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Pre- and Post-Last Glacial Maximum Groundwater Recharge in a Glaciated Region

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ABSTRACT

Continental glaciations during the Pleistocene Epoch created complex systems of aquifers and aquitards across many northern regions of the Earth. Past measurements of δD and $\delta^{18}O$ measurements show that tills have retained subglacial meltwater but the behaviour of intertill and buried valley aquifers in these regions is less clear. Here, we characterize groundwater ages in these aquifers in Saskatchewan, Canada. Groundwater ages in intertill aquifers are predominantly younger than ~10.3 ka, indicating that they primarily contain water recharged after the retreat of the Laurentide Ice Sheet. Buried valley aquifers contained waters with ages >38 ka in some locations, indicating that recharge occurred prior to the Last Glacial Maximum (LGM). These ages suggest the presence of flow systems with recharge taking place both before and after the LGM, deemphasizing the importance of that event in emplacing groundwater resources in intertill and buried valley aquifers.

PLAIN LANGUAGE SUMMARY

Continental-scale glaciations have profoundly affected the geology and hydrology of northern regions. In many areas of Canada and the northern USA, meltwater beneath ice sheets was forced into the subsurface, forming groundwater resources that are still present today. In this study, we examined the distribution of groundwater ages in sand and gravel aquifers in Saskatchewan, Canada. These ages revealed that groundwater was primarily recharged either prior to the last major ice sheet advance in the region or following its retreat. Groundwater recharge to these groundwater reservoirs appears to have been ongoing during the past several thousand years and replenishment does not require another ice age.

1.0 INTRODUCTION

Pleistocene glaciation profoundly eroded northern landscapes, leaving behind glacial deposits that became widespread buried valley and intertill aquifers –important groundwater resources in many glaciated regions (e.g., Brosius et al. 2021; Porter 1989; Stephenson et al. 1988). These complex and heterogeneous aquifer systems were generated over numerous glaciations. For example, there were at least ten advances and retreats of the Laurentide Ice Sheet over the past ~1 Ma (Batchelor et al. 2019), eroding and depositing sediments across North America. Despite extensive knowledge of the overall history of Pleistocene glaciation (e.g., Christiansen 1979; Dalton et al. 2022), ice sheet extent (e.g., Christiansen 1979; Dalton et al. 2022) and resulting glacial deposits (e.g., Christiansen 1992; Cummings et al. 2012; Dawson et al. 1994; King & MacLean 1970; MDH 2011; Whitaker & Christiansen 1972), influences of these glacial and interglacial cycles on groundwater recharge to glacial sediments is less well understood.

Past studies have found very low hydraulic conductivity (Keller et al. 1988; Keller et al. 1991; Ferris et al., 2020) and diffusion dominated transport in the glacial tills of Saskatchewan

(Hendry & Wassenaar 2005; Hendry & Wassenaar 2011), suggesting that intertill and buried valley aquifer systems are isolated from one another and from the surface, resulting in the retention of Pleistocene groundwater. These studies have primarily relied on measurements of stable water isotopes in groundwater, inferring that low δD and $\delta^{18}O$ values that plot along the global meteoric water line (GMWL) indicate Pleistocene subglacial recharge (Hendry & Wassenaar 1999; Grasby et al., 2000). Groundwater with δD and $\delta^{18}O$ values overlapping with modern precipitation has been presumed to be 'modern'; however, there may be a much older groundwater component with similar values recharged during interglacial periods (North Greenland Ice Core Project members, 2004). Additionally, recharge may have been limited during some glacial periods due to the presence of permafrost beneath and adjacent to ice sheets (Edmunds and Milne, 2001; Bense and Person, 2008).

Groundwater age tracers can help constrain the timing and source of recharge; yet ^{14}C (Keller et al., 1988; Wassenaar & Hendry 2000) and ^{4}He (Hendry et al., 2005) dating has been only applied to select samples from till aquitards in a few locations. Groundwater ages in till aquitards correspond to recharge during the Last Glacial Maximum (~20 ka), where groundwater recharge is thought to have been as much as 10 times modern subaerial rates (Person et al., 2007). However, with limited datasets the distribution of groundwater ages in intertill and buried valley aquifers and recharge history throughout the Pleistocene in less well-constrained.

