Regional Hydrochemistry of Lower Paleozoic Aquifers in the Northern Portion of the Williston Basin, Saskatchewan–Manitoba

Dan Palombi[1] *and Ben Rostron*[1]

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Abstract

The Williston Basin hosts an active groundwater flow system and its formation waters record processes and events occurring throughout the evolution of the sedimentary basin. Delineating and understanding the hydrochemistry of the basin is, therefore, fundamental to characterizing the composition, classification, and distribution of subsurface waters. Previous regional hydrochemical studies in the Williston Basin generally were not integrated across political boundaries and used a less refined geological framework than currently available. This work presents a revised analysis of the Canadian sector of the basin incorporating hydrochemical data from subsurface to outcrop.

As part of a Canada-Saskatchewan-Manitoba Targeted Geoscience Initiative (TGI-2) project, a detailed, systematic geological characterization of the northern portion of the Williston Basin has been undertaken. The resulting geological framework aided development of a refined Lower Paleozoic hydrostratigraphic section that comprises eight major aquifers and several intervening aquitards. Detailed mapping of water chemistry has been conducted on aquifers ranging in age from Cambrian to uppermost Devonian. Mapped formation-water salinities range from 2 to 471 g/L and indicate that significant density and compositional variations occur between formations and across the area. Four distinct formation-water compositions are identified on the basis of major ion chemistry: 1) $Ca\text{-}SO_4$ *fresh waters, 2)* $Na\text{-}SO_4$ *brackish waters, 3) Na-Cl brines, and 4) Ca-Cl brines. Formation-water classification and mapped water chemistry has led to increased understanding of lateral hydraulic continuity, compositional variations across and within the Lower Paleozoic strata, and provided new insights into Pleistocene subglacial recharge along the Paleozoic outcrop edge. Cross-formational flow associated with the salt-dissolution edge of the Prairie Evaporite Formation has resulted in dissolution features within Devonian formations*

The integrated study spanning eastern Saskatchewan and western Manitoba has provided the opportunity to analyze the regional hydrogeological flow system in the discharge zone of the basin and its signatures in response to major basin events. Mapping and characterizing formation-water chemistry through the Lower Paleozoic section within Canada will provide new insights into salt-dissolution features, saline-spring geochemistry, and mixing processes. These hydrogeological results are assisting with new understanding of the paleohydrogeology in the northern portion of the Williston Basin.

Keywords: Saskatchewan, Manitoba, Williston Basin, regional hydrogeology, hydrochemistry, Paleozoic, Devonian, Targeted Geoscience Initiative (TGI), water chemistry, salt dissolution.

1. Introduction

A diverse range of hydrogeologically influenced economic resources such as water, minerals, and hydrocarbons is present within the sediments of the Williston Basin and a clear understanding of regional hydrogeological and hydrochemical processes is essential to accessing and exploiting these resources (Rostron *et al*., 2002). Comparing hydrochemical distributions of subsurface waters is fundamental to hydrogeological mapping for delineating patterns of regional flow (Back, 1961; Tóth, 1984).

Previous studies of regional groundwater flow in the Williston Basin have focused on the American side of the basin primarily for water supply assessments by the United States Geological Survey (*e.g*., Downey, 1982; Neuzil *et al*., 1982; Bredehoft *et al*., 1983; Downey *et al*. 1987; Downey and Dinwoodie, 1988; LeFever, 1998; DeMis, 1995). Regional hydrogeological mapping has been presented, albeit on a limited set of aquifers, for the Canadian side of the basin by Hannon (1987), and Bachu and Hitchon (1996). Betcher *et al*. (1995) have conducted groundwater studies in Manitoba discussed in terms of occurrence, groundwater availability, yield, and quality, mainly for domestic and industrial supply in Manitoba. Grasby (2000) sampled saline-spring waters along the western shore of Lake Winnipegosis and suggested that Pleistocene glaciation had a significant impact on the

[1] Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, AB T6G 2E3;
E-mails: palombi@gmail.com and rostron@darcy.eas.ualberta.ca

regional flow system of Paleozoic aquifers in the area. Khan and Rostron (2004) have completed detailed cross-border regional hydrogeological mapping studies between the Canadian and American sides of the basin, whereas the regional basin-wide hydrochemistry studies of Cambrian to Devonian aquifers has been conducted by Benn and Rostron (1998).

