

Regional hydrogeochemistry of the carbonate rock aquifer, southern Manitoba¹

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Abstract: Middle Ordovician to Middle Devonian carbonates in the Manitoba lowlands form an extensive aquifer system along the eastern edge of the Williston Basin. The aquifer is divided into fresh and saline portions by a series of topographic lows defined by major river systems and lakes that create a north–south-trending hydraulic divide. East of this divide Ca–Mg–HCO₃ fresh waters are derived by active modern-day recharge focused in the Sandilands and Interlake regions. Stable isotope and geochemical data indicate that Na–Cl saline waters west of the divide are a mixture of original basin brines and glacial melt water pushed into the basin during Pleistocene glaciation. High Na/Cl and Cl/Br ratios are consistent with significant salt dissolution by glacial melt water.

Résumé : Des carbonates datant de l'Ordovicien moyen au Dévonien moyen dans les basses terres du Manitoba forment un vaste système aquifère le long de la bordure est du bassin de Williston. L'aquifère est divisé en portions d'eau douce et d'eau salée par une série de creux topographiques définis par les grands systèmes de rivières et de lacs qui créent une ligne de partage des eaux à tendance nord–sud. À l'est de cette ligne de partage, les eaux douces Ca–Mg–HCO₃ proviennent de recharges actives contemporaines concentrées dans les régions de Sandilands et d'Interlake. Des données géochimiques et d'isotopes stables indiquent que les eaux salées Na–Cl à l'ouest de la ligne de partage sont un mélange des saumures du bassin original et de l'eau de fonte glaciaire qui a été poussée dans le bassin au cours de la glaciation au Pléistocène. Des rapports Na/Cl et Cl/Br élevés concordent avec une grande dissolution de sel par les eaux de fonte glaciaire.

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Introduction

The carbonate rock aquifer is the largest freshwater aquifer in Manitoba, stretching from north of The Pas southward through the Interlake region and continuing along the east side of the Red and Rat rivers into Minnesota (Fig. 1). West of this freshwater zone, the aquifer contains increasingly saline groundwaters, with brines occurring in the deeper parts of the aquifer in southwestern Manitoba. The freshwater portions of the aquifer are heavily utilized for municipal, industrial, agricultural, and residential water supply in the Interlake region and southeastern Manitoba, being the sole source of potable groundwater within extensive parts of this area. The aquifer also forms the major source of water supply to ring communities near the City of Winnipeg and is heavily utilized for heating and cooling systems within the city.

Due to the importance of the carbonate rock aquifer to Manitoba, we have initiated a comprehensive study to advance our understanding of the factors that govern the water supply

capacity, sensitivity to contamination, quality, and dynamics of this groundwater system. In this paper, we examine groundwater analyses from over 1100 wells to provide a regional overview of the hydrogeochemistry of the carbonate rock aquifer. We examine regional variations in water chemistry and the origins of waters in the aquifer.

The carbonate rock aquifer

The carbonate rock aquifer occurs along the eastern edge of the Williston Basin in southern and central Manitoba. It is formed by a series of gently west-dipping Middle Ordovician to Middle Devonian carbonates with minor shales and evaporites (Figs. 1, 2). The aquifer forms the lower portion of the carbonate–evaporite hydrostratigraphic unit of Simpson et al. (1987) (Fig. 2). Although termed a single aquifer here, it is recognized that the Paleozoic carbonate sequence should more properly be referred to as an aquifer system. The aquifer crops out along a northwest–southeast-trending zone, lying to the east and north of the Manitoba Escarpment (Figs. 1, 3), which marks the transition to overlying argillaceous Mesozoic and Cenozoic sediments that form a low-permeability cap over the aquifer. In the Manitoba lowlands, where Middle Ordovician to Upper Devonian carbonates crop out, the carbonate rock aquifer is generally considered a single hydrostratigraphic unit (Render 1970; Simpson et al. 1987; Betcher et al. 1995), although thin extensive argillaceous units do act as inter- or intra-formational aquitards. West of the Manitoba Escarpment, aquitards become more effective and restrict, to some degree, cross-formational flow, as evidenced by vertical variations in salinities observed in western Manitoba (Simpson et al. 1987) and stable isotope

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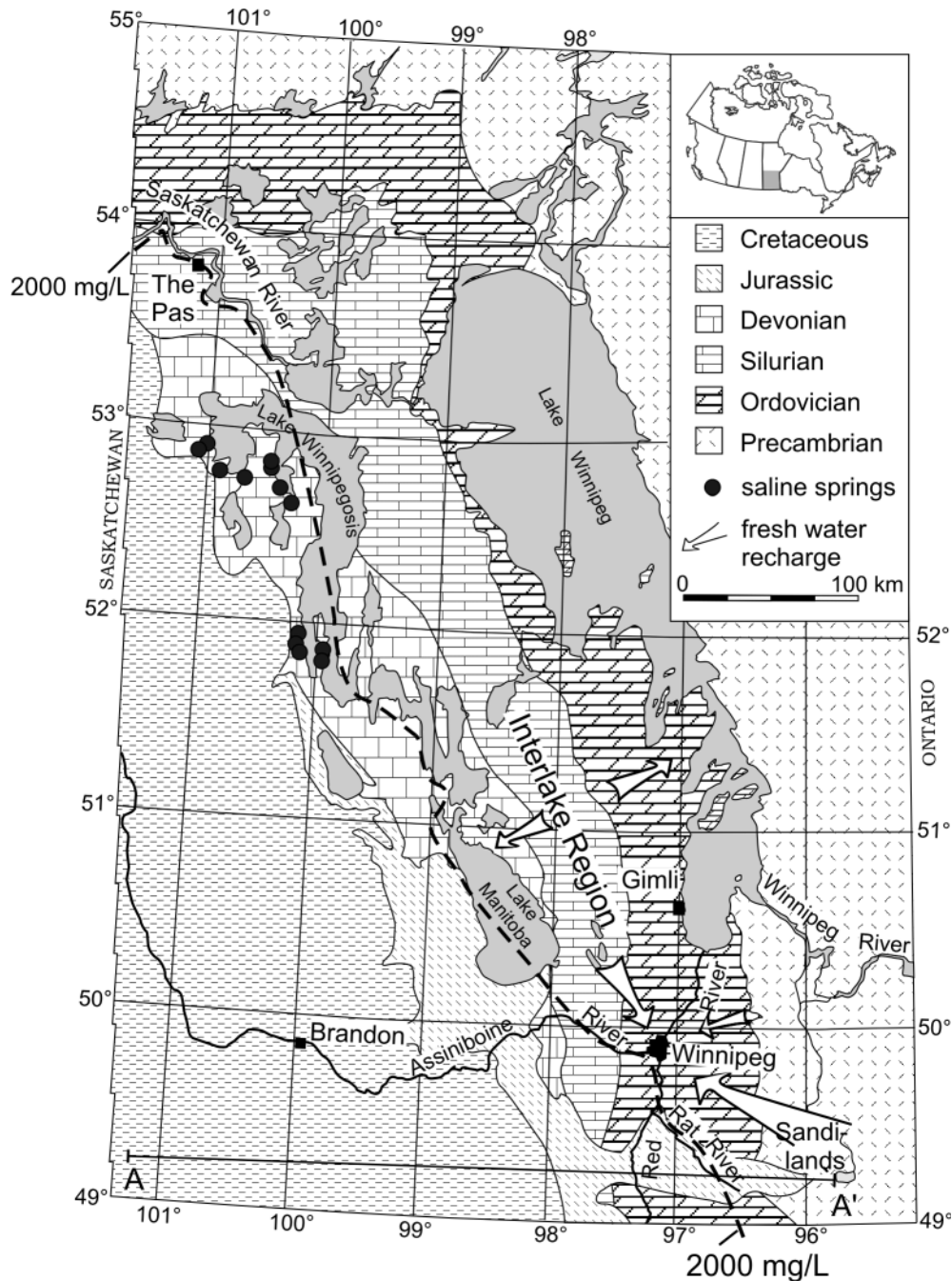
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Fig. 1. Regional geology of southern Manitoba showing the outcrop belt of the carbonate rock aquifer. The 2000 mg/L isocon (heavy broken line) follows the major topographic lows of the province, defining a hydraulic divide between the intermediate-scale freshwater flow system and the regional-scale updip flow of saline waters from the Williston Basin. Numerous saline springs occur west of the 2000 mg/L line along the shore of Lake Winnipegosis. Cross section in Fig. 3 is indicated by A–A'.



