
Hydrogeology of the Winnipeg Formation in Manitoba, Canada

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Abstract The Winnipeg Formation is the basal sedimentary unit throughout much of southern and central Manitoba, Canada, where it forms a regional aquifer over most of its extent. This aquifer is an important source of water in southeastern Manitoba and in Manitoba's Interlake area, but in most other areas, groundwater within the aquifer is saline. Chemical and isotopic evidence indicate the presence of groundwaters of three different origins: (1) basin brines; (2) modern meteoric recharge; and (3) subglacial recharge that occurred during the late Pleistocene. Hydraulic head and sedimentary facies distributions indicate that the flow system in parts of the area is not in a state of equilibrium and saline waters will encroach on areas currently occupied by freshwater in some areas, while in other areas, freshwater will replace saline water. These features must be considered in groundwater resource management, as groundwater withdrawals will likely hasten these processes.

Résumé La Formation de Winnipeg est l'unité sédimentaire de base sur la plus grande partie du Sud et du centre du Manitoba au Canada, où elle forme un aquifère régional sur pratiquement toute son extension. Cet

aquifère représente une ressource en eau importante dans le Sud-Est du Manitoba et dans les zones d'entre les lacs, mais salée dans la plus part des autres zones. Les indications isotopiques et chimiques permettent de distinguer trois différentes origines des eaux souterraines: (1) les saumures de bassin; (2) la recharge météoritique moderne; (3) la recharge sub-glaciaire qui est apparue durant le Pléistocène récent. Les charges hydrauliques et la distribution des faciès sédimentaires indiquent que le système d'écoulement dans certaines zones n'est pas dans un état d'équilibre et que les eaux salées empièteront sur des zones d'eau douce, tandis que dans d'autres zones l'eau douce remplacera les eaux salées. Ces aspects doivent être considérés dans la gestion des ressources en eau souterraine, car le prélèvement des eaux souterraines pourrait accentuer ces processus.

Resumen La Formación Winnipeg es la unidad sedimentaria basal en la mayor parte de Manitoba central, Canadá, donde forma un acuífero regional en la mayor parte de su extensión. Este acuífero es una fuente importante de agua en el Sureste de Manitoba y el área de entrelagos de Manitoba, pero en la mayoría de las otras zonas del acuífero, el agua es salina. Las evidencias químicas e isotópicas indican que existen aguas subterráneas de tres orígenes diferentes: (1) salmueras de cuenca; (2) recarga meteórica actual; y (3) recarga subglacial ocurrida durante el Pleistoceno Superior. Los niveles piezométricos y la distribución de las facies sedimentarias indican que el sistema de flujo no se encuentra en estado de equilibrio en parte del área y las aguas salinas irán invadiendo áreas actualmente ocupadas con aguas dulces, mientras que en otras zonas el agua dulce está reemplazando al agua salina. Estos hechos deben ser considerados en la gestión de las aguas subterráneas como recurso, ya que las extracciones de agua acelerarán probablemente estos procesos.

Keywords Paleohydrology · Canada · Salinization · Hydrochemistry · Stable isotopes

Introduction

The Winnipeg Formation, composed of sandstone and shale units, forms the basal sedimentary aquifer in much

Received: 8 June 2005 / Accepted: 26 October 2006
Published online: 29 November 2006

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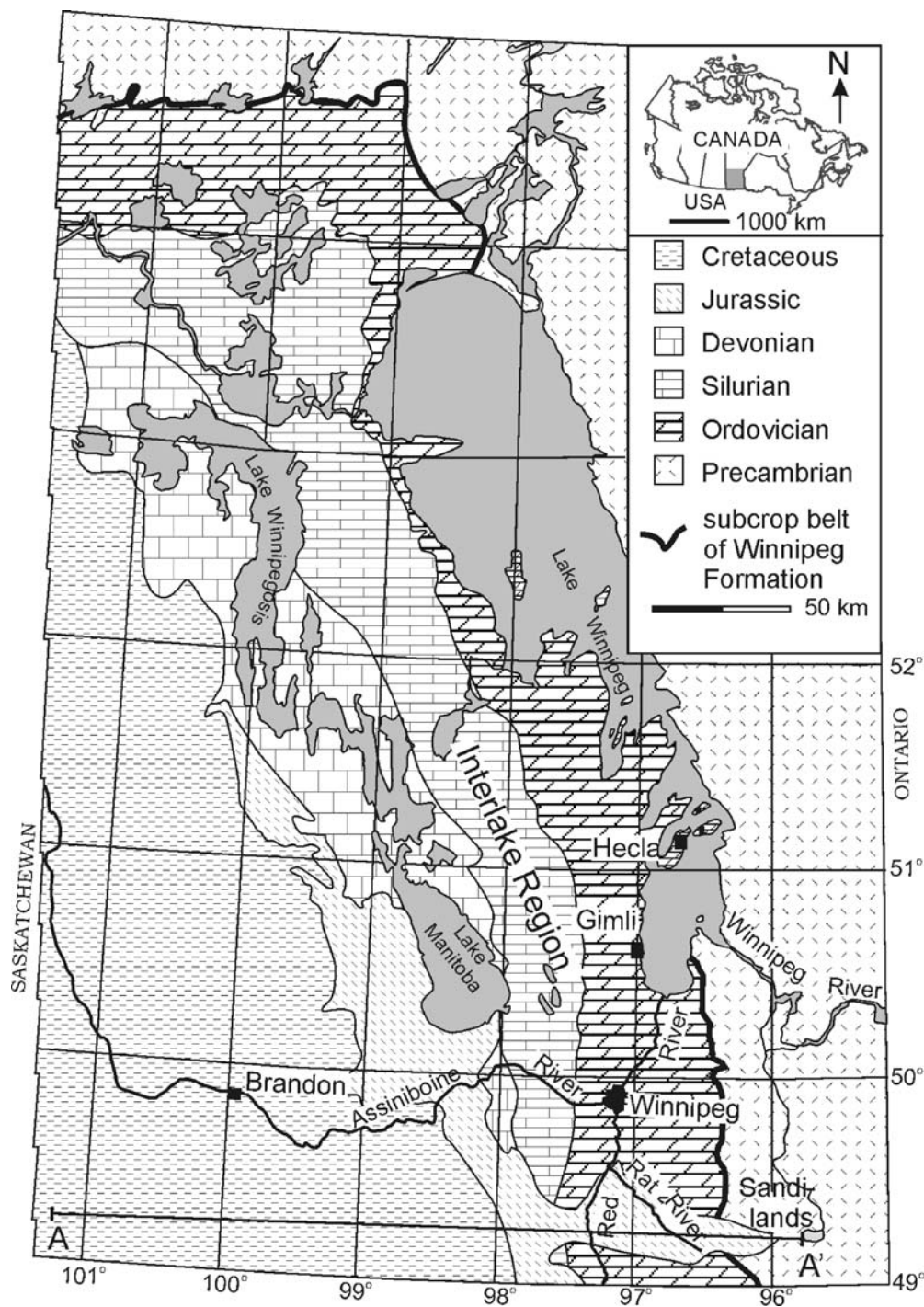
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of southern and central Manitoba (Fig. 1). This aquifer is an important source of groundwater in both southeastern Manitoba and in an area along the western shore of Lake Winnipeg. Provincial water well records indicate that approximately 1,500 water supply wells have been completed in the Winnipeg Formation in these areas since 1970, however, many more unrecorded wells likely exist. Historically, the majority of the wells completed into the aquifer were for small farm or residential use, but since the 1980s, there has been an increasing number of wells

installed for industrial and other high capacity users. This aquifer was originally seen as a desirable drilling target due to flowing artesian conditions that existed in parts of southeastern Manitoba during the early part of the twentieth century and because of the presence of “soft” groundwater. Due to the practice of completing wells as open holes through the Winnipeg Formation and overlying formations, and increasing withdrawals from the formation, the areal extent of artesian conditions has

Fig. 1 Extent of the Winnipeg Formation in southern Manitoba (after Grasby and Betcher 2002). Subcrop belt of the Winnipeg Formation is shown as the *thick black line* at the eastern and northern edge of the Ordovician rocks, adjacent to the Precambrian rocks. The formation extends eastward from this line under overlying Paleozoic sediments



declined (Betcher and Ferguson 2003). Despite this, development of the aquifer is still active.

Although the aquifer is a source of high-quality water in southeastern Manitoba and parts of the Interlake, brackish or saline waters or brines occupy the Winnipeg Formation in many parts of Manitoba, particularly to the west of the Red River in the south, and west of Lake Manitoba in the north. A principal concern for managing the long-term sustainable development of the aquifer is the potential for migration of these saline waters into freshwater bearing areas, a threat similar to that of salinization of coastal aquifers; however, in this case, within mid-continental North America. Therefore the origin, distribution, and movement of these high total dissolved solids (TDS) waters needs to be understood to allow sustainable management of the Winnipeg Formation as a source of potable groundwater. In order to better understand the dynamics of fresh and saline waters in the aquifer, we conducted a study based on historical data collected by the Province of Manitoba and a recent sampling program conducted by the Geological Survey of Canada.

Geological setting

Winnipeg Formation

The Winnipeg Formation is an extensive geological unit that is found throughout southern and central Manitoba (Fig. 1) and extends westward into eastern and central Saskatchewan and southward into North Dakota, South Dakota, Montana and Wyoming. The shales and sandstones of the Winnipeg Formation were deposited under marine conditions in a northward advancing sea during the Middle to Late Ordovician (McCabe 1978). These sedi-

ments are among the first to be deposited in the Williston Basin and represent an expansion of the basin during the Ordovician (Osadetz and Haidl 1989). The sediments of the Winnipeg Formation are the basal Paleozoic sediments throughout Manitoba, except where they are underlain by the Cambrian Deadwood Formation in the extreme southwest of the province (Fig. 2).

The carbonates of the Upper Ordovician Red River Formation overlie the Winnipeg Formation (McCabe 1971). This unit is the base of a thick sequence of Paleozoic carbonates, evaporites and minor clastics which attain a maximum thickness of approximately 1,200 m in southwestern Manitoba (Fig. 2). In this area, these strata are overlain by up to 1,100 m of Mesozoic and Cenozoic rocks consisting of shales, sandstones and minor evaporites (Fig. 2).

