, SWEETGRASS HILLS. From outcrop 1 to outcrop 11, sample interval 1 m (page 1/4)

SAMPLE ID.	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I	H I
outcrop 1 1	99.9	437.0	0.63	0.65	0.60	0.49	1.08	0.10	1.91	34	31	34
2	100.4	454.0	0.07	0.23	0.58	0.23	0.39	0.02	0.40	57	145	57
3	100.7	451.0	0.95	2.32	1.52	0.29	1.52	0.27	3.06	75	49	75
4	100.3	438.0	0.35	1.33	1.01	0.21	1.31	0.14	1.55	85	65	85
5	100	447.0	0.21	1.20	2.58	0.15	0.46	0.11	3.07	39	84	39
6	101	441.0	0.21	0.82	1.21	0.21	0.67	0.08	1.39	58	87	58
7	100.3	445.0	1.08	3.16	1.65	0.25	1.91	0.35	4.61	68	35	68
8	100.9	467.0	0.01	0.20	1.52	0.05	0.13	0.01	0.91	21	167	21
9	100.3	447.0	0.92	3.12	1.15	0.23	2.71	0.33	3.82	81	30	81
10	100	453.0	0.03	0.22	0.91	0.12	0.24	0.02	0.71	30	128	30
11	101.1	449	0.92	1.44	0.58	0.39	2.48	0.19	2.47	58	23	58
12	100	449	1.17	2.21	0.27	0.35	8.18	0.28	2.42	91	11	91
13	100.1	446	1.49	2.19	0.57	0.4	3.84	0.3	2.55	85	22	85
14	100.3	444	1.06	1.91	0.33	0.36	5.78	0.24	2.65	72	12	72
15	100.4	447	0.76	1.81	0.25	0.3	7.24	0.21	2.37	76	10	76
16	100.3	447	0.73	1.39	0.26	0.34	5.34	0.17	2.09	66	12	66
17	100.4	450	0.72	1.3	0.12	0.36	10.83	0.16	1.66	78	7	78
18	100.4	451	0.73	1.72	0.18	0.3	9.55	0.2	2.09	82	8	82
19	100.3	446	0.97	1.83	0.29	0.35	6.31	0.23	2.37	77	12	77
20	100.5	451	0.65	0.98	0.37	0.4	2.64	0.13	1.63	60	22	60
21	100.5	440	0.49	1.27	0.36	0.28	3.52	0.14	2.19	57	16	57
22	100.7	445	0.56	1.25	0.3	0.31	4.16	0.15	2.08	60	14	60
23	100.5	445	0.84	1.56	0.35	0.35	4.45	0.2	2.21	70	15	70
24	100.3	443	0.46	1.11	0.51	0.29	2.17	0.13	2.28	48	22	48
25	100.9	445	0.01	0.22	1.04	0.05	0.21	0.01	2.26	9	46	9
26	100.4	439	0.45	1.07	0.59	0.3	1.81	0.12	2.39	44	24	44
27	100.3	436	0.37	0.92	0.72	0.29	1.27	0.1	2.21	41	32	41
28	101	447	0.07	0.42	1.02	0.15	0.41	0.04	1.69	24	60	24
29	100.4	453	1.87	2.27	0.2	0.45	11.35	0.34	1.96	115	10	115

Deer Creek samples, SWEETGRASS HILLS. From outcrop 1 to outcrop 11, sample interval 1 m(page 2/4)

SAMPLE ID.	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I	H I
30	101.2	443	2.4	1.55	0.14	0.61	11.07	0.32	1.98	78	7	78
31	100.1	448	0.91	1.85	0.15	0.33	12.33	0.23	2.34	79	6	79
32	99.7	458	0.37	0.75	0.46	0.33	1.63	0.09	1.68	44	27	44
33	99.9	452	0.71	1.86	0.21	0.28	8.85	0.21	2.17	85	9	85
34	99.8	451	1.22	2.1	0.11	0.37	19.09	0.27	2.29	91	4	91
35	100.1	449	0.86	1.8	0.17	0.32	10.58	0.22	2.03	88	8	88
36	100.5	450	0.65	1.45	0.35	0.31	4.14	0.17	2.18	66	16	66
37	100.7	450	1.03	1.84	0.16	0.36	11.5	0.23	2.1	87	7	87
38	100.9	449	1.03	2.17	0.2	0.32	10.85	0.26	2.33	93	8	93
39	100.6	449	1.1	1.76	0.17	0.38	10.35	0.23	2.05	85	8	85
40	99.9	448	1.09	1.95	0.38	0.36	5.13	0.25	2.15	90	17	90
41	100.3	442	0.71	1.79	0.52	0.28	3.44	0.2	2.72	65	19	65
42	99.9	443	1.2	2.35	0.32	0.34	7.34	0.29	2.49	94	12	94
43	100.1	443	1.26	2.91	0.24	0.3	12.12	0.34	2.63	110	9	110
44	99.9	445	1.06	2.12	0.31	0.33	6.83	0.26	2.43	87	12	87
45	101.3	448	1.05	2.16	0.24	0.33	9	0.26	2.08	103	11	103
46	99.6	442	0.8	1.95	0.39	0.29	5	0.22	2.32	84	16	84
47	100.2	442	0.62	1.6	0.38	0.28	4.21	0.18	2.06	77	18	77
48	100	454	0.2	0.57	0.25	0.26	2.28	0.06	1.36	41	18	41
49	100.1	489	0.02	0.14	0.65	0.12	0.21	0.01	0.8	17	81	17
50	100.5	448	0.16	0.53	0.17	0.24	3.11	0.05	1.37	38	12	38
51	100.1	449	0.26	0.75	0.37	0.26	2.02	0.08	1.59	47	23	47
52	100.5	449	0.24	0.77	0.17	0.24	4.52	0.08	1.39	55	12	55
53	100.2	446	0.19	0.64	0.25	0.23	2.56	0.06	1.56	41	16	41
54	100.7	448	0.24	0.69	0.28	0.26	2.46	0.07	1.62	42	17	42
55	100.5	443	0.22	0.73	0.24	0.23	3.04	0.07	1.7	42	14	42
56	99.7	448	0.3	0.98	0.21	0.23	4.66	0.1	1.78	55	11	55
57	99.9	447	0.28	0.82	0.14	0.25	5.85	0.09	1.56	52	8	52
58	101.2	447	0.15	0.44	0.34	0.26	1.29	0.04	1.39	31	24	31

Deer Creek samples, SWEETGRASS HILLS. From outcrop 1 to outcrop 11, sample interval 1 m (page 3/4)

SAMPLE ID.	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I	H I
60	99.8	455	0.07	0.48	0.34	0.13	1.41	0.04	1.31	36	25	36
61	100	484	0.06	0.09	0.42	0.43	0.21	0.01	0.58	15	72	15
62	100.4	454	0.1	0.51	0.1	0.17	5.1	0.05	1.37	37	7	37
63	100.3	450	0.23	1.06	0.13	0.18	8.15	0.1	1.74	60	7	60
64	100.7	469	0.01	0.18	0.33	0.06	0.54	0.01	0.82	21	40	21
65	100.6	448	0.11	0.54	0.1	0.17	5.4	0.05	1.22	44	8	44
66	100.6	447	0.11	0.6	0.11	0.16	5.45	0.05	1.27	47	8	47
67	99.7	446	0.07	0.41	0.19	0.15	2.15	0.04	1.23	33	15	33
68	100.8	490	0.01	0.13	0.09	0.07	1.44	0.01	0.75	17	12	17
69	101	481	0.02	0.16	0.12	0.11	1.33	0.01	0.74	21	16	21
70	100.8	494	0.01	0.08	0.43	0.12	0.18	0	0.74	10	58	10
71	100	449	0.11	0.57	0.2	0.16	2.85	0.05	1.44	39	13	39
72	100.6	448	0.32	1.51	0.2	0.18	7.55	0.15	2.05	73	9	73
73	101.2	452	0.22	1.02	0.18	0.18	5.66	0.1	1.87	54	9	54
74	100.3	453	0.14	0.56	0.18	0.2	3.11	0.05	1.34	41	13	41
75	101	445	0.56	1.94	0.17	0.22	11.41	0.2	2.24	86	7	86
76	100.1	454	0.18	0.61	0.11	0.23	5.54	0.06	1.32	46	8	46
77	100.5	451	0.14	0.47	0.11	0.23	4.27	0.05	1.07	43	10	43
78	99.8	449	0.12	0.37	0.13	0.25	2.84	0.04	1.05	35	12	35
79	100.1	442	0.11	0.48	0.13	0.19	3.69	0.04	1.06	45	12	45
80	100	450	0.2	0.74	0.17	0.21	4.35	0.07	1.32	56	12	56
81	101	445	0.39	0.5	0.1	0.44	5	0.07	0.75	66	13	66
82	99.6	437	0.23	0.78	0.22	0.23	3.54	0.08	1.7	45	12	45
83	99.8	447	0.48	2.06	0.15	0.19	13.73	0.21	2.12	97	7	97
84	100.6	441	0.8	2.77	0.2	0.22	13.85	0.29	2.51	110	7	110
85	100.7	444	0.61	2.18	0.17	0.22	12.82	0.23	2.18	100	7	100
86	101	445	0.24	0.73	0.3	0.25	2.43	0.08	1.6	45	18	45
87	100.3	442	0.25	0.78	0.3	0.25	2.6	0.08	1.52	51	19	51
88	100.3	446	0.21	0.89	0.17	0.19	5.23	0.09	1.5	59	11	59

Deer Creek samples, SWEETGRASS HILLS. From outcrop 1 to outcrop 11, sample interval 1 m (page 4/4)

SAMPLE ID.	QTY (mg)	TMAX	S 1	S 2	S 3	P I	S2/S3	P C	TOC	H I	O I	H I
89	100.2	441	0.25	0.89	0.14	0.22	6.35	0.09	1.35	65	10	65
90	100.8	439	0.12	0.44	0.26	0.21	1.69	0.04	0.94	46	27	46
91	99.8	442	0.44	1.72	0.18	0.2	9.55	0.18	1.73	99	10	99
92	100.5	443	0.51	1.52	0.54	0.25	2.81	0.16	1.86	81	29	81
93	100.4	445	0.48	1.69	0.98	0.22	1.72	0.18	2.19	77	44	77
94	100.8	449	0.05	0.34	0.9	0.13	0.37	0.03	0.48	70	187	70
95	100.2	441	0.54	2.47	0.55	0.18	4.49	0.25	2	123	27	123
96	99.7	442	0.45	1.71	0.45	0.21	3.8	0.18	1.71	100	26	100
97	100.1	441	0.11	0.71	0.59	0.13	1.2	0.06	1	71	59	71
98	99.7	439	0.21	0.94	0.62	0.18	1.51	0.09	1.38	68	44	68
99	99.8	446	0.29	1.2	0.46	0.2	2.6	0.12	1.45	82	31	82
100	100.1	445	0.03	0.35	0.75	0.08	0.46	0.03	0.73	47	102	47
101	100.3	446	0.08	0.41	1.11	0.17	0.36	0.04	1.14	35	97	35
102	100.7	438	0.28	0.86	0.39	0.25	2.2	0.09	1.07	80	36	80
103	100.4	440	0.21	0.73	0.12	0.22	6.08	0.07	1.14	64	10	64
104	99.8	445	0.09	0.41	0.71	0.18	0.57	0.04	1.04	39	68	39
105	101	443	0.06	0.37	0.38	0.14	0.97	0.03	0.87	42	43	42
106	100.3	445	0.06	0.53	1	0.1	0.53	0.04	0.86	61	116	61
outcrop. 11 107	99.6	446	0.02	0.17	0.84	0.11	0.2	0.01	0.72	23	116	23

Ghost Dam Spillway, west of Calgary. Medicine Hat Member outcrop analogue and First White Specks Member

Sample*	Qty (mg)	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	Sample	HI	OI
6.5	100.7	439	0.08	0.36	0.30	0.18	1.20	0.04	6.5	44	37
9	100.1	439	0.09	0.37	0.43	0.20	0.86	0.05	9	44	51
11	100.2	437	0.07	0.26	0.31	0.20	0.84	0.03	11	41	49
14.5	100.4	439	0.22	1.18	0.60	0.16	1.97	0.12	14.5	87	44
17.5	100.0	437	0.31	1.41	0.48	0.18	2.94	0.15	17.5	89	30
19	100.1	439	0.27	1.80	0.21	0.13	8.57	0.18	19	118	14
21	100.4	438	0.16	1.12	0.24	0.13	4.67	0.11	21	84	18

*: Metres from the bottom of the outcrop

APPENDIX B

SEDIMENTARY LOGS OF CORES FROM THE SUBSURFACE OF SOUTHERN ALBERTA AND SOUTHWESTERN SASKATCHEWAN

Legend

Planar Tabular Cross Bedding\ lamination

Coal fragment

Pebbles

Ammonite

Osters

Fish remains or scales

Dewatering

Ripples symmetrical
asymmetrical

Bioturbation slight
intense

Concretion

Fault

Normal graded fine lamination

Normal graded bedding

Shells undiff. convex
concave

Shell debris layer

Shell fragm.

Low angled paralle lamination (hummocky)

Parallel lamination

Lenticular bedding with or without mud drap

Cone on Cone structure

Bentonite xxxxxx

Pyrite Py

Siderite Sid

Trace Fossils

Terebellina

Skolithos

Zoophycos

Teichichnus

Planolites

Chondrites

Gordia

Escape structure

Siphonites

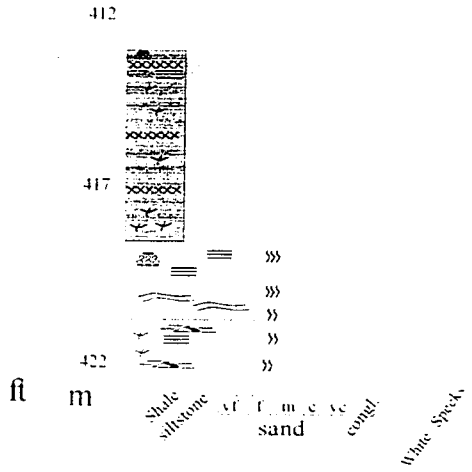
APPENDIX 2-I

CORE LOCATION	Stratigraphic Interval										Geoche.	Micropal.	Nannofossils	Petrology
Alberta Core	Milk R	FW	Med.	Hat		Verger		Carlile		SwsF				
00/02-09-017-10W4-0											no	yes	no	no
00/04-08-013-27W4-0											yes	yes	yes	yes
00/04-14-008-07W4-0											no	no	no	yes
00/05-03-027-14W4-0											no	no	no	no
00/06-03-024-13W4-0											yes	no	no	no
00/06-05-015-02W4-0											no	no	no	no
00/06-05-019-01W4-0											no	no	no	no
00/06-07-015-02W4-0											no	no	no	no
00/06-08-026-19W4-0											yes	yes	yes	yes
00/06-10-010-08W4-0											no	no	no	no
00/06-10-013-07W4-0											no	no	no	yes
00/06-10-019-14W4-0											no	no	no	yes
00/06-12-013-04W4-0											yes	no	no	no
00/06-23-023-22W4-0											no	no	no	yes
00/06-32-011-20W4-0											no	no	no	no
00/06-35-016-03W4-0											no	no	no	no
00/06-36-020-25W4-0											no	no	no	no
00/07-01-029-19W4-0											no	no	no	no
00/07-09-012-21W4-0											no	no	no	no
00/07-10-014-06W4-0											no	no	no	no
00/07-17-003-07W4-0											no	no	no	no
00/07-19-015-03W4-0											no	no	no	no
00/07-20-011-06W4-0											no	no	no	no
00/07-25-013-01W4-0											no	no	no	yes
00/07-27-020-03W4-0											no	no	no	yes
00/08-06-026-17W4-0											no	no	no	no
00/08-15-019-15W4-0											no	no	no	no
00/08-26-017-14W4-0											yes	no	no	no
00/09-30-014-04W4-0											no	no	no	no
00/10-01-016-05W4-0											no	no	no	no
00/10-10-015-04W4-0											no	no	no	yes
00/10-11-012-04W4-0											no	no	no	no
00/10-13-011-23W4-0											yes	yes	yes	no
00/10-14-015-04W4-0											no	no	no	no
00/10-15-017-01W4-0											yes	yes	yes	no
00/10-17-019-02W4-0											no	no	no	yes
00/10-26-015-04W4-0											no	no	no	yes
00/10-27-012-02W4-0											no	no	no	yes
00/10-28-015-03W4-0											no	no	no	no
00/10-29-011-05W4-0											nn	no	no	no
00/11-11-016-09W4-0											no	no	no	no
00/11-15-012-05W4-0											no	no	no	no
00/11-26-020-23W4-0											yes	no	no	no
00/11-33-016-01W4-0											no	no	no	no

CORE LOCATION	Stratigraphic Interval	Geoche.	Micropal.	Nannofossils	Petrology
Alberta Core	Milk R. FW. Med. Hat Verger Carlile SwsF				
00/13-20-017-07W4-0		yes	yes	yes	no
00/14-23-019-15W4-0		no	no	no	no
00/14-26-019-08W4-0		no	no	no	yes
00/14-36-013-04W4-0		yes	yes	yes	no
00/16-04-022-15W4-0		yes	yes	yes	no
00/16-18-013-07W4-0		no	no	no	no
00/16-20-024-21W4-0		no	no	no	no
00/16-23-012-04W4-0		no	no	no	no
00/16-28-014-02W4-0		yes	yes	no	no
02/03-07-013-27W4-0		yes	no	no	no
02/06-18-015-03W4-0		no	no	no	no
02/07-13-010-08W4-0		yes	no	yes	yes
02/16-10-015-01W4-0		no	no	no	no
03/06-26-013-03W4-0		no	no	no	no
02/08-36-024-13W4-0		no	no	no	no
Saskatchewan core					
01/05-21-011-29W3-0		no	no	no	no
01/11-24-013-30W3-0		no	no	no	no
11/13-09-014-28W3-0		yes	no	no	yes
01/04-25-014-28W3-0		no	no	no	no
21/06-13-014-29W3-0		no	no	no	no
01/06-16-014-29W3-0		no	no	no	no
01/06-19-014-29W3-0		no	no	no	no
01/10-23-014-30W3-0		no	no	no	no
21/08-07-015-28W3-0		no	no	no	no
01/03-24-015-28W3-0	?	no	no	no	no
01/10-34-015-28W3-0	?	no	no	no	no
01/13-12-012-28W3-0		no	no	no	no
21/14-29-014-29W3-0		no	no	no	no
01/06-12-014-30W3-0		no	no	no	no
01/11-10-010-28W3-0		no	no	no	no
01/10-03-005-26W3-0		yes	no	no	no
01/07-31-016-29W3-0		yes	yes	no	no
01/06-11-018-29W3-0		no	no	no	no
01/06-33-013-29W3-0		no	no	no	no
01/10-30-011-29W3-0		no	no	no	no
41/07-22-009-28W3-0		no	no	no	no
Outcrops					
Bear Dam, Sweetg.		no	no	no	no
Deer Creek, Sweetg.		yes	yes	yes	no
Kevin, Montana		yes	yes	no	yes
Highwood River		no	yes	yes	yes
Ghost Dam Spilway		no	yes	no	no
Deer Creek, Alberta	?	no	yes	no	no

Well 2-9-17-10 W 4
Logged 3. July 1997, KSN
Core intervals 422.3 - 413 meter
Samples every 1 meter
Slabbed yes or no
Core quality good
page 1 of 1

Niobrara Formation
Med. Hat Mbr. First White Specks Member



bentonite 1 cm thick

bentonite ~ 1.5 cm thick

bentonite ~ 0.5 cm thick

Very sharp boundary

hummocky beds, 5 cm thick

Remarks

Top Medicine Hat sand A ?