values in eastern Saskatchewan (Rostron et al. 1998). Middle Ordovician to mid-Devonian strata are in lateral continuity with the outcrop belt to the east, whereas Upper Devonian and Mississippian strata subcrop against the Jurassic unconformity (Fig. 3). Mississippian oil accumulations tend to be trapped below the unconformity, indicating it is an effective aquiclude. The lateral hydraulic continuity between Mississippian strata and older strata to the east is less clear.

Fractures, joints, and bedding planes form primary pathways for water movement in most of the aquifer, with dissolution

processes having enhanced the permeability of these fractures in some areas. In particular, the upper few metres of the bedrock surface is often found to be extensively fractured and is locally referred to as the “upper” aquifer. This fracturing may be attributed to remnant preglacial fracturing and solution development or to subglacial fracturing (Trainer 1973).

During Pleistocene glaciation Manitoba was entirely covered by a continental ice sheet. Silt- to clay-rich glacial tills, left behind by melting and retreat of the ice, form a mantle of varying thickness over the aquifer throughout almost all of

the outcrop area, with bedrock exposures restricted to limited portions of the upland areas of the Interlake and northern outcrop areas. In addition, during the retreat of the last major ice sheet, a large melt water lake (Glacial Lake Agassiz) developed over the present-day Red River Valley and extended northward with the retreat of the ice sheet. As a result, thick deposits of glaciolacustrine sediments, predominantly clay, were laid down over the till mantle in the topographically lower parts of the Manitoba lowlands. These tills and clays form a low-permeability cap over the carbonate rock aquifer throughout most of the outcrop area and, to a significant degree, depending on local thickness and permeability, restrict recharge to the aquifer. Highlands in the Interlake region (north of Winnipeg) and the Sandilands area (southeast of Winnipeg; Fig. 1) either were left exposed during Lake Agassiz time, or were covered by silty tills with bulk permeabilities somewhat greater than those of the lacustrine clays.

Methods

Data used here are from samples collected over the past 40 years by the Manitoba Water Branch from domestic water wells, monitoring wells, test holes, saline springs, and selected oil wells. These analyses have been compiled and stored in a provincial database referred to by the acronym GWCHEM. Collection, preservation, and handling techniques for samples included in this database have varied considerably over time and from study to study. Chemical analyses were completed at provincial or commercial laboratories. For this study, only analyses that include all major and most minor ions and have a charge balance ratio of less than 10% were utilized. Given that relatively few analyses are available for the saline portion of the flow system, all available analyses, including those from Mississippian strata, are included with data from the carbonate rock aquifer. This is consistent with the definition of the carbonate–evaporite hydrostratigraphic unit of Simpson et al. (1987).

Samples for ¹⁸O and D were analyzed at University of Waterloo using standard methods. Stable isotope compositions (¹⁸O/¹⁶O and D/H) are expressed using the usual δ notation:

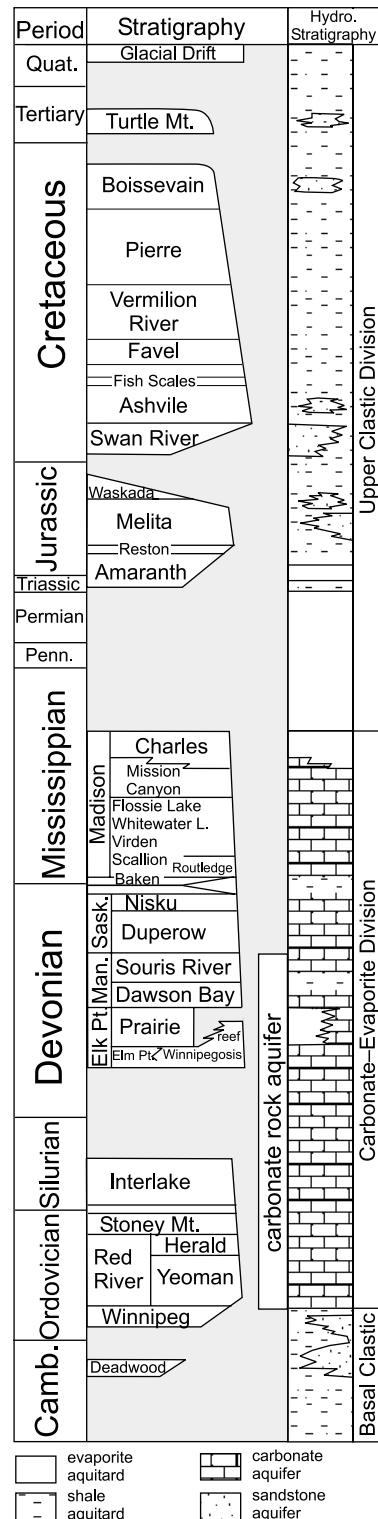
$$[1] \quad \delta(\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 10^3$$

were *R* is the ratio of the heavy to light isotope abundances. Samples are measured relative to the standard mean ocean water (SMOW) standard. Analytical errors are estimated to be ±2‰ for δD and ±0.2‰ for δ¹⁸O.