The Winnipeg Formation consists predominantly of fine to coarse-grained siliceous sandstone and is arenaceous in some areas and non-arenaceous in other locations (Baillie 1953; Genik 1952; McCabe 1978). The thickness of the formation varies from local areas of non-deposition or absence due to erosion along the northern edge of the Paleozoic outcrop belt to in excess of 50 m in the southern part of Manitoba (Fig. 2). Exposures are scarce and are only found locally along the western shore of southern Lake Winnipeg and the shores of several islands in the south basin of the lake. Several authors have attempted to subdivide the Winnipeg Formation into stratigraphically distinct units (Baillie 1953; Genik 1952; Vigrass 1971) with subdivisions generally consisting of a lower sandstone unit and one or two overlying units consisting of sandstone and shale. In some studies, these have been referred to as the Black Island and Icebox Members (e.g. Ellingson 1995), but we choose here to treat the Winnipeg Formation after the manner proposed by McCabe (1978).

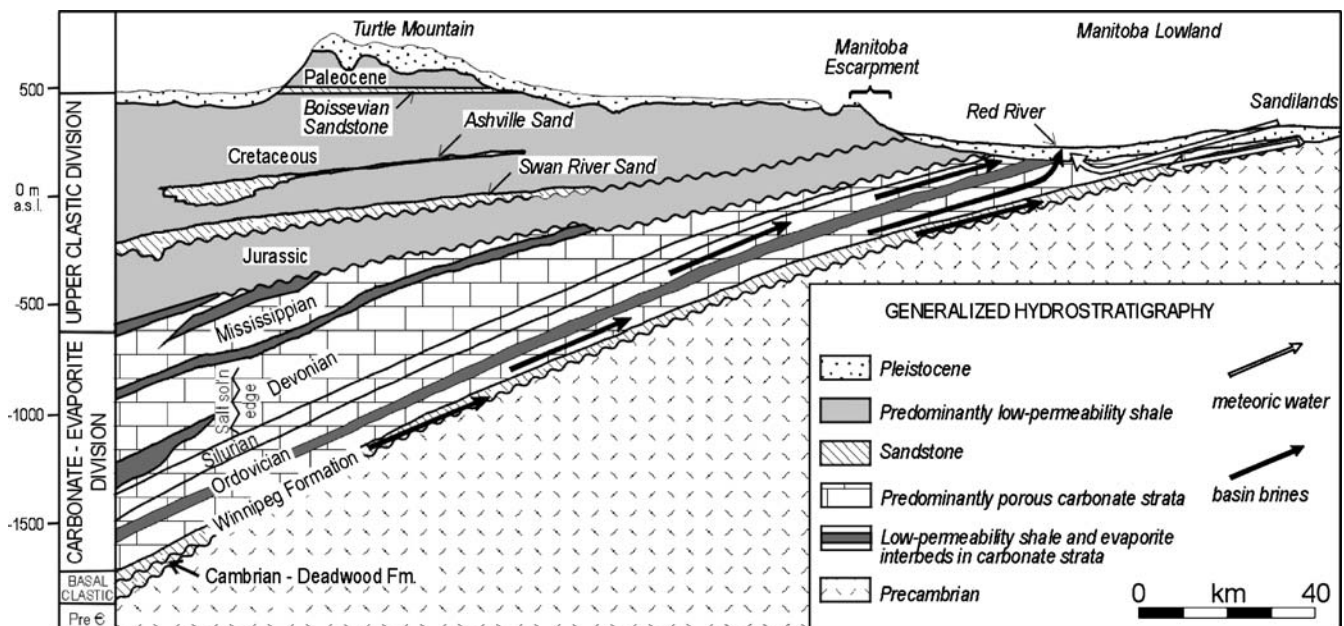


Fig. 2 Geological cross-section of southeastern Manitoba (after Simpson et al. 1987) along with interpreted flow systems for basin waters (see text). Trace of cross-section is shown on Fig. 1 (A to A')

He concluded that stratigraphic subdivision of the Winnipeg Formation into members is not widely applicable in Manitoba and suggested subdivision based on the spatial facies distributions in the lower and upper parts of the formation. Somewhat similar distributions are found in each of the upper and lower sections consisting of a northern sandstone facies, a central to southwestern transitional facies of interbedded sandstone and shale and a southern shale facies (Figs. 3 and 4). The Carman sand body, an anomalous E–W trending zone of clean very-fine-to-medium-grained sandstone up to 30 m thick, interrupts the southern shale facies in the upper part of the Winnipeg Formation. This feature extends from south of Brandon to the eastern outcrop area, a distance of approximately 240 km (Fig. 1).

Other features are persistent in the Winnipeg Formation over large areas. A basal sandstone of varying thickness has been intersected in all but a few boreholes penetrating

the full thickness of the Winnipeg Formation. McCabe (1978) considers this sandstone to be a “blanket-type” deposit that is continuous throughout the depositional area of the formation in Manitoba. Sandstone horizons found stratigraphically higher in the formation probably do not have the widespread continuity of this basal sandstone. The upper part of the formation is composed of a shale layer of varying thickness throughout southern Manitoba. This feature is absent as a major stratigraphic feature in the northern sand facies area. This shale layer serves as an effective hydraulic barrier separating the overlying Red River Formation carbonates from the underlying Winnipeg Formation sandstones.

Sandstones of the Winnipeg Formation predominantly consist of well-rounded, frosted and pitted quartz grains. Sandstones are generally poorly cemented but moderately-to-well-cemented sandstones are occasionally encountered, generally in the middle and upper portions of the

Fig. 3 Depositional facies in the upper 50% of the Winnipeg Formation (after McCabe 1978)

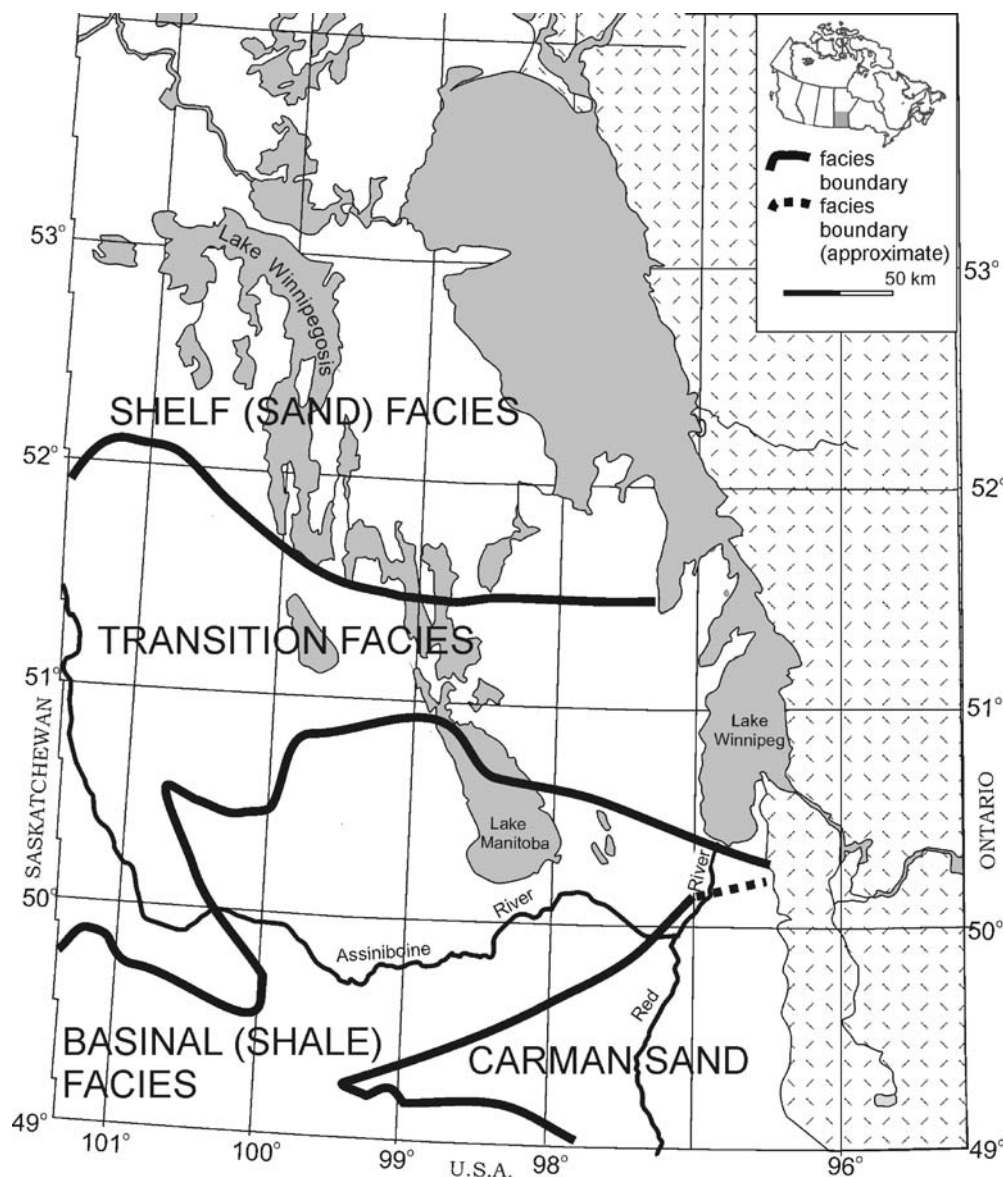
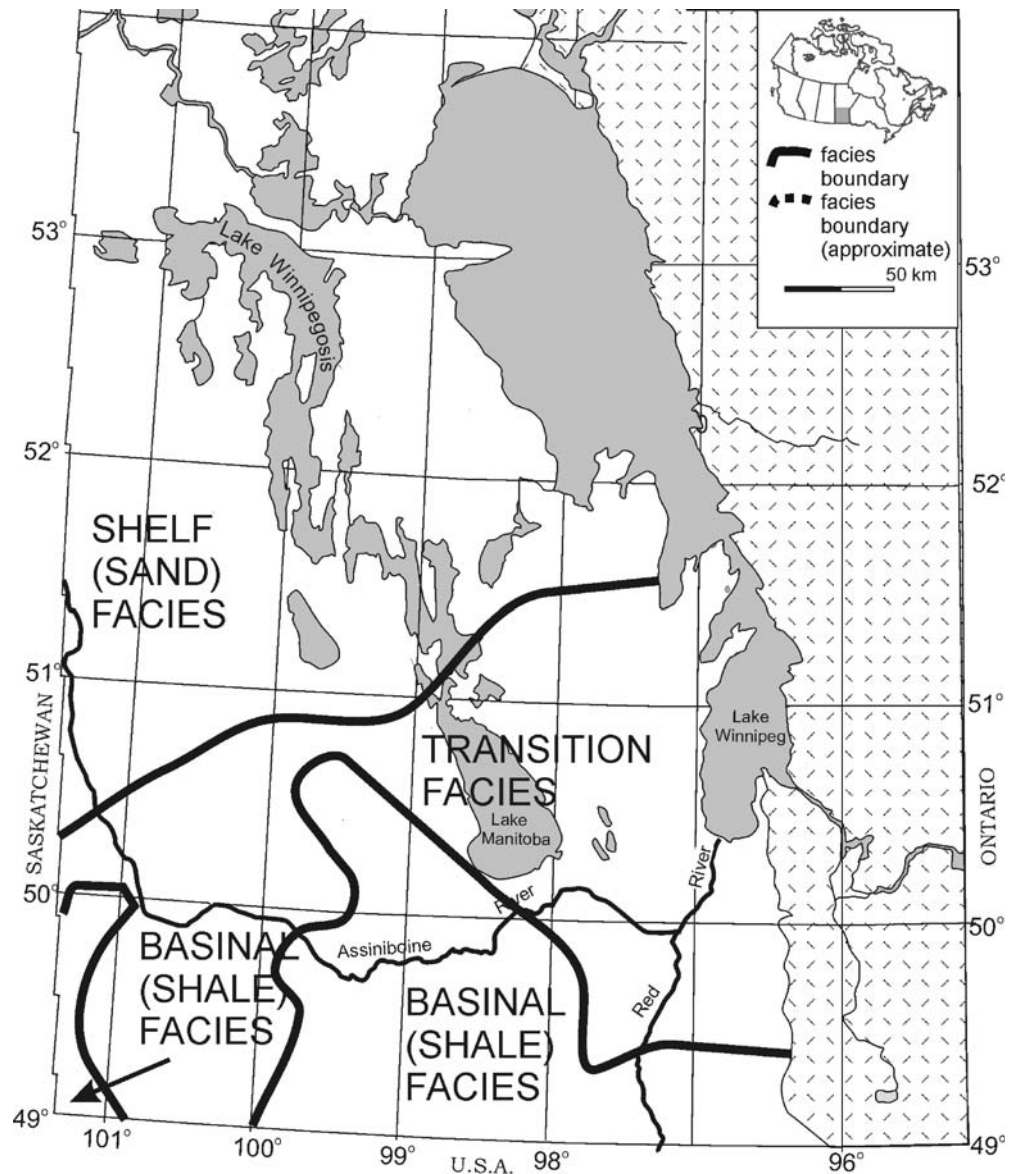