Considerable amounts of recent data have become available as a result of deep drilling for petroleum exploration (Haidl *et al*., 1996) that were not included in previous hydrochemical and hydrogeological studies in the Williston Basin. In addition, most previous studies did not have the hydrostratigraphic detail now available. For example, the majority of groundwater studies in Manitoba have used a broad stratigraphic subdivision comprising Middle Ordovician to Silurian and Middle Devonian to Mississippian strata (the Carbonate Rock Aquifer of Grasby and Betcher, 2002), and increased hydrostratigraphic resolution is required to better delineate the patterns and distributions of formation waters for regional studies. Thus, Saskatchewan Industry and Resources (SIR), Industry Economic Development and Mines (IEDM) of Manitoba, Natural Resources Canada (NRCan), and the Universities of Alberta and Saskatchewan have embarked on “The Williston Basin Architecture and Hydrocarbon Potential Project” (Kreis *et al.,* 2004). As part of NRCan’s second round of Targeted Geoscience Initiatives (TGI-2), this project will build upon successful geoscience-framework studies carried out within the International Energy Agency (IEA) Weyburn CO_2 Monitoring and Storage Project (Gilboy *et al*., 2001; Whittaker *et al*., 2002; Whittaker and Gilboy, 2003).

The purpose of this paper is to present preliminary results of the detailed hydrochemical mapping completed across the TGI-2 study area using newly updated geological mapping and revised data compilations for the aquifer units. The level of stratigraphic detail available to this study provides a basis by which Paleozoic outcrop data can be integrated with the subsurface regime to give insights into the subglacial recharge effects and manifestations remaining in the basin.

2. Study Area

The TGI-2 project study area encompasses the IEA GHG Weyburn CO_2 Monitoring and Storage Project area in Canada, extending it to longitude 96ºW in the east, longitude 106ºW in the west and, to the north and northeast, the edge of the Phanerozoic cover (Figure 1). While not encompassing the basin depocentre, the study area captures most of the Phanerozoic succession present in Saskatchewan and Manitoba. Hydrogeologically, this area is limited to previous extensive studies and proves favourable for analyzing the discharge site of the Williston Basin.

a) Hydrostratigraphy

The generation of a hydrostratigraphic column incorporates detailed stratigraphic data and requires identification of hydraulically similar flow units that are relatively transmissive (aquifers) *versus* those of relatively low permeability (aquitards). The classification of a stratum or a group of strata as either an aquifer or an aquitard is based largely on the purpose of study and the timescales of the processes under consideration (Tóth, 1995). A hydrostratigraphic column consisting of 19 major aquifers and 13 major aquitards was developed for the Weyburn CO_2 Project and this level of detail will be maintained in the TGI-2 project (Figure 2). The focus of this paper will be on the Lower Paleozoic aquifers; however, mapping yet to be completed of Mississippian and Mesozoic aquifers will also use this hydrostratigraphy.

b) Lower Paleozoic Aquifers

The hydrostratigraphic subdivision used for the Lower Paleozoic follows that devised by Benn and Rostron (1998), and used in subsequent studies by Iampen and Rostron (2000), Rostron and Holmden (2003), and Khan (2006). Eight major aquifers have been mapped within what have been previously considered thick confining aquitards (Downey, 1984a and b, 1986; Downey *et al*., 1987; Busby *et al*., 1995), undifferentiated aquifer systems (Bachu and Hitchon, 1996), and the carbonate rock aquifer (Grasby and Betcher, 2002). This hydrostratigraphic grouping has many intervening aquitards of variable composition ranging from the Winnipeg Aquitard comprising marine shales and siltstones, to the thick salt of the Prairie Evaporite Formation that is one of the most effective aquitards in the basin. For a more detailed geological description of the hydrostratigraphic section refer to Whittaker *et al*. (2004) and the basis for the hydrostratigraphic subdivision is explained further in Benn and Rostron (1998).

c) Data And Methodologies

A hydrogeological database of over 2100 formation-water analyses was assembled for the Lower Paleozoic strata from a combination of public and private data sources. The geologists at Saskatchewan Industry and Resources and Industry Economic Development and Mines of Manitoba mapped the stratigraphic surfaces for the TGI-2 project (Kreis *et al*., 2004) and made them available for this hydrogeological study. The geological framework developed within the TGI-2 project was used to generate structural grids of each stratigraphic horizon. Having the tops and bases of water sample intervals and the stratigraphic surfaces defining the aquifers, it was possible to quantify the exact sample location and thus assign every sample into its respective aquifer unit (Khan, 2006).

