University of Alberta

Regional Hydrogeology of Southwestern Saskatchewan

by

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Abstract

Twelve deep aquifers and 12 aquitards were defined in southwestern Saskatchewan. Four major water types were identified: Type 1 (Ca-SO_4) freshwaters, found in Paleozoic aquifers; Type 2 (Na-Cl) brines, found in all aquifers; Type 3 (Na-SO_4) waters, mixture of Type 1 and Type 2 waters; and Type 4 (Na-HCO_3) meteoric waters, found mainly in Mesozoic aquifers. Total Dissolved Solids range from >300 g/L in Paleozoic aquifers to <25 g/L in Cretaceous and shallow aquifers. Fluid flow in the Paleozoic aquifers is directed towards the north. Water in the Lower Cretaceous aquifers flows from the Alberta Basin towards the east and northeast. Fluid flow in the Upper Cretaceous aquifer is controlled by local topography. Significant density effects exist in the Lower Paleozoic aquifers only. Hydrodynamic effects on hydrocarbon accumulations have been observed in the Jurassic and Lower Cretaceous aquifers.

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Chapter 1 – Introduction

1.1 Background and Motivation

The Williston Basin (Figure 1.1) is rich in petroleum, fluids containing mineral salts, and metals to some degree. Understanding how these fluids migrate through the basin is essential for understating how various mineral and petroleum deposits formed and can provide clues for further exploration. Comparison of hydrochemical compositions and distributions of these formation waters is useful in understanding of the regional subsurface fluid migration and evolution (Chebotarev, 1955; Back, 1961; Clayton et al., 1966; Collins, 1975; Tóth, 1984; Hanor, 1994).

The deep hydrogeology of the Williston Basin has been previously studied both in the USA and Canada. During the 1980's the US Geological Survey conducted a series of regional-scale hydrogeologic studies in the USA portion of the Williston Basin spanning across North Dakota, South Dakota, and parts of Montana and Wyoming (Downey, 1982, 1984; Bredehoeft et al., 1983; Downey et al., 1987; Downey and Dinwiddie, 1988; Berg et al., 1994; DeMis, 1995; LeFever, 1998). Downey and Dinwiddie (1988) defined five major aquifer units in the Williston Basin portion of the USA (in ascending stratigraphic order): AQ1 – Cambrian/Ordovician, AQ2 – Lower Mississippian, AQ3 – Pennsylvanian, AQ4 – Lower Cretaceous, and AQ5 – Upper Cretaceous/Tertiary. They stated that meteoric water enters the basin from uplifted areas and is gravity-driven to depth where it becomes hypersaline (TDS >300 g/L) by dissolving formation salts. The recharge zones are located in the southwestern parts of the basin (Montana and Wyoming) with flow direction towards the north and northeast.

In Canada, several regional scale hydrogeological studies covering all or parts of the Williston Basin have been conducted (Hitchon, 1969a, 1969b; Hannon, 1987; Bachu and Hitchon, 1996). Bachu and Hitchon (1996) identified seven major aquifer systems (in ascending stratigraphic order): Basal (Cambrian/Ordovician), Winnipegosis, Devonian, Lower Mississippian, Mannville, Viking, and Upper Aquifer System (Upper Cretaceous, Tertiary, and Quaternary). The groundwater flow in these aquifers is driven by basin scale topography towards north and northeast. Basinal brines are mixed with refluxing Pleistocene-age glacial melt water and discharge into the saline springs of Manitoba (Grasby et al, 2000; Grasby and Betcher, 2000; Grasby and Chen, 2005).

Recent studies have shown that the existing hydrostratigraphy is generalized and needs significant refinement (Toop, 1992, Benn and Rostron, 1998; Rostron and Holmden, 2000; Iampen, 2003; Khan, 2006; Jensen, 2007; Palombi, 2008). However, these studies were either limited to a single aquifer (e.g., Birdbear Aquifer in Alkalali, 2002, and Red River Aquifer in Margitai, 2002) or limited to a specific area (mostly southeastern Saskatchewan). There has not yet been any detailed hydrogeological characterization done for the entire Phanerozoic strata of southwestern Saskatchewan.

1.2 Objectives

This thesis is part of a larger project named the Saskatchewan Phanerozoic Fluid and Petroleum Systems Assessment (SPFPS) co-ordinated by the Petroleum Technology Research Centre (PTRC) in Regina, Saskatchewan. The results of this study will be used for petroleum exploration, geothermal energy exploration and development, assessment of CO_2 sequestration potential, and groundwater management and allocation.

The objectives of this study are to:

1. Define the detailed hydrostratigraphic framework for southwestern Saskatchewan using the most recent geologic framework provided by Saskatchewan Ministry of Energy and Resources (SMER).

2. Characterize the regional groundwater flow system in southwestern Saskatchewan through detailed mapping of fluid potential and hydrochemistry using newly available data.

3. Identify regions of, and quantify, density-dependent flow in southwestern Saskatchewan.

4. Examine the influence of groundwater flow on hydrocarbon migration and entrapment in southwestern Saskatchewan.

The chosen study area ranges from Townships 1 to 38 and Ranges 12 to 30 west of the Third Meridian (Figure 1.2). Two additional townships (not shown) on each side of the study area were incorporated in order to eliminate contouring edge effects and for better regional correlation.

Twelve aquifers have been defined within the study area (as opposed to seven aquifers previously defined by Bachu and Hitchon, 1996) and are described in detail in Chapter 2. Pressure and chemistry data obtained from drill-stem tests and water analysis reports were compiled for each aquifer (Chapter 3). These data were culled for poor quality, production-influenced pressures and contaminated chemical data to ensure that only representative values were used to produce the final maps. The detailed methodologies and results of chemistry and pressure data analyses are presented in Chapters 4 and 5, respectively, and Appendix A. The results are supplemented with the hydrogeological synthesis and discussion in Chapter 6.

This study has also produced an integrated and complete suite of hydrogeological data and maps for each aquifer that are consistent with the recent work performed in the rest of the basin by the University of Alberta hydrogeological group (Iampen, 2003; Khan, 2006; Jensen, 2007; Palombi, 2008). The results are presented in the form of:

1. Hydrostratigraphic chart for southwestern Saskatchewan (Figure 2.1).
2. Total Dissolved Solids (TDS) distribution maps (Figures 4.1 – 4.12) and detailed hydrochemical analyses (Figures 4.13 – 4.24, Appendix B).
3. Density-dependent and freshwater flow maps (Figures 5.1 – 5.12) and pressure-elevation plots (Figures 5.13 – 5.16).
4. Representative vertical hydraulic and TDS cross-sections (Appendix C).

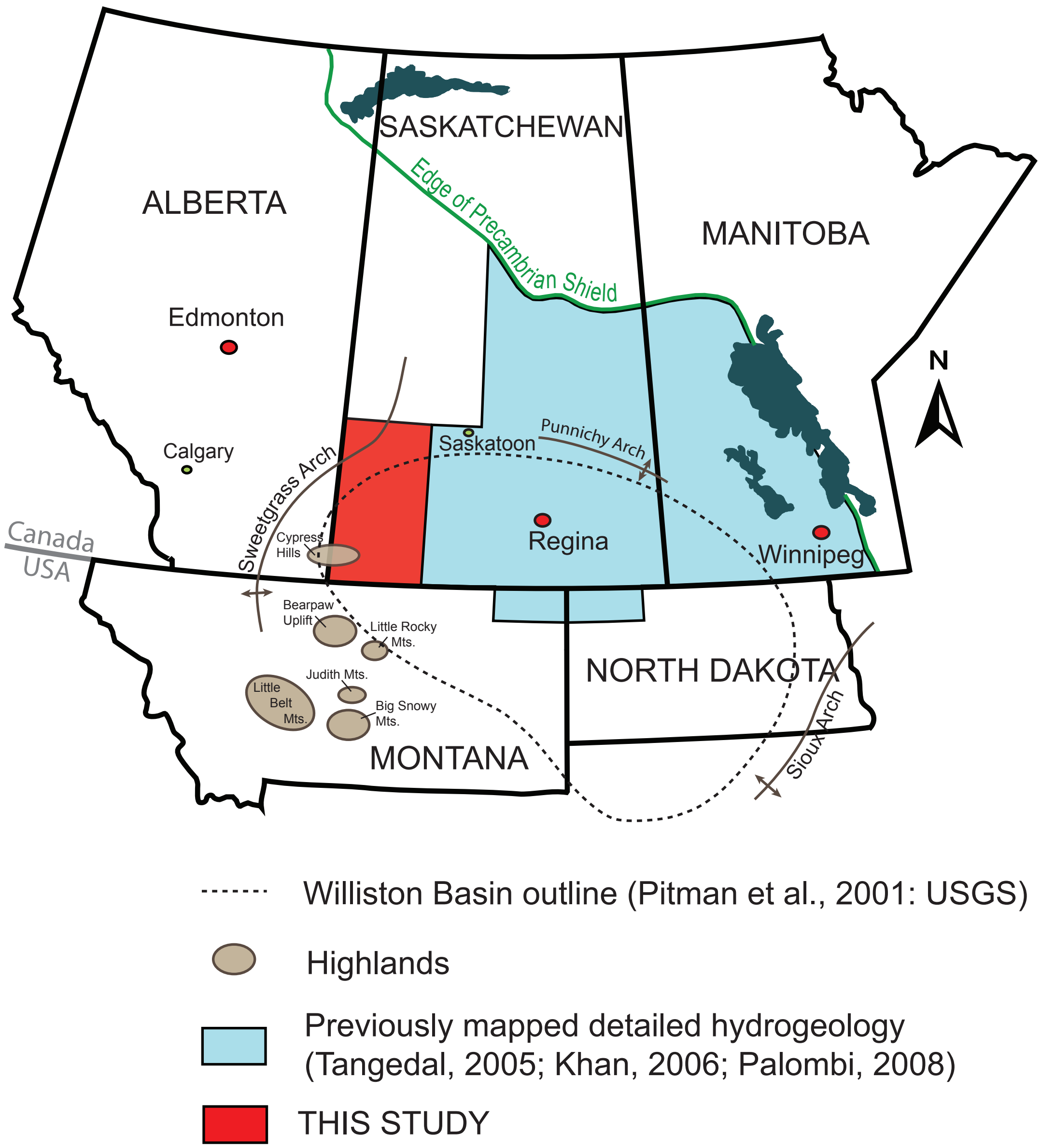

Figure 1.1: Locations of the previous and present study areas.

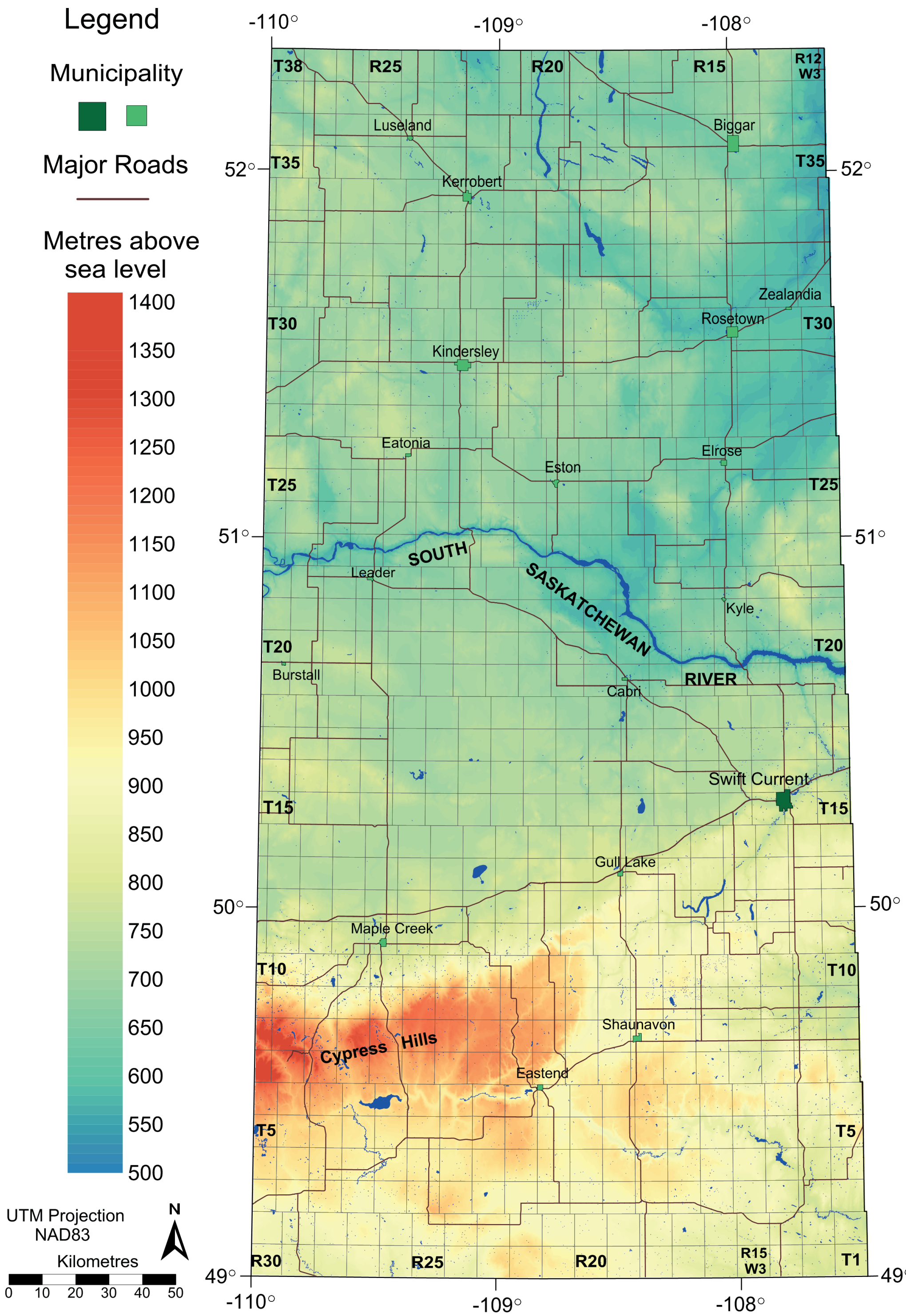

Figure 1.2: Topographic map of the study area showing major rivers, lakes, roads and municipalities (DEM from GeoBase, grid and other features from GeoScout).

CHAPTER 2 – Geology and Hydrostratigraphy

2.1 Regional Geology

The geology of the Williston Basin has been extensively studied both in Canada and the United States, e.g. Carlson and Anderson (1965), Peterson and MacCary (1987), Mossop and Shetsen (1994). The most recent "Regional Stratigraphic Framework of Western Saskatchewan" was completed by Marsh and Heinemann (2005) at the Saskatchewan Ministry of Energy and Resources (SMER). Their work was fully integrated into this study for consistent interpretation of geology and hydrogeology of the study area. Only a summary of geology relevant for this study in the context of hydrogeology is provided.

The Williston Basin is a thick (up to 4500 m), bowl-shaped, intracratonic, sedimentary basin with its depositional centre in western North Dakota (Peterson and MacCary, 1987; Figure 1.1). It is bounded by large structural highs: Sweetgrass Arch to the west and northwest; Sioux Arch to the east and southeast; Punnichy Arch to the north and northeast; and highlands of Montana to the south and southwest.

The subsidence and development of the Williston Basin began in Late Cambrian to Early Ordovician periods and continued until Late Cretaceous (Kent and Christopher, 1994). The basin contains a relatively complete sedimentary package ranging from Late Cambrian to Quaternary periods. Paleozoic strata are dominated by carbonate sediments and evaporitic sequences with minor clastic sediments in the Cambrian Period. The Mesozoic and Cenozoic strata are dominated by clastic sediments with minor carbonates in the Jurassic Period.

2.2 Lithostratigraphic Framework

The following is the detailed lithological description of the geologic strata (Figure 2.1) relevant for this study area.

2.2.1 PRECAMBRIAN

The Precambrian surface represents a regional unconformity at the base of the basin and dips south towards Canada-US border. In the southwestern corner, the Precambrian surface dips towards east and north east, away from the structural high of the Sweetgrass Arch. The Precambrian rocks consist of igneous and metamorphic rocks with the top being heavily weathered. Wright et al. (1994) and Kreis et al. (2004) provide more detailed information regarding the Precambrian surface in Alberta and Saskatchewan.

2.2.2 CAMBRIAN

The Cambrian strata consist of the Deadwood Formation. The bulk of the formation is composed of shales and siltstones, and minor sandstone intervals. The lowermost part of the Deadwood Formation is represented by highly permeable quartz sandstone which covers most of the study area (Kent, 1994; Kreis et al., 2004). The Deadwood Formation ranges in thickness from 200 m in the southwest to almost 500 m in the northwest (Marsh and Heinemann, 2005).

2.2.3 ORDOVICIAN-SILURIAN

The Ordovician and Silurian strata consist of the Bighorn Group and Interlake Formation.

BIG HORN GROUP

The Big Horn Group (Red River, Stony Mountain, and Stonewall formations) unconformably overlies the Deadwood Formation and represents the lowermost carbonate-dominated units in the study area. This group thickens towards Williston Basin centre reaching 150 m in thickness in the southeastern corner of the study area (Marsh and Heinemann, 2005). The lowermost Red River Formation is composed of heavily burrowed fossiliferous limestones, dolostones and evaporites reaching up to 50 m in thickness in the southeast of the study area (Kreis et al., 2004). The Stony Mountain Formation is composed of argillaceous dolomitic limestones and mudstones and evaporite sediments (Kreis et al., 2004). Lastly, the Stonewall Formation is characterized by fossiliferous dolomitic mudstones and shales and anhydrites (Kreis et al., 2004). The Stonewall Formation thickens towards the southeast reaching 25 m and is completely absent in the southwest of the study area.

INTERLAKE FORMATION

The Lower Silurian Interlake Formation conformably overlies the Big Horn Group. It is characterized by a sequence of shallow-water carbonates with minor evaporites (Kreis et al., 2004). This formation is composed of interbedded fossiliferous dolomitic mudstones and wackestones. It thickens up to 50 m towards the east and is completely absent in the west (Figure 2.2) due to truncation by the sub-Devonian unconformity (Marsh and Heinemann, 2005; Kreis et al., 2004).

2.2.4 DEVONIAN

ELK POINT GROUP

The Upper Silurian-Lower Devonian transgression resulted in deposition of the Elk Point Group (Meijer Drees, 1994). The Ashern Formation is the oldest formation of the Elk Point Group that unconformably overlies the Interlake Formation. Its thickness varies from 0 to 20 m in the study area reaching up to 30 m north of Lloydminster (Marsh and Heinemann, 2005). It is completely absent near Swift Current (Figure 2.2). This formation is composed of the lower red-brown, massive, dolomitic mudstone and the upper medium to dark-grey, pyritic, argillaceous dolostone. It completely lacks fossils and has very few depositional structures. The deposition is thought to have occurred through direct precipitation of calcium carbonate from the hypersaline shallow sea (Kendall, 1975; Lobdell, 1984; Kent and Haidl, 1993).

The Winnipegosis Formation conformably overlies the Ashern Formation. It was originally subdivided by Jones (1965) into the lower and upper members: a Lower carbonate/platform member (Elm Point Member of Kendall, 1975) that is of relatively uniform thickness of up to 30 m and composed of fossiliferous, organic-rich dolostones or packstones. It is absent in the southwestern corner of the study area (Marsh and Heinemann, 2005). The upper member of the Winnipegosis Formation is present only in the northeastern part of the study area and consists of more than 100 m thick dolomitized reef mounds. The mounds are composed of peloidal wackestones and grainstones (Jones, 1965; Kendall, 1975). Another unit, the Ratner Member, was deposited between the reef mounds and composed of dolomitic laminated mudstone and anhydrite (Kendall, 1975; Gendzwill and Wilson, 1987; Kent and Haidl, 1993; Meijer Drees, 1994; Fu et al., 2005). The Winnipegosis formation is capped by the Whitkow Salt of the Prairie Formation (Holter, 1969).

The Prairie Formation overlies the Winnipegosis Formation. It is up to 200 m thick in the north and northeast of the study area, in particular the inter-reef areas of Upper Member of Winnipegosis Formation, but completely absent in the south-southeast due to dissolution. The Prairie Formation is subdivided into three members: The lowermost Whitkow Member is present between the Winnipegosis reef mounds and composed of a sequence of salt and anhydrite

(Holter, 1969). Overlying the Whitkow Member is the Shell Lake Member; it is present throughout the area and composed of massive anhydrite (Gendzwill and Wilson, 1987). The uppermost Leofnard Member is up to 100 m thick and consists of several members composed of halite and sylvite described by Holter (1969) and Fuzesy (1983) in detail.

MANITOBA GROUP

The Manitoba Group consists of two formations: Dawson Bay and Souris River formations. The Dawson Bay Formation represents a single transgressive carbonate-evaporate cycle (Peterson and MacCary, 1987; Oldale and Munday, 1994). This cycle consists of four members: 1) Second Red Bed – approximately 10 m thick layer of very fine grained dolomitic mudstone; 2) Burr Member – fossiliferous, dolomitic limestone with several hardgrounds; 3) Neely Member – organic rich, halite cemented, fossiliferous limestone; 4) Hubbard Evaporite – up to 14 m thick halite layer restricted to a relatively small area south-east of Saskatoon.

The Dawson Bay Formation ranges from 5 m thick in the south, west, and northwest to 40 m thick in the eastern part of the study area. Dissolution of the Prairie Evaporite at the base of Second Red Bed resulted in collapse structures and normal faulting or fracturing of the overlying formations, contributing to hydraulic connectivity of the Manitoba Group (Dunn, 1982; Braun and Mathison, 1986; Oldale and Munday 1994; Kendall, 2000; Marsh and Heinemann, 2005).

The Souris River Formation conformably overlies the Dawson Bay Formation and is 40 – 200 m thick in most of the study area. It represents regressive depositional phase of the Manitoba Group and consists of carbonate-evaporite sequences (Lane, 1964). The three members identified are Davidson, Harris and Hatfield Members. The Davidson Member is composed of one carbonate cycle with the First Red Bed at the bottom, followed by limestone, and capped by Davidson Evaporite. The other two members also contain similar cycles described in much greater detail by Lane (1964).

SASKATCHEWAN GROUP

The Saskatchewan Group conformably overlies the Manitoba Group. It represents the thickest Devonian carbonate succession and comprises two formations: Duperow and Birdbear. The Duperow Formation has an average thickness of 200 m with local highs of up to 300 m concentrated in the west-central part of the study area (Marsh and Heinemann, 2005). Kent (1968) has subdivided the Duperow Formation into four members (in ascending order): Saskatoon, Eltstow, Wymark, and Seward. The primary lithology of the

Saskatoon, Wymark, and Elstow members is fossiliferous limestone with variable amounts of dolomite, anhydrite and argillaceous limestone. The Seward Member is composed of widespread argillaceous limestone and shale. Detailed descriptions can be found in Kent (1968), Dunn (1975), Lake (2004), and Cen and Hersi (2006).

The Birdbear Formation is present throughout most of the study area and subcrops underneath Cretaceous sediments between Townships 38 and 40 (Figure 2.2). Generally the Birdbear Formation is less than 40 m thick with local reefal buildups up to 60 m (Marsh and Heinemann, 2005). It is subdivided into upper and lower members (Kent, 1968). The lower member is predominantly composed of limestones, dolomitic limestones, and dolomites and the upper member is composed of dolomites and interbedded anhydrites (Halabura, 1982; Whittaker and Mountjoy, 1996).

THREE FORKS GROUP

The Three Forks Group consists of three formations: Torquay, Big Valley and Bakken. All three formations subcrop beneath the Cretaceous sediments in the north (Figure 2.2). The Three Forks Group represents a transgressive stage of advancing Late Devonian to Early Mississippian seaway. The Devonian-Mississippian boundary is placed within the Bakken Formation (Peterson and MacCary, 1987).

The Torquay Formation conformably overlies the Birdbear Formation and is composed of massive dolostone, shale and anhydrite. Its thickness varies from 15 m in the north subcrop edge up to 65 m in the central part of the study area. A more detailed description of this formation can be found in Christopher (1961).

Conformably overlaying the Torquay is the Big Valley Formation. Its thickness varies from 8 m at the northern subcrop to over 40 m south of Saskatoon. Lithologically, the Big Valley Formation is composed of silty shale and massive mudstone (Christopher, 1961).

The Bakken Formation unconformably overlies the Big Valley and Torquay formations. It is of Upper Devonian to early Lower Mississippian age and well-correlated regionally (Smith and Bustin, 2000). According to recent geological studies and mapping (Marsh and Heinemann, 2005), the thickness of the Bakken Formation varies from 5 to 55 m and it is not present at the northernmost part of the study area. It consists of three members: 1) Lower Bakken Member, 2) Middle Bakken Member, and 3) Upper Bakken Member (Christopher, 1961). The Lower and Upper Bakken members are composed of finely laminated, organic rich, black mudstones. They are interpreted to be deposited in anoxic conditions of deep marine waters. The Middle Bakken member consists of several interbedded layers of mudstone, siltstone and fine sandstone interpreted as shoreface deposits (Smith and Bustin, 1998; 2000).

2.2.5 MISSISSIPPIAN

MADISON GROUP

Mississippian strata in southwestern Saskatchewan belong to the Madison Group. Lowermost is the Lodgepole Formation and it covers most of the study area except for the northern parts, where it is truncated by sub-Cretaceous unconformity (Figure 2.2). The overlying middle and upper parts of the Madison Group (Mission Canyon and Charles formations) are present only in the southeastern corner of the study area. The upper boundary of the Madison Group is truncated by sub-Mesozoic unconformity. The Madison Group is composed of limestone, lime mudstone, and calcite cemented sandstone together reaching up to 200 m in thickness in the central and southern parts of the study area (Kent, 1974).

2.2.6 TRIASSIC-JURASSIC

WATROUS FORMATION

The Watrous Formation represents the earliest Mesozoic sediments in the Saskatchewan Williston Basin (Carlson, 1968; Kent, 1994). The formation is up to 50 m thick around Swift Current and absent by non-deposition north of Township 22 (Figure 2.2). It is also absent in the west and southwest of the study area where the Jurassic and underlying Mississippian formations are in direct contact. This formation is further subdivided into Lower (Triassic) and Upper (Middle Jurassic) members (Carlson, 1968). The Lower Watrous Member is composed of mud- and silt-dominated red beds and Upper Watrous Member is composed of mudstones and massive anhydrites (Carlson, 1968).

GRAVELBOURG FORMATION

The Middle Jurassic Gravelbourg Formation conformably overlies the Watrous Formation, overstepping it to the north and west of its depositional edge (Figure 2.2). It comes in direct contact with the Madison Group in the west and southwest (Kent and Kreis, 1995). The Gravelbourg Formation thins towards the west and north where it is truncated by the sub-Cretaceous unconformity. It generally dips towards the southeast reaching up to 70 m in thickness just south of Swift Current. The Gravelbourg Formation is subdivided into carbonate mudstone-dominated Lower Gravelbourg Member and dolomitic limestone and shale of the Upper Gravelbourg Member (Marsh and Heinemann, 2005).

SHAUNAVON FORMATION

The Shaunavon Formation conformably overlies the Gravelbourg Formation. It dips towards southeast reaching thickness of 60 m in the southeast. In the central part of the study area (between Townships 18 and 23) the Shaunavon Formation is truncated by the sub-Cretaceous unconformity (Figure 2.2). It is also subdivided into Upper and Lower Shaunavon members (Christopher, 1964). The Lower Member is composed of oolitic lime mudstone and the Upper Member is composed of interbedded carbonate-cemented sandstone and shale (Christopher, 1964). The Lower Shaunavon is interpreted to be deposited in quiet marginal marine setting. The Upper Shaunavon's depositional settings vary from “marine shelf” in the west to “deep basinal” in the east (Carlson, 1968).

VANGUARD GROUP

The Vanguard Group conformably overlies the Shaunavon Formation and consists of two distinct formations: Rierdon and Masefield. The lowermost Rierdon Formation ranges in thickness from zero between townships 15 and 20 (Figure 2.2) to over 100 m in the southeast. This unit is further subdivided into shales of the Rush Lake Member and shoreface sandstone deposits of the Roseray Member (Christopher, 1974). The Masefield Formation is composed of massive shale and caps the Vanguard Group sequence (Christopher, 1974; Christopher, 2003; Marsh and Heinemann, 2005).

SUCCESS FORMATION

The unconformity-bounded Jura-Cretaceous Success Formation sporadically overlies all Jurassic formations in the south and Mississippian Madison Formation in the north-central part of the study area (Christopher, 2003). The Success Formation is composed of detrital sandstones and shales and represents the remainders of a once extensive clastic sheet (Christopher, 2003). It ranges in thickness from zero at its erosional margins to over 60 m with randomly oriented and elongate lithologic packages (Christopher, 1974; Christopher, 2003; Marsh and Heinemann, 2005).

2.2.7 CRETACEOUS

MANNVILLE GROUP

Clastic sediments of the Lower Cretaceous Mannville Group overlie the sub-Cretaceous unconformity and are present throughout the study area. This group is composed primarily of sands interbedded with shales and consists of two formations: Cantuar and Pense. The fluviatile to estuarine Cantuar Formation varies from less than 20 m in the south to 180 m in the north. It is further subdivided into three members (McCloud, Dimmock Creek, Atlas) and seven lithostratigraphic beds (Dina, Cummings, Lloydminster, Rex, General Petroleums, Sparky, Waseca) (Christopher, 2003).

In contrast, the marine deposits of the Pense Formation range in thickness from 10 m in the north and west to 50 m in the southeast. The Pense Formation unconformably overlies the Cantuar Formation and is subdivided into McClaren and Colony lithostratigraphic beds. All formations contain significant quantities of hydrocarbons, primarily heavy oil. More information on the Mannville Group can be found in reports by Christopher (1974; 2002; and 2003).

COLORADO GROUP

The southeast-dipping Lower and Upper Cretaceous Colorado Group is a thick package (up to 500 m in the south) of transgressive dark grey to green glauconitic shales with several sandstone intervals (Marsh and Heinemann, 2005). This group is subdivided into Lower clastic dominated and Upper carbonate/clastic units by a regionally widespread unconformity at the base of Second White Specks Formation (Buckley and Tyson, 2003; Pedersen, 2004).

The Lower Colorado Group contains the Joli Fou, Viking, Westgate, Fish Scales, and Belle Fourche formations. Together these formations reach over 250 m in thickness in the southwest and are present throughout the study area. Joli Fou Formation is up to 80 m thick in the south and consists of dark grey shales. The Viking Formation conformably overlies Joli Fou ranging in thickness from 10 m in the north up to 50 m in the southwest. It is composed of massive quartz sandstones throughout the area that pinch-out towards northeast (Jones, 1961; Reinson et al., 1994). The Westgate, Fish Scales, and Belle Fourche formations conformably overlie Viking Formation and are primarily composed of shales with few lenses of very fine sands.

The Upper Colorado Group (Second White Specks, Carlile, Medicine Hat, and Niobrara formations) is composed of siltstones and dark grey shales. They range in thickness from 40 m in the northeast to almost 300 m in the southwest. The Medicine Hat Sandstone interfingers with the Niobrara Formation in the southwest and is typically less than 20 m thick (Marsh and Heinemann, 2005).

MILK RIVER and LEA PARK FORMATIONS

The Upper Cretaceous Milk River and Lea Park formations conformably overlie the Colorado Group and are composed of greenish grey shales and siltstones with minor sandstone interbeds (Ridgley, 2000; Pedersen, 2003). Both formations generally dip towards the east and locally reach 150 m in thickness (Marsh and Heinemann, 2005).

BELLY RIVER GROUP

Belly River Group consists of several sandstone tongues extending from Alberta and pinching out or eroded (by South Saskatchewan River) in parts of the study area. The group has variable thickness of up to 200 m in the south and southwest. The Belly River Group consists of Foremost and Oldman formations that are composed of poorly consolidated fine-grained sand and bentonitic mudstone with abundant coal seams (McLean, 1971).

The Belly River Group is capped by shales of Bearpaw Formation followed by Quaternary glacial till throughout most of the study area.

2.3 Hydrostratigraphy

A composite Hydrostratigraphic Chart (Figure 2.1) for southwestern Saskatchewan is presented herein. It has been developed by combining geologic formations into aquifers based on (a) their hydrochemical and hydraulic properties, (b) geologic framework provided by the Saskatchewan Ministry of Energy and Resources (SMER), (c) data availability and quality, and (d) previous hydrogeological studies in the province. This was an iterative process which involved a continuous improvement in understanding of intra- and inter-formational hydraulic continuity. Three levels/types of hydrostratigraphic units used in this study are defined below:

- *Aquifer* - Geologic formation(s) “capable” of transmitting “appreciable” quantities of fluid on a “specified” time scale.
- *Hydrogeologic System* - Group of aquifers showing similar hydrochemical characteristics and flow patterns.

- *Aquitard* – Geologic formation(s) of relatively low hydraulic conductivity adjacent to an aquifer.

Twelve aquifers separated by 12 aquitards were defined (Figure 2.1). Aquifers have been combined into hydrogeologic systems based on their similarities in hydrochemistry and flow directions. A total of five systems were identified:

(1) Lower Paleozoic (Basal Deadwood - Birdbear aquifers),

(2) Mississippian (Mississippian Aquifer),

(3) Jurassic (Shaunavon Aquifer),

(4) Lower Cretaceous (Lower Mannville – Viking aquifers)

(5) Upper Cretaceous (Belly River Group Aquifer).

2.3.1 LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

PRECAMBRIAN AQUITARD

Igneous and metamorphic rocks of the Precambrian basement in this study area represent the lowermost aquitard. This is consistent with the previous hydrogeological studies throughout the Western Canadian Sedimentary Basin. It should be noted that the weathering of the Precambrian surface may have created sufficient permeability for it to be considered an aquifer. However, this cannot be confirmed due to the lack of data (cores, DSTs) in the study area.

BASAL DEADWOOD AQUIFER

The Basal Deadwood Aquifer sits on top of the Precambrian surface and consists of widespread quartz sandstone. It is assumed to be continuous throughout the study area despite few available data points (wells). In some wells the sand appears to be missing by non-deposition due to local structural highs (observed on the geophysical logs). The top of this aquifer remains undefined due to the lack of geological picks in the area. However, it appears that the sand can reach up to 50 m thickness across the study area.

UPPER DEADWOOD AQUITARD

The Upper Deadwood Aquitard overlies the Basal Deadwood Aquifer and consists of thick shales of the Deadwood Formation. Several minor sandstone units interbedded with the shales appear to be geologically and hydraulically isolated from the basal sands, and therefore, are not considered to be a part of the underlying aquifer. These sandstone layers appear as tongues extending from eastern Saskatchewan where they become thicker and merge with basal sands into one major Cambro-Ordovician Aquifer (Benn and Rostron, 1998; Khan, 2006; Palombi, 2008).

ORDO-SILURIAN AQUIFER

The Ordo-Silurian Aquifer consists of four major formations: Red River, Stony Mountain, Stonewall, and Interlake. Together they form an aquifer reaching 200 m in thickness. Previous hydrogeological studies in southeastern and central Saskatchewan have refined this carbonate package into two aquifers (Benn and Rostron, 1998; Khan, 2006; Palombi, 2008). There may be significant differences in hydraulic head and chemistry between the Red River and Interlake formations. However, these were combined into one major aquifer due to the insufficient data in this study area.

ASHERN AQUITARD

The Ashern Formation is considered to be an aquitard due to its low-permeability lithology (shales) as well as observable differences in water dynamics and chemistry between the overlying and underlying aquifers. The Ashern Aquitard is widespread throughout the study area but absent around Swift Current (Figure 2.2).

WINNIPEGOSIS AQUIFER

The Winnipegosis Aquifer consists of permeable carbonates of the Winnipegosis Formation. The thickness of the aquifer is highly variable ranging from 20 m in the south to 100 m in the northeast part of the study area due to the presence of reefal buildups.

PRAIRIE AQUITARD

The Prairie Aquitard consists of salts and evaporates of the Prairie Formation and the shales of the overlying 2nd Red Beds (i.e. lower part of Dawson Bay Formation). The Prairie Aquitard is thickest in the north reaching 200 m, thinning toward the south and southeast where it is completely missing.

MANITOBA AQUIFER

The Manitoba Aquifer consists of the Dawson Bay and Souris River formations. They are composed of primarily limestone and evaporitic sequences and reach 200 m in thickness in the northern half of the study area. Although the

Dawson Bay Formation is capped by the 1st Red Beds, a regionally extensive shale, there are not enough data to map it as a separate aquifer. The majority of pressure and chemistry data are from the Souris River Formation, while less than five data points are from Dawson Bay Formation.

SOURIS RIVER AQUITARD

The Souris River Aquitard consists of Harris and Hatfield members (the upper members of the Souris River Formation), and Saskatoon and Elstow members (lower members of Duperow Formation). Together they are composed of thick evaporites and argillaceous sediments and range from 100 m to 250 m in thickness across the study area.

DUPEROW AQUIFER

In southwestern Saskatchewan, the Duperow Aquifer consists of the Wymark Member of the Duperow Formation. The Wymark Member is composed of numerous limestone units capped by evaporites (anhydrite). These evaporites form local aquitards enhancing trapping potential of this member. Karst features are observed in the Middle Wymark Member which significantly enhances permeability (Kent, 1968). Almost all data in the Duperow Aquifer are from the Wymark Member (except for areas near erosional subcrop in the north).

SEWARD AQUITARD

The Seward Aquitard consists of the Seward Member of the Duperow Formation. This member overlies the Wymark Member and is readily recognizable from gamma ray logs due to its high argillaceous content.

BIRDBEAR AQUIFER

The Birdbear Aquifer consists of the entire Birdbear Formation, and reaches 50 m in thickness across the study area. This aquifer subcrops into the sub-Cretaceous unconformity and is not present at the northernmost limit of the study area. Although most of the data come from a more permeable upper member of the Birdbear Formation, both upper and lower members are treated as one aquifer.

THREE FORKS AQUITARD

Overlying the Birdbear Aquifer is the Three Forks Aquitard which consists of the Torquay and Big Valley formations and Lower Shale Member of the Bakken Formation. These formations are composed primarily of calcareous shales and reach 100 m thickness in the north. The Three Forks Aquitard is completely absent (subcrops to sub-Cretaceous unconformity) north of Township 33 allowing direct communication between the Birdbear and overlying Mannville Aquifers.

2.3.2 MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

MISSISSIPPIAN AQUIFER

The Mississippian Aquifer System consists of the Madison Group strata combined with the Middle Bakken Member. The overlying Lower Gravelbourg Formation was also combined with the Mississippian Aquifer in the western part of the study area, where the red shales and anhydrites of the Watrous Formation are missing. This decision was based on, and confirmed by, the similarities in hydrochemistry and hydrodynamics of the Mississippian and the Lower Gravelbourg formations.

The Mississippian Aquifer is in hydraulic communication with the overlying Lower Mannville Aquifer over a large area north of Township 23 due to the lack of the Watrous-Gravelbourg Aquitard.

2.3.3 JURASSIC HYDROGEOLOGIC SYSTEM

WATROUS-GRAVELBOURG AQUITARD

Both the Gravelbourg (mainly Upper Gravelbourg) and Watrous formations represent a major Triassic-Jurassic regional aquitard. It is a weak aquitard in the area west of Range 26, where Watrous is not present and Upper Gravelbourg is relatively thin (less than 15 m). The Watrous – Gravelbourg Aquitard extends north up to its erosional limit between Townships 20 and 26 represented by the Gravelbourg's edge.

SHAUNAVON AQUIFER

Both Lower and Upper Shaunavon members are combined to form the Shaunavon Aquifer. It covers the entire southern portion of the study area up to the erosional edge between Townships 19 and 24. The main water-bearing and highly permeable unit is the Upper Shaunavon Member. The distribution of permeability in this member is controlled entirely by the depositional settings and geologic facies. The Shaunavon Aquifer is in hydraulic communication with the Lower Mannville Aquifer in areas where the Vanguard Aquitard is not present (Rierdon erosional edge, Figure 2.2).

VANGUARD AQUITARD

The Vanguard Aquitard consists of the shales of Rush Lake and Masefield formations. Situated in between those two shales is the Roseray Formation, which is composed of highly permeable sandstone. The Roseray Formation is present throughout southeast and is in hydraulic communication with the overlying Lower Mannville Aquifer in areas where Masefield shales are missing (Figure 2.2). Therefore, it was not considered to be a major standalone aquifer in this study and combined with the overlying aquifer.

2.3.4 LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

LOWER AND UPPER MANNVILLE AQUIFERS

The Lower Cretaceous Mannville Group is composed of extremely heterogeneous sediments with complicated geology posing a great challenge to hydrogeological interpretation. In this study, significant differences in water potential and chemistry were observed between upper and lower parts of the group, indicating that there are two separate aquifers. Therefore, the Mannville Group was subdivided into two aquifers: the Upper and Lower Mannville aquifers separated by the top of the Cantuar Formation.

The Lower Mannville Aquifer includes Success, Roseray, and Cantuar formations. The Cantuar Formation is present throughout the entire study area, while the Roseray Member is present only in the southeastern and central parts. The unconformity-bounded Success Formation, also referred to as Detrital or Basal Quartz, is sporadically present throughout most of the study area.

The Upper Mannville Aquifer System consists of Pense and Spinney Hill formations. The Pense Formation is present throughout the entire study area, and Spinney Hill sands exist only in the northeast.

JOLI FOU AQUITARD

Shales of the Joli Fou Formation range in thickness from 80 m in the south to 20 m in the north and represent a major regional aquitard overlying the Upper Mannville Aquifer.

VIKING AQUIFER

Sandstones of the Viking Formation make up the Viking Aquifer. This aquifer is over 50 m thick in the southwest and thin-out towards northeast. The Viking Aquifer is undefined (no hydraulic data) in the northeast where the permeability of sediments is very low and sparsely available drill-stem tests did not recover any water.

2.3.5 UPPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

COLORADO – LEA PARK AQUITARD

Overlying the Viking Aquifer are thick successions of shales and siltstones of the Colorado Group, Milk River, and Lea Park formations. Together these three reach over 600 m in thickness in the south (Marsh and Heinemann, 2005). Drill-stem tests from 2nd White Specks, Milk River, and Medicine Hat formations did not recover any water, and therefore, these units are not major regional aquifers. However, this interpretation changes towards west and southwest, into Alberta and Montana, where the Milk River Formation is considered to be a major aquifer and water source (Meyboom, 1960).

BELLY RIVER AQUIFER

Belly River Aquifer consists of Belly River Formation (also known as Judith River Formation). Minor differences in hydrochemistry and hydrodynamics have been observed between Lower (Basal) Belly River and Upper Belly River. However, due to the lack of good geological control of these units, it was decided to combine them into one major aquifer. The Belly River Aquifer is present throughout most of the study area and thickest in the south reaching over 150 m. It is eroded by the South Saskatchewan River forming the Tyner Valley. South of the Tyner Valley this aquifer is primarily utilized by oil companies to produce formation water for water floods of producing oil fields (e.g. Shaunavon oil pools). North of the eroded area Belly River Formation represents a major water source for domestic uses such as agriculture and municipalities.

BEARPAW AQUITARD

The shales of the Bearpaw Formation overlie the Belly River Formation. The Bearpaw Aquitard is also eroded by the South Saskatchewan River and several of its tributaries allowing partial hydraulic communication between the Belly River Aquifer and the overlying shallow Quaternary aquifers. The aquifers above the Bearpaw Formation are parts of the shallow groundwater system, and therefore, were not investigated in this study.

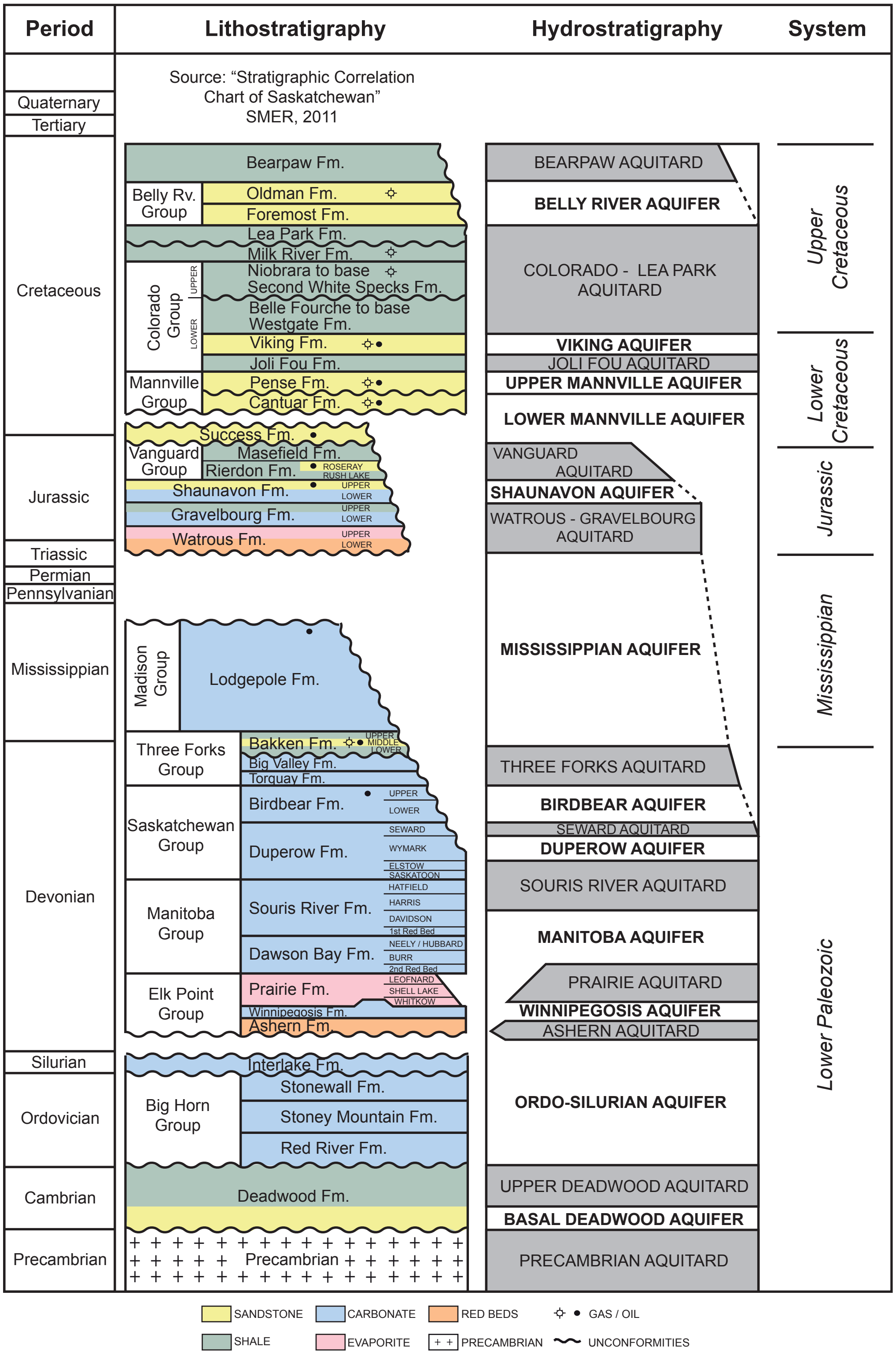

Figure 2.1: Lithostratigraphic and hydrostratigraphic charts for the study area.