Fig. 4 Depositional facies in the lower 50% of the Winnipeg Formation (after McCabe 1978)



Winnipeg Formation. Cementing materials include carbonates, particularly in the upper portion of the formation in proximity to the overlying Red River Formation, as well as silica, iron oxides, iron sulfides, gypsum and white kaolinitic clay (Genik 1952; Andrichuk 1959; Paterson 1971; McCabe 1978). Shales vary from massive pure shales to arenaceous shales, containing floating quartz grains and thin lenses of quartz sand. The shales are sometimes lightly calcareous near the contact with the overlying Red River Formation (Genik 1952).

Late Quaternary geology of southeastern Manitoba

Quaternary sediments dominate the surficial geology of southern Manitoba. These sediments include tills and glaciofluvial sediments deposited during the Wisconsinan Glaciation, glaciolacustrine sediments deposited by proglacial lakes and alluvium and organic sediments deposited during the Holocene. During the late Wisconsinan Glacia-

tion, the Laurentide and Keewatin Ice Sheets advanced across Manitoba from the northeast and northwest respectively (Teller and Fenton 1980). The ice overlying southern Manitoba is estimated to have been approximately 1,500 m thick (Peltier 1994). Near the end of the Wisconsinan Glaciation, several glaciofluvial complexes were formed in the vicinity of the boundary between the Canadian Shield and the Williston Basin sediments, including the Sandilands Interlobate Moraine (Figs. 1 and 2), the Belair Moraine and the Birds Hill glaciofluvial complex, and a large buried esker north of the Sandilands moraine. These features indicate that large quantities of subglacial water would have been present along the subcrop belt of the Winnipeg Formation during the last glaciation.

Lake Agassiz formed at the end of the last glaciation as glacial meltwater was impounded by the ice sheet to the north (Teller and Clayton 1983). During this time, thick clay and silt units were deposited in parts of southern Manitoba. Beneath Lake Winnipeg, which would have at

times been the deepest area of Lake Agassiz, as much as 100 m of fine-grained, low permeability sediments have accumulated along the northern portion of the Winnipeg Formation's subcrop belt (Todd et al. 1998). Above the Lake Agassiz sediments, up to 10 m of clay and silt have been deposited in Lake Winnipeg (Todd et al. 1998).

Hydrodynamics

Although local intra-formational flow regimes are recognized within the interlayered sandstone aquifer-shale aquitard system, we treat the Winnipeg Formation as a single hydraulically connected unit on a regional scale. Heads measured in open boreholes completed through the Paleozoic carbonates and Winnipeg Formation were assumed to be representative of the Winnipeg Formation in areas where the hydraulic head in the Winnipeg Formation exceeds that in the overlying carbonates. This distribution of head is present throughout much of the Winnipeg Formation east of the Red River (Betcher 1986).

Hydraulic conductivity estimates are available for a limited number of locations. Pumping tests conducted on 20 wells during the early 1980s gave hydraulic conductivities ranging from 1.1×10^{-3} to 3.6×10^{-6} m/s, with 16 of these 20 tests giving values between 10^{-4} and 10^{-6} m/s. These tests were all conducted in either sandstone intervals or over the entire Winnipeg Formation and therefore give little indication of the permeability of the shale units.

In groundwater systems where the fluid velocity is small, Hubbert (1940) defined groundwater potential (Φ) as:

$$\Phi = gz + \int_{p_0}^p \frac{dp}{\rho} \quad (1)$$

where g is the acceleration due to gravity, z is the elevation difference from a reference elevation, p_0 is the reference fluid pressure, p is fluid pressure and ρ is fluid density. The more physically representative quantity of hydraulic head is generally used to describe fluid potential. Hydraulic head is defined as

$$h = \Phi/g \quad (2)$$

In the Winnipeg Formation, groundwater density varies spatially, primarily due to variations in the total dissolved solids (TDS) content of the water (Fig. 5). Due to these variations in density, Eq. 1 is no longer applicable.

A number of techniques have been developed to analyse groundwater flow in variable groundwater density systems. These techniques usually involve approximating the groundwater head distribution in the system by referencing all measurements to a common groundwater density (e.g. McNeal 1965; Hitchon 1969; Bond 1972). However, Jorgensen et al. (1982) has shown that this approach may lead to serious errors in estimating flow in dipping variable density systems. Bachu (1995); Bachu and Michael (2002) indicate that use of equivalent

freshwater heads is not completely accurate in dipping formations due to buoyancy effects. Bachu (1995) suggests that when the driving force ratio, a measure of the ratio between buoyancy and potential forces, is significantly greater than one, the use of equivalent freshwater heads is not appropriate. For this reason, we employ the concept of point-water head, which accounts for density driven flow, to approximate the groundwater potential field in this study. Luszczynski (1961) defines point-water head as:

$$h_{ip} = z + \frac{p}{\rho_i g} \quad (3)$$

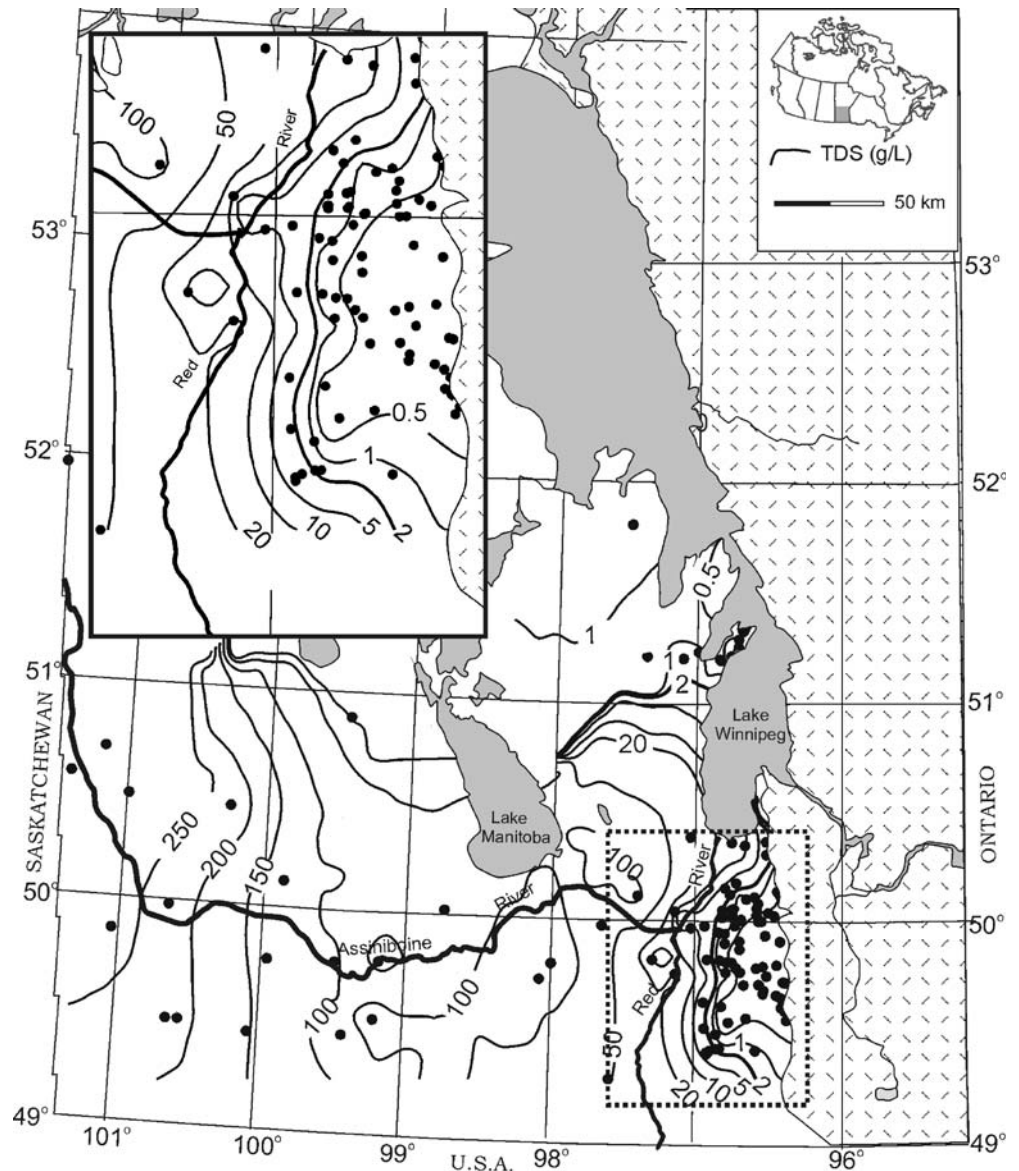
where ρ_i is the groundwater density at the point of completion of a piezometer being used to measure groundwater pressure and z is the elevation of the point of completion. The use of point-water heads gave different gradient magnitudes but did not change the direction of groundwater flow.