Here, we analyzed multiple age tracers (^{3}H, ^{14}C and ^{4}He), spanning from the present through the Pleistocene, noble gases, and stable water isotopes ($\delta^{18}O$ and δD) of groundwater from multiple intertill and buried valley aquifers in Saskatchewan, Canada (Figure 1a). Results provide key insights into how groundwater systems in glaciated regions have functioned before, during and after the LGM.

2.0 STUDY AREA

Saskatchewan has experienced eight to ten periods of substantial glacial advance and retreat over the past two million years, with the final glacial retreat between 17 ka to 10 ka (Christiansen, 1979). Glacial stratigraphy of the area is complicated by extensive faulting caused by subglacial recharge-induced dissolution of deep evaporite deposits and their subsequent collapse (Christiansen 1967; Grasby et al. 2000; Christiansen & Sauer 2001). Formation of numerous discontinuous and hydraulically separated stratified deposits occurred as the depressions left behind by faulting were filled in by tills during glaciation (MDH 2011).

The formations of interest are the Upper Cretaceous Lea Park, Judith River, and Bearpaw formations; the Empress Group ("buried valley aquifers"), which straddles the Neoogene-Quaternary boundary; and the Quaternary, Sutherland, and Saskatoon groups (Figure 1b). The Upper Cretaceous formations are generally non-calcareous shales of varying marine clay, silt, and sand content, which are spatially variant due to erosion (Dawson et al. 1994; McLean 1971; MDH 2011). Above the Bearpaw, the Tyner and Battleford Valleys were incised into bedrock predominantly before and during the first glaciation of the Pleistocene. Substantial clastic deposits, carried by meltwater, filled these valleys in the lowlands. The two buried valleys encompass slightly different areas—the Tyner Valley trends from southwest to central Saskatchewan while the Battleford Valley runs from northwest to central Saskatchewan (MDH 2011; Cummings et al., 2012). The Empress Group is divided into two units. The lower unit is Neogene in age and composed of stratified valley fill sediments (quartzite, chert, clastics, organics). The upper unit is Quaternary in age and was deposited during the first Pleistocene glacial advance and consists of clastic sediments derived from igneous, metamorphic, and carbonate rocks (MDH 2011; Whitaker & Christiansen 1972). The Sutherland Group is divided into the Mennon, Dundum, and Warman units, which are further subdivided into several till, intertill, and stratified units, that can be differentiated by carbonate and clay content, as well as the presence of paleo-oxidized horizons and/or intertill stratified deposits (Christiansen 1992; MDH 2011). The Saskatoon Group is divided into the Floral and Battleford units and surficial stratified deposits. The Floral and Battleford units can be differentiated from Sutherland Group units by their higher carbonate content and coarser lithology, and from one another as Floral Formation sediments can be delineated based upon the presence of paleo-oxidized horizons and/or intertill stratified deposits (MDH 2011). The uppermost unit of the Saskatoon Group is the surficial stratified deposits, which are postglacial sediments lain by fluvial, lacustrine, aeolian, and topsoil depositional processes (MDH 2011).

3.0 METHODS

3.1 Field Methods

Twelve monitoring wells were sampled June 9–17, 2022 (Figure 1a). A submersible pump was used to purge water from the well until temperature, pH, electrical conductivity (EC), oxygen reduction potential (ORP), and dissolved oxygen (DO) stabilized, prior to sample collection. All parameters were measured using a YSI Pro. All samples except for ^{14}C were field-filtered through a 0.45 μm nylon filter into pre-cleaned sample containers. Cation, anion, trace element, and alkalinity samples were collected into 30 mL high-density polyethylene (HDPE) bottles with minimal headspace. Cation and trace element samples were field-acidified with ultra-pure nitric acid to a pH < 2. Samples for $\delta^{18}O$ and δD of water were collected into 30 mL glass vials with conic tops and no headspace. ^{3}H was collected into 1 L HDPE bottles and carbon-13 ($\delta^{13}C$) of dissolved inorganic carbon (DIC) into 30 mL glass serum vials crimp sealed with no headspace. Unfiltered samples were collected for ^{14}C into 1 L glass amber bottles. All samples were stored on ice in the field and refrigerated in the laboratory to remain at or below 4 °C. Noble gases were collected by pumping water into copper tubes, which were crimp sealed and shipped to the Noble Gas Laboratory at the University of Utah (Solomon, 2000).