Well 4-8-13-27 W 4

Logged 18. August 1997

Core intervals 5465-5515, 5415-5463, 5365-5415, 5365-5415

Samples Every one meter

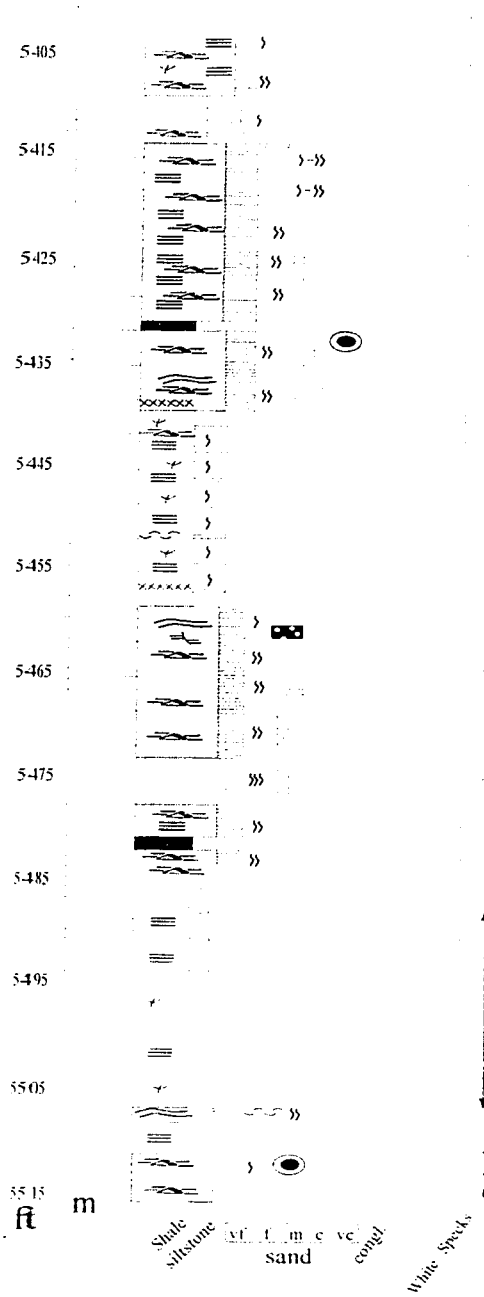
Slabbed yes or no

graded boundary

Core quality Medium to good

page 1 of 2

463



6 cm unbioturbated fine sand, hummocky with internal erosion
thin bentonite (0.5 cm)

thin sand lenses

Few vertical borrows in sand laminars

Thin bentonite
Sharp boundary

8-10 cm hummocky bed.
Fault, displacement ??

Only interval in this core with intensive bioturbation

Vertical borrow (skolithos?)

Black shale, with no bioturbation.
Some thin laminar of sand or very thin lenses of sand

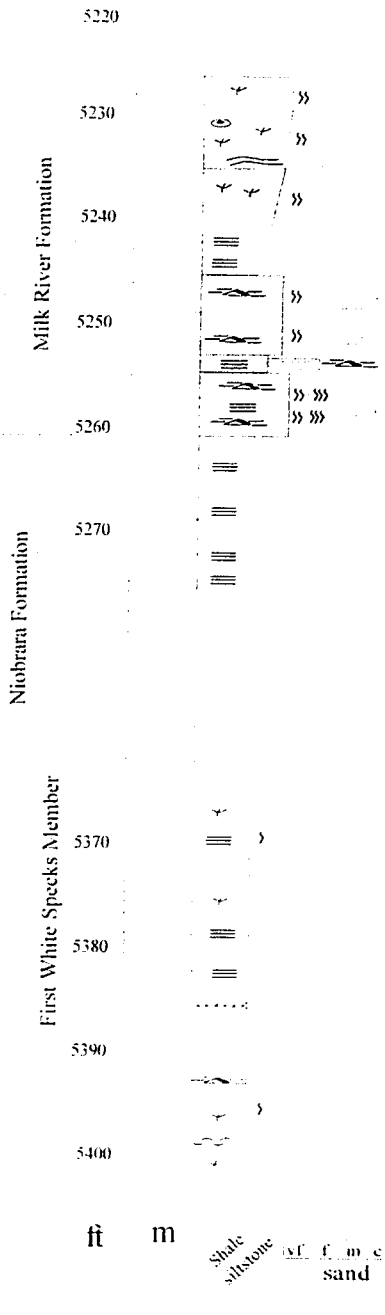
Thin hummocky with basal shell debris

A few spots with white specks
Also some subvertical to vertical unlined borrows

Remarks

General: No Gordia trace fossil observed in the whole core.
Core well cemented compared to core in the MH area

Well 4-8-13-27 W4
Logged 18. August 1997
Core intervals 5465-5515, 5415-5465, 5365-5415+ 5365-5415
Samples Every one meter
Slabbed yes or no
Core quality Medium to good
page2 of 2



concretion

Hummocky bedding

fine laminated black shale, no shell fragments

Sharp boundary (direct contact missing, due to box change)

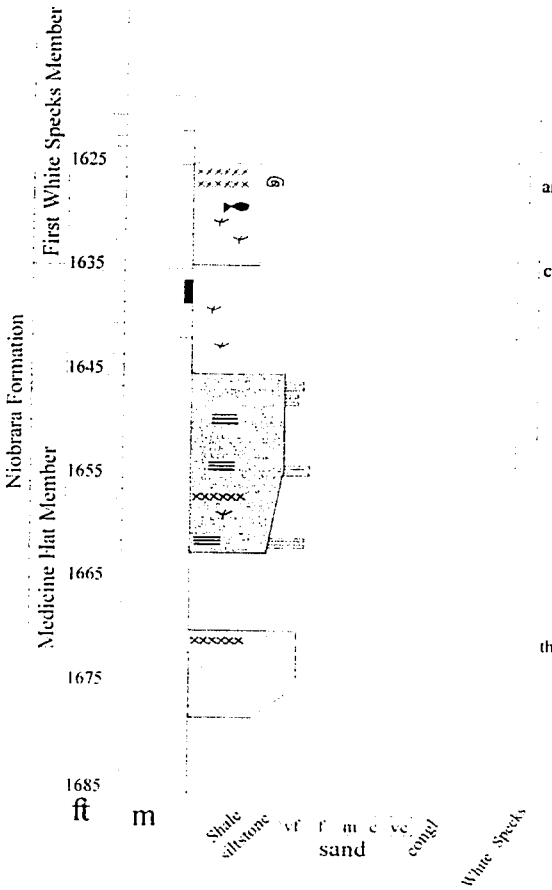
Fine laminated black shale
No shell fragments

Black shale with fine laminated v.f. sand.
White specks present, but not abundant

Bentonite, 1 cm

Remarks

Well 4-14-8-7 W 4
Logged 17. June 1997
Core intervals 1685 - 1625 ft
Samples yes
Slabbed yes or no
Core quality very dirty muddy one inch core
page 1 of 1



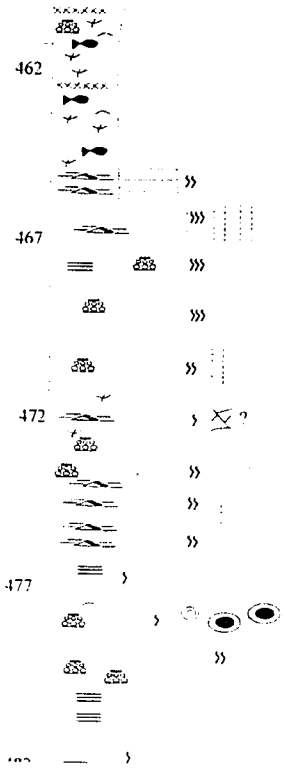
ammonite ?

contact identified and sampled

thin bentonite

Remarks

Well 6-3-24-13 W 4
Logged 9. June 1997
Core intervals 520-500, 487-477, 469-478, 469-460 meter
Samples every one meter
Slabbed yes or no
Core quality good
page 1 of 2



bentonite 0,5 cm

bentonite 1 cm

some silty laminar and thin beds

Graded contact
6 teichichinus identified

Intensive bioturbated

Interbedded sand lenses and upward fining beds

Fine lamination with some lenticular bedding

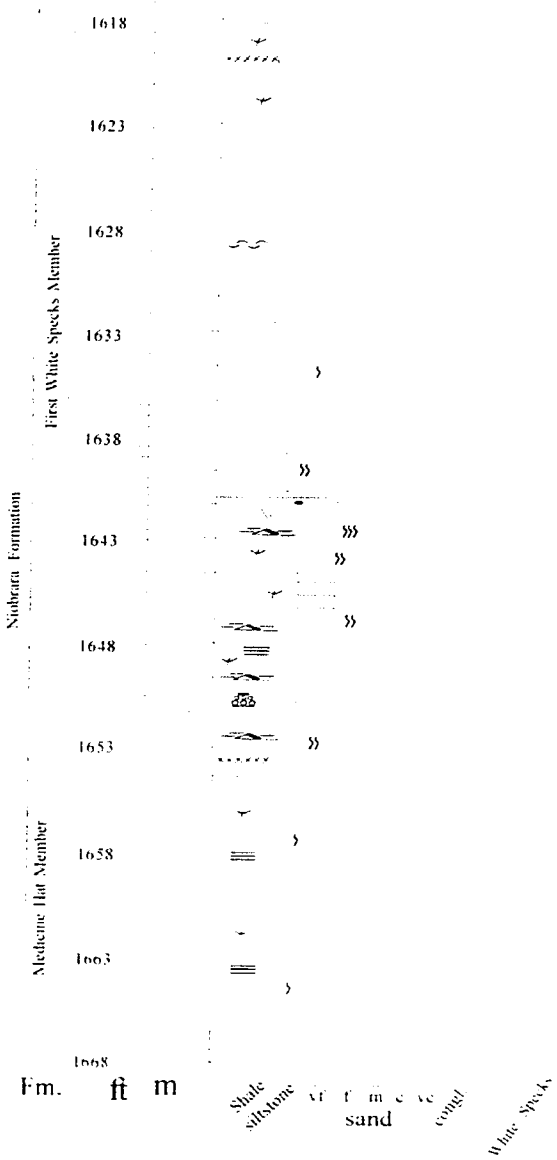
Very fine lamination, with some fining up beds

Sharp based fining up beds (2 cm)

Well 6-5-15-2 W 4
Logged 23 June 1997
Core intervals 1578'-1625'
Samples 11 samples
Slabbed yes or no
Core quality good
page 1 of 1

Remarks

Well 6-5-19-1 W 4
Logged 12. June 1998
Core intervals 1618-1668 ft
Samples no
Slabbed yes or no
Core quality moderate
page 1 of 1



Remarks

Well 6-8-26-19 W 4
Logged 29 January 1997, KSN
Core intervals 860 - 810 m
Samples not sampled
Slabbed yes or no
Core quality medium to good
page 1 of 2

Niobrara Formation

Sweetgrass Mbr.

First White Specks Member

Medicine Hat Member

825
830
835
840
845
850
855
860

Vertical to subvertical sandfilled borrows

shell debris layer

bentonite - thickness ?

ammonite. *Desmoscaphites aff. novimexicanus*

Abundance of osters and other shell fragm.

thin bed of medium grain sand

abundance of coal fragments

ammonite

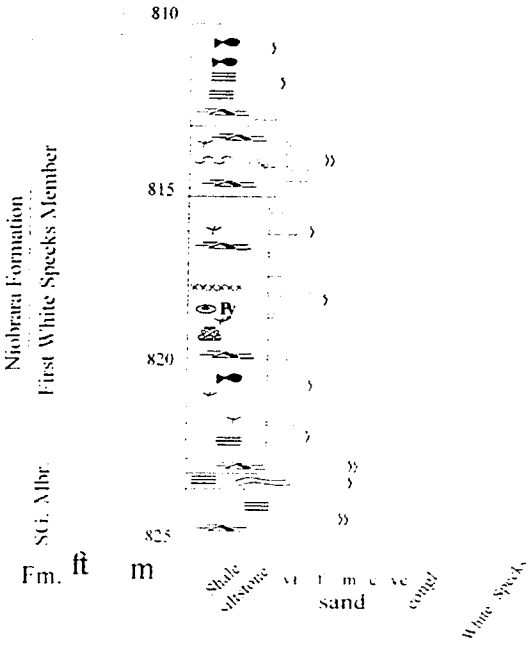
some graded bedding

few to no shell fragments

Three meters of core are missing, presumed to be the lower three

Fm. ft m Shale siltstone vf f m c vc congl sand White Specks Remarks

Well 6-8-26-19 W 4
Logged 29 January 1997, KSN
Core intervals 860 - 810 m
Samples not sampled
Slabbed yes or no
Core quality medium to good
page 2 of 2



Abundant white specks, but few to no shells

small normal fault, displacement ~ 0.5 cm

fish scales and debris

Remarks

Well 6-19-19-8 W 4
Logged 13. June 1997, KSN
Core intervals 328.5-321 meter
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1

319

Niobrara Formation
Medicine Hat Member

324

10 cm structureless sandbed

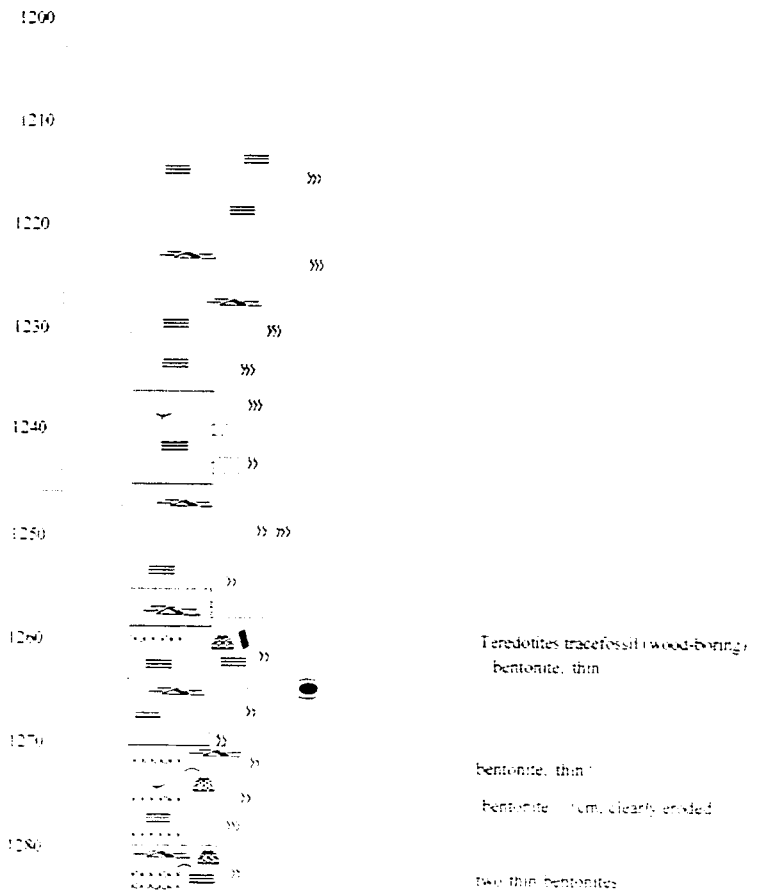
329

ft m

sand

Remarks

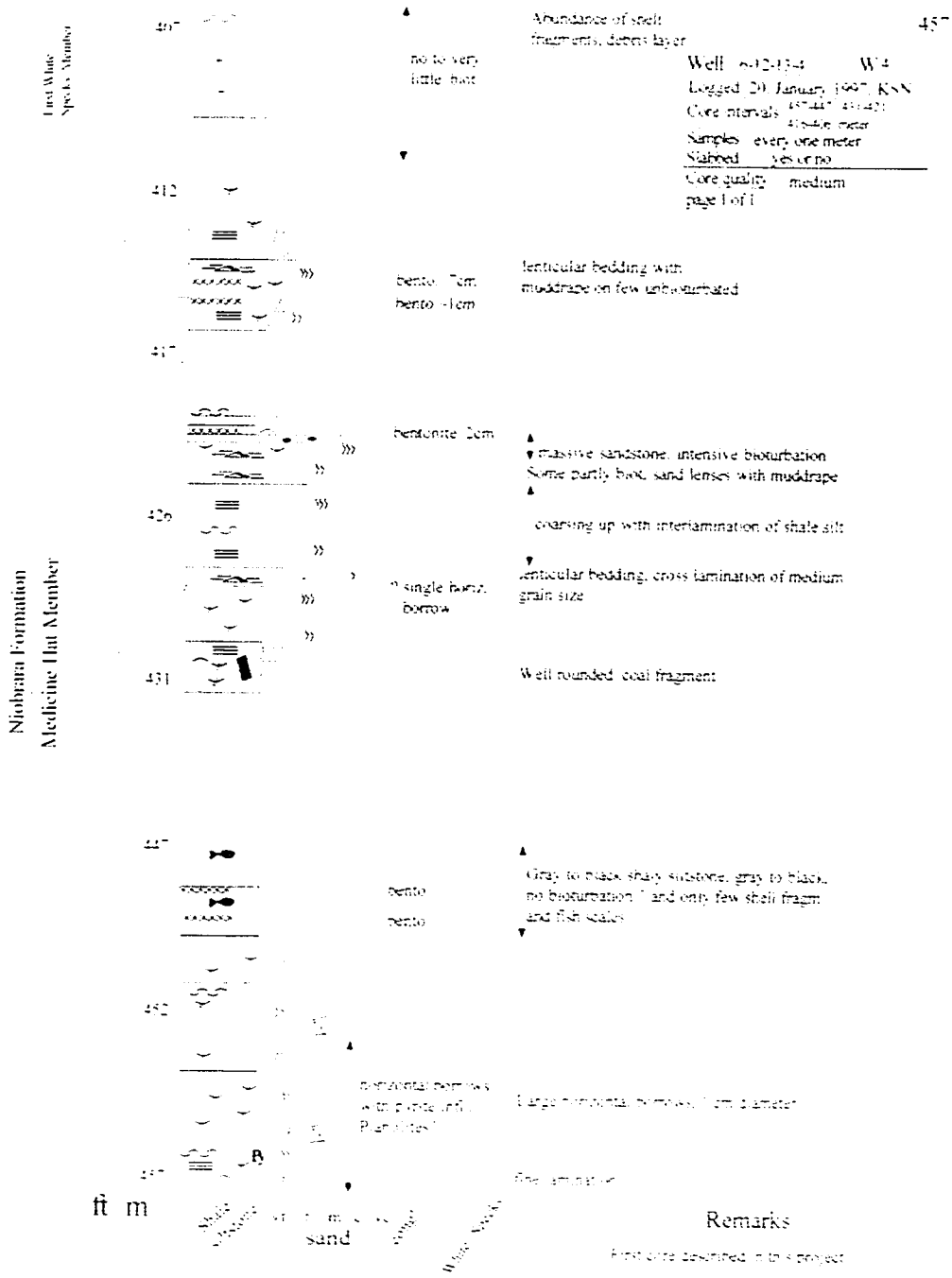
Well 6-19-13-7 W 4
Logged 28. January 1997, KSN
Core intervals 1284 - 1269 ft
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1