The point-water apparent potentiometric surface for the Winnipeg Formation (Fig. 6) was constructed using water well and test-hole data from Manitoba Conservation and drill-stem test data from petroleum wells from the Manitoba Department of Industry, Trade and Mines. Point-water heads show a general west to east decline, from greater than 480 m in the southwest to less than 220 m beneath Lake Winnipeg, which has an elevation of 217 m. The general pattern is interrupted by an area of high point-water head near the southeastern outcrop area where heads are greater than 300 m. Lake Winnipeg appears to form the natural regional discharge area for groundwaters in the Winnipeg Formation based on the distribution of point-water head. The larger scale system is in agreement with the observations of Bachu and Hitchon (1996) on the hydrogeology of the Williston Basin but the smaller scale system in southeastern Manitoba is not apparent in that study. It should be noted that, Bachu and Hitchon (1996) treat the Winnipeg Formation and the overlying Ordovician and Silurian carbonates to form a single hydrostratigraphic unit. This grouping leads to some loss of detail because there are important differences in flow direction and water chemistry between the Winnipeg Formation and the overlying carbonates in Manitoba (Betcher 1986; Grasby and Betcher 2002).

In southwest Manitoba, an area with point-water heads greater than 400 m occurs (Fig. 6) with steep negative gradients occurring to the north and east of this region. These areas with steep gradients are thought to be the result of low permeabilities. The Carman sand body occurs just to the east of the high point-water head area and is an area of low hydraulic gradients, likely due to its high permeability.

In the Interlake area, point-water heads show a gentle regional west to east decline, with an apparent hydraulic gradient of approximately 3.0×10^{-4} . This gradient suggests that groundwater is discharging towards Lake

Fig. 5 Total dissolved solids present in Winnipeg Formation groundwaters contoured in g/L. Dots represent sampling points. Contouring was performed using a kriging routine with a search radius of 75 km. Inset shows area in southeastern part of the study area where sampling density is highest

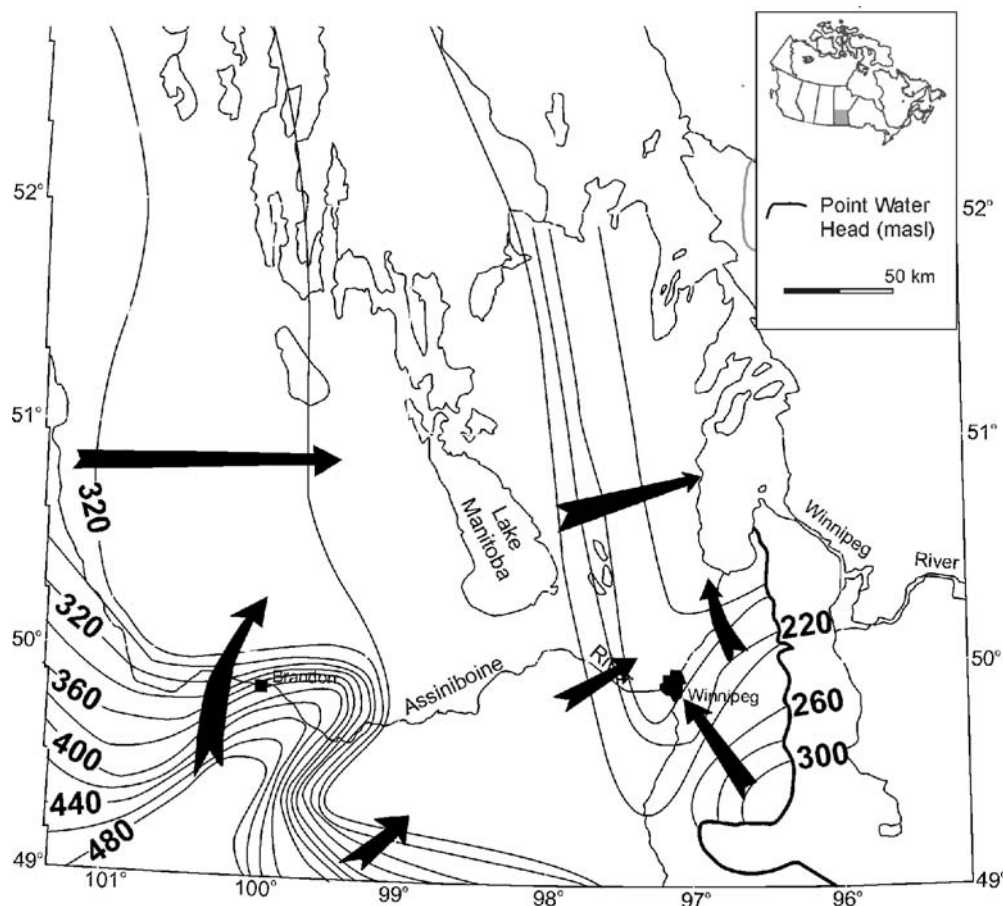


Winnipeg, but there is not a reliable estimate of the discharge rate nor has active discharge been shown. However, the presence of thick clay units beneath Lake Winnipeg suggests that discharge rates would be extremely low. Isotopic studies of the pore waters in these clays south of Winnipeg (Remenda et al. 1994) and beneath Lake Winnipeg (Buhay and Betcher 1998) have indicated that there are waters with low $\delta^{18}\text{O}$ values present in the lower reaches of these clays. In the area south of Winnipeg, these low $\delta^{18}\text{O}$ values are thought to indicate the presence of connate waters within Lake Agassiz sediments. However, beneath Lake Winnipeg it is unclear whether these isotopic values are the result of water discharging from the Winnipeg Formation or due to the presence of Lake Agassiz water or some combination of the two (see discussion on stable isotope data below). West of Lake Manitoba and Lake Winnipegosis, point-water heads are somewhat erratic and few measurements

are available. Downey (1984) indicates that west to east groundwater flow occurs in this area which is consistent with the west to east drop in topography.

As previously mentioned, an area of high groundwater head occurs in association with the subcrop belt of the Winnipeg Formation beneath the Sandilands Moraine in southeastern Manitoba (Fig. 6). This moraine rises approximately 80 m above the plain to the west and is a major recharge area for the Winnipeg Formation (Cherry 2000; Ferguson et al. 2003; Hinton 2003). Point-water heads greater than 300 m occur along the subcrop belt and decrease to the west and northwest. Eastward-moving water from southwestern Manitoba and westward-moving water emanating from the Sandilands are both deflected northwards in the area of the Red River. This region near the Red River south of the City of Winnipeg roughly corresponds to the transition from brines in the west to fresh groundwaters to the east.

Fig. 6 Point-water head data contoured in metres above sea level for the Winnipeg Formation, along with interpreted flow lines (after Betcher 1986). Arrows show interpreted directions of ground-water flow



Hydrochemistry

Methodology

Chemical analyses of water samples from 683 wells covering a large section of southern Manitoba were used in this study (Fig. 5). The sample locations extend from the Canada–United States border in the south to the Hecla area in the north and from the subcrop belt of the Winnipeg Formation in the east to an area south of Lake Manitoba in the west. Analyses come from 2 main sources: (1) a large database compiled by Manitoba Water Stewardship and (2) the Geological Survey of Canada. For this study, only samples with all major ions analysed and with charge balance errors of less than 10% were used. Additional samples from oil wells given by McCabe (1978) and a database maintained by the Petroleum Branch of Manitoba Industry, Economic Development and Mines are also used in this study. The complete dataset is presented in Ferguson et al. (2005). The data are classified based on Hem (1985): brines (>35 g/L); saline waters (10–35 g/L); brackish waters (2–10 g/L); and freshwaters (<2 g/L).