Regional flow system

The carbonate rock aquifer occurs on the northeastern edge of the Williston Basin. The present-day flow system of the basin is characterized by the influx of fresh water along northwest–southeast-trending topographic highs in the western United States, regional movement of formation fluids to the northeast, and discharge along the erosional edge of the basin in Manitoba (Bachu and Hitchon 1996; Plummer et al. 1990; Downey et al. 1987; Hannon 1987; van Everdingen 1971). Although regional-scale models indicate a southwest to northeast movement of groundwaters, Simpson et al. (1987) and Betcher et al. (1995) indicate that intermediate-scale

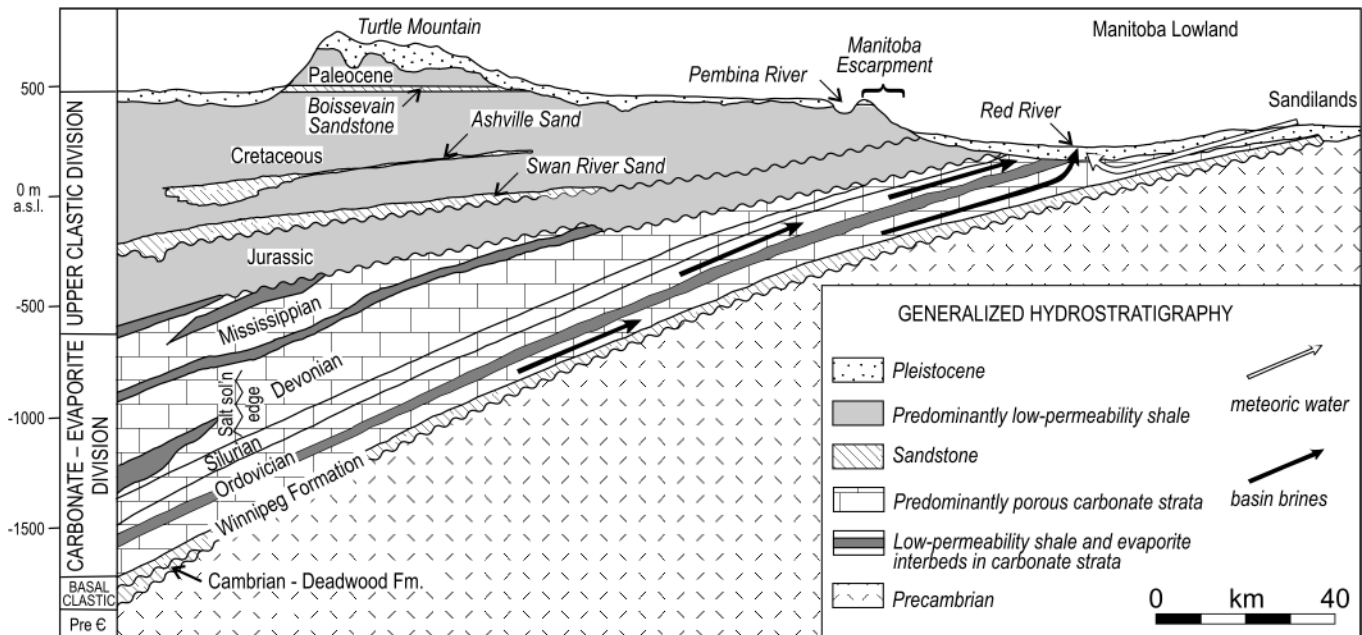
Fig. 2. Generalized hydrostratigraphy of southern Manitoba.



flow systems in the Interlake region and Sandilands area are pushing fresh waters from east to west.

We generated a regional hydraulic head map of southern Manitoba based on initial water level measurements recorded in drilling records from monitoring and domestic wells and calculated equivalent freshwater heads from pressure

Fig. 3. Hydrostratigraphic cross section of southern Manitoba (after Simpson et al. 1987). West of the Manitoba Escarpment the aquifer is capped by overlying Mesozoic shales. East of the escarpment Pleistocene glaciolacustrine silts and clays cover most of the outcrop belt. The Sandilands in the east is underlain by relatively higher permeability tills and forms an important freshwater recharge zone.



measurements in petroleum wells. The head map, along with interpreted flow lines, is presented in Fig. 4. Three dominant flow systems can be observed: (i) a strong eastward gradient in the southwest related to the regional-scale flow of saline waters from the Williston Basin; (ii) a northwest gradient in the southeast related to freshwater recharge from the Sandilands area; and (iii) a groundwater mound in the Interlake region with westward-, eastward-, and southward-directed flow lines. The major topographic lows in Manitoba, defined by the Rat, Red, and Saskatchewan rivers and lakes Winnipegosis and Manitoba, appear to define a hydraulic divide between northeastward up-dip flow from the Williston Basin and westward down-dip flow of fresh groundwaters related to local recharge (Fig. 4). This is consistent with regional geochemical and stable isotope trends discussed in the next section.

Regional hydrogeochemistry

Water chemistry

Due to the large number of samples (over 1100), the culled data set used for this study is presented elsewhere (Grasby et al. 1999), and only general data trends are discussed here. The spatial variations in total dissolved solids (TDS) of the aquifer are illustrated in Fig. 5. The TDS of groundwaters in the carbonate rock aquifer show a broad range, from 240 mg/L in the shallow eastern portion of the aquifer to over 230 000 mg/L in the deeper, western portion.

Chemical data from the carbonate rock aquifer are plotted in ternary diagrams in Fig. 6. The data are divided based on the classification system of Hem (1985): brines (>35 000 mg/L), saline waters (10 000 – 35 000 mg/L), brackish waters (2000 – 10 000 mg/L), and fresh water (<2000 mg/L). This division roughly corresponds to the source of samples: brines from oil wells, saline waters and