Fm. ft m shale siltstone vf f m c vc sand conglomerate coal Remarks

Well [illegible] W [illegible]
Logged 31 July 1997
Core intervals 1528-1476
Samples
Slabbed yes or no
Core quality moderate, 0.5 inch
page 1 of 1

Remarks

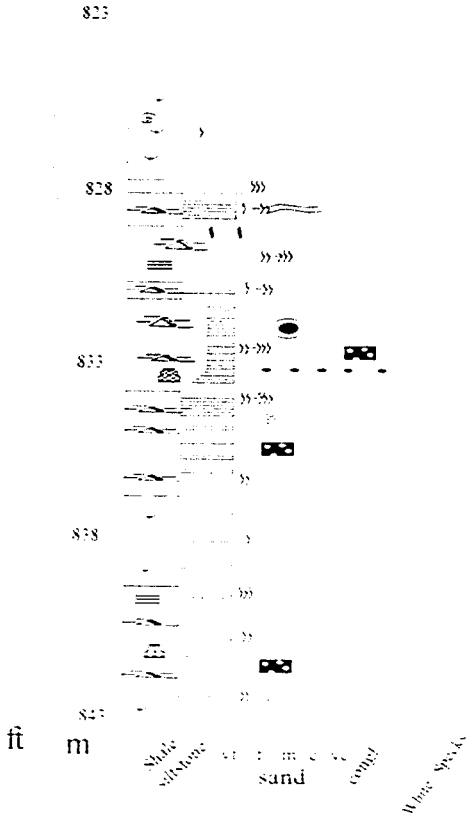

Niobrara Formation
Medicine Hat Member
First White Specks Member
407
412
417
426
431
437
452
457
no to very little bioturbation
bento 7cm
bento 1cm
bentonite 2cm
single horiz. burrow
bento
bento
Abundance of shell fragments, debris layer
Well
Logged 20 January 1997 KNN
Core intervals
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1
lenticular bedding with muddrape on few unbioturbated
massive sandstone, intensive bioturbation
Some partly bioturbated sand lenses with muddrape
coarsing up with interlamination of shale silt
lenticular bedding, cross lamination of medium grain size
Well rounded coal fragment
Gray to black shaly siltstone, gray to black, no bioturbation and only few shell fragm and fish scales
Large horizontal burrows
ft m
sand
Remarks

Well 6-23-23-22 W 4
Logged 10 June '99, by KSN
Core intervals 824.5 - 833.4 m rec 9.2 m
833.6 - 842.8 m rec 9.4 m
Samples Yes, 7 samples
Slabbed yes or no partly
Core quality good
page 1 of 1

General:
Shale: Dark gray and fizzel.
Mainly moderate to intensively bioturbated.

PEBBLES within bioturbated zone. Surrounding lithology very fine sand with few coarse-grained fragments. Within here small brown fragments.
Pebble: Black chert, 1.5 * 1 cm, rounded.
Pebble 2 : Round (1 cm), irregular rim, with some volatiles inside (or eroded inclusions)

Niobrara Formation
First White Specks Member
Medicine Hat Member



ammonite

sharp boundary

Thick (1.5 cm) subvertical trace, sand infilled.
Small mud clasts

Large subvertical trace, sand infilled

Some graded beds
Change in trace fossil assemblage
Mud filled escape structures — Upwards increase in sand lenses

Few shell fragments — Dark gray shale with very few very thin sand lenses

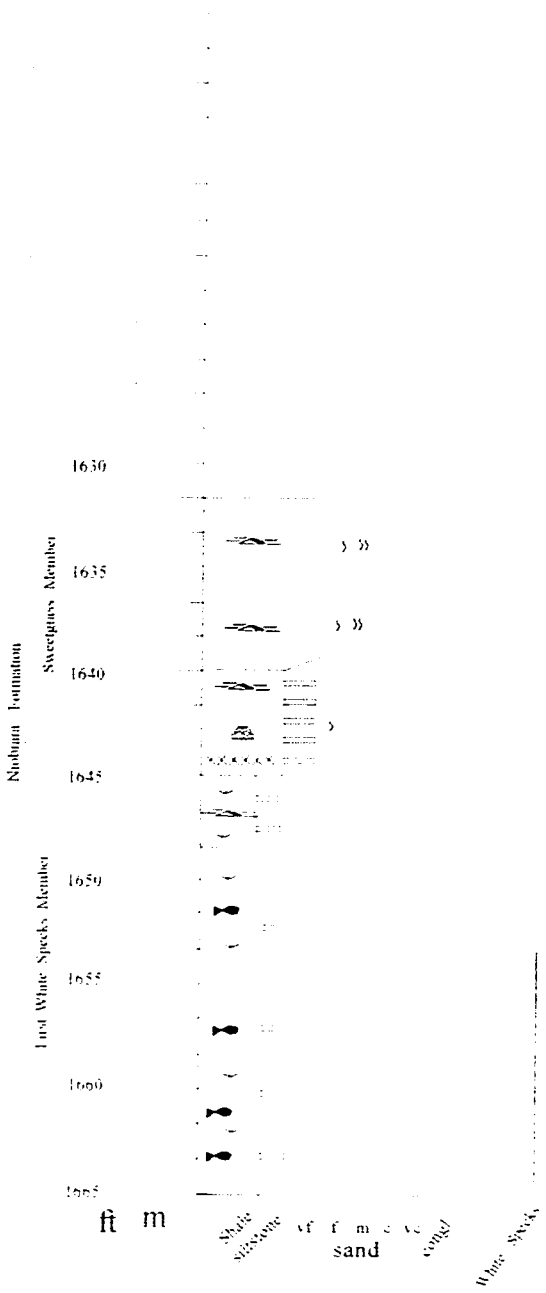
Sharp Boundary

Sharp boundary, ripples with mudcrapes 1.5 cm — Dark gray shale

Some normal graded bedding

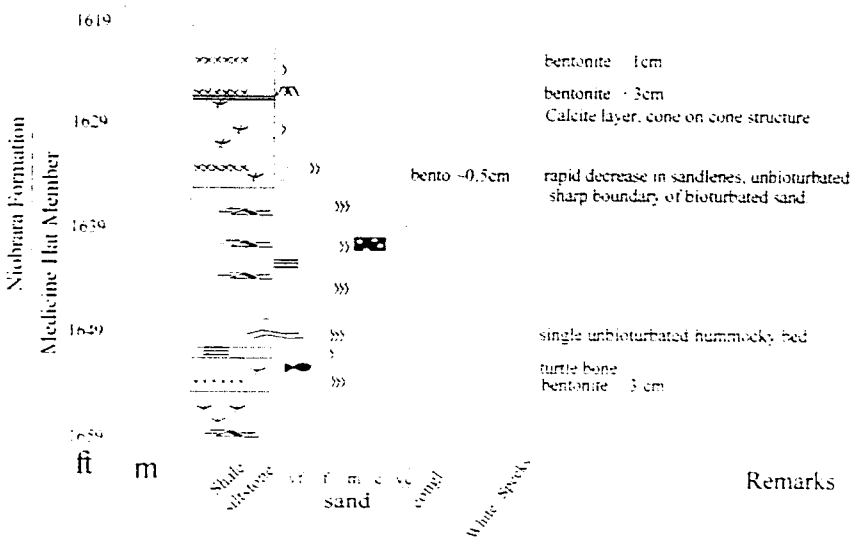
Remarks

Well 6-32-11-20 W 4
Logged 1. August 1997
Core intervals 1630' - 1665'
Samples every 3 feet
Slabbed yes or no
Core quality good
page 1 of 1

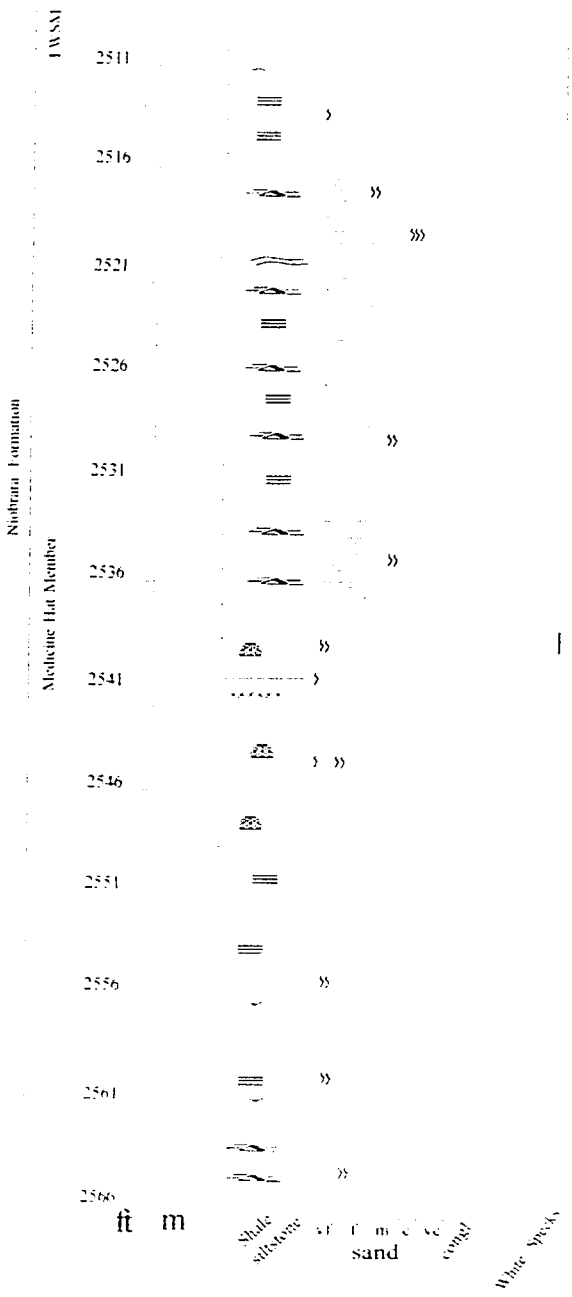


Remarks

Well 6-35-16-3 W 4
Logged 30 June 1997, KSN
Core intervals 1646-1621 ft
1659-1647 ft
Samples
Slabbed yes or no
Core quality medium to good
page 1 of 1



Well 7-1-29-19 W 4
Logged 20 August 1997
Core intervals 2512-2561 ft.
Samples
Slabbed yes or no
Core quality good
page 1 of 1



Remarks

Well 7-9-12-21 W 4
Logged 5. August 1997, KSN
Core intervals 1941 - 1860 ft
Samples every one meter
Slabbed yes or no
Core quality Good
page 1 of 1

Remarks

Lamination of white specks and some very thin sand lenses

Sharp boundary, from fine sand to shale.

hummocky bedding ~ 6 cm

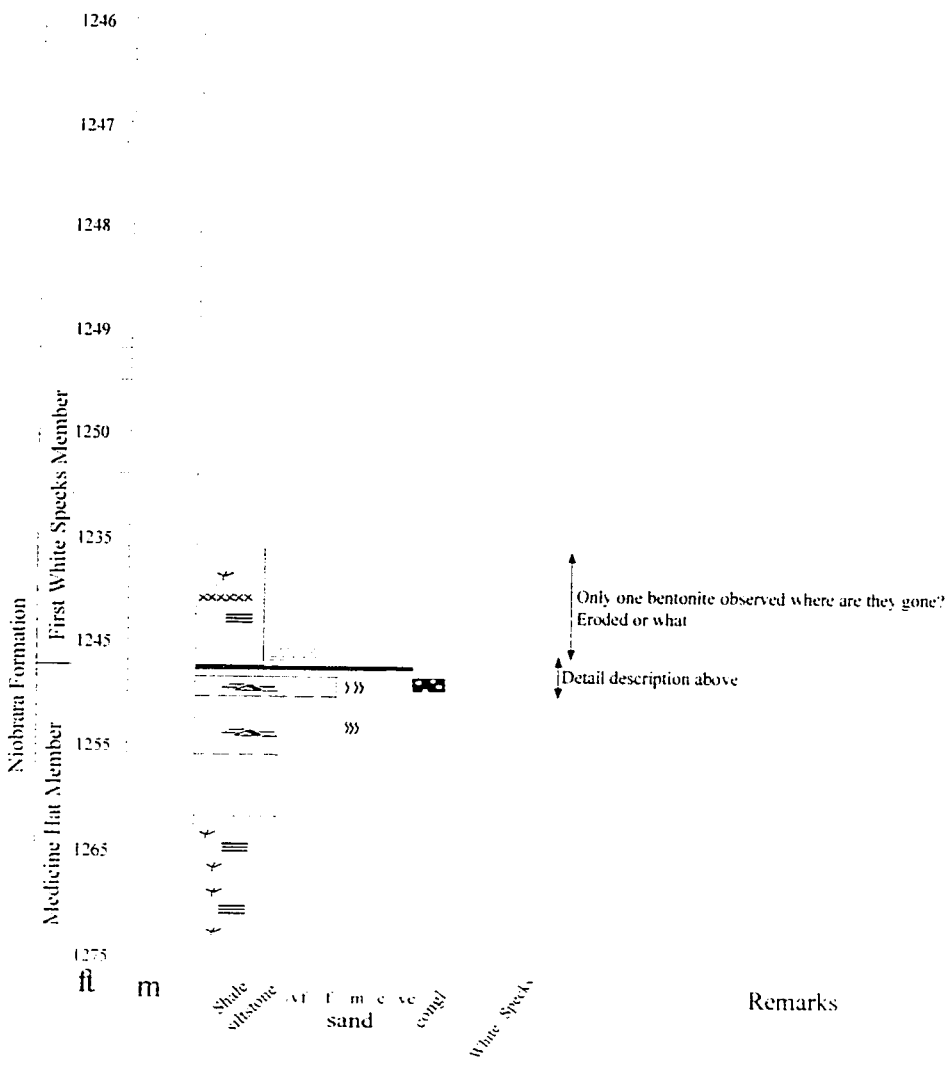
Graded contact, but change in colour from black to dark gray.

Interval with lenticular bedding

Some single fine sand lenses with muddrape. Ripple high max 1.5 cm. Abundant Inoceramides

Calcite layer 9 cm thick. Lower part as cone on cone, and upper part massive calcite

Well 7-10-14-6 W4
Logged 30. June 1997, KSN
Core intervals 1274 - 1235 ft
Samples every one meter
Slabbed yes or no
Core quality medium to poor
page 1 of 1



Well 7-17-3-7 W 4
Logged 22. January 1997
Core intervals 1066.9 - 1037.1 ft
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1

Niobrara Formation
Medicine Hat Member

1037
1047
1057
1067
ft m

Massive structureless sand, calcite cementated, intensively bioturbated

Many low angled laminar or thin beds interpred as hummocky bedding

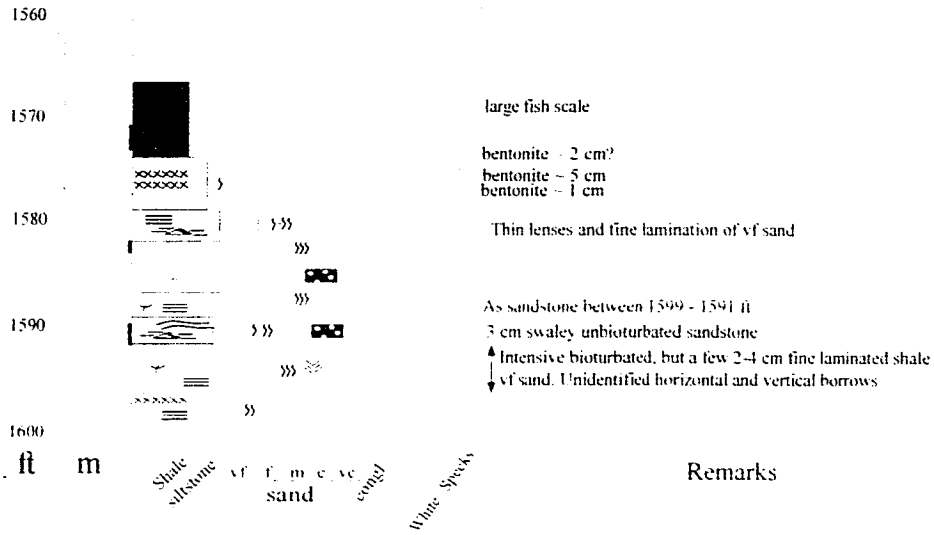
fish scales
thin bentonite

Gordia in thin shale silty layer
Abundance of only partly bioturbated graded sand laminar and beds
Intensive bioturbated

Remarks

White specks have not been recorded in this core, might be present

Well 7-19-15-3 W 4
Logged 25. June 1997. KSN
Core intervals 1599 - 1566 ft
Samples every one meter
Slabbed _____ yes or no
Core quality good
page 1 of 1

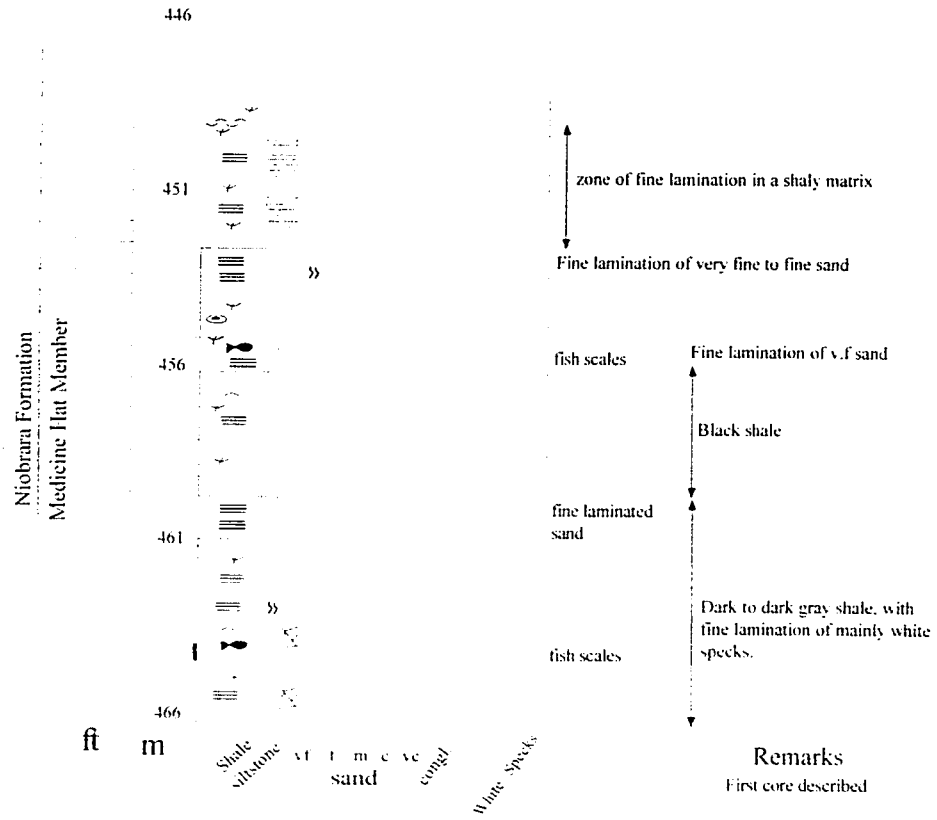


7-20-11-6 W 4

Logged:	January 1997
Interval	Petrophysic log: 1095-1065 ft. (rec. 24)
General description:	Poor core. First W. Speaks at the very bottom of the core. General upward-coarsening to fine sand. Only very few shell fragments. Lower part dominated by fine lamination, but with variety of bioturbation.
Samples:	Not sampled.
Photos:	No photos.