Procedures to select only representative formation-water samples were roughly based on data culling criteria set forth in previous studies (Hitchon and Brulotte, 1994). Khan (2006) modified these standard procedures to accommodate Williston Basin waters

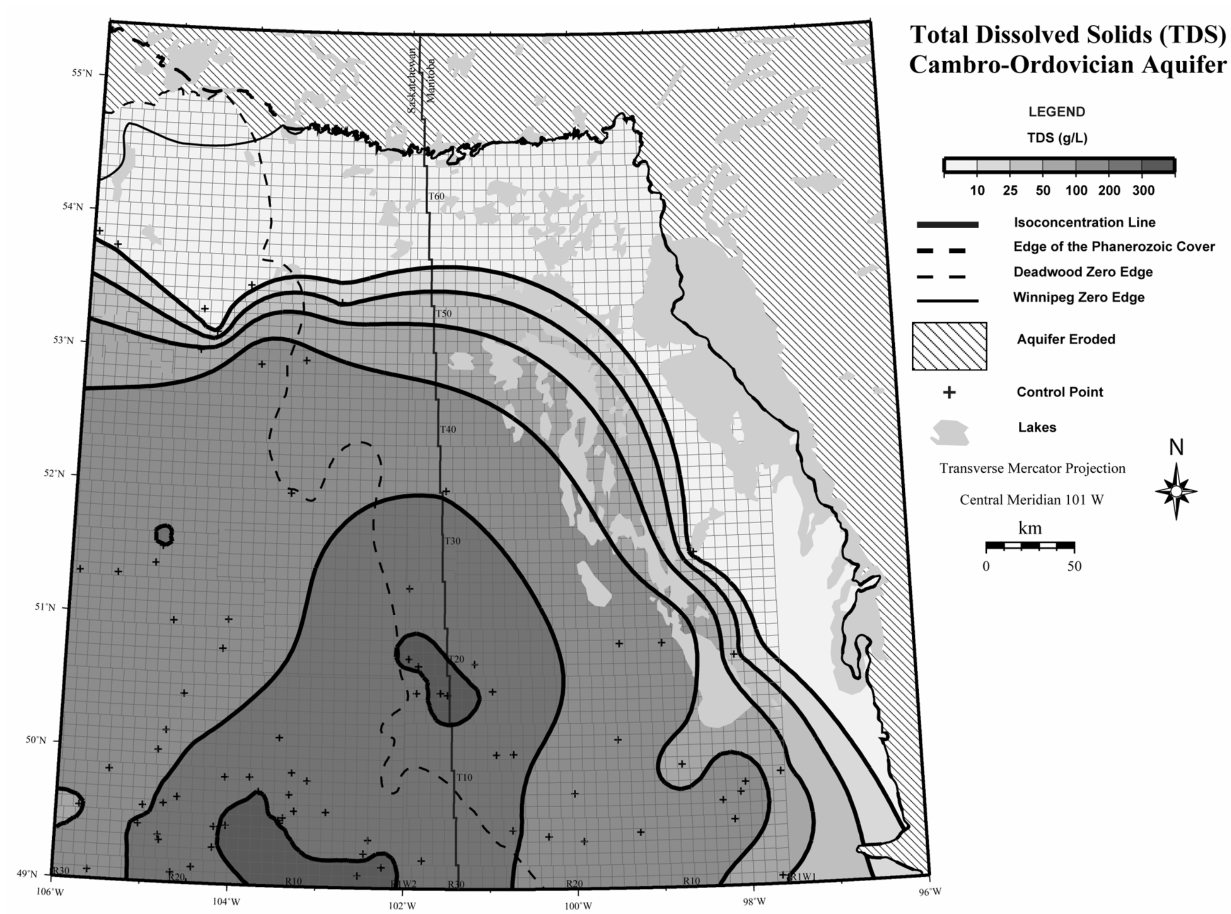

Figure 1 - Total Dissolved Solids in the Cambro-Ordovician Aquifer with formation edges shown for the Deadwood and Winnipeg formations. The TGI-2 project area in Saskatchewan and Manitoba is shown bounded by the edge of Phanerozoic cover.

that are compositionally different than Alberta Basin waters. Differences in fresh Ca-Na-SO_4 waters having low Na/Ca and high Na/Cl ratios, and the presence of high K^+ contents in the Williston Basin can result in the culling of otherwise quality data (Khan, 2006). The data culling process is repetitive and largely manual due to the variability of formation waters present in the basin. Moreover this data culling procedure, albeit iterative, produces the best representation of the hydrochemical composition, classification, and distribution of subsurface waters in the basin.

