



Abstract

# Regional variations in oxygen isotopic compositions in the Yeoman and Duperow aquifers, Williston basin (Canada–USA)

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## Abstract

Oxygen isotope compositions of formation waters from drill stem tests and produced waters are reported from the Yeoman and Duperow aquifers across the Williston basin. Mapped isotopic distributions vary across the basin from  $<-24\text{‰}$   $\delta^{18}\text{O}$  to values over  $+9.4\text{‰}$   $\delta^{18}\text{O}$ , relative to Standard Mean Ocean Water (SMOW). Areal distributions of oxygen isotopes support a complex model of paleohydrogeology of the basin. They can be used to trace meteoric recharge into the basin, identify slow or stagnant brine-flow areas, and the presence of glacially induced recharge water deep in the subsurface.

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## 1. Introduction

Fluid transport in deep basinal aquifers is recognized as playing a key role in many basin-wide geologic processes, including hydrocarbon migration and ore-deposit formation (e.g., Garven, 1995). Two of the most informative tracers of fluid migration are the isotopic compositions of hydrogen and oxygen, which have been used in hydrogeochemical studies of many basins (Clayton et al., 1966; Hitchon and Friedman, 1969; Connolly et al., 1990; and many others). Notably lacking are results from one of world's largest confined aquifer systems: the Williston basin (Canada–USA).

Hydrogen and oxygen isotope compositions for Williston basin formation waters have been reported for aquifers overlying three potash mines in Saskatchewan (Wittrup et al., 1987; Wittrup and Kyser, 1990), a vertical isotopic profile of formation waters from pre-Mississippian aquifers in the Midale area of southeastern Saskatchewan (Rostron et al., 1998; Rostron and Holmden, 2000), and for shallow water wells and springs in central Manitoba (Grasby et al., 1999, 2000). All of the previously published data have been relatively confined in horizontal extent, and thus have been of limited use for interpreting regional groundwater flow patterns. In this paper, we report regional patterns of oxygen isotope composition for the Yeoman and Duperow aquifers, two of the more important hydrocarbon-producing aquifers in the basin.

Regionally, the hydrogeology and hydrochemistry of the Williston basin have been widely studied. Examples include work on the Canadian (Bachu and

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Hitchon, 1996), and American portions (Downey, 1986; Busby et al., 1995), and on a basin-wide scale (Benn and Rostron, 1998). The groundwater flow system in the Williston basin is one of the best examples of a large-scale confined aquifer system in the world. Recharge is thought to occur in the west to southwestern portions of the basin via a series of Tertiary-aged intrusive uplifts (e.g., Fig. 1: 48°N, 108°W). Discharge of the flow systems occurs approximately 1000 km to the northeast, along the lowlands at the margin of the basin in Manitoba (e.g., Fig. 1: 50°N, 98°W). Elevation differences between the recharge and discharge areas of more than 1000 m provide the driving force for fluid flow. Hydrochemically, there are three main types of waters present in the basin: (1) a “fresher” water of dominantly Ca–SO<sub>4</sub> type with Total Dissolved Solids (TDS) less than seawater (35 g/l); (2) a “brine” of dominantly Na–Cl type with TDS > 100 g/l; and (3) a “brine” of Na–Ca–

Cl composition with TDS > 200 g/l. Water composition across the basin varies areally and vertically with a general, but not pervasive, pattern of increasing TDS with depth. Fresh waters represent meteoric recharge into the basin, while the brines are mixtures of waters derived from dissolution of evaporites and evaporatively concentrated seawater (Jampen and Rostron, 2000).

The Yeoman and Duperow aquifers were chosen for presentation because their isotopic distributions represent typical results for pre-Mississippian aquifers in the basin. Geologically, strata that make up the Yeoman aquifer are 0–200 m of variably dolomitized limestones belonging to the upper Ordovician-aged Yeoman Formation. The Yeoman aquifer is confined by the shales of the Winnipeg Formation below, and above by a mixed package of low-permeability evaporitic units belonging to the Herald and Stony Mountain formations. In contrast, rocks that make up the