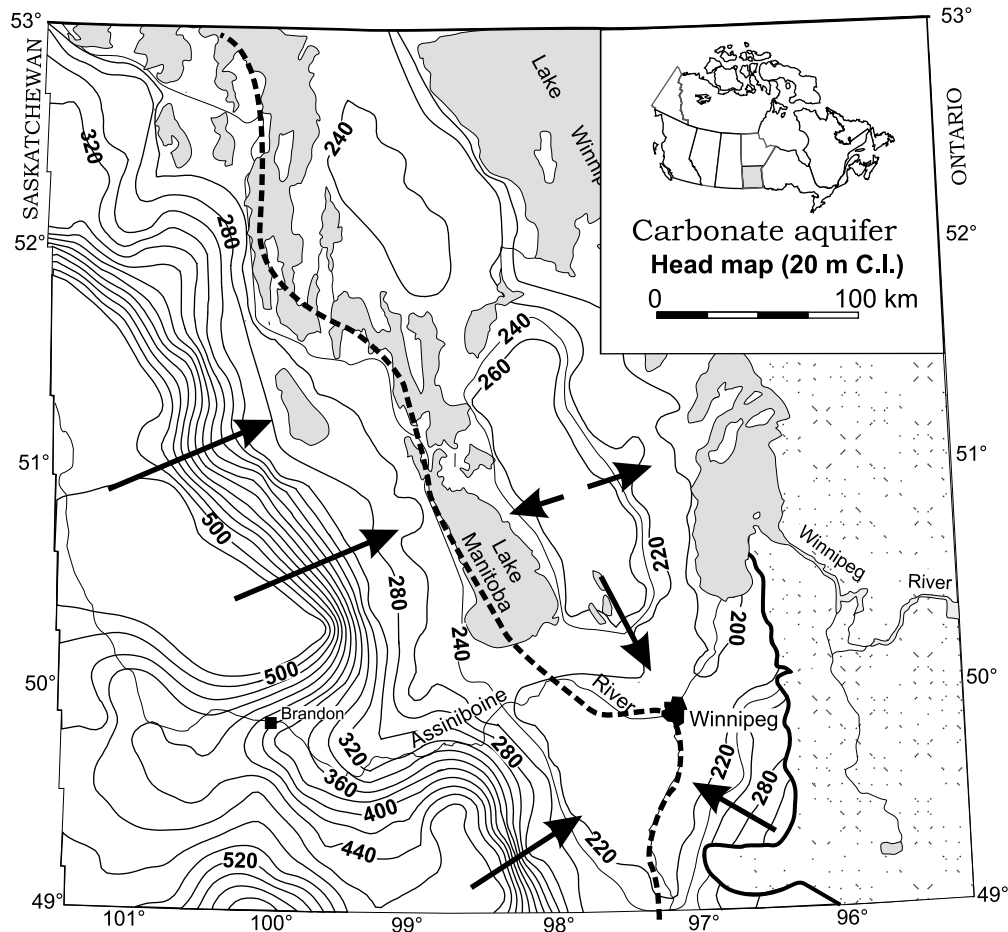
brines from springs, and fresh to brackish waters from domestic wells, test holes, and monitoring wells. Brines are characterized by cations being over 80% Na and anions over 90% Cl. Na and Cl also dominate saline and brackish waters, however, these waters may also have a significant proportion of Ca + Mg and SO₄. Fresh waters (<2000 mg/L) show a continuous range in compositions, from Na + K to Ca + Mg dominated waters, but tend to be Ca–Mg–HCO₃ waters with local areas of high SO₄.

Taking 2000 mg/L as a cutoff (Fig. 5), we can define a fresh water – saline water boundary within the aquifer (heavy broken line in Fig. 1). The 2000 mg/L isocon closely follows topographic lows defined by the major rivers and lakes in southern Manitoba and is similar to the trend of the hydraulic divide defined by head contours in Fig. 4. In the Winnipeg area, this fresh water – saline water boundary has been consistent since at least 1934 (Charron 1965; this work). This relationship suggests that the topographic lows form a quasi-stationary hydraulic divide that prevents eastward migration of saline water into freshwater-bearing portions of the aquifer. These saline waters appear to discharge into surface waters, leading to local anomalous Na and Cl values (van Everdingen 1971; Strobel and Haffield 1995).

To the east and north of the fresh water – saline water boundary there is a relatively wide zone of low-TDS water (generally <1000 mg/L). The lowest TDS waters are observed in the Sandilands area and the Interlake region, consistent with these highlands forming local recharge areas (Simpson et al. 1987; Betcher et al. 1995). West of the 2000 mg/L isocon, there is a zone of brackish waters followed by a rapid westward transition to saline waters and brines.

Figure 7 illustrates the variation in Br and Na as a function of Cl. The ion/Cl ratio is shown for average seawater (Holland 1978), and experimentally derived evaporation–dilution curves

Fig. 4. Regional head map for the carbonate rock aquifer with interpreted flow lines. The heavy broken line outlines the hydraulic divide defined by head contours and closely follows the course of the Red and Assiniboine rivers and lakes Manitoba and Winnipegosis. Hydraulic head contour interval (C.I.) = 20 m.



are indicated as solid lines (Carpenter 1978). The data in Fig. 7a do not show any enrichment in Br which is characteristic of waters that have reached halite saturation (Carpenter 1978), suggesting that Cl behaves conservatively within the carbonate aquifer. Br is depleted relative to the evaporation–dilution trend and seawater values (Cl/Br ratios are up to 2000 as compared with 292 for seawater), although for the highest TDS waters the Cl/Br ratio moves toward the evaporated seawater trend. For high-TDS waters, Na shows a strong correlation with Cl and follows the trend of the evaporation–dilution curve. It is important to note that although Devonian brines from the Western Canada Sedimentary Basin typically have Na/Cl ratios of <0.8, brines in Manitoba, along the eastern edge of the basin, have an average Na/Cl ratio of 0.91 (Fig. 7b).

O and H isotope data

Stable isotope data have not been routinely collected; however, over 300 analyses covering the majority of the carbonate aquifer are available and δD and $\delta^{18}O$ data are plotted in Fig. 8a. The local meteoric water line (MWL) for the town of Gimli (60 km north of Winnipeg) is also shown, defined by the relation $\delta D = 8.2\delta^{18}O + 10.7$ (Day 1977; Pach 1994), consistent with the Global MWL of Rozanski et al. (1993). The data in Fig. 8a define two trends. Samples from