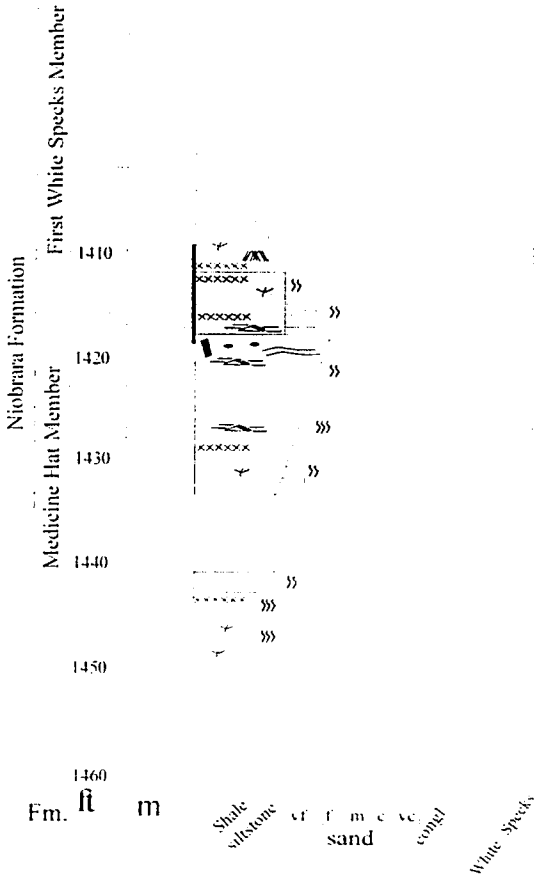
Well 7-25-13-1 W 4
Logged 20. January 1997, KSN
Core intervals 466- 448 meter
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1

General: First core described and a very muddy core which swells. General description okay, but may miss some features, as trace fossils concretions and sedimentological structures. Abundance of inoceramids fragments through the whole core.



Remarks
First core described

Well 7-27-20-3 W 4
Logged 31. January 1997. KSN
Core intervals 1460-1410 ft
Samples every one meter
Slabbed yes or no ?
Core quality poor
page 1 of 1



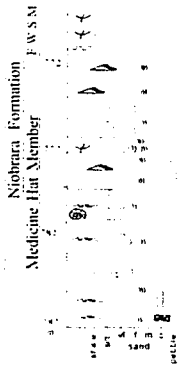
Remarks

cone on cone structure in calcite layer above bentonite

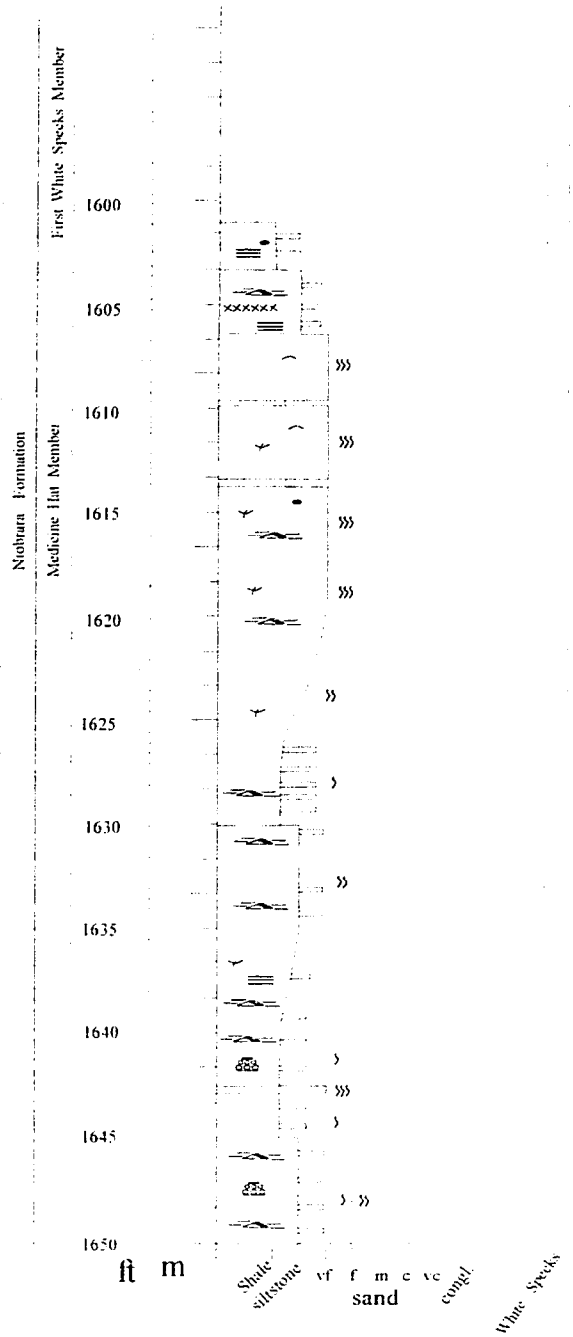
Debris layer with brown pebbles, coal fragm. and shell fragm.

Hummocky bedding

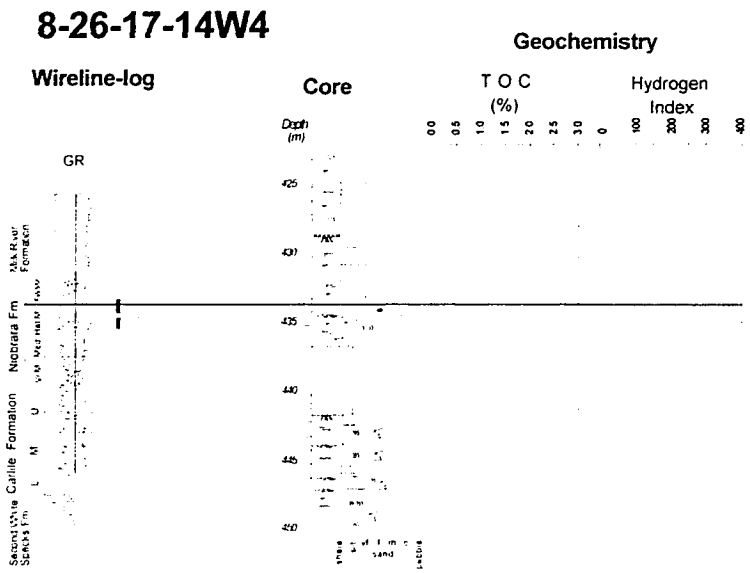
Well 8-6-26-17 W 4
Logged 27. August. 1999. KSN
Core intervals 769-787 meter
Samples no
Slabbed yes or no
Core quality good
page 1 of 1



Well 8-15-19-15 W 4
Logged 6. August 1997
Core intervals 1650- 1601 ft.
Samples
Slabbed yes or no
Core quality moderate
page 1 of 1

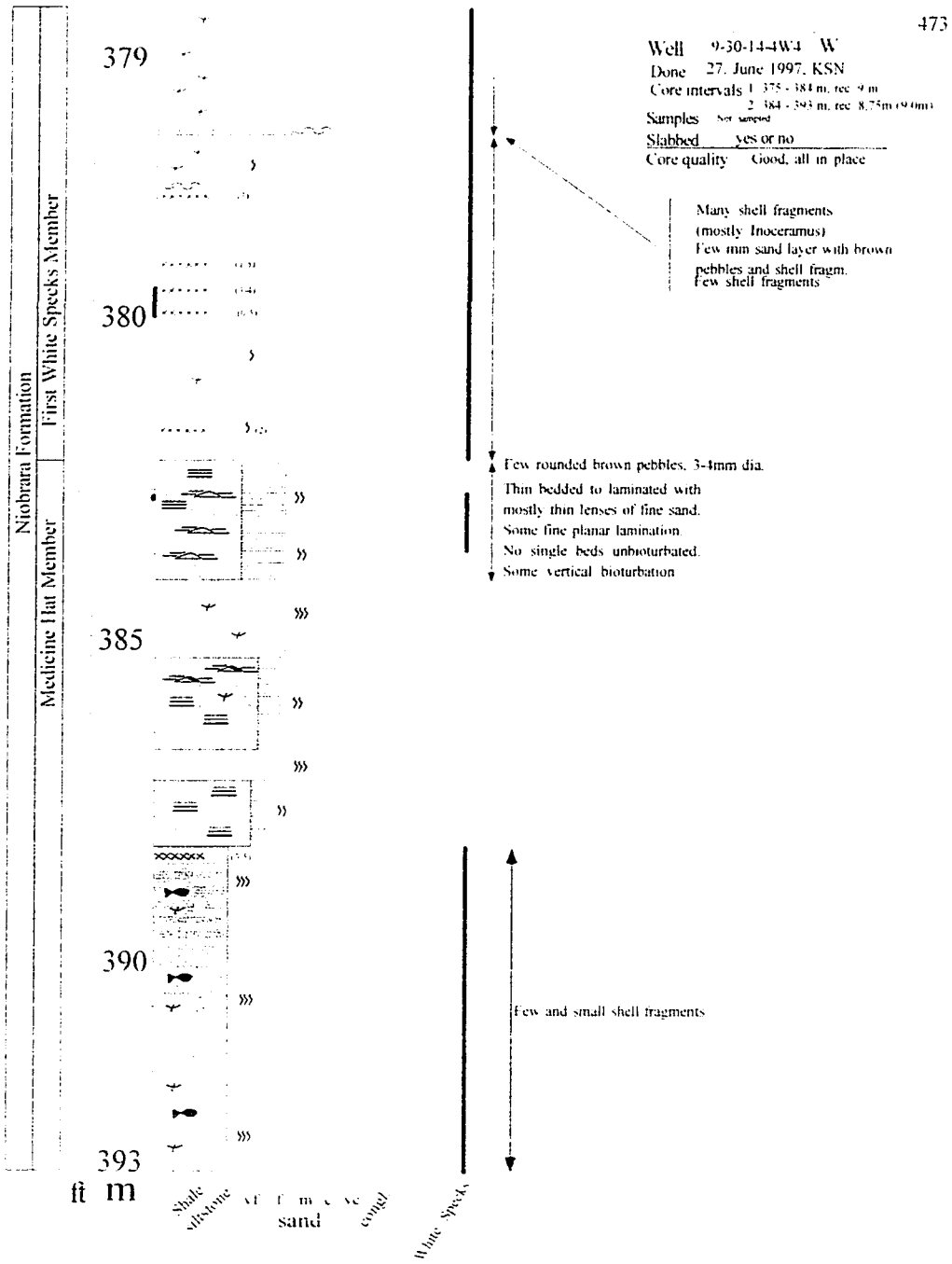


Remarks

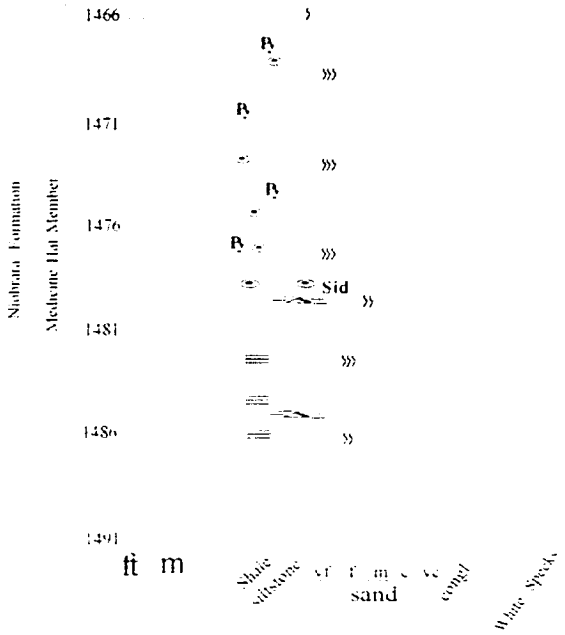

8-26-17-14W4
Wireline-log
Core
Geochemistry
T O C
(%)
Hydrogen
Index
Depth
(m)
GR
Niobrata Fm
Carlile Formation

Geochemistry
T O C
(%)
Hydrogen
Index
S1
00/08-36-024-13W4
GR
ILD
Milk River
Formation
Niobrara Formation
Carlile Formation
Second White
Specks Fm
upp u
middleunit
lower unit
Verger M
Meg Hat M
FVSM
500
550
600
650
700
530
535
540
545
550
sand

Well 9-30-14-4W4 W
Done 27. June 1997. KSN
Core intervals 1 375 - 384 m. rec 9 m
2 384 - 393 m. rec 8.75m (9.0m)
Samples Not sampled
Slabbed yes or no
Core quality Good, all in place



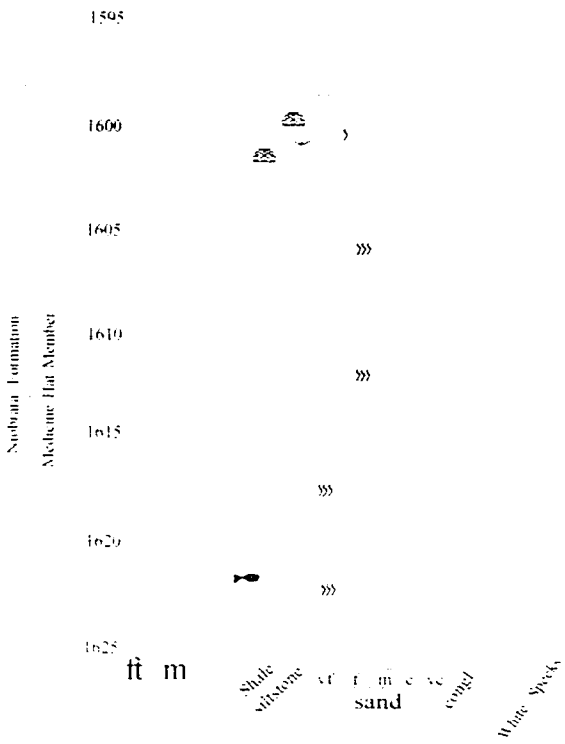
Well 10-1-16-5 W 4
Logged 2. July 1997
Core intervals 1465- 1491 ft.
Samples Every 3 ft.
Slabbed yes or no
Core quality poor
page 1 of 1



"D" sandstone of the Medicine Hat Member
(Medicine Hat sandstone 4)

Remarks

Well 10-10-15-4 W 4
Logged 26. June 1997
Core intervals 1624 - 1599 ft.
Samples no
Slabbed yes or no
Core quality poor
page 1 of 1

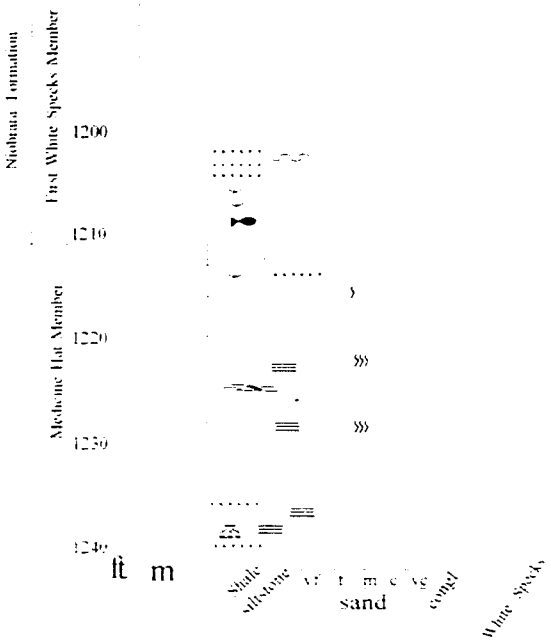


Core in very bad condition

"D" sandstone of the Medicine Hat Member

Remarks

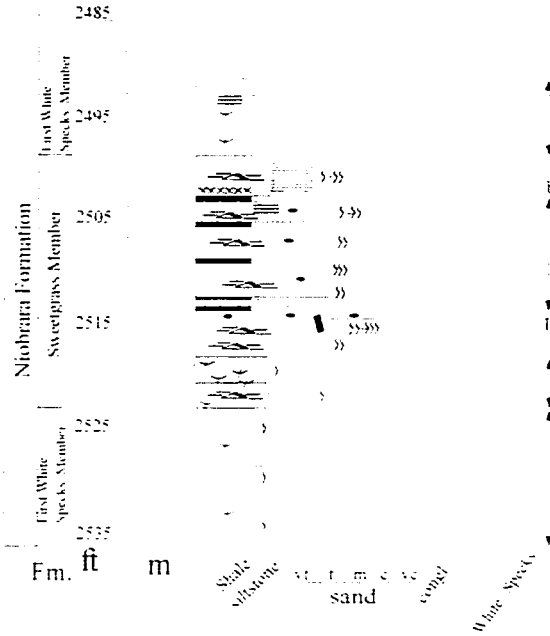
Well 10-11-12-4 W 4
Logged 18 June 1997
Core intervals 1200 - 1258 ft. 40 ft rec.
Samples
Slabbed yes or no
Core quality poor
page 1 of 1



Remarks

Well 10-13-11-23 W4
Logged 1. August, 1997
Core intervals 2535-2491 ft
Samples not sampled
Slabbed yes or no
Core quality medium
page 1 of 1

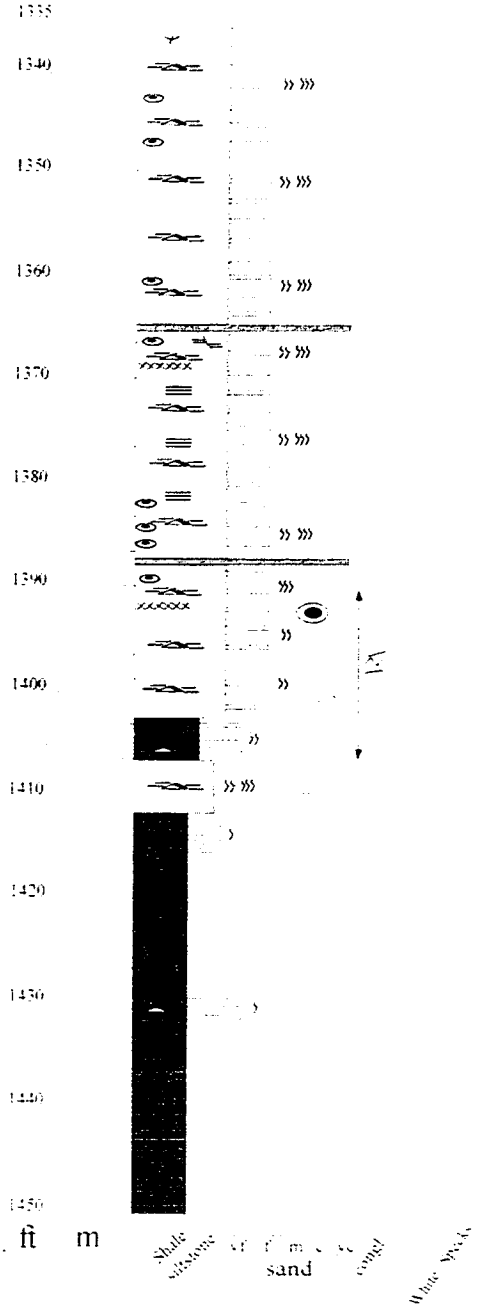
General remarks: Bioturbation dominated by horizontal borrows; planolites ??
In sand intervals bioturbation decreases towards top



Remarks

- few sand laminar
- black homogenous shale
- bentonite ~ 2 cm
- slight to moderate bioturbated, with upto 10 cm interbedded shale intervals showing no bioturbation
- Intensive biot., abundance pebbles and coal fragm
- sharp boundary
  many shell fragments,
  dark gray to gray
- black shale
  few shell fragments
  few fine sand lenses

10-14-15-4W4



Well 10-14-15-4 W 4
Logged 14 August 1997, KSN
Core intervals 1450-1270 ft
Samples every one meter
Slabbed yes or no
Core quality medium to good
page 1 of 2

Abundance of siderite concretions

conglomerate, see discription on page 2
fault, displacement ?
bentonite ~10 cm

conglomerate, se description on page 2

Last occurence of white specks

bentonite few mm

fine laminated fine sand and lenses

Fine laminated with white specks
Abundance of shell fragments

Remarks

Well 10-14-15-4 W 4
Logged 14. August 1997, KSN
Core intervals 1450-1270 ft
Samples every one meter
Slabbed yes or no
Core quality medium to good
page 2 of 2

Conglomerates

General

Two conglomerates founded in the lower part of core 5, box 1 and 7. Both conglomerates are thin and wedge shaped (3 to 7 cm). Consists of relative large rounded to subrounded pebbles. Some are elongated, and got a fabrix. The conglomerates are matrix supported with a silty to very fine sandy matrix. Pebbles max. size 1*4*6 cm.