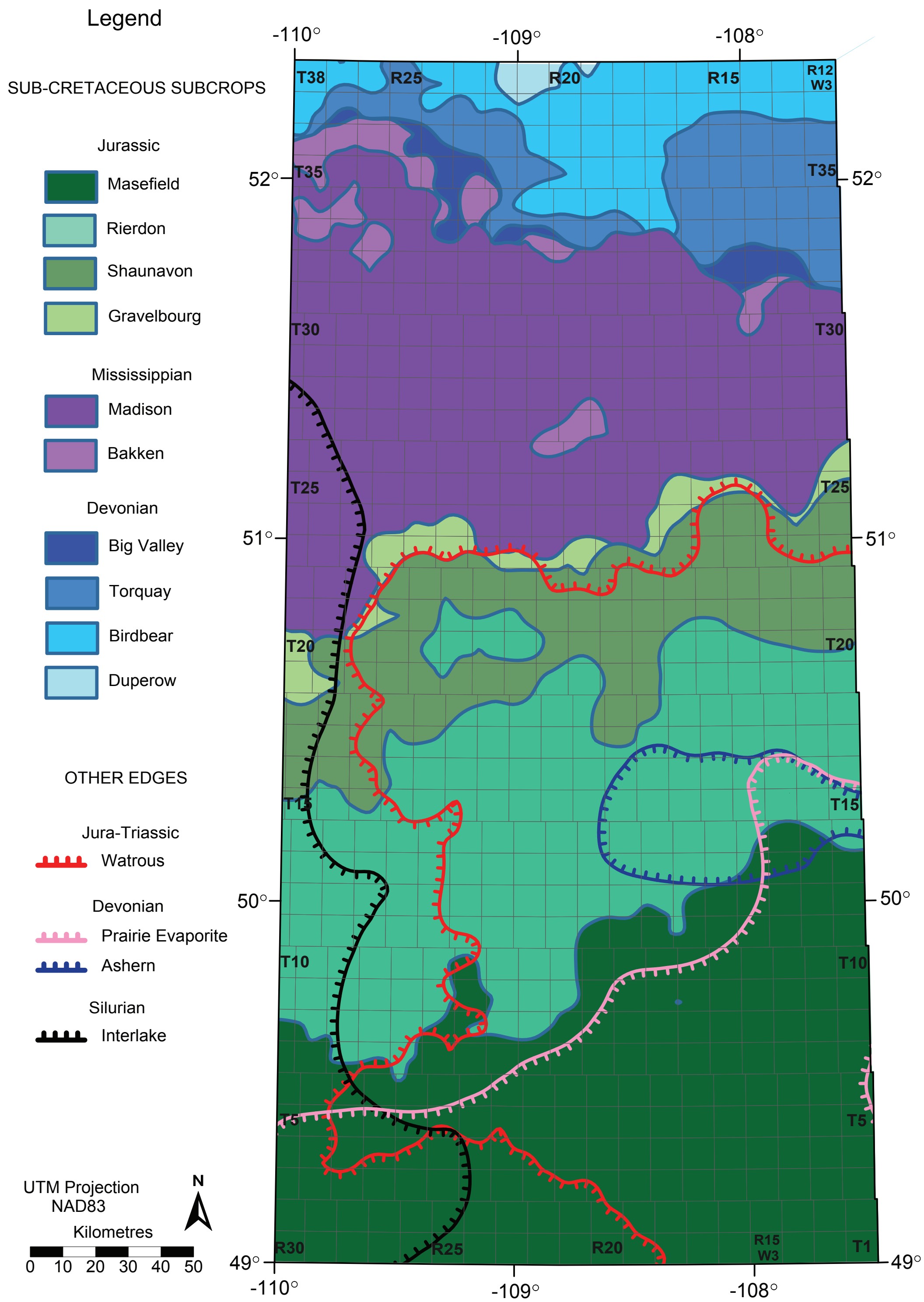

Figure 2.2: Formation edges in the study area (Christopher, 2003; Marsh and Heinemann, 2005).

CHAPTER 3 – Data and Methodology

The two primary data types used for this study are 1) water chemistry and 2) pressure data. These data were extracted from commercial databases and processed according to methods described below.

3.1 Water Chemistry

The water chemistry database for deep aquifers was assembled using the Geofluids software (Rakhit Petroleum Consulting Ltd., now Canadian Discovery Ltd.). In the study area it consists of 7,609 water analyses of samples obtained in drill-stem tests (DSTs), production tests and wellhead samples (Table 1). Each analysis was placed into the corresponding aquifer/formation using the stratigraphic picks and structural grids provided by the SMER. Since the majority of the analyses are from DSTs and wellhead samples, they have a high risk of contamination by (acid) completion fluid, corrosion inhibitor, and various drilling muds (Hitchon and Brulotte, 1994). Removal of these contaminated water analyses was required to ensure that only samples representative of true formation water were used for further analysis.

Culling water chemistry is an iterative process due to variability of formation-water chemistry throughout the study area. The culling procedure developed by the University of Alberta Hydrogeological group was applied whereby each analysis was tested against a number of culling criteria indicative of sample contamination (Appendix A). The analyses with the highest number of matching contamination criteria (generally above 3) were automatically removed from the database and the rest were manually examined. Almost 75% of initial data were culled as a result of this process (Table 1).

Total Dissolved Solids (TDS) were calculated through the summation of all ionic constituents dissolved in a groundwater sample. The TDS values were posted for all aquifers and contoured using industry software as well as manual contouring. The TDS maps were supplemented with cross-plots of major ions (sodium, Na^+; calcium, Ca^{2+}; magnesium, Mg^{2+}; chloride, Cl^-; sulphate, SO_4^{2-}; bicarbonate, HCO_3^-) versus TDS in order to better understand groundwater evolution and help identify contaminated samples.

Groundwater was classified based on the relative proportions of anions and cations (% of meq/L), similar to the previous works by Benn and Rostron (1998), Khan (2006), and Palombi (2008). Specific percentage cut-offs, which determine the water types, were chosen to represent the observed trends in this particular study area are described below. Maps of water types' distribution have been constructed for aquifers showing any identifiable variability in water chemistry with good data coverage (from Manitoba to Lower Mannville aquifers). Stiff plots for each water type in all aquifers were created showing the averages and ranges of ionic concentrations for all existing water types in each aquifer (Appendix B).

<table>
<tr><th>Aquifer</th><th>Raw Chemistry Data</th><th>Mapped Chemistry Data</th></tr>
<tr><td>Belly River</td><td>759</td><td>445</td></tr>
<tr><td>Viking</td><td>1337</td><td>199</td></tr>
<tr><td>Upper Mannville</td><td rowspan="2">2934</td><td>147</td></tr>
<tr><td>Lower Mannville</td><td>461</td></tr>
<tr><td>Shaunavon</td><td>1009</td><td>316</td></tr>
<tr><td>Mississippian</td><td>1044</td><td>174</td></tr>
<tr><td>Birdbear</td><td>218</td><td>71</td></tr>
<tr><td>Duperow</td><td>159</td><td>50</td></tr>
<tr><td>Manitoba</td><td>54</td><td>20</td></tr>
<tr><td>Winnipegosis</td><td>22</td><td>13</td></tr>
<tr><td>Ordo-Silurian</td><td>27</td><td>16</td></tr>
<tr><td>Basal Deadwood</td><td>46</td><td>12</td></tr>
<tr><td>Total</td><td>7609</td><td>1924</td></tr>
</table>

Table 1: Summary of water chemistry data collected and mapped in this study.

3.2 Pressure

Drill-stem tests (DSTs) measure reservoir pressures, flow rates and subsurface temperature, allow determination of potential productivity of oil or gas reservoirs, and provide the means of collecting samples of formation fluid (Dahlberg, 1994). Pressure data from DSTs were downloaded from GeoScout (Hydrofax database) and AccuMap (Canadian Hydrodynamics database), and combined into a single database. Additional water-level data for the Belly River Aquifer were obtained from the Saskatchewan Watershed Authority and integrated into the database. Duplicates were eliminated resulting in a total of 12,672 data points. In addition to fluid pressures, production data were also downloaded from GeoScout. Drill-stem tests were placed into the corresponding aquifer/formation using the stratigraphic picks and structural grids provided by the SMER.

All DSTs were screened using both automated and manual techniques to remove poor-quality and inaccurate fluid pressures (Appendix A).

A “Cumulative Interference Index” (CII) was used to determine and quantify the influence of production and injection on the pressures within the respective aquifer/formation (Barson, 1993). The original "Interference Index" (I), as proposed by Tóth and Corbet (1986), is a method of assessing the influence of a single production/injection well on a near-by DST. It accounts for the radial proximity of a DST to a producing/injecting well and the duration of production/injection and defined as:

$$I = \log_{10} \frac{t}{r^2} \tag{3.1}$$

where t is the pre-DST production time (years) and r is distance (km) between the producing well and the DST. This index is based on Theis Equation, which relates aquifer properties and pumping rate to the hydraulic head drawdown for a specified time and distance away from the production well (Freeze and Cherry, 1979).

Barson (1993) has shown that, for confined homogeneous aquifer and constant production rates, the drawdown in the aquifer depends only on the duration of production (time) and the distance to the producing well. Based on this result and the Principle of Superposition (i.e. the total drawdown is the sum individual drawdowns produced by multiple production wells, Freeze and Cherry, 1979) he proposed the "Cumulative Interference Index". The CII is the sum of all interference indices accounting for multiple production/injection wells and calculated for each DST (Barson, 1993; Rostron, 1994).

The CIIs for every DST were calculated using the Visual Basic Code developed by Alkalali (2002). DSTs with CII >0.2 were automatically removed from the database (Barson, 1993). The remaining DSTs were examined manually due to the fact that the hydraulic properties (transmissivity and storativity) of each aquifer are different and require subjective evaluation of production interference (different CII should be applied to each aquifer). Table 2 shows the number of preliminary pressure data points downloaded and the number of data points subsequently used. Over 80% of preliminary data were culled.

True formation pressures were estimated using the Horner extrapolation method (Horner, 1951), in most cases, provided by the data vendors. Manual pressure extrapolations were performed for DSTs that did not have true formation pressures supplied by the data vendor. Pressure data were converted to fresh-water hydraulic heads using the following equation:

$$h_f = z + \frac{P}{\rho_f g} \tag{3.2}$$

where: h_f is the freshwater hydraulic head, P is the extrapolated (true) formation pressure, ρ_f is the freshwater density (1000 kg/m^3), g is the gravitational constant, and z is the elevation of the point of measurement (recorder elevation). The freshwater hydraulic head values were posted for all aquifers and contoured using industry software as well as manual contouring.

Aquifer	Preliminary Pressure Data	Used Pressure Data
Belly River	1348	1090
Viking	2403	272
Upper Mannville	3625	49
Lower Mannville		296
Shaunavon	3309	417
Mississippian	1207	149
Birdbear	272	63
Duperow	265	43
Manitoba	109	15
Winnipegosis	29	14
Ordo-Silurian	50	11
Basal Deadwood	55	9
Total	12672	2428

Table 2: Summary of pressure data collected and mapped in this study.

The three main assumptions in construction of fresh-water head maps are: (a) the water density is uniform and has a value of 1000 kg/m^3, (b) the aquifer is near horizontal, and 3) the flow has no vertical component (i.e. flow is parallel to the aquifer). However, these assumptions have been shown to be incorrect in deep, saline, and sloping aquifers introducing significant errors into the flow interpretation (Davies, 1987; Bachu, 1995; Bachu and Michael, 2002). Therefore, water density and aquifer slope must be taken into account. One way of doing this is using Water Driving Forces vectors.

Darcy's Law can be reduced to a well-known form to reflect three-dimensional flow of variable density fluids (Bear, 1972; de Marsily, 1986):

$$q_i = -\frac{k_i g \rho_f}{\mu}\left[\nabla h_f + \frac{\rho - \rho_f}{\rho_f}\nabla z\right], \quad i = x, y, z \tag{3.3}$$

where: q_i is the specific discharge in the i^{th} direction, k is the rock's absolute permeability, μ is the dynamic fluid viscosity, ρ and ρ_f are the variable and freshwater densities (respectively), h_f is the freshwater hydraulic head, and z is the elevation.

Davies (1987) modified Equation 3.3 for confined flow in sloping aquifers:

$$q = -K\left[\nabla H_f + \frac{\rho - \rho_f}{\rho_f}\nabla E\right] \quad (3.4)$$

where: K is the hydraulic conductivity, ∇H_f is the freshwater head gradient, and ∇E is the slope of the aquifer or the corresponding formation top. The net Water Driving Force on the formation water is represented by vector addition of the two terms within the brackets of equation 3.4:

$$\overrightarrow{WDF} = \overrightarrow{\nabla H_f} + \frac{\Delta\rho}{\rho_f}\overrightarrow{\nabla E} \quad (3.5)$$

The density of the formation water (ρ) under specific temperature and pressure conditions was calculated using Chierici's (1994) equation, also used by Khan (2006) and Palombi (2008):

$$\begin{aligned}\rho_w = 730.6 + 2.025T - 3.8 \times 10^{-3}T^2 \\ + [2.362 + 1.197 \times 10^{-2}T + 1.835 \times 10^{-5}T^2] \\ + [2.374 - 1.024 \times 10^{-2}T + 1.49 \times 10^{-5}T^2 - 5.1 \\ \times 10^{-4}P]C\end{aligned} \quad (3.6)$$

where: ρ_w is the formation water density, P is the pressure (MPa), with a range of validity between 0-50 MPa, T is the temperature (K) applicable over 293-373 K, and C is the TDS (g/L).

Density effects are represented by the differences in the magnitude and direction between the freshwater and density-dependent gradients. Angular differences between the gradients were calculated and contoured on the hydraulic head maps (Khan, 2006; Palombi, 2008).

CHAPTER 4 – Hydrochemistry

Variations and patterns in TDS (Figures 4.1 – 4.12) and formation water chemistry (Figures 4.13 – 4.17) can aid in deciphering the chemical evolution (Chebotarev, 1955) and flow path in a regional-scale flow system (Tóth, 1995).

Four main water types (Figures 4.18 – 4.24) were identified in the study area:

1) ***Ca(Mg)-SO_4:*** *(Na <70% and SO_4 >50%)*
   Type 1 waters have low TDS (<10 g/L), high Ca and SO_4 concentrations. They are identified as recharge-area waters with short residence time, rapid flow and low reactivity.
2) ***Na-Cl:*** *(Na >70% and Cl >50%)*
   Type 2 waters have variable TDS (10-300 g/L) and generally indicate long residence time or flow path.

3) ***Na-SO_4:*** *(Na >70% and SO_4 >50%)*
   Type 3 are waters with TDS of 10 - 50 g/L. They represent mixing between Ca-SO_4 (1) and Na-Cl (2) water types.

4) ***Na-HCO_3:*** *(Na >70% and HCO_3 >50%)*
   Type 4 waters are characterized by low TDS (<10 g/L) and high HCO_3 concentrations and generally represent fresh-water recharge.

This chapter describes the results of hydrochemical mapping.

4.1 Total Dissolved Solids

LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

The Total Dissolved Solids in the Lower Paleozoic aquifers generally ranges from less than 10 g/L in the south, the deepest part of the study area, to over 300 g/L in central and northern parts of the study area (Figures C.1 – C.4).

The values of Total Dissolved Solids in the Basal Deadwood Aquifer range from less than 10 g/L in the south and over 300 g/L in the north (Figure 4.1).

The TDS in the Ordo-Silurian Aquifer ranges from less than 10 g/L in the south and southeast to almost 300 g/L in the central and north-western half of the study area (Figure 4.2). The low TDS area correlates to the edge of the Prairie Formation, although lack of data south of Township 5 makes it difficult to interpret the exact boundary between brackish water and brine. It is also important to note that this aquifer consists of several formations that possibly have slightly different TDS values but lack sufficient data to be mapped separately.

The Winnipegosis Aquifer underlies the Prairie Evaporite Formation and contains brines with the highest observed salinities in the study area (Figure 4.3). Lack of data south of Township 12 made it very difficult to delineate the TDS distribution in the south; however, several data points from outside of the study area (not shown) provided control for this map. Total Dissolved Solids ranges from less than 10 g/L in the south and southeast to over 350 g/L in the central and north-western parts of the study area. The low TDS area corresponds to Prairie Evaporite edge.

The Manitoba Aquifer sits directly on top of the Prairie Evaporite Formation. The TDS ranges from less than 10 g/L in the southeast to over 100 g/L throughout most of the study area (Figure 4.4). The sharp increase in TDS corresponds very well to the Prairie Evaporite zero edge. There are no water chemistry data in the central and northwestern parts of the study area. However, the TDS values are predicted to be above 300 g/L due to the aquifer's proximity to the Prairie Evaporite[1].

Total Dissolved Solids in the Duperow Aquifer is highly variable, from less than 10 g/L in the south and southeast to over 200 g/L in the north-central area (Figure 4.5). It also appears to sharply decrease towards the very north (< 50 g/L), outside of the study area. The rapidly decreasing TDS in the south also appears to correspond well to the Prairie Evaporite, similarly to the underlying aquifers.

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[1] A well of particular interest is located at 8-18-21-20W3 (Figure 4.4). This well was drilled down to the Interlake Formation at the total vertical depth of 1732.8 m. Souris River Formation *(Manitoba Aquifer*) was drill-stem tested at the interval of 1574.3 – 1586.5 m, with the bottom packer set in the 1st Red Beds, located above the Dawson Bay Formation. The Drill-stem test was mechanically successful and recovered 882 m of salt water with TDS of 430 g/L. Detailed chemical analysis showed that these waters contained 93 g/L of calcium (> 60% of total cations by weight) and 275 g/L of chloride (>99% of total anions by weight) with the pH of 5.1. This is the only water analysis with such a unique chemistry found within the study area. However, it appears to be representative of true formation waters in the Manitoba Aquifer for that particular area despite being flagged as contaminated by numerous culling criteria due the high calcium content and relatively low pH.

Formation waters with similar chemical composition are also found throughout the Silurian - Middle Devonian aquifers in other sedimentary basins (Case, 1945; Hitchon and Holter, 1971). Numerous hypotheses for the origin of these waters exist, ranging from local water-rock interactions (Carpenter, 1978; Nesbitt, 1985; Spencer, 1987; Walter et al, 1990) to secular variations in global seawater chemistry (Lowenstein, 2003).

The Birdbear Aquifer appears to have different and lower TDS from all underlying Paleozoic aquifers (Figure 4.6). TDS is less than 25 g/L south of Township 20 and in the northwest. Relatively high TDS (up to 100 g/L) is limited to the northeast. The TDS pattern in the Birdbear Aquifer is different from all the underlying aquifers and does not correspond to Prairie Evaporite dissolution edge.

MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

Total Dissolved Solids in the Mississippian Aquifer is less than 25 g/L (Figure 4.7). Lowest TDS values (< 5 g/L) are observed in the south and southeast. There is a plume of > 20 g/L water located in the northwest part of the study area.

JURASSIC HYDROGEOLOGIC SYSTEM

The Shaunavon Aquifer has relatively low TDS (< 25 g/L) with an average value of 10 g/L (Figure 4.8). Highest values (> 20 g/L) are observed in the area of Townships 4 to 8 and Ranges 17 to 20.

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

Both the Lower and Upper Mannville aquifers (Lower Cretaceous) have very similar TDS patterns (Figures 4.9 – 4.10, respectively). TDS range from 5 g/L to 70 g/L but generally are low (< 20 g/L). TDS increase to over 70 g/L in the northeast corner where the Lower Mannville Aquifer is in direct contact with the underlying Devonian Birdbear Aquifer (i.e. Three Forks Aquitard is missing).

TDS in the Viking Aquifer are generally below 20 g/L. The lowest values are observed in the southwest and progressively increase towards north and northeast (Figure 4.11).

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

Water in the Belly River Aquifer is fresh with TDS generally being less than 5 g/L (Figure 4.12). Subtle TDS differences were observed between lower and upper parts of Belly River Group. These differences, however, could not be further investigated due to the lack of detailed geological framework of the Belly River Group.

3.2 Major Ion Chemistry

LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

Chloride is present in all Lower Paleozoic aquifers and is the most dominant anionic species, increasing linearly versus TDS (Figure 4.13). Concentrations of sulphate are generally low (<10%) at TDS over 50 g/L, however, sulphate becomes the dominant anion (>80%) at very low TDS. Concentrations of bicarbonate in the Lower Paleozoic aquifers are very low and remain low regardless of the variations in TDS.

Sodium is the dominant cation in the Lower Paleozoic aquifers (Figure 4.13). Its concentration increases linearly with TDS, similar to Chloride. Calcium generally has higher concentration than magnesium; however, both cations show similar trends. Their proportion increases significantly at lower TDS, similar to sulphate.

MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

The observed trend of chloride versus TDS is linear (Figure 4.14). However, the concentrations of chloride are lower than expected at low TDS (<15 g/L). Upon closer examination of these water analyses it appears that sulphate has replaced chloride at low TDS. The proportions of both sulphate and bicarbonate are decreasing with increasing TDS. However, this trend is not as obvious as in the Lower Paleozoic aquifers due to much lower TDS in the Mississippian Aquifer.

Sodium shows a strong positive linear relationship with TDS (Figure 4.14). Concentrations of calcium and magnesium are increasing with decreasing TDS showing similar trend to Lower Paleozoic aquifers.

JURASSIC HYDROGEOLOGIC SYSTEM

Overall, the Shaunavon Aquifer shows similar anionic trends to the Mississippian Aquifer. Concentrations of chloride increase linearly with increasing TDS (Figure 4.15). A small group of water samples have slightly lower concentrations of chloride than predicted by the linear relationship. Manual examination of these analyses revealed that bicarbonate is the dominant anion in these waters. The proportions of both sulphate and bicarbonate anions are decreasing with increasing TDS. However, this trend is not as well developed as in the Lower Paleozoic aquifers due to much lower TDS in the Shaunavon Aquifer.

Sodium has a strong positive relationship with TDS and is the dominant cation (Figure 4.15). Calcium and magnesium have generally low concentrations without any obvious trend with TDS and are considered to be minor components of the water chemistry in the Shaunavon Aquifer.

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

There is a strong positive linear relationship between chloride and TDS in the Lower Cretaceous aquifers (Figure 4.16). Both sulphate and bicarbonate are decreasing with increasing TDS, a similar trend to the Lower Paleozoic aquifers.

Sodium also shows a positive linear relationship with the TDS (Figure 4.16). On the other hand calcium and magnesium do not show any trend and are relatively minor chemical components of the Lower Cretaceous waters.

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

There are two distinct trends of chloride in the Belly River Aquifer (Figure 4.17). The first trend is similar to all other aquifers where the chloride concentration increases linearly with increasing TDS. The second trend is shown by the consistently low chloride concentrations at increasing TDS. Proportions of sulphate versus TDS also have two distinct trends, similar to chloride. Upon manual examination of these water analyses it appears that sulphate is replacing chloride and has high concentrations when chloride has low concentrations, and vice versa. Bicarbonate anion, on the other hand, shows only one trend where its concentrations decrease with increasing TDS.

Sodium has a positive linear relationship with TDS (Figure 4.17). Proportions of calcium and magnesium decrease with increasing TDS, although are generally higher and more scattered than in the underlying aquifers.

3.2 Classification

LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

All Lower Paleozoic aquifers are characterized by two major water types (Figures 4.18 – 4.20): Ca(Mg)-SO_4 (Type 1) and Na-Cl (Type 2). The Ca(Mg)-SO_4 water type is typically present in the southern parts of the study area and correlates with relatively fresh water associated with salt dissolution area. The extent of Type 1 water is highly variable with its maximum areal coverage in the Birdbear Aquifer, where Ca(Mg)-SO_4 occupies almost half of the study area. It is impossible to accurately constrain the areas of Type 1 and Type 2 waters due to the very low data density (or no data) and the transition from Type 1 to Type 2 waters is subject to interpretation. Na-Cl (Type 2) waters are present across most of the central and all of the northern parts of the study area (green area) and are associated with a wide range of TDS (up to 350 g/L).

The hydrochemical maps for Deadwood, Ordo-Silurian, and Winnipegosis aquifers were not created due to the lack of sufficient data for accurate interpretation in the south.

MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

The Mississippian Aquifer contains all four major water types (Figure 4.21). Ca(Mg)-SO_4 waters are present only in the southern and southeastern parts of the study area. While sulphate remains the dominant anion throughout the south, calcium is gradually replaced by sodium, thereby creating Na-SO_4 water type (Type 3). The edge of the Na-SO_4 water is correlated very well to the edge of anhydrite-rich Watrous Formation. The other two water types in the Mississippian Aquifer are Na-HCO_3 (Type 4) and Na-Cl (Type 2). Na-HCO_3 water is present only in the western parts of the study area adjacent to the Alberta border. Na-Cl water type is only found in the north and close to erosional edge of the Mississippian Aquifer.

JURASSIC HYDROGEOLOGIC SYSTEM

The Jurassic Shaunavon Aquifer has three major water types (Figure 4.22) which have a significantly different spatial distribution compared to the underlying Mississippian Aquifer. It is important to note that Type 1 water (Ca-SO_4) is not present in this aquifer. Na-HCO_3 waters are dominating the eastern part (almost one third) of the study area having a much greater spatial coverage than in the underlying Mississippian Aquifer. The central region is dominated by Na-Cl water associated with almost all of the producing oil fields in the Shaunavon Oil Trend. Type 2 waters form a large plume surrounding the oil fields and extending at least four additional townships towards the west. A relatively well defined boundary between Na-Cl and Na-HCO_3 can be observed. Na-SO_4 water is present in the east and north also having a well-defined boundary with Na-Cl water. However, due to the lack of data in the east and southeast, the distribution of Na-SO_4 water cannot be accurately described.

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

The Lower Cretaceous aquifers are dominated by Na-Cl type waters with varying amounts of Na-HCO_3 and Na-SO_4 types (Figures 4.23 – 4.24). Lower Mannville Aquifer has HCO_3 water in the southwest and southeast, and Na-SO_4 water type is present in a small area in the east. Upper Mannville Aquifer has mostly Na-Cl water with very small areas of HCO_3 and Na-SO_4 water in the southwest and east, respectively.

Water in the Viking Aquifer is composed entirely of Na-Cl with negligible amounts of other constituents (not shown).

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

The Belly River Aquifer has all four major water types based on the ionic cross-plots (Figure 4.17). However, the distribution of these water types cannot be ascertained due to the lack of detailed geological framework within the Belly River Group. It appears that the lower part of the Belly River Aquifer is dominated by the Na-Cl waters while the upper parts of the aquifer have variable compositions and water types.

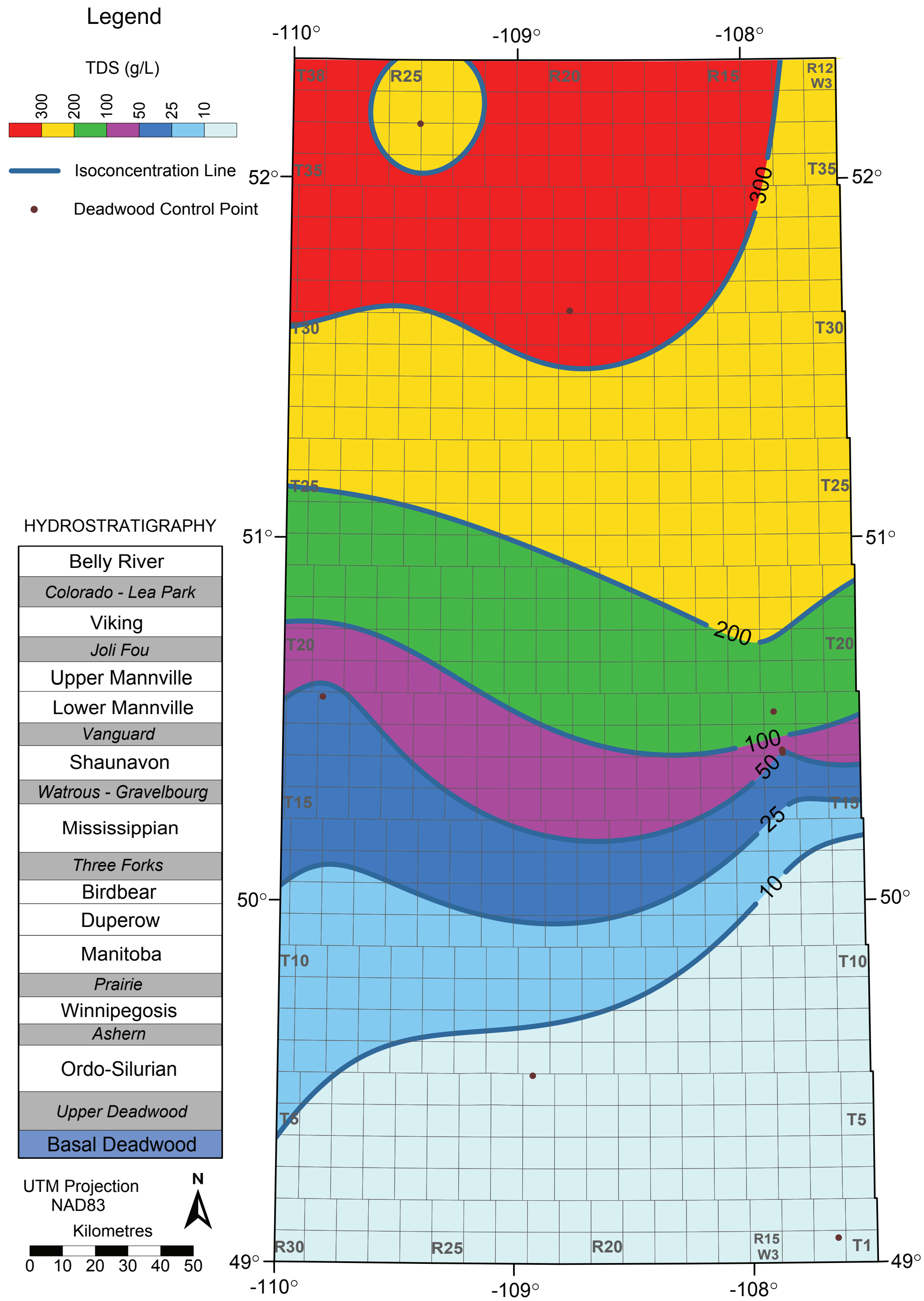

Figure 4.1: Distribution of TDS in the Basal Deadwood Aquifer.

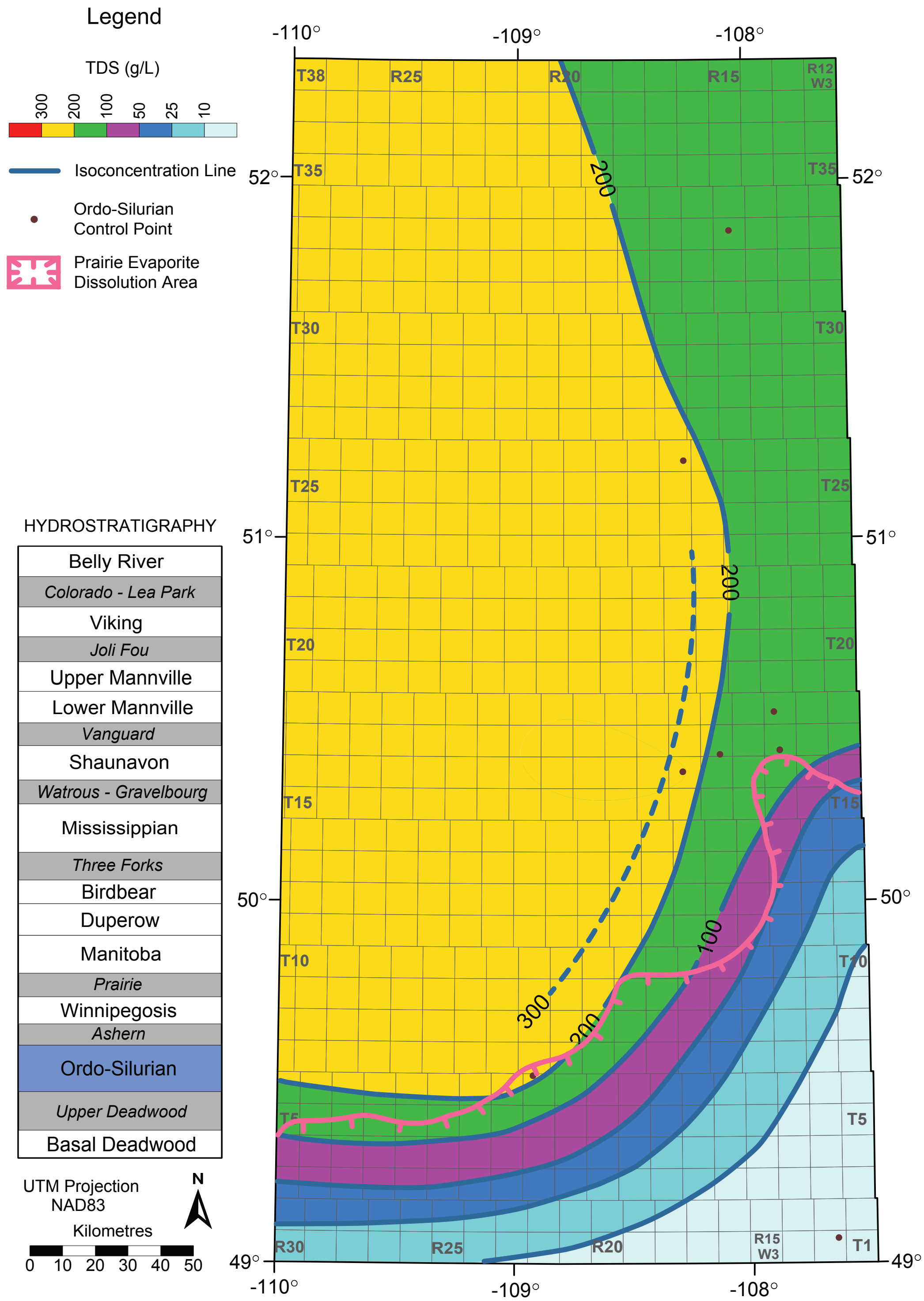

Figure 4.2: Distribution of TDS in the Ordo-Silurian Aquifer.

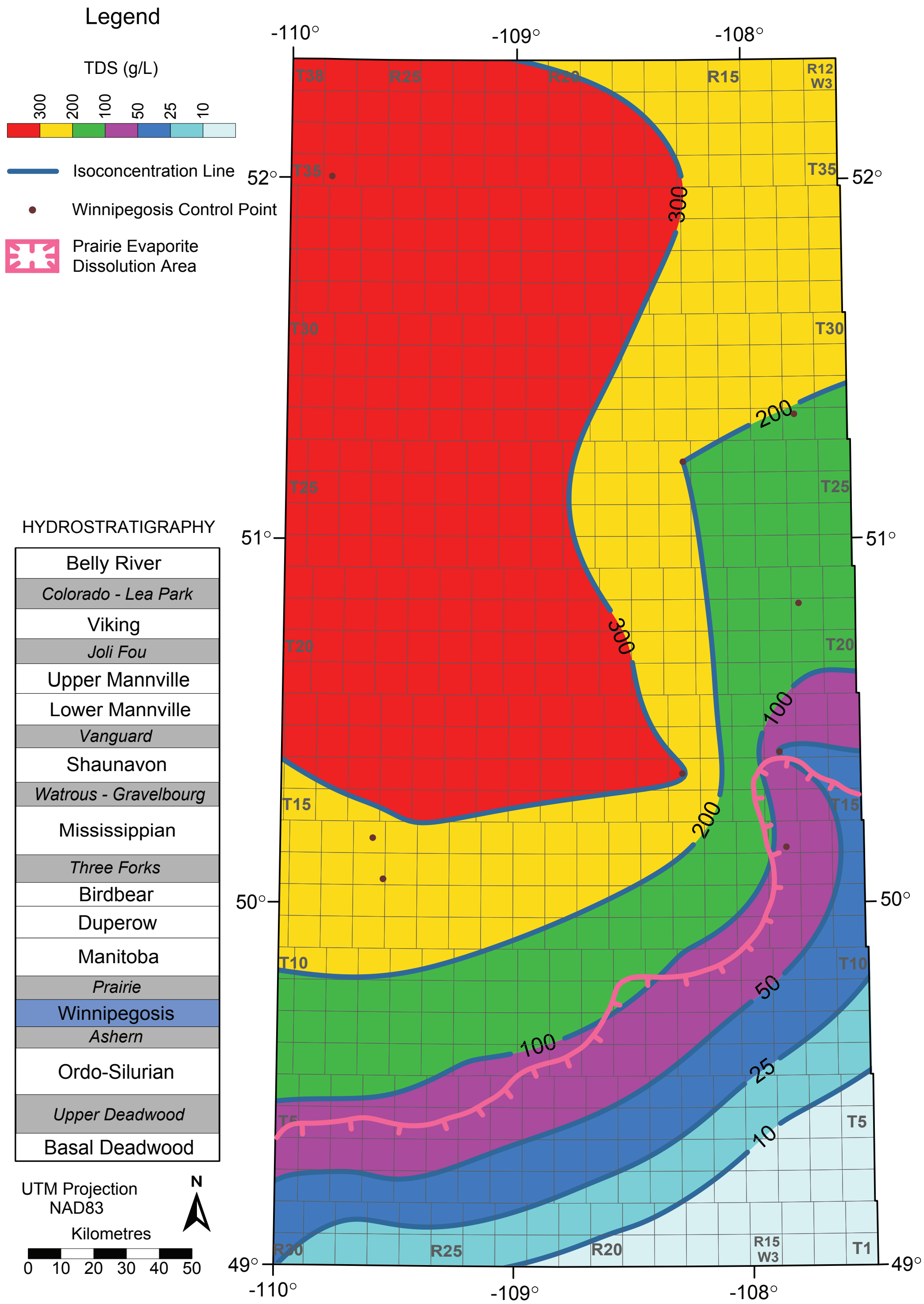

Figure 4.3: Distribution of TDS in the Winnipegosis Aquifer.

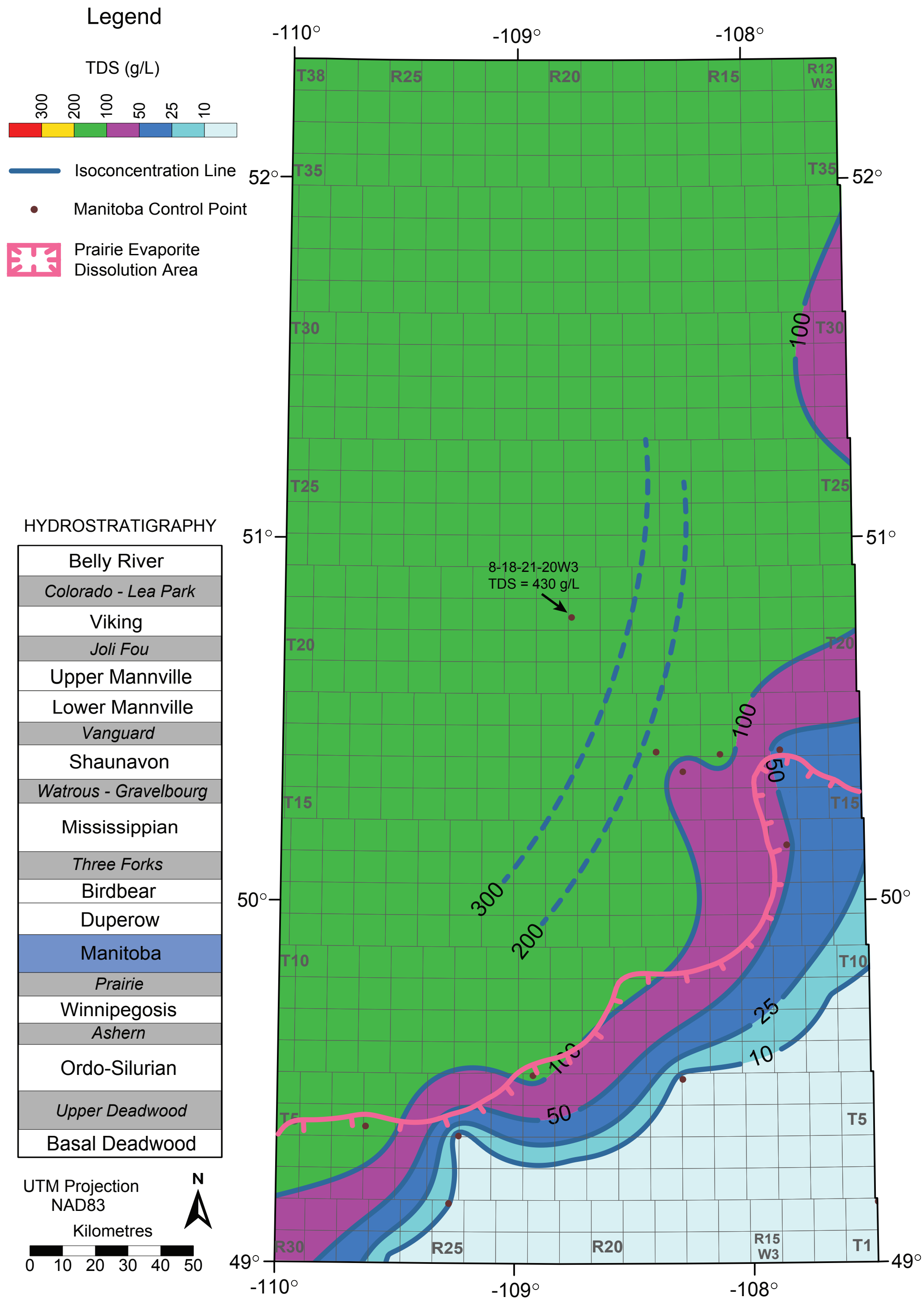

Figure 4.4: Distribution of TDS in the Manitoba Aquifer.

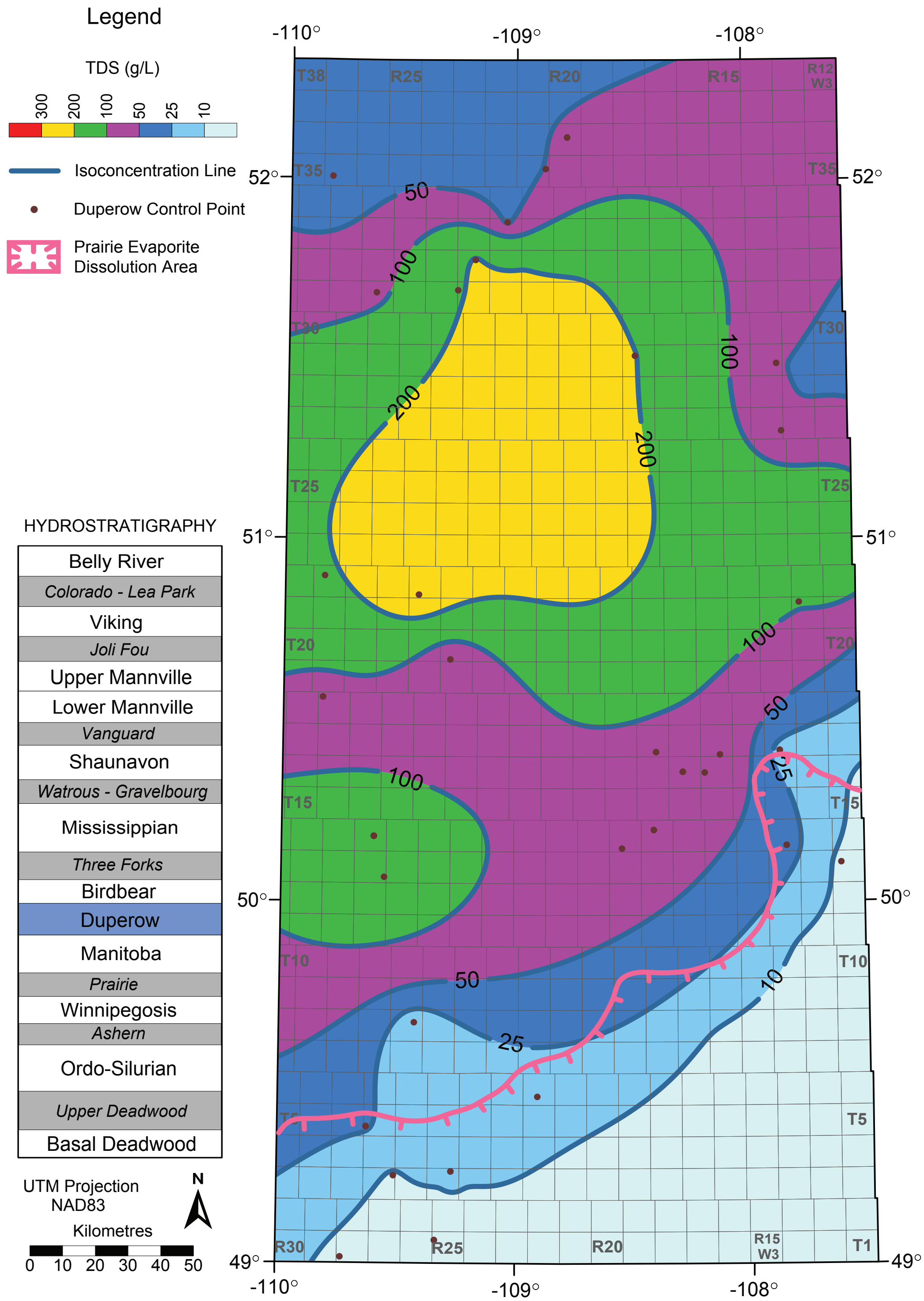

Figure 4.5: Distribution of TDS in the Duperow Aquifer.