3. Results

The hydrochemistry of each aquifer unit in the Lower Paleozoic was analyzed using maps of Total Dissolved Solids (TDS), individual ions (in particular SO_4^{2-} and HCO_3^-), and the cationic fraction of Ca^{2+}. For the purposes of this paper only a selected set of aquifer units will be shown that identify both compositional variations and varying distributions within and across the Lower Paleozoic system, as well as a sample of the hydrogeological mapping and analyses that will be completed for the entire stratigraphic section.

a) Total Dissolved Solids

TDS in formation waters within the Lower Paleozoic of the study area range from from 2 to 471 g/L, and include fresh waters (< 5 g/L) and brines (>100 g/L; Carpenter, 1978). The variable contour interval chosen to map TDS is set to illustrate significant changes in composition across the isoconcentration lines (Figure 1). All of the Lower Paleozoic aquifers exhibit a fresh-water signature in the west with salinity increasing gradationally towards the basin centre. North and northeast toward the edge of Phanerozoic cover, the salinity systematically decreases to compositions characteristic of fresh water with the exception of the Ordo-Silurian, Winnipegosis, and Birdbear aquifers. The geochemical gradient in many cases is steep, and fresh-water incursion zones prevalent to the west, north and northeast of the study area are not necessarily of the same origin.

Cambro-Ordovician Aquifer

The TDS map for the basal Cambro-Ordovician Aquifer comprises 82 data points (Figure 1). Values range from 3 g/L in northern Saskatchewan to 347 g/L in eastern Saskatchewan adjacent to the interprovincial border with Manitoba. Regions of high TDS (> 300 g/L) mark the centre of the TGI-2 study area just north of the basin centre beneath North Dakota. Another region of high TDS straddles the Saskatchewan–Manitoba border around Township 20, and coincides with the zero edge of the Deadwood Formation and a potash mine location. The map shows a systematic trend of decreasing TDS from the centre of the study area toward the zero edge of the Cambro-Ordovician Aquifer. Three localized areas having low TDS are noted on this map located in the west, north, and northeast. The low feature in the west, supported by only one data point, honours a fresh-water incursion tongue present to the west of the study area depicted in Benn and Rostron (1998). The remaining two fresh-water signatures present to the north and northeast are relatively close to the aquifer zero edge and are part of a large geochemical gradient existing on the flank of the basin.

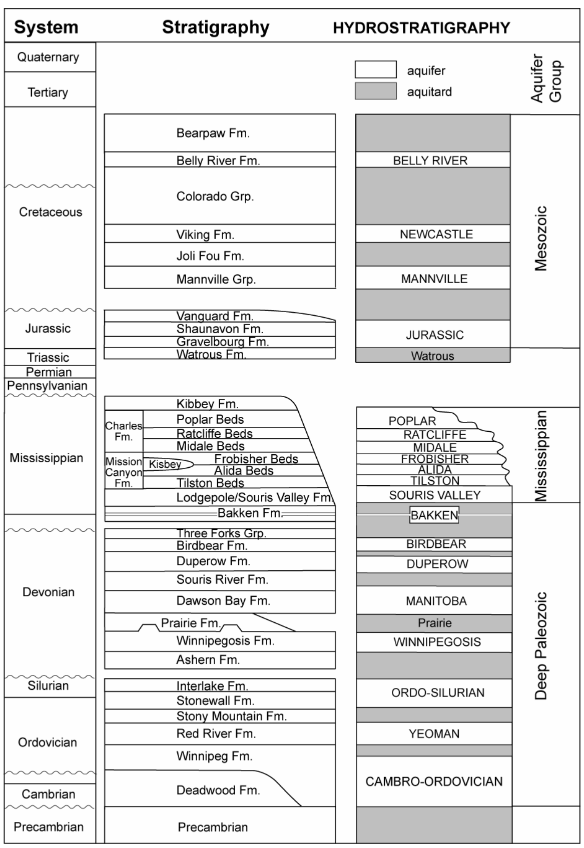

Figure 2 - Williston Basin stratigraphy and hydrostratigraphic framework adopted for the Weyburn Project geological model (Whittaker et al., 2004).