Three different kinds of pebbles identified.

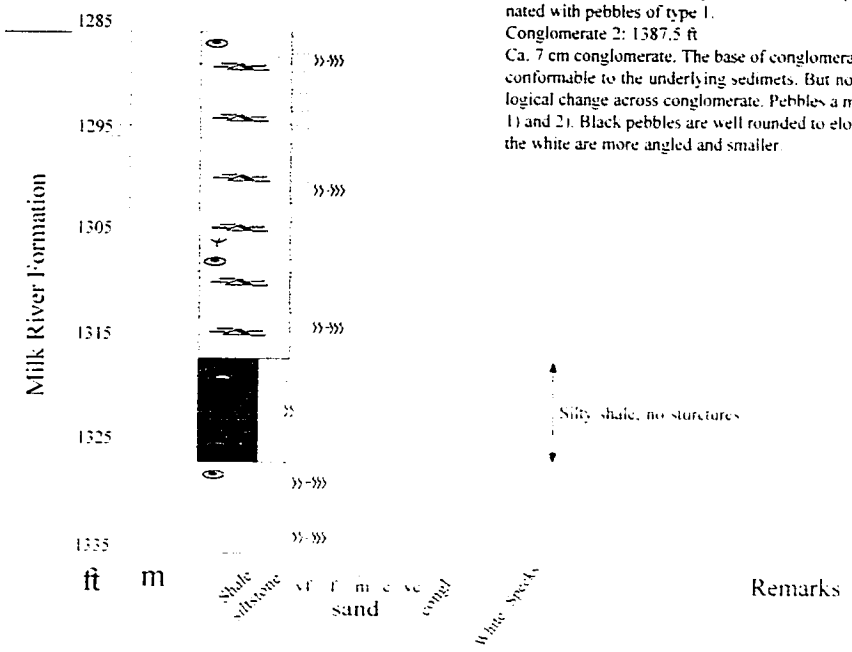
1) Black, very hard and non calc. pebbles; cherts ?
2) White, typical smaller pebbles, fisses as powder, soft compared to 1).
3) Same as 2), but rusty; siderite fragments.

Conglomerate 1: 1365 ft

(Under the conglomerate is a non calc. concretion observed. Its diameter is abourt 6 cm, and it is slightly elipse in shape). The conglomerae is seen as a thin bed (~4 cm). Contains the largest pebble of the two conglomerates. 2*3*6 cm. A slight fabrix orientation is present. Conglomerate matrix supported. Dominated with pebbles of type 1.

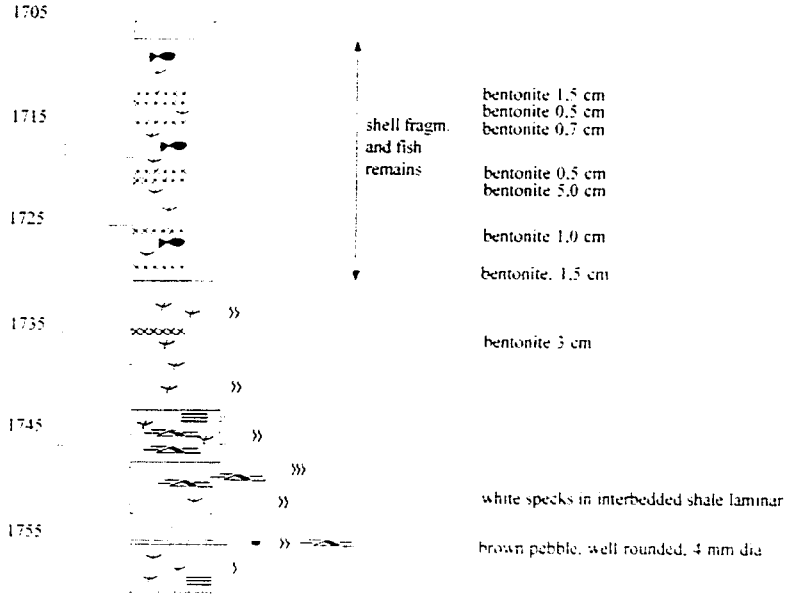
Conglomerate 2: 1387.5 ft

Ca. 7 cm conglomerate. The base of conglomerae clarely unconformable to the underlying sedimets. But no visible lithological change across conglomerate. Pebbles a mixture of type 1) and 2). Black pebbles are well rounded to elongated, where the white are more angled and smaller.



10-15-17-1W4

Well 10-15-17-1 W4
Logged 3. July 1997, KSN
Core intervals 1775-1705 ft
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1

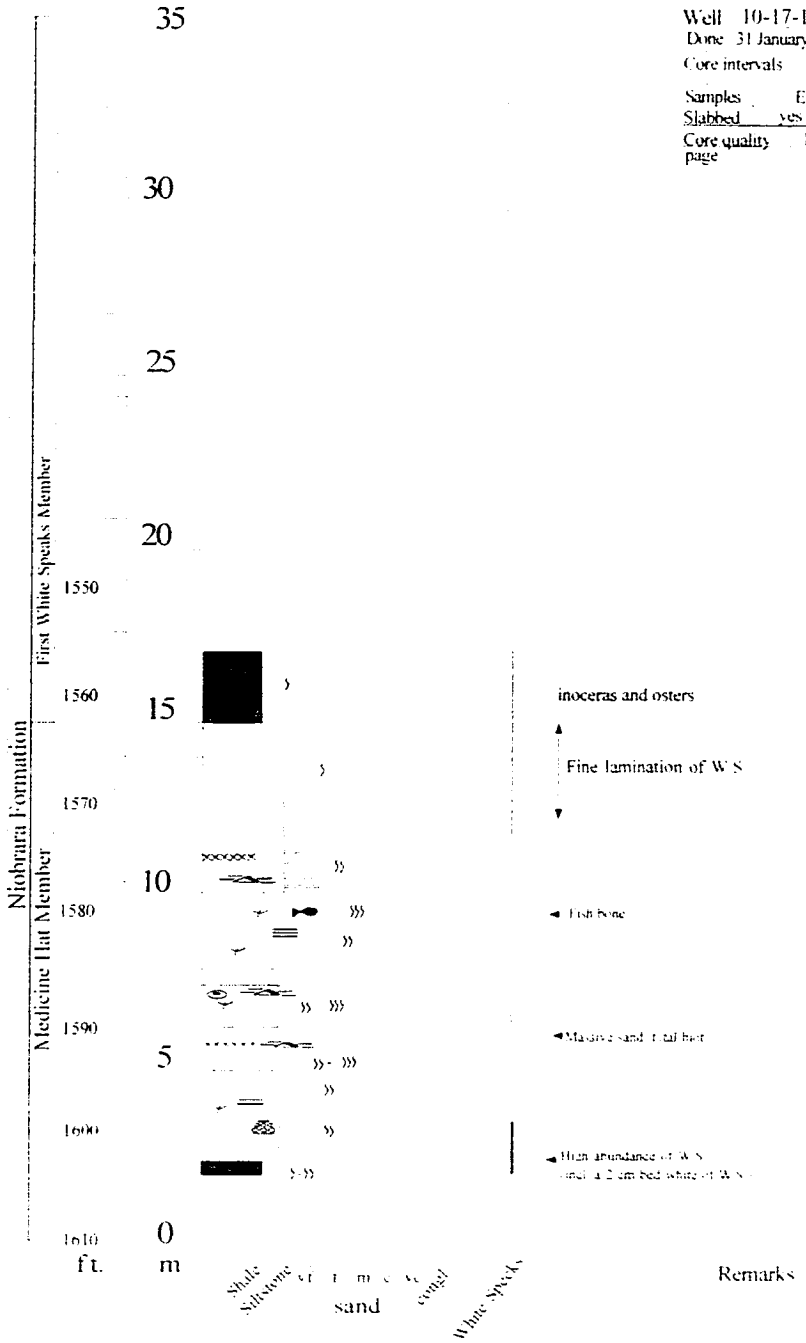


Fm. ft m Shale Siltstone vf f m c vc congl sand White specks Remarks

Well 10-17-19-2W4 481
Done 31 January, KSN
Core intervals 1555-1603 ft.

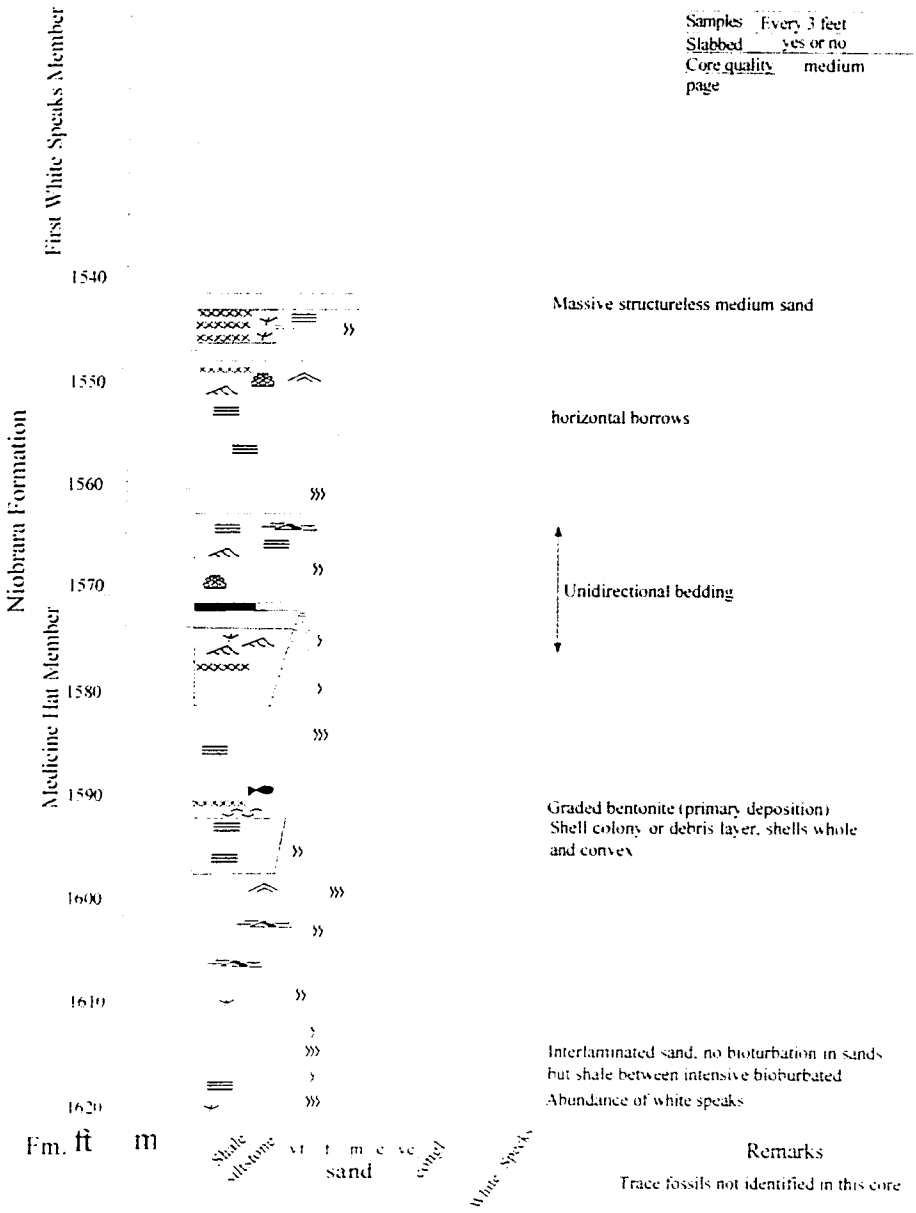
Samples Every 3 feet
Slabbed yes or no

Core quality Medium
page



Well 10-27-12-2 W 4
Logged 23 January 1997 by KSN
Core intervals 1540-1616 ft

Samples Every 3 feet
Slabbed yes or no
Core quality medium
page

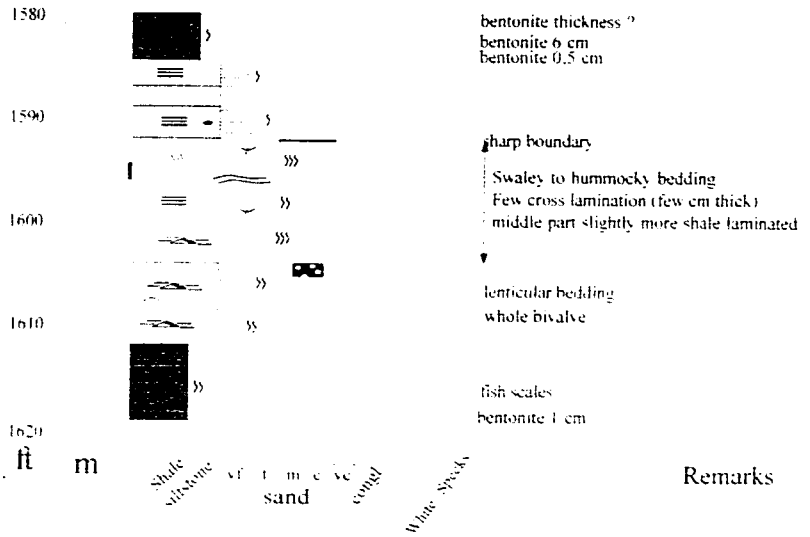


Remarks

Trace fossils not identified in this core

10-28-15-3W4

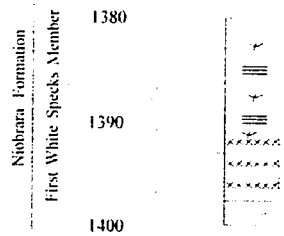
Well 10-28-15-3 W 4
Logged summer 1997, KSN
Core intervals 1620 - 1579 ft
Samples every one meter
Slabbed yes or no ?
Core quality from poor to good
page 1 of 1

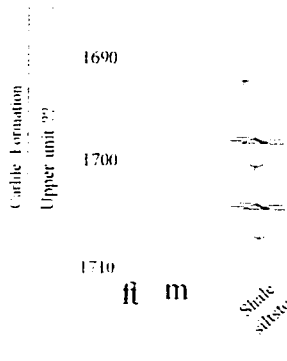


10-29-11-5 W 4

Logged:	January 1997
Interval:	1184-1220 ft
General description:	Very poor condition. Two coasing upward cycles recognised. with max. grainsize of fine sandUseless for detailed sedimentology. not logged. because part of it might be drilling mud.
Samples:	Not sampled
Photos:	No photos

Well 11-11-16-9 W 4
Logged 12 June 1998 and 10 June 1999
Core intervals 1380-1400 and 1690-1710 ft.
Samples
Slabbed yes or no
Core quality moderate
page 1 of 1



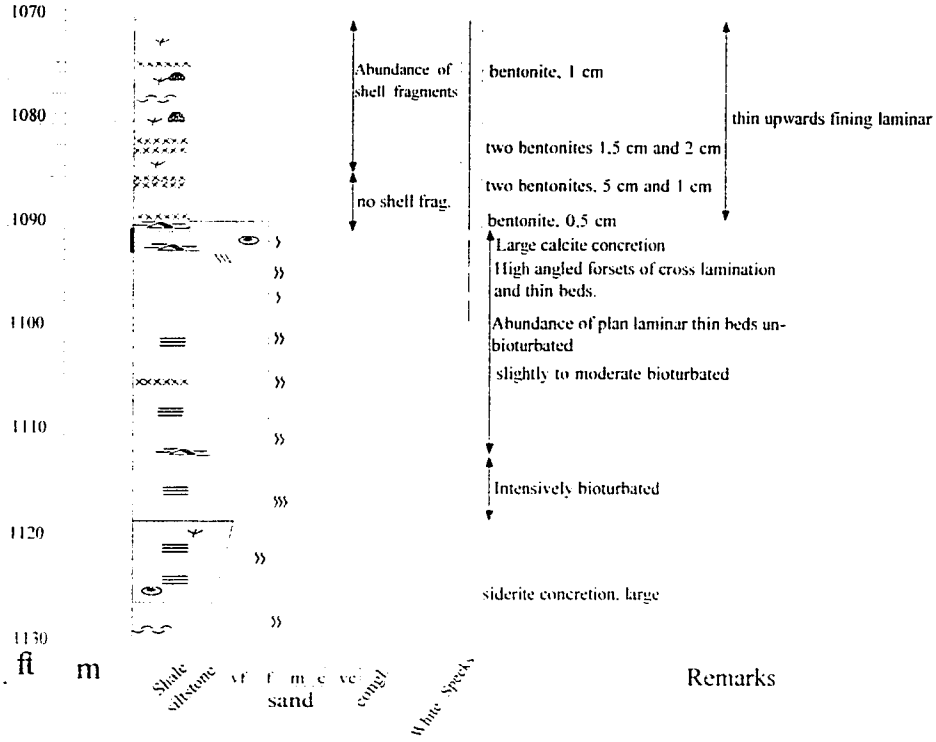


A question if this is Carlile Formation.
No logs were avaliable.