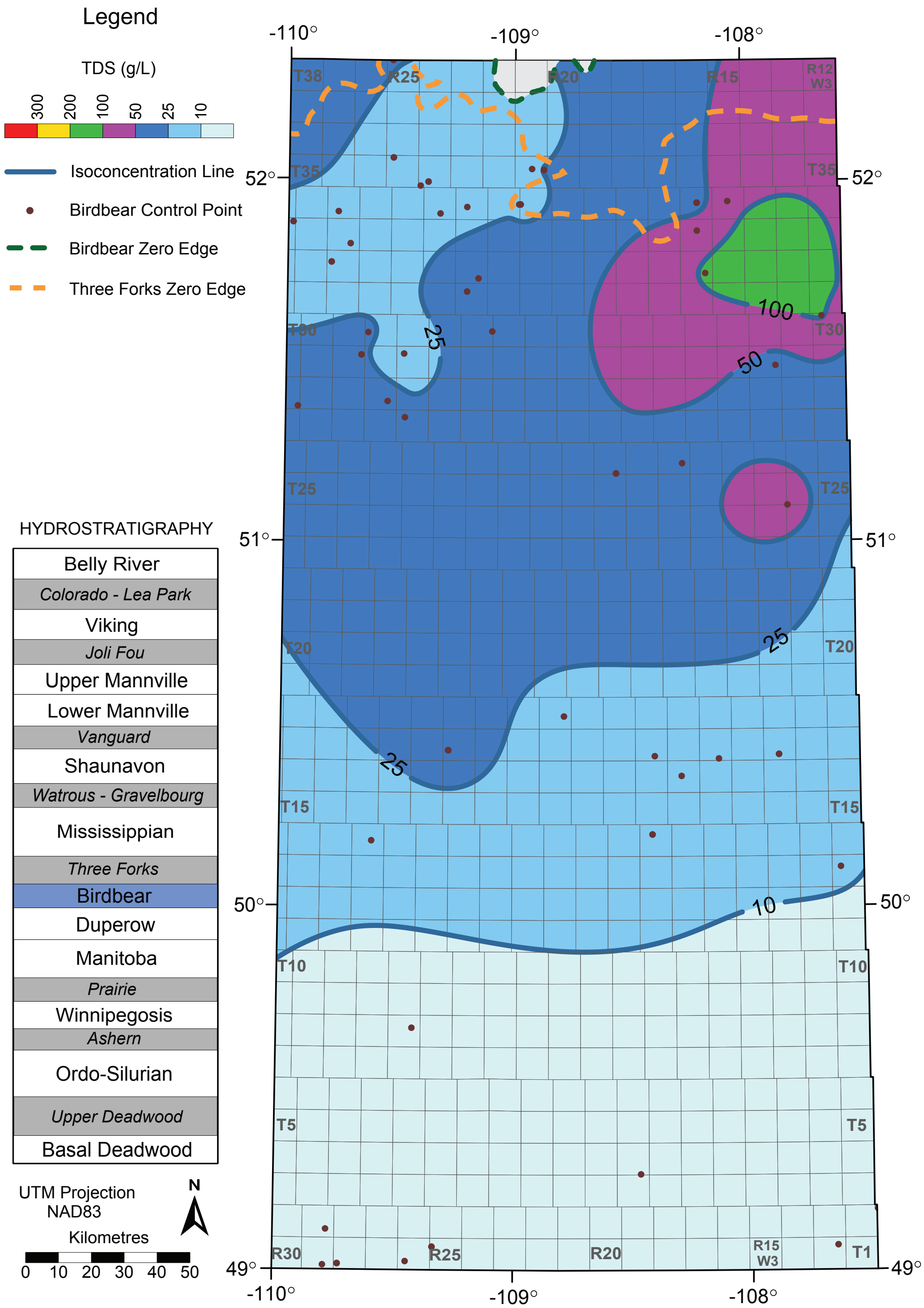

Figure 4.6: Distribution of TDS in the Birdbear Aquifer.

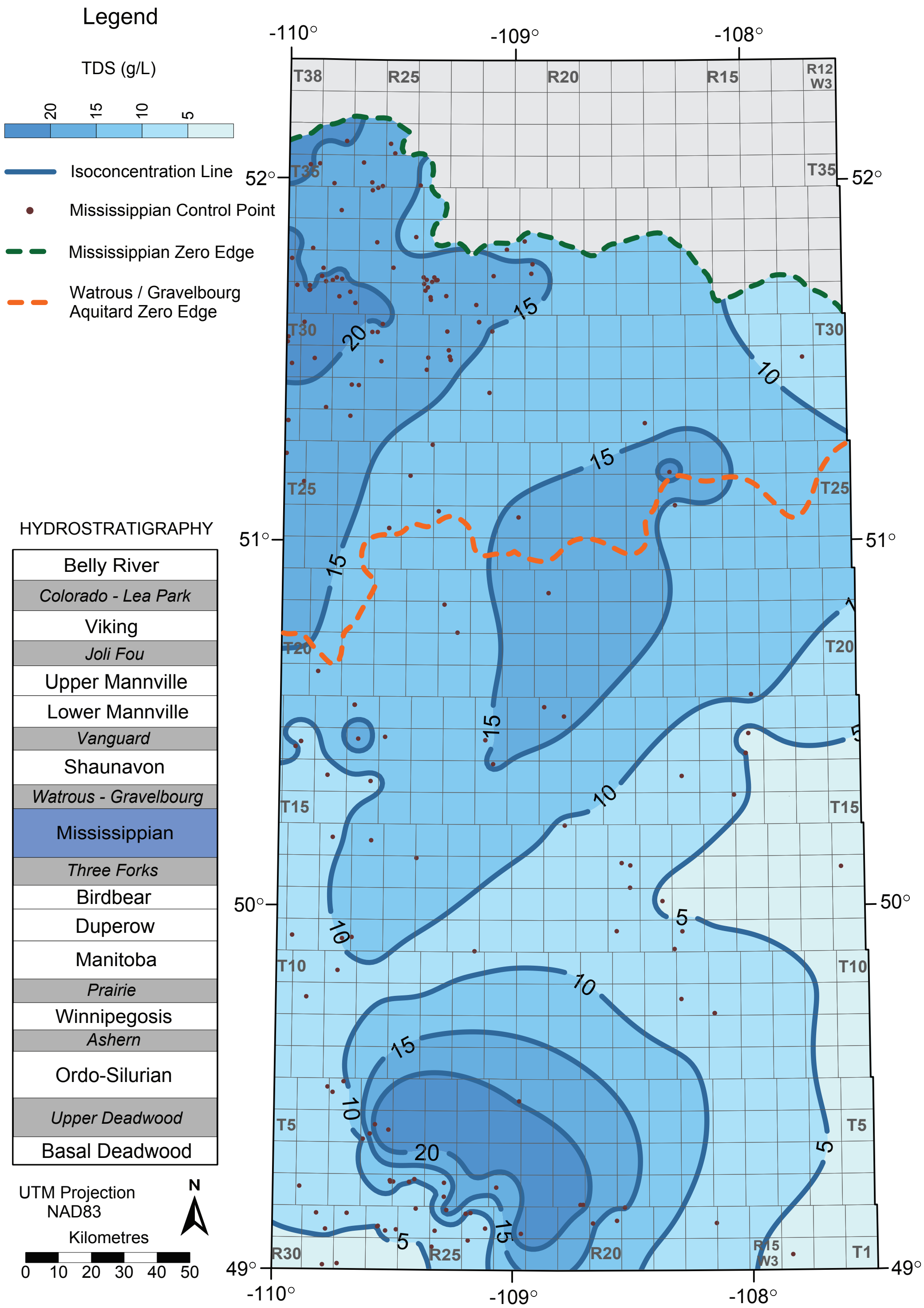

Figure 4.7: Distribution of TDS in the Mississippian Aquifer.

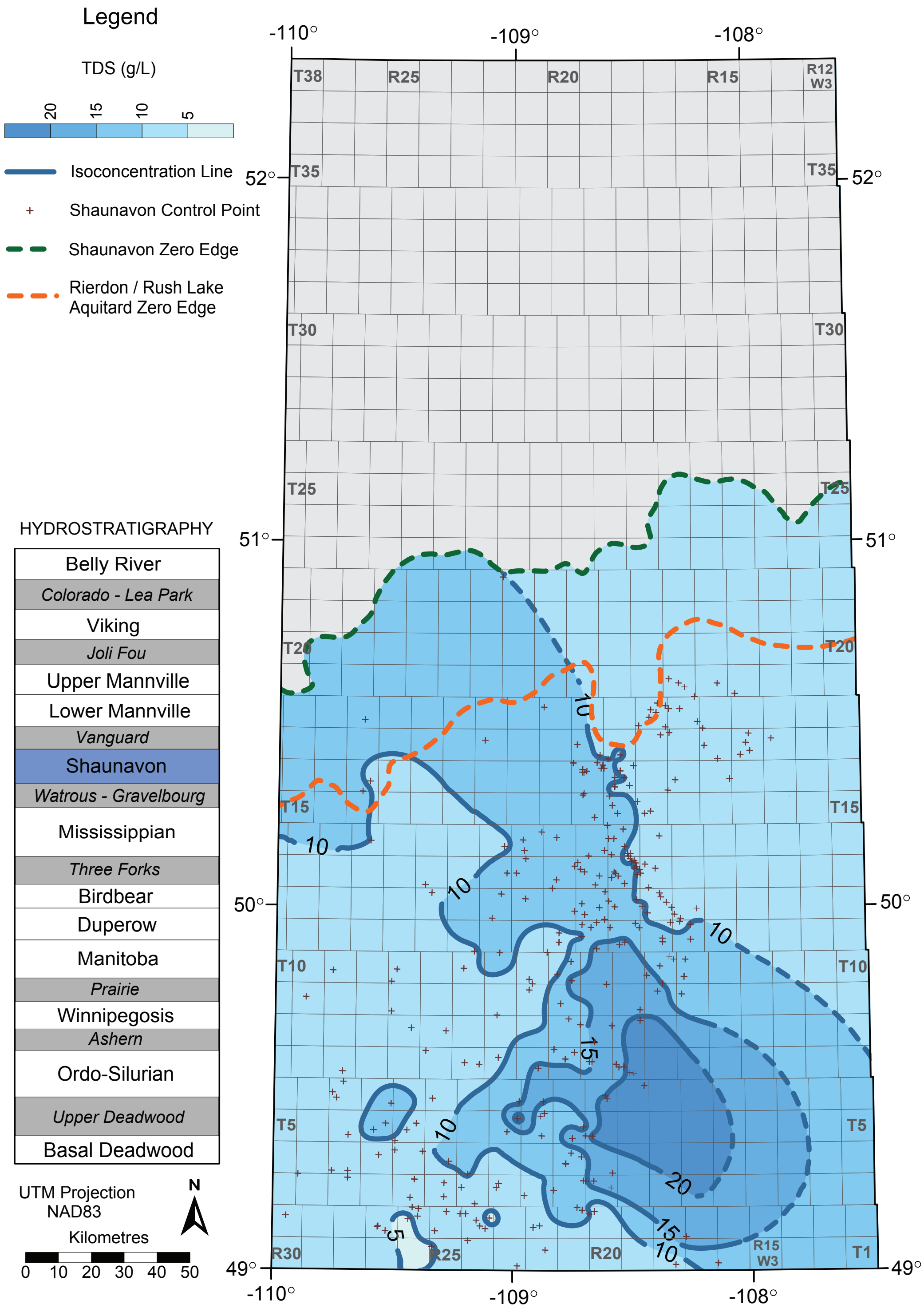

Figure 4.8: Distribution of TDS in the Shaunavon Aquifer.

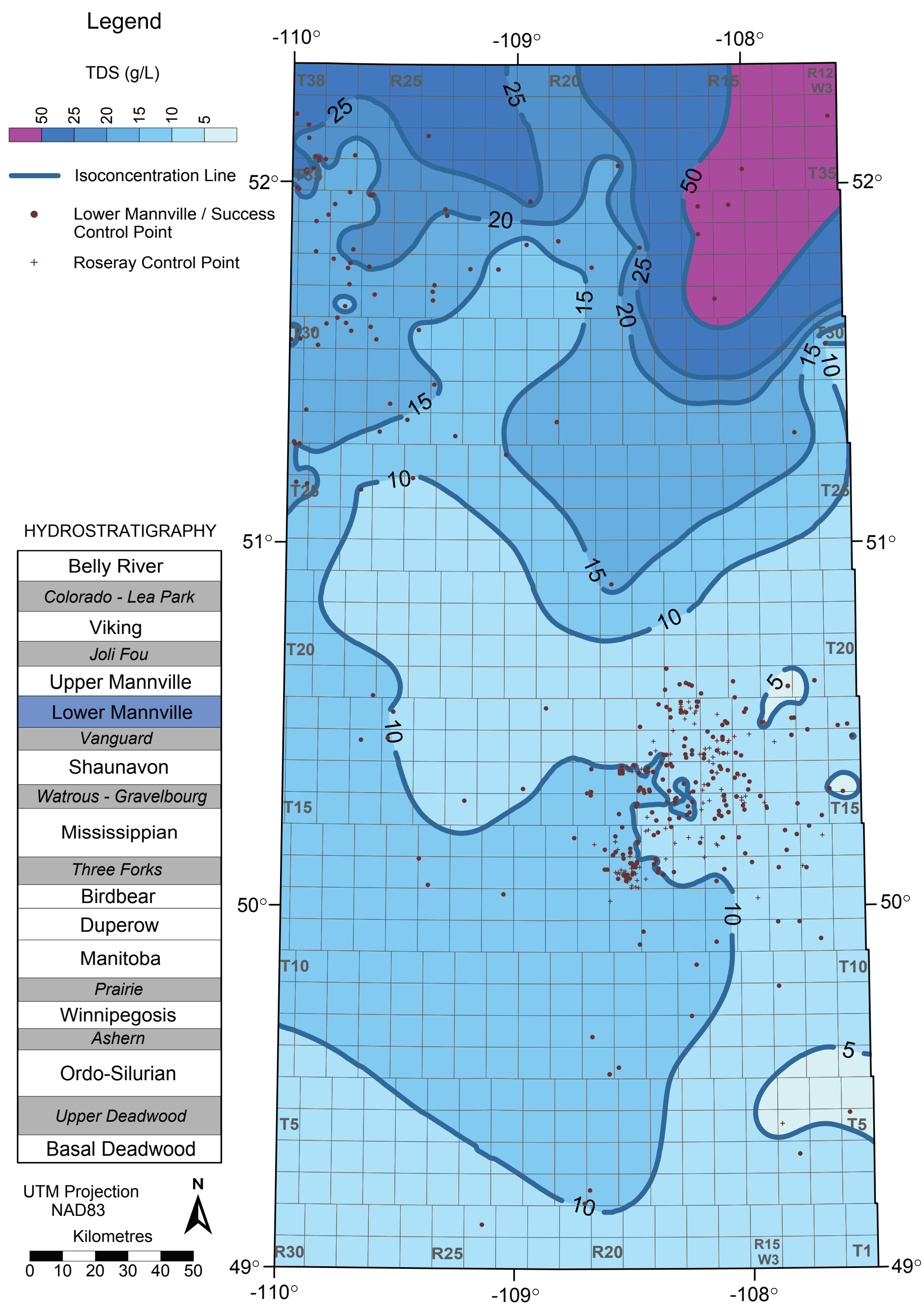

Figure 4.9: Distribution of TDS in the Lower Mannville Aquifer.

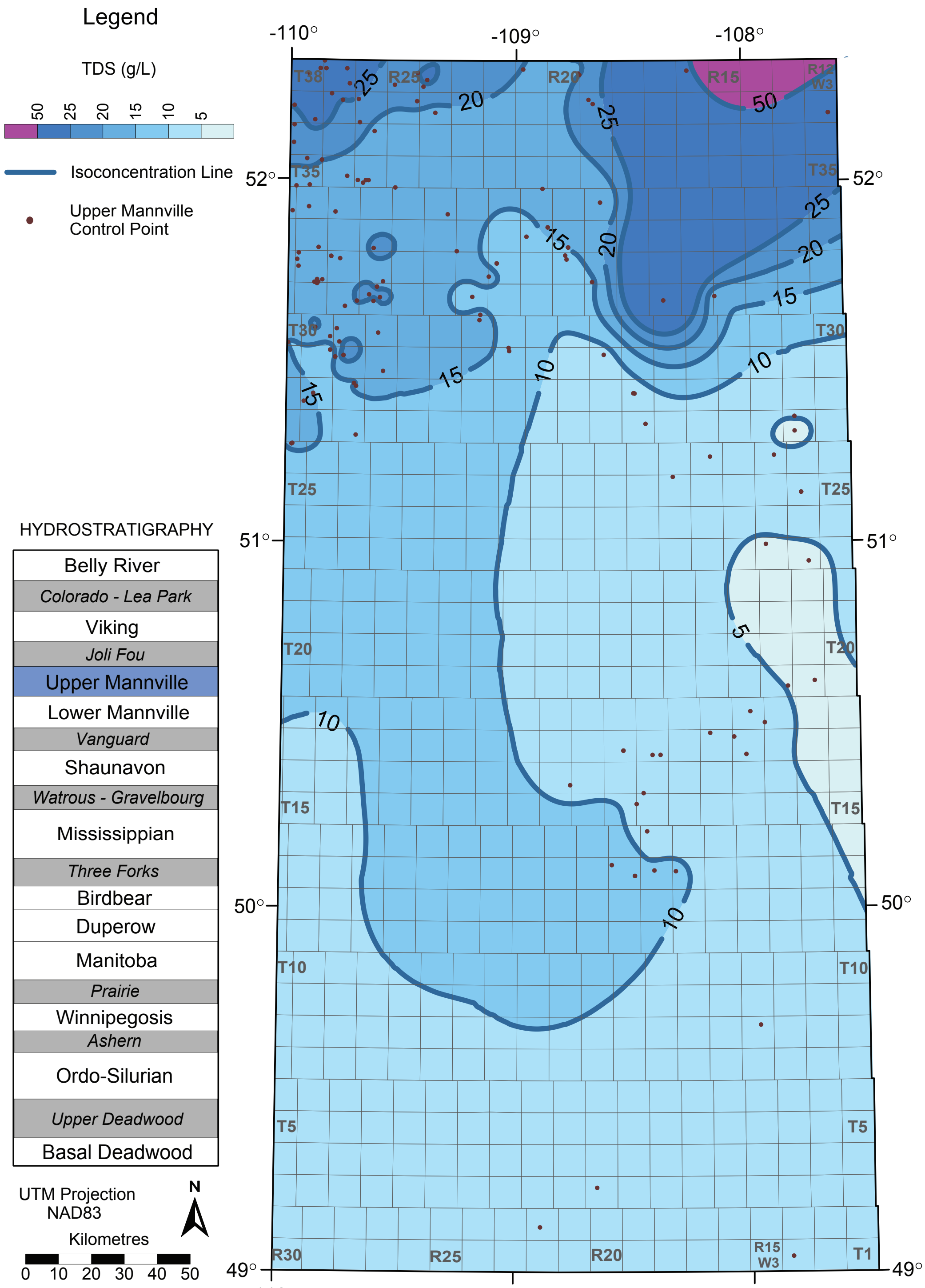

Figure 4.10: Distribution of TDS in the Upper Mannville Aquifer.

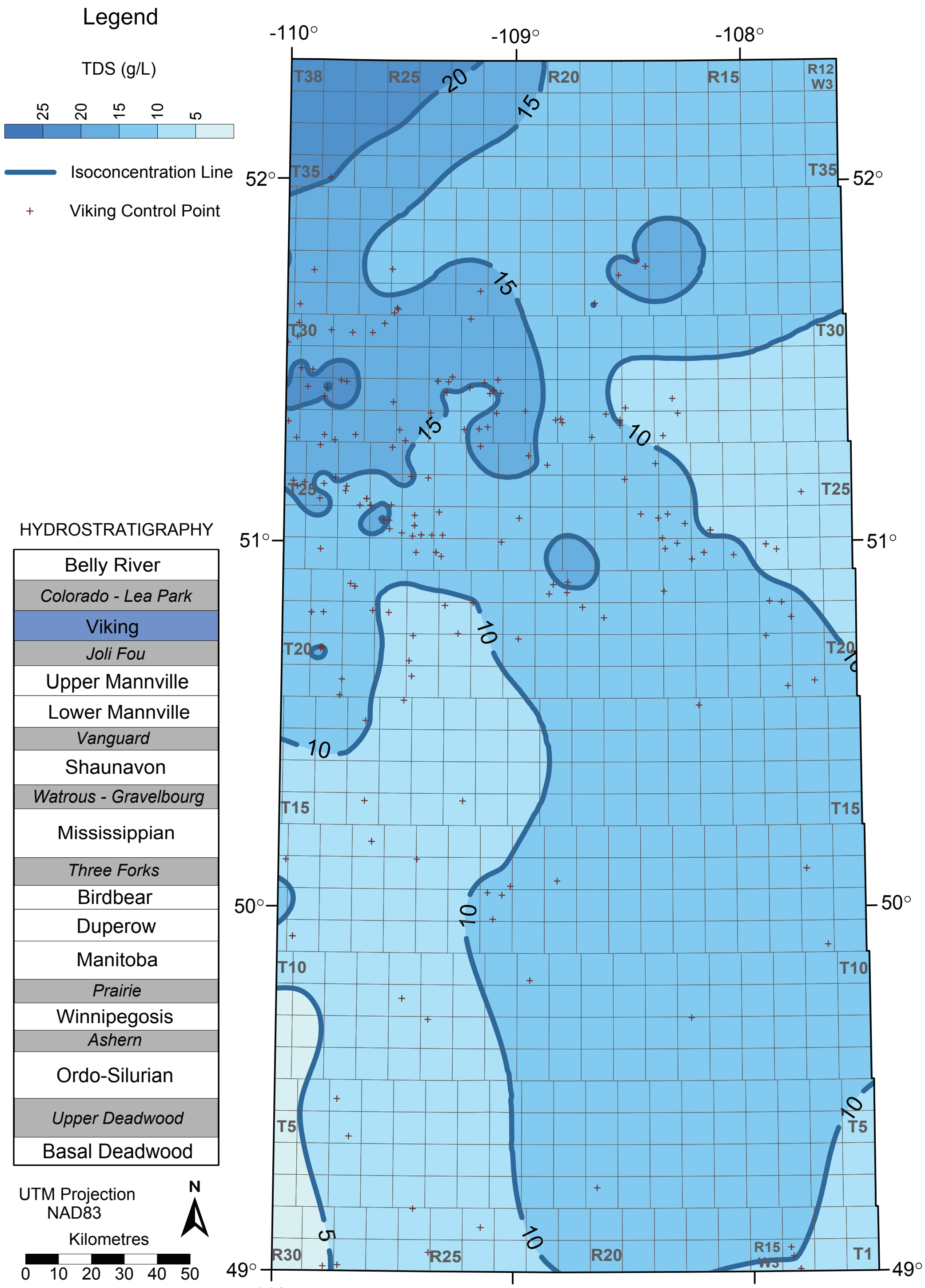

Figure 4.11: Distribution of TDS in the Viking Aquifer.

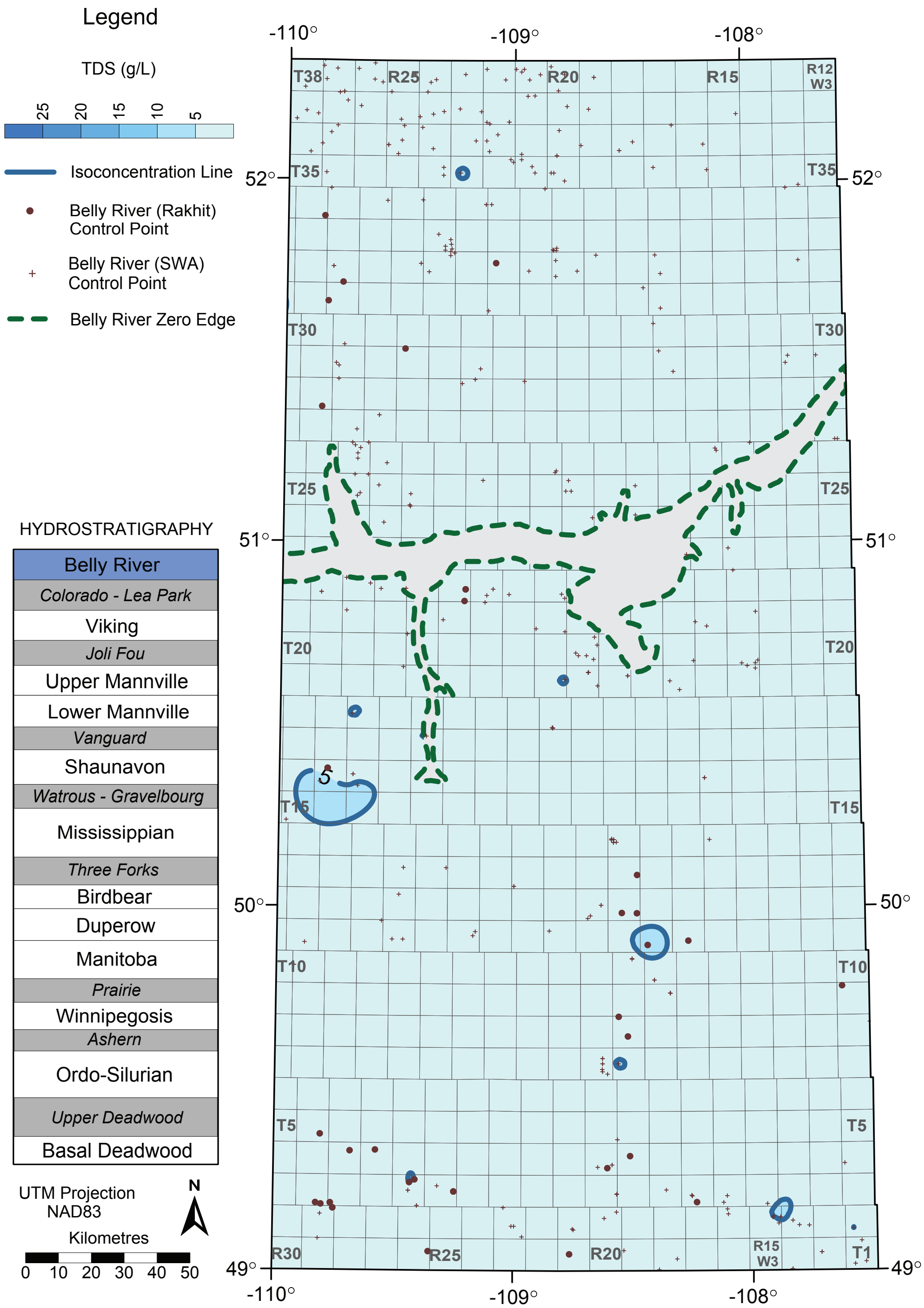

Figure 4.12: Distribution of TDS in the Belly River Aquifer.

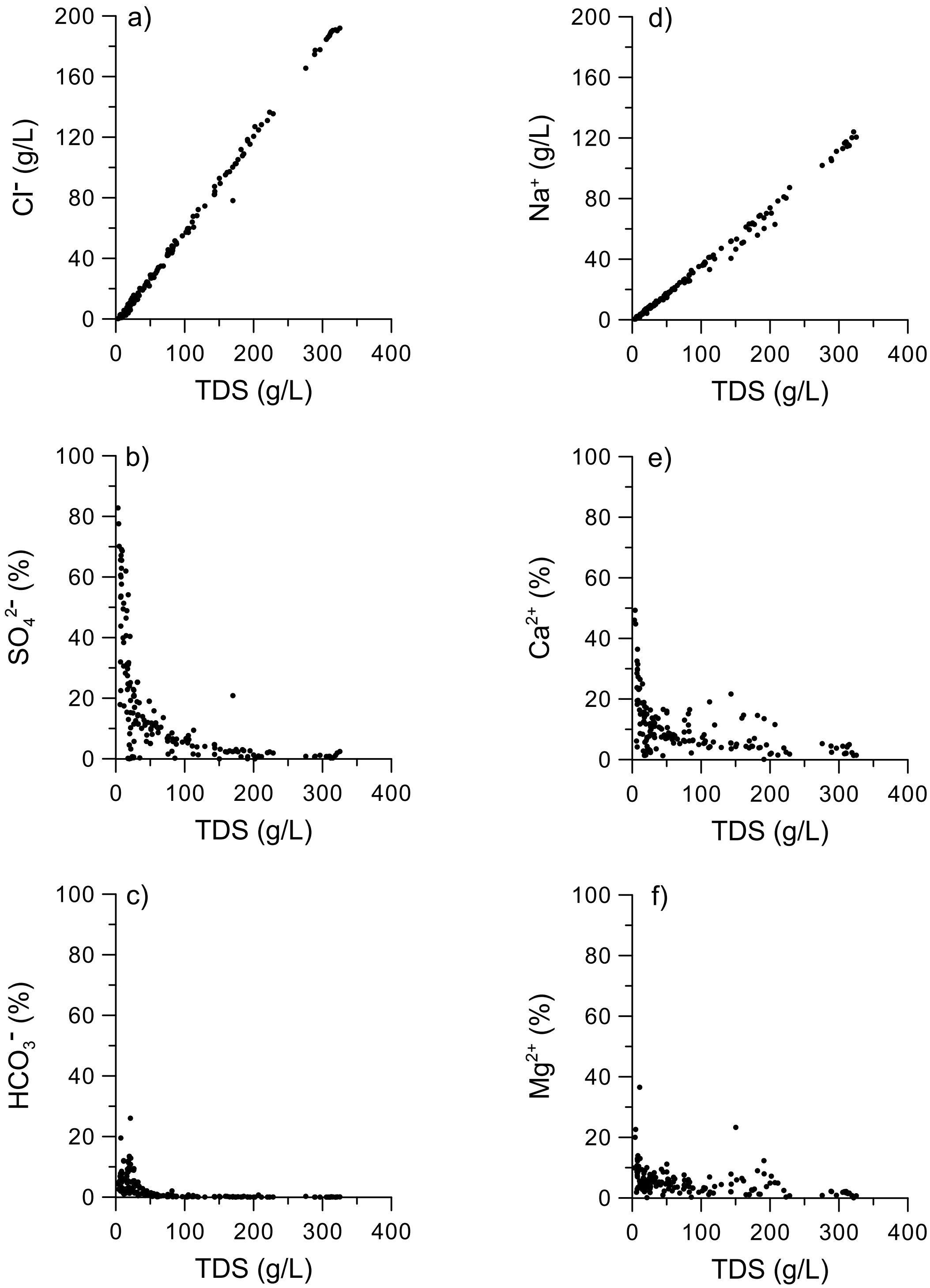

Figure 4.13: Total Dissolved Solids (g/L) versus a) chloride (g/L), b) sulphate (%), c) bicarbonate (%), d) sodium (g/L), e) calcium (%), and f) magnesium (%) in the **Lower Paleozoic** aquifers.

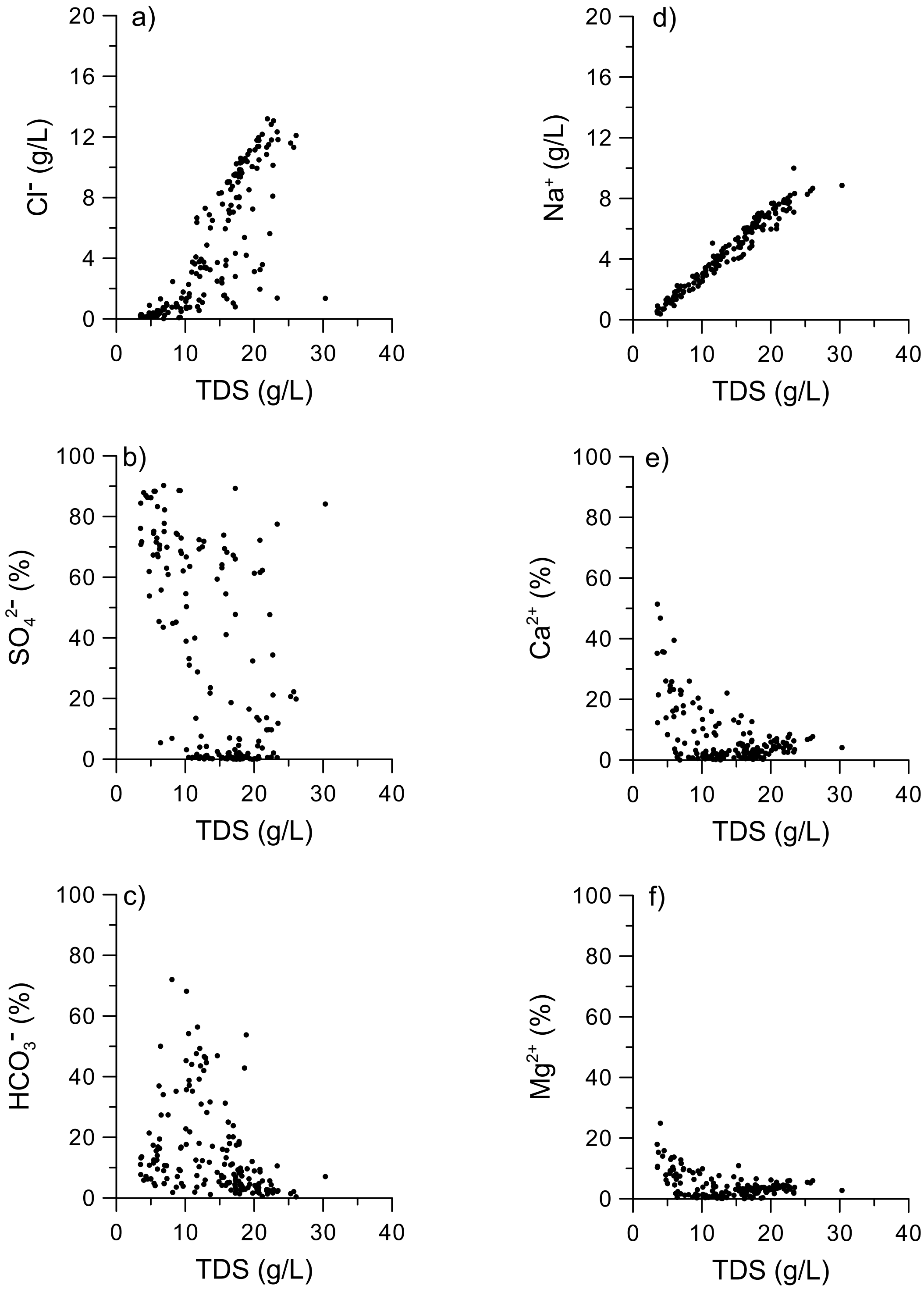

Figure 4.14: Total Dissolved Solids (g/L) versus a) chloride (g/L), b) sulphate (%), c) bicarbonate (%), d) sodium (g/L), e) calcium (%), and f) magnesium (%) in the **Mississippian** Aquifer.

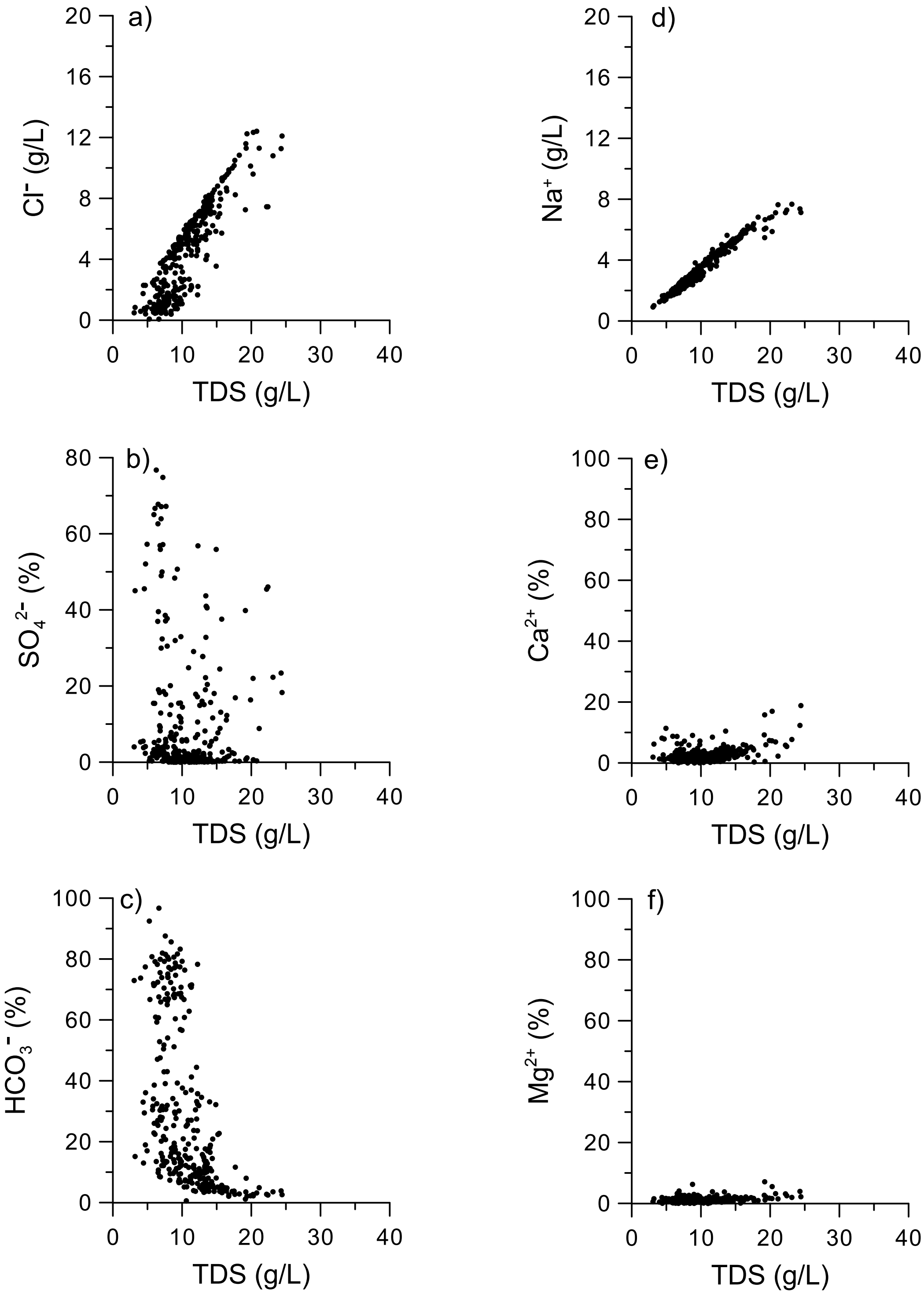

Figure 4.15: Total Dissolved Solids (g/L) versus a) chloride (g/L), b) sulphate (%), c) bicarbonate (%), d) sodium (g/L), e) calcium (%), and f) magnesium (%) in the **Jurassic** aquifer.

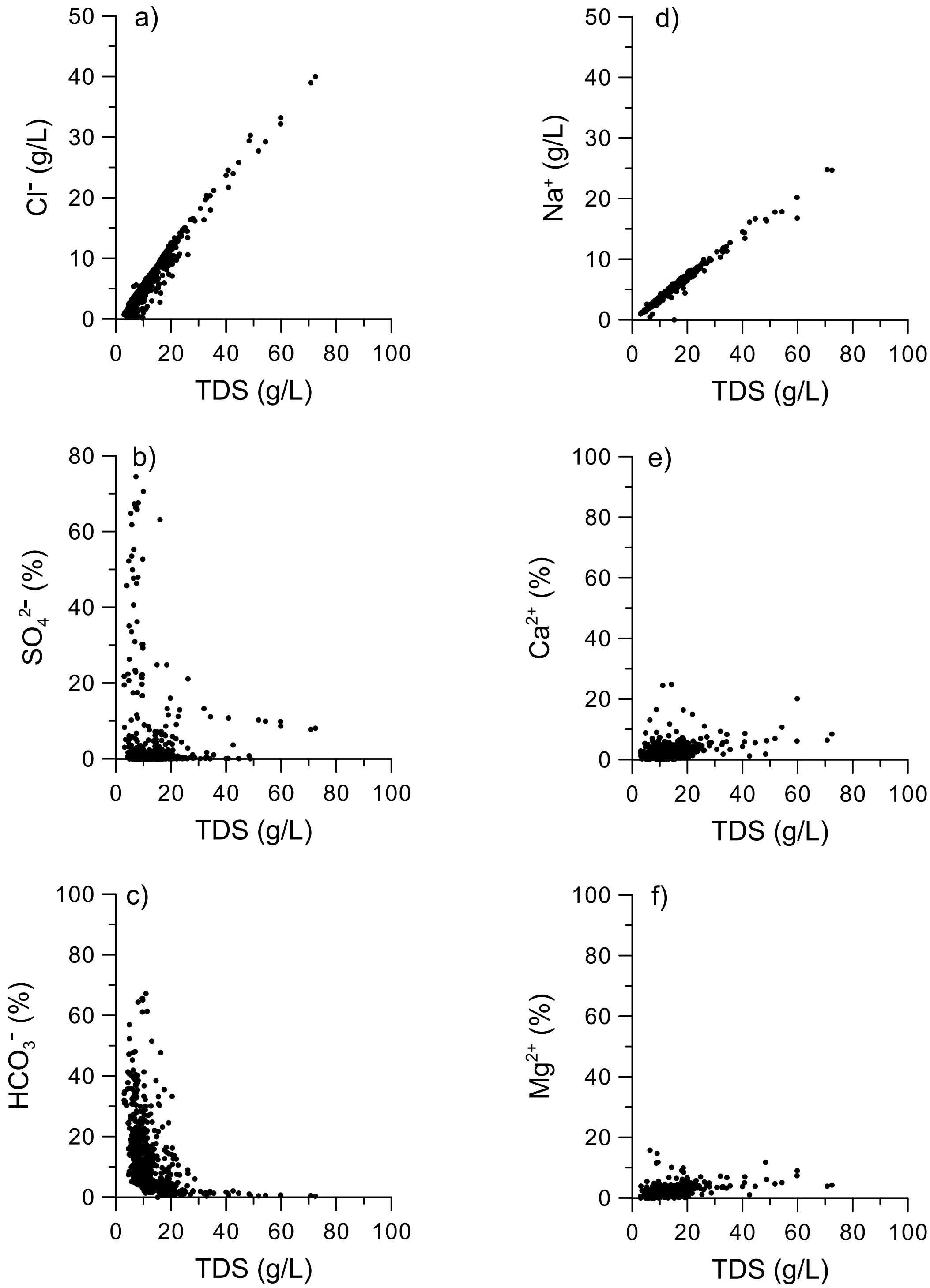

Figure 4.16: Total Dissolved Solids (g/L) versus a) chloride (g/L), b) sulphate (%), c) bicarbonate (%), d) sodium (g/L), e) calcium (%), and f) magnesium (%) in the **Lower Cretaceous** aquifers.

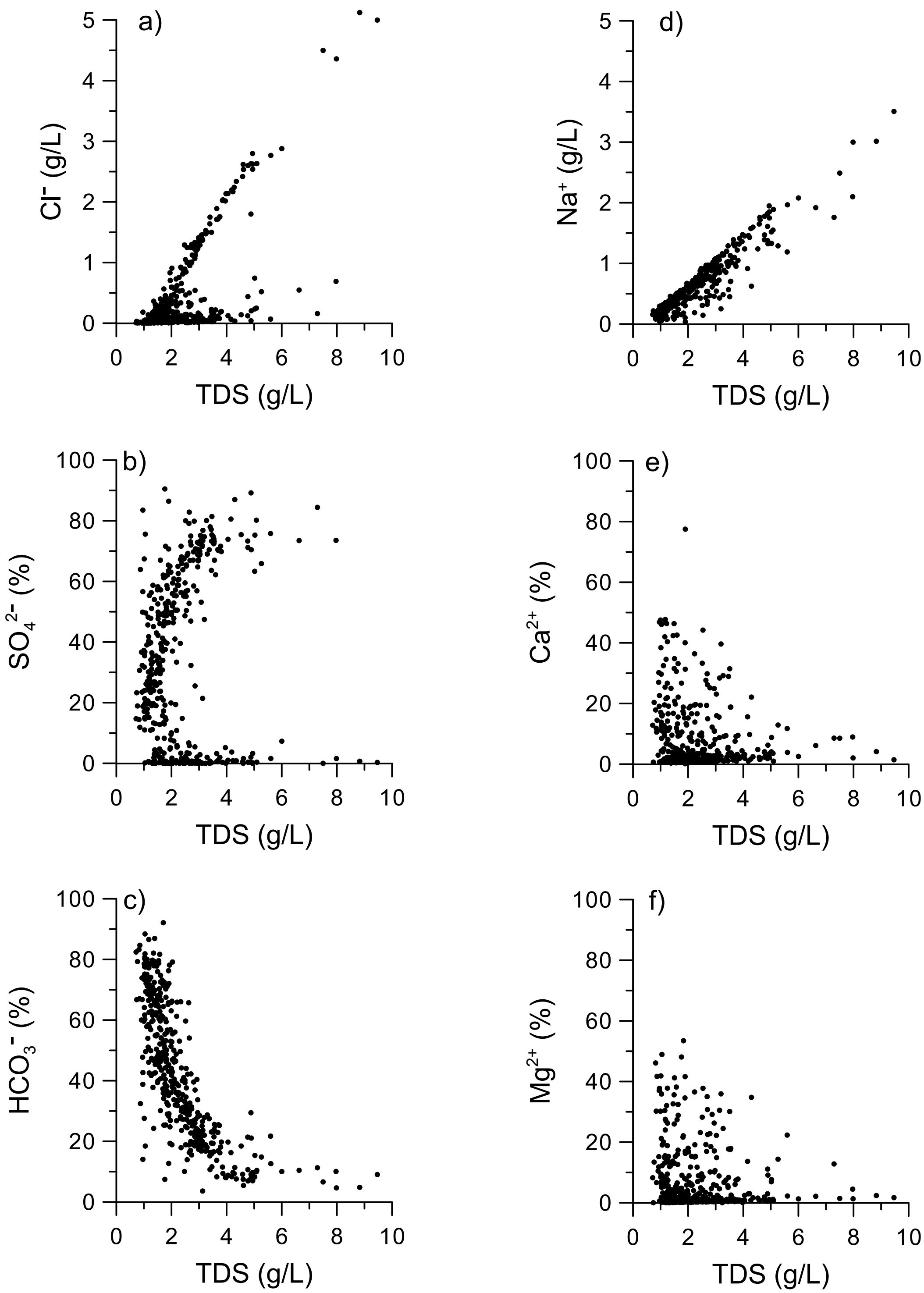

Figure 4.17: Total Dissolved Solids (g/L) versus a) chloride (g/L), b) sulphate (%), c) bicarbonate (%), d) sodium (g/L), e) calcium (%), and f) magnesium (%) in the **Upper Cretaceous** aquifer.

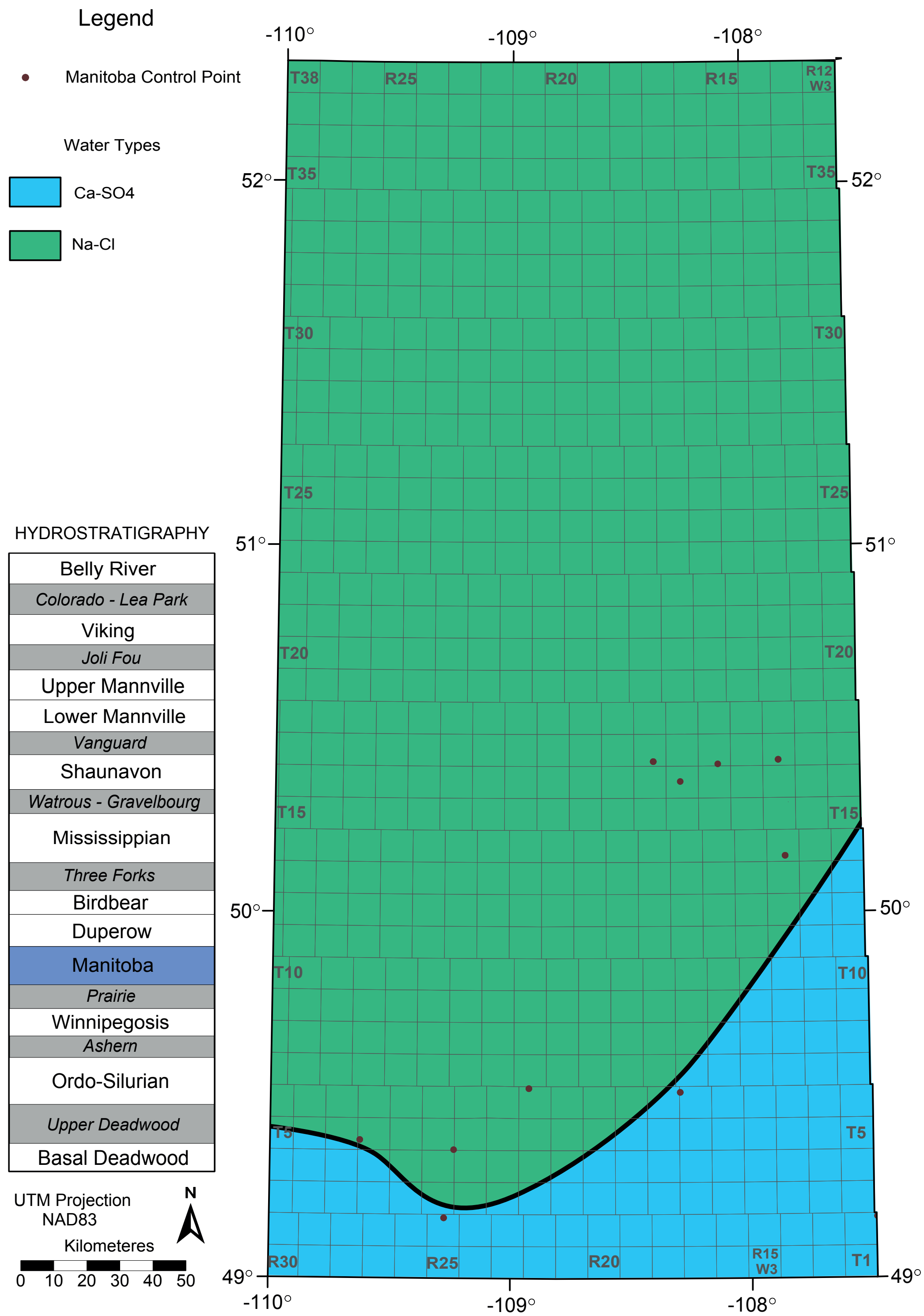

Figure 4.18: Distribution of water types in the Manitoba Aquifer.