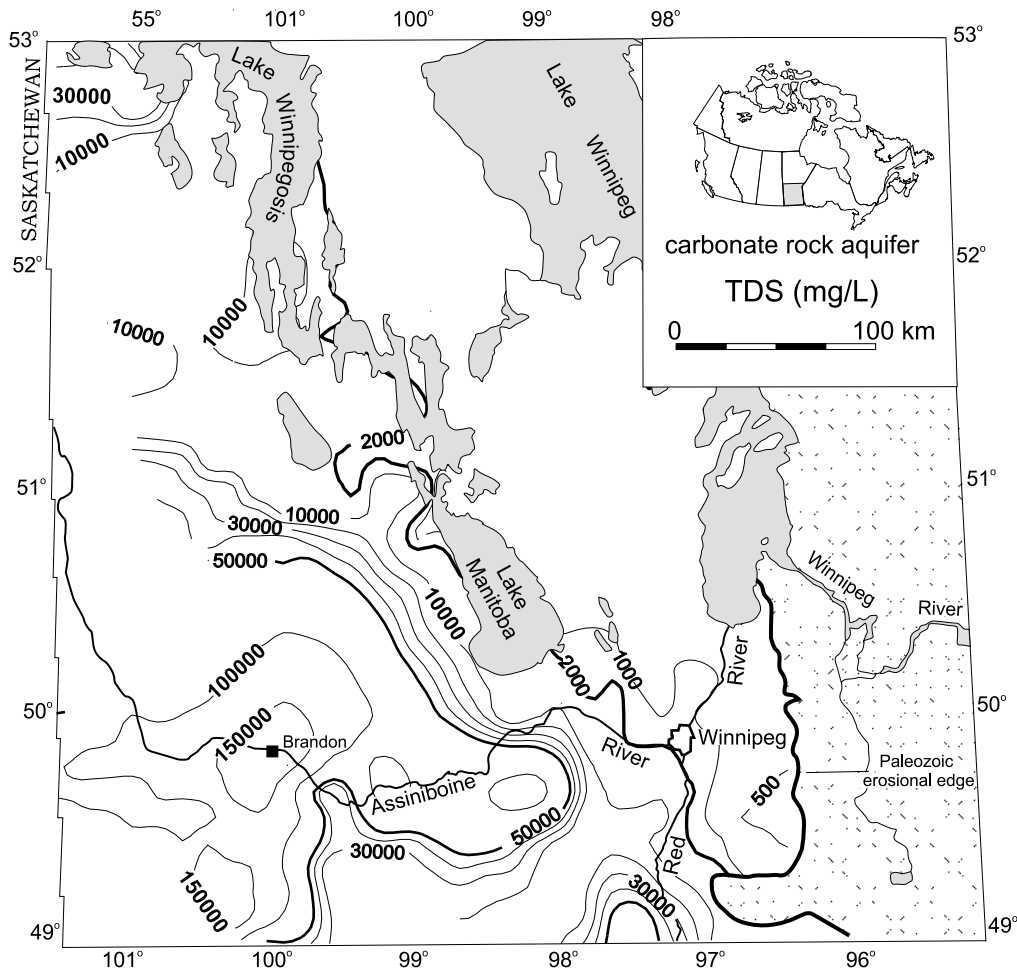
domestic wells, test holes, and monitoring wells (solid circles) plot along the Gimli MWL. Oil field waters (open circles) define a best-fit line with a slope of 4.9 ($r^2 = 0.99$) that intersects the Gimli MWL at a $\delta^{18}O$ value of -20‰ . Saline springs plot along both the Gimli MWL and the trend defined by the oil field waters.

Values of $\delta^{18}O$ are plotted versus TDS in Fig. 8b. Again, two main trends are observed: (i) oil field waters and saline springs show a positive correlation between TDS and $\delta^{18}O$, where the highest TDS waters have $\delta^{18}O$ values close to 0‰ and the lowest TDS waters have values down to -20‰ ; and (ii) samples from domestic wells, test holes, and monitoring wells tend to show an inverse relation with TDS, where the lowest TDS waters have $\delta^{18}O$ values consistent with modern meteoric water and the highest TDS (brackish) waters have $\delta^{18}O$ values down to -25‰ (insert in Fig. 8b).

Origin of waters in the carbonate rock aquifer

From the description given previously, we can separate the aquifer into portions bearing fresh and saline water, with 2000 mg/L as the cutoff. This division is not arbitrary; as described previously, the 2000 mg/L isocon closely follows the hydraulic divide defined by the head map in Fig. 4. In addition, there are distinct geochemical and isotope trends

Fig. 5. Regional variation in total dissolved solids (TDS, in mg/L) of the carbonate rock aquifer. The 2000 mg/L isocon closely corresponds to the trend of the hydraulic divide defined in Fig. 4. Note that the contour interval changes at 2000 and 50 000 mg/L.



observed on either side of the 2000 mg/L isocon. For this reason, we address the origin of the two waters separately.

Origin of fresh waters

Waters east of the 2000 mg/L isocon generally have $\delta^{18}\text{O}$ values in the range of -11‰ to -15‰ , consistent with modern meteoric waters in southern Manitoba (-13‰ to -15‰ , Fritz et al. 1974). These waters show a broad range in chemistry, from Na-Cl to Ca-Mg-HCO₃ dominated waters. Ca-Mg-HCO₃ waters are typical of geochemical development in carbonate terrains, where fresh meteoric water charged with CO₂ from the soil zone reacts with the carbonate host rock, or with carbonate-rich unconsolidated materials overlying the bedrock, and subsequent dedolomitization reactions along the flow path (Plummer et al. 1990). As indicated in Fig. 4, the freshwater portion of the aquifer has two dominant recharge zones, the Sandilands and Interlake regions. Waters show evidence of progressive water-rock interaction along flow lines away from these recharge zones. Local areas of high sulphate waters are related to oxidation of sulfides in clayey unconsolidated sediments overlying recharge zones (Grasby 2001). Locally, sulfate may also be contributed by dissolution of gypsum in Jurassic infills of paleokarst or cryptoexplosion features (McCabe 1971). Freshwater portions of the aquifer that are dominated by Na-Cl tend to be close to the east

bank of the Red River, which suggests that there is limited diffusion of saline waters across the hydraulic divide.

Origin of saline waters

Fresh Ca-Mg-HCO₃ waters transition westward across the hydraulic divide to brackish Na-Cl or Na-Cl-SO₄ waters with $\delta^{18}\text{O}$ values as low as -25‰ . As shown in Figs. 8b and 9, the $\delta^{18}\text{O}$ of brackish waters is significantly lower than that of modern meteoric water. Westward of the brackish waters, salinities and stable isotope values increase towards values more typical of deep basin brines.

Formation brines in Paleozoic rocks of western Canada have TDS values over 300 000 mg/L. These waters are generally interpreted to be evaporated residual seawater, which has undergone various degrees of mixing-dilution and water-rock interaction (e.g., Hitchon et al. 1971; Spencer 1987; Connolly et al. 1990; Simpson 1999). This is supported by Cl/Br ratios that are typically equal to or less than that of seawater (e.g., Spencer 1987; Kharaka 1986) and $\delta^{18}\text{O}$ values that are typically -3‰ to $+6\text{‰}$ (e.g., Rostron et al. 1998). Recent work by Simpson (1999) demonstrates that brines in Paleozoic rocks of western Canada have Na/Cl ratios significantly lower than that of seawater, and he suggests that this is related to water-rock interaction that buffers Na. This is similar to Hanor (1994a, 1994b, 1996),

Fig. 6. Ternary plots for major cations and anions for waters from the carbonate rock aquifer, divided by salinity using the classification system of Hem (1985): (a) brines (> 35 000 mg/L), (b) saline water (10 000 – 35 000 mg/L), (c) brackish water (2000 – 10 000 mg/L), and (d) fresh water (<2000 g/L). High-TDS waters are dominantly Na–Cl, whereas low-TDS waters show a mixing relationship. *n*, number of samples.