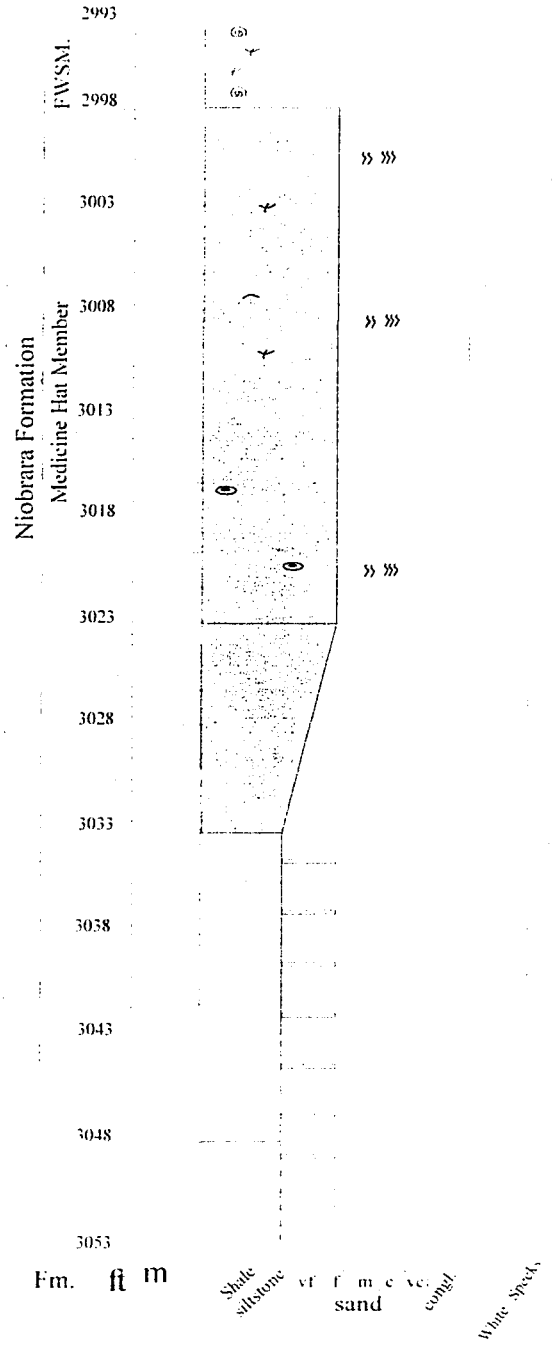
ft m Shale siltstone vf f m c vc sand congl White Specks

Remarks

Well 11-15-12-5 W 4
Logged 18. June 1997, KSN
Core intervals 1130 - 1070 ft
Samples every one meter
Slabbed yes or no partly
Core quality medium
page 1 of 1



Well 11-26-20-23 W 4
Logged 26. March 1999
Core intervals 2995-3053 ft (62 rec.)
Samples
Slabbed yes or no
Core quality Good
page 1 of 1



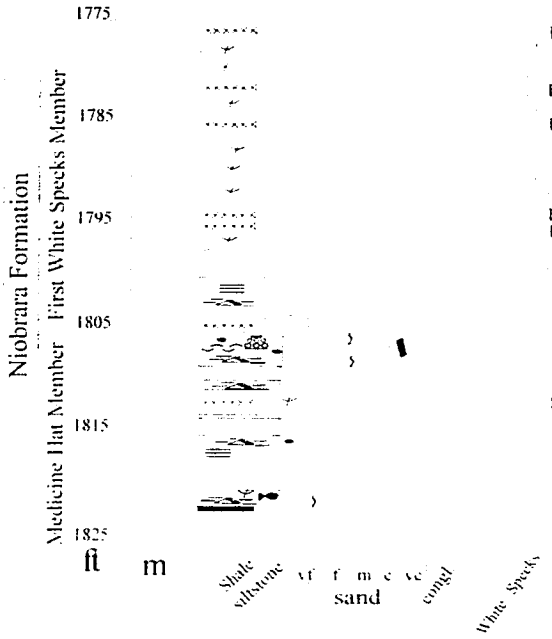
Ammonite exactly on top of sand

Sept. concretions

Few concentration layer of White Specks

Remarks

Well 11-33-16-1 W 4
Logged 30. June 1997
Core intervals 1825-1775 ft
Samples every 3 feet
Slabbed yes or no
Core quality medium
page 1 of 1



bentonite 1 cm

bentonite ~ 3 mm

bentonite ~ 3 cm

bentonite 1 cm
bentonite ~ 5 mm

bentonite ~ 6 mm

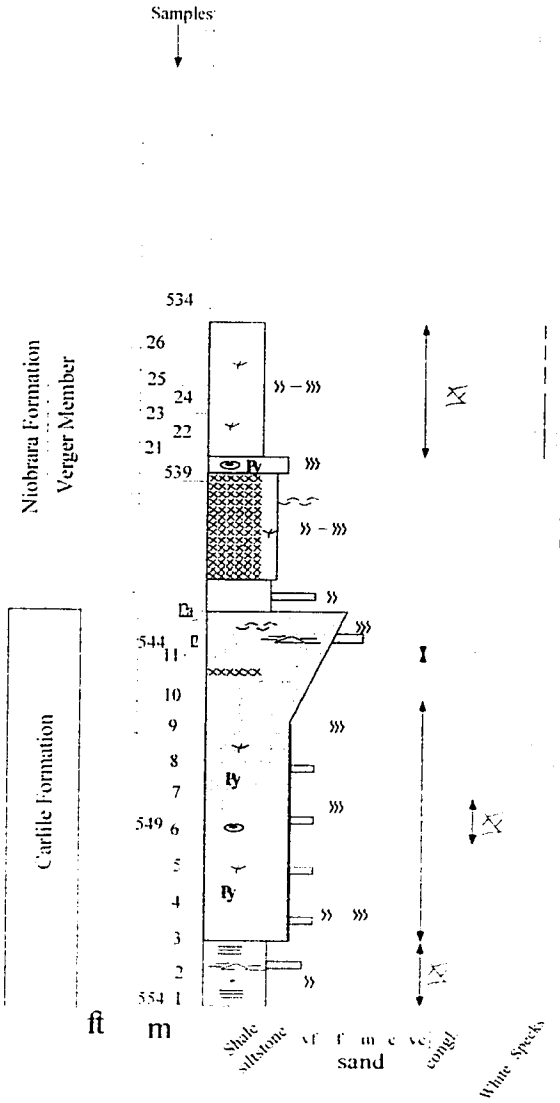
Two thin lags of shell fragm., pebbles, wood fragm. and minor sand.

bentonite 2-3 mm

vertical burrows

Remarks

Well 13-20-17-7 W 4
Logged 2. July 97 and 15. June 98
Core intervals 554-536 m
Samples every one meter + detail
Slabbed (yes) or no
Core quality moderate to good
page 1 of 2



3 meter zone with 18 bentonites, with a thickness range from 0.5 to 16 cm, sharp based.

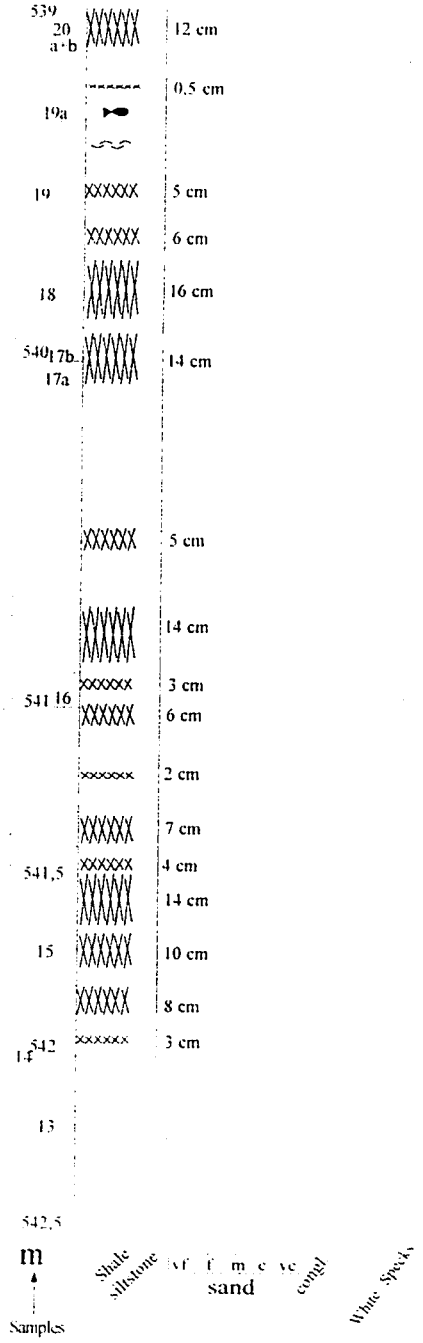
graded boundary
total bioturbated sandstone, dark gray, a few primary structure seen as lenticular bedding.

Few, but large Inoceramus fragments.
Gray sand sitstone, coasering up
Totally bioturbated

silty shale, dark gray

Remarks

Well 13-20-17-7 W 4
Logged 2. July 97 and 15. June 98
Core intervals 554-536 m
Samples as indicated by 1.
Slabbed yes or no
Core quality moderate to good
page 2 of 2



Remarks

Well 14-23-19-15 W 4
Logged 6. August 1997. KSN
Core intervals 485.25 - 476.5 meter
Samples every one meter
Slabbed yes or no
Core quality good
page 1 of 1

Niobrara Formation
First White Specks Member
Sweetgrass Member

ft m

471
476
481
486

Shale siltstone vf f m c vc congl
sand
White Specks

General
Note: Sandy intervals dominated by fine lamination,or thin beds or laminar with sharp base and normal graded.

black shale, few shell fragments

shell debris layer ~ 1 cm

vf sand, light gray and only slightly bioturbated

Many shell fragments and thin upwards fining laminar or beds

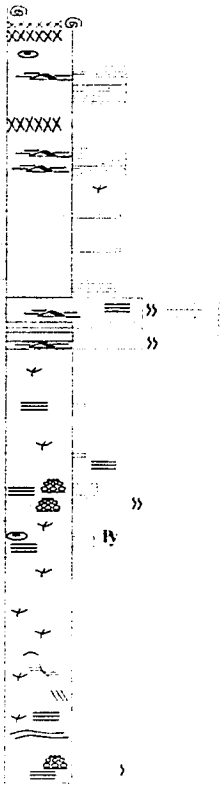
black shale, no shell fragments

Remarks

Well 14-26-19-8 W 4
Logged 7. July 1997
Core intervals
683.5 - 679.35, 679.35 - 670.2
670.2 - 661.0,
508.65 - 501.25, 501.25 - 492.1 meter
Samples
Slabbed yes or no
Core quality medium to good
page 1 of 4

Second White Specks Formation

659
664
669
674
679
684



Dark black shale, abundace in white specks Ammonites
bentonite (12 cm thich)

bentonite (17 cm thick)

Very rich in white specks

pyrite concretions

Black to dark gray shale with some sandstone lamination and small scale sand lenses.
Small chunks or lenses of white specks.

Fault, displacement about 20 cm

Cross lamination 1.5 cm thick

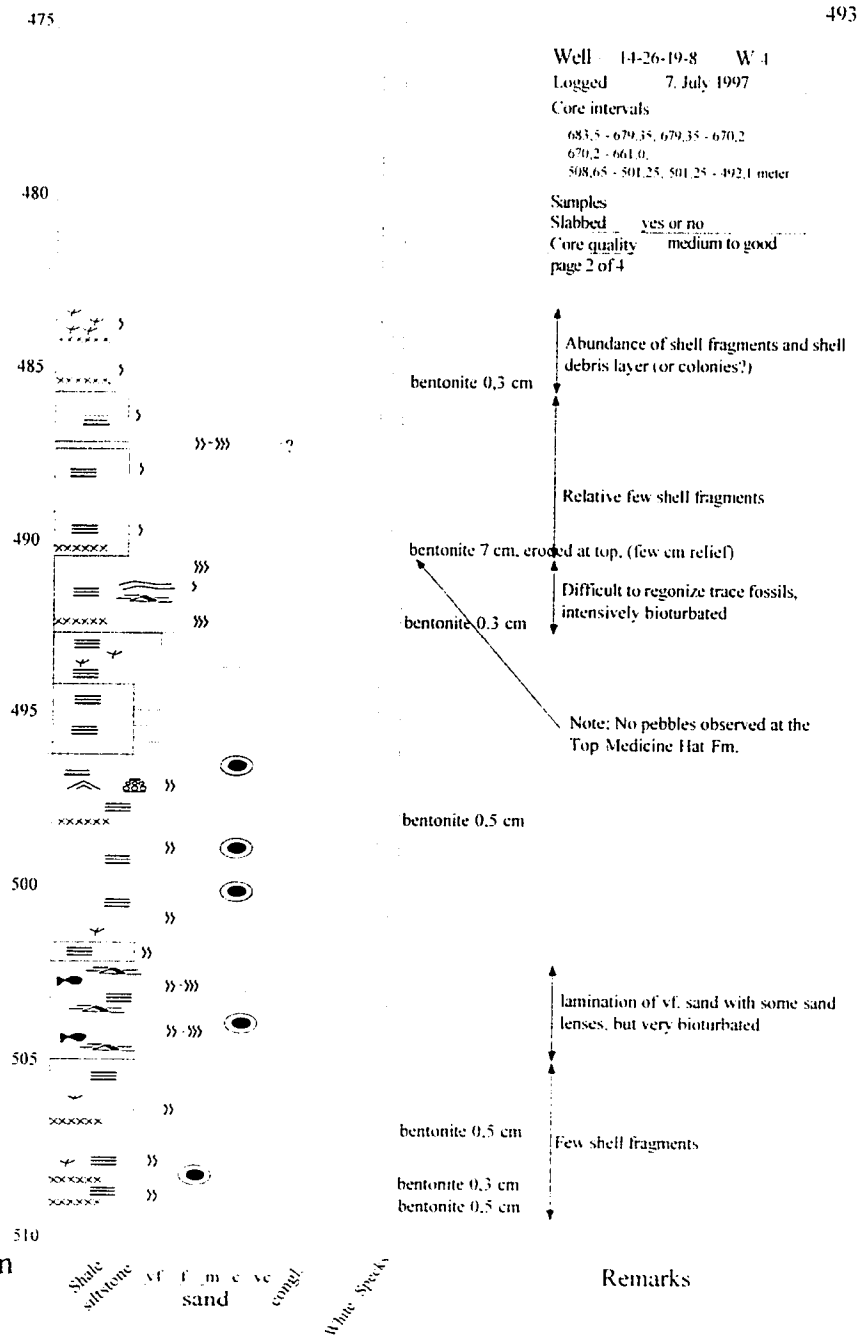
Few shell fragments, abundant white specks

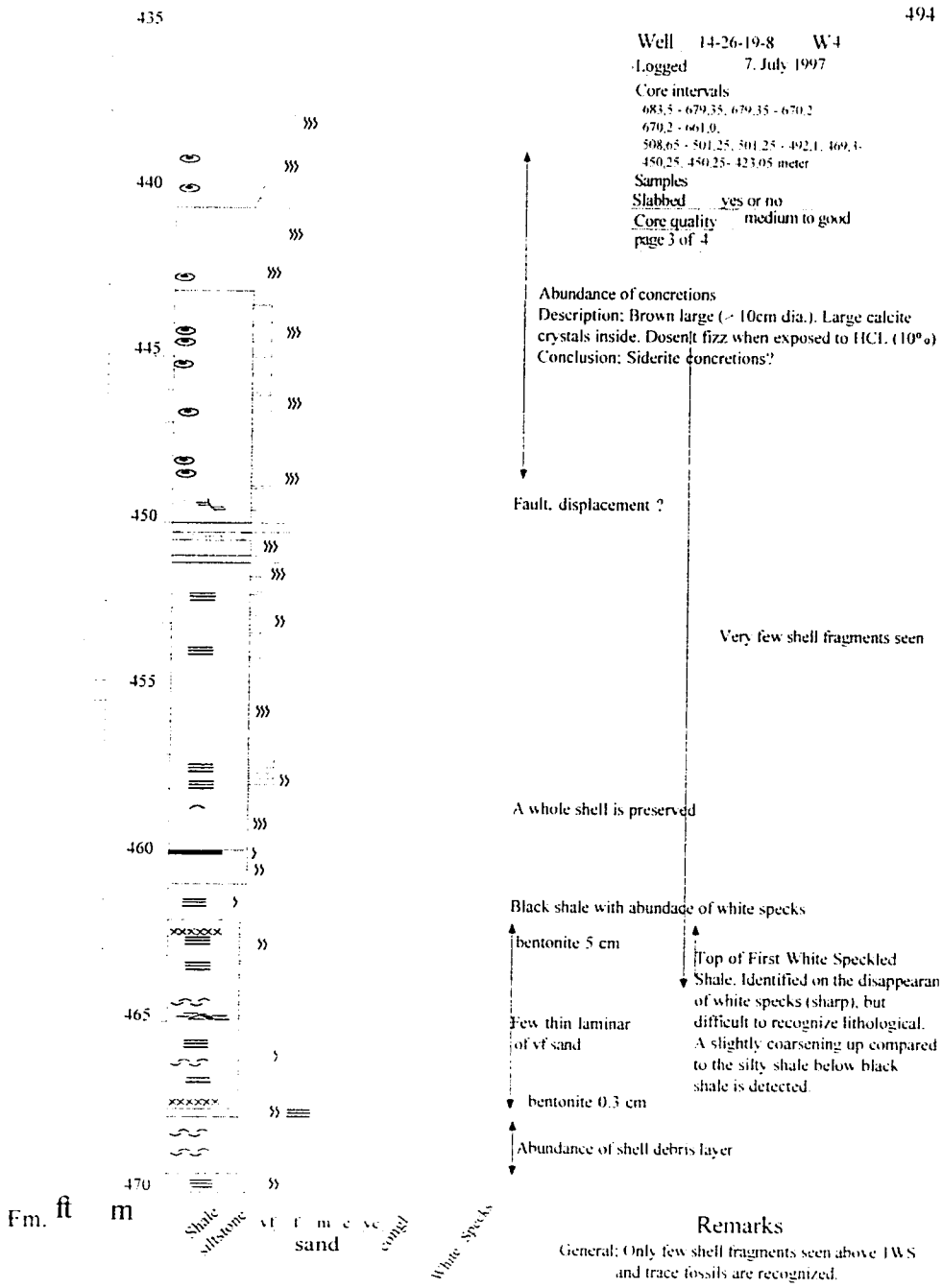
ft m

Shale siltstone vf f m c vc congl sand White Specks

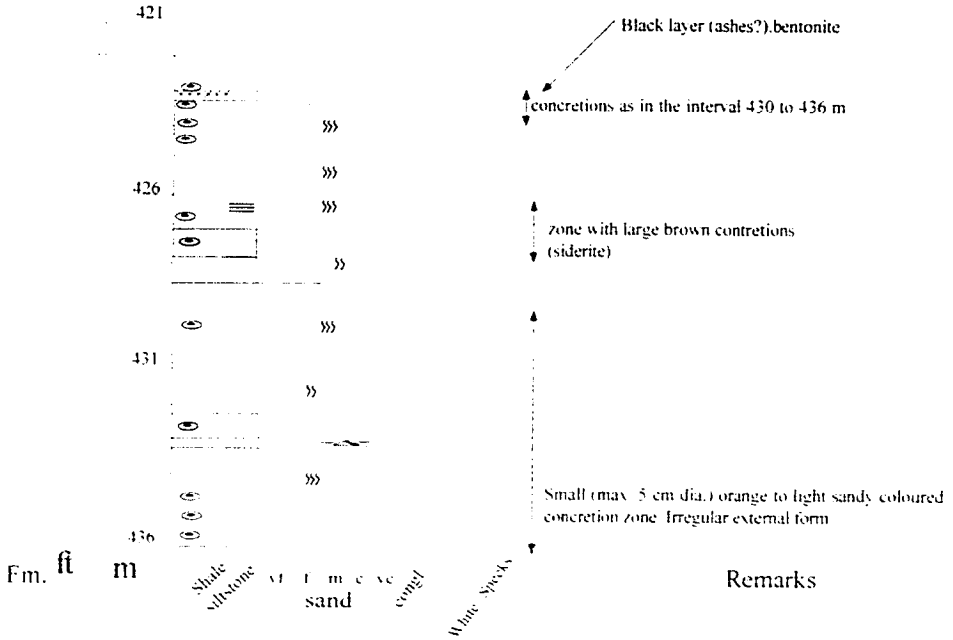
Remarks

Well 14-26-19-8 W 4
Logged 7. July 1997
Core intervals
683,5 - 679,35, 679,35 - 670,2
670,2 - 661,0,
508,65 - 501,25, 501,25 - 492,1 meter
Samples
Slabbed yes or no
Core quality medium to good
page 2 of 4




435
494
Well 14-26-19-8 W4
Logged 7. July 1997
Core intervals
683,5 - 679,35, 679,35 - 670,2
670,2 - 661,0,
508,65 - 501,25, 501,25 - 492,1, 469,3-
450,25, 450,25- 423,05 meter
Samples
Slabbed yes or no
Core quality medium to good
page 3 of 4
440
445
450
455
460
465
470
Abundance of concretions
Description: Brown large (~ 10cm dia.). Large calcite crystals inside. Dosen't fizz when exposed to HCL (10%)
Conclusion: Siderite concretions?
Fault, displacement ?
Very few shell fragments seen
A whole shell is preserved
Black shale with abundace of white specks
bentonite 5 cm
Top of First White Speckled Shale. Identified on the disappearan of white specks (sharp), but difficult to recognize lithological. A slightly coarsening up compared to the silty shale below black shale is detected.
Few thin laminar of vf sand
bentonite 0.3 cm
Abundance of shell debris layer
Fm.
ft
m
Shale
siltstone
vf f m c vc
sand
congl
White Specks
Remarks
General: Only few shell fragments seen above IWS and trace fossils are recognized.