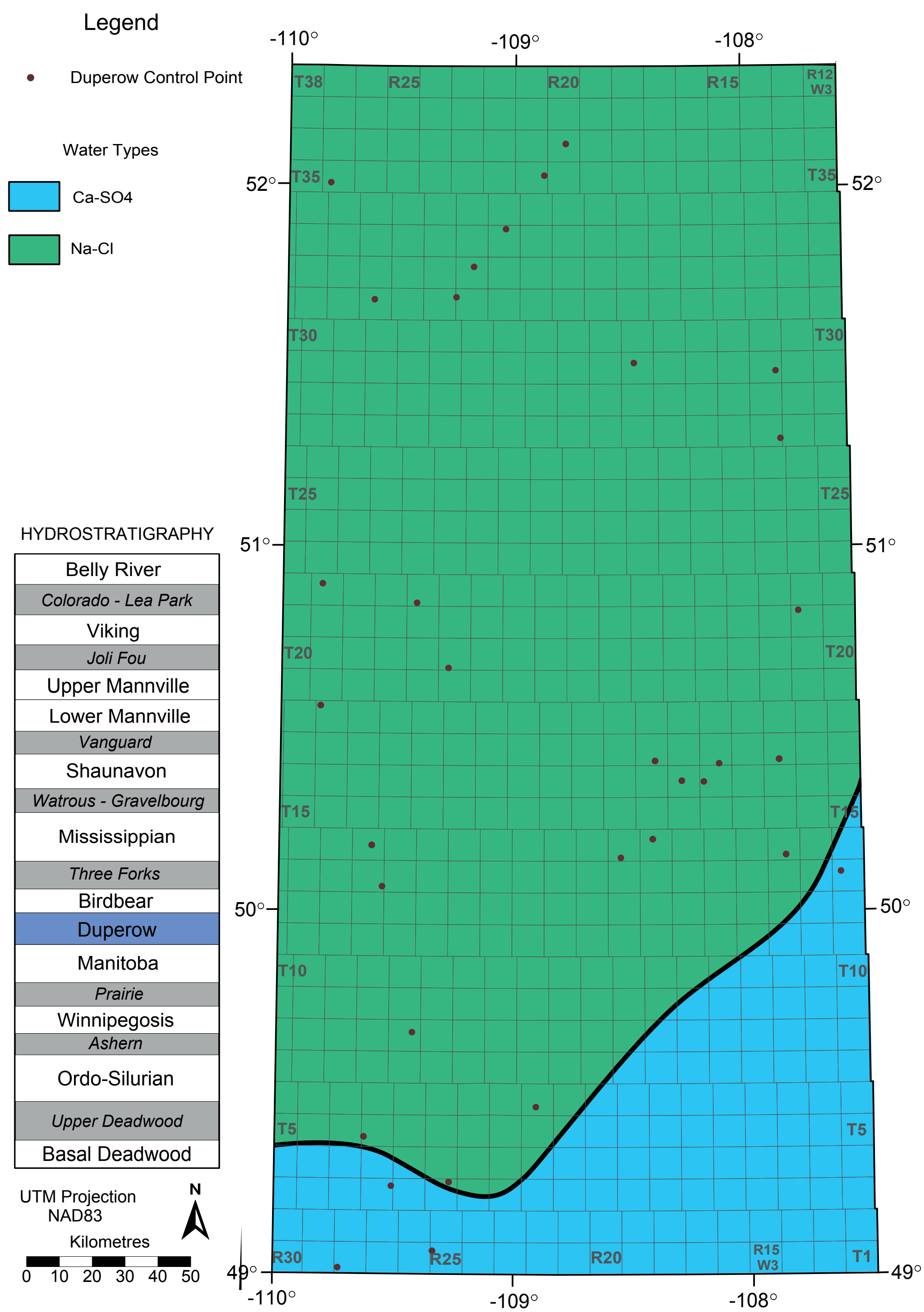

Figure 4.19: Distribution of water types in the Duperow Aquifer.

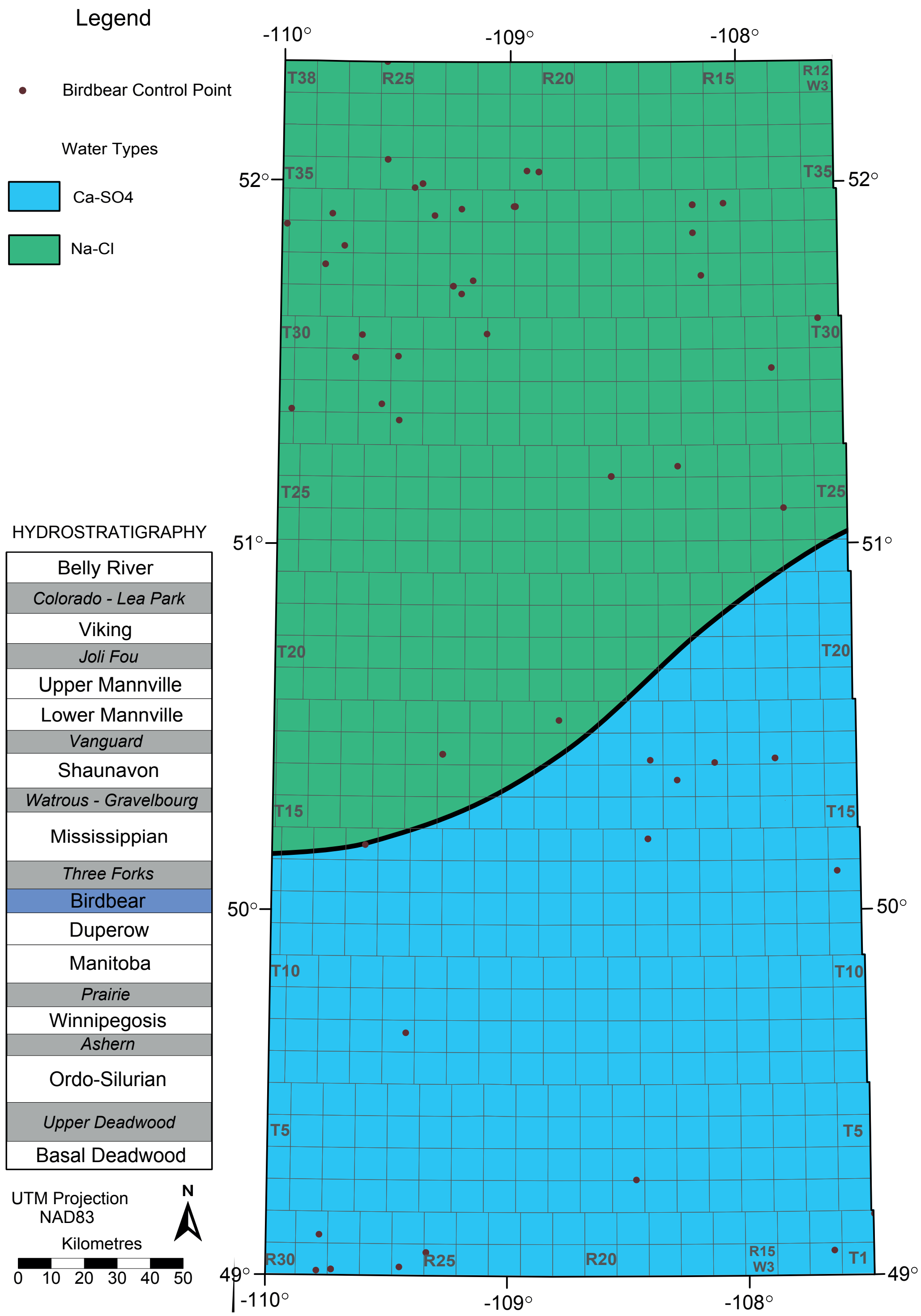

Figure 4.20: Distribution of water types in the Birdbear Aquifer.

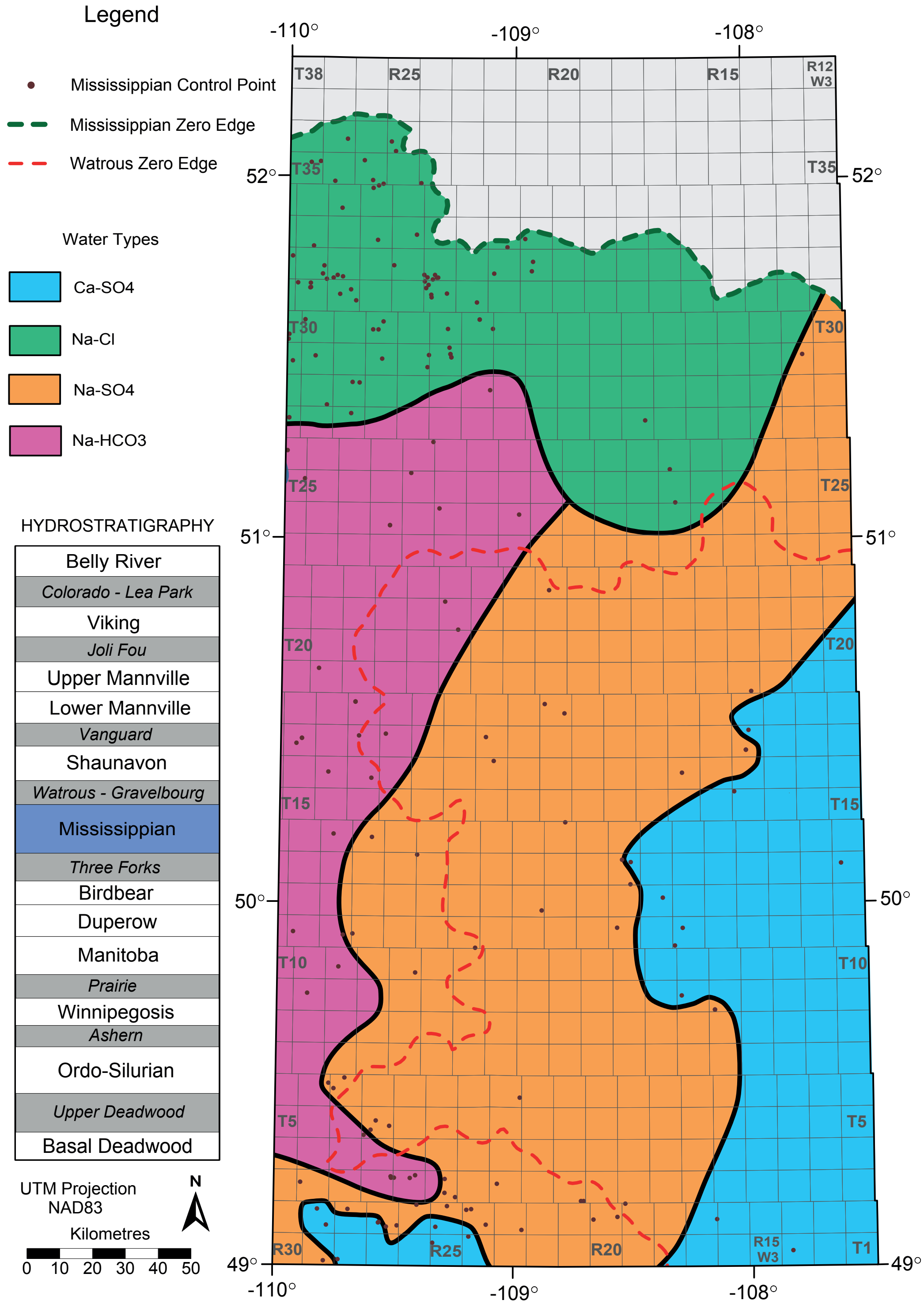

Figure 4.21: Distribution of water types in the Mississippian Aquifer.

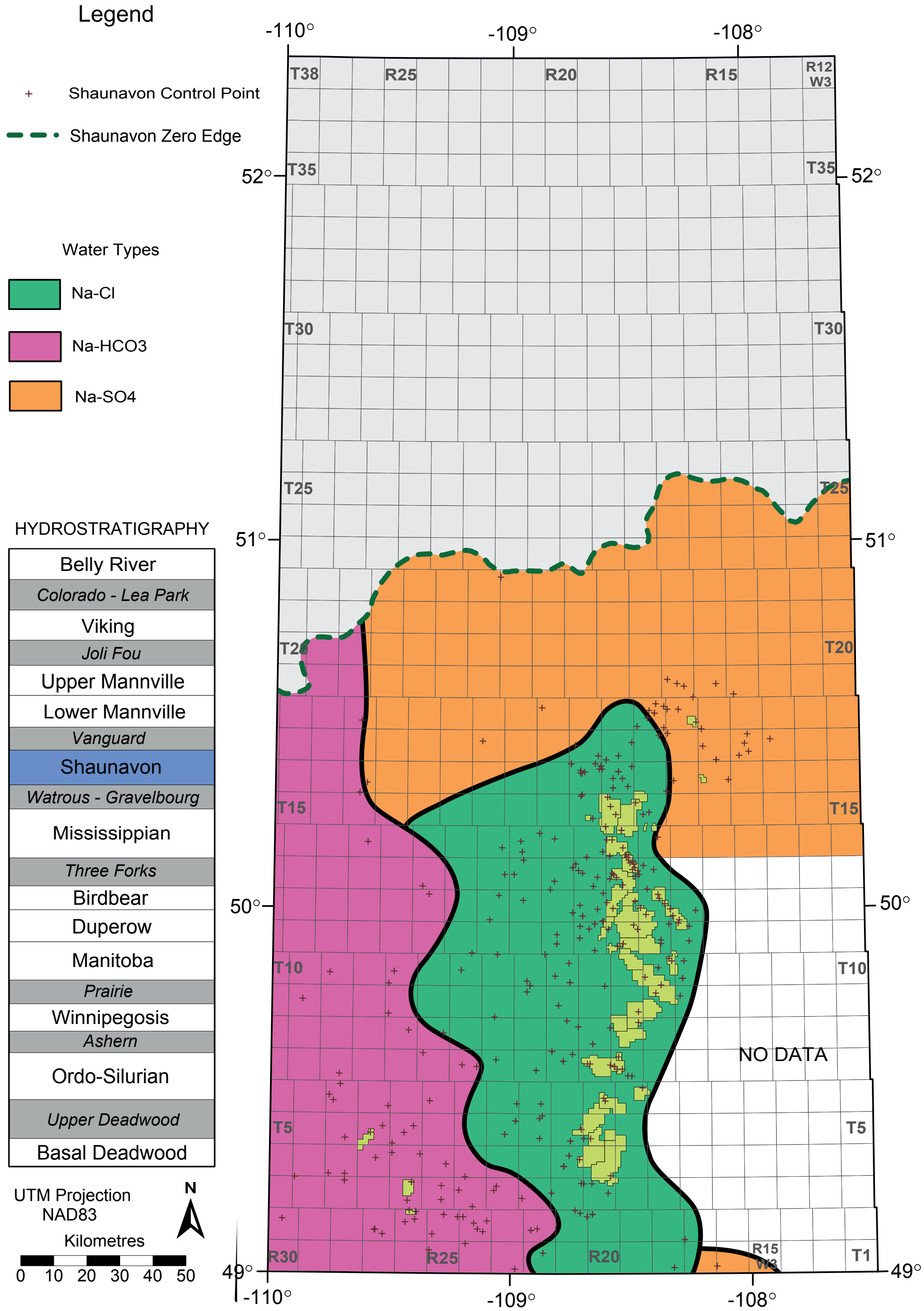

Figure 4.22: Distribution of water types in the Shaunavon Aquifer.

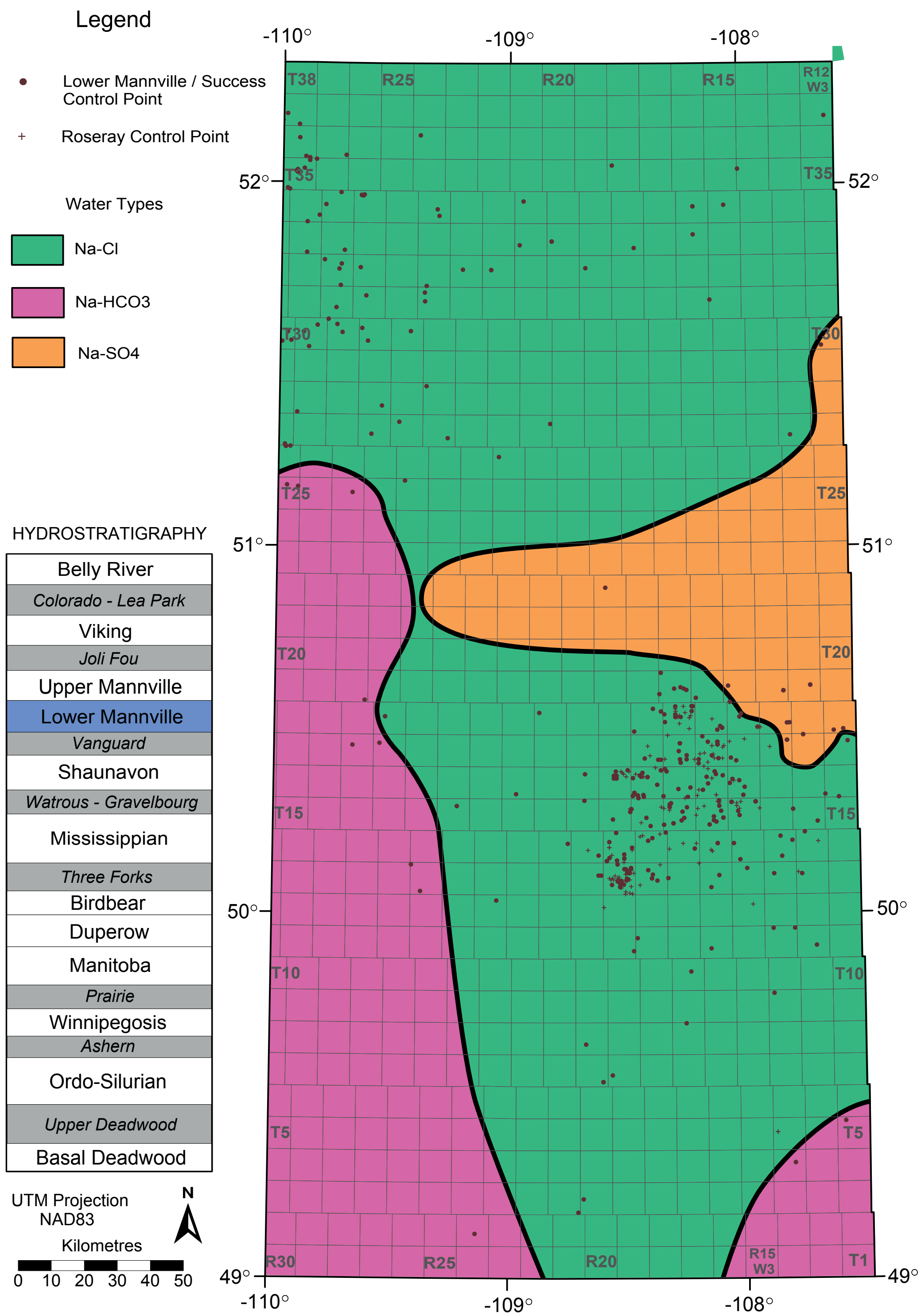

Figure 4.23: Distribution of water types in the Lower Mannville Aquifer.

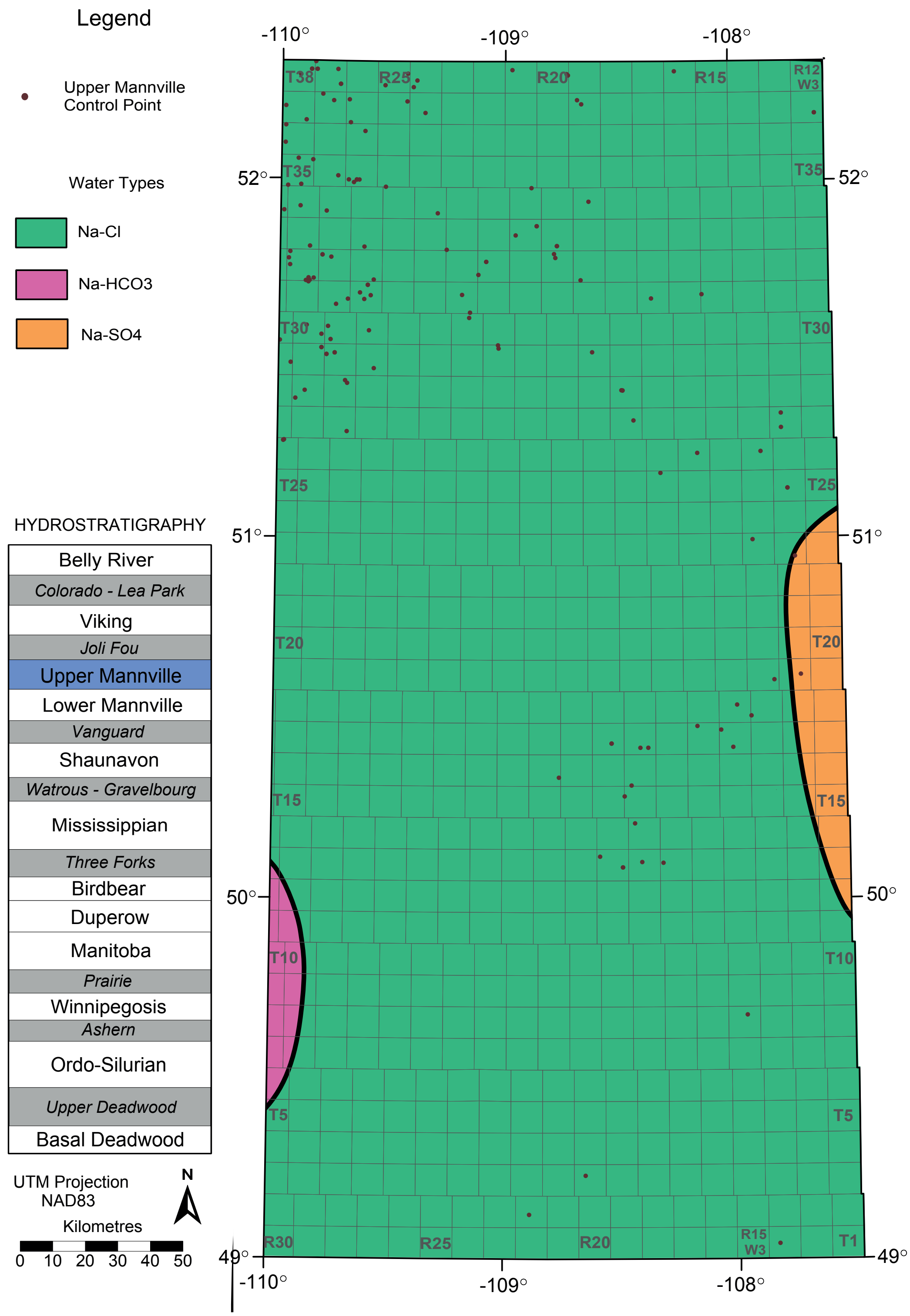

Figure 4.24: Distribution of water types in the Upper Mannville Aquifer.

CHAPTER 5 – Hydrodynamics

This chapter presents freshwater head contour maps combined with Water Driving Force (WDF) vectors (Figures 5.1 – 5.12). These maps show the direction of lateral groundwater flow in each of the identified individual aquifers. WDF vectors account for variable density flow in a sloping aquifer as well as provide relative magnitude of the freshwater head gradient. In addition, the angular difference between freshwater head gradient and WDF vectors has been calculated and contoured to show the areas of most significant density effects.

Vertical variations in hydraulic heads were examined by using pressure-elevation plots (Figures 5.13 – 5.16) and representative hydraulic cross-sections (Figures C.5 – C.8). Pressure-depth (p-d) plots were not used for this study area due to large variations in topography (i.e. from 1500 m in the Cypress Hills area to 700 m in the north) which resulted in significant data scattering on these plots.

5.1 Potentiometric Analysis

LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

Flow in the Basal Deadwood Aquifer is directed towards the north and northwest (Figure 5.1). The freshwater head gradients are generally low (<2 m/km) with exception of the southwest corner, where the observed gradients exceed 3 m/km. Fresh-water hydraulic head values range from 840 m in the southeast to 540 m in the north. Significant density effects, in terms of both magnitude and direction, are observed north of Township 30 due to the high TDS, low gradients and steep aquifer slope. The combination of these three factors results in a significant deviation of flow direction (up to being completely reversed) or reduced gradient.

Flow directions in Ordo-Silurian, Winnipegosis, and Manitoba aquifers are generally towards the north with consistently low freshwater head gradients (<2 m/km) (Figures 5.2 – 5.4). Significant density effects, in terms of both magnitude and direction, are observed in all three aquifers corresponding to areas of high TDS leading to a possible reversal of flow direction in the central and northern parts of the study area. These density effects are shown as contoured angular differences between the freshwater head gradients and WDF. Fresh-water hydraulic head values are significantly higher than those in the Basal Deadwood Aquifer and range from 900 m in the south to 600 m in the north.

Duperow and Birdbear aquifers have higher freshwater head gradients (over 4 m/km) than the underlying Paleozoic units (Figures 5.5 – 5.6). The largest gradients are observed in the south up to Township 10 in the Duperow Aquifer and up to Township 25 in the Birdbear Aquifer. Fresh-water hydraulic heads range from 940 m in the south to 540 m in the north; therefore, the primary flow direction is to the north. There are almost no density related effects due to lower TDS in both aquifers. However, small density-related flow deviations are observed in the central area of the Duperow Aquifer. The Birdbear Aquifer shows an easterly shift in flow direction in northern parts adjacent to Alberta border. This is the onset of a gradual transformation of flow direction from northward to eastward as it will be described in the paragraphs below. A very low freshwater head gradient exists north of Township 25 close to the subcrop edge, where the Birdbear Formation is in direct contact with the Mannville Group.

MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

The Mississippian Aquifer has the highest fresh-water hydraulic heads observed in the entire study area ranging from well over 1040 m in the south to 560 m in the north (Figure 5.7). Although the general flow direction still is towards the north, more easterly flow is observed in areas close to the Alberta border and the Madison Formation subcrop edge. The freshwater head gradients are over 4 m/km in the south and slowly decrease towards the erosional edge. There are no density effects in the Mississippian Aquifer and all the overlying aquifers due to the low TDS and water density.

JURASSIC HYDROGEOLOGIC SYSTEM

Fresh-water hydraulic heads in the Shaunavon Aquifer range from slightly over 1000 m in the south to 720 m in the north along the erosional edge (Figure 5.8). Overall, groundwater flow is directed to the north and there are no density related effects.

The central part of the study area is characterized by an eastward flow towards the Shaunavon Oil Trend. It should be noted that the pressure data used for mapping along the Shaunavon Oil Trend were obtained from pre-production wildcat wells. Therefore, Figure 5.8 shows the undisturbed potentiometric surface of the Shaunavon Aquifer.

Overall, flow in the Shaunavon Aquifer is lateral (along the aquifer). Two potentiometric anomalies, marked by closed contours (Township 7 – Range 19 and Township 10 – Range 18), are the result of slight vertical flow within the aquifer and indicative of the presence of high permeability lenses or zones. The latter is reinforced by the sudden drop in freshwater head gradients along the Shaunavon Oil Trend. These low gradients (<1 m/km) are present along the Shaunavon Oil Trend from Township 7 to Township 15 and are marked by almost constant freshwater hydraulic head of 800 m.

Fluid flow south of Township 15 and east of Range 16 cannot be accurately interpreted due to the lack of data. The map shows a complete lack of data to the east of the Shaunavon Oil Trend due to the poor quality of the drill-stem tests (i.e. insufficient development of the build-up curves and very low recoveries consisting of drilling fluid).

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

Fluid potentials in the Lower Mannville Aquifer mark a pronounced shift in flow direction throughout the study area (Figure 5.9). Water flows primarily from the west (Alberta) towards the east and northeast, unlike all of the underlying aquifers. Hydraulic heads range from 950 m in the southwest corner to less than 540 m in the northeast. There are two main features observed: 1) a high freshwater head gradient (> 4 m/km) and a downdip flow in the east-central area which corresponds to Success-Roseray oil pools, and 2) potentiometric high around Township 28 and Range 30. The eastern side of the map is marked by very low freshwater head gradients and coincides with the presence of Roseray Formation sands.

The Upper Mannville Aquifer has a similar flow pattern to the Lower Mannville Aquifer (Figure 5.10). Hydraulic heads range from 900 m in the southwest corner to 500 m in the northeast. The main distinction between Upper and Lower Mannville aquifers can be made by comparing their hydraulic heads which are on average 60 m lower in the Upper Mannville Aquifer than in the Lower Mannville Aquifer. A large potentiometric low stretching between Townships 15 to 38 and Range 13 to 16 can be attributed to the presence of permeable Spinney Hill sands which are combined with the Pense Formation to form the Upper Mannville Aquifer.

Formation fluids in the Viking Aquifer generally flow from southwest towards northeast; however, the flow pattern is significantly different from the underlying aquifers (Figure 5.11). Hydraulic heads range from 780 m in the southwest to 620 m in the northeast. The majority of hydraulic heads fall between 720 m to 680 m (i.e. 700 m regional average). The Viking Aquifer is characterized by relatively low freshwater head gradients throughout the entire study area. There are several important features observed: 1) a large potentiometric high is present in the southwest, 2) two potentiometric highs (> 700 m) are situated around several oil fields in the east-central area, and 3) very steep gradient is present between the contours of 680 m and 620 m. The 680 m contour line marks an approximate boundary north of which little or almost no water can be recovered. This contour coincides with the facies change whereby permeability is significantly reduced due to increased shale content and thinning of the Viking Formation (Jones, 1961; Reinson et al., 1994).

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

Flow directions in the Belly River Aquifer are variable and resemble the overlying topographic surface (Figure 5.12, compared to topography Figure 1.2). Water flows towards low-lying subcrops and erosional areas controlled by numerous creeks and incised valleys. For example, one the major features is the flow convergence towards the South Saskatchewan River, which divides the aquifer (through erosion) into two parts: northern and southern. In the south a potentiometric high with hydraulic heads exceeding 840 m coincides with Cypress Hills. Water flows away from Cypress Hills in all directions with high freshwater head gradients. As the topography flattens out towards the north, gradients also decrease. The lowest hydraulic heads (< 580 m) are observed in the Tyner Valley and South Saskatchewan River.

5.2 Vertical Pressure Variations

Three representative areas have been carefully selected for the evaluation of vertical fluid flow using p-z plots (Figure 5.13). The selection was based on data availability and on potential areas of cross-formational flow indicated by geology. The best fit gradients were calculated for each aquifer or hydrogeologic system.

LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

Vertical pressure gradients in the Lower Paleozoic aquifers range from 9.8 kPa/m in the south (Figure 5.14) to 11.9 kPa/m and 13.1 kPa/m in the north (Figures 5.15 – 5.16). These pressure gradients appear to be hydrostatic and the increase in gradient values in the north appears to be largely due to higher TDS in the deepest aquifers (Deadwood, Ordo-Silurian, Winnipegosis, and Manitoba). However, there are two major exceptions to the above statement: 1) The vertical pressure gradients in the Birdbear and Duperow aquifers in the north (Figures 5.15 – 5.16) are super-hydrostatic because their TDS values are much lower (averaging at 30 g/L) than in the underlying aquifers; and 2) data point from the Basal Deadwood Aquifer plots significantly lower (i.e. underpressured) than the average regional pressure gradient in the Lower Paleozoic aquifers (Figure 5.16).

Hydraulic cross-sections A and B (Figures C.5 – C.6) show that the groundwater flow in the Lower Paleozoic aquifers is generally lateral (along the aquifer) throughout the southern and central parts of the study area. However, in the north of the study area groundwater has a strong upward flow component, especially in the Birdbear and Duperow aquifers.

MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

Pressure-elevation plot of Area A (Figure 5.14) shows that the vertical pressure gradient in the Mississippian Aquifer is super-hydrostatic and has a value of 12.3 kPa/m. This gradient appears to be different from the one in the Lower Paleozoic aquifers. The Mississippian Aquifer is overpressured relative to the underlying Lower Paleozoic aquifers on average by at least 2 MPa. This difference reaffirms the aquifer's classification as a separate system from the underlying Lower Paleozoic aquifers. There are no data from the Mississippian Aquifer in the north due to its erosion.

Hydraulic cross-sections A and B (Figures C.5 – C.6) show that the Mississippian Aquifer has the highest hydraulic heads and that groundwater flows parallel to the aquifer throughout the entire study area.

JURASSIC HYDROGEOLOGIC SYSTEM

The vertical pressure gradient in the Shaunavon Aquifer is super-hydrostatic of 12.0 kPa/m (Figure 5.14). The Jurassic pressure data form a separate and slightly underpressured hydrogeologic system relative to the Mississippian Aquifer. It should be noted, however, that several pressure data points from the Shaunavon Aquifer in the Area A fall on the Mississippian Aquifer's vertical pressure gradient indicating hydraulic communication between the two aquifers.

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

Vertical pressure gradients in the Mannville aquifers are highly variable. They range from sub-hydrostatic in the northwest (7.8 kPa/m; Figure 5.15), to super-hydrostatic in the northeast (11.9 kPa/m; Figure 5.16) and central parts of the study area (not shown). The Mannville aquifers have the same vertical gradient in the northeast as the underlying Birdbear and Duperow aquifers.

The Viking Aquifer is significantly underpressured relative to the Mannville aquifers (Figures 4.14 and 4.15). The vertical pressure gradients are nearly hydrostatic ranging from 10.0 kPa/m in the south (Figure 5.14) to 10.7 kPa/m in the northwest (Figure 5.15).

All four hydraulic cross-sections (Figures C.5 – C.8) show that the vertical groundwater flow directions in the Mannville aquifers are highly variable and depend on the geographic location. Strong upward water drive exists throughout the subcrop areas of the Jurassic, Mississippian, and Devonian aquifers (i.e. central and northern parts of the study area). The only exception is in the northwest, where the flow is directed downward.

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

Vertical pressure gradients in the Belly River Aquifer range from sub-hydrostatic to super-hydrostatic (from 2.8 to 11.0 kPa/m) (Figure 5.14). Figures 5.14 – 5.16 show that pressure data from higher elevations fall on the sub-hydrostatic gradient while pressure data from lower elevations fall on super-hydrostatic gradient. This observation is valid throughout the entire study area and consistent with local scale topographically-driven flow shown by all cross-sections (Figures C.5 – C.8). Groundwater flows downward from topographically high areas (recharge) towards low-lying subcrops and erosional valleys (discharge).

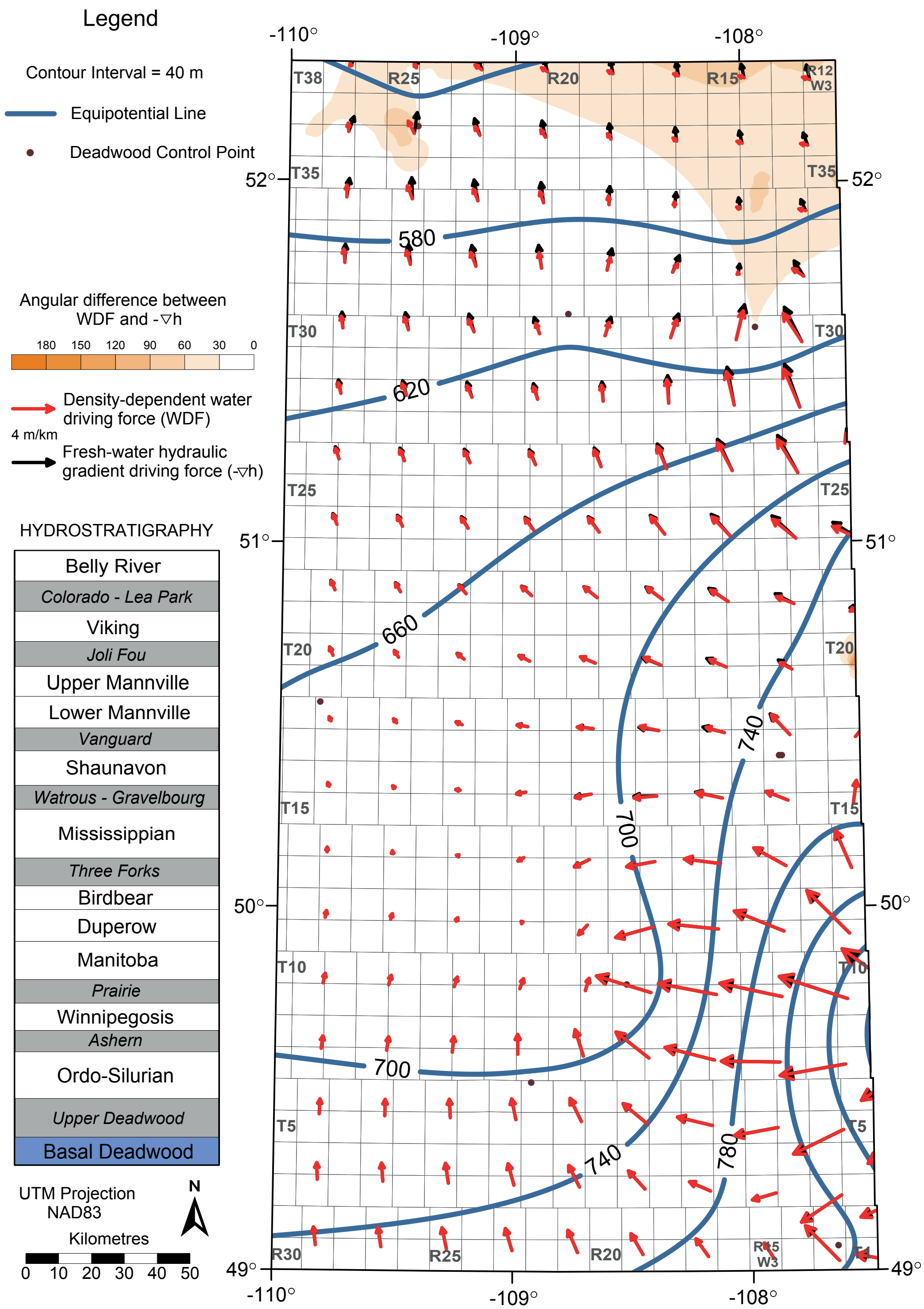

Figure 5.1: Distribution of hydraulic heads (m) and water driving forces in the Basal Deadwood Aquifer.

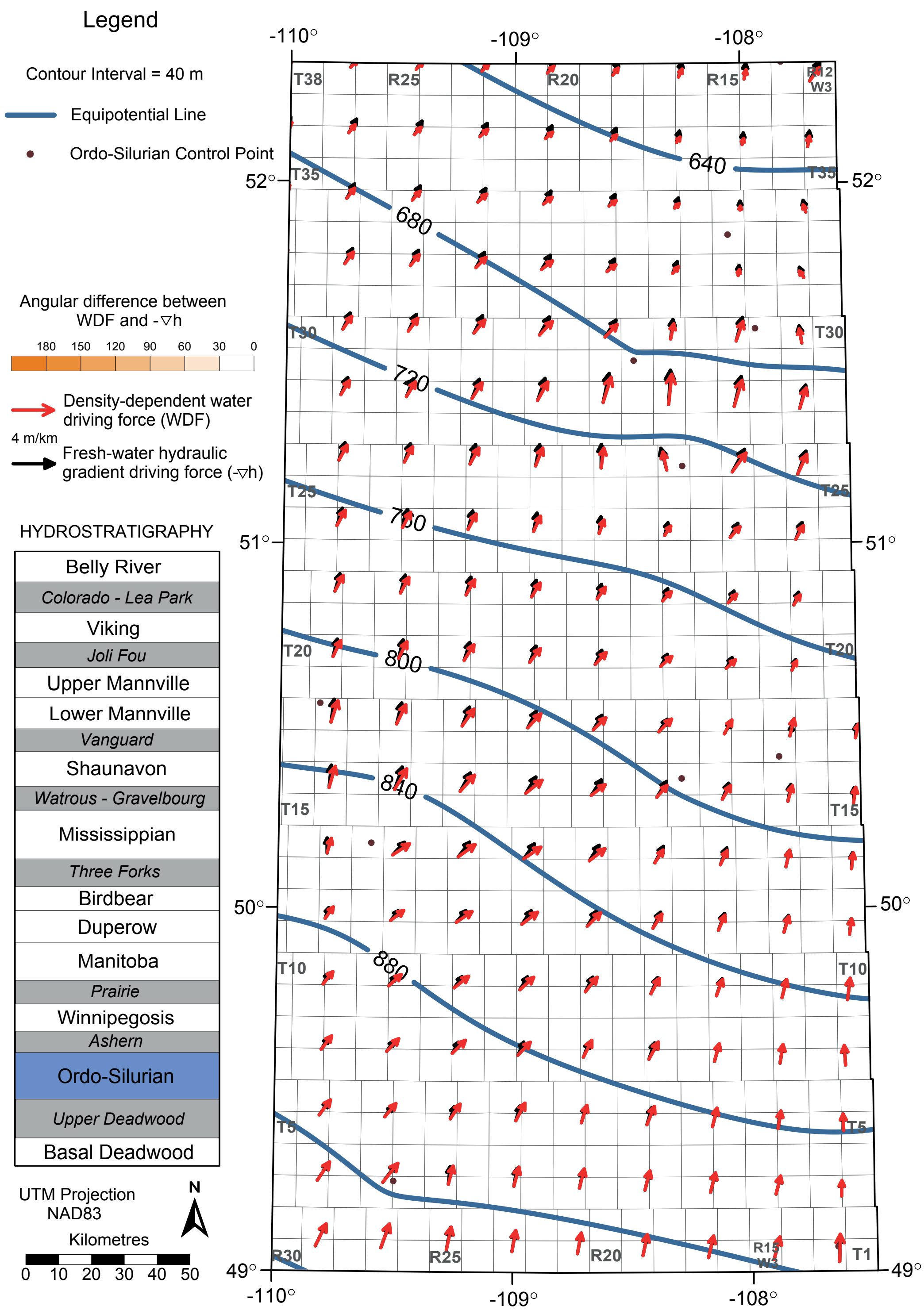

Figure 5.2: Distribution of hydraulic heads (m) and water driving forces in the Ordo-Silurian Aquifer.

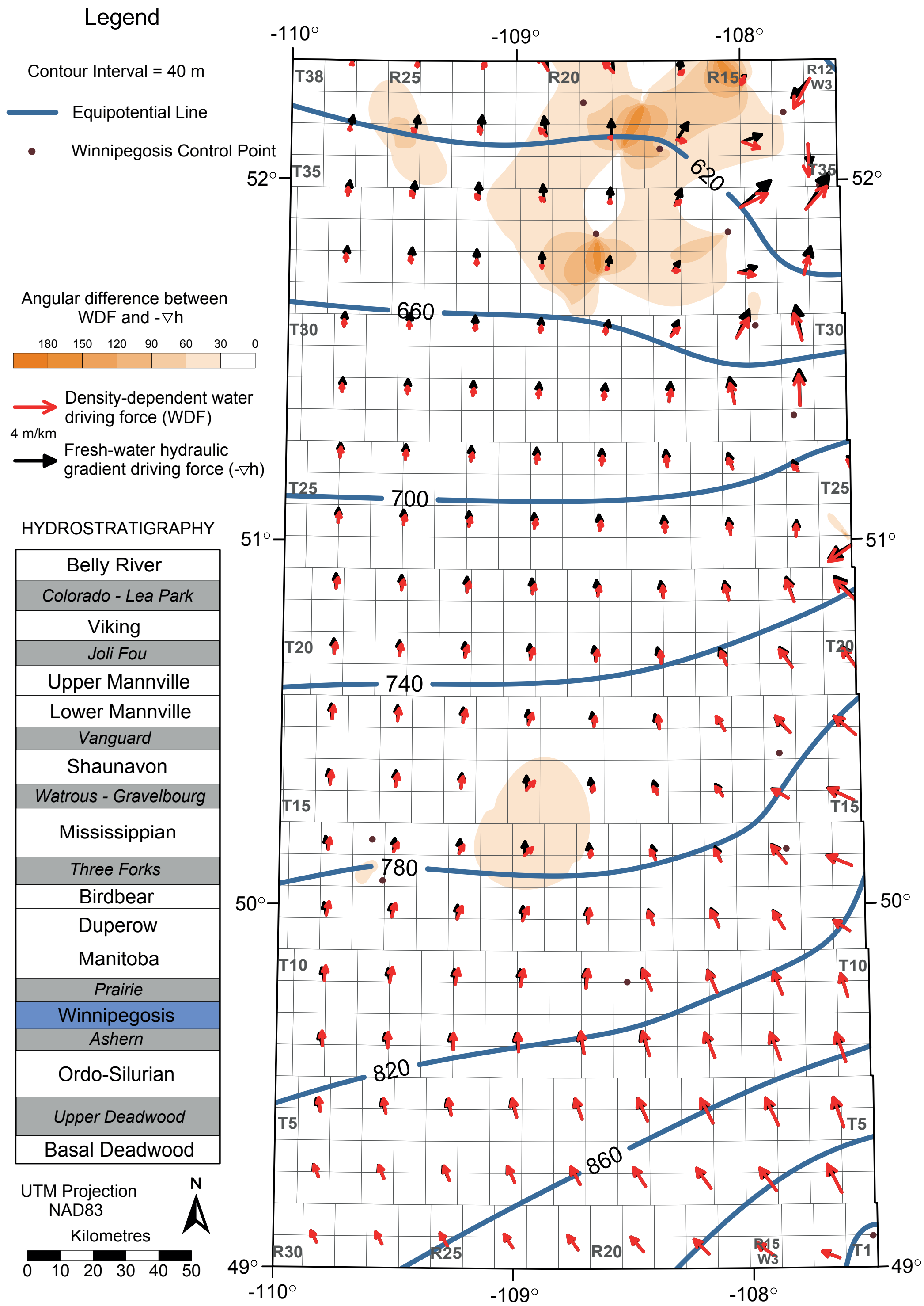

Figure 5.3: Distribution of hydraulic heads (m) and water driving forces in the Winnipegosis Aquifer.