The current database also contained 88 analyses of stable isotopes of oxygen and hydrogen with all but eight of these samples having corresponding major ion analyses with acceptable charge balances. These analyses were performed at the Environmental Isotope Laboratory and the University

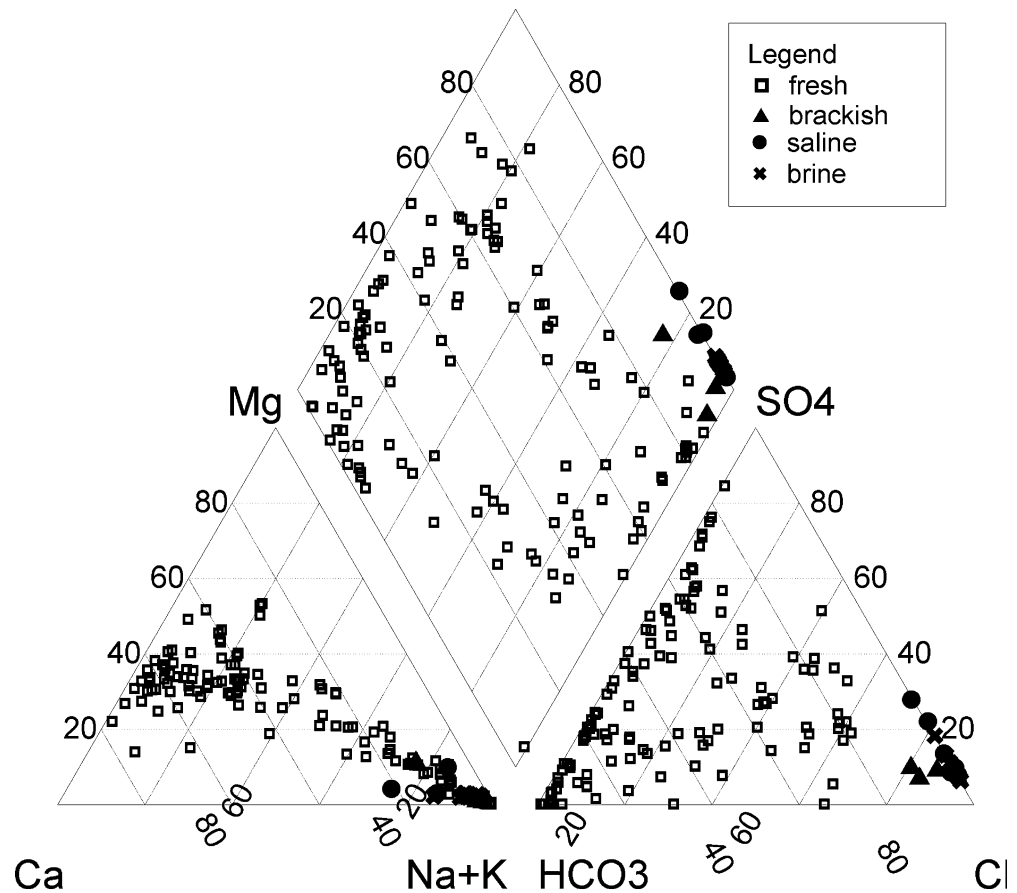
of Waterloo. $^{18}\text{O}/^{16}\text{O}$ and D/H ratios are expressed using δ notation. Values are relative to Vienna standard mean ocean water (VSMOW). Analytical errors are estimated to be approximately $\pm 2\%$ for δD and $\pm 0.2\%$ for $\delta^{18}\text{O}$.

Water chemistry

The 2 g/L TDS isocon is used to define a boundary between freshwaters and saline waters within the Winnipeg Formation (Fig. 5). The freshwater–saline water interface occurs approximately 70 km west of the subcrop area in the extreme southern portion of the aquifer in Manitoba and just to the west of Lake Winnipeg in the Interlake area. An anomalous region of saline water occurs immediately south of Lake Winnipeg and extends eastward to the subcrop edge. Near the City of Winnipeg, the 2 g/L isocon occurs to the east of the Red River. To the west of this interface, TDS increases sharply to 50 g/L. TDS levels then increase more gradually from 50 to 100 g/L in the central part of Manitoba. In the southwestern part of the province, TDS increases from 50 g/L to over 250 g/L in the area coincident with the boundary between the transitional sandstone and shale facies in the west and the shale facies in the east in the lower part of the Winnipeg Formation (Fig. 4).

Fresh groundwaters exhibit a range of geochemical facies (Fig. 7), the development of which will be discussed in

Fig. 7 Piper plot of water samples from the Winnipeg Formation



more detail later in this report. In southeastern Manitoba, Ca–Mg–HCO₃ groundwaters are present beneath and immediately downgradient of the Sandilands recharge area. Further along this flow path, groundwaters transition to a Na–HCO₃ facies bordering parts of the aquifer occupied by saline waters. In the Interlake freshwater area, groundwaters are typically very soft sodium-mixed anion type with significant chloride and sulfate content. The pH of these waters in places exceeds 9 and many groundwaters effervesce strongly and analyses indicated the presence of N₂ gas. The log Na–Cl ratio by molar concentration has values between 0 and 2 for freshwaters (Fig. 8). In areas of the aquifer occupied by freshwater, sulfate concentrations are generally low (<0.3 g/L).

Areas of the Winnipeg Formation where TDS is greater than 2 g/L are dominated by Na–Cl groundwaters. Log Na–Cl ratios for samples with TDS concentrations above 2 g/L are all approximately zero. Bromide results were available for 207 of the samples used in this study, with concentrations ranging from 0.052 mg/L to 1.2 mg/L. Bromide, like Cl, increases in concentration with increasing TDS. However, Br and Cl do not maintain a constant ratio in waters with TDS greater than 2 g/L (Fig. 9). Samples from brackish waters, saline waters and brines have molar ratios between 1,156 and 8,079. These ratios are noticeably higher than the average Cl–Br ratio of sea water (658 by molar ratio; Holland 1978) and may

indicate that the Na and Cl have originated from dissolution of salt deposits low in Br.

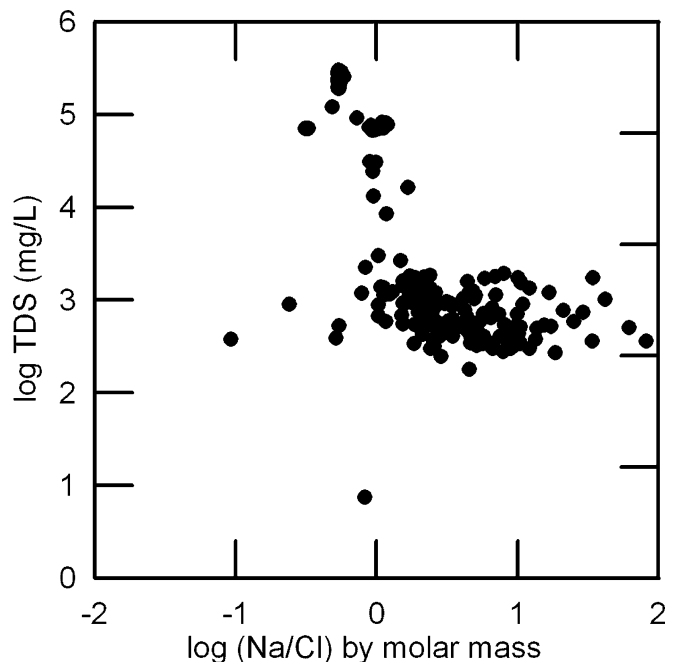


Fig. 8 Na–Cl ratios by molar mass plotted vs. TDS for Winnipeg Formation groundwaters

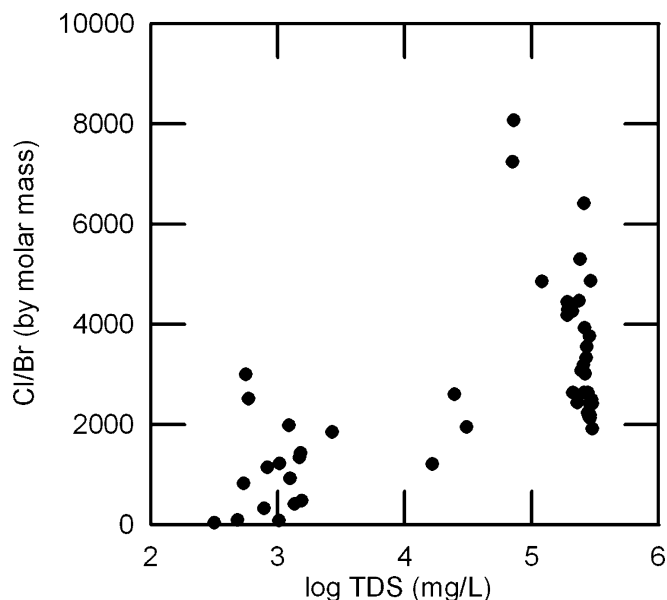


Fig. 9 Cl–Br ratios by mass plotted vs. TDS for Winnipeg Formation groundwaters. Note that lack of points for brackish and saline waters is due to a lack of bromide data for those regions of the Winnipeg Formation

Stable isotopes of hydrogen and oxygen

The local meteoric water line (MWL) for Gimli, Manitoba, approximately 60 km north of Winnipeg is defined as (Day 1977):

$$\delta D = 8.2\delta^{18}O + 10.7\text{‰} \quad (4)$$

This relationship is consistent with the global MWL given by Rozanski et al. (1993). The δD and $\delta^{18}O$ measurements used in this study generally follow this relationship, and have an R^2 coefficient of correlation of 0.94 for the Gimli MWL (Fig. 10). However, there is a slight deviation from this relationship in waters with the higher isotope values. These samples also have the highest salinities of samples analysed for stable isotopes.

Near the subcrop of the Winnipeg Formation, in the vicinity of the Sandilands area, $\delta^{18}O$ values, ranging from -12 to -14‰ , are consistent with modern average values (Fritz et al. 1975; Fig. 11). To the north and west of the Sandilands area, $\delta^{18}O$ values decrease to less than -16‰ . This area of decreasing $\delta^{18}O$ values roughly corresponds to the position of the Carman Sand. An area of increasing $\delta^{18}O$ values that occurs in Winnipeg Formation groundwater northwest of Winnipeg roughly corresponds to an area where the upper half of the Winnipeg Formation is dominated by shale facies. In the Interlake area, $\delta^{18}O$ values as low -24‰ are observed, with values becoming higher towards the shore of Lake Winnipeg.