3.2 Laboratory Analysis

Alkalinity analysis was performed at the University of Arizona (UArizona)'s Department of Hydrology and Atmospheric Science using the Gran-Alk titration method (Gieskes & Rogers, 1973) with an analytical precision of ± 0.6%. Anions, cations, and trace elements were quantified at the Analytical Geochemistry Laboratory in the Department of Geological Sciences at the University of Saskatchewan. Anions (SO_4, Cl, F, Br, and NO_3) were measured using a Thermo Dionex Integriong HPIC system fitted with an IonPac AS11-HC-4 µm column (analytical precision of ± 1%). Cations (Ca, Mg, Na, K, Si) were measured using a SPECTRO Analytical Instruments SPECTROBLUE ICP-OES system (analytical precision of ±2%). Trace elements (B, Fe, Mn, Sr) were measured using a Thermo Scientific iCAP TQe ICP-MS system (analytical precision of ±2%). Charge balances for all samples were within 5%.

^3H and $\delta^{13}C$-DIC analyses were performed at UArizona's Department of Geosciences Environmental Isotopes Laboratory. ^3H was analyzed using a Quantulus 1220 Spectrometer in an underground counting laboratory using electrolytic enrichment and liquid scintillation decay counting methods (Theodorsson, 1996), with a detection limit of 0.5. $\delta^{13}C$-DIC was analyzed using a ThermoQuest Finnigan Delta PlusXL coupled with a Gasbench automated sampler with a precision of ±0.30‰ (VPDB).

$\delta^{18}O$and δD were analyzed at the USask's Hillslope Hydrology Lab using a Los Gatos Research liquid water Off-Axis Integrated-Cavity Output Spectrometer. Stable water isotope values are reported in parts per thousand (‰) relative to the Vienna Standard Mean Ocean Water and Standard Light Antarctic Precipitation (VSMOW-SLAP) standards. The 2-sigma uncertainties were ^{18}O (0.8‰) and δD (2‰). ^{14}C analyses were performed at the University of Ottawa's Andre E. Lalonde AMS Laboratory on an Ionplus AG MICADAS (Mini Carbon Dating System). Uncertainty on ^{14}C results (1σ) ranged from 0.01–0.07 percent modern carbon (pmC).

Noble gases (Ar, Kr, Xe, Ne, ^{4}He, $^{3}He/^{4}He$ ratio) were measured at the University of Utah's Noble Gas Lab. Measurement of all noble gases except helium were completed using a Stanford Research SRS – Model RGA 300 quadruple mass spectrometer; helium was analyzed using a Mass Analyzers Products – Model 215-50 magnetic sector mass spectrometer. Analytical precision for total concentration of the gases was Ar (±2%), Kr (±4%), Ne (±2%), Xe (±4%), ^{3}He (±1%), and ^{4}He (±1%).

3.3 Tracer Corrections

Uncorrected ^{14}C ages were corrected to account for geochemical reactions occurring in the subsurface—e.g., carbonate mineral dissolution—that impact ^{14}C activity by the addition of "dead carbon" (0 pmC ^{14}C), artificially increasing the apparent groundwater age (Clark and Fritz, 1997). To make these corrections, NetpathXL (Parkhurst & Charlton, 2008), a revised version of NETPATH (Plummer et al., 1994), was used. NetpathXL employs the revised Fontes and Garnier model of Han and Plummer (2013) and performs basic inverse modeling, based upon the major ion chemistry, $\delta^{13}C$-DIC, and radiocarbon values. The program then plots sample points on a graph, which depending on where the samples plot, indicates whether the Tamers model, gas exchange model, or solid exchange model should be used in radiocarbon age corrections. In this study, the ^{14}C and $\delta^{13}C$ of soil CO_2 were assumed to be 100 pmC and -25‰, respectively, and the ^{14}C and $\delta^{13}C$ of carbonate minerals were assumed to be 0 pmC and 0‰, respectively.