Winnipegosis Aquifer

The Lower Devonian Winnipegosis Aquifer is unique because the Prairie Evaporite Formation caps it where dissolution of the evaporite has not occurred. A total of 117 points were retained after culling, and some new features in comparison to the Cambro-Ordovician Aquifer are observed (Figure 3). The variation in TDS is similar to that of the Cambro-Ordovician Aquifer, ranging from 5 g/L located in the far north of Saskatchewan to 338 g/L near the centre of the study area. The region of brine with TDS greater than 300 g/L is larger than that of any of the underlying units, but does not extend as far north as in the Cambro-Ordovician Aquifer. The distribution of brine >200 g/L is significantly different, spanning much greater distances across the study area than the Cambro-Ordovician. Also of interest in the Winnipegosis Aquifer is the presence of the fresh-water incursion zones. The TDS-low observed in the west in the Cambro-Ordovician Aquifer is more prevalent in the Winnipegosis Aquifer, and seemingly influences the higher TDS composition present across much of Saskatchewan. Fresher waters are observed also along the northern flank of the basin as far north as Township 30. Updated subsurface maps of the geological formations have proven to be fundamental because, as observed within this aquifer, the dissolution edge of the Prairie Evaporite Formation coincides very closely with tongues of low TDS.

Manitoba Aquifer

Comprising the Dawson Bay and Souris River formations, the Manitoba Aquifer contains 72 sample points with TDS ranging from 5 to 330 g/L, similar to the ranges of the other hydraulic units mapped (Figure 4). This unit is situated above the Prairie Aquitard, and displays general patterns of hydrochemical distribution similar to those in the underlying aquifers. The areas of high TDS brines in southern Saskatchewan found in the lower aquifers are not as prominent, but formation waters of greater than 200 g/L have increased in distribution and occur as far north as 52.5ºN latitude. The fresher water incursion from the west is larger and more prominent with brackish waters spanning toward 51ºN. In Manitoba, there is further brackish saline intrusion along the northeastern flank of the basin. In the Winnipegosis Aquifer, this TDS low corresponds to the dissolution edge of the Prairie Evaporite and was oriented N-S, whereas in the Manitoba Aquifer there is a strong SW-NE trend (mildly depicted in the Cambro-Ordovician Aquifer) that extends south to around Township10, Range 22W1. Moreover, on the northeastern margin, the chemical gradient appears to diminish and the lower fresh- to saline-gradient trends NW-SE. Lastly in the Manitoba Aquifer, the Davidson Member Salt is present as outlined on the TDS map. The salt bed correlates closely with >200 g/L saline waters in central Saskatchewan. In addition, dissolution of the Davidson Member Salt correlates very closely with the fresh-water tongue encroaching from the west starting around Township17, Range 29W2.

Birdbear Aquifer

The Birdbear Aquifer contains a large quantity of data (192 samples) compared to the other Lower Paleozoic aquifers with TDS ranging from 4 to 301 g/L. Overall

