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Groundwater age investigation of eskers in the Amos region, Quebec, Canada

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SUMMARY

Noble gases, in particular $^3He/^4He$ (R) ratios, were measured together with tritium activity in groundwater from eskers and moraines of the Abitibi-Temiscamingue region of northwestern Quebec (eastern Canada). These high-latitude glaciofluvial landforms contain precious freshwater resources that need to be quantified. Here we provide estimates of residence time for groundwater in glaciofluvial sediments forming the Saint-Mathieu–Berry (SMB) and Barraute eskers, the Harricana moraine and in the underlying fractured bedrock aquifer. The $^3He/^4He$ ratios range from 0.224 ± 0.012 to 1.849 ± 0.036Ra, where Ra is the atmospheric $^3He/^4He$ ratio (1.386×10^{-6}). These results suggest the occurrence of ^3He produced by decay of tritium and terrigenic ^4He produced by decay of U and Th. Calculated $^3H/^3He$ apparent ages of groundwater from the SMB esker and the Harricana moraine range from 6.6 ± 1.1 a to 32 ± 7.4 a. Terrigenic ^4He ($^4He_{terr}$) was found in the deeper wells of the SMB esker and in the wells tapping water from the deeper fractured aquifer located below the eskers and moraines and confined by postglacial clays. The amount of $^4He_{terr}$ ranges from 3.4×10^{-9} to 2.2×10^{-6} cm^{3}STP g^{-1} and shows a clear gradient with depth, suggesting addition of a $^4He_{terr}$ flux entering the bottom of the eskers. Modeled $^4He_{terr}$ fluxes range from 2.0×10^{-8} cm^{3}STP cm^{-2} yr^{-1} at the Harricana moraine to 6.6×10^{-7} cm^{3}STP cm^{-2} yr^{-1} in the southern section of the SMB esker. Calculated fluxes are highly variable and 5–165 times lower than the helium continental crustal flux, suggesting local helium sources, with helium being driven upward through preferential pathways such as local faults. Maximum U–Th/^{4}He ages obtained for the groundwater in the fractured bedrock range from 1473 ± 300 a to 137 ± 28 ka, suggesting the occurrence of several generations of fossil meltwater trapped under the clay plain after the last two glaciations.

1. Introduction

Continental areas of the Northern Hemisphere, notably Canada, were severely affected by ice cover during the late Pliocene and Pleistocene. A wide range of glacial and deglacial landforms were formed during this period, notably eskers, which consist in long, linear and relatively narrow ridges composed of stratified sand and gravel. Eskers were mainly deposited within ice-walled tunnels by highly organized meltwater flow systems (e.g., Banerjee and McDonald, 1975; Shilts et al., 1987; Clark and Walder, 1994). Moraines also represent heterogeneous accumulations of sand and gravel that were generally deposited at or near the ice margin during ice retreat. From a hydrogeological perspective, these landforms (eskers and moraines) may be considered equivalent entities due to their similar composition (sorted granular material).

The last deglaciation in the Abitibi-Temiscamingue region, Quebec (Fig. 1), was marked by the breakup of the ice margin into two lobes, as recorded by the Harricana interlobate moraine, a large body of sand and gravel oriented north–south that extends for several hundred kilometers (Veillette, 1996; Dyke, 2004). Ice retreat resulted in the deposition of eskers that show two different trends: those oriented NW–SE to the west of the Harricana moraine, and those oriented NE–SW to the east of this major landform (Veillette et al., 2004, 2007). Meltwater produced during the deglaciation also led to the development of Lake Ojibway, a large proglacial lake that inundated the area. As a result, thick accumulations of fine-grained

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rhythmites (clay and silt) cover entirely or partially most eskers, thereby forming confined or semi-confined aquifers, with porosity reaching up to 30% near the core of the landform. The groundwater has generally very low salinity and excellent organoleptic characteristics as drinking water, which is commercialized as the bottled water ESKA® near the city of Amos. Accordingly, these eskers and the Harricana moraine represent an important water resource in this area, as its quality is superior to slightly salty groundwater from the fractured bedrock. The hydraulic regime of these systems is not fully understood, mainly because of the spatial complexity and heterogeneous character of these glaciofluvial deposits (Boulton et al., 1995, 2009).

The hydrogeology of this area has been recently the focus of a study by the *Université du Québec en Abitibi-Témiscamingue* (UQAT) (Cloutier et al., 2011, 2013). The goals of this study were to better understand the hydraulic regime of eskers and moraines, and to assess their potential as a long-term source of drinking water in the region, as well as to evaluate their vulnerability to pollution (Cloutier et al., 2013). Except for a few unpublished ^{14}C ages (Riverin, 2006) and ^{3}H measurements (Castelli, 2012), there are no chronological constraints on the groundwater of this region. The aim of this work was to fill this gap by producing $^{3}H/^{3}He$ and U–Th/^{4}He residence times based on noble gases measurements of groundwater, and to provide a basis for future high-resolution groundwater age surveys.