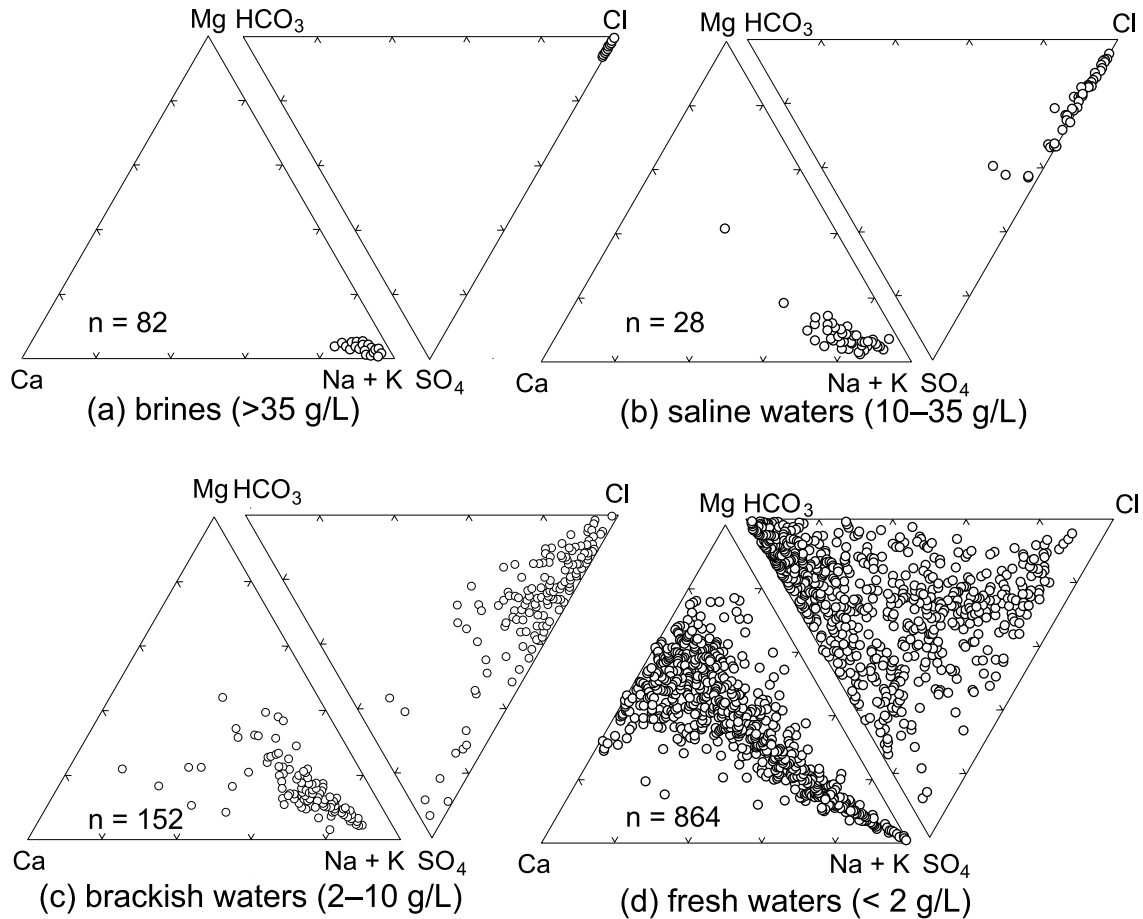
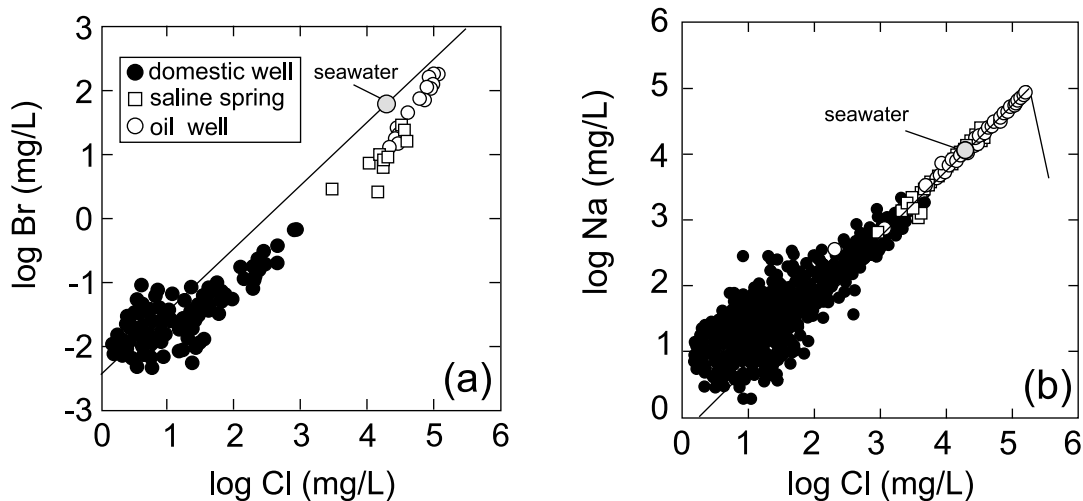


Fig. 7. Plot of Cl versus (a) Br and (b) Na for waters from the carbonate rock aquifer, with samples defined by source (domestic wells, saline springs, and oil wells). Trend lines are experimentally derived evaporation–dilution curves for seawater (Carpenter 1978).



who suggests that for high-TDS waters in sedimentary basins, mixing is a first-order control on Cl concentrations, and variations in major cations are controlled by mixing as well

as metastable thermodynamic buffering by carbonate–silicate mineral assemblages.

Saline waters in western Manitoba show a progressive

Fig. 8. (a) δD and $\delta^{18}O$ for domestic wells, saline springs, and oil wells. The meteoric water line (MWL) for the town of Gimli (60 km north of Winnipeg) and the best-fit line for waters from saline springs and oil wells are shown. The stable isotope data show domestic well waters are derived from modern meteoric recharge, whereas springs and oil wells show a mixing relation between meteoric water and basin brines. (b) Variation of TDS with respect to $\delta^{18}O$, showing two stages of mixing (see text).