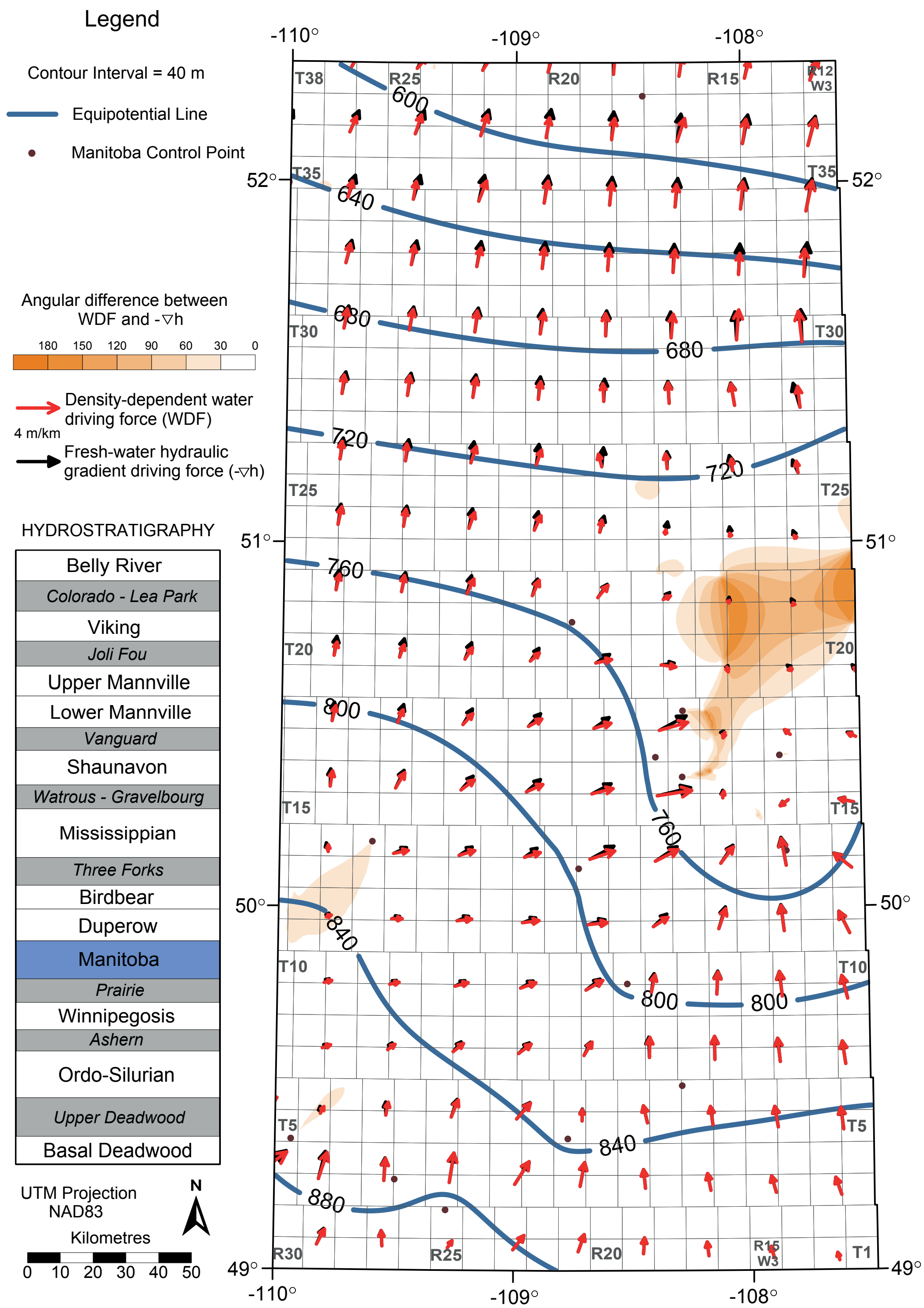

Figure 5.4: Distribution of hydraulic heads (m) and water driving forces in the Manitoba Aquifer.

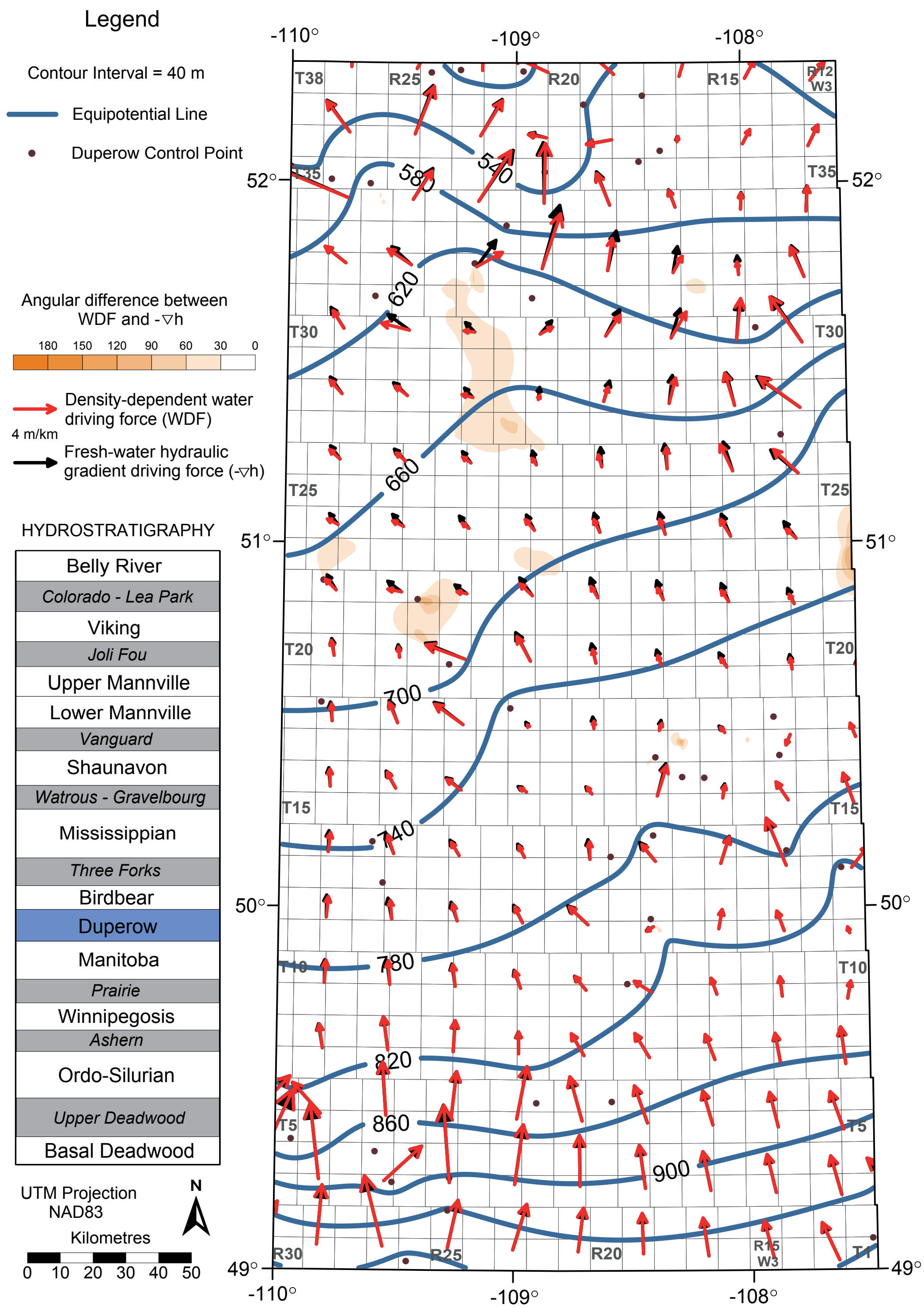

Figure 5.5: Distribution of hydraulic heads (m) and water driving forces in the Duperow Aquifer.

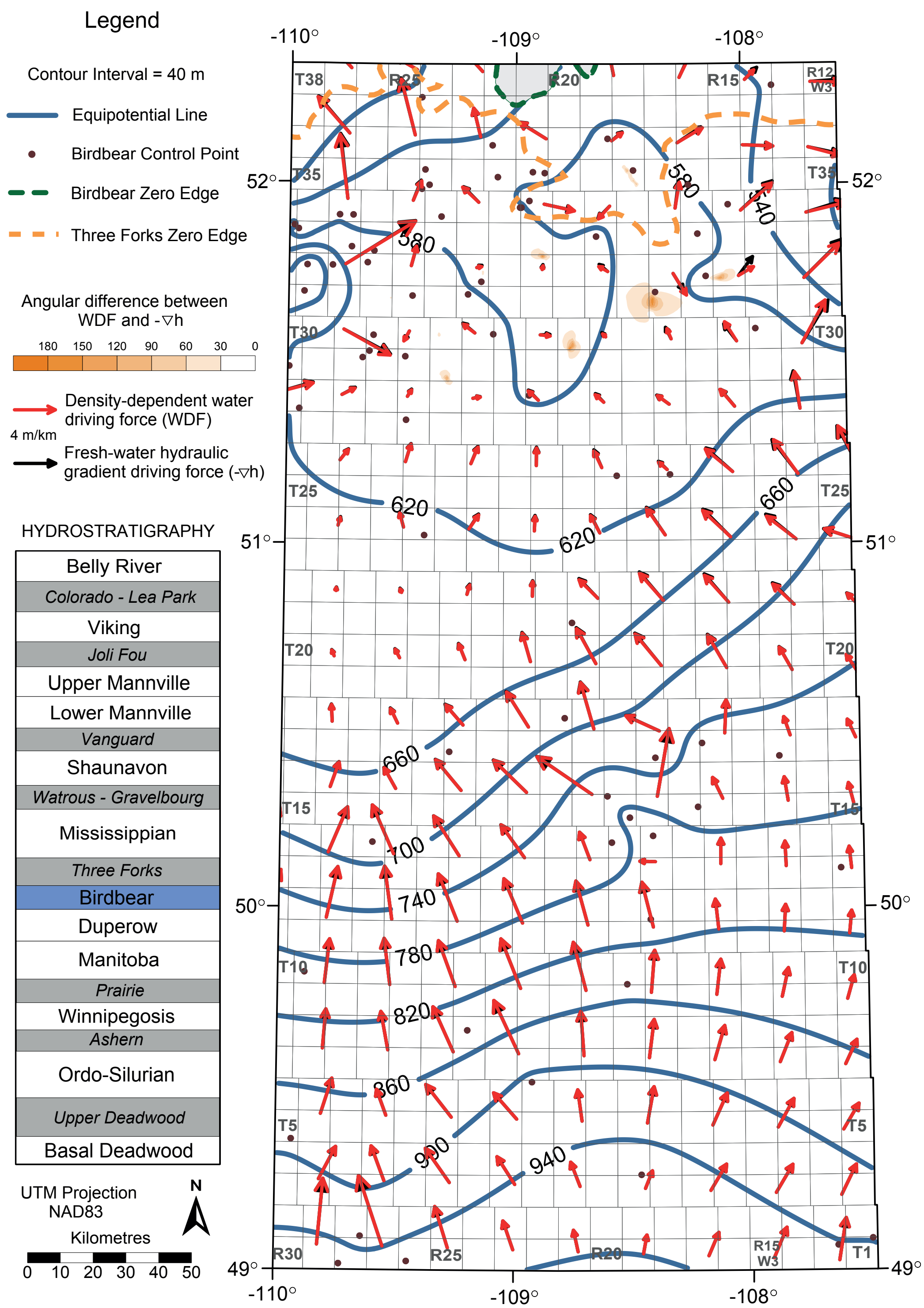

Figure 5.6: Distribution of hydraulic heads (m) and water driving forces in the Birdbear Aquifer.

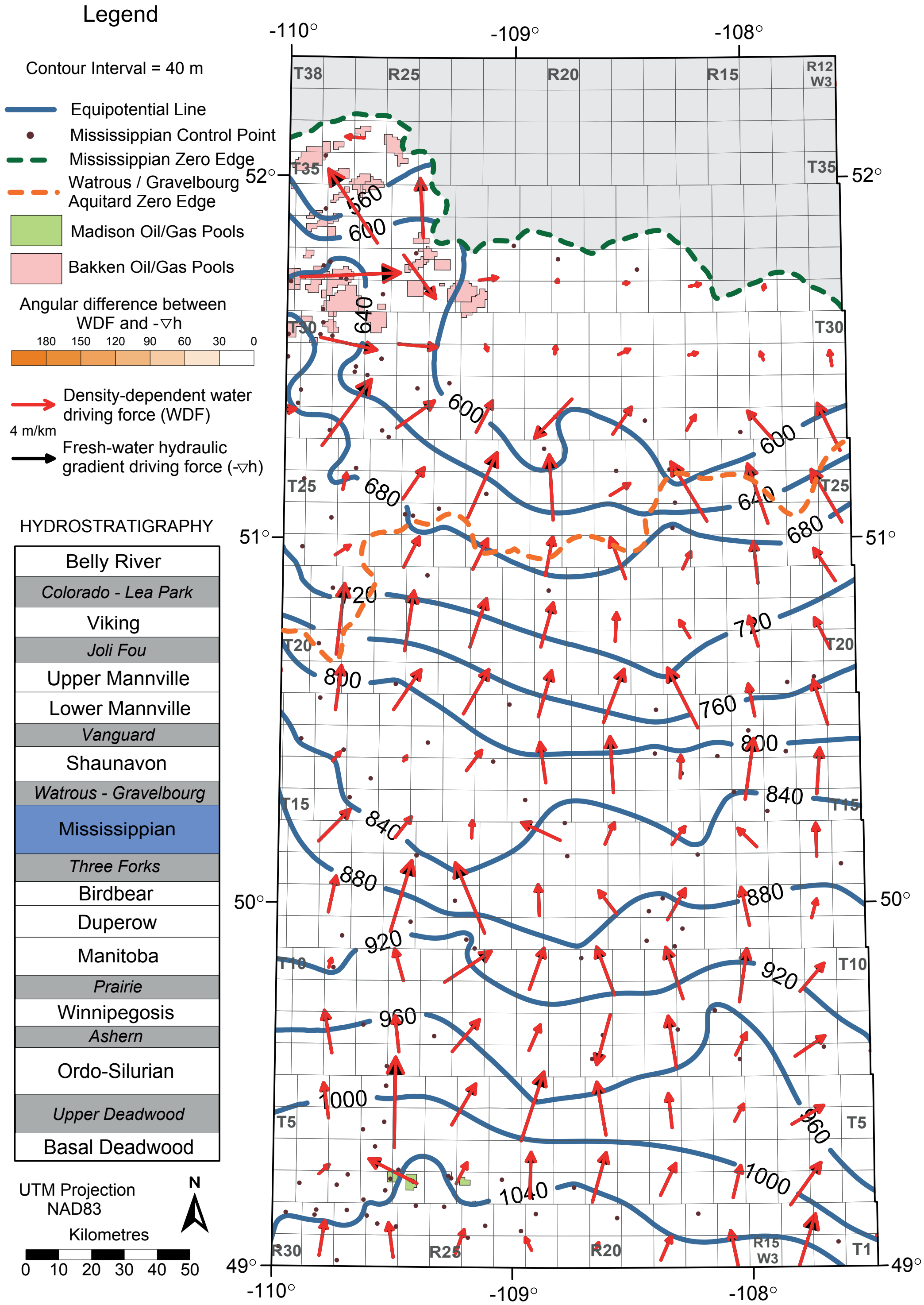

Figure 5.7: Distribution of hydraulic heads (m) and water driving forces in the Mississippian Aquifer.

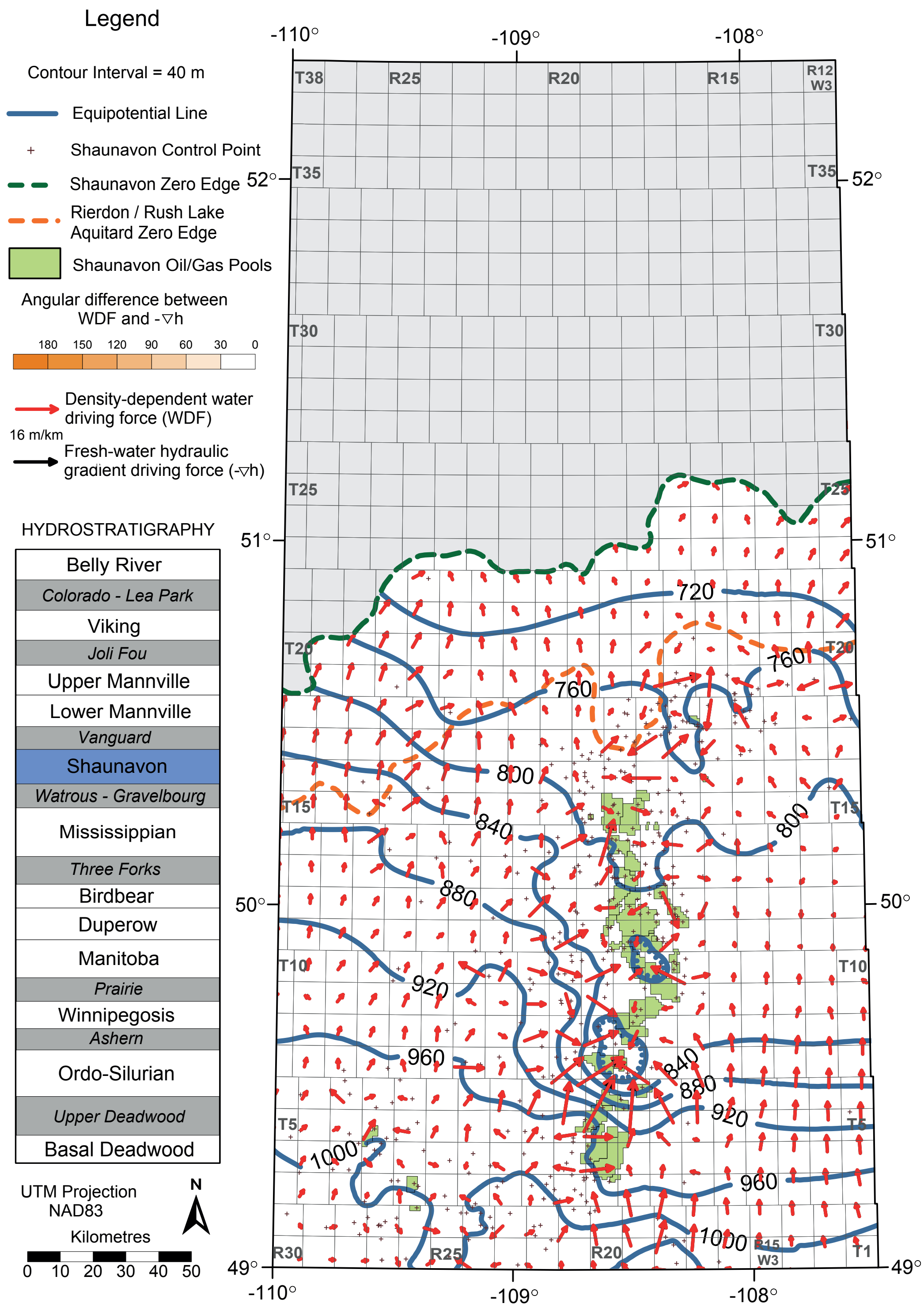

Figure 5.8: Distribution of hydraulic heads (m) and water driving forces in the Shaunavon Aquifer.

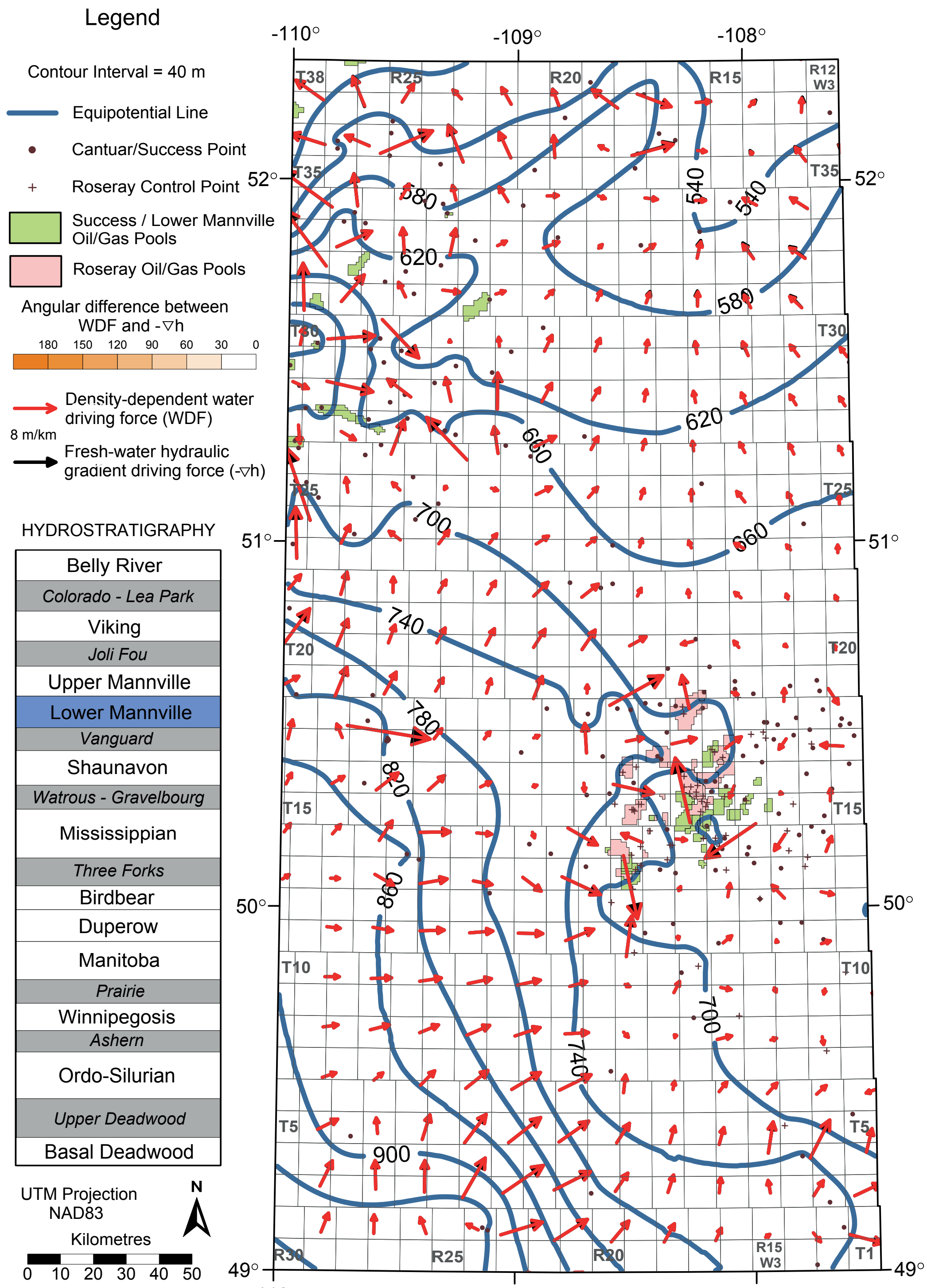

Figure 5.9: Distribution of hydraulic heads (m) and water driving forces in the Lower Mannville Aquifer.

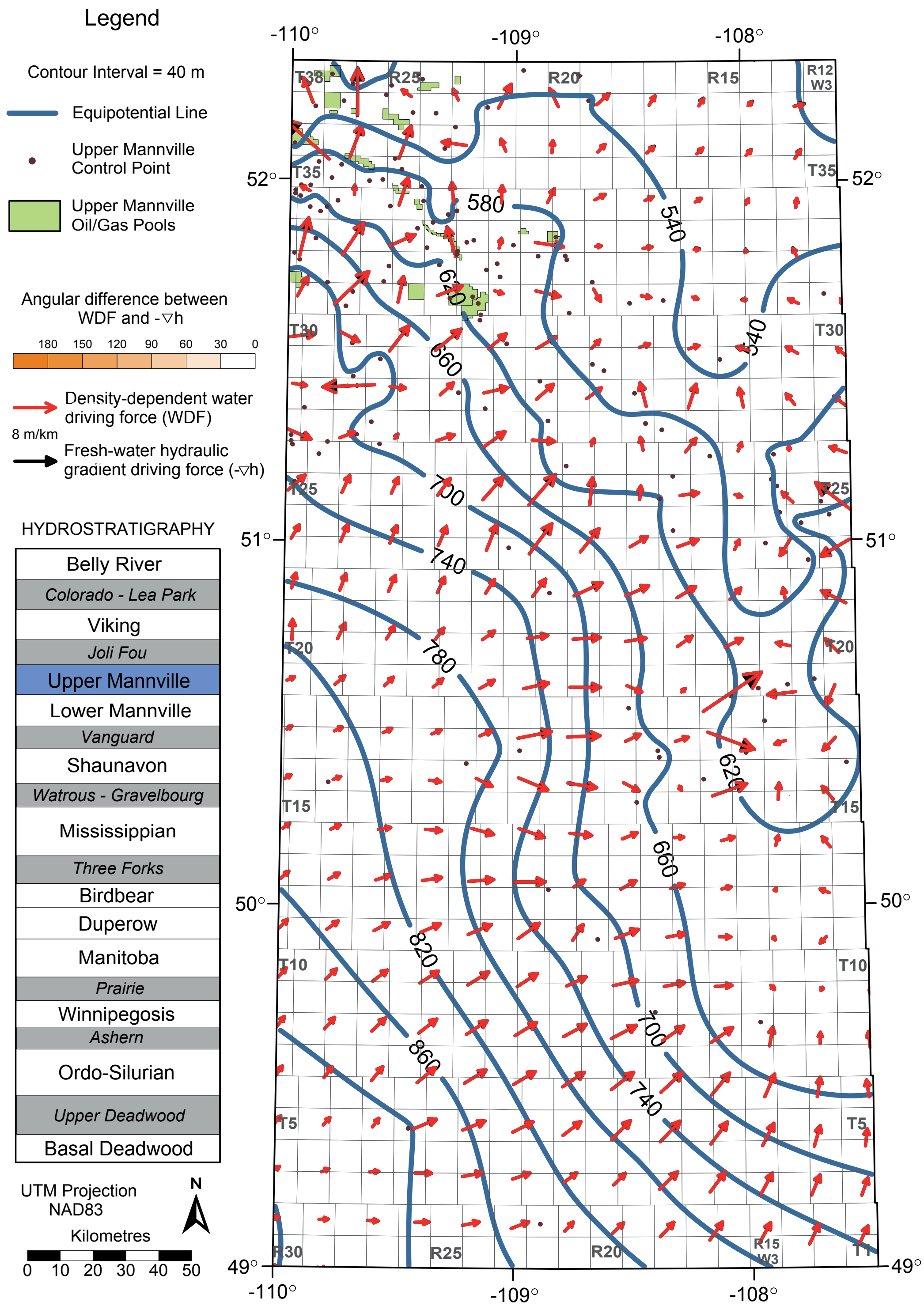

Figure 5.10: Distribution of hydraulic heads (m) and water driving forces in the Upper Mannville Aquifer.

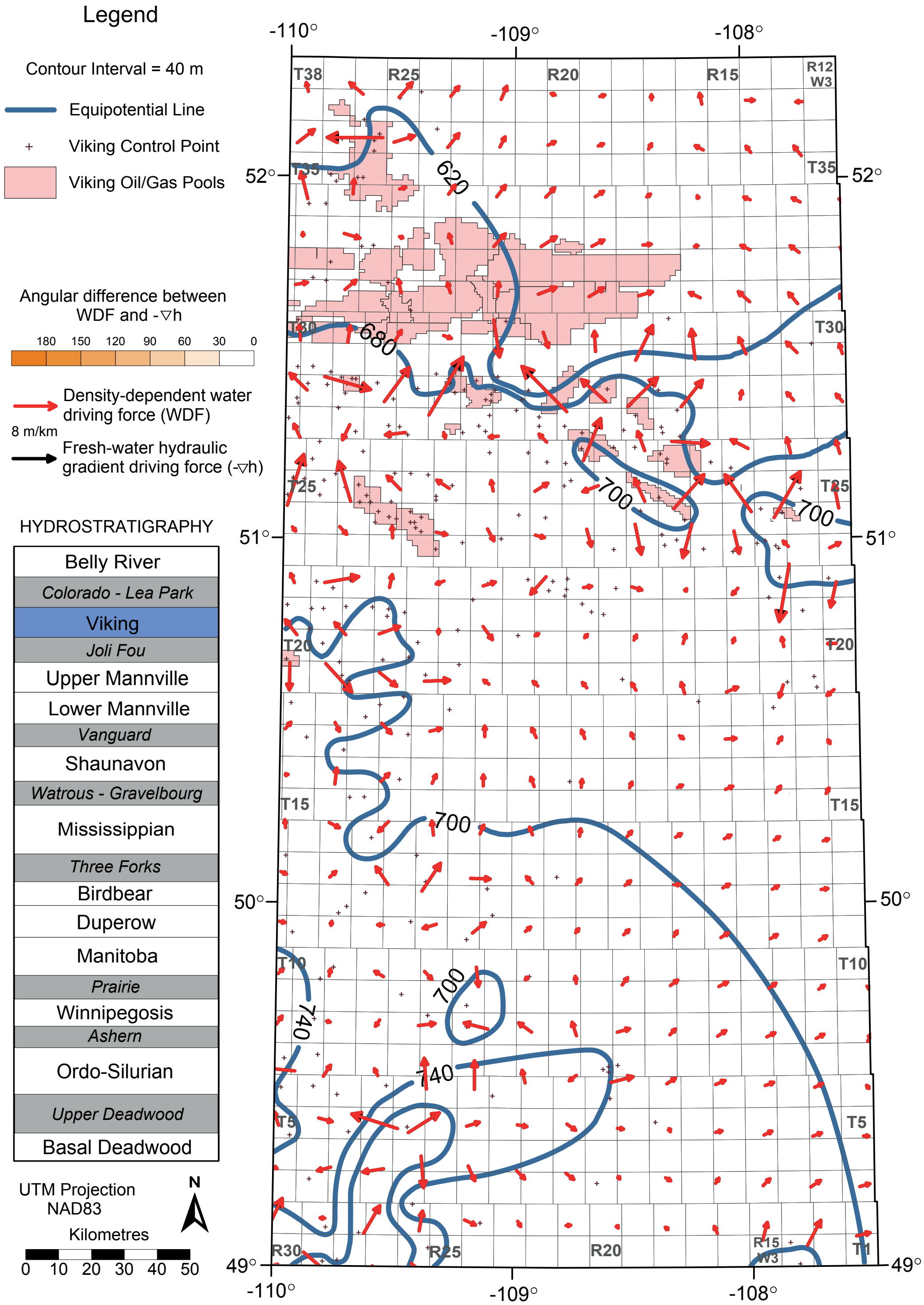

Figure 5.11: Distribution of hydraulic heads (m) and water driving forces in the Viking Aquifer.

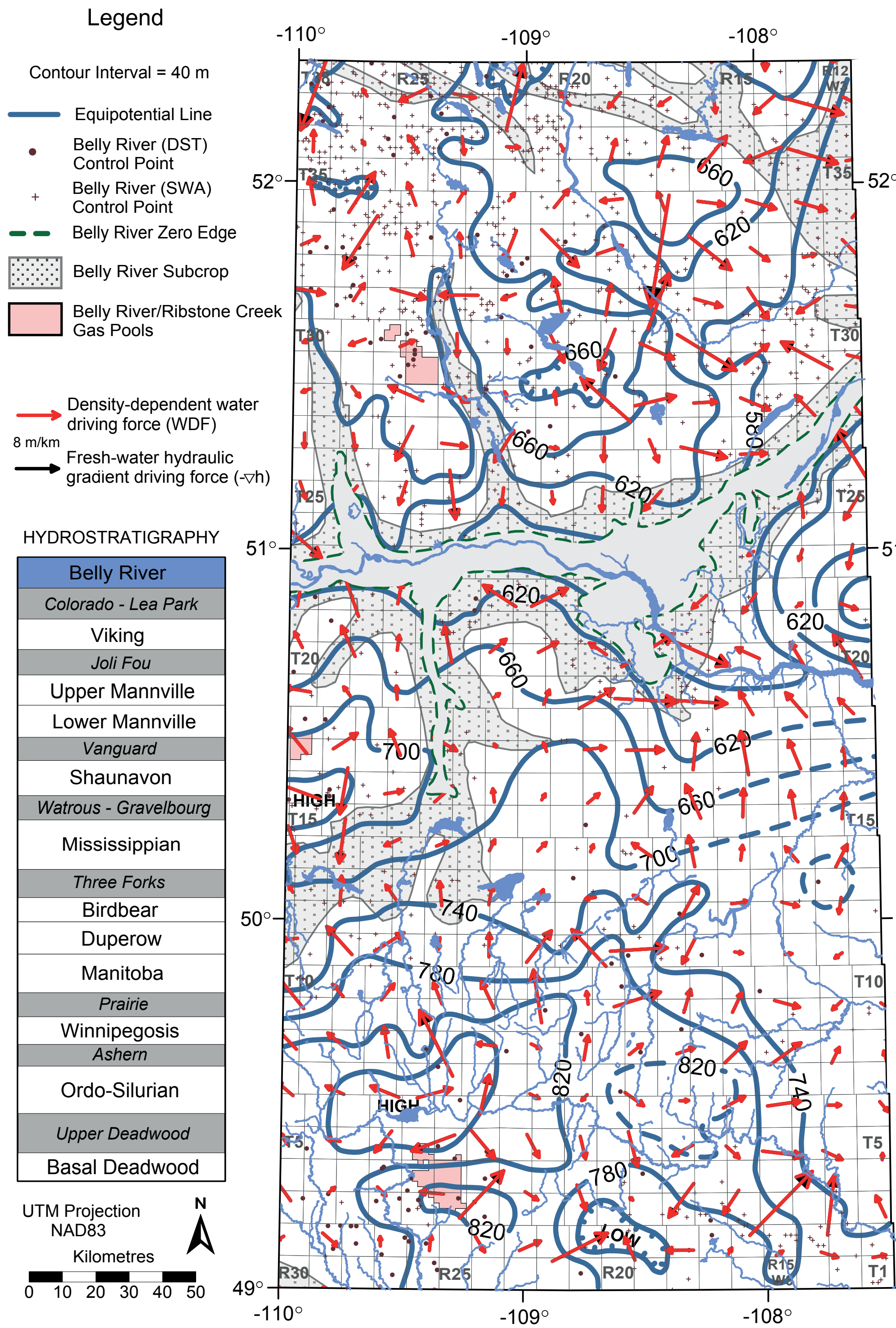

Figure 5.12: Distribution of hydraulic heads (m) and water driving forces in the Belly River Aquifer.

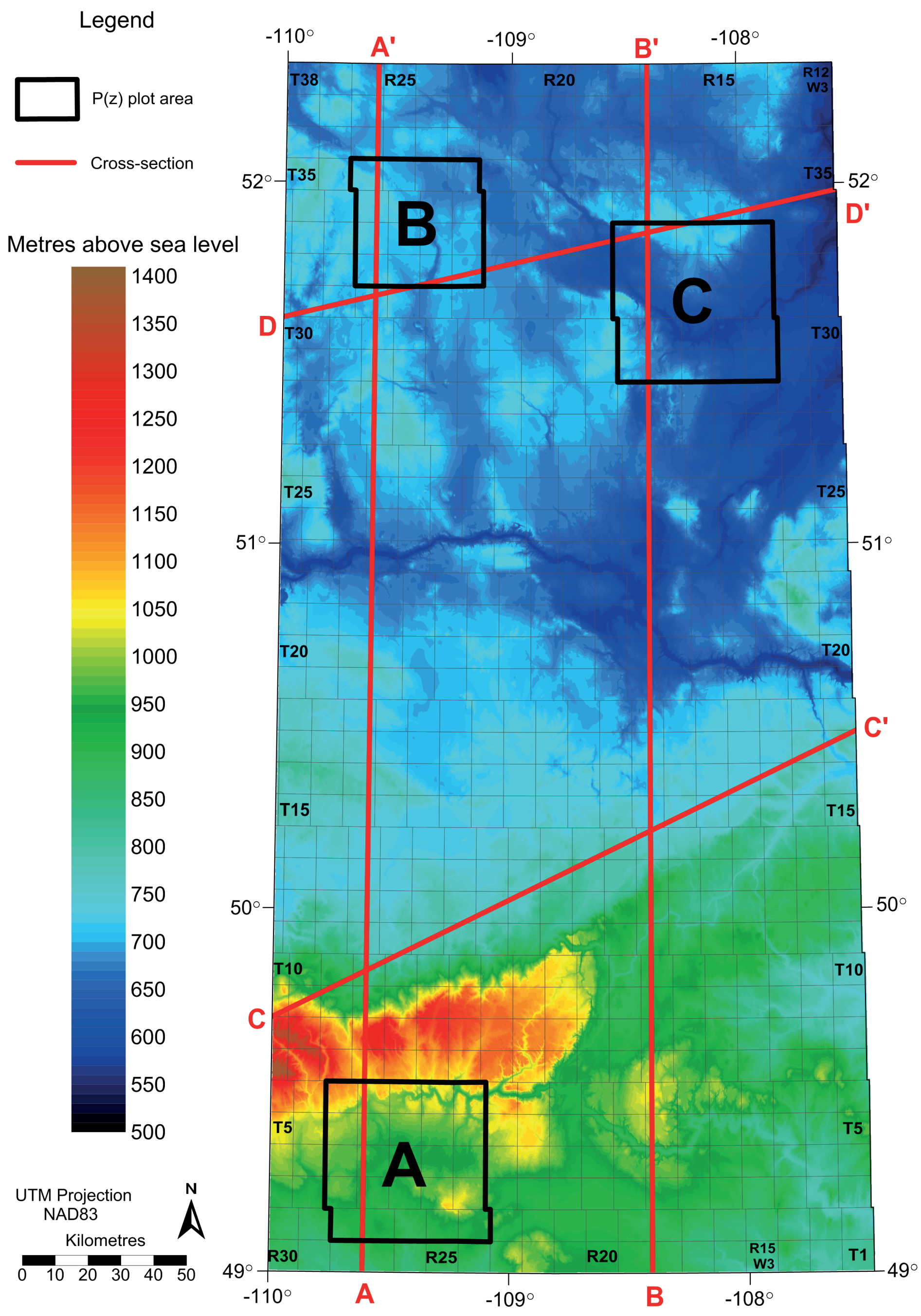

Figure 5.13: Topographic map showing areas of pressure-elevation plots and cross-sections' locations.

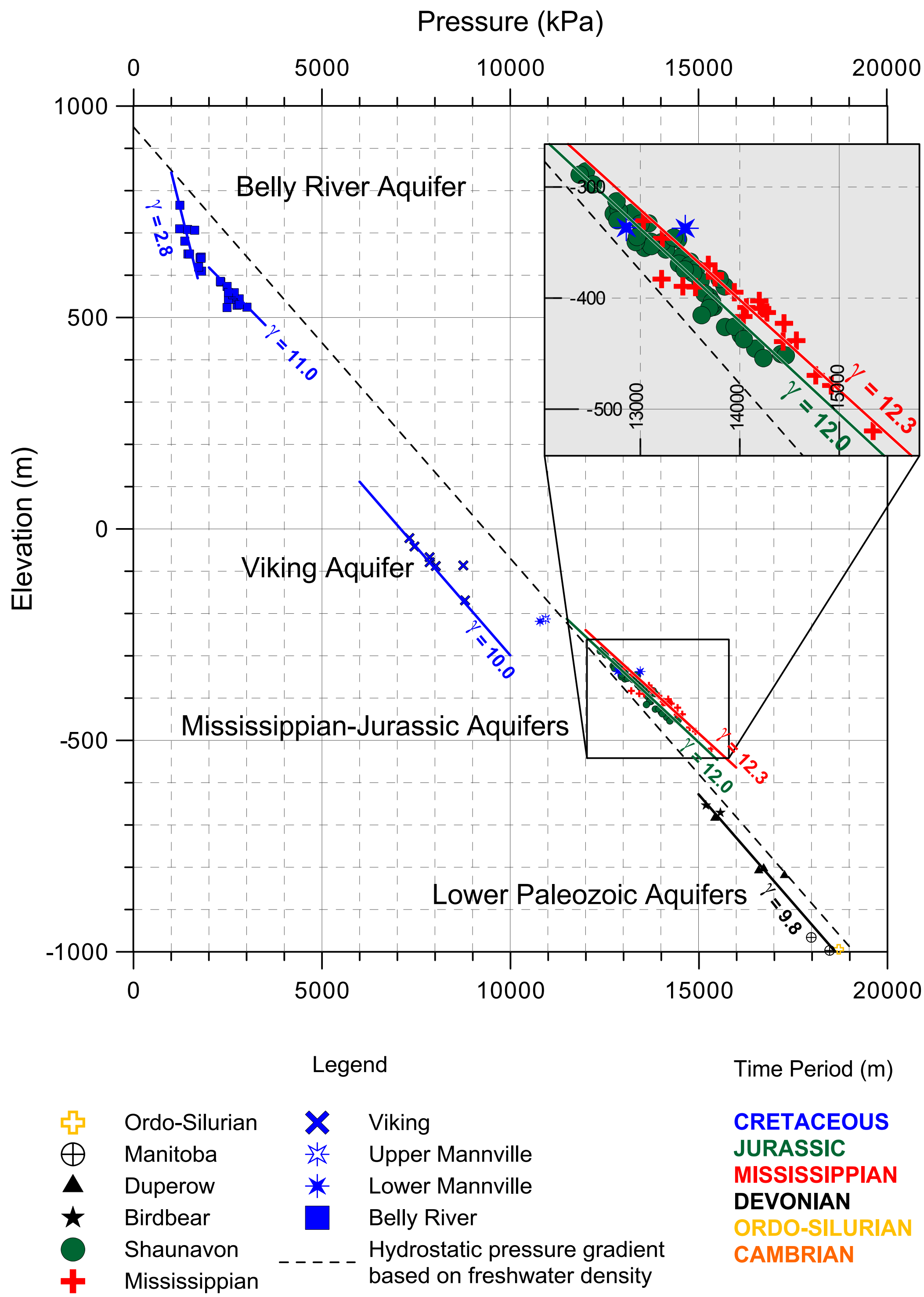

Figure 5.14: Regional pressure-elevation plot for southwestern part of the study area (**Area A** on Figure 5.13).

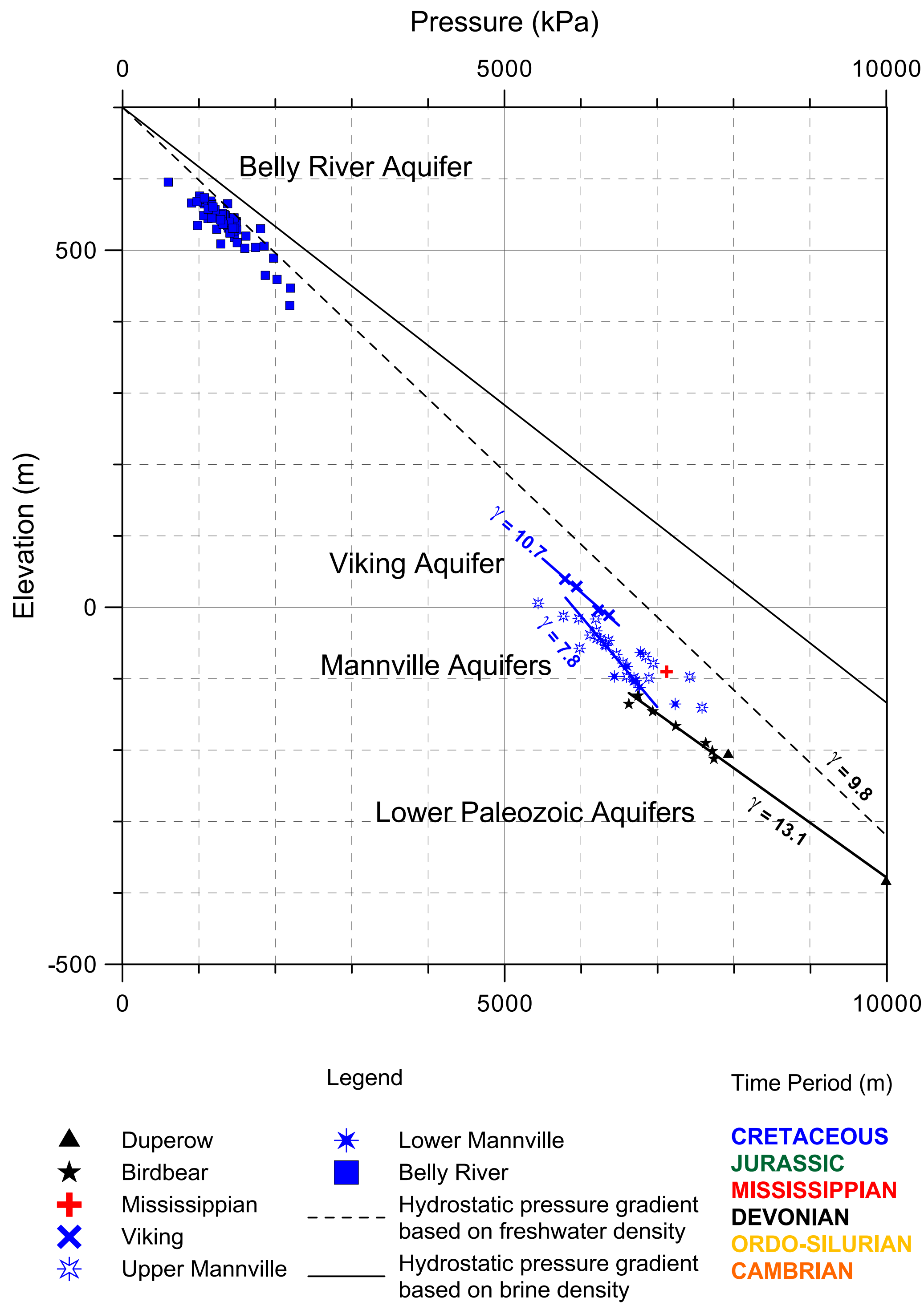

Figure 5.15: Regional pressure-elevation plot for northwestern part of the study area (**Area B** on Figure 5.13).