3.4 Helium-4 Corrections

To estimate ^{4}He ages, the contributions from atmospheric, mantle, and crustal sources had to first be deconvolved (Text S1). After delineating the components of ^{4}He, an aquifer accumulation rate was estimated based upon average aquifer properties (density, porosity, U, and Th) and was compared to the expected hydrologic ^{4}He aquifer accumulation rate that can be extrapolated from a plot of ^{4}He vs ^{14}C age. Finally, three different ^{4}He ages were estimated: 1) assuming all ^{4}He present was produced in-situ, 2) correcting ^{4}He for bulk crustal production, and 3) based on the ^{4}He aquifer accumulation rate. These computations and the various assumptions required are detailed at length by Craig & Lupton (1976), Torgersen (1980), Torgersen & Clarke (1985), Hilton (1996), Ballentine et al. (1996), Castro et al. (2000), Ballentine & Burnard (2002), and Saar et al. (2005).

4.0 RESULTS

4.1 Field Parameters, Major Ions, Trace Elements

Field parameters (Table S1), alkalinity, and major ions of groundwater samples were measured at all 12 observation wells (Table S2). Temperature ranged from 5.9–10.6°C, pH ranged from 7.10–8.42, and conductivity ranged from 1,300–4,389 µS/cm. Alkalinity ranged from 298–827 mg/L. Given that all samples had a pH < 9, bicarbonate (HCO_3) was assumed to be the dominant constituent of alkalinity. In general, four predominant groundwater types were observed: Ca-Mg-SO_4 (Saskatoon, Dalmeny, Tessier, Conquest 500, Conquest 502), Na-SO_4 (Tyner, Vanscoy, Nokomis), Ca-Mg-HCO_3 (Agrium, Unity, Lilac), and Na-HCO_3 (Hearts Hill). Finally, NO_3 was detected in six wells ranging from 0.54–25.3 mg/L.

4.2 Stable Isotopes

Stable water isotope values ranged from -21.1 to -16.2‰ and -163 to -137‰ for $\delta^{18}O$ and δD, respectively (Table S3; Figure 2). Most samples plot on or below the Local Meteoric Water

Line (LMWL) for Saskatoon (Koehler 2019), given by $\delta D = (\delta^{18}O \times 7.69 \pm 0.096) - 2.22 \pm 1.72$. The LMWL for Saskatoon has a lower slope and different y-intercept than the GMWL as reported in Craig (1961), where $\delta D = (\delta^{18}O \times 8.0) + 10$, consistent with Saskatoon's semi-arid climate. Given the strong correlation between $\delta^{18}O$ and δD values of groundwater samples ($R^2 = 0.967$; $P = 4.33x10^{-15}$), further discussion of stable water isotopes will be limited to $\delta^{18}O$.

4.3 Radioactive Isotope Age Tracers

^3H was detected at four locations: Saskatoon (0.7 ± 0.28 TU), Dalmeny (0.9 ± 0.31 TU), Conquest 500 (2.9 ± 0.18), and Tessier (< 0.6 TU; apparent 0.3 ± 0.21 TU) (Table S3). In the other remaining wells, ^3H was below detection. ^{14}C was detected at ten of twelve locations with uncorrected ^{14}C ranging from 0.69–62.0 pmC. At two locations (Tyner and Vanscoy) ^{14}C was non-detect (< 0.51 pmC). Geochemical modeling using NetPathXL (Parkhurst and Charlton, 2008) produced corrected ^{14}C 'ages' ranging from modern to 43.1 ka; excluding Nokomis (43.1 ka), groundwater ^{14}C ages were much younger, ranging from modern to 15.5 ka.

4.4 Noble Gases

Noble gas (He, Ne, Ar, Kr, Xe) concentrations were measured at all twelve locations, however the focus of this study pertains to the light noble gases (He, Ne, Ar) and their pertinent isotope relationships ($^3He/^4He$, $^4Ne/^{20}Ne$, $^{40}Ar/^{36}Ar$) (Table S4). Air corrected R_c/R_a values ranged from 0.008–0.332 (Text S1; Table S4), with estimated mantle contributions of ^4He ranging from 0.0–3.9% (Table S5) using aquifer and crustal parameters consistent with the region and subsurface setting (Table S6). Estimated ^4He ages assuming all ^4He was produced in-situ ranged from 14.4–12,787 ka; estimated external flux-corrected ^4He ages ranged from 0.02–15.6 ka; and ^4He ages based on the aquifer accumulation rate ranged from 6.14–73.5 ka (Table S5). The