Origins of waters in the Winnipeg Formation

The Winnipeg Formation can be divided into two regional groundwater flow systems based on head gradients

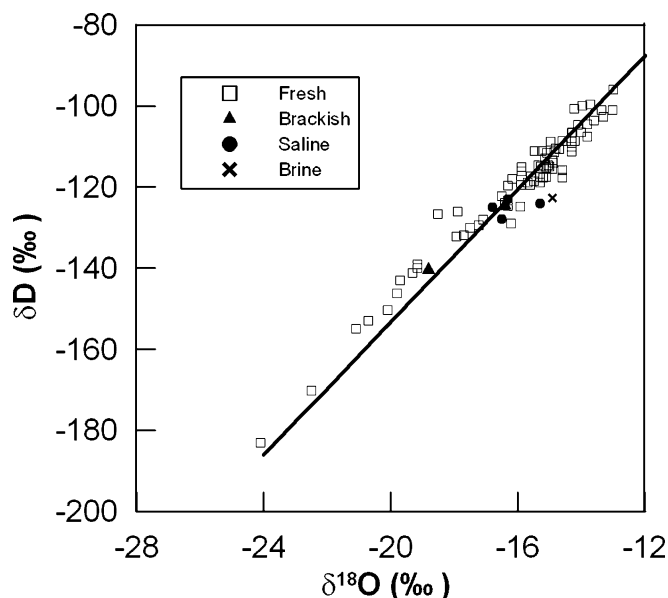


Fig. 10 $\delta^{18}O$ vs. δD for Winnipeg Formation groundwaters plotted as open circles. The Gimli meteoric water line is plotted as a solid line and has a correlation coefficient of 0.94 with the observed data

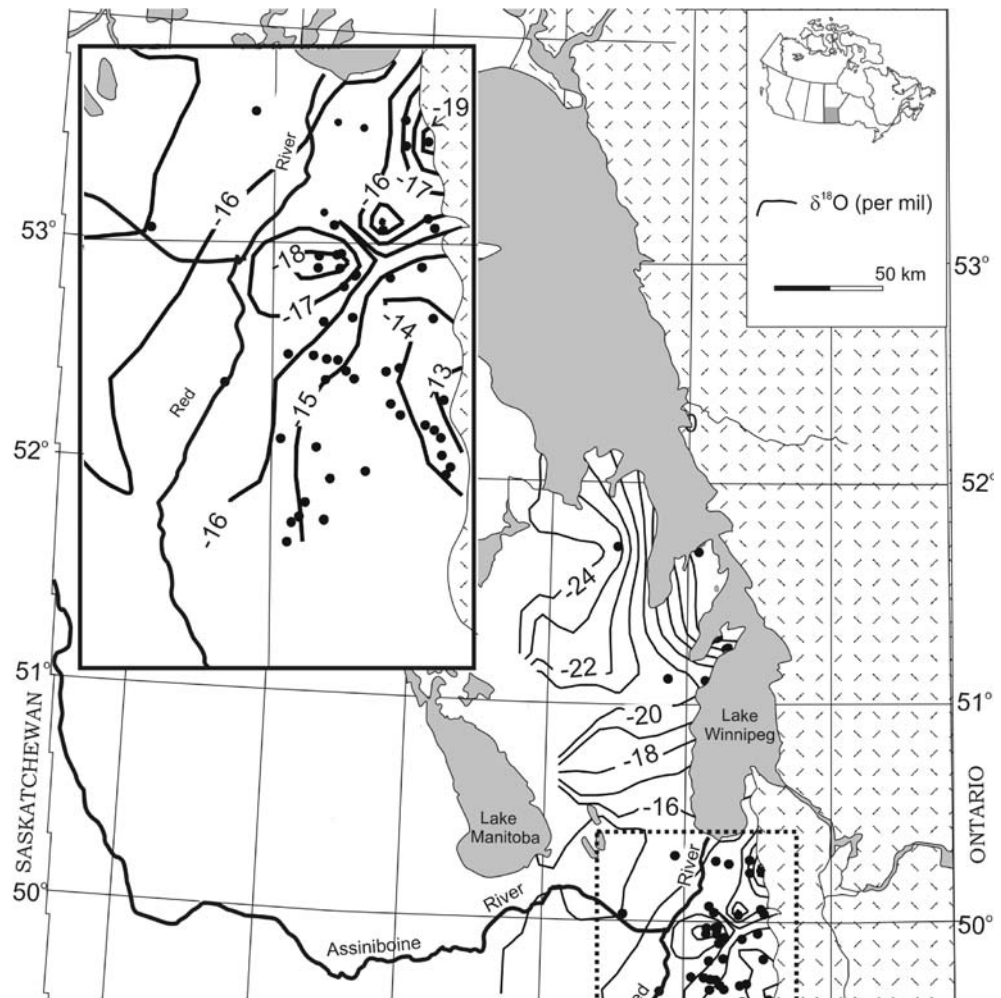
(Fig. 6): (1) an area where groundwater is generally flowing towards the northeast from the Williston Basin dominated by high TDS; and (2) a region in southeast Manitoba where modern low TDS groundwater is recharged in the Sandilands area and flows to the north and west.

Origin of freshwaters

Freshwaters within the Winnipeg Formation in Manitoba plot along the Gimli MWL and have $\delta^{18}O$ values ranging from -12 to -24‰ , indicating recharge under a wide range of climatic conditions. In southeastern Manitoba, where isotopic values are consistent with modern precipitation in the region, low TDS, Ca–Mg– HCO_3 facies groundwater are found. This signature is consistent with recharge waters reacting with carbonate minerals present in the glaciofluvial and glacial sediments overlying the Winnipeg Formation in the Sandilands area.

Northwest of the subcrop belt, $\delta^{18}O$ values decrease to approximately -16 to -18‰ , with the lowest values occurring near the transition area between freshwater and saline water. These values are lower than those observed in average modern precipitation in southern Manitoba, suggesting that these waters were recharged during a colder climate than present. Researchers in other areas have explained low $\delta^{18}O$ values of groundwater by suggesting recharge during the Wisconsin Glaciation (e.g. Siegel 1991; Martini et al. 1998; Clark et al. 2000; Grasby and Chen 2005) and this has also been suggested for the Carbonate Rock aquifer in southern Manitoba (Fritz et al. 1975; Grasby and Betcher 2002). These low

Fig. 11 Distribution of $\delta^{18}\text{O}$ in Winnipeg Formation groundwaters, contoured in per mil relative to VSMOW. Contouring was performed using a kriging routine with a search radius of 75 km. *Inset* shows area in southeastern part of the study area where sampling density is highest



values are similar to low $\delta^{18}\text{O}$ values documented in Lake Agassiz sediment pore waters, and are considered to represent Pleistocene meltwater signatures (Remenda et al. 1994; Buhay and Betcher 1998).

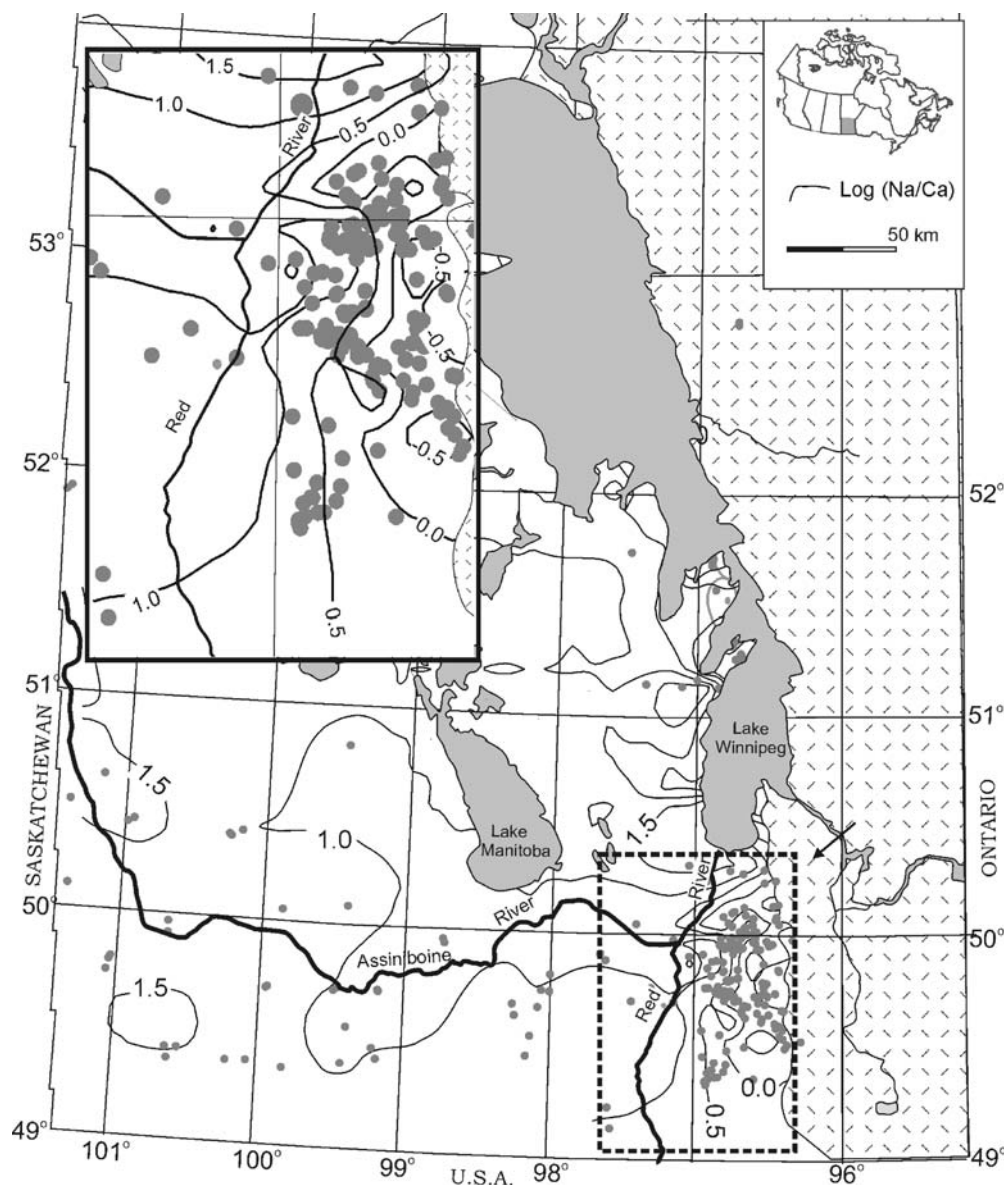
While the current NE directed basin-scale flow system is thought to be driven from recharge areas in north-central United States (Bachu and Hitchon 1996), conditions during the Pleistocene were significantly different. Subglacial water would have been under approximately 1,500 m of cryostatic head during the time of maximum ice thickness in the late Wisconsinan Glaciation (Peltier 1994). This increase in head would have been greater than that present at the southwest end of the Williston Basin in South Dakota and Wyoming and caused a reversal in the flow direction within the Williston Basin (Grasby et al. 2000), thus allowing an influx of basal meltwater into the underlying aquifer systems of what is now southern Manitoba. Therefore, following this previous work, we interpret the low $\delta^{18}\text{O}$ waters ($<-15\text{‰}$) to represent relict subglacial recharge into the Winnipeg Formation.