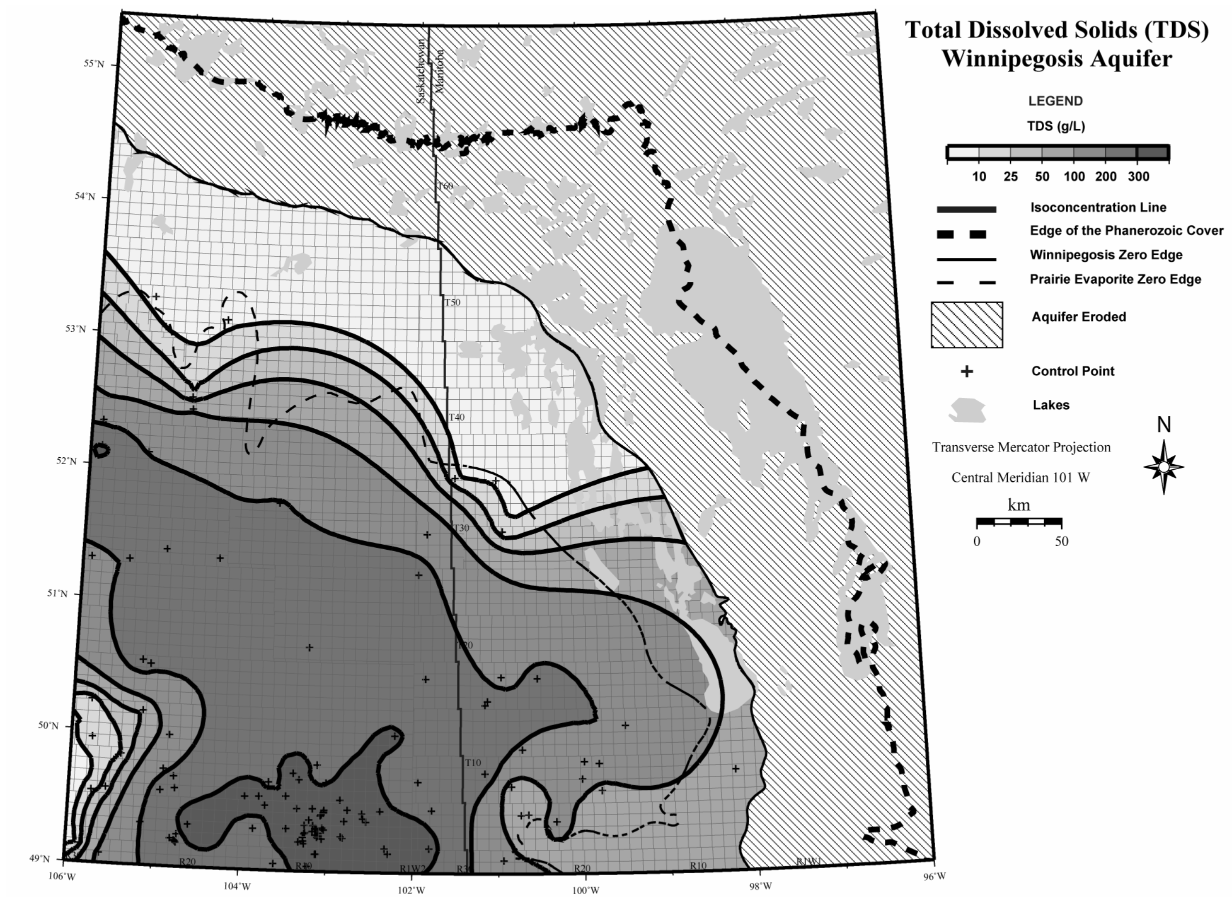

Figure 3 - Total Dissolved Solids in the Winnipegosis Aquifer. Note the Prairie Evaporite dissolution edge coincident with zones of low TDS.

TDS decreases upward in the Lower Paleozoic and this pattern remains consistent in the Birdbear Aquifer, as high TDS brine is absent within the study area. Where formation waters mapped in the Manitoba Aquifer were generally >200 g/L, within the Birdbear Aquifer formation waters in this same geographic area are from 50 to 100 g/L. Migration of the >100 g/L waters is eastward with only an outlier of brackish water remaining. Congruently, the western fresh-water tongue has become increasingly larger and encroaches toward the centre of the study area. Also notable is that the fresh-water incursion from the northeast is no longer present in the Birdbear Aquifer.

4. Discussion

The Lower Paleozoic aquifers generally show consistent patterns of TDS observed within the study area. First, in the west, there is a systematic increase in the total area occupied by the fresh waters (Figures 1, 3, 4, 5). In the Manitoba Aquifer this incursion zone corresponds with the dissolution edge of the Davidson Member Salt. Secondly, a transition zone marked by brackish waters (25 to 100 g/L) separate significantly different water chemistries. This possible mixing zone was previously referred to as having a high geochemical gradient and its configuration changes across the Lower Paleozoic units analyzed. Whether this edge of hydrodynamic mixing that occurs throughout the study area is of glacial recharge influence, supported by dissolution features and isotopic analyses (Grasby and Chen, 2005), or a discharge effect from an evolving basin configuration remains to be determined.

Despite the generally consistent patterns of TDS distribution in the Lower Paleozoic aquifers, the new detailed stratigraphic subdivision has proven to be of importance. When comparing the basal, siliciclastic Cambro-Ordovician Aquifer to the carbonate Devonian Winnipegosis Aquifer, it is obvious the two units are significantly different in both composition and distribution across the study area. Examining the aquifers above the Prairie Evaporite Formation, the Manitoba and Birdbear aquifers, supports the rationale behind the specific subdivisions chosen in this study. The Manitoba Aquifer has relatively similar overall TDS distribution to that of the Winnipegosis Aquifer, although when mapping the two aquifers independently, the coincidence between the dissolution edge of the Prairie and localized zones of low TDS is now evident. The Birdbear Aquifer is entirely