$^4He/^{20}Ne$ ratio ranged from 0.31–124 , with all samples except one (Conquest 500) exceeding the $^4He/^{20}Ne$ ratio for air (0.319), generally indicative of excess air during recharge. Noble gas data from Conquest 500 suggest that fractionation occurred during either sampling or laboratory processing. Because it is unclear how and to what extent fractionation occurred, this sample was excluded from ^4He age calculations. A linear regression between ^4He concentrations and ^{14}C ages (Figure 3) had the following equation:

$$^{14}C\ age = 0.197\ ^4He + 6.14 \qquad [1]$$

This relationship had an R-squared of 0.938, which is significant at *p = 0.0167* and predicts groundwater ages of 40.5 ka at Tyner and 73.5 ka at Vanscoy

5.0 DISCUSSION

A prevailing view of Pleistocene and early Holocene-aged groundwaters in glaciated regions is that these waters originated as subglacial meltwater (Grasby et al., 2000; Person et al., 2007; McIntosh et al., 2012; Ferguson & Jasechko, 2015). However, the study area is thought to have been free of glacial ice for most of the period between ~75 to 20 ka (Dredge & Thorleifson, 1987; Dalton et al., 2022) and after ~12 ka (Christiansen 1979; Dalton et al., 2020) (Figure 4). This suggests much of the groundwater in intertill and buried valley aquifers in the study area has an origin other than subglacial meltwater.

Groundwater in the intertill aquifers had ^{14}C ages ranging from 0.0–10.3 ka, aside from one well (Saskatoon) with an age of 15.5 ka. These values are younger than the youngest glacial tills in the study area (Christiansen 1979; Christiansen 1992), indicating that much of the groundwater present in these upper intertill aquifers has recharged since the last retreat of the Laurentide Ice Sheet. The presence of ^3H, which was sourced from nuclear weapons testing in the

1960s (Clark & Fritz, 1997; Gleeson et al., 2016; Lindsey et al., 2019), indicates that these aquifers have received modern recharge in some areas. Nitrates, which commonly indicate that groundwater that has been affected by fertilizer application in agricultural areas (Power & Schepers, 1989; Burow et al., 2010), are present at concentrations also indicative of the presence of modern recharge. The major ions further suggest a chemistry that is less evolved in intertill aquifers than in the older groundwaters found in buried valley aquifers, with Ca-Mg-HCO_3 and Ca-Mg-SO_4 present in the former and Na-SO_4 found in the latter (Palmer & Cherry, 1984).

Groundwater ages closer to the LGM are present at the Saskatoon well have also been observed in Sutherland Group tills in the study area by others, where uncorrected ^{14}C ages ranging from 19.9–24.8 ka were observed (Keller et al., 1988). The range of ages in this study suggests that these older groundwaters are not always preserved due to active flushing within these subregional groundwater flow systems. For example, the Dalmeny aquifer has a modern hydraulic gradient of ~0.002 over a flow system ~ 10 km in length (Fortin et al., 1991). The aquifer has a typical porosity of 0.30 and hydraulic conductivity of 5 x 10^{-5} m/s (MDH, 2011). This gradient, hydraulic conductivity, and porosity provides a groundwater velocity of ~2 m/yr, which would result in flushing of Pleistocene-aged groundwater from this aquifer. Replenishment of intertill aquifers appears to be occurring under current climate conditions.

Groundwater ages in some buried valleys were near or beyond the limit of ^{14}C dating. Estimates of groundwater age based on ^{4}He concentrations and in-situ production and diffusive fluxes were not in agreement with ^{14}C dates, likely because upward diffusion of ^{4}He has not reached steady state in these sediments (Hendry et al., 2005). Groundwater ages of 40.5 ka at Tyner and 73.5 ka at Vanscoy estimated from the relationship between ^{4}He and ^{14}C, the study area was to the south of the Laurentide Ice Sheet when these waters were recharged, except for a brief advance ~60 ka (Dalton et al., 2022).

These ^{14}C ages found in buried valley aquifers indicate that these groundwater flow systems have been flushed, potentially many times, since their deposition in the late Pliocene to early Pleistocene. The absence of younger water in the Tyner Valley (Tyner and Vanscoy) and Hatfield Valley aquifers (Nokomis) indicate that the aquifers have not received recharge since the LGM, perhaps due to the deposition of youngest glacial till aquitards during the late Wisconsinan glaciation. Groundwater age does not have an obvious relationship with regional groundwater flow system in these aquifers. The two samples from the Tyner aquifer are separated by ~150 km and appear to have similar ages based on their ^{4}He concentrations. Hydraulic head data is scarce from this aquifer but based on their proximity to major river valleys, groundwater flow is southward at Tyner and northeastward at Vanscoy. The presence of a similar groundwater age in a separate buried valley aquifer at Nokomis indicates that groundwater flow systems changed and perhaps "deactivated" to some extent during the late Wisconsinan glaciation.