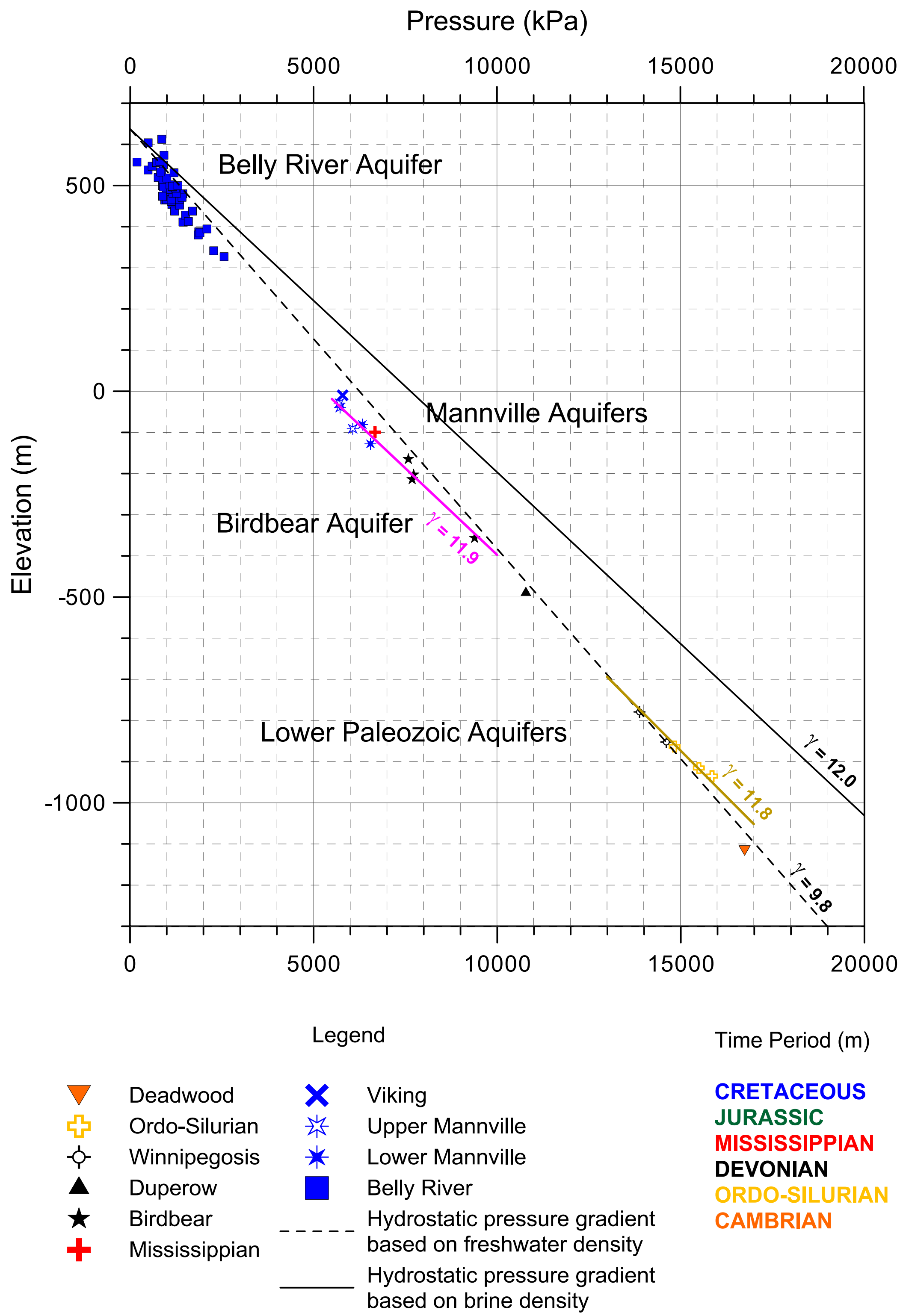

Figure 5.16: Regional pressure-elevation plot for northeastern part of the study area (**Area C** on Figure 5.13).

CHAPTER 6 – Hydrogeological Synthesis

The results presented in Chapters 4 and 5 indicate the existence of five major hydrogeologic systems: Lower Paleozoic, Mississippian, Jurassic, Lower Cretaceous, and Upper Cretaceous. These hydrogeologic systems were identified based on similarities in flow directions and water chemistry of each aquifer. This chapter will discuss the significance of the observed features and trends, and provide a regional interpretation of the hydrogeology in the southwestern Saskatchewan.

6.1 Regional Fluid Flow

LOWER PALEOZOIC and MISSISSIPPIAN HYDROGEOLOGIC SYSTEMS

Fluid flow in all Lower Paleozoic and Mississippian aquifers is generally directed up-dip towards the north (Figure 6.1, Figures 5.1 – 5.7). The gradients are low in the deepest aquifers (Basal Deadwood, Ordo-Silurian, Winnipegosis, Manitoba, and Duperow) which may suggest low flow rates (depending on hydraulic conductivity) and longer residence time. Slightly higher gradients are observed in the Birdbear and Mississippian aquifers suggesting higher flow rates (also depending on hydraulic conductivity). The potentiometric surfaces in the Lower Paleozoic and Mississippian aquifers do not correlate to the local topography (Hannon, 1987). The groundwater flow in these aquifers is driven by basin-scale topography with the recharge areas primarily in the highlands (up to 1500 m above sea level) of southwestern and central Montana towards low-lying (< 500 m above sea level) discharge areas in the north and northeast (Downey and Dinwiddie, DeMis, 1995).

Areas of significant density effects on the flow exist in the Basal Deadwood, Ordo-Silurian, Winnipegosis, Manitoba, and Duperow aquifers (Figures 5.1 – 5.5) due to high TDS (Figure 5.2, Figures 4.1 – 4.5). As a result, actual flow directions are different from those predicted by the freshwater head gradients. Significantly lower gradients and different flow directions (even “flow reversals”, as described by Khan (2006) and Palombi (2008)) are most prominent in the northern areas of the Basal Deadwood and Winnipegosis aquifers (Figures 5.1 and 5.3). The reduced gradients and reversed flow directions suggest that these waters do not have sufficient potential (gravity, or topographic drive) to overcome the negative buoyancy forces and are interpreted as slugs of heavy (high TDS) water either stagnant or slowly sinking under their own weight towards the deeper parts of the aquifer. Similar results were obtained by Khan (2006) and Palombi (2008) in southeastern Saskatchewan. It is likely that similar or even greater density effects are present in the central and northern parts of the Ordo-Silurian and Manitoba aquifers. However, this could not be confirmed due to the lack of water chemistry data in these aquifers. There are no density effects in the aquifers above Duperow due to relatively low TDS.

JURASSIC HYDROGEOLOGIC SYSTEM

The Shaunavon Aquifer has a very unique flow system marked by a distinct flow pattern. Water is generally flowing updip towards the north and gradually shifts downdip toward the Shaunavon Oil Trend in the east. Variations in hydraulic heads along the Shaunavon Oil Trend are the result of slight vertical flow within the aquifer due to the presence of high permeability lenses or zones.

The Upper Shaunavon Member is the main carrier of formation fluids owing to its high permeability sandstones (S. Leggett, Husky Energy, 2011, personal communication). Water enters the aquifer in the recharge areas of Montana (Downey and Dinwiddie, 1988; Bachu and Hitchon, 1996) and flows along the Upper Shaunavon sandstone unit discharging at the subcrop into the overlying aquifers. The limestone-dominated Lower Shaunavon Member is much less permeable (S. Leggett, Husky Energy, 2011, personal communication), and therefore, not capable of transmitting fluids laterally for large distances. Instead, it is being recharged from the overlying Upper Shaunavon Member.

The flow pattern in the Shaunavon Aquifer appears to be controlled by permeability and depositional environment and facies of the Upper Shaunavon Member (Figure 6.3). The Transitional facies correspond very well to the potentiometric low due to excellent permeability found in many reservoirs along the Shaunavon Oil Trend (S. Leggett, Husky Energy, 2011, personal communication). The Shelf facies are continuous throughout the west (Carlson, 1968) and are characterized by a uniform flow towards the north and northeast. Very few drillstem tests are located within the Lagoonal facies. The Basinal facies have virtually no permeability (S. Leggett, Husky Energy, 2011, personal communication), and therefore, no significant flow through them exists marked by extremely low gradients and lack of good data east of the Shaunavon Oil Trend (Figure 5.8).

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

Flow pattern in the Lower and Upper Mannville aquifers is highly complex and significantly different from the underlying aquifers (Figures 5.9 – 5.10). Water flows from the Alberta sub-Basin towards east as well as from Montana towards the northeast. Regionally, these aquifers are recharged in the Montana highlands (Downey and Dinwiddie, 1988) as well as by the ascending

Mississippian waters in south-eastern Alberta (Bachu and Hitchon, 1996; Anfort et al, 2001).

A strong downdip flow exists in the central area associated with the Success-Roseray oil pools (Figure 5.9). Water from the west and southwest is pushed towards east into much more permeable sandstones of the Success and Roseray formations (Christopher, 1974), marked by a sudden drop in horizontal gradients to the east of the 700 m contour line; an indication of sudden pressure dissipation due to increased permeability.

Significant differences in potentiometric surface are observed between the Viking and all other aquifers indicating that the Viking Aquifer is isolated from the overlying and underlying aquifers (i.e. anomalies within the Viking Aquifer appear to be self-contained and not influenced by other pressure regimes) (Figure 5.11). Regional flow direction is towards the northeast with recharge areas in Montana (Downey and Dinwiddie, 1988).

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

Water flow in the Belly River Group Aquifer is controlled by local surface topography (Figure 6.4). Areas of potentiometric highs correspond to topographic highs (e.g. Cypress Hills) (Figure 5.12). Generally, the flow is directed towards low-lying erosional boundaries and incised valleys. Most of the flow is directed towards South Saskatchewan River from the southern and the northern portions of the aquifer.

6.2 Cross - Formational Flow

Fluid flow in the study area is generally parallel to the aquifers (Figure 6.1). However, there are also many areas where cross-formational flow and hydraulic communication exist. These areas can be identified through comparison of water chemistry and potentiometric surface maps of the over- and under-lying aquifers as well as variations in their vertical hydraulic gradients. Hydraulic communication exists at the formation subcrop edges and areas where the intervening aquitard is thin or missing (by erosion or non-deposition), resulting in direct contact between the aquifers.

The Birdbear Aquifer shows cross-formational flow along its northern subcrop identified by the similar flow pattern and hydraulic heads in both Birdbear and the Lower Mannville aquifers (Figures 5.6 and 5.10). Cross-section B (Figure C.6) shows that water in the northeast flows upward from the Birdbear Aquifer into the Lower Mannville Aquifer creating the high-TDS plume (Figure

4.9). This is also supported by the pressure-elevation plot (Figure 5.16) which shows that pressure data from the Birdbear and Mannville aquifers fall on the same super-hydrostatic gradient. However, in the northwest, there is a downward water drive from the Lower Mannville Aquifer towards the Birdbear Aquifer (Cross-section A, Figure C.5). This downward flow from the Mannville aquifers dilutes (< 25 g/L) the formation water in the Birdbear Aquifer (Figure 4.6).

The Mississippian Aquifer is also in hydraulic communication with the overlying Lower Mannville Aquifer throughout the northern half of the study area. The Watrous-Gravelbourg Aquitard is missing north of Townships 20-25 (Figure 5.7) allowing direct communication between these aquifers. Cross-sections A and B (Figures C.5 – C.6) show that the Mississippian Aquifer is very thin north of Township 25 and effectively becomes a part of the Lower Mannville Aquifer. The hydraulic communication between the two aquifers is evident through the similarity in flow directions and hydraulic heads (compare Figures 5.7 and 5.9), and formation water chemistry (compare Figures 4.7 and 4.9).

Two areas of cross-formational flow or hydraulic communication have been identified in the Shaunavon Aquifer. The first area is located along the western margin of the study area and coincides with the absence of the Watrous Formation (Figure 2.2) and thinning of the Gravelbourg Formation (i.e. Watrous–Gravelbourg Aquitard). It appears that the Mississippian and Shaunavon aquifers are in hydraulic communications shown by the similarities in their hydraulic heads (Figures 5.7 and 5.8) and water chemistry, both TDS (Figures 4.7 and 4.8) and water types (Figures 4.21 – 4.22).

The second area of cross-formational flow in the Shaunavon Aquifer is located at the north end of the Shaunavon Oil Trend, between Townships 18-20 and Ranges 16-18. Here, the Shaunavon Aquifer is in hydraulic communication with the overlying Lower Mannville Aquifer due to the fact that the Vanguard Aquitard is missing (Figure 5.8) and as indicated by their similar hydraulic heads (Figures 5.8 – 5.9).

6.3 Controls on Water Chemistry

LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

The lateral TDS variations in the Lower Paleozoic aquifers are controlled by the presence of the Prairie Evaporite (Figure 6.2). Low salinities are generally confined to the southern and southeastern parts of the study area and are associated with Prairie Evaporite zero edge (Cross-Sections A and B, Figures C.5 – C.6). The highest salinities are generally observed in areas where the Prairie Evaporite is present and in aquifers adjacent to the Prairie Evaporite.

The Basal Deadwood and Birdbear aquifers are not affected by the presence of the Prairie Evaporite (TDS distribution does not follow the Prairie Evaporite's zero edge). The TDS pattern in the Basal Deadwood Aquifer is the result of very long path and sluggish flow whereby water is progressively enriched with salts (sodium chloride). On the other hand, the Birdbear Aquifer has an overall much lower TDS than the underlying aquifers which is the result of comparatively higher flow rates flushing the formation (Iampen, 2003), as well as dilution by the brackish water from the overlying Mannville aquifers in the northwest.

The low TDS (<10 g/L) areas in the south are dominated by Ca-SO_4 (Type 1) waters while the high TDS areas are dominated exclusively by Na-Cl (Type 2) waters (Figures 4.18 – 4.20). In addition, the areal extent of water types is different for most aquifers. For example, the Birdbear Aquifer, the shallowest of all Lower Paleozoic aquifers, has the largest extent of Ca-SO_4 water type covering almost half of the entire study area (Figure 4.20).

Previous studies in the Williston Basin have identified Ca-SO_4 type as recharge-area waters with short residence time, rapid flow and low reactivity (Benn and Rostron, 1998; Iampen, 2003; Khan, 2006; Palombi, 2006). Therefore, the extent of the Ca-SO_4 water type is related to the flow intensity and residence time. Based on the extent of these waters, it can be concluded that the Birdbear Aquifer has high intensity flow and shorter residence time while deeper aquifers (e.g., Deadwood, Ordo-Silurian, etc.) with smaller Ca-SO_4 extent have lower flow rates and longer residence time.

MISSISSIPPIAN HYDROGEOLOGIC SYSTEM

The waters of the Mississippian Aquifer have relatively low TDS (< 25 g/L) and highly variable composition. The Mississippian Aquifer hosts all four types of water (Ca-SO_4, Na-SO_4, Na-HCO_3, and Na-Cl). Ca-SO_4 waters in the south are characteristic of active recharge flow, similar to underlying Lower Paleozoic aquifers (Benn and Rostron, 1998; Iampen, 2003; Khan, 2006; Palombi, 2006).

The edge of the Na-SO_4 water coincides with the edge of the Watrous Formation (Figure 4.21), which is composed of anhydrite and shale (Carlson, 1968). Therefore, the composition of the Mississippian water in the high sulphate areas is likely controlled by rock-water interaction with the Watrous Formation (possibly dissolution of anhydrite).

In the western area, the waters of Mississippian Aquifer are dominated by Na-HCO_3. The geographic distribution of these waters indicates that their source may be located in southern Alberta. In fact, recent studies have shown that the bacterial sulphate reduction (BSR) in southern Alberta has produced CO_2 rich fluids, which in turn increased concentrations of HCO_3 (Cody et al, 1998).

The HCO_3-rich waters in the Mississippian, Shaunavon, and Lower Mannville aquifers appear to have a common origin because of their shared geographic location and the fact that all three aquifers are in hydraulic communication in parts of southern Alberta (Tóth and Corbet, 1986).

JURASSIC HYDROGEOLOGIC SYSTEM

Both Mississippian and Shaunavon aquifers appear to have similar TDS (Figures 4.7 – 4.8); however, their hydrochemistry is different (Figures 4.21 – 4.22). The Shaunavon Aquifer has three distinct hydrochemical zones which do not coincide with the underlying Mississippian Aquifer. The most prominent feature is the plume of chloride-rich (Na-Cl type) water that coincides with the Shaunavon Oil Trend. Surrounding the Na-Cl plume are the large areas of Na-HCO_3 water to the west and Na-SO_4 waters to the north and east.

LOWER CRETACEOUS HYDROGEOLOGIC SYSTEM

Lower Mannville, Upper Mannville, and Viking aquifers are dominated by Na-Cl waters. This indicates a longer flow path and increased residence time (Collins, 1975; Benn and Rostron, 1998). The source of these waters appears to be from both west (Alberta) and south (Williston Basin) (Section 5.2; Bachu and Hitchon, 1996). Devonian and Mississippian aquifers discharge their waters into the Mannville aquifers in the north of this study area (Figure 6.1) and in Alberta (Bachu and Hitchon, 1996; Rostron and Toth, 1997; Rostron et al., 1997). These waters generally have high TDS and are dominated by Na-Cl composition.

UPPER CRETACEOUS HYDROGEOLOGIC SYSTEM

Belly River Group Aquifer has very low TDS (< 5 g/L) and highly variable hydrochemistry (not shown). This is a shallow aquifer that has all four water types. There appears to be a difference in hydrochemistry between waters from the Basal Belly River sandstone and Upper Belly River sediments (not shown). Waters from the Basal Belly River are dominated by Na-Cl ions, while waters from the Upper Belly River have Na-SO_4, Na-HCO_3, and an additional new Ca-CO_3 water type. The difference in hydrochemistry perhaps indicates the presence of a barrier (aquitard) between the basal and upper units. However, these units are mapped together due to the lack of proper geologic framework within the Belly River Group.

6.4 Implications for Petroleum Migration and Accumulation

The influence of water flow on the hydrocarbon migration and accumulation has been previously demonstrated by Hubbert (1953). Since then, numerous examples of hydrodynamic traps and tilted oil/water contacts were discovered and mapped, particularly in the Williston Basin (Berg et al., 1994; DeMis, 1995). Evaluation of pressure conditions and water flow directions and intensity is essential for understanding hydrocarbon behaviour in the subsurface. This section presents an assessment of possible hydrocarbon migration pathways and the origin of existing accumulations in the selected aquifers.

To date, oil has not been found in most of the Lower Paleozoic strata of southwestern Saskatchewan. Drill-stem test recoveries from Basal Deadwood, Ordo-Silurian, Winnipegosis, Manitoba, and Duperow aquifers in the southwestern Saskatchewan consist of water without any shows of oil. Hydrocarbon production from these aquifers occurs outside of the study area in the southeastern Saskatchewan, North Dakota, and eastern Montana.

6.4.1 KINDERSLEY HEAVY OIL DISTRICT

The Birdbear Aquifer is the only Lower Paleozoic unit with numerous oil shows located in the northwest of the study area (Figure 6.5). In fact, minor production has occurred throughout the years from several isolated wells and currently developed into a subcrop play between Townships 38 and 39 (Yang and Kent, 2010). However, the oil shows can be found further within the formation reaching as far south as Township 29 (Figure 6.5).

Much more significant production occurs from the overlying the Bakken and Madison formations (Figure 6.6) and Lower Cretaceous beds of Cantuar and Pense formations (Lower and Upper Mannville Aquifers, Figure 6.9). In many areas there is comingled production from multiple zones. The oil produced from all formations is heavily biodegraded with API gravity ranging between 11 and 17 (Reid, 1984). The Mississippian (Middle Bakken Sands) pools are primarily structural traps, which resulted from the dissolution of anhydrite within the Torquay Formation followed by the collapse of the overlying strata (Reasoner and Hunt, 1954). Kents (1959) argued against “Theory of Solution Collapse” pointing out the lack of sufficient quantities of anhydrite as well as its disseminated nature rather than massive. Stratigraphic traps also occur in the Mannville Group and along the erosional edge of the Bakken Formation (Christopher, 2002).

The spatial correlation and similarity in physical and chemical properties of oils from Birdbear, Mississippian, and Mannville aquifers indicate that these oils are related and have a common source. According to Osadetz et al (1994), oils produced from the Mississippian (primarily Bakken) and Lower Cretaceous (Mannville) belong to Family E of oils which are sourced from the Exshaw/Bakken Formation in the Alberta/Montana Trough, west of range 23W4. This implies that these oils have migrated from the west (Alberta) into Saskatchewan. The existence of active flow from the west in the Mississippian and Mannville aquifers is consistent with the above hypothesis. Water flow could have facilitated oil migration from the west as well as may be responsible for its low gravity (i.e. biodegradation). This is further reinforced by the fact that all three aquifers are in hydraulic communication as indicated by the similar water chemistry (Figures 4.7 – 4.10 and 4.20 – 4.24) and flow pattern/direction (Figures 5.7 – 5.10).

Reasoner and Hunt (1954) suggested that oil migrated from the overlying Mannville sections into the Mississippian (Bakken). Hydraulic head values in Mannville aquifers are higher than in the underlying Mississippian and Birdbear aquifers indicating downward water drive in this study area (Figures 5.6, 5.7, 5.9). The difference in the potential may be sufficient enough to drive heavy oils into the underlying Mississippian and Birdbear aquifers through direct contact between the formations at the erosional edges or through fracture systems.

6.4.2 SHAUNAVON OIL TREND

The production from the Shaunavon Formation occurs along the north-south Shaunavon Oil Trend (Figure 6.7). The bulk of the production is from the sandstones of the Upper Shaunavon Member (Carlson, 1968). Limited production occurs from the oolitic layer of the Lower Shaunavon Member (Marsh and Yurkowski, 2008). Shaunavon pools do not have gas caps and only produce medium gravity oil (22 API on average, 35 API maximum in the southwest) (Yurkowski, 2011). Shaunavon oil pools are interpreted as stratigraphic traps of shallow marine and shoreface sands (Christopher, 1961; Carlson 1968). Minor production of heavy oil (11 API) from the Shaunavon Formation and the underlying Madison Formation (Kent, 1995) occurs in the southwest (Battle Creek area).

A biomarker study conducted by Osadetz et al (1994) has shown that the Jurassic oils from the Shaunavon Oil Trend and from the southwest belong to Family C with the source from the Lodgepole Formation in the Williston Basin. They concluded that cross-formational migration of oil has occurred along the Shaunavon Oil Trend from the underlying Mississippian strata through fractures. However, the water chemistry between the Shaunavon and Mississippian aquifers is significantly different and does not support their conclusion. The Shaunavon Oil Trend is dominated by Na-Cl (Type 2) water while Mississippian waters underneath have Ca/Na-SO_4 (Types 1 and 3) compositions. Moreover, there has not been any oil shows reported in DSTs from the Mississippian Aquifer in this area. In light of this evidence, the question remains: How did the oil migrate into Shaunavon Formation?

Under hydrostatic conditions hydrocarbon migration is controlled solely by buoyancy and permeability and is directed updip (Figure 6.8a). Under hydrodynamic conditions, such as in the Shaunavon Formation, hydrocarbons can be swept in a different direction depending on the intensity of water flow and oil density. Therefore, UVZ analysis (Hubbert, 1953) has been used to evaluate the possibility of hydrodynamic migration and trapping in the Shaunavon Oil Trend. This method evaluates hydrocarbon potential resulting from the effects of hydrocarbon density (buoyancy), structural elevation, and water flow.

Two maps of oil potential using two different oil densities (maximum and average) have been constructed and migration pathways inferred. Figure 6.8b shows that, under the present hydrodynamic conditions, 35 API oil would be swept towards closed potentiometric lows situated along the Shaunavon Oil Trend. It appears that oil pools would be charged from the south and southwest. This observation is confirmed by numerous oil shows and minor accumulations found along the flow paths in the southwest and west of the Shaunavon Oil Trend.

Similar results were obtained using average oil gravity of 22 API (Figure 6.8c). Here the potentiometric surface is more irregular with larger closures due to the fact that heavier oil is swept more readily towards the traps and is more likely to remain trapped.

It is generally accepted that Shaunavon oil is trapped stratigraphically by the surrounding rock of lower permeability; either by shales or by carbonate cemented sandstones and siltstones (Carlson, 1968). However, it appears that hydrodynamics also plays an important role in migration and trapping mechanism. Water-transported oil is forced towards the Shaunavon Oil Trend and against the tight rocks of the basinal facies to the east. Water drive and capillary forces push oil into the more permeable reservoirs. Once oil is in the reservoir, the capillary forces prevent the oil from leaving the trap. Progressive charging of Shaunavon reservoirs occurred from south to north along the entire trend following the general flow path towards the north.

According to the UVZ maps (Figures 6.8b – 6.8c), the source of Shaunavon oils may be located directly south or southwest of this study area, in Montana or even southern Alberta. In fact, oil of similar properties is produced from the Bowes Member, a unit equivalent to the Upper Shaunavon in Montana, in the Bowes and Rabbit Hills oil fields (Carlson, 1968; Porter et al., 1998). Numerous oil shows are also present in the DSTs directly south of this study area. Vertical migration of oil through fracture systems may have also occurred in the southwest (Battle Creek area) where dual production exists from Shaunavon Formation and the underlying Madison Formation (Mississippian).

6.4.3 SUCCESS AND ROSERAY OIL POOLS

The Jurassic pools of Success and Roseray formations are located at the northeastern end of the Shaunavon Oil Trend (Figure 6.9) and produce medium to heavy oil (22 API) (Christopher, 2003). The traps are identified as stratigraphic (Roseray sands) and unconformity related (Success sands) (Christopher, 1974; 2003). Minor oil accumulations are found in the overlying sands of the Cantuar Formation and several oil fields have comingled production from all units.

Christopher (1974) has analyzed the hydraulic regime and identified strata between Rush Lake Shale and Joli Fou Shale as hydraulically continuous forming a single aquifer system with flow direction towards the east. He tied the Success-Roseray oil pools to the Shaunavon Oil Trend based on their spatial relation and similarities in oil properties. A biomarker study by Osadetz et al (1994) has confirmed a common origin of Success-Roseray and Shaunavon oils and identified the source as the Lodgepole Formation in the Williston Basin (i.e. Family C).

The results of this study indicate that the oil has migrated vertically from the Shaunavon Formation upward into the Cantuar, Success and Roseray Formations. The most likely area of upward migration is located between Townships 15 – 18 and Ranges 19 – 22 due to the thinner or complete lack of Rush Lake shales (Figure 2.2), which otherwise provide a top seal to Shaunavon Aquifer. In this area, Shaunavon and Lower Mannville aquifers have similar potentiometric surface (Figures 5.8 – 5.9) and formation water chemistry indicating hydraulic communication between the two aquifers. Strong eastward water drive in the Lower Mannville Aquifer pushed oil further into Success and Roseray formations where it became trapped.

6.4.4 VIKING OIL AND GAS POOLS

Large quantities of light oil (35 API) and gas sourced from Alberta (Osadetz et al., 1994) are stratigraphically trapped in the Viking Formation in the north (Figure 6.10). Hydrocarbons are trapped along the zone where sands pinch out into shales towards the northeast (Reinson et al, 1994). According to Osadetz et al (1994) oil in the Viking Formation is belongs to Family F and is sourced from the Lower Colorado shales in Alberta/Montana trough west of Calgary. A migration study by Bekele et al (2001) has shown that regional groundwater flow was essential for charging Viking pool in western Saskatchewan. The flow directions mapped in this study are in agreement with their findings and indicate the possibility of hydrodynamically enhanced oil migration from Alberta.

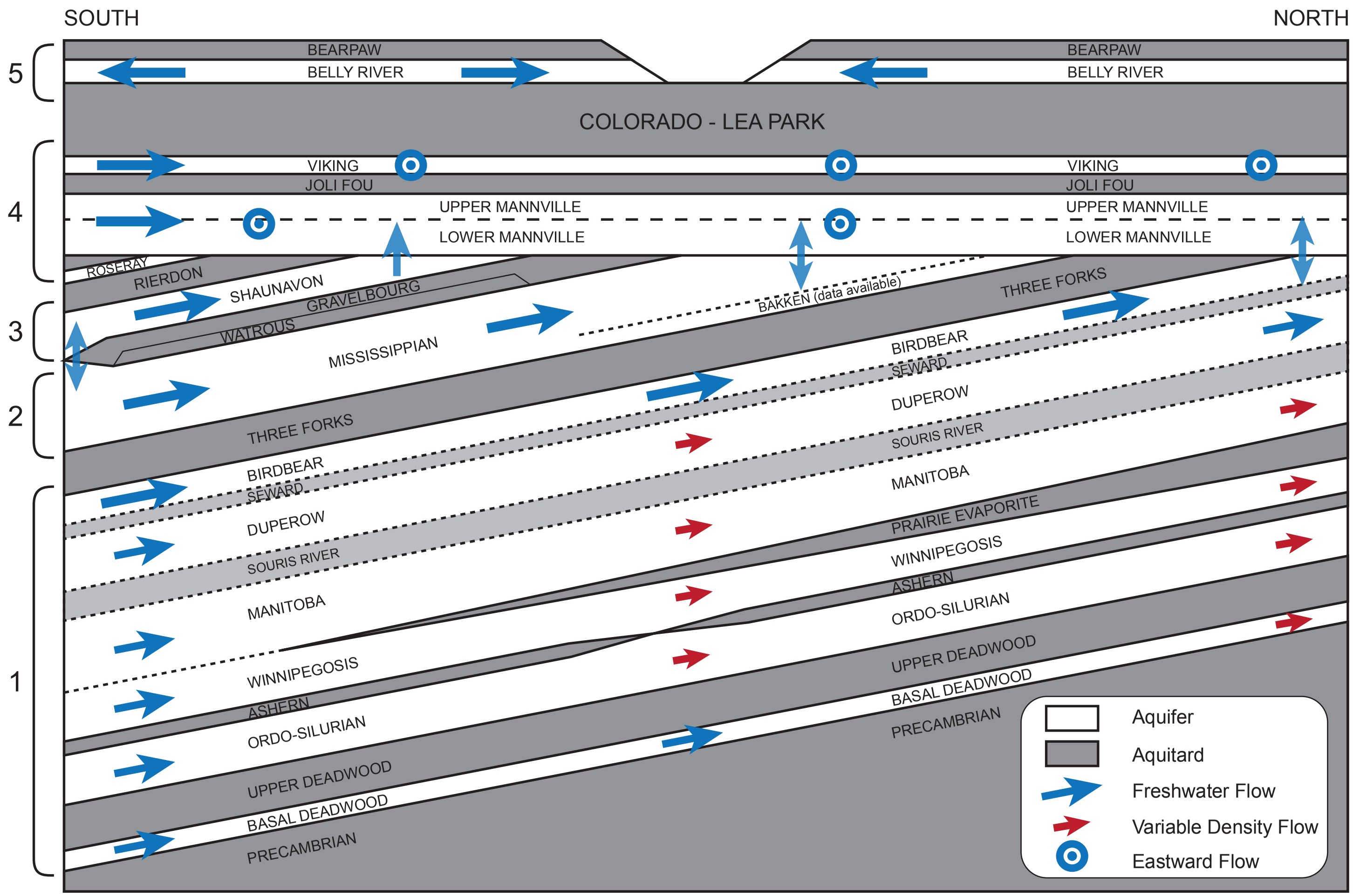

Figure 6.1: Schematic south-north cross-section showing relative flow directions and magnitudes in the five hydrogeologic systems: 1. Lower Paleozoic, 2.Mississippian, 3. Jurassic, 4. Lower Cretaceous, and 5. Upper Cretaceous.

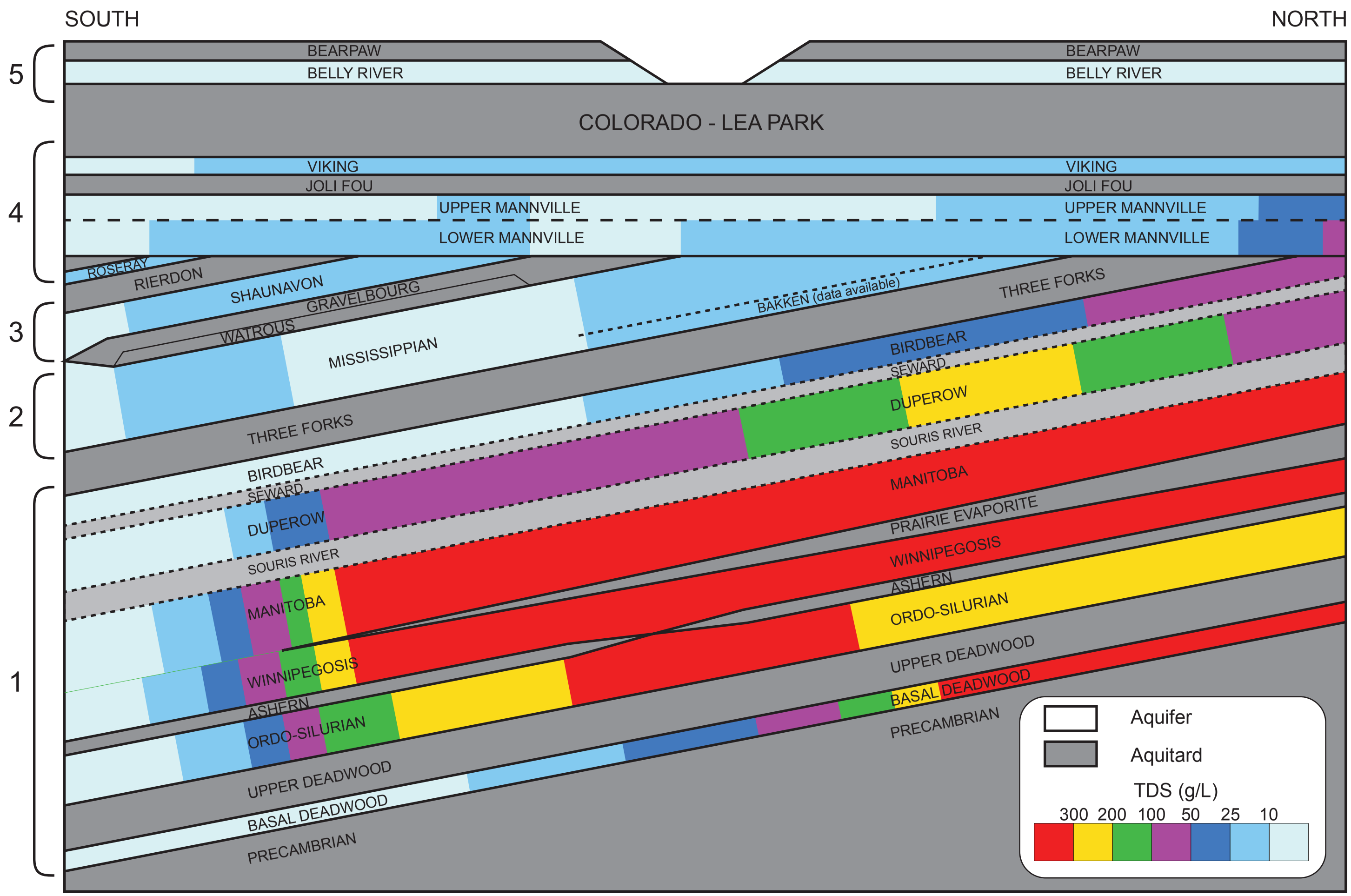

Figure 6.2: Schematic south-north cross-section showing the distribution of TDS in the five hydrogeologic systems: 1. Lower Paleozoic, 2.Mississippian, 3. Jurassic, 4. Lower Cretaceous, and 5. Upper Cretaceous.

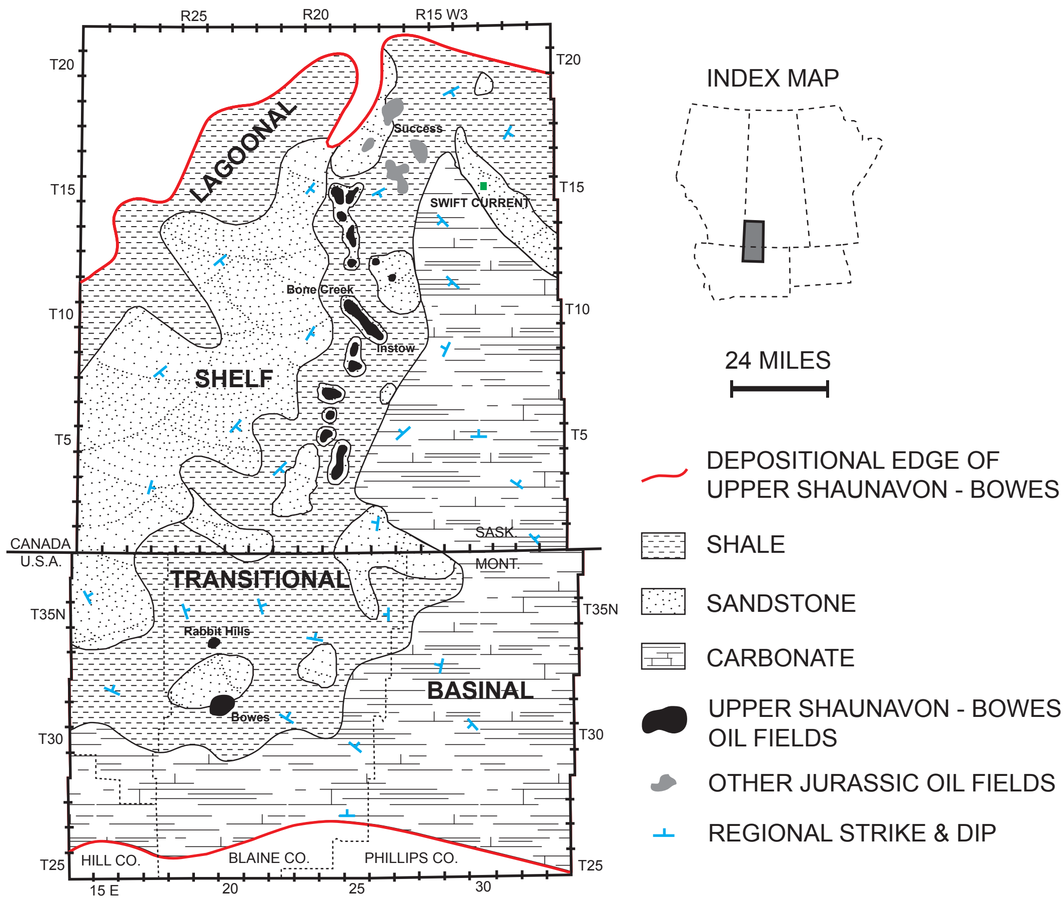

Figure 6.3: Depositional environments and facies map of the Upper Shaunavon Member (modified from Carlson, 1968: Fig. 11).

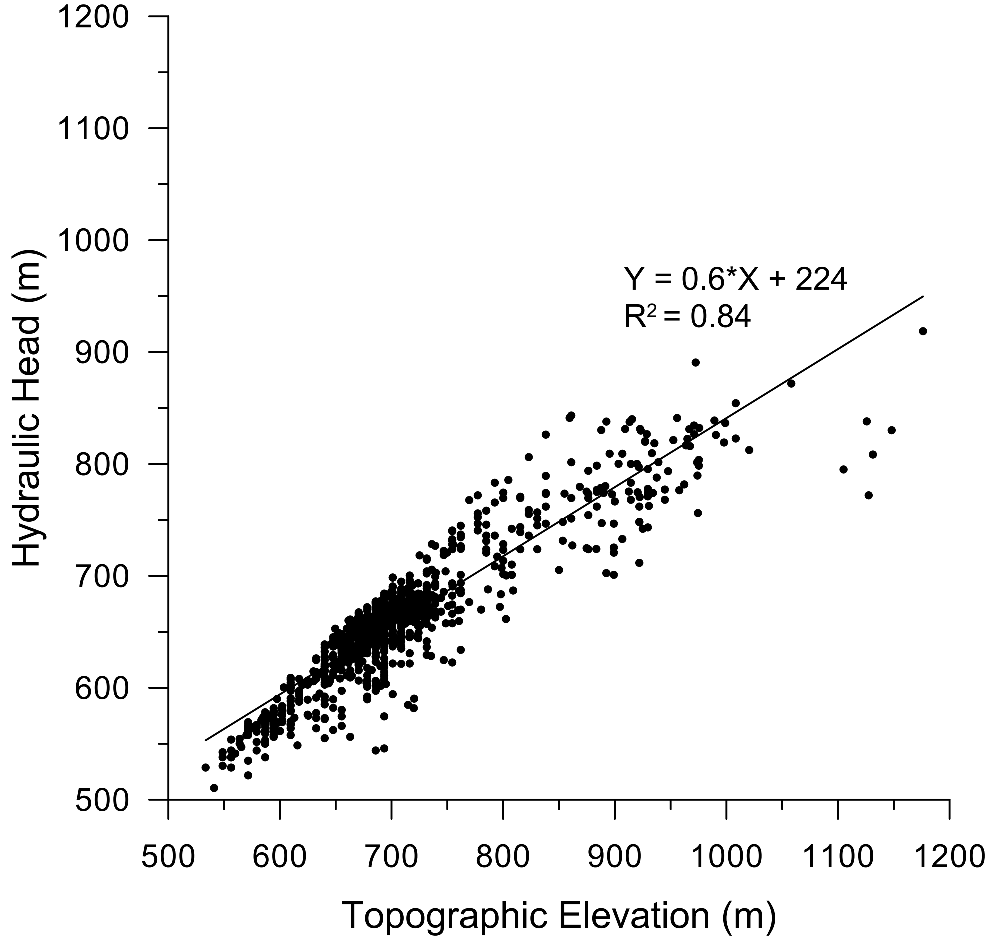

Figure 6.4: Plot of the topographic elevations versus the corresponding hydrualic heads in the Belly River Aquifer.

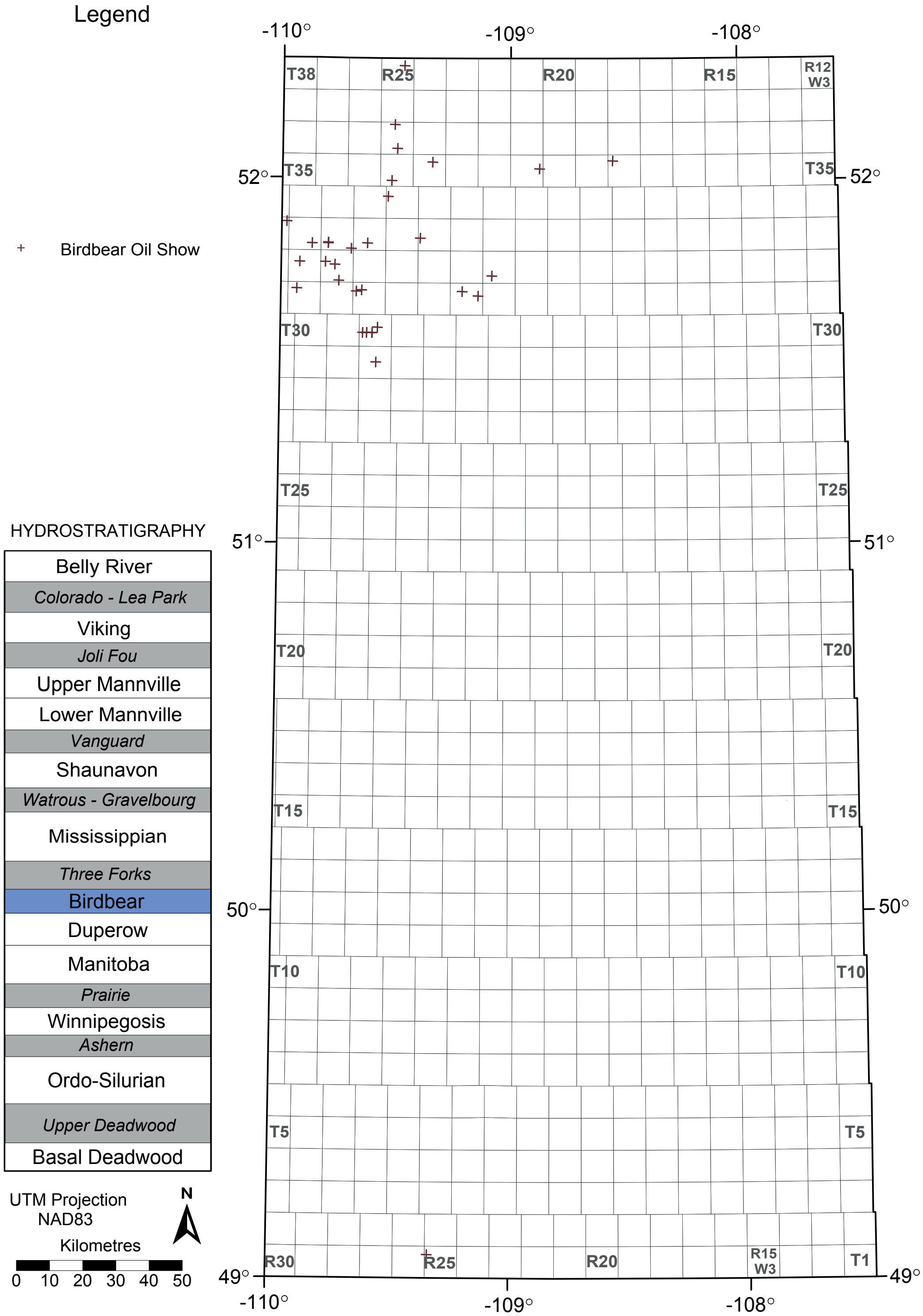

Figure 6.5: Oil shows from DSTs in the Birdbear Aquifer.

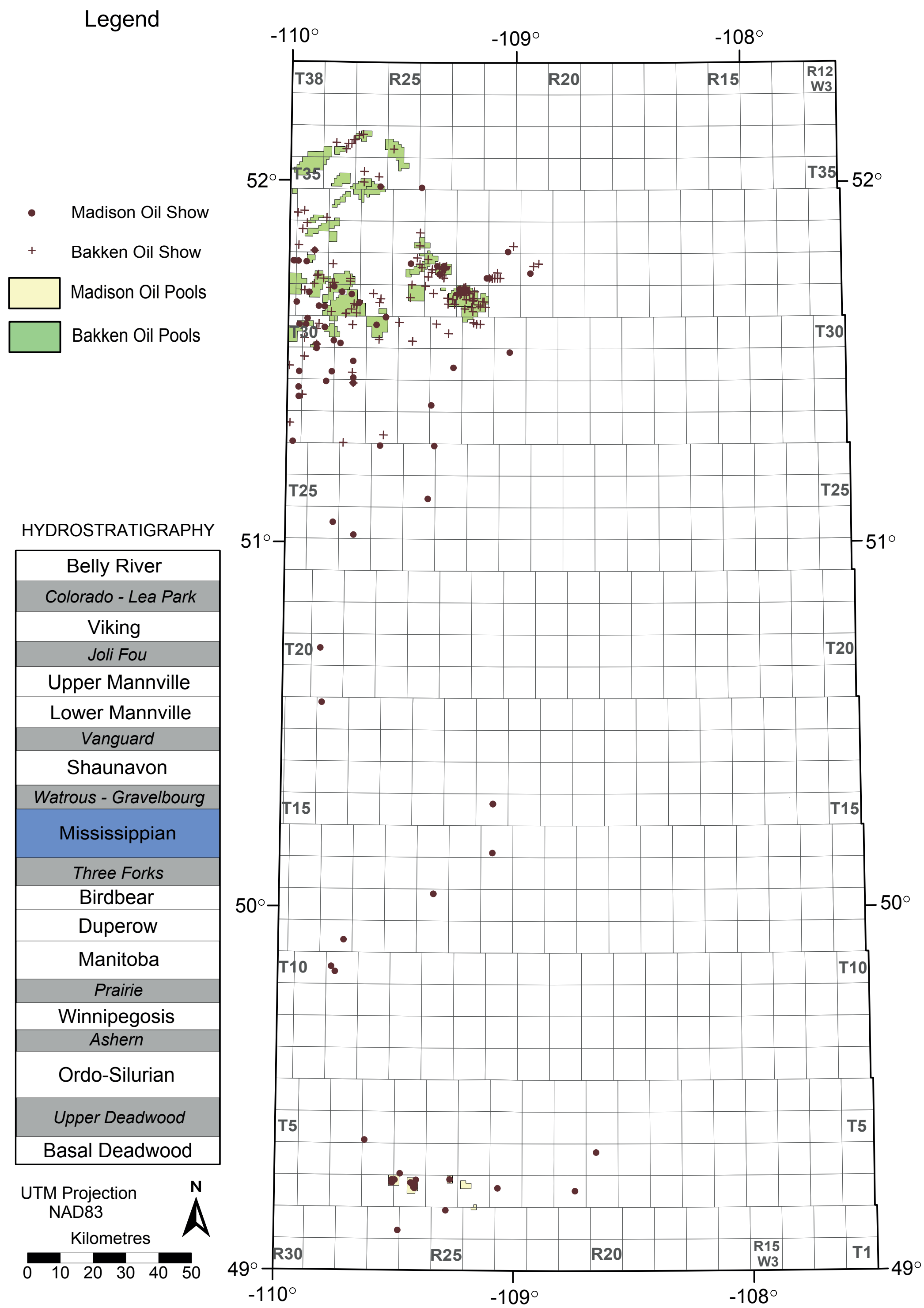

Figure 6.6: Oil shows from DSTs in the Mississippian Aquifer.