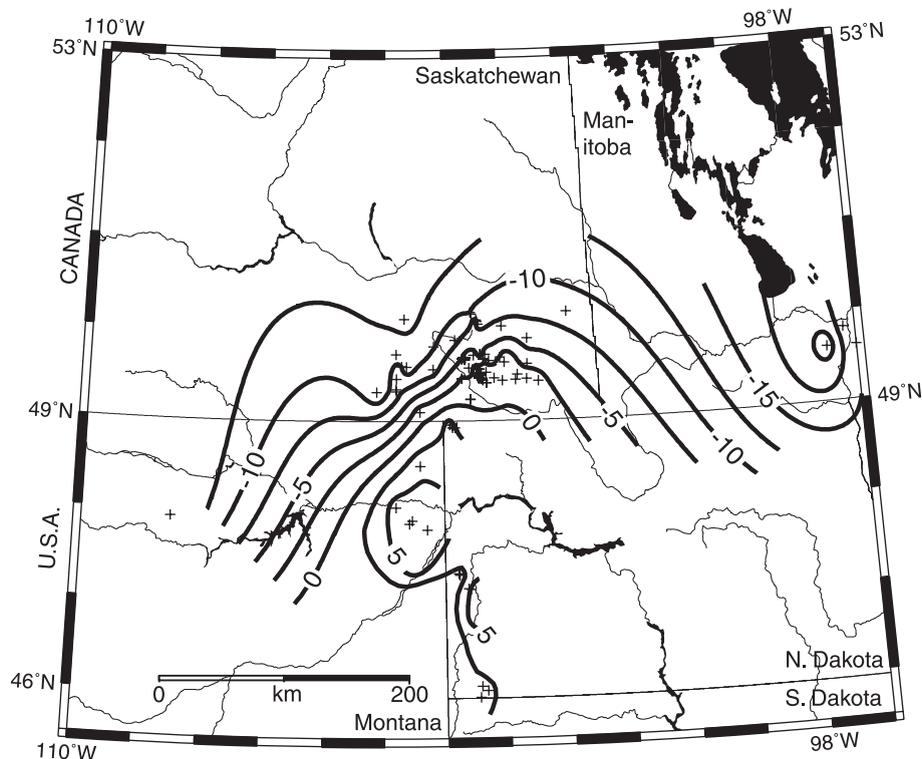


Fig. 1. Oxygen isotope composition of formation waters from the Yeoman aquifer, relative to Standard Mean Ocean Water (SMOW). Crosses are sample locations. Contour interval equals 2.5‰ SMOW.

Duperow aquifer are 0–150 m thick, mixed assortment of high- and low-permeability carbonates (limestones and dolostones), evaporitic units, along with layers of sandstones, siltstones, and shales belonging to the upper-Devonian aged Duperow Formation. The Duperow aquifer is bounded below by lower permeability strata belonging to the Souris River Formation (Middle Devonian), and above by a thin shale unit known locally as the Seward Member. Between the Yeoman and Duperow aquifers are several other basin-wide aquifers, most notably the regionally extensive Prairie aquitard—a halite and potash-bearing unit over 200 m thick in places.

Since 1996, we have collected >900 samples of produced waters and Drill Stem Tests from 15 different aquifers (ranging in age from Cambrian to Cretaceous) and surface samples across the Williston basin (Can-

ada–USA). Formation waters were collected from producing oil wells with high water cuts (>50% WOR) and from DSTs sampled from the bottom of the column of recovered water. Oil–water emulsions were sampled at the wellhead in 12 l pre-cleaned plastic jugs. The water fraction was passed through a 0.45- $\mu\text{m}$  filter and then aliquoted for field tests and laboratory analyses including temperature, density, pH, alkalinity, major and minor ions, and O, H, and Sr isotopes.

Only the oxygen isotope results are reported in this paper. Oxygen isotope measurements were performed by the  $\text{CO}_2\text{--H}_2\text{O}$  equilibration method following the procedure of Roether (1970). Samples were equilibrated for >48 h in a shaker bath at 25 °C to ensure equilibrium between  $\text{CO}_2$  and formation waters with high ionic strengths. Corrections for the