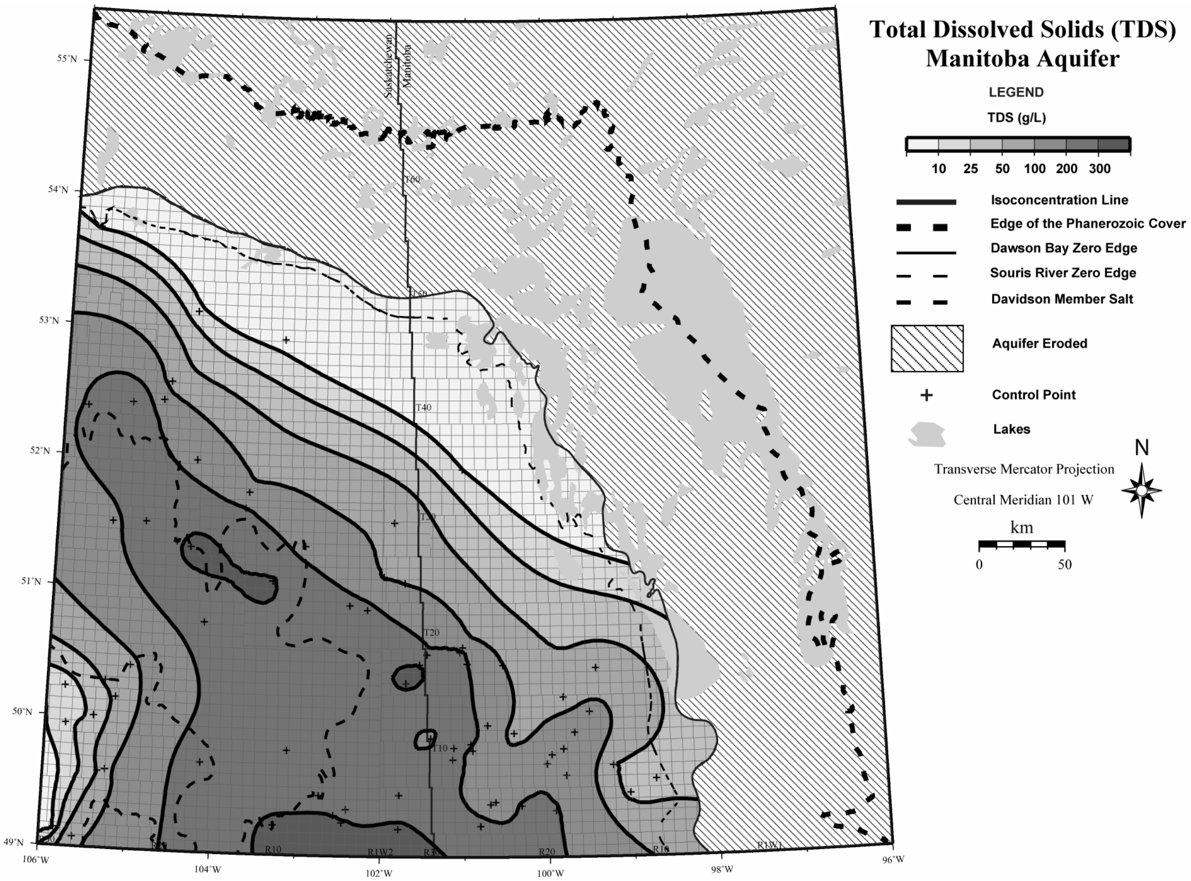

Figure 4 - Total Dissolved Solids in the Manitoba Aquifer. Note the Davidson Member Salt-dissolution edge relative to TDS distribution.

different in composition and distribution of TDS relative to all underlying aquifers.

Formation-water compositions are consistent with those reported by Benn and Rostron (1998) and Khan (2006) that were identified on the basis of major ion chemistry. Four distinct formation-water compositions are identified: 1) Ca-SO_4 fresh waters, 2) Na-SO_4 brackish waters, 3) Na-Cl brines, and 4) Ca-Cl brines. The Na-SO_4 brackish waters are interpreted as a mixing product of Ca-SO_4 fresh waters and Na-Cl brines. For the detailed major ion chemistry refer to Benn and Rostron (1998) and Khan (2006).