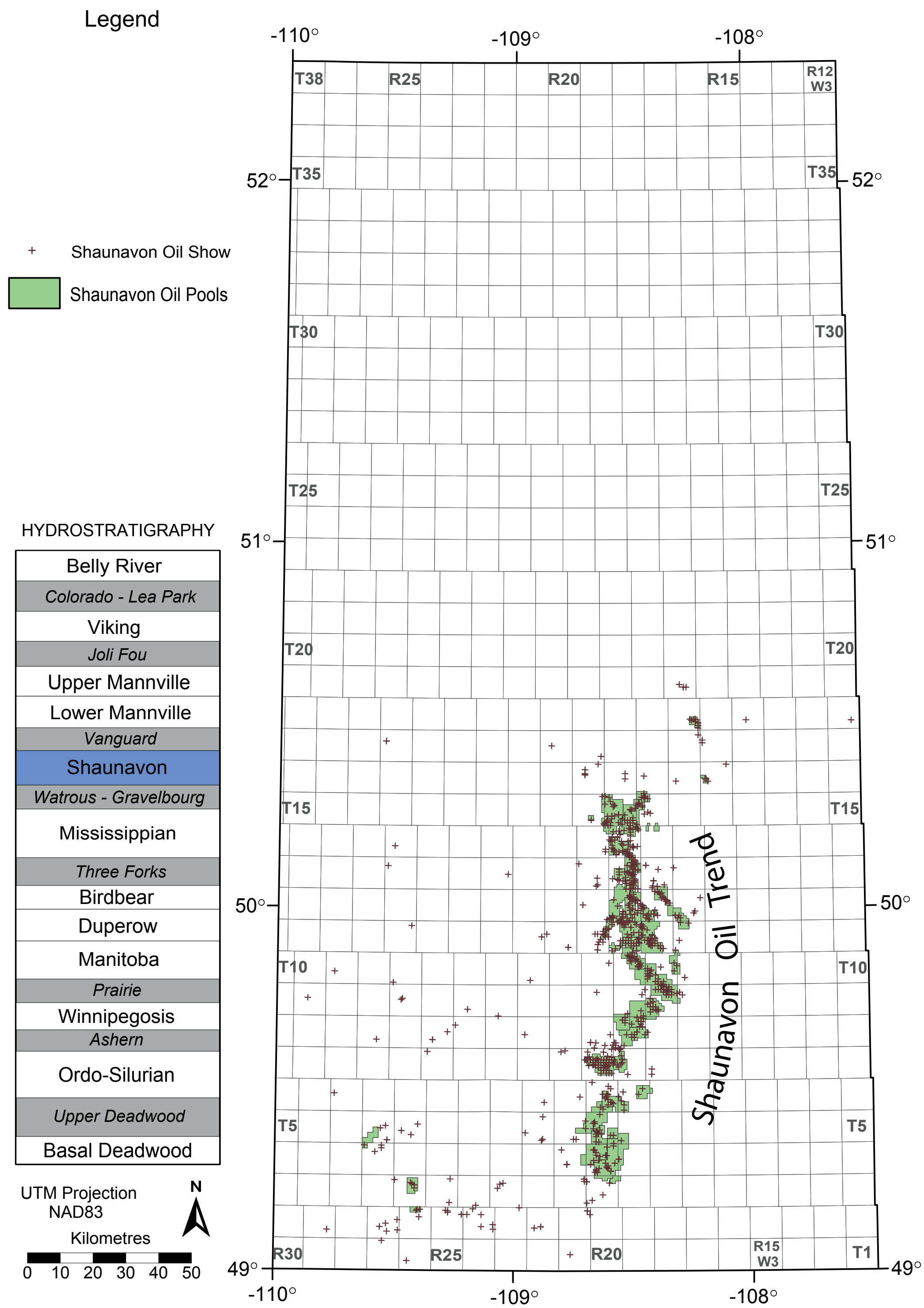

Figure 6.7: Oil shows from DSTs in the Shaunavon Aquifer.

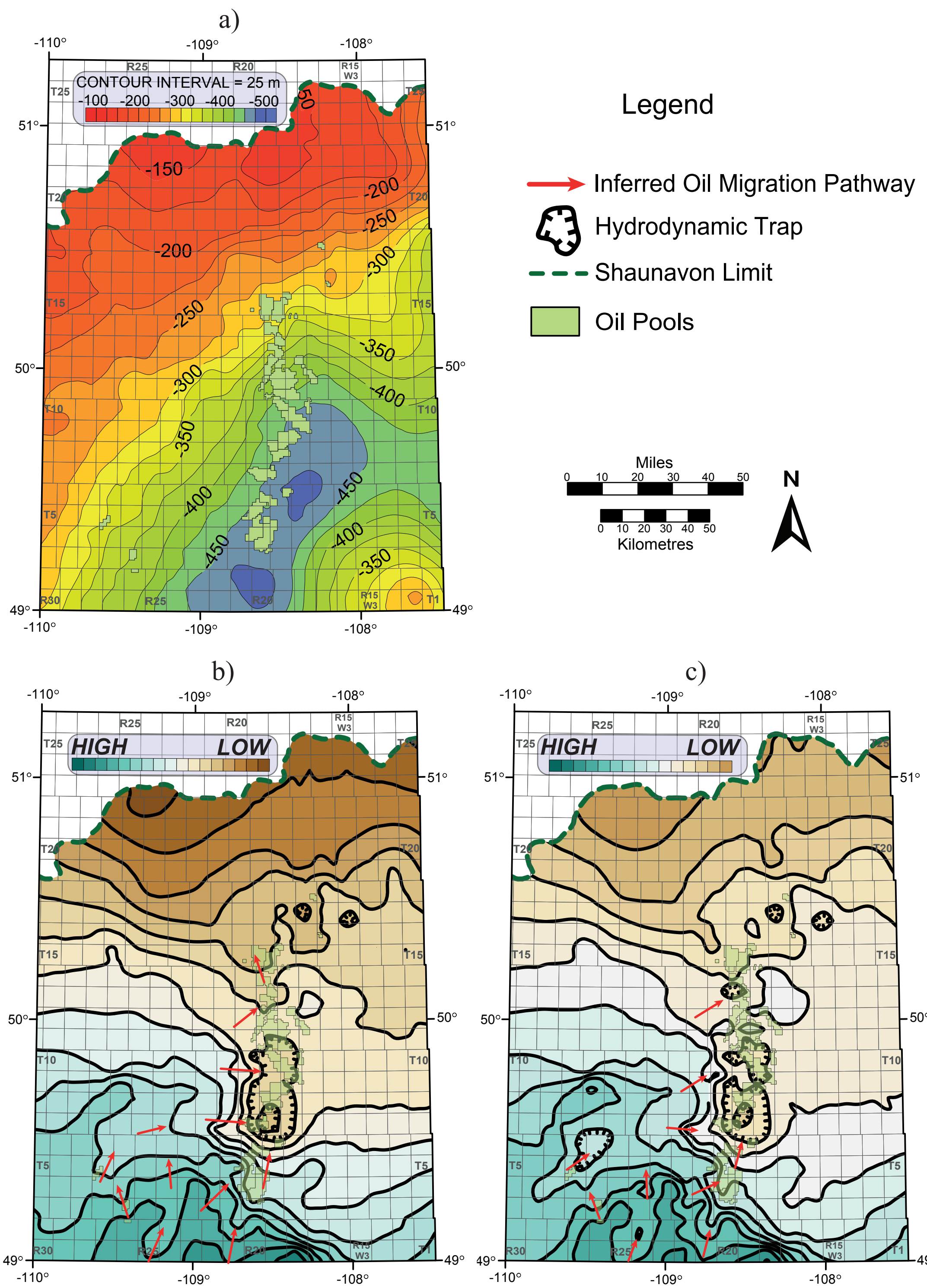

Figure 6.8: a) Structure map of the Shaunavon Formation, b) oil potential (flow) map for a maximum gravity of 35API, and c) oil potential map for average gravity of 22 API.

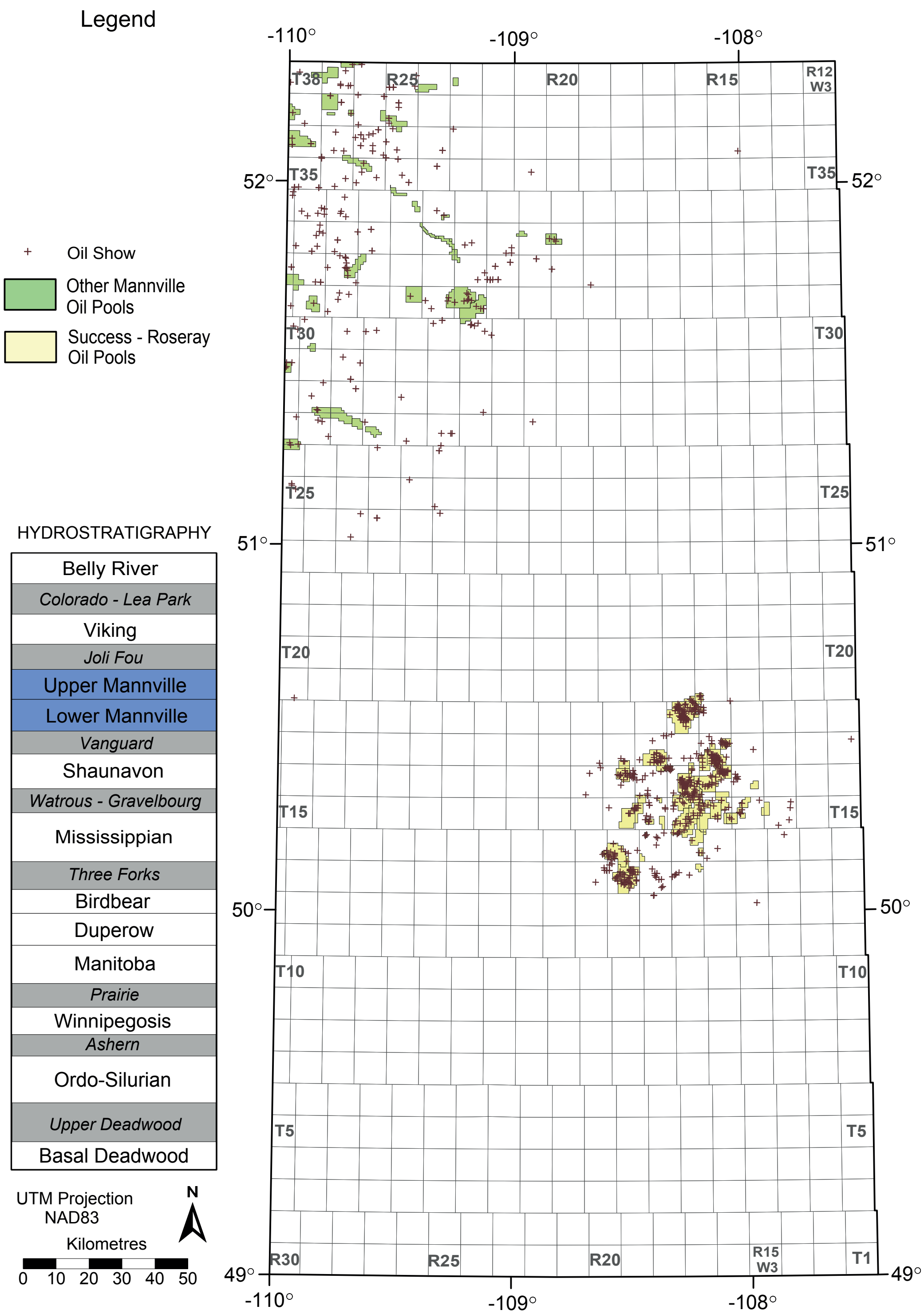

Figure 6.9: Oil shows from DSTs in the Mannville aquifers.

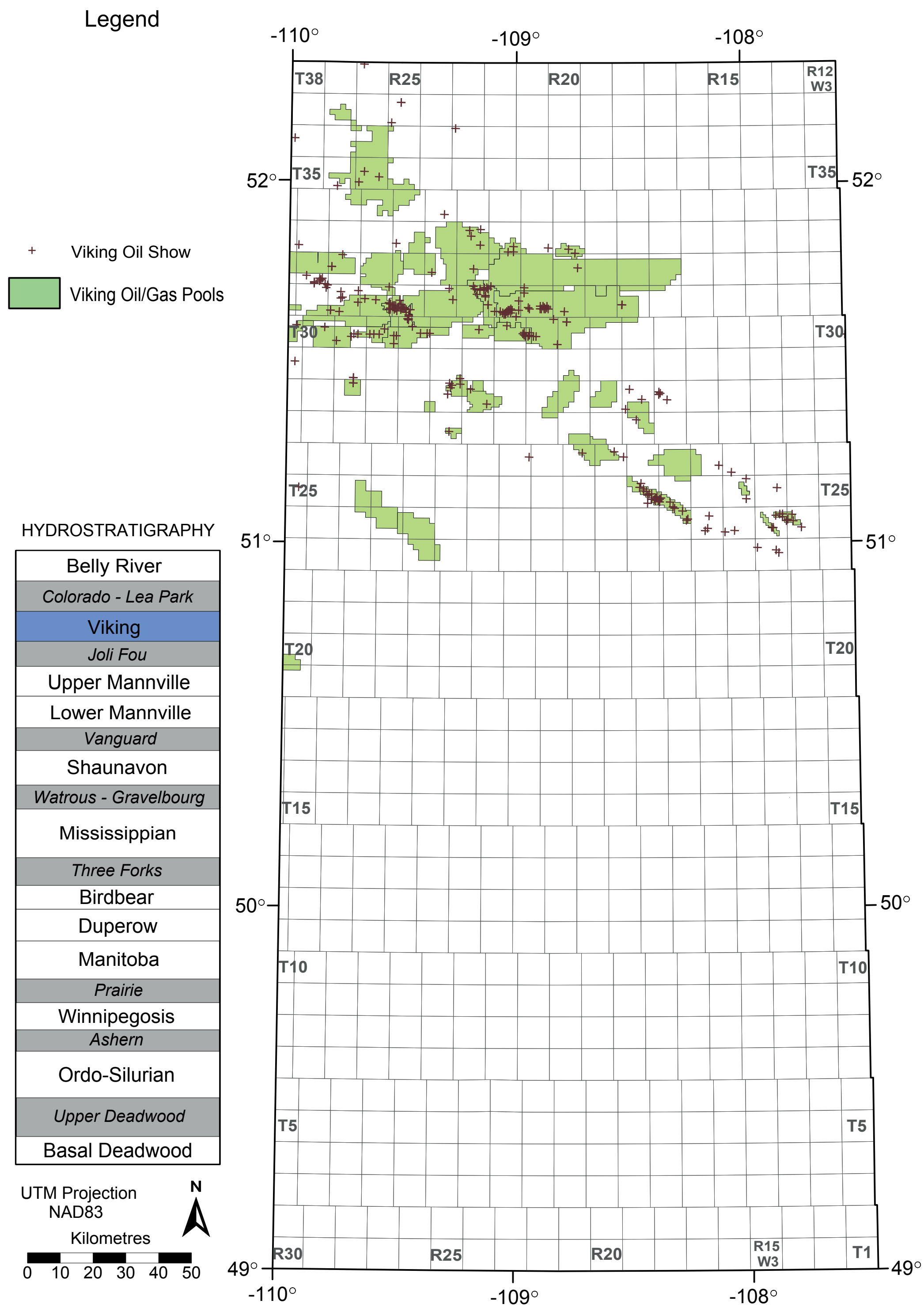

Figure 6.10: Oil shows from DSTs in the Viking Aquifer.

Chapter 6 – Conclusions

1. Twelve aquifers separated by 12 aquitards have been identified in southwestern Saskatchewan. These aquifers were grouped into five major hydrogeologic systems based on their similarities in hydrochemistry and hydrodynamics: **1) Lower Paleozoic** (Basal Deadwood, Ordo-Silurian, Winnipegosis, Manitoba, Duperow, and Birdbear aquifers), **2) Mississippian** (Mississippian Aquifer), **3) Jurassic** (Shaunavon Aquifer), **4) Lower Cretaceous** (Lower Mannville, Upper Mannville and Viking aquifers), and **5) Upper Cretaceous** (Belly River Aquifer).

2. Four main water types were identified in the study area:

   Type 1: Ca(Mg)-SO_4 *(Na <70% and SO_4 >50%)* waters have low TDS (<5 g/L), high Ca and SO_4 concentrations. They are identified as recharge-area waters with short residence time, rapid flow and low reactivity. Type 1 waters are found only in Paleozoic aquifers in the southern parts of the study area. These fresh waters originate in the uplifted recharge areas in Montana.

   Type 2: Na-Cl *(Na >70% and Cl >50%)* waters have variable TDS (10-300 g/L), and represent evolved formation waters derived from salt dissolution with long residence time and flow path. Type 2 waters are present in all aquifers and represent evolved formation water.

   Type 3: Na-SO_4 *(Na >70% and SO_4 >50%)* are brackish waters with TDS of <50 g/L, and are derived from mixing between Ca-SO_4 (1) and Na-Cl (2) water types and dissolution of anhydrite. Type 3 waters are found largely in the Mississippian Aquifer and are associated with anhydrite dissolution and mixing between waters of Types 1 and 2.

   Type 4: Na-HCO_3 *(Na >70% and HCO_3 >50%)* waters are characterized by low TDS (<10 g/L) and high HCO_3 concentrations. Type 4 waters originate from southern Alberta as a result of bacterial sulphate reductions and are found in the Mississippian, Jurassic, and Cretaceous aquifers.

3. High TDS waters (100 - 300 g/L) are found in the Lower Paleozoic aquifers and are associated with dissolution of salts in the Prairie Formation. Low-TDS waters (< 25 g/L) are found in areas where Prairie Evaporite Formation is absent. Mississippian, Jurassic and Lower Cretaceous aquifers have relatively low TDS ranging between 5 – 25 g/L. High TDS plume is present in the Mannville Aquifer in the northeast as a result of ascending Devonian brines from the Birdbear Aquifer. Upper Cretaceous Belly River Aquifer has the lowest TDS (< 5 g/L) representing fresh and shallow groundwater.

4. Fluid flow in all aquifers throughout the study area is generally lateral or along aquifers. Formation waters in Lower Paleozoic and Mississippian aquifers are generally flowing updip and north toward their subcrop locations. This is a part of larger Williston Basin flow system with recharge located in the uplifted areas of western and central Montana. Flow directions in the northwestern parts of Birdbear and Mississippian aquifers (along their subcrop) are from west to east due to hydraulic communication with the overlying Lower Mannville Aquifer.

5. Flow directions in the Jurassic Shaunavon Aquifer are regionally towards the north. However, waters are diverted towards the Shaunavon Oil Trend. This flow pattern is the result of permeability contrast associated with the changing depositional facies.

6. Formation waters in the Lower Cretaceous aquifers flow from west to east (also from southwest to northeast). This flow system originates in the northwestern Montana and flows north/northeast into Alberta Basin and across Sweetgrass Arch into western Saskatchewan.

7. Upper Cretaceous Belly River Aquifer is controlled by surface topography. Water flows from topographically high areas (e.g. Cypress Hills) toward low-lying erosional boundaries and incised valley, in particular toward South Saskatchewan River.

8. Birdbear, Mississippian, and Shaunavon aquifers are in hydraulic communication along their subcrops with overlying Lower Mannville Aquifer.

9. Flow reversals and reduced lateral gradients due to density-related flow effects are observed in Lower Paleozoic aquifers in areas of high TDS (Basal Deadwood, Ordo-Silurian, Winnipegosis, Manitoba, and Duperow aquifers).

10. The effects of water flow on hydrocarbon migration and accumulation in southwestern Saskatchewan have been demonstrated by previous research and confirmed by the results of this study. Water flow in the Mannville aquifer could have facilitated migration of heavy oil from Alberta and subsequent trapping in the Mannville, Bakken, and Birdbear reservoirs in the northwest. UVZ analysis of Shaunavon Aquifer has demonstrated the hydrodynamic nature of oil traps along the Shaunavon Oil Trend with the possible migration pathways from the south and southwest. The Success and Roseray pools are the result of upward migration of oil from the Shaunavon Oil Trend and strong eastward hydrodynamics in the Lower Mannville Aquifer. Lastly, flow directions in the Viking Aquifer confirm the possibility of a long range migration of oil from Alberta.

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APPENDIX A – Culling Methods for Hydrogeological Data

A.1 – CHEMISTRY

The following specific culling criteria are based on previous studies by Hitchon and Brulotte (1994) and Hitchon (1996).

Incomplete Analyses

Many chemical analyses are incomplete or have missing information (such as test interval, pH, and type of test). All water samples must be analysed for major ionic species: chloride (Cl^-), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), sodium (Na^+), Calcium (Ca^{2+}), and Magnesium (Mg^{2+}). Analyses that are missing any one of these ions were removed from database or flagged as potentially erroneous. However, certain chemical species are not reported due to their very low concentrations (bellow the detection limit). This does not mean that the entire analysis is invalid and manual examination is required.

Charge Balance Error

Charge Balance Error (CBE) is a fundamental parameter in the quality control of chemical analyses (Davis, 1988). Poor quality analyses can be detected by a simple calculation based on the fact that dissolved chemical species exist in equilibrium (by molar mass and charge). The % CBE is calculated using the following equation (Freeze and Cherry, 1979):

$$\%CBE = \left[\frac{\sum Z \times m_c - \sum Z \times m_a}{\sum Z \times m_c + \sum Z \times m_a} \right] \times 100\%$$

where: Z is the absolute value of ion's charge, m_c is the molar mass of cations, and m_a is the molar mass of anions. Analyses with CBE greater than 10% were flagged and subsequently eliminated from further consideration.

Identification of Contaminated Samples

The following are diagnostic criteria used to identify contaminated water samples (e.g. Hitchon and Brulotte, 1994; Rostron, 1994; Khan, 2006; Palombi, 2008):

a) General Criteria

- pH < 5 or > 8: generally formation water falls within this pH boundary. Any samples with pH from outside of this range could potentially be contaminated by completion fluid or corrosion inhibitor.

- Hydroxide reported (OH^-): presence of hydroxide may indicate large amount of mud recovery during the test.

- Carbonate reported (CO_3^{2-}): dissolved CO_3^{2-} cannot exist in a pH environment below 8.1 (Langmuir, 1997). Most subsurface brines do not contain CO_3^{2-}, therefore, its presence may indicate potential contamination with drilling fluid.

- Density < 1 g/cm^3 (1000 kg/m^3): measured water density of less than 1 g/cm^3 may indicate contamination by an alcohol-based drilling fluid.

- Recovery < 100 m (measured in drill-pipe stands during DSTs only): drill-stem tests with low recoveries were avoided whenever possible due their higher risk of contamination with drilling fluid ("filter cake").

b) Acid Water / Completion Fluid Criteria

- pH < 4.5
- Ratio Ca/Cl > 0.3 and pH < 5.7
- Ratio Na/Ca < 1.2
- Ratios Na/Ca < 5 and Na/Mg < 10 and pH < 6
- Ratio Na/Cl < 0.4 and pH < 6.8

c) Corrosion Inhibitor Criteria

- pH > 9

- Ratios Na/Cl > 3.5 and SO_4/Cl > 1.5
- SO_4/Cl > 10

d) Mud Filtrate / GelChem Criteria

- Ratio Na/Cl > 5
- Ratios Na/Cl > 3.5 and SO_4/Cl > 1.5

e) KCl Mud Filtrate (“Kill Fluid”) Criterion

- Ratio Na/K < 20

In addition to the above criteria, a number of other parameters were used to assess the quality of the water analyses. First, the location of the sampling point was used to identify where in the fluid column a sample has been taken. Typically locations described in the water analysis report include: the top; middle; and bottom of fluid recovery; specified distance above the tool; top of tool (above the down-hole sampler); and the down-hole sampler. The lower in the fluid column the sample was taken, the better ("cleaner") the sample is likely to have been recovered since larger volume of formation water has entered the drill pipe and flushed the drilling fluid (filter cake) up the tool string. Thus, the bottom of the fluid recovery and top of tool are the preferred locations. Samples from the down-hole sampler are generally good but it is often found that drilling fluid is erroneously sampled instead of the formation water. The least favourable sampling locations include the top and middle of the fluid recovery, but sometimes they can also produce representative water samples in DSTs with large water recoveries (hundreds of metres).

A water cushion, a volume of water placed in the tubing prior to flow, is often used in deep drill-stem tests to avoid wellbore damage due to high pressure differential. Water cushion can significantly dilute the sample, therefore, it is important to know which DSTs contained them and take precautions.

For the final culling stage the TDS and chemistry of each analysis were manually examined to ensure a fit with the general data trend. Previous work has shown that formation water chemistry is locally consistent, i.e. does not vary (Benn and Rostron, 1998; Khan, 2006; Palombi, 2008). Data points with anomalous TDS were further examined. In cases where TDS values were similar, ionic ratios were calculated and samples with anomalous ratios were identified as contaminated or being from a different formation.

A.2 – PRESSURE

The following paragraphs describe additional culling criteria used to evaluate the quality of pressure measurements (similar to Khan, 2006; and Palombi, 2008):

1. Interval Length: The length of tested interval (between top and bottom packer) can often be too large and straddle over several formations or aquifers with different pressure regimes. Tests with intervals greater than 50 m were manually examined and generally culled.

2. Quality Code: Data vendors assign a code to subjectively asses the quality of the pressure test. Both Hydrofax and CIFE have similar quality codes: (A) best quality; (B) nearing stabilization; (C) caution (possible tool plugging); (D) questionable or misrun; (E) low permeability and low pressure; (F) low permeability and high pressure; (G) misrun. Data with quality from A to C were generally retained for further mapping. Quality D data were also used in areas where better quality data were not available or areas of sparse data. Very poor quality tests (E to G) were discarded. Additional verification and manual culling was performed on lesser quality data (C and D).

3. Qualitative Permeability: This code provides a permeability rating based on subjective examination of the DST chart(s) by the database vendors. The following are the assigned codes: excellent (EX) – final flow has stabilized with the final shut-in pressures; high (HI) final flow nearing stabilization with the final shut-in pressures; relatively high (RH) – final flow and shut-in are still building up slightly; average (AV) - final flow and shut-in are still building up rapidly; relatively low (RL) – flow pressure is low and shut-in pressure is building rapidly; low (LO) – very low flowing pressure with rapidly building-up shut-in pressure; virtually none (VN) – almost no flow and rapidly building pressure. DSTs with qualitative permeabilities of lower than average (AV) were generally culled.

4. Qualitative Hydro-Factor: This code indicates the type of fluid recovered: water, oil, gas, mud, or water cushion. With a mixed recovery the larger amount of is taken to be representative fluid type. For example “Gas-cut water” will be marked as W (water). DSTs with water recoveries were preferred. However, most DSTs with oil and water cushion recoveries were used since they still represent flow conditions in the formation. Mud and gas recoveries were generally not used.

5. Flow and Shut-In Times: These are the times allowed for the fluid to flow into the drill-pipe and then stabilize during the shut-in time. Tests with longer flow and shut-in times are likely to better represent true formation pressure or provide more accurate extrapolation results.

6. Recovery and Blow Description: on-site operator's comments can often be useful in determining the quality of the test. Those comments could include any breakdown events during the test, equipment malfunctions, tool skids, and mud leaks all of which could affect pressure measurements.

7. DST chart: Visual examination of a DST chart can give some indication of the quality of the test if no additional information or interpretation is given. Certain older tests also required proper Horner extrapolation directly from the DST chart due to the lack of digital pressure readings.

Appendix B - Stiff Plots

Stiff plots were created for each water type in all aquifers. Red line represents average ionic concentrations. Grey-shaded areas represent the observed ranges of ionic concentrations (i.e. maximum and minimum).

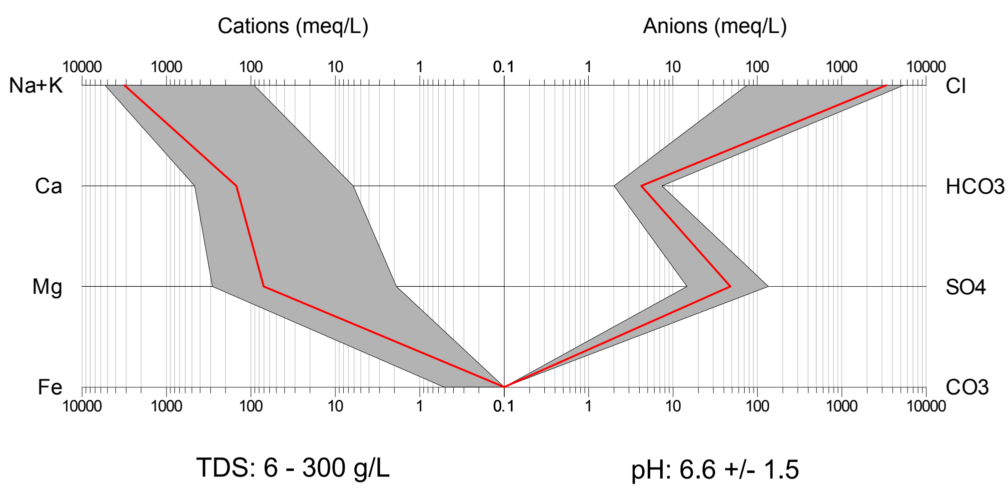

Figure B.1 Stiff diagram of the **Basal Deadwood** ***Na-Cl*** type water.

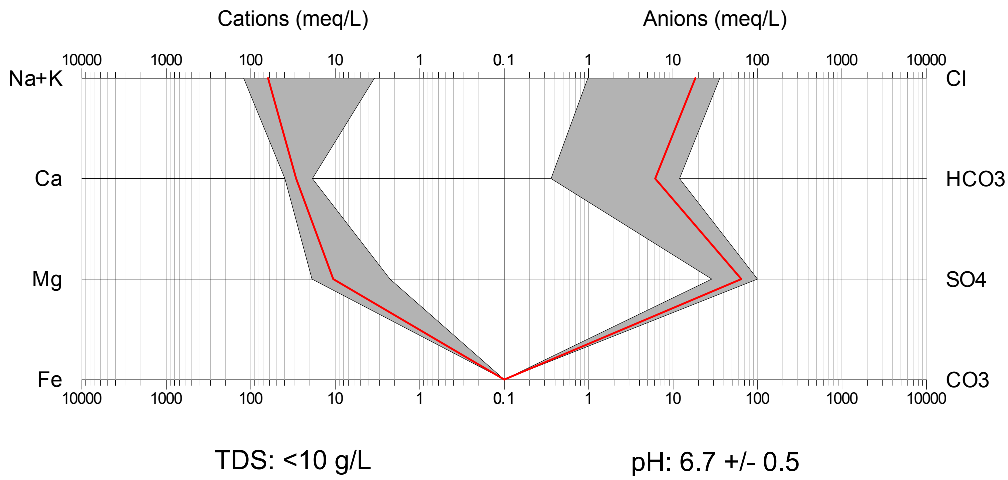

Figure B.2a Stiff diagram of the **Ordo-Silurian** ***Ca-SO$_4$*** type water.

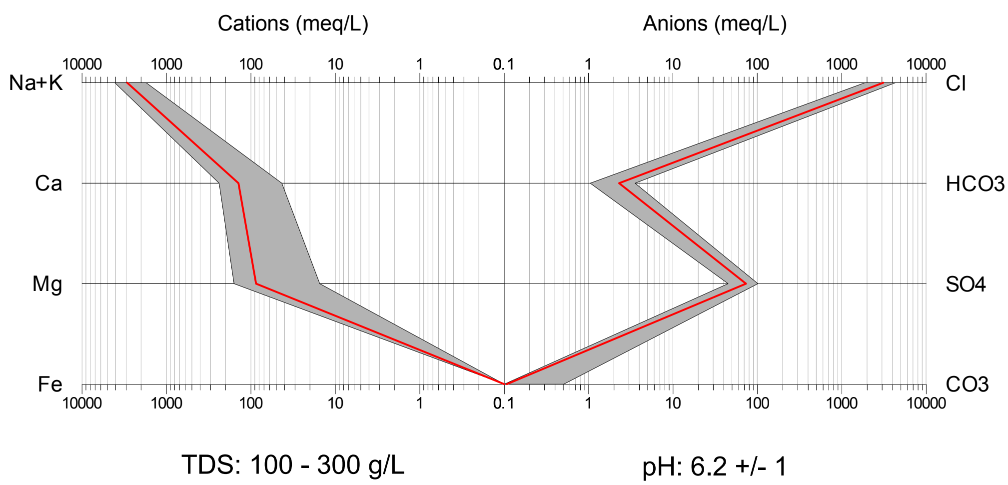

Figure B.2b Stiff diagram of the **Ordo-Silurian** ***Na-Cl*** type water.

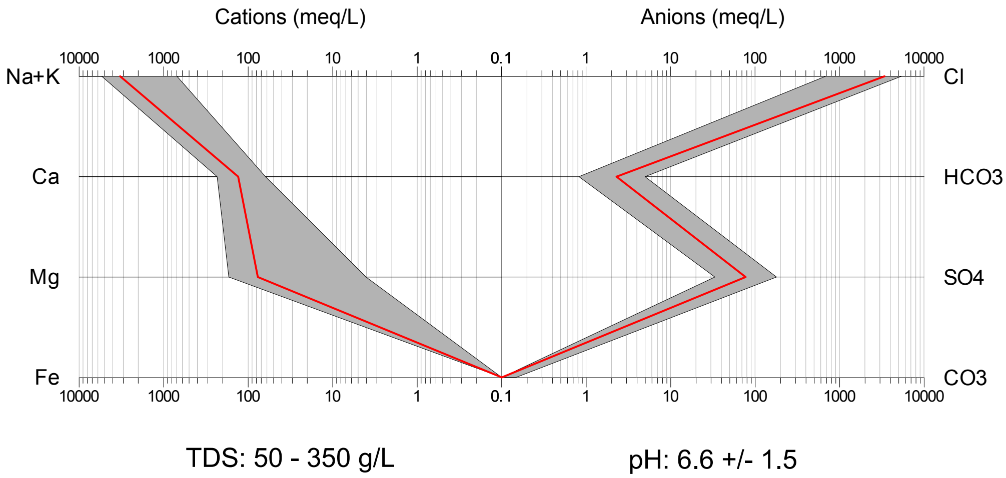

Figure B.3 Stiff diagram of the **Winnipegosis** ***Na-Cl*** type water.

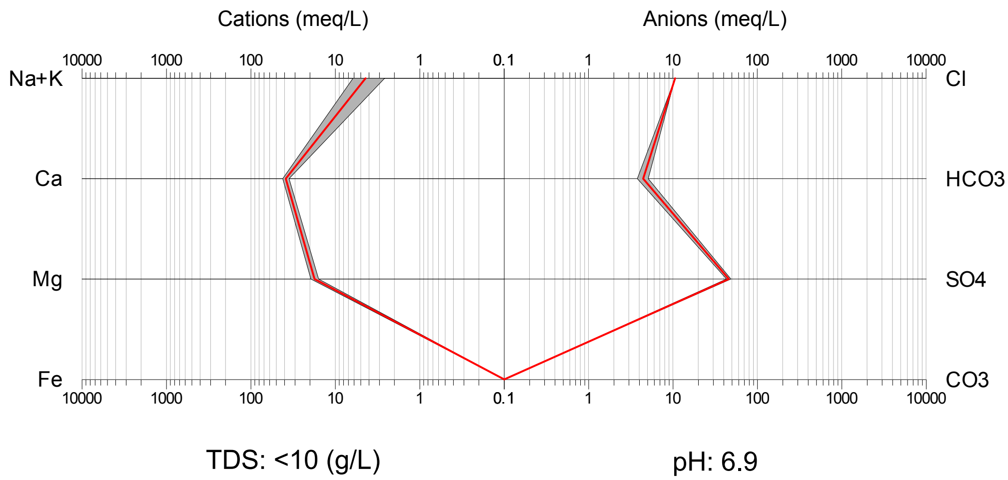

Figure B.4a Stiff diagram of the **Manitoba** ***Ca-SO$_4$*** type water.

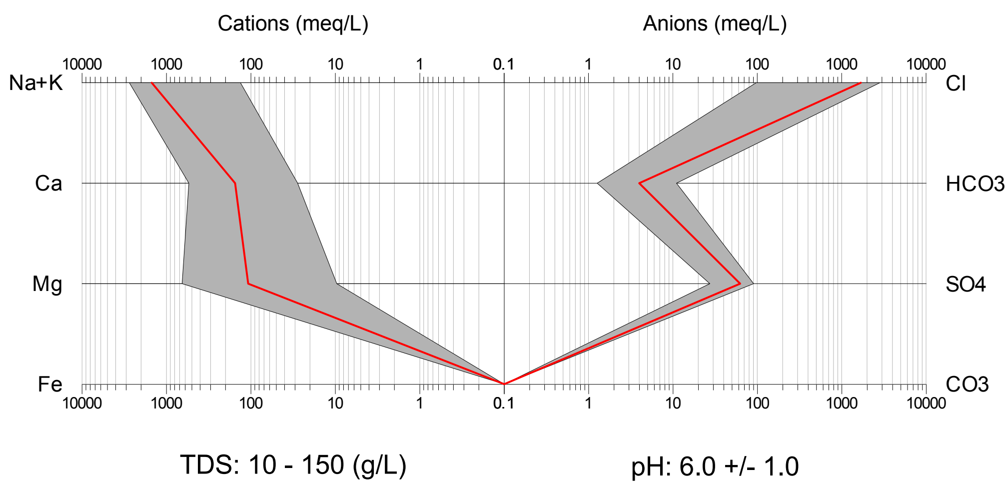

Figure B.4b Stiff diagram of the **Manitoba N*a-Cl*** type water.

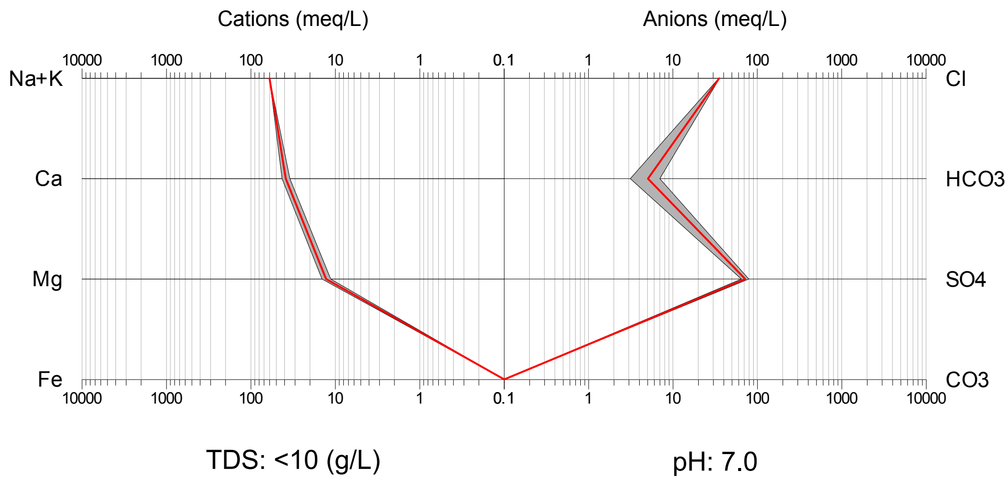

Figure B.5a Stiff diagram of the **Duperow** ***Ca-SO₄*** type water.

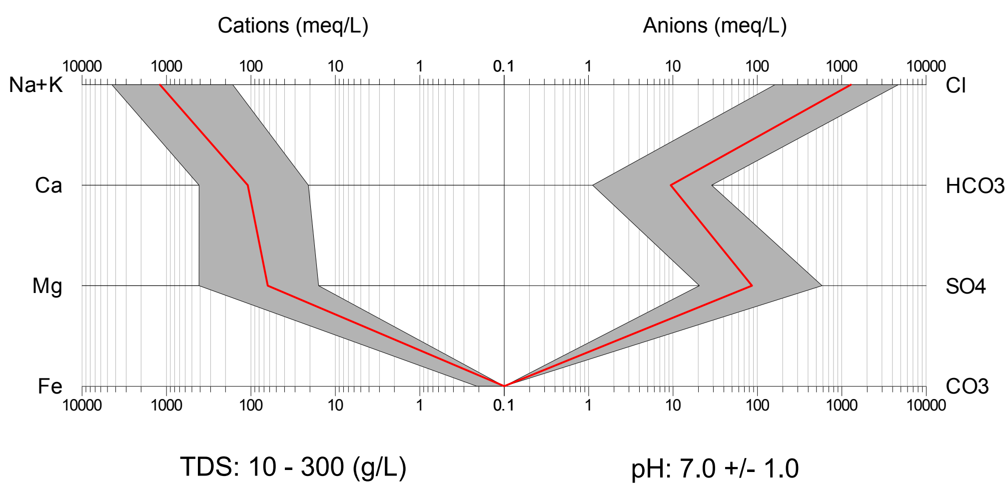

Figure B.5b Stiff diagram of the **Duperow** ***Na-Cl*** type water.

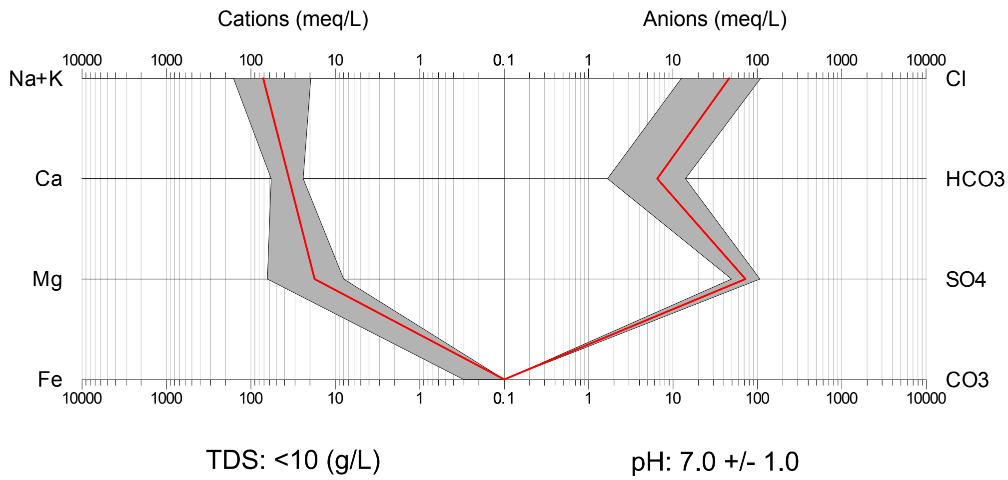

Figure B.6a Stiff diagram of the **Birdbear** ***Ca-SO$_4$*** type water.

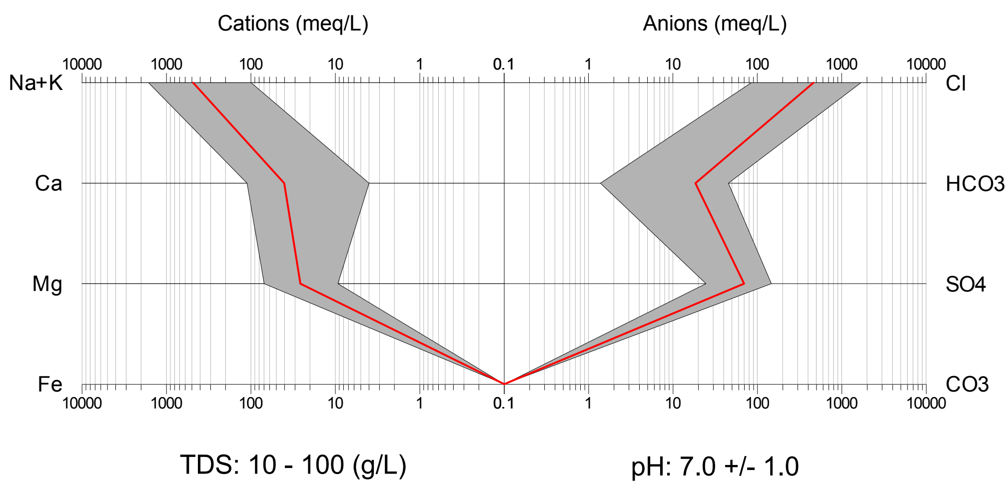

Figure B.6b Stiff diagram of the **Birdbear** ***Na-Cl*** type water.

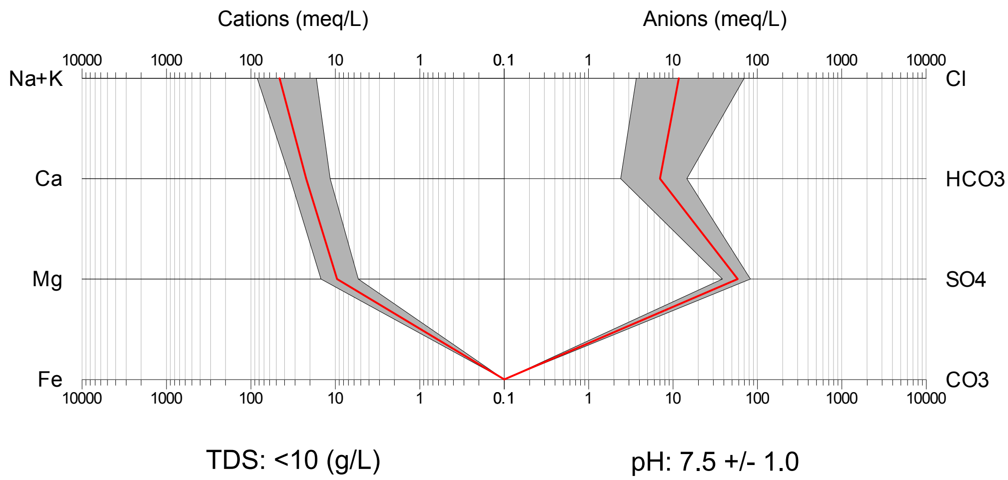

Figure B.7a Stiff diagram of the **Mississippian** ***Ca-SO$_4$*** type water.