Well 14-26-19-8 W4
Logged 7. July 1997
Core intervals
683.5 - 679.35, 679.35 - 670.2
670.2 - 661.9,
508.65 - 501.25, 501.25 - 492.1, 469.3-
450.25, 450.25- 423.05 meter
Samples
Slabbed yes or no
Core quality medium to good
page 4 of 4



Well 14-36-13-4 W 4
Logged 28. Janunary 1997
Core intervals 457 - 450 meter
450 - 400 meter
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 2

Niobrara Formation
Medicine Hat Member

ft m

422
427
432
437
442
447
452
457

Py

Gordia
Chondrites
Teichichnus

Trace fossils not recorded

shale siltstone vf f m c vc congl sand

White specks

Fine laminated with abundant white specks

Medium sand, with shell fragm.

Fish scales

Fish scales

Interval with many small pyrite filled concretions

Pyrite filled subvertical burrows
Muddraps on forset of ripples
Normal graded beds
Fine laminated vf sand

14-36-13-4

Low angled parallel lamination

Intensive bioturbated

Intensive bioturbated

Whole single shells

Elongated shell fragment
Many small broken shell fragments

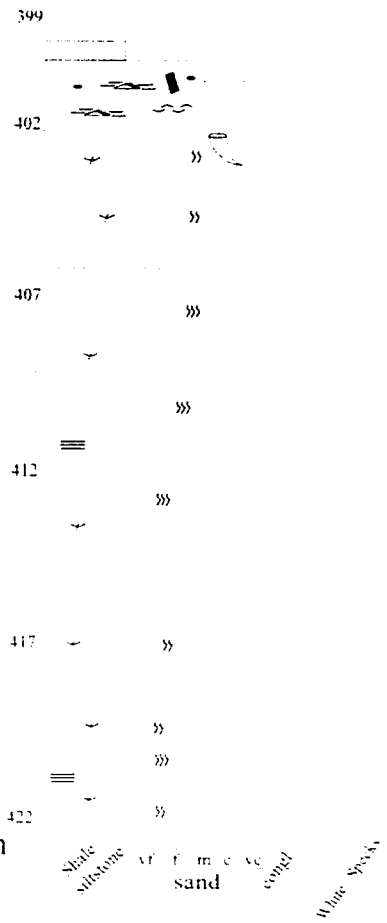
Fine laminated with some graded bedding

Remarks

Well 14-36-13-4 W 4
Logged 28. January 1997
Core intervals 457 - 450 meter
450 - 400 meter
Samples every one meter
Slabbed yes or no
Core quality medium to poor
page 2 of 2

First White Specks Member

Niobrara Formation
Medicine Hat Member



Lenticular bedding and less bioturbation at top.
Coal fragments and brown pebbles and shell debris layer identified.

Rosselia ?

Very bad core condition
Intensive bioturbated
Few to no primary sedimentary structures

Few broken shells,
no trace fossils identified

Remarks

Well 16-4-22-15 W 4
Logged 11. August 1997, KSN
Core intervals 568.0 - 531.25; 529.25 - 493.5; 493.5 - 457; 457 - 421 meter

Samples every one meter
Slabbed yes or no partly (493 - 484 m)
Core quality medium to good
page 1 of 5

533
538
543
548
553
558
563
568

Sid
By
Cal
Cuvdia

bentonite ~3 cm

bentonite (greenish to yellow) thickness ?
Zone of brown rusty concretions (siderite) and pyrite concretions. One concretion filled with white specks

bentonite (yellow) 5-7 cm

bentonite ~ 1 cm

bentonite, thickness ?

bentonite ~ 1 cm

bentonite ~ 5 cm

abundance of pyrite concretions, small ~ 0.5-1 cm
in some instance infilling horizontal borrows

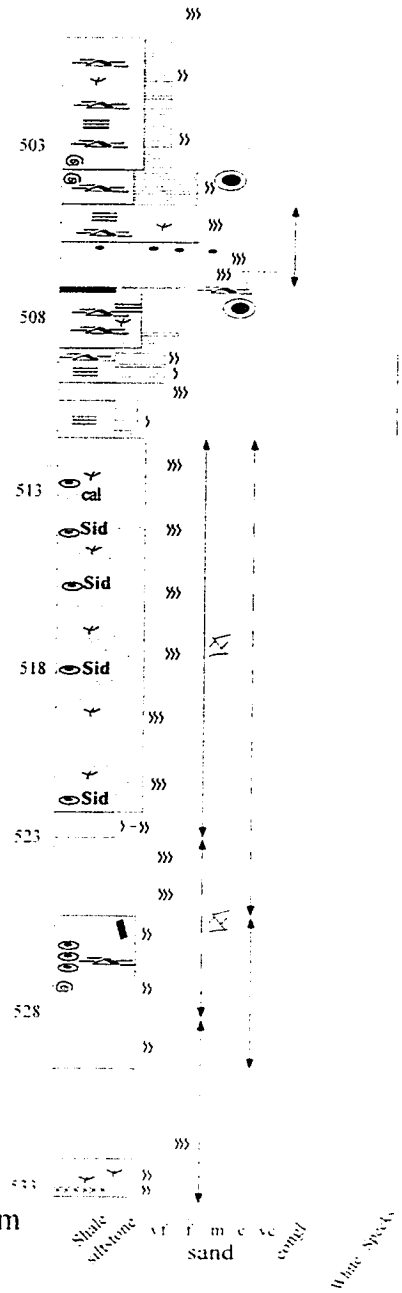
Calcite concretion, 15 cm dia.

bentonite ~ 20 cm

Fm. ft m Shale Siltstone vf f m c vc conglomerate sand White specks Remarks

498

Well 16-4-22-15 W 4 499
Logged 11. August 1997, KSN
Core intervals 568.0 - 531.25;
marked increase in bioturbation 529.25 - 493.5; 493.5 - 457; 457 - 421 meter
Samples every one meter
Slabbed yes or no partly (493 - 484 m)
Core quality medium to good
page 2 of 5



Remarks

Ammonites * 2; Scaphites novimevicanus

interbedded with thin shales
sharp boundary
pebbles, small back and brown

sharp lower boundary

First occurrance of white specks

Homogeneous, intensively bioturbated siltstone with terebell and gordia trace fossils throught the wholw interval. Siderite concretions with dia. of 5 - 15 cm.

brown concretion, siderite

coal fragment, 1 cm dia.

Siderite concretions
Ammonites (Scaphites aff. novimexicanus; Reeside, 1927)

bentonite, thin

Well 16-4-22-15 W 4

Logged 11. August 1997, KSN

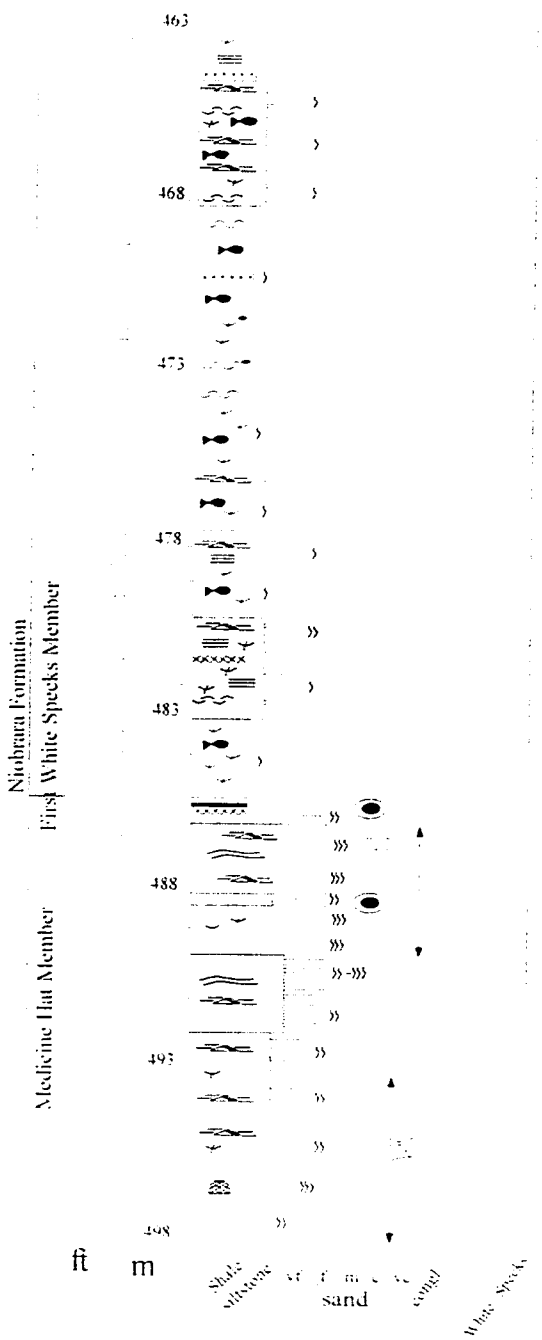
Core intervals 568,0 - 531,25; 529,25 - 493,5; 493,5 - 457; 457 - 421 meter

Samples every one meter

Slabbed yes or no partly (493 - 484 m)

Core quality medium to good

page 3 of 5



500

bentonite - 3cm

brown pebble

Shell debris layer with small brown pebbles

bentonite - 0.5 cm

bentonite - 5 cm

graded contact

hummocky bedding - 5 cm

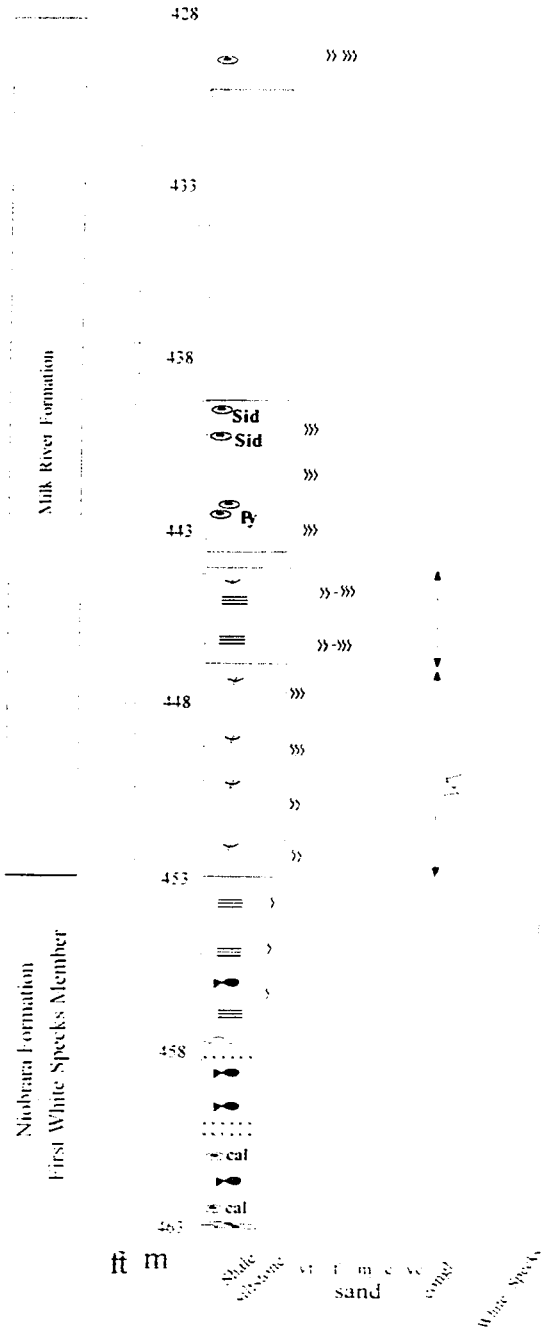
hummocky bedding - 5 cm

A few normal graded beddings

Remarks

Well 16-4-22-15 W 4
Logged 11. August 1997. KSN
Core intervals 568.0 - 531.25, 529.25 - 493.5, 493.5 - 457; 457 - 421 meter

Samples from 430 m to 421 only 2
Slabbed yes or no partly (493 - 484 m)
Core quality medium to good
page 4 of 5



Remarks

Intensively bioturbated

graded boundary, 75 cm above the last occurrance of white specks

last occurrance of white specks (453.4 m), 453.4 to 455.75 m white specks only in few laminars

few to no shell fragments

bentonite 4 cm

bentonite 3 cm
bentonite 1 cm

Well 16-4-22-15 W 4
Logged 11. August 1997, KSN
Core intervals 568,0 - 531,25;
529,25 - 493,5; 493,5 - 457;
457 - 421 meter

Samples from 430 m to 421 only 2
Slabbed yes or no partly (493 - 484 m)
Core quality medium to good
page 5 of

418

Milk River Formation

423

Sid

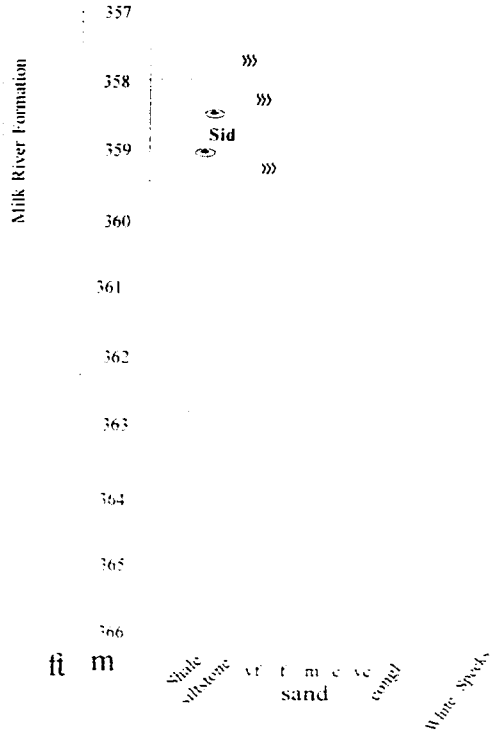
Sid

Many siderite concretions Large 15-20 cm dia

428

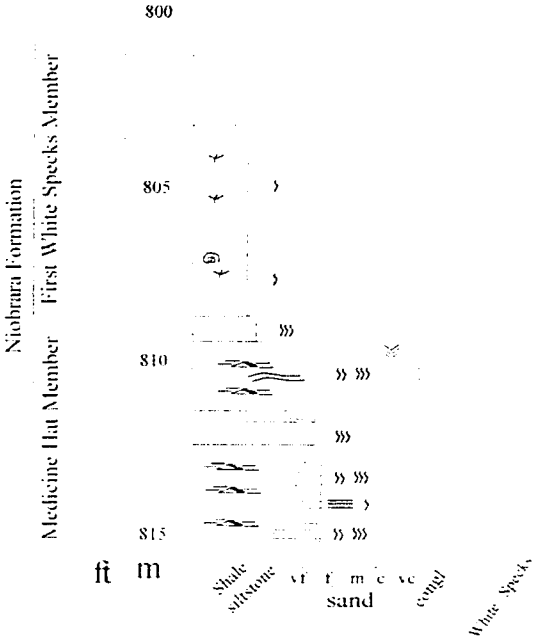
Fm. ft m Shale siltstone vf f m c vc sand congl White Specks Remarks

Well 16-18-13-7 W 4
Logged 18. August 1997
Core intervals 357-366m, rec. 2.5m
Samples
Slabbed yes or no
Core quality poor
page 1 of 1



Remarks

Well 16-20-24-21 W 4
Logged 10. June 1999
Core intervals [illegible]
Samples NO
Slabbed yes or no
Core quality good
page 1 of 1



General:

Possible that upper sand is one of the sands within the FWSS.

High fluctuation of energy without evidences of tidel processes.

Moderate to intensive bioturbated vf. to f sand with some interbedded shale and abundances of shale laminar. Muddraps on lenses abundant.

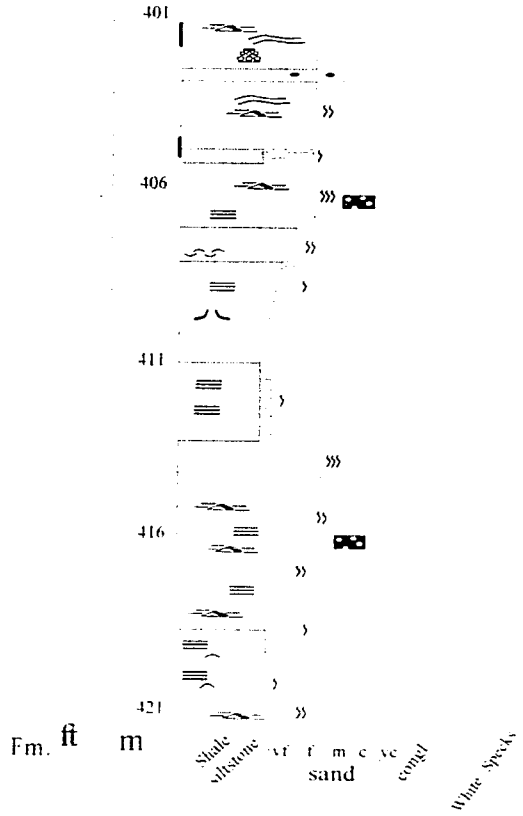
Ammonite

Mainly lenticular, but also some possible hummocky beds.

Plan laminated bed (10 cm).