The area with low $\delta^{18}\text{O}$ values is dominated by low TDS Na– HCO_3 waters with relatively high Na–Ca ratios (Fig. 12). These waters have chemical characteristics that

are distinct from waters found closer to modern recharge areas suggesting some process has added Na during or after Pleistocene meltwater intrusion. Prior to the Pleistocene glaciations, the regional groundwater movement appears to have been eastward in this part of the Williston Basin, similar to present-day conditions (Grasby and Chen 2005). At this time, it would be expected that the entire Winnipeg Formation would have been occupied by more saline basin type Na–Cl waters extending from deeper portions in the basin. If this were the case, the ion exchange sites would be occupied predominantly by Na. The influx of fresh glacial meltwater into the Winnipeg would have displaced saline waters, but then also led to an ion-exchange process generated the Na– HCO_3 water observed today. This is consistent with areas where freshwater recharge into saline coastal aquifers occurs, resulting in Na– HCO_3 facies groundwater (Appelo 1994; Lambrakis and Kallergin 2001). The observation that the modern recharge zones in the Sandilands area show Ca– HCO_3 waters, suggests that the limited capacity of the exchange sites in the recharge zones has been exhausted.

Groundwater in the Interlake area has the lowest $\delta^{18}\text{O}$ values ranging from -16 to -24‰ , suggesting that this

Fig. 12 Log Na–Ca ratio by molar mass in the Winnipeg Formation. Contouring was performed using a kriging routine with a search radius of 75 km. *Inset* shows area in southeastern part of the study area where sampling density is highest



water was also recharged during the Wisconsin Glaciation. In contrast to the Sandilands, this groundwater appears to have been relatively stagnant throughout the Holocene due to the low hydraulic gradients present in this region and the low permeability sediments that have been deposited in Lake Winnipeg, the regional discharge area, since the late Pleistocene. Thus, this region likely holds the most pure end member, as represented by the lowest isotope values, of Pleistocene meltwater. The presence of Na–HCO₃ facies groundwater in this area suggests that ion exchange during the influx of subglacial water occurred in this area as well.

Origin of saline waters

In brackish and saline water regions of the aquifer, few $\delta^{18}\text{O}$ values are available. $\delta^{18}\text{O}$ values range between -14.9 and -16.8 ‰, with -14.9 ‰ being the $\delta^{18}\text{O}$ value for the sample

with highest TDS values. These samples plotted slightly below the Gimli MWL, similar to the relationship observed for oil-well data in the overlying Carbonate Rock aquifer (Grasby and Betcher 2002), although a more clearly defined departure from the Gimli MWL was found in that study. This deviation from the MWL suggests mixing with basin brines, which typically have $\delta^{18}\text{O}$ values of -3 to $+4$ ‰ in the Williston Basin and plot beneath the meteoric water line (e.g. Rostron et al. 1998). The few samples available for brines and saline waters in the current study tend to plot beneath the MWL and suggest that a similar trend may be present in the Winnipeg Formation.

Groundwaters with TDS greater than 2 g/L in the Winnipeg Formation are of Na–Cl facies. The log Na–Cl ratio shows a slight decrease from approximately 0.2 in brackish waters to approximately 0.0 in more saline waters. Grasby and Chen (2005) observed similar Na–Cl ratios in the eastern part of the Williston Basin and

attributed them to halite dissolution. Halite dissolution is also supported by Br concentrations, which are much lower than expected for sea water and Cl are much higher in some cases (Carpenter 1978). High Cl–Br ratios are also present in the overlying Carbonate Rock aquifer (Grasby and Betcher 2002).

Mixing of Winnipeg Formation groundwaters

Stable isotope and major ion data suggest the presence of waters resulting from mixing of three different end-member waters in the Winnipeg Formation (Fig. 13): (1) a poorly characterized high TDS, high $\delta^{18}\text{O}$ water which represents basin brines; (2) low TDS, high $\delta^{18}\text{O}$ water consistent with modern recharge; and (3) low to intermediate TDS water with low $\delta^{18}\text{O}$ values related to subglacial recharge. Associated with these three end members are two mixing events: (1) mixing of basin brines with subglacial recharge, and (2) mixing of subglacial recharge with modern recharge. The decrease in $\delta^{18}\text{O}$ values with increasing TDS, up to approximately 2 g/L, followed by increasing $\delta^{18}\text{O}$ values for still greater salinities (Fig. 12), is the result of these mixing events.

The composition of more saline waters also suggests the presence of subglacial waters mixed with pre-existing formation water. Saline waters and brines in south-central Manitoba have Cl–Br ratios, which are much higher than the average value of sea water. However, these ratios are also considerably lower than the Cl–Br ratios found in minerals of the Williston Basin (e.g. 6,000 for the Prairie Evaporite Formation), suggesting mixing of these two types of water (Grasby and Betcher 2002). The presence of saline waters and brines with $\delta^{18}\text{O}$ values lower than those found deeper in the basin also suggests that there is some component of subglacial recharge in these waters.

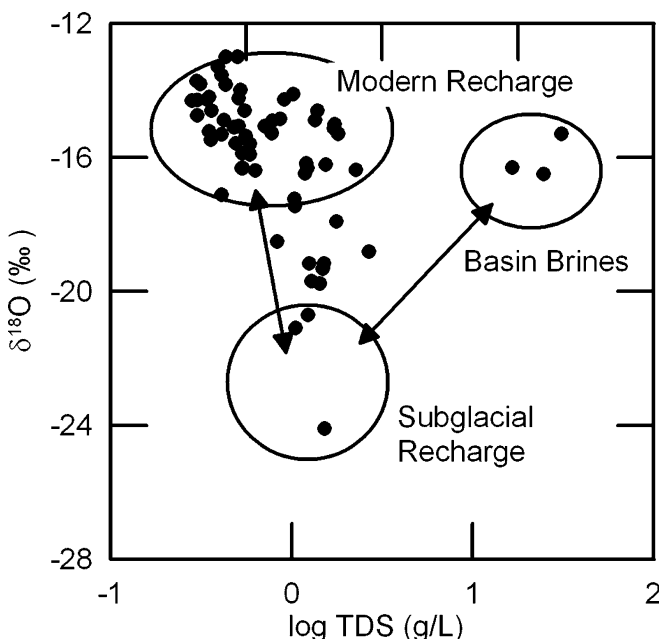


Fig. 13 $\delta^{18}\text{O}$ vs. TDS concentration for Winnipeg Formation groundwaters showing origins and probable mixing trends

Comparison to Carbonate Rock aquifer

From a standpoint of groundwater resource evaluation in southern Manitoba, it is of interest to compare the Winnipeg Formation to the overlying Carbonate Rock aquifer. Both aquifers are important sources of water in Manitoba and there is a substantial amount of interaction between the two aquifers through wells that are completed through both units (Betcher and Ferguson 2003). The Carbonate Rock aquifer, like the Winnipeg Formation, also contains components of basin brines, subglacial recharge, and modern recharge (Grasby and Betcher 2002).

In the Carbonate Rock aquifer, subglacial recharge is generally mixed with either basin brines or modern meteoric water. The division of saline and freshwater in this aquifer is coincident with what appears to be a quasi-stationary hydrogeological divide controlled by major river and lake systems in southern Manitoba (Grasby and Betcher 2002). This semi-confined aquifer is no longer significantly affected hydrodynamically by the last glaciation, but it is not known how quickly this readjustment occurred.

The Winnipeg Formation appears to be recovering from the effects of the last glaciation much more slowly than the overlying Carbonate Rock aquifer. Large areas of the Winnipeg Formation still contain subglacial recharge, including the Interlake area where point-water heads indicate that the direction of flow has reverted to pre-glacial conditions following the Wisconsin Glaciation. The Winnipeg Formation does not appear to be affected by surface hydrology to the same degree and in some cases the relationship between water chemistry and current hydrodynamics is not as clear. Relict glacial meltwater present in southeastern Manitoba aquifers will likely discharge into Lake Winnipeg eventually if present hydraulic conditions persist. The movement of the interface between fresh and saline waters in the Winnipeg Formation appears to be more likely. This interface does not currently correlate with a discharge area or flow divide related to surface hydrology that would fix its location. The re-equilibration of regional flow system in response to glacial unloading will eventually result in further adjustment of the potentiometric surface and a significant reduction of the area of the Winnipeg Formation containing freshwater in southeastern Manitoba, but the amount of time required for this to happen is poorly constrained. The difference in time required to remove the effects of the glaciation on the two aquifers is likely due to differences in the spatial distribution of modern recharge and discharge areas and due to the greater permeability in the Carbonate Rock aquifer relative to that of the Winnipeg Formation. These differences are of particular interest due to the many hydraulic connections between the two aquifers that have been introduced over the past century by drilling (Betcher and Ferguson 2003). The presence of water with increased TDS and low $\delta^{18}\text{O}$ values in the Carbonate Rock aquifer may indicate upward flow of water through wells from the Winnipeg Formation in some areas. Efforts are currently being made by the

Province of Manitoba to locate and seal off boreholes and wells that connect the two aquifers to eliminate contamination of groundwater in the Carbonate Rock aquifer. In the future, the saline waters in the Winnipeg Formation will move eastward under freshwater bearing portions of the overlying Carbonate Rock aquifer, potentially exacerbating this problem.

Conclusions

The portions of the Winnipeg Formation bearing potable freshwater have an origin largely related to the recent glacial history. The distribution of major cations suggests that prior to glaciation, the formation was occupied by more saline Na-rich waters. These high TDS waters were displaced near the subcrop area by an influx of subglacial meltwaters, resulting in the low $\delta^{18}\text{O}$, Na-rich waters found in some areas of the Winnipeg Formation today. Large glacial complexes deposited over the subcrop of the formation in southeastern Manitoba have also resulted in modern freshwater recharge to the aquifer. However, there is a gradual process of re-establishing a new equilibrium in response to offloading of the glacial ice. Hydraulic head distribution indicates that saline formation waters from the Williston Basin are moving eastward and resalinizing portions of the aquifer currently occupied by freshwater. The Winnipeg Formation is unlike the overlying Carbonate Rock aquifer which has a hydraulic divide defined by major river and lake systems which restricts eastward movement of saline waters into the freshwater zone (Grasby and Betcher 2002). The eastward movement of saline waters in the aquifer are less inhibited and can be more easily enhanced by over production in the freshwater zone.