5. Conclusions

This paper summarizes preliminary results of the hydrochemical data compiled as part of the hydrogeological characterization of the TGI-2 project area. TDS maps have been generated illustrating not only the level of detail undertaken in the TGI-2 project, but also the hydrostratigraphic framework necessary for detailed regional investigations of the Williston Basin. The improved geological resolution is providing a foundation on which the integration of subsurface to outcrop can now be completed. The hydrostratigraphic subdivisions previously used can be further subdivided to provide the resolution required to investigate the relation of hydrogeological signatures to major basin events. Preliminary mapping has indicated that the framework used for the IEA Weyburn CO_2 Monitoring and Storage Project is thorough and identifies features that would otherwise be masked by coarse hydrostratigraphic divisions. Mapping and characterizing the formation-water chemistry through the Lower Paleozoic section in Canada have shown new salt-dissolution features correlative with water chemistry, provided a basis for the influence of regional hydrodynamics on saline springs, and illustrated the lateral continuity present in the Lower Paleozoic strata. These hydrogeological results are assisting with new understanding of the paleohydrogeology in the northern portion of the Williston Basin.

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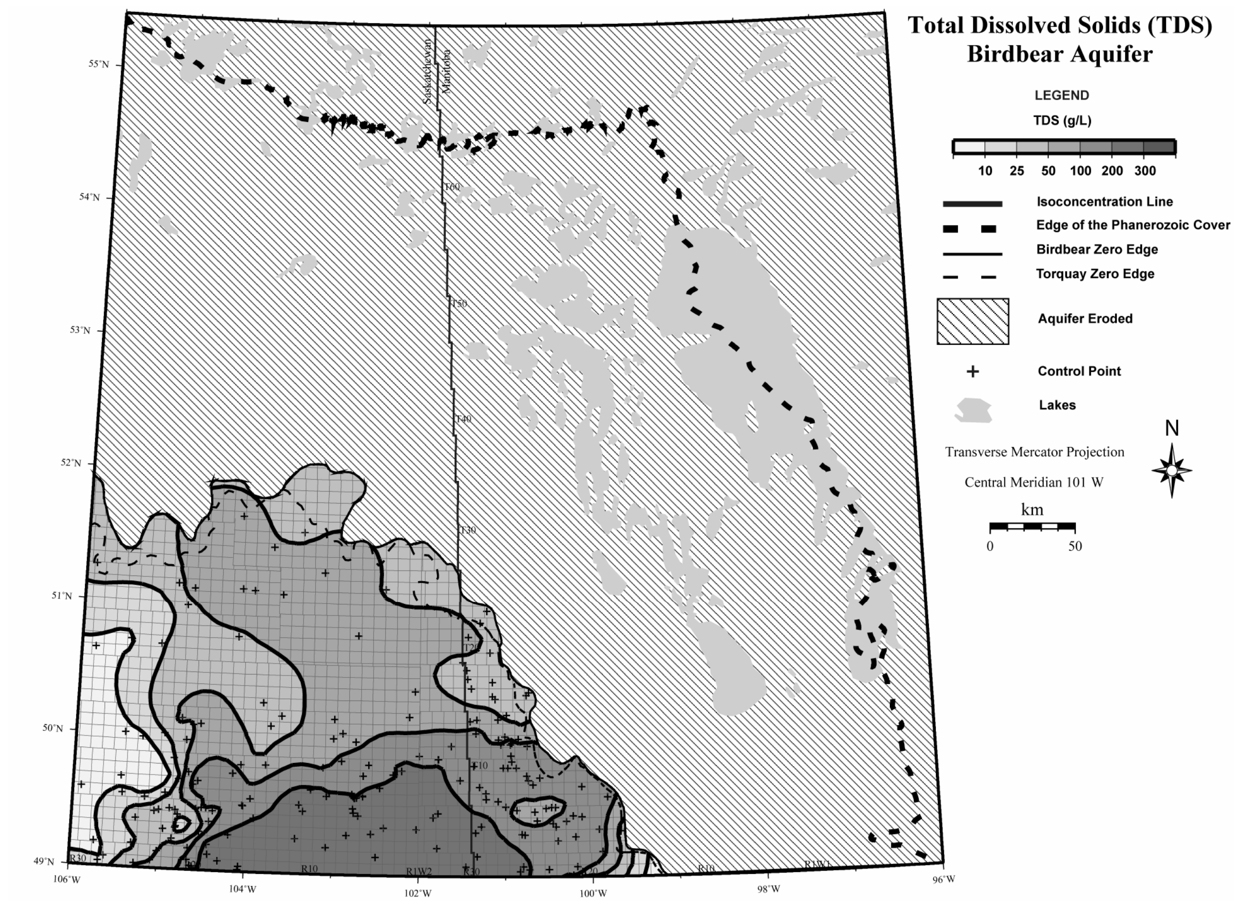

Figure 5 - Total Dissolved Solids in the Birdbear Aquifer.

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