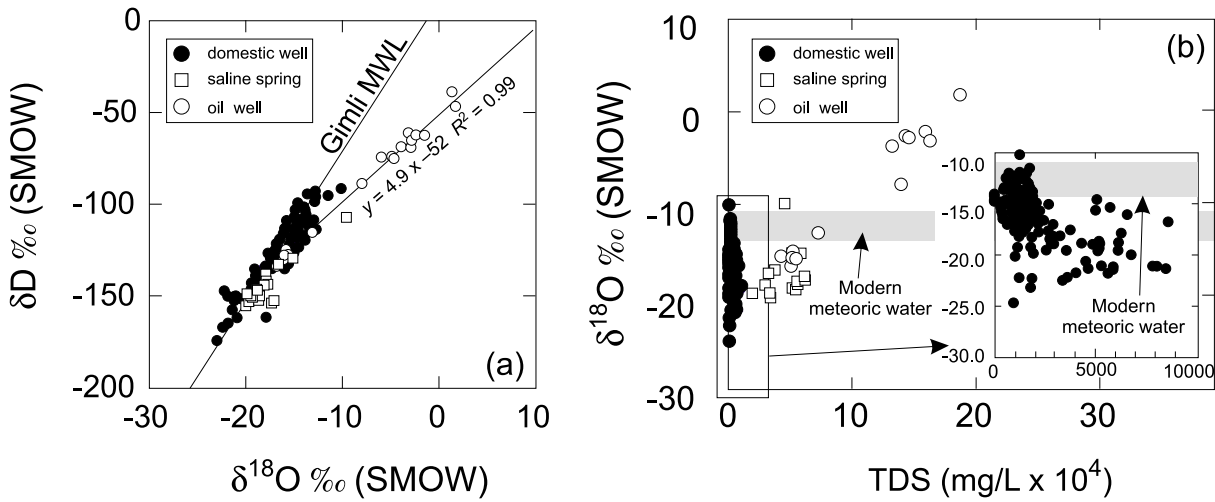
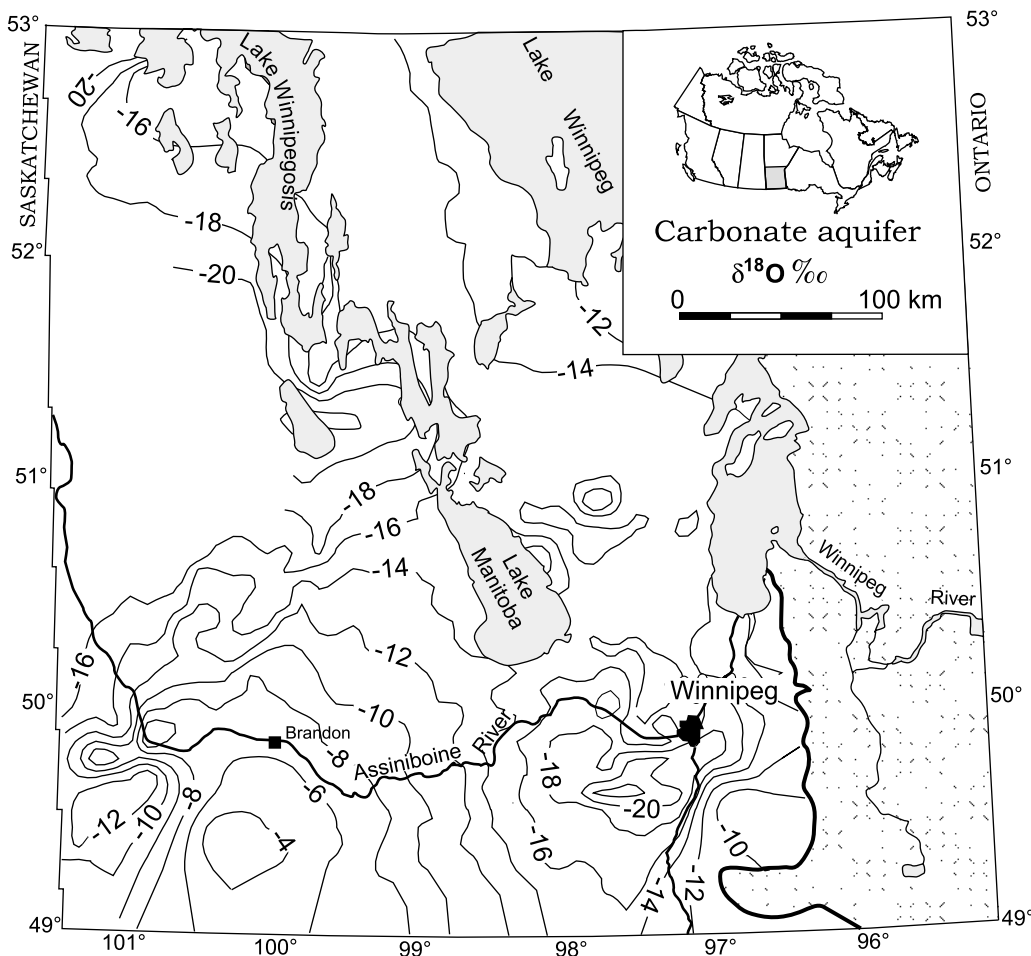


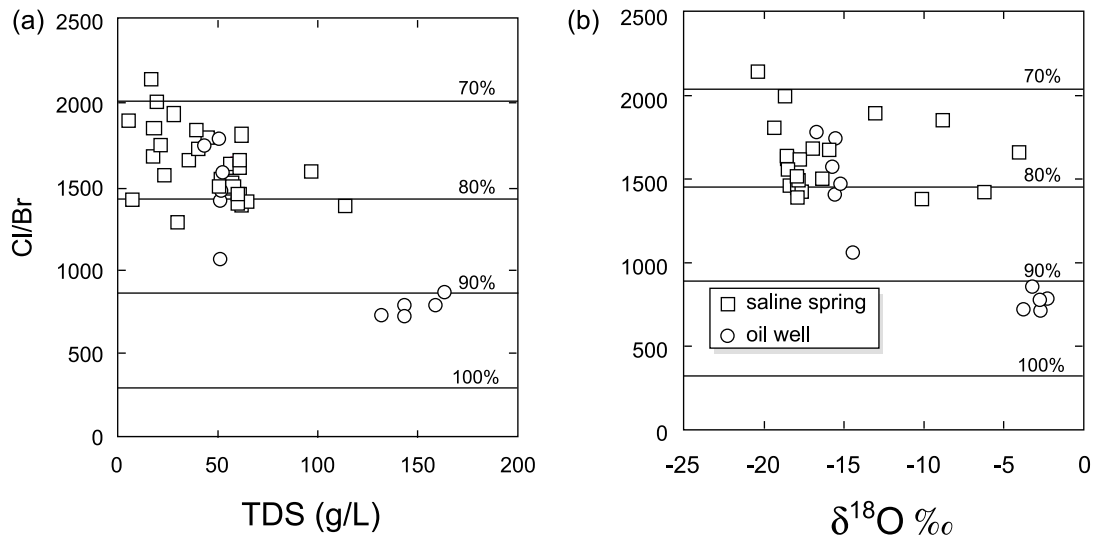
Fig. 9. Spatial variation in $\delta^{18}O_{H_2O}$ (in ‰) of waters from the carbonate rock aquifer.



mixing trend between two end members (Fig. 8b): (i) a high-TDS brine with $\delta^{18}O$ and Cl/Br values consistent with deep basin brines, and (ii) intermediate-TDS waters (5000 to 30 000 mg/L) with $\delta^{18}O$ values as low as -24‰ and Cl/Br

ratios up to 2000. These intermediate-TDS waters also have Na/Cl molar ratios close to 1, as compared with <0.8 typical of deep brines in the Western Canada Sedimentary Basin (Fig. 7b).