Point-water heads of the Winnipeg Formation indicate the presence of two flow systems: (1) updip flow out of the Williston Basin from southwest to northeast in western Manitoba and the Interlake area, and (2) freshwater recharge emanating from the Sandilands area flowing to the west and northwest in southeastern Manitoba. However, three distinct origins are found within the aquifer: (1) basin brines; (2) modern meteoric recharge; and (3) subglacial recharge that occurred during the Pleistocene. Freshwater from subglacial recharge is located primarily in an area between the Sandilands and the Red River in southeastern Manitoba and in the Interlake area. If the current hydraulic head regime persists, eventually the Interlake area will be occupied by saline water. The creation of the glaciofluvial complexes along the subcrop belt of the Winnipeg Formation during the Wisconsin Glaciation means that as long as there is sufficient recharge to these areas, there will likely be an area of freshwater in the aquifer in southeastern Manitoba. However, the freshwater-saline-water boundary does not appear to be in equilibrium. The interface in the area south of Lake Winnipeg appears to be moving northwards and eventually the zone of saltwater in this area will likely disappear, resulting in a continuous zone of freshwater

between the Sandilands and Lake Winnipeg. In the area near the Red River, the interface appears to be moving towards the east in this area and some wells near the interface may cease to produce potable water as the system tries to equilibrate. This influx of saline water could be accelerated by excessive withdrawals and further modeling of the movement of this interface is required for groundwater management purposes. The eastward movement of saline water in the Winnipeg Formation underneath freshwater bearing portions of the overlying Carbonate Rock aquifer raises the importance of insuring the segregation of the two aquifers' systems during well completions.

Acknowledgements The authors wish to thank Frank Render for insightful conversations on the Winnipeg Formation and providing access to data. The authors are also grateful to Matt Leybourne and the late Dan Boyle for allowing us access to unpublished data collected by the Geological Survey of Canada. Graham Phipps and two anonymous reviewers provided thoughtful reviews of an earlier version of the manuscript.

References

- Andrichuk JM (1959) Ordovician and Silurian stratigraphy and sedimentation in southern Manitoba, Canada. *Bull Am Assoc Petrol Geol* 43:2333–2398
- Appelo CAJ (1994) Cation and proton exchange, pH variations, and carbonate reactions in a freshening aquifer. *Water Resour Res* 30:2793–2805
- Bachu S (1995) Flow of variable-density formation water in deep sloping aquifers: review of methods of representation with case studies. *J Hydrol* 164:19–38
- Bachu S, Hitchon B (1996) Regional-scale flow of formation waters in the Williston basin. *AAPG Bull* 80:248–264
- Bachu S, Michael K (2002) Flow of variable-density formation water in deep sloping aquifers: minimizing the error in representation and analysis when using hydraulic head distributions. *J Hydrol* 259:49–65
- Baillie AD (1953) Devonian names and correlation in the Williston Basin area. *Bull Am Assoc Petrol Geol* 37:444–447
- Betcher RN (1986) Regional hydrogeology of the Winnipeg formation in Manitoba. In: van der Kamp G, Madunicky M (eds) *Proceedings of the Third Canadian Hydrogeological Conference*, Saskatoon, SK, April 1986, pp 159–174
- Betcher RN, Ferguson GAG (2003) Impacts from boreholes interconnecting multiple aquifers—a case study of Paleozoic aquifers in south-eastern Manitoba. 4th Annual Joint CGS-IAH Conference. Winnipeg, MB, 29 Sept. 1– Oct. 2003
- Bond DC (1972) Hydrodynamics in deep aquifers of the Illinois Basin. *Illinois State Geol Surv Circ* 470
- Buhay WM, Betcher RN (1998) Paleohydrologic implications of ^{18}O enriched Lake Agassiz water. *J Paleolimnol* 19:285–296
- Carpenter AB (1978) Origin and chemical evolution of sedimentary brines in sedimentary basins. *Oklahoma Geol Surv Circ* 79:60–77
- Cherry AJ (2000) A multi-tracer estimation of groundwater recharge in a glaciofluvial aquifer in southeastern Manitoba. MSc Thesis, University of Ottawa, Ottawa, ON
- Clark ID, Douglas M, Raven K, Bottomley D (2000) Recharge and preservation of Laurentide glacial meltwater in the Canadian Shield. *Ground Water* 38:735–742
- Day MJ (1977) The movement and hydrochemistry of groundwater in the fractured clayey deposits of the Winnipeg Area. MSc Thesis. University of Waterloo, Waterloo, ON
- Downey JS (1984) Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming. *US Geol Surv Prof Pap* 127, 3-G

- Ellingson JB (1995) Depositional environments and paleogeography of the Winnipeg Group (Ordovician), Williston, Basin, North Dakota. MSc Thesis, University of North Dakota, Grand Forks, ND
- Ferguson G, Woodbury AD, Matile GLD (2003) Estimating recharge beneath an interlobate moraine using temperature profiles. *Ground Water* 41(5):640–646
- Ferguson G, Betcher, RN, Grasby SE (2005) Water chemistry of the Winnipeg formation in Manitoba. *Geol Surv Can Open File* 4933:37
- Fritz P, Render FW, Brown RM, Drimmie RJ (1975) Environmental isotopes in the groundwater of the Upper Carbonate Aquifer in central Manitoba. *Proceedings of the Canadian Hydrology Symposium* 75, Winnipeg, MB, 11–14 August 1975, pp 370–376
- Genik GJ (1952) A regional study of the Winnipeg Formation. MSc Thesis, University of Manitoba, Winnipeg, MB
- Grasby SE, Betcher RN (2002) Hydrogeochemistry of the Carbonate Rock aquifer, Manitoba. *Can J Earth Sci* 39:1053–1063
- Grasby SE, Chen Z (2005) Subglacial recharge into the Western Canada Sedimentary Basin: impact of Pleistocene glaciation on basin hydrodynamics. *GSA Bull* 117:500–514
- Grasby S, Osadetz K, Betcher R, Render F (2000) Reversal of the regional-scale flow system of the Williston Basin in response to Pleistocene glaciation. *Geology* 28:635–638
- Hem JD (1985) Study and interpretation of the chemical characteristics of natural water. USGeol Surv Water Suppl Pap 2254
- Hinton M (2003) Comparison of groundwater sampling methods for measuring recharge. 4th Annual Joint CGS-IAH Conference. Winnipeg, MB, 29 Sept. 1– Oct. 2003
- Hitchon B (1969) Fluid flow in the Western Canada Sedimentary Basin. 2. Effect of geology. *Water Resour Res* 5(2):460–469
- Holland HD (1978) *The chemistry of the atmosphere and oceans*. Wiley, New York, p 351
- Hubbert MK (1940) The theory of ground-water motion. *J Geol* 48(8):785–944
- Jorgensen DG et al (1982) Determination of flow in aquifers containing variable-density water. *Ground Water Monit Rev* 2(2): 40–45
- Lambrakis N, Kallergin G (2001) Reaction of subsurface coastal aquifers to climate and land use changes in Greece: modelling of groundwater refreshing patterns under natural recharge conditions. *J Hydrol* 245:19–31
- Luszczynski NJ (1961) Head and flow of ground water of variable density. *J Geophys Res* 66(12):4247–4256
- Martini AM, Walter LM, Budai JM, Ku TCW, Kaiser CJ, Schoell M (1998) Genetic and temporal relations between formation waters and biogenic methane: Upper Devonian Antrim shale, Michigan Basin, USA. *Geochim Cosmochim Acta* 62:1699–1720
- McCabe HR (1971) Stratigraphy of Manitoba: an introduction and review. *Spec Pap Geol Assoc Can* 9:167–187
- McCabe HR (1978) Reservoir potential of the Deadwood and Winnipeg formations, southwestern Manitoba. *Geological Paper* 78–3, Manitoba Department of Mines, Winnipeg, MB
- McNeal RP (1965) Hydrodynamics of the Permian Basin. In: Young A, Galley JE (eds) *Fluids in subsurface environments*, AAPG Memoir no. 4, AAPG, Tulsa, OK, pp 308–326
- Osadetz KG, Haidl FM (1989) Tippecanoe sequence: middle Ordovician to lowest Devonian vestiges of a great epeiric sea. In: Ricketts BD (ed) *Western Canada Sedimentary Basin: a case history*. Canadian Society of Petroleum Geologists, Calgary, AB
- Paterson DF (1971) The stratigraphy of the Winnipeg Formation (Ordovician) of Saskatchewan. SIR Report no. 140. Saskatchewan Industry and Resources, Regina, SK
- Peltier WR (1994) Ice age paleotopography. *Sci* 265:195–201
- Remenda VH, Cherry JA, Edwards TWD (1994) Isotopic composition of old ground water from Lake Agassiz: implications for late Pleistocene climate. *Sci* 265:1975–1981
- Rostron BJ, Holmden C, Kreis LK (1998) Hydrogen and oxygen isotope composition of Cambrian to Devonian formation waters, Midale area, Saskatchewan. In: Christopher JE, Gilboy CF, Paterson DF, Bend SL (eds) *Eighth International Williston Basin Symposium*. Sask Geol Soc Spec Publ 13:267–273
- Rozanski K, Araguas-Araguas L, Gonfiantini R (1993) Isotope patterns in modern global precipitation. In: *Climate change in continental isotopic records*. Am Geophys Union Monogr 78:1–36
- Siegel DI (1991) Evidence for dilution of deep, confined ground water by vertical recharge of isotopically heavy Pleistocene water. *Geology* 19:433–436
- Simpson F, McCabe HR, Barchyn D (1987) Subsurface disposal of wastes in Manitoba, part I: current status and potential of subsurface disposal of fluid industrial wastes in Manitoba. *Geological Paper GP93-1*, Geological Services, Manitoba Energy and Mines, Winnipeg, MB
- Teller JT, Clayton L (1983) An Introduction to Glacial Lake Agassiz. In: Teller JT, Clayton L (eds) *Glacial Lake Agassiz*. Geol Assoc Can Spec Pap 26:3–6
- Teller JT, Fenton MM (1980) Late Wisconsinan glacial stratigraphy and history of southeastern Manitoba. *Can J Earth Sci* 17:19–35
- Todd BJ, Lewis C, Nielsen E, Thorleifson LH, Bezys RK, Weber W (1998) Lake Winnipeg: geological setting and sediment seismostratigraphy. *J Paleolimnol* 19:215–243
- Vigrass LW (1971) Deposition framework of the Winnipeg Formation in Manitoba and eastern Saskatchewan. *Geol Assoc Can Spec Pap* 9:225–234