The one bedrock aquifer sample taken in this study was from the Judith River Formation and had a ^{14}C age of 10.2 ka. This suggests the occurrence of groundwater recharge since the LGM and suggests the presence of a system that is flushing older waters. Groundwater flow is towards the south in this region with discharge occurring to the South Saskatchewan River approximately 20 km south of the well that was sampled (Ferris et al., 2017). Water originating in the LGM or earlier could be present downgradient of this well.

The relationship between groundwater age and δD and $\delta^{18}O$ may not be as straightforward as suggested in some previous studies. Multiple studies of groundwater in bedrock aquifers in the Canadian Prairies have used a shift in δD and $\delta^{18}O$ values similar to those in modern recharge to lower values as an indication of the presence of Pleistocene meltwater (Grasby et al., 2000; Grasby & Betcher, 2002; Ferguson et al., 2007). Such a shift is not obvious in the data collected in this study (Figure 4). In intertill aquifer samples, $\delta^{18}O$ values ranges from -21.1 to -16.2‰. In samples with ^{14}C ages < 5 ka, $\delta^{18}O$ values are between -19.7 and -16.2‰, while the Saskatoon sample, with ^{14}C age of 15.5 ka has a $\delta^{18}O$ value of -19.6‰. $\delta^{18}O$ values associated with older groundwater samples in buried valley aquifers have values of -20.6 to -18.5‰, showing no obvious difference from samples with ages corresponding to the LGM or Holocene.

6.0 SUMMARY & CONCLUSIONS

This study used groundwater age tracers of varying timescales (^{3}H, ^{14}C, ^{4}He), noble gases, and stable water isotopes to examine the recharge history and connectivity of multiple, stacked glacial intertill aquifers in southern Saskatchewan, Canada. The majority of groundwater present throughout the upper Sutherland and Saskatoon group intertill aquifers was recharged after the LGM (i.e., < 10.3 ka), and in several areas contains a component of modern recharge (< 60 years old). Pleistocene glacial meltwater, still retained in adjacent till aquitards, must have been flushed by regional groundwater flow, which appears to have been operating throughout the Holocene. This suggests that groundwaters in these aquifers is being replenished under currently conditions, although at low rates. Groundwater in the buried valley aquifers of the Empress Group is substantially older than the overlying Sutherland and Saskatoon groups, with recharge likely occurring during interglacial periods from 75–40 ka when southern Saskatchewan was ice-free. Groundwater in the underlying Judith River Bedrock is similar in age to the Sutherland and Saskatoon groups, suggesting post-LGM recharge.

No trends were observed in $\delta^{18}O$ and δD values compared to groundwater age, reflecting the presence of waters recharged both before and after the LGM. Glacial periods undoubtedly affected the hydrogeology in the study area, but subglacial recharge does not make up the bulk of water in intertill and buried valley aquifers. Recharge and regional groundwater flow appear to have been functioning, likely at variable rates, throughout the late Quaternary. Caution should be exercised when interpreting the effect of paleoclimate events on groundwater flow systems without sufficient age tracer data that provide sufficient temporal and spatial coverage.