Fig. 10. (a) Plot of the Cl/Br ratio versus total dissolved solids (TDS) of water from the carbonate rock aquifer. A percent dissolved halite contribution to the brine is calculated based on a seawater Cl/Br value of 292 (100%) and a Cl/Br value for the Prairie Evaporite of 6000. (b) Plot of Cl/Br versus $\delta^{18}\text{O}$ of water. For both cases, the Cl/Br ratio approaches that of deep basin formation waters as salinity increases.



Since Br tends to be excluded from the crystal structure of evaporite minerals well past the point of halite saturation, halite deposits have a significantly higher Cl/Br ratio than seawater. Consequently, brines formed by the dissolution of halite will also have significantly higher Cl/Br ratios than residual evaporated seawater. Likewise, waters that dissolve halite beds and have not had sufficient time to react with silicate mineral assemblages should have a 1:1 Na/Cl ratio. This suggests that brines in western Manitoba (particularly the saline springs) with low $\delta^{18}\text{O}$ and high Cl/Br ratios have a local origin related to dissolution of evaporites and are different from residual evaporative brines. This is counter to regional-scale flow models of the Williston Basin (Bachu and Hitchon 1996; Downey et al. 1987; Hannon 1987) that predict northeastward-directed flow of basin waters towards central Manitoba, suggesting that at some point an influx of fresh water occurred along the eastern edge of the basin (Grasby et al. 2000).

Mixing of waters in the carbonate rock aquifer

Stable isotope and chemical data for the carbonate rock aquifer suggest three-component mixing (Fig. 8), with end members being (i) high-TDS, high- $\delta^{18}\text{O}$ water consistent with deep basin brines; (ii) intermediate-TDS, very low $\delta^{18}\text{O}$ meteoric water; and (iii) low-TDS water (<2000 mg/L), with $\delta^{18}\text{O}$ values of -11‰ to -15‰ consistent with modern meteoric recharge. The $\delta^{18}\text{O}$ values of brackish to saline waters (as low as -24‰) are lower than the modern range for meteoric water in southern Manitoba (-11‰ to -15‰ , Fritz et al. 1974) but are consistent with pore waters found in thick, unweathered clay deposits of Glacial Lake Agassiz (Remenda et al. 1994), glaciolacustrine deposits in northern Ontario (Desaulniers 1986), and tills in southern Saskatchewan (Remenda 1993). Based on this, Grasby et al. (2000) argue that these low- $\delta^{18}\text{O}$ waters represent Pleistocene melt water pushed into the aquifer during Pleistocene glaciation. Similar evidence for an influx of Pleistocene melt water is observed in the Illinois Basin (Stueber and Walter 1994), the Michigan

Basin (Martini et al. 1998), and the Canadian Shield (Clark et al. 2000). Given this, the check mark (\checkmark) shape defined by data in Fig. 8b suggests two mixing events: (i) an influx of Pleistocene melt water mixing with preexisting formation water, and (ii) modern meteoric water mixing with Late Pleistocene formation water. The spatial variations in $\delta^{18}\text{O}$ and TDS are consistent with this interpretation (Figs. 5, 9). High-TDS, ^{18}O -enriched waters occur in the deeper western part of the aquifer and show a steady gradation updip to saline and brackish ^{18}O -depleted waters. The lowest TDS waters, with a $\delta^{18}\text{O}$ signature consistent with modern meteoric water, are found in association with topographic highs of the Sandilands and Interlake regions, east of the hydraulic divide, that the head map in Fig. 4 indicates are significant areas of modern-day recharge.

For saline springs west of Lake Winnipegosis, geochemical data are consistent with Pleistocene melt water dissolving evaporite beds and mixing with preexisting formation water in western Manitoba. As mentioned previously, the Cl/Br ratios of brines in deeper portions of the Williston Basin are close to or less than the seawater ratio of 292. If a brine were solely derived from dissolution of the Prairie Evaporite Formation (with Cl/Br \approx 6000), it should end up with a similar Cl/Br ratio. Figure 10a illustrates that the Cl/Br ratio, and thus the percent dissolved halite contribution to the brines, varies as a function of TDS, where the highest TDS waters have Cl/Br ratios most characteristic of deep basin brines. A similar relationship is observed when the Cl/Br ratio is plotted versus $\delta^{18}\text{O}$ (Fig. 10b). Again, the Cl/Br ratio decreases as $\delta^{18}\text{O}$ values increase westward, deeper into the basin.

Conclusions

Head maps of the carbonate rock aquifer illustrate that flow is characterized by regional-scale updip flow out of the Williston Basin in the western portion of the aquifer, and intermediate-scale, south- and west-directed flow related to

freshwater recharge in the eastern portion of the aquifer. Topographic lows in the province, defined by major river and lake systems, define a hydraulic divide running approximately north-south. The 2000 mg/L TDS isocon tends to follow the trend of this hydraulic divide, indicating that it acts as a quasi-stationary boundary between saline waters to the west and fresh waters to the east.

Brines in western Manitoba are distinct from those in lateral continuity deeper and farther west into the Williston Basin. We show evidence that the brines in western Manitoba are a mixture of original deep basin brines and a meteoric water component that dissolved evaporite beds in the basin. Stable isotope data suggest that this is related to an influx of subglacial melt water during the Pleistocene (Grasby et al. 2000). Fresh waters east of the 2000 mg/L isocon are related to modern meteoric recharge.

Betcher (1986) has noted the eastward advance of saline brines in the Interlake area in the confined Winnipeg Formation aquifer. In contrast, the current position of the fresh water – saline water boundary in the overlying carbonate rock aquifer follows major topographic divides, indicating a quasi-stationary front. The high permeabilities in the carbonate rock aquifer would have allowed a much more rapid post-glacial readjustment to the apparent stable conditions observed today, particularly in the freshwater portion of the aquifer where little evidence of Pleistocene melt water remains. The low $\delta^{18}\text{O}$ values of brackish to saline waters west of the major rivers and lakes in southern Manitoba may reflect the fact that Pleistocene-age aquitards are much thicker here, and inhibit discharge of these waters.

Increasing withdrawals of groundwater east of the fresh water – saline water boundary, particularly in the populous areas of southeastern Manitoba, including the City of Winnipeg, may disturb the current quasi-stationary boundary and result in an eastward movement of saline groundwaters. Charron (1965) has observed a shift of the boundary in the Winnipeg area, where major withdrawals occur. As well, a local disturbance of the boundary occurred during a dewatering project as part of construction of the Red River Floodway (Render 1970). More research into the hydrogeology of the aquifer is needed to ensure that current and future rates of withdrawal will not adversely affect the current position of the freshwater boundary.

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