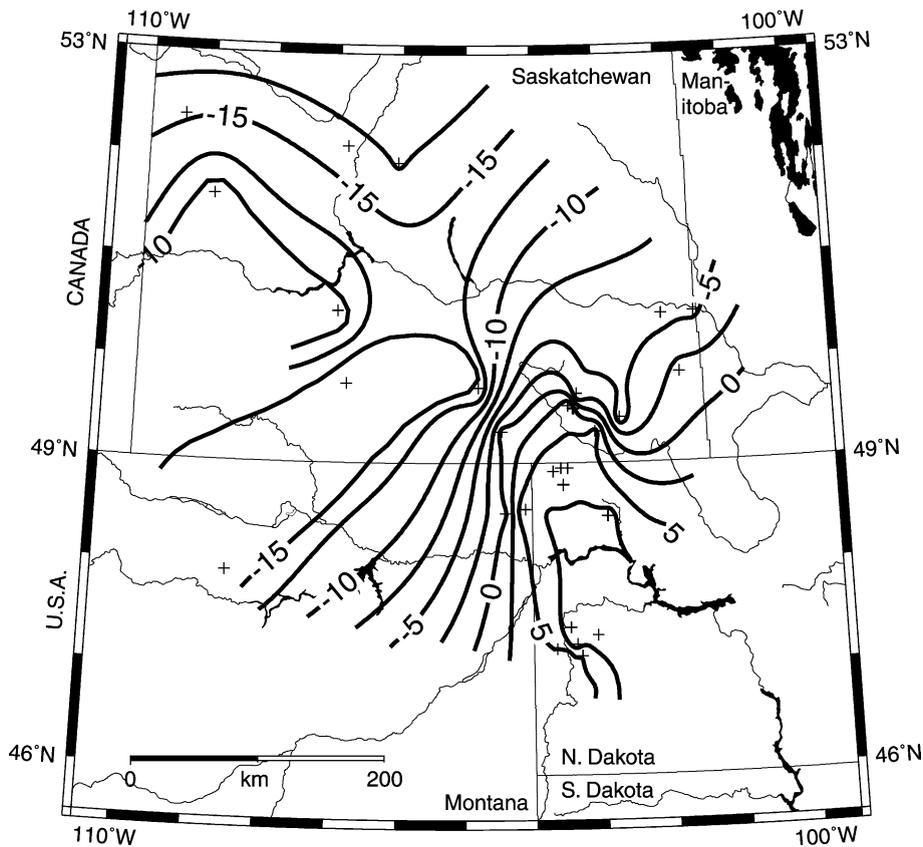


Fig. 2. Oxygen isotope composition of formation waters from the Duperow aquifer, relative to Standard Mean Ocean Water (SMOW). Crosses are sample locations. Contour interval equals 2.5‰ SMOW.

'salt effect' of Sofer and Gat (1972) were not applied.

## 2. Results

Mapped oxygen isotope compositions of formation waters from the Yeoman and Duperow aquifers are shown (Figs. 1 and 2). Isotopic compositions vary over an enormous range across the Williston basin, from less than  $-24\text{‰}$   $\delta^{18}\text{O}$  in the Yeoman aquifer (Fig. 1) to over  $9.4\text{‰}$   $\delta^{18}\text{O}$  in the Duperow aquifer (Fig. 2). As expected, samples of shallow groundwater recharging all formations in the basin to the southwest are relatively depleted ( $-18\text{‰}$   $\delta^{18}\text{O}$ ). Unexpectedly, the most depleted formation waters in the basin ( $-24\text{‰}$   $\delta^{18}\text{O}$ ) are found near the eastern margin of the basin in the so-called "discharge area" (Fig. 1). The heaviest isotopic compositions are found in the deepest portions of both aquifers in Montana and North Dakota. Isotopic compositions in the Duperow aquifer are approximately  $5\text{‰}$  heavier than in the Yeoman aquifer, both in terms of maximum values ( $9.4\text{‰}$  vs.  $5.5\text{‰}$ ) and overall areal distribution. The difference in areal distribution can be seen for example, by examining the area enclosed by the  $7.5\text{‰}$  contour, and the relative positions of the  $0\text{‰}$  and  $-10\text{‰}$  contour lines. There is no overall trend of increasing isotope concentrations with depth, as seen in other basins. In several cases, vertical isotope profiles display pronounced "reversals", with isotopic compositions getting lighter with depth (Rostron and Holmden, 2000). The observed isotopic compositions are interpreted to reflect regional fluid flow and hence mixing patterns across the basin.

## 3. Discussion

Mapped isotopic data in conjunction with routine water chemistry data point to a revised model of fluid flow for the Williston basin. The previous model envisaged fresh recharging waters moving into the basin and dissolving the Prairie Evaporite, generating the brines found in the center of the basin. Saline brines were thought to migrate up out of the basin under topographic drive, and discharge along the up-

dip flank of the basin to the east and northeast. The distribution of oxygen isotopes shown here points to a more complex paleohydrogeology for the basin. In particular:

- (1) Recharging groundwaters from the southwest do not pervasively penetrate all formations across the basin. Instead, they appear to preferentially move into the basin as fingers or "tongues" of isotopically light water. This can be seen, for example, in Fig. 2, where light recharge waters ( $<-15\text{‰}$   $\delta^{18}\text{O}$ ) extend across the basin from Montana into Saskatchewan.
- (2) There appears to have been down-dip flow of isotopically light formation waters in the discharge area of the basin in Manitoba. This has been attributed to recharge during Pleistocene glaciation (Grasby et al., 2000).
- (3) The brines in the center of the basin are part of a long-lived, very slow to stagnant, flow system there. Isotopically heavy waters correspond to previously mapped areas of evaporatively concentrated brines (Iampen and Rostron, 2000). This would suggest that the heavy stable isotopic compositions in the basin were produced either by evaporative concentration of original seawater, water-rock interactions after burial, or a combination of both mechanisms.
- (4) The lack of increase in isotopic composition with depth (hence temperature) suggests that fluid movement (mixing) must play a key role in controlling the stable isotope composition of fluids in the basin. One possible mechanism to produce lighter formation waters at depth is to have more rapid infiltration of recharge waters in Cambrian- to Silurian-aged aquifers beneath the Prairie Evaporite, thus creating layers of isotopically heavier waters in shallower, more isolated Devonian aquifers. On-going sampling and numerical modelling of groundwater flow are aimed at further understanding this phenomenon.

## 4. Conclusions

Isotopic signatures of formation fluids from the Yeoman and Duperow aquifers across the Williston basin were measured on fluid samples from produced

wells and Drill Stem Tests. Areal distributions of oxygen isotopes provide new insights into regional groundwater flow and mixing across the basin, including: (1) recharge waters infiltrate the basin in preferential areas laterally and vertically, producing lighter isotopes in deeper aquifers of the basin; (2) there is a slow flow to stagnant zone of brines in the deepest/central part of the basin; (3) recent glacial recharge is evident along the up-dip flank of the basin.

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