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Figures

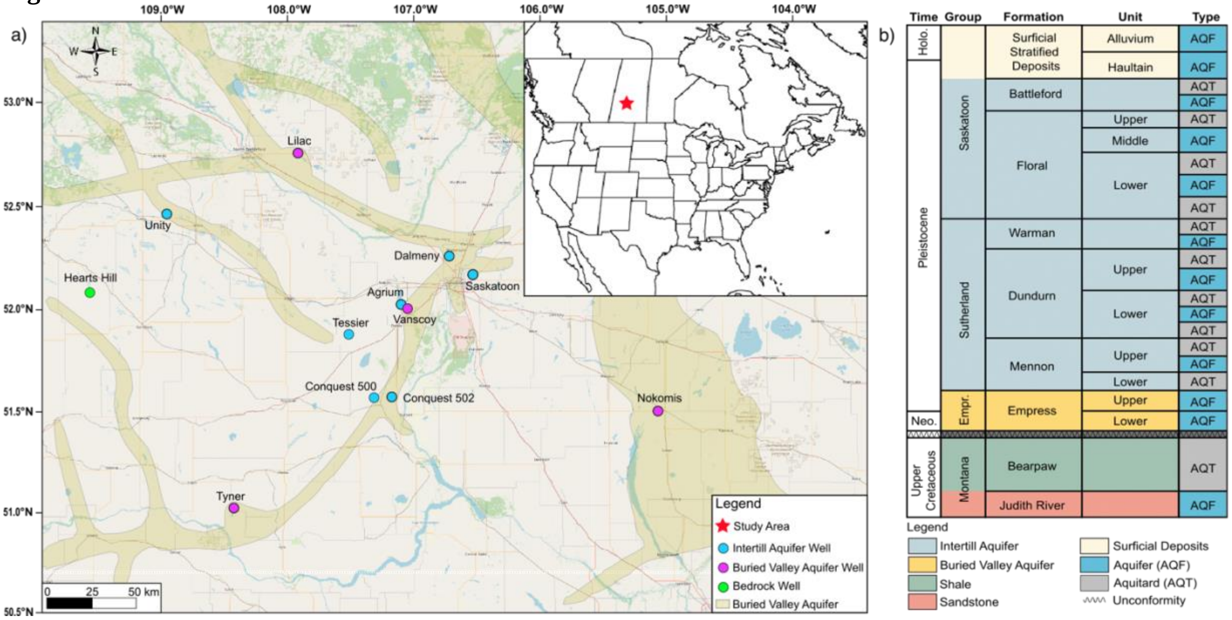

Figure 1: Site map (a) showing sampled wells, aquifer type, and the approximate extent of buried valley aquifer locations (buried valley aquifer shape file modified from Cummings et al. 2012) Generalized stratigraphic column (b) showing time, group, formation, unit, and type (aquifer/aquitard) of the study area. Modeled after Christiansen (1992) and MDH (2011).

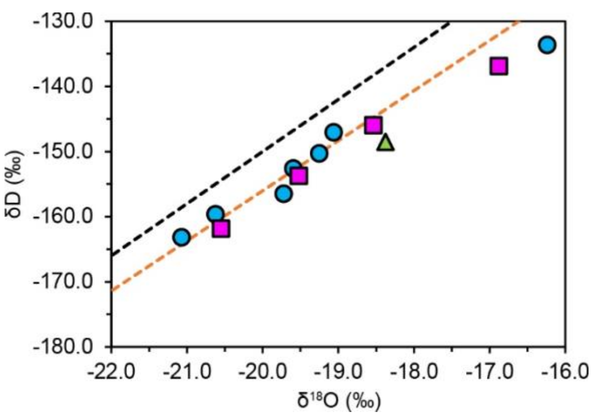

Figure 2: Stable water isotope values of intertill (*blue circles*), buried valley (*magenta squares*), and bedrock (*green triangle*) aquifers relative to the Global Meteoric Water Line (*dashed black line*) (Craig 1961) and Local Meteoric Water Line (*dashed yellow line*) (Koehler 2019).

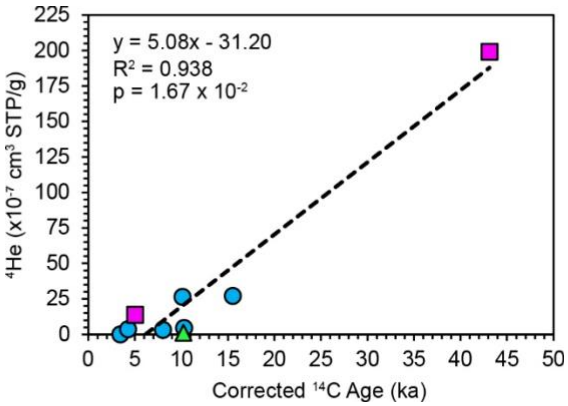

Figure 3: Corrected ^{4}He (cm^3 STP/g) versus corrected ^{14}C age (ka) of intertill (*blue circles*), buried valley (*magenta squares*), and bedrock (*green triangle*) aquifers and the linear correlation (*black dashed line*) between these parameters.