2. Geology and hydrogeology of the studied area

The study area (Fig. 1a) has a surface area of 860 km^2 and includes the municipalities of Amos, Barraute, La Motte and Landrienne, in Abitibi-Temiscamingue, Quebec, Canada. This region lies on crystalline bedrock of the Canadian Shield, more specifically in the Abitibi greenstone belt of the Superior Province, which is upper Archean in age (2.85–2.65 Ga). The bedrock is composed of mafic to intermediate volcanic rocks intercepted by lenses of felsic volcanic rocks and metasediment belts (wacke, conglomerates and iron formations). These lithologies are intruded by Archean granitic and tonalitic plutons (and later by Proterozoic diabases) and cross-cut by gneissic rocks (Weber and Latulippe, 1964). Precambrian metamorphic rocks constitute an aquifer characterized by a low hydraulic conductivity whose potential increases locally with fractures and fissures (Cloutier et al., 2007).

The Abitibi-Temiscamingue region was completely covered by the Laurentide Ice Sheet during the last glacial cycle and deglaciation began at ~9 ka (Dyke, 2004). Progressive thinning of the ice margin led to the isolation of the Hudson Bay ice dome and the New-Quebec ice dome, in between which a major complex of glaciofluvial sediments was deposited (the Harricana interlobate moraine; Fig. 1) along with a dense network of eskers (Veillette et al., 2003). Subsequent ice retreat occurred away from the Harricana glaciofluvial sediment complex, toward the northwest and northeast, in contact with the waters of glacial Lake Ojibway (Veillette, 1994; Roy et al., 2011). These deglacial landforms are composed of heterometric and chaotic accumulations of pebble, gravel and sand derived from the glacial erosion of the local Archean bedrock (Veillette et al., 2004). The study area is crossed, from west to east, by three major glaciofluvial bodies: the Saint-Mathieu–Berry (hereafter denoted as SMB) esker, the Harricana interlobate moraine and the Barraute esker (Fig. 1a). The SMB esker is 120 km in length, 25–45 m thick, and 1–5 km wide. The Harricana moraine is the most voluminous in the region, with a total length of 278 km and a maximum width of 4.4 km. The Barraute esker is 20 km in length, with height and width resembling the SMB esker.

Eskers and moraine are deposited on the Precambrian bedrock, sometimes separated by glacial deposits (tills). Glacial deposits can be continuous with a thickness of several meters or discontinuous with a thickness of less than 1 meter (Cloutier et al., 2013). Often isolated patches of tills are found in glacially scoured bedrock depressions, protected from glacial erosion. The extension of these deposits under the eskers is difficult to evaluate because they are often mixed with glaciofluvial deposits (Cloutier et al., 2013).

The presence of Lake Ojibway left a strong imprint on the landscape (Roy et al., 2011). Thick accumulations of fine-grained glaciolacustrine sediments cover most deglacial features (eskers and ice-marginal deposits, such as moraines). The vast expanses of Ojibway clay form a very low permeability unit, which might confine totally or partially the esker's aquifers (Veillette et al., 2004). The Ojibway clay plain is broken in places by rare bedrock knobs (hills) and the crests of some eskers or the Harricana moraine (Fig. 1a). Eskers deposited near the former lake level may be reworked into beaches onto their crests or flanks, whereas eskers deposited in deep-water conditions may be associated with subaqueous outwash fans.

This particular depositional environment led to a classification of eskers of the Abitibi-Temiscamingue region into four types (A–D) on the basis of the depositional setting and sedimentological characteristics of the confined and unconfined eskers (Veillette et al., 2004, 2007; Nadeau, 2011). In the study area, eskers are of type C, which consists in eskers and moraines partially confined by clay (SMB and Harricana), and of type D that consists in eskers completely buried by clay (parts of SMB and Barraute). This classification may vary for a given esker, mainly due to changes in the clay cover along its length. Direct recharge from precipitation occurs in partially confined aquifers (eskers type C) while recharge areas of buried landforms (such as Barraute esker) remain to be fully determined. For example, the Harricana moraine, located about 10 km to the west of the buried Barraute esker, could correspond to its recharge zone (Veillette et al., 2007). This moraine, partially covered by clays and characterized by a high permeability, is directly recharged by rainfall. Accordingly, water from this formation is expected to be young. South of this moraine, the elevated zone of Mont Video (Fig. 1a) could be a preferential recharge zone for both the Harricana moraine and the nearby Barraute esker (buried). In the SMB esker, two types of flow were documented (Riverin, 2006). One is longitudinal and controlled by the topography of bedrock, with water moving from the southern and northern elevated zones toward the center of the esker. The second flow is transversal to the esker and originates from infiltration toward the edge of the esker and is subsequently diffused into bogs or contact zones between clay and gravel.

Groundwater flows rapidly within the highly porous (porosity ~25–30%) and permeable gravel aquifers formed by eskers. A detailed geochemical study of springs associated with eskers showed that the water is mainly of Ca–HCO_3 type, with average total dissolved solids (TDS) of 87 mg L^{-1} (Castelli et al., 2011). However, the bedrock is locally fractured and local aquifers show higher salinities reaching 760 mg L^{-1} (Table 1). Riverin (2006) estimated qualitatively groundwater residence times for the SMB esker. Tritium (^{3}H) measurements and uncorrected ^{14}C ages pointed to the presence of an active (top part of the aquifer) and a less active (lower portions of the confined aquifer) flow zones. Based on uncorrected ^{14}C ages, these zones might contain modern (1–25 a), intermediate (300–6000 a) and fossil groundwater (>6000 a) (Riverin, 2006).

3. Sampling and analytical methods

A total of fifteen groundwater samples (Fig. 1a; Tables 1 and 3) were collected in the study area during the summers of 2011