Remarks

Well 16-23-12-4 W 4
Logged 16. June 1997. KSN
Core intervals 421 - 400 meter
Samples every one meter
Slabbed yes or no
Core quality medium to poor
page 1 of 1



Medium grain size with fish remains and coal fragments

shell debris layer

fine lamination, very limited bioturbation

sharp based lenticular bedding with muddrapes

Whole shell fragments

Remarks

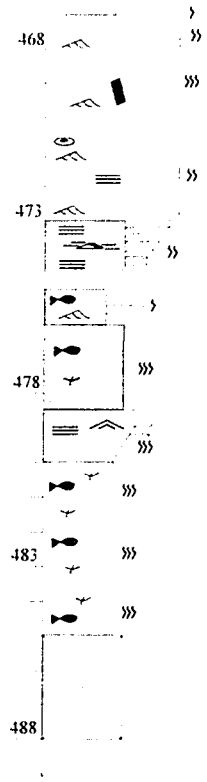
upto 2 cm crossbedding

Coal fragment well rounded

Red-brownish concretion, dia. 10cm, heavy = siderite?

Well	16-28-14-2 W 4
Logged	19. June 1997
Core intervals	467 - 476, 476 - 488 499,5 - 508 meter
Samples	every one meter
Slabbed	yes or no
Core quality	medium to pore

page 1 of 1

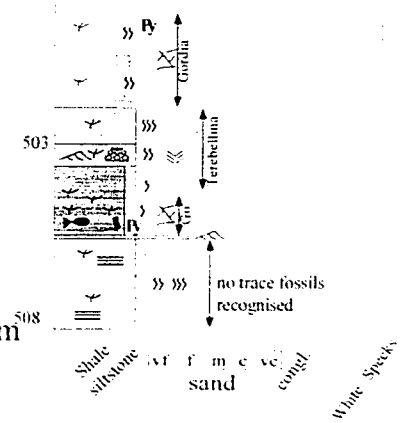


16-28-14-2

Fish bone

General;
Very bad core.
Very homogenous texture of silt to v.f. sand
Abundance of fish scale and fish fragments.
Asumped to be total bioturbated, but no trace fossil recognised.

498.



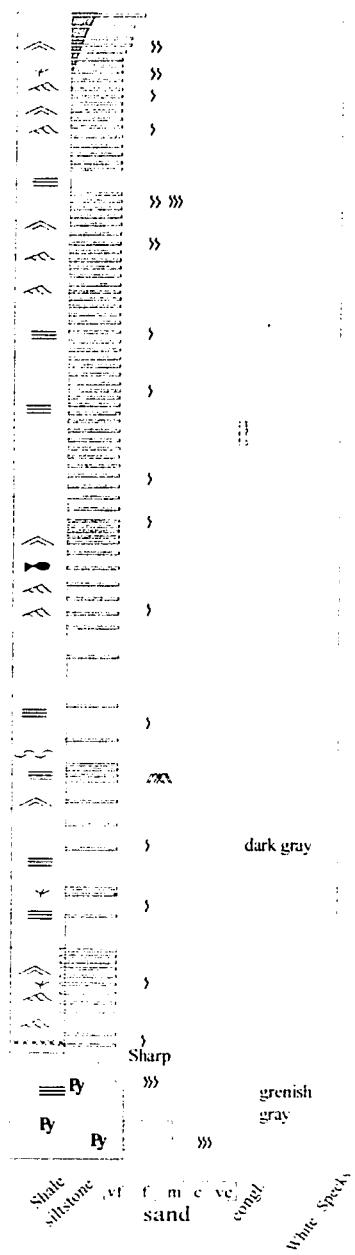
Abundance of Gordia + large horizontal borrows with pyrite

Escape structure through sand linse

Coal fragment, fish scales
3 cm sand, ripple

Remarks

Well 02-3-7-13-27 W 4
Logged 22. Marth 1999
Core intervals 5520-5571 ft, 5571-5622.5 ft
Samples Every 10 ft
Slabbed yes or no
Core quality good
page 1 of 2



graded fewer ripples mainly unidirectional ripples

zone of few lenses and laminar

Terrebellina

Ophiomorpha ?

Possible white specks

abundant fish scales

calcite layer, large crystals, ~ 2 cm

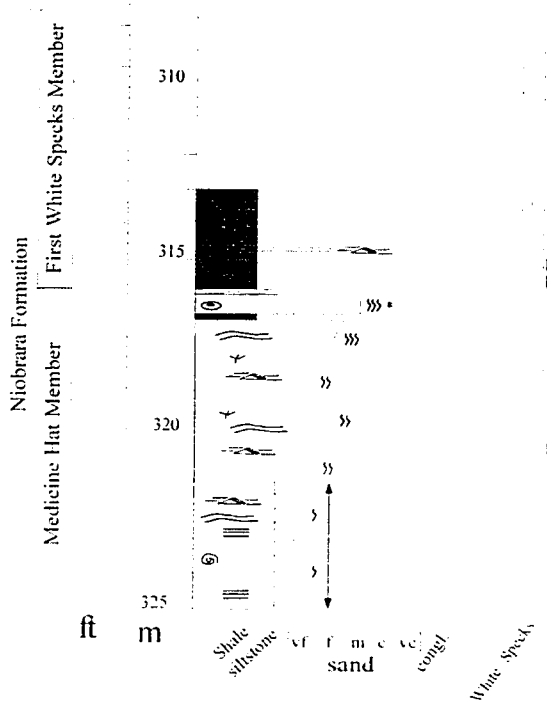
dark gray

wave ripple
broken inoceramus
unidirectional ripples
Bentonite
large vertical borrow, (10cm long, 1 cm dia)
abundance of pyrite infill
irregular infill of medium grain sand

Fm. ft m

Remarks

Well 7-13-10-8 W 4
Logged 12. June 1997. KSN
Core intervals 325-313 meter
Samples every one meter
Slabbed yes or no
Core quality Good
page 1 of 1



*: 15-20 cm massive sandstone, structureless, calcite cemented. Grain size fine to medium and well sorted. Mainly quartz and volcanic grains. A large calcite concretion is within the sandstone.

bentonite 4.5 cm
fish remains

bentonite, 1 cm
bentonite, double with 3mm shale between, 4 cm
concretion, large calcite

hummocky beds up to 5 cm, with no bioturbation, in an interval with intensive biot.

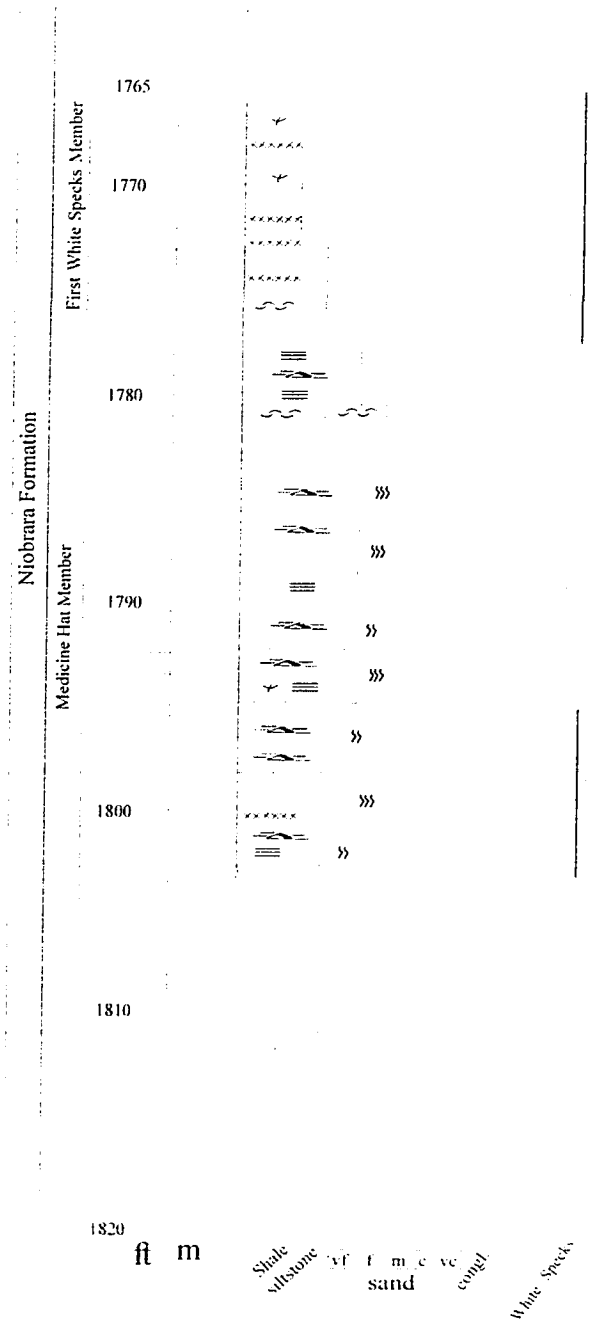
lenticular and hummocky bedding

thin hummocky beds

ammonite

Remarks

Well 16-10-15-1 W 4
Logged 24 June 1997
Core intervals 1766-1816 ft.
Samples yes
Slabbed yes or no
Core quality medium-good
page 1 of 1



Remarks

Well 10-23-14-30 W3
Logged 27. August 1997. KSN
Core intervals 1582-1561, 1520-1525 ft
Samples
Slabbed yes or no
Core quality medium to poor
page 1 of 1

1512

1522 » lenticular bedding
› fine lamination
↑ upwards increase in sand

1532

1542

1552

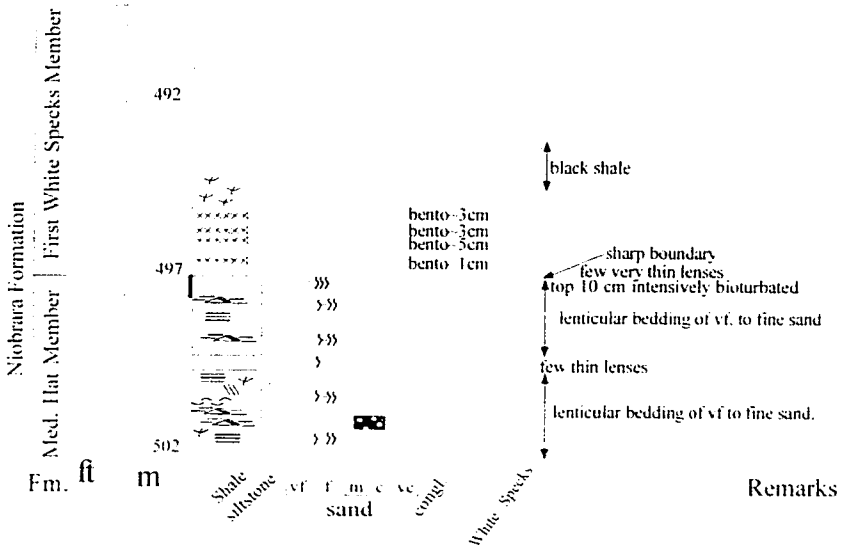
1562 bentonite 1cm
bentonite 0.5cm convolute sandlense
bentonite 2cm
few black pebbles

1572 » »
» »
› »

1582 »

Fm. ft m Shale siltstone vf f m c vc cmgl sand White Specks Remarks

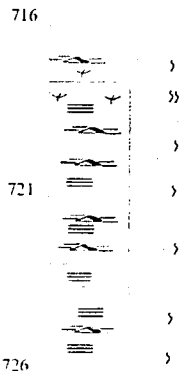
Well 13-9-14-28 W5
Logged 26. August 1997. KSN
Core intervals 493-502 m
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1



Well 10-3-5-26 W 3
Logged 25. August 1997
Core intervals 868-859; 726-717m
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 2

General: White Specks seen throught the whole core.
Slightly to no bioturbation

Niobrara Formation
First White Specks Member
Medicine Hat Member



single 2 mm sand lense
sharp boundary
large fragment of Inoceamus

ft m Shale Siltstone vf f m c vc congl sand White Specks Remarks

Well 11-10-10-28 W 3
Logged 27. August 1997. KSN
Core intervals 628 - 619 meter
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1

General: Silty shale
Only sand observed in lower part
very swally clay. Goes out of boxes.
The low gamma ray on the petrophysic
log in the interval 616 to 620 is not observed
as a sandy interval in the core.

Niobrara Formation
First White Speeks Member

ft m

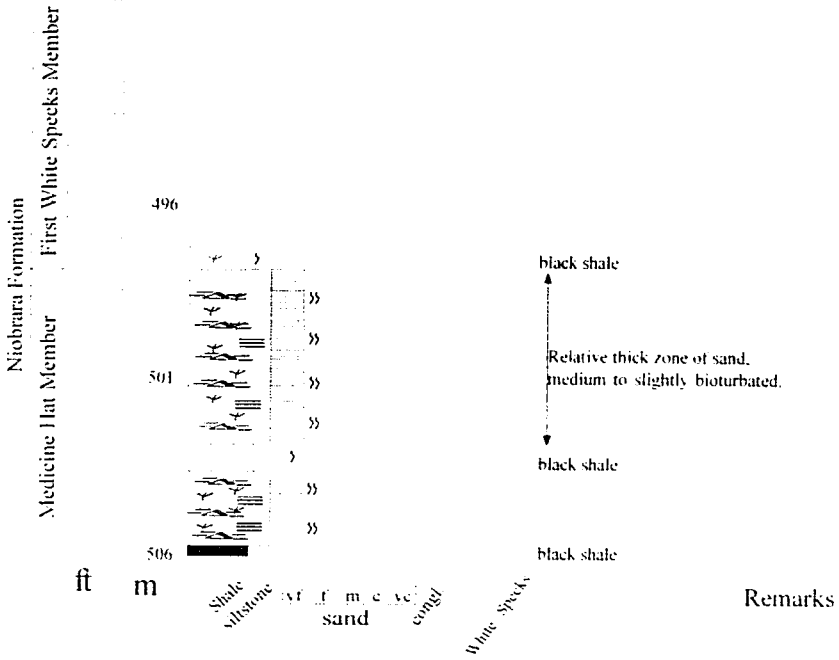
608
613
618
623
628

Shale
siltstone
vf f m c vc
sand
congl
White Speeks

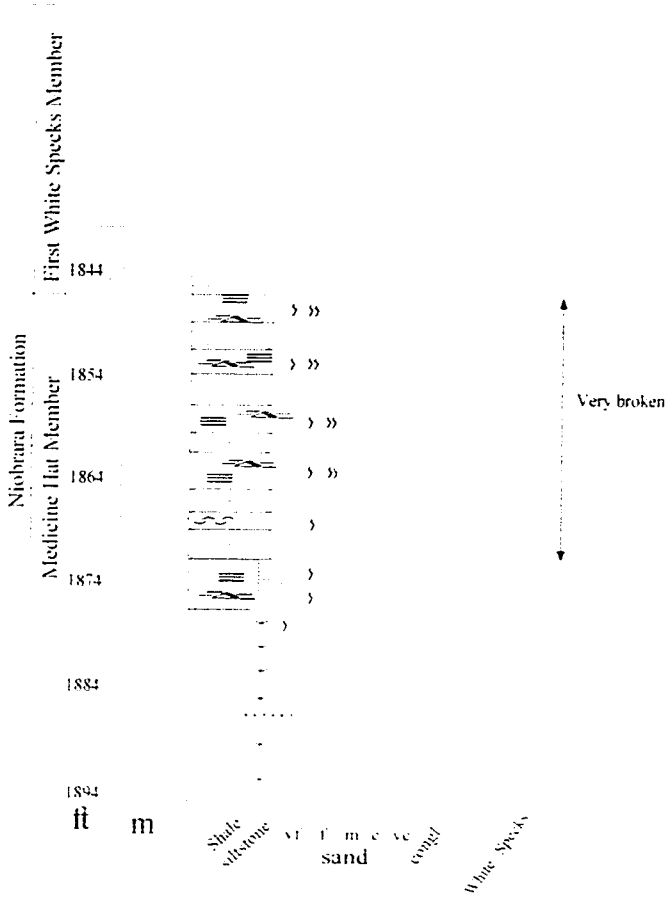
Abundance of shell fragments
Sand lenses and laminar

Remarks

Well 8-7-15-28 W 3
Logged 28. August 1997
Core intervals 506 - 497 m
Samples every one meter
Slabbed yes or no
Core quality medium to bad
page 1 of 1



Well 7-31-16-29 W 3
Logged 28. August 1997, KSN
Core intervals 1894 - 1845 ft
Samples every one meter
Slabbed yes or no
Core quality medium to poor
page 1 of 1



Remarks

Well 6-13-14-29 W3
Logged 27. August 1997. KSN
Core intervals 482-473 meter
Samples every one meter
Slabbed yes or no
Core quality medium
page 1 of 1

Niobrara Formation
Medicine Hat Member

472 Sharp boundary

477

482

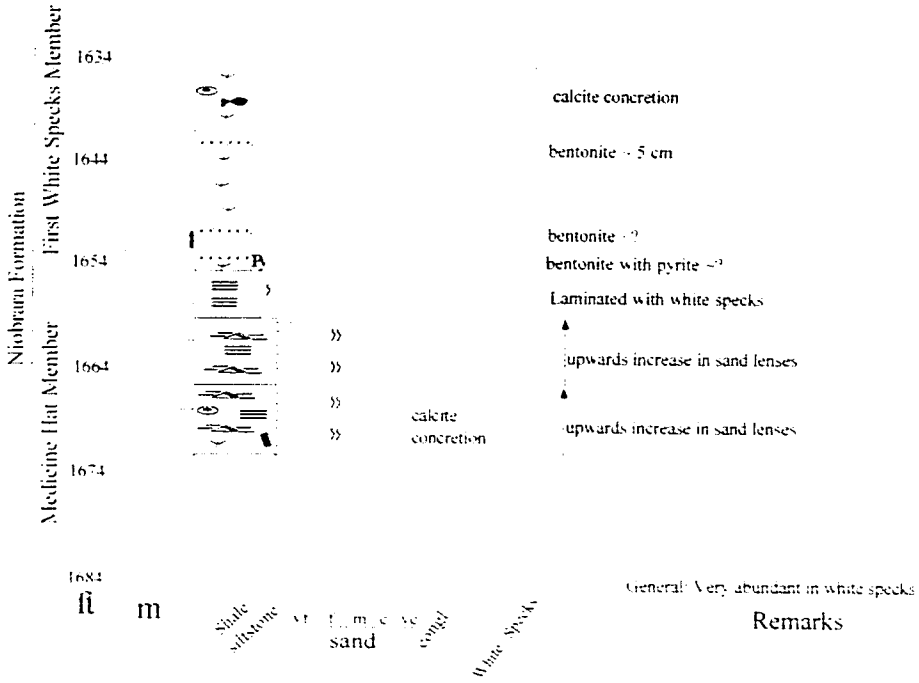
ft m

Shale
siltstone
sand
congl
White Specks

Intensive bioturbated sand 1.5 m above "MH" Siphonites very commen.

Shale with abundance of white specks.

Some ripples look like unidirctional ripples.
Upwards increase in ripples and in size of ripples, from thin (mm) to 2 cm high
All with muddrape

Remarks

Well 6-11-18-29 W3
Logged 26. August 1997, KSN
Core intervals 1684- 1635 ft
Samples every one meter
Slabbed yes or no ?
Core quality ?
page 1 of 1