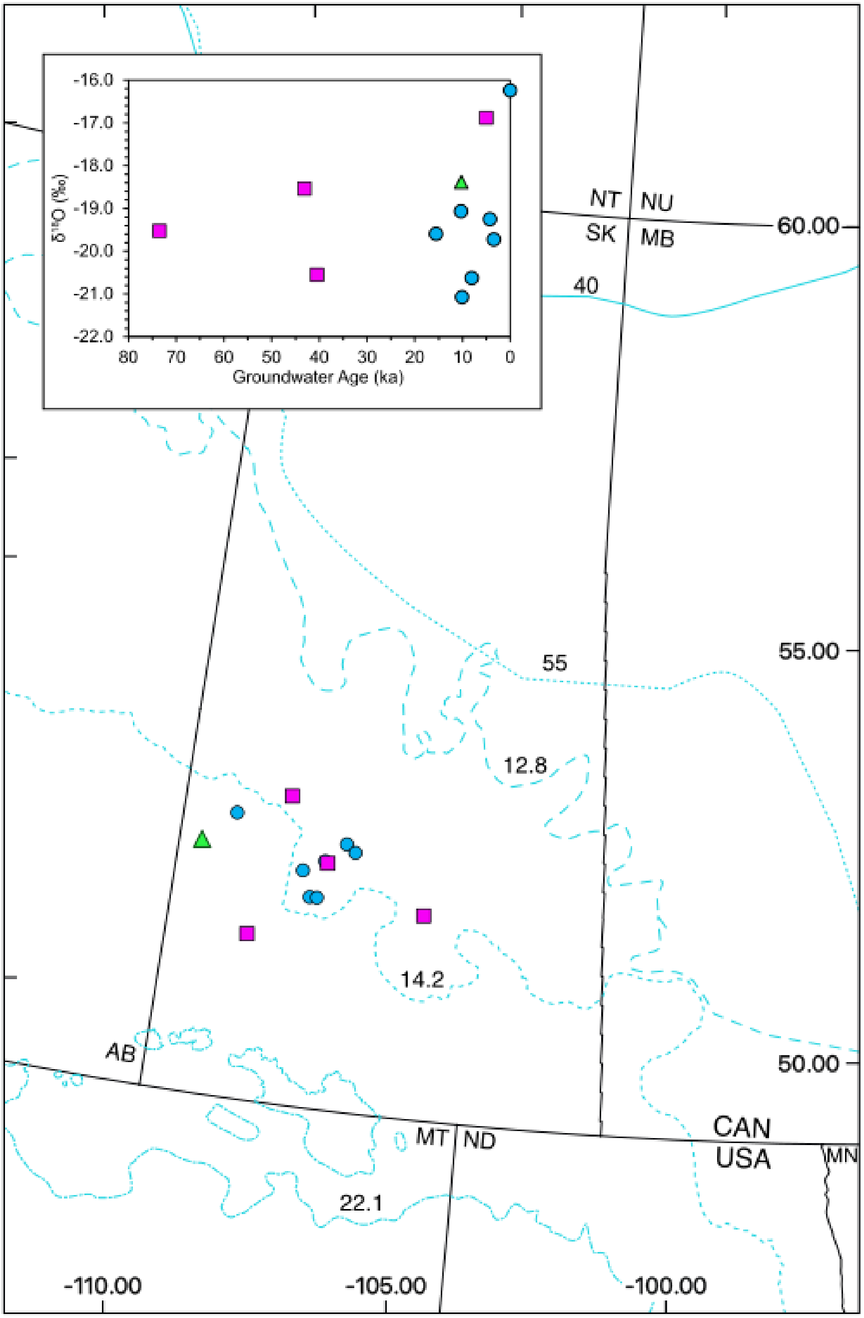

Figure 4: The southern extent of the Laurentide Ice Sheet (ages in ka) was beyond the study area during the LGM (i.e., 22.1 to 14.2 ka) for intertill (*blue circles*), buried valley (*magenta squares*), and bedrock (*green triangle*) aquifers. The study area has been ice-free since at least 12.8 ka and for much of the time prior to the LGM back to 65 ka. $\delta^{18}O$ (‰) shows no clear relations with groundwater age for intertill (*blue circles*), buried valley (*magenta squares*), and bedrock (*green triangle*) aquifers. Note: groundwater age is the corrected ^{14}C age or estimated age based on the ^{4}He versus ^{14}C relationship where samples were non-detect for ^{14}C.