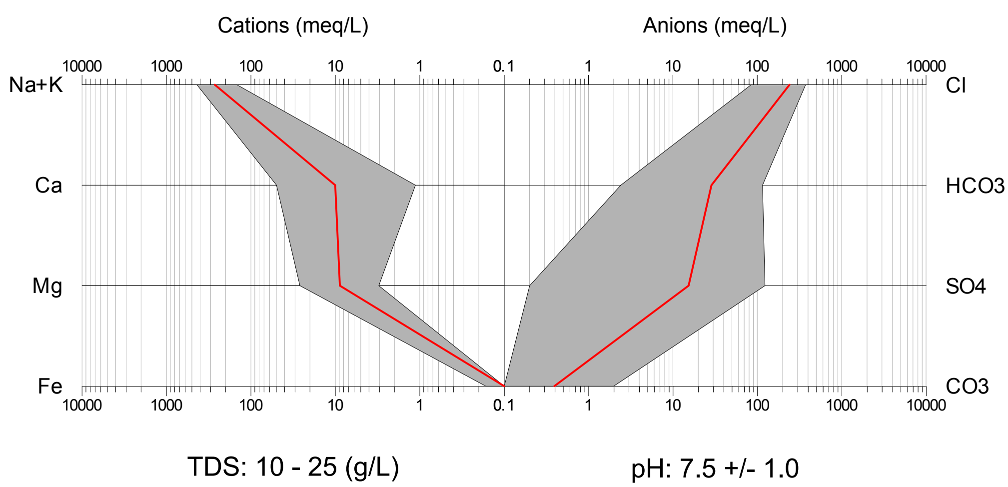

Figure B.7b Stiff diagram of the **Mississippian** ***Na-Cl*** type water.

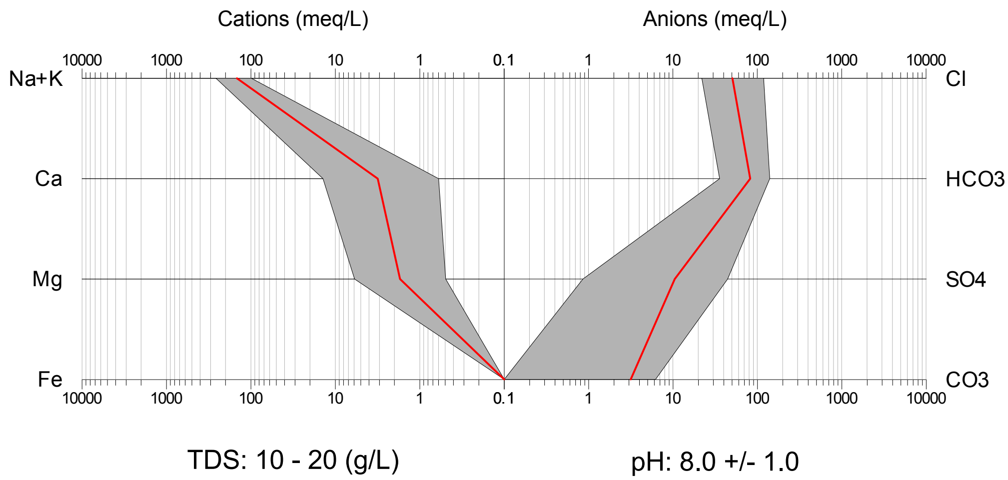

Figure B.7c Stiff diagram of the **Mississippian** ***Na-HCO$_3$*** type water.

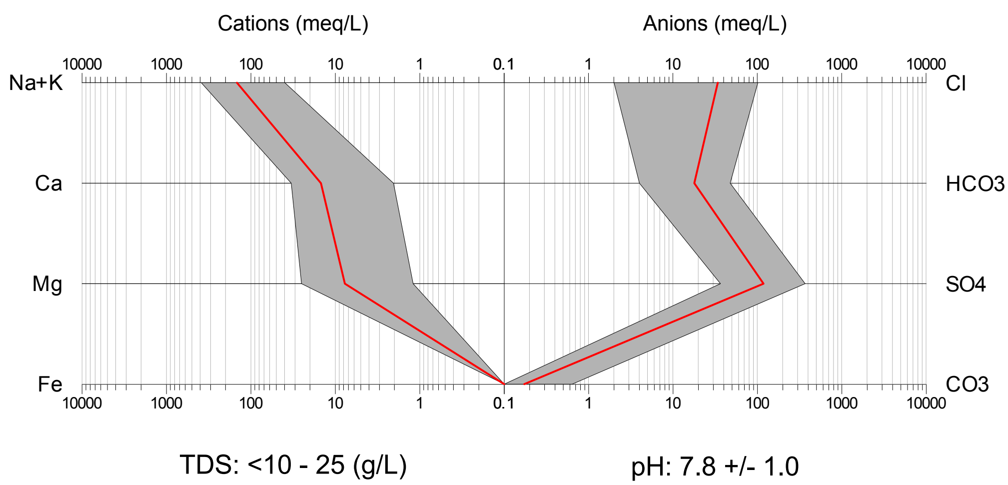

Figure B.7d Stiff diagram of the **Mississippian** ***Na-SO$_4$*** type water.

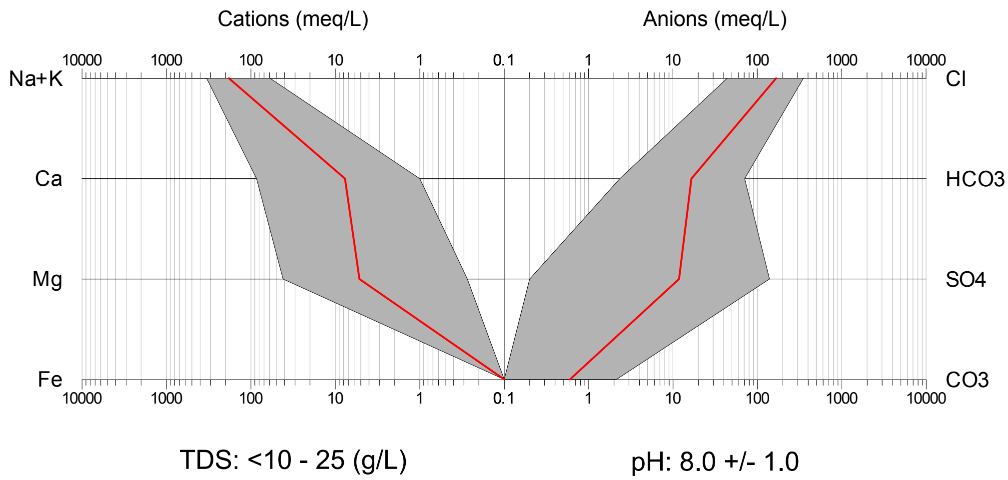

Figure B.8a Stiff diagram of the **Shaunavon** ***Na-Cl*** type water.

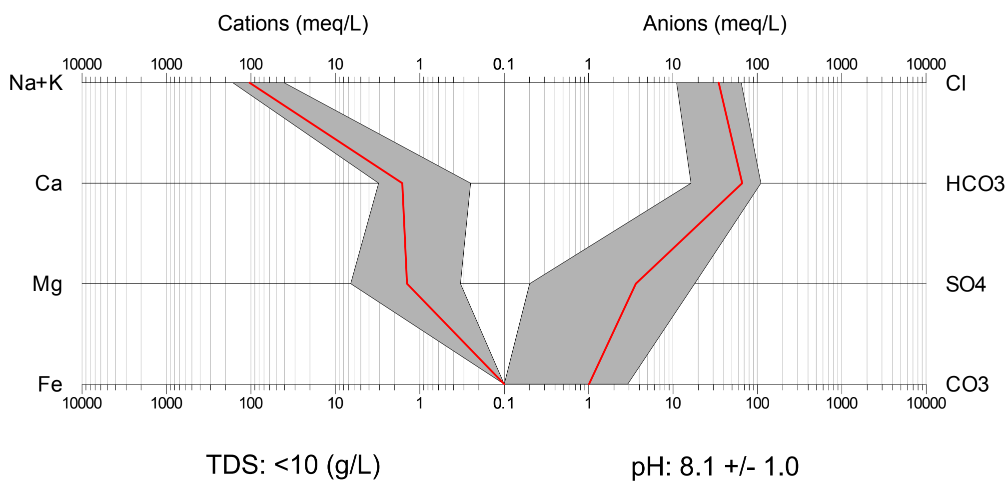

Figure B.8b Stiff diagram of the **Shaunavon** ***Na-HCO_3*** type water.

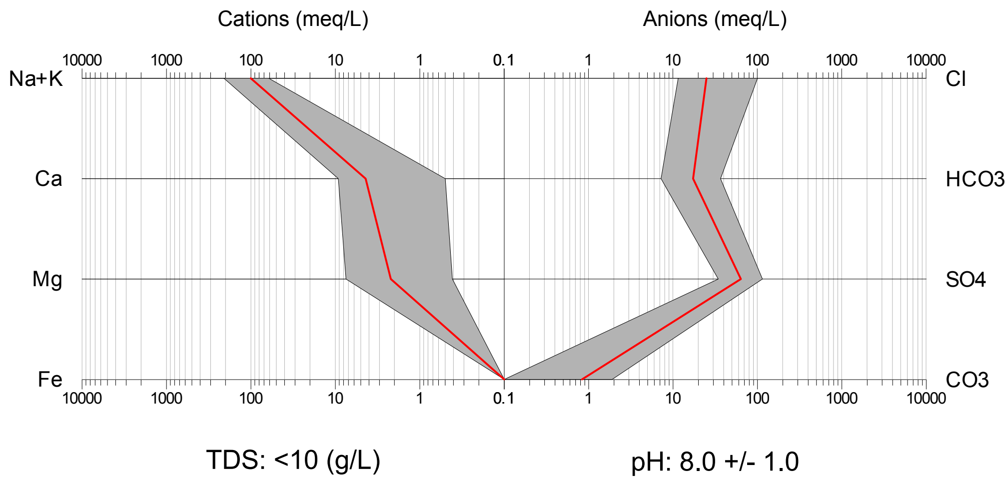

Figure B.8c Stiff diagram of the **Shaunavon** ***Na-SO₄*** type water.

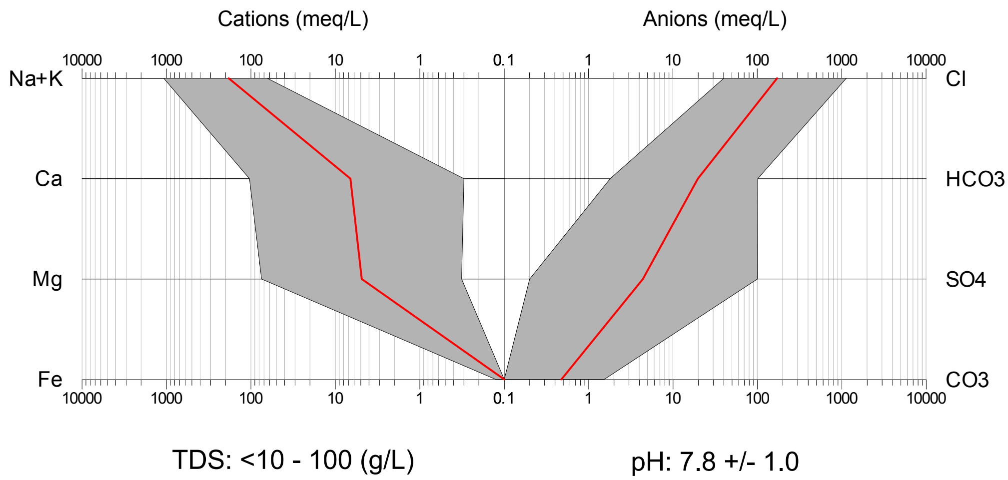

Figure B.9a Stiff diagram of the **Lower Mannville** ***Na-Cl*** type water.

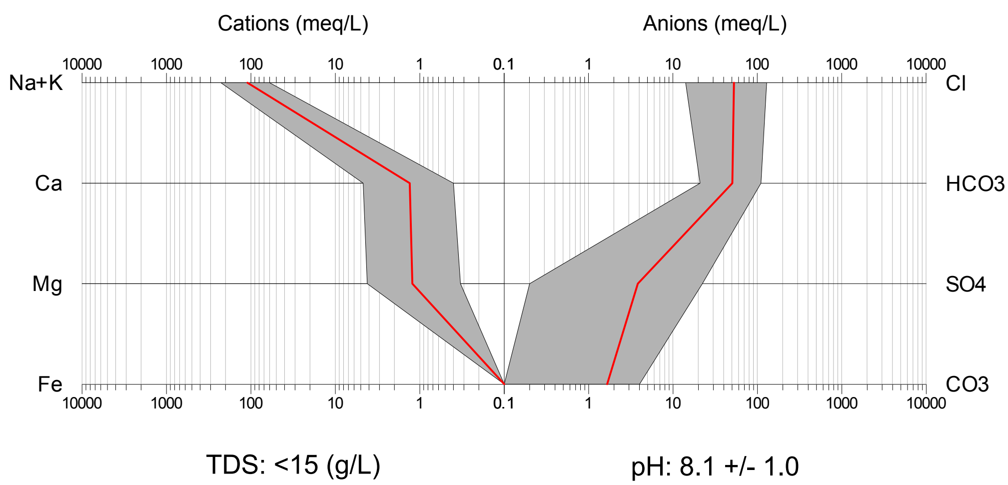

Figure B.9b Stiff diagram of the **Lower Mannville** ***Na-HCO$_3$*** type water.

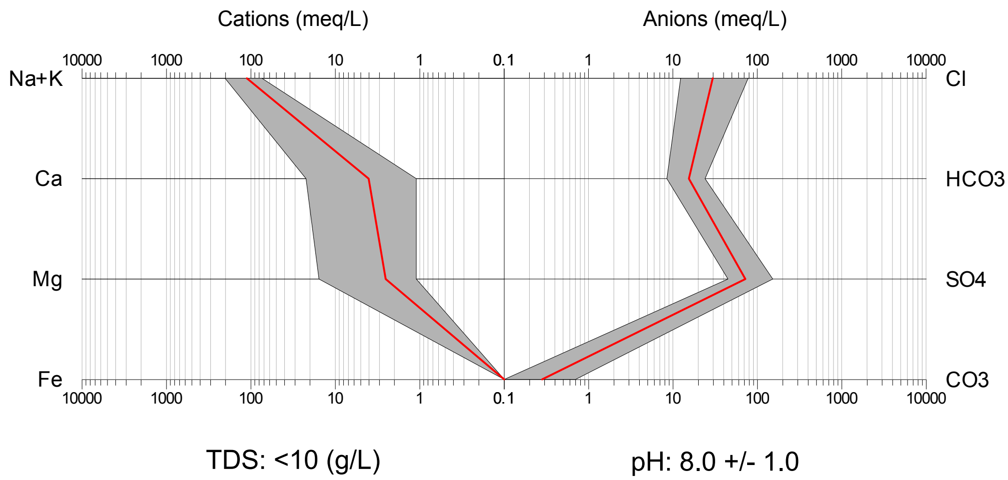

Figure B.9c Stiff diagram of the **Lower Mannville** ***Na-SO$_4$*** type water.

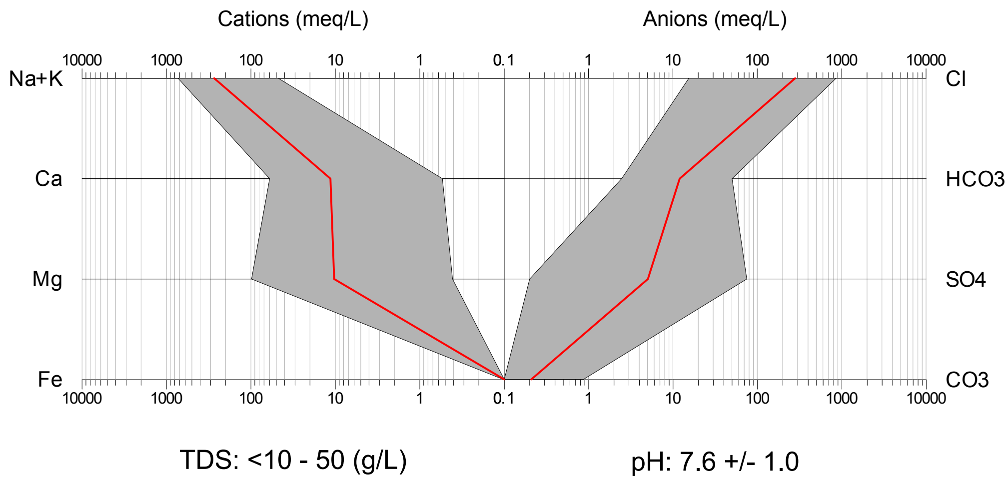

Figure B.10 Stiff diagram of the **Upper Mannville** ***Na-Cl*** type water.

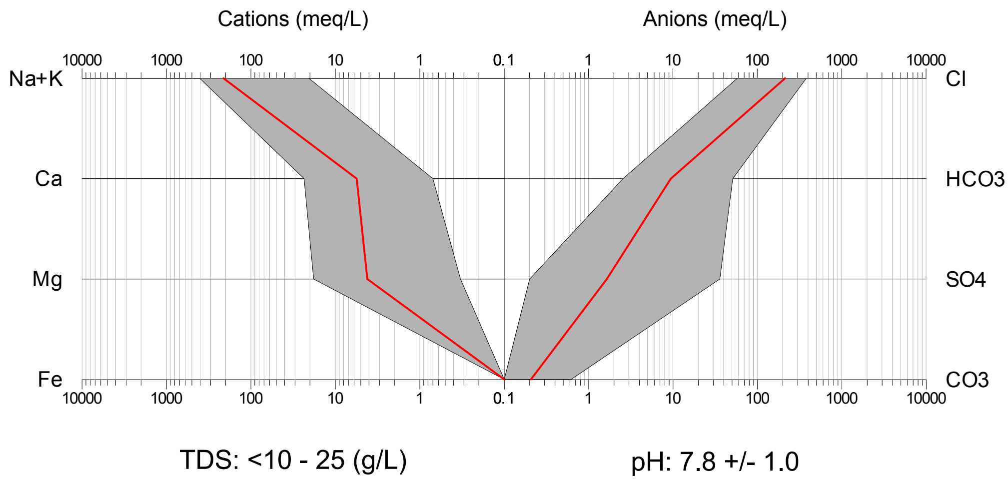

Figure B.11 Stiff diagram of the **Viking** ***Na-Cl*** type water.

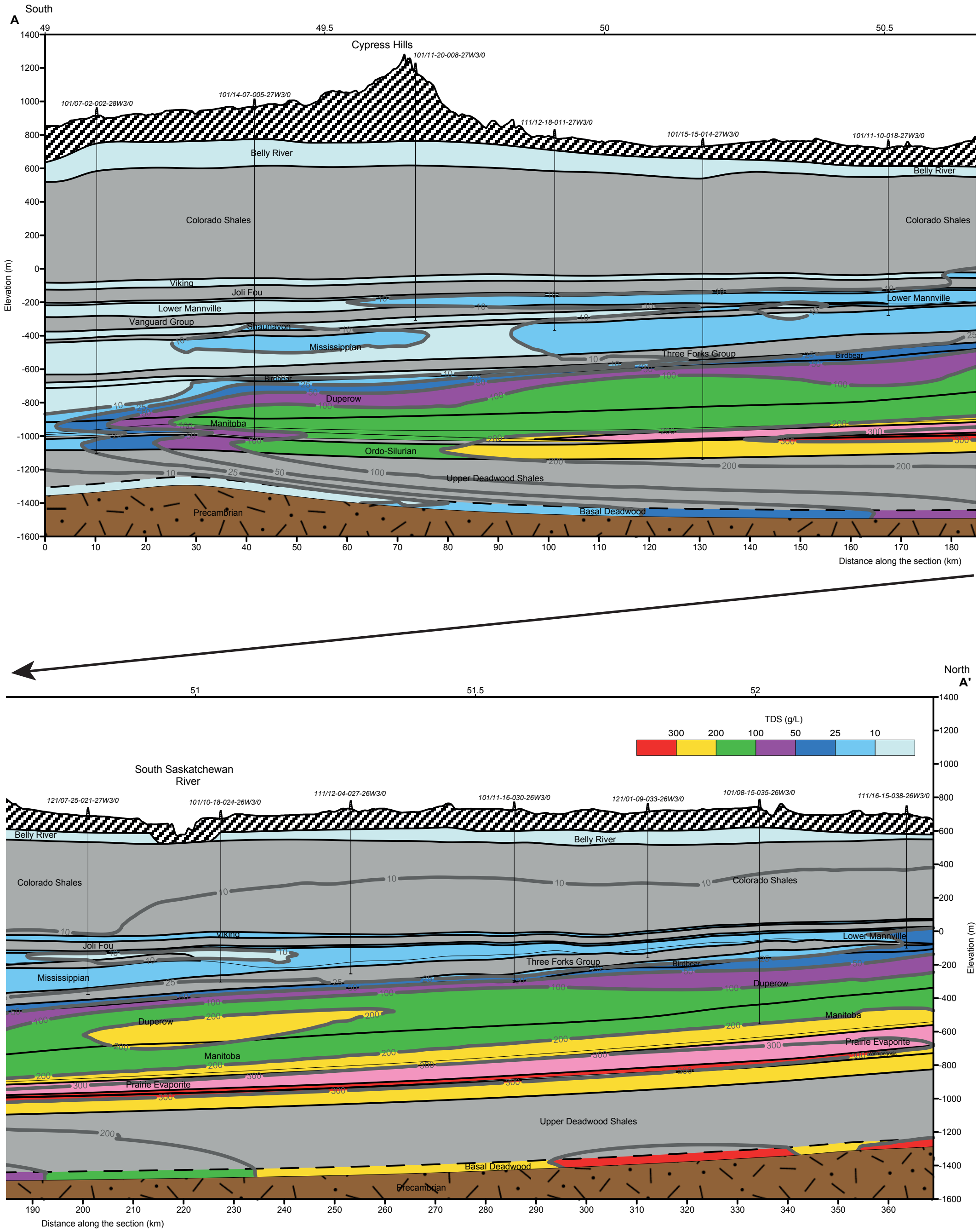

Figure C.1: TDS Cross-Section A-A'

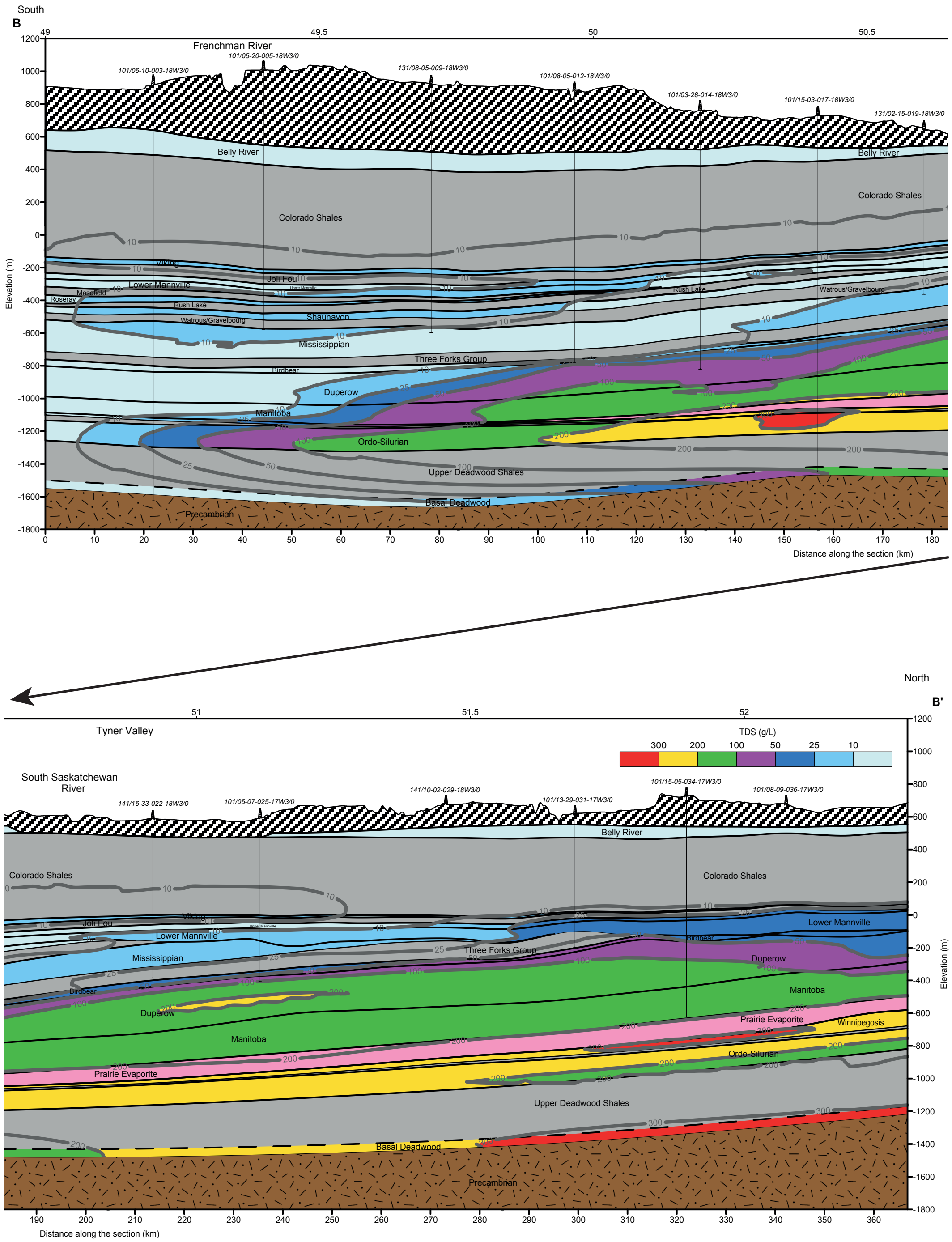

Figure C.2: TDS Cross-Section B-B'

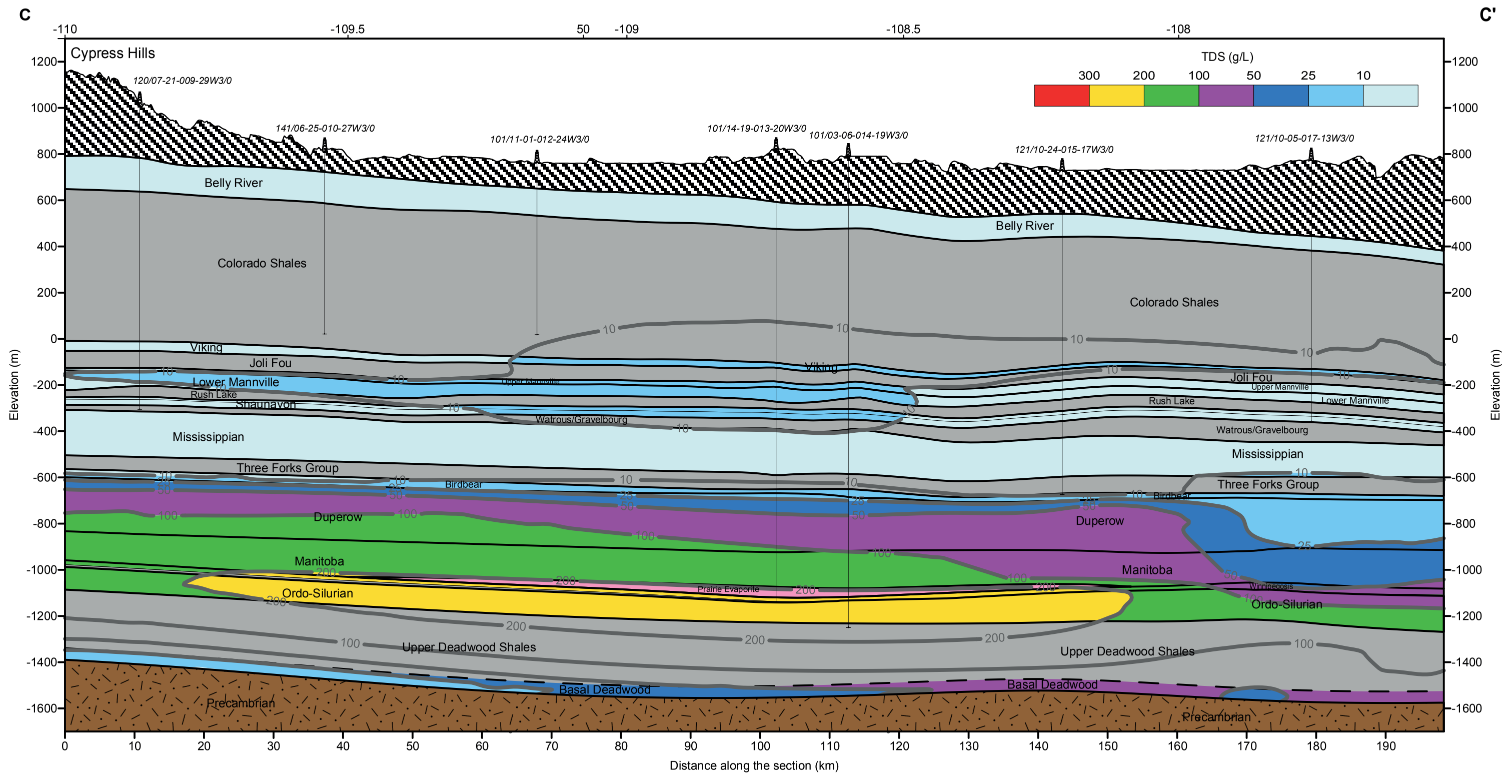

Figure C.3: TDS Cross-Section C-C'.

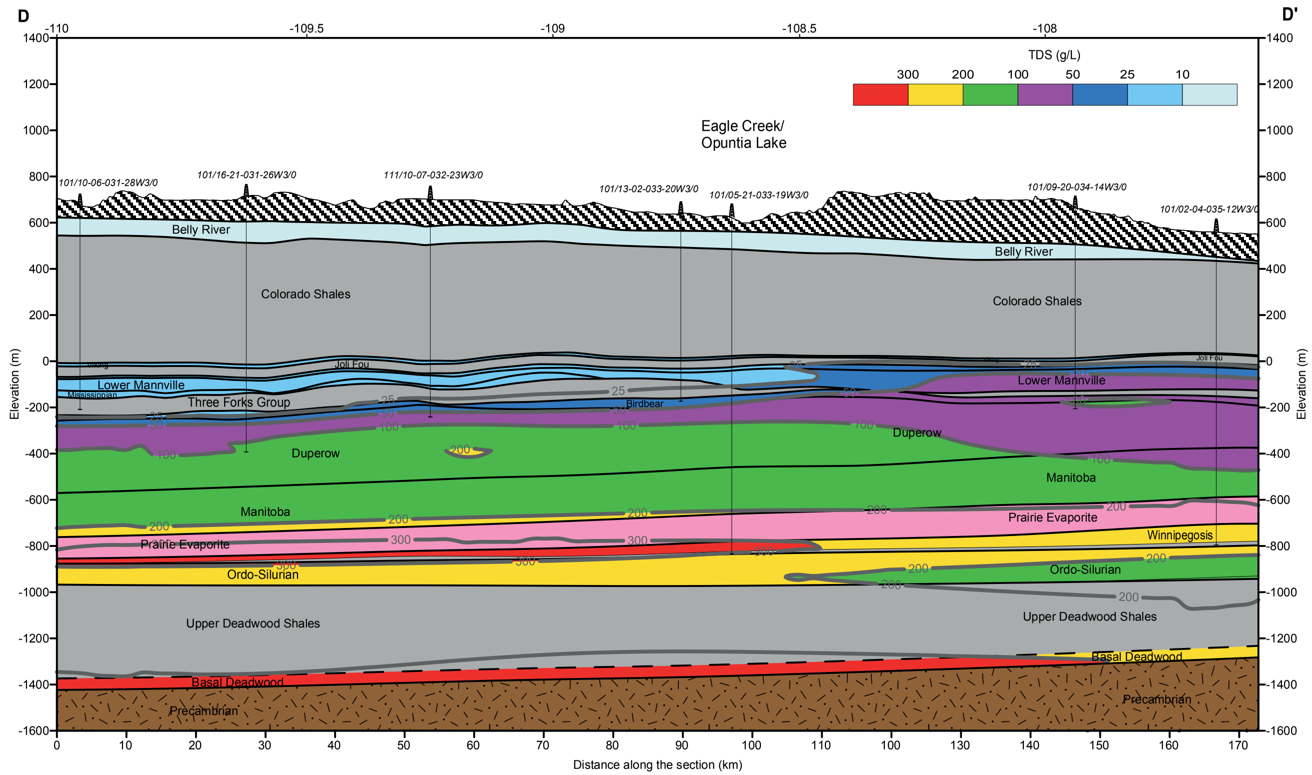

Figure C.4: TDS Cross-Section D-D'.

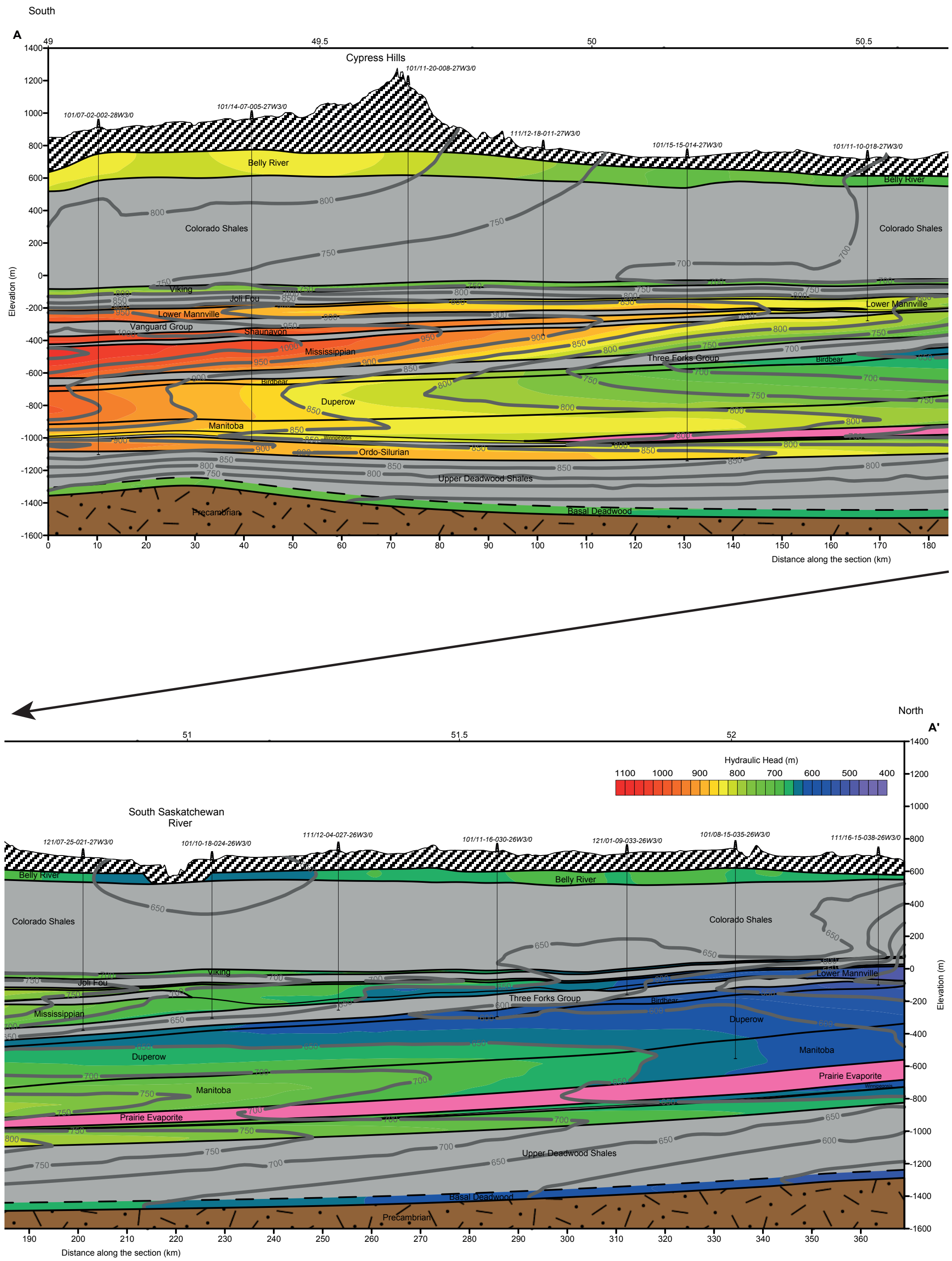

Figure C.5: Hydraulic Cross-Section A-A'

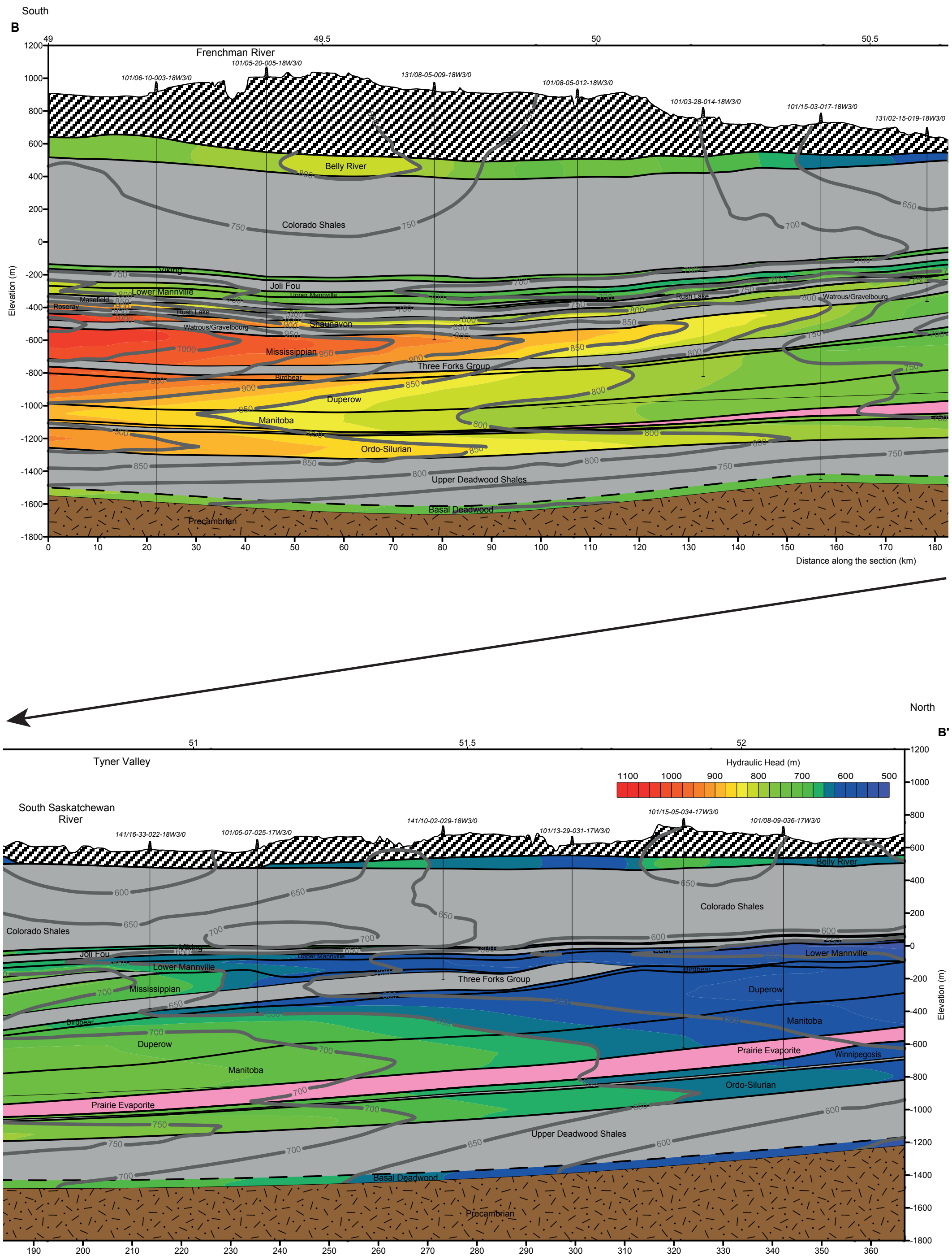

Figure C.6: Hydraulic Cross-Section B-B'

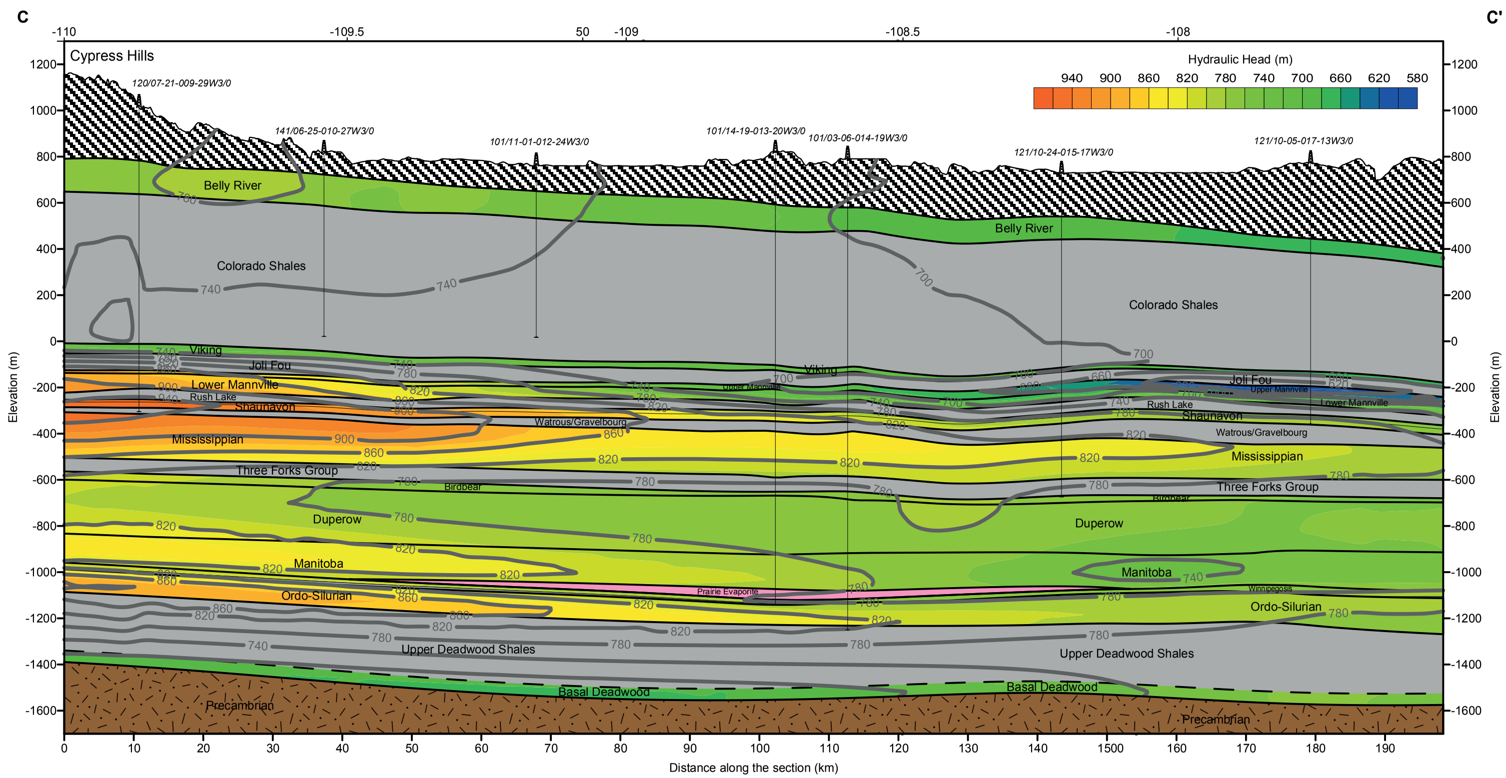

Figure C.7: Hydraulic Cross-Section C-C'.

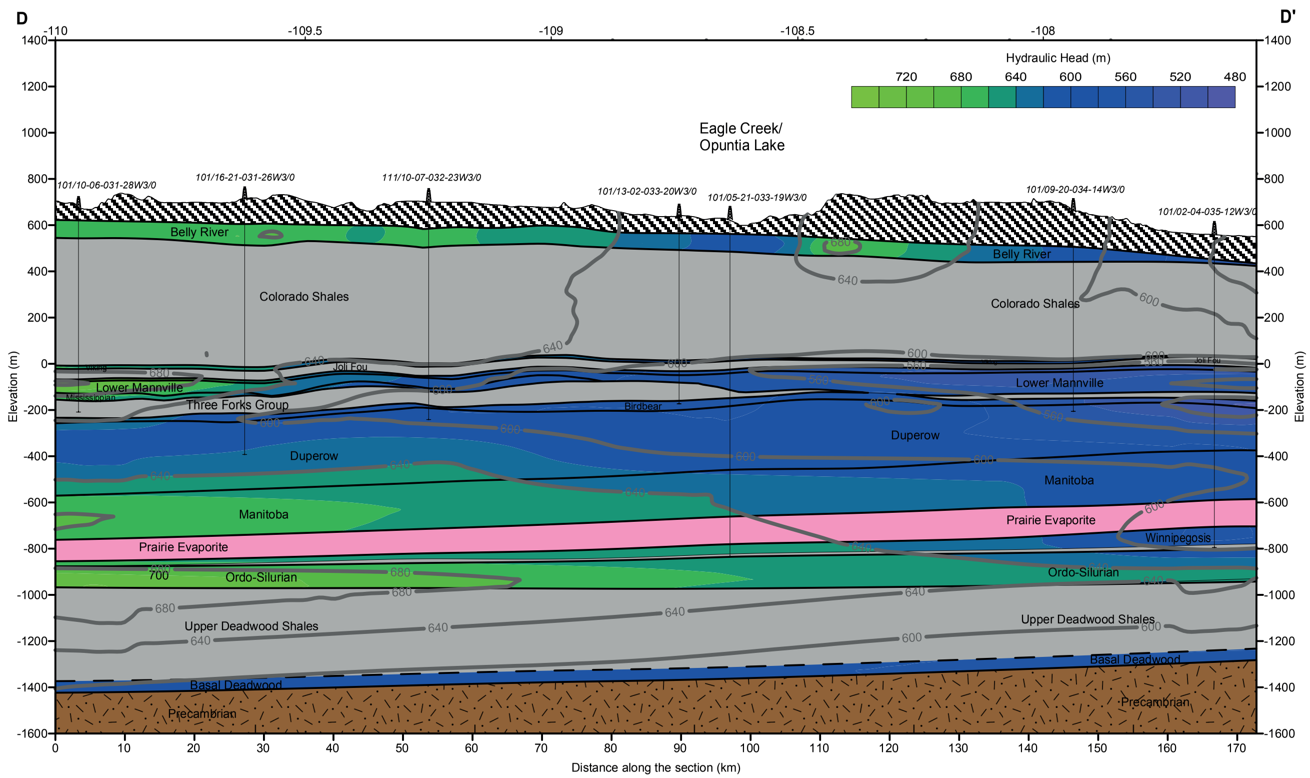

Figure C.8: Hydraulic Cross-